Andrew Y.C. Nee · Bin Song · Soh-Khim Ong *Editors*

Re-engineering Manufacturing for Sustainability

Proceedings of the 20th CIRP International Conference on Life Cycle Engineering, Singapore 17–19 April, 2013

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Andrew Y.C. Nee, Bin Song, and Soh-Khim Ong (Eds.)

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Preface

For two decades, the CIRP Life Cycle Engineering (LCE) Conference has continued its steady course since its creation. It has grown significantly beyond its original scopes and objectives and has seen researchers in this field doubled and tripled in the last 10 years. Sustainable manufacturing is a major initiative of almost all the manufacturing industries worldwide, in an effort to prolong the life of products, reduce the use of toxic materials and carbon footprint, conserve energy, not only for meeting the needs of the manufacturers and consumers, but also the multi-stakeholders in the entire business chain.

In 2013, Singapore has the honor of hosting the 20^{th} CIRP LCE, with its organizers from SIMTech , the Singapore Institute of Manufacturing Technology and the National University of Singapore. For Singapore, this is a major CIRP event since the General Assembly which was held in 1994.

The conference has accepted some 117 papers from 28 countries. All the papers have been subject to the rigorous peer review and revision process by experts in the field. The topics covered in LCE2013 include Sustainabledesign – approaches and methodologies, methods and tools; Methods and tools for resource efficient manufacturing; technologies for energy efficient machine tools; Sustainable manufacturing process – machining, cleaning, coating, forming and molding; Analysis and tools for reuse and recycling; Supply chain management; Sustainability analysis – methodologies and tools, various case studies; Sustainability management; Remanufacturing – business and management, design and analysis, process technologies, reliability assessment; Social sustainability.

Keynote speeches will be delivered by eminent researchers in the field of LCE: Prof ShahinRahimifard from Loughborough University, Prof Nabil Nasr from Rochester Institute of Technology, Prof I S Jawahir from University of Kentucky, Prof Zhang Hong-Chao from Texas Tech University.

We would like to thank all the reviewers, authors, support from the National University of Singapore and SIMTech, and all the participants for making LCE2013 a real success. We understand that some participants travel no less than some 15 hours to come to Singapore, and it could also be their very first visit. We wish them a most pleasant stay, and enjoy the food, culture, and the latest attractions in Singapore, in addition to fruitful discussion at the Conference.

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How to Manufacture a Sustainable Future for 9 Billion People in 2050

Shahin Rahimifard, Leila Sheldrick, E. Woolley, J. Colwill, and M. Sachidananda

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Abstract

There is a growing body of evidence which increasingly points to serious and irreversible ecological consequences if current unsustainable manufacturing practices and consumption patterns continue. Recent years have seen a rising awareness leading to the generation of both national and international regulations, resulting in modest improvements in manufacturing practices. These incremental changes however are not making the necessary progress towards eliminating or even reversing the environmental impacts of global industry. Therefore, a fundamental research question is: 'How can we meet the long term demand of our growing global population, and in this context, what are the key challenges for the future of manufacturing industry?' A common approach adopted in such cases is to utilise foresighting exercises to develop a number of alternative future scenarios to aid with long-term strategic planning. This paper presents the results of one such study to create a set of 'SMART Manufacturing Scenarios' for 2050.

Keywords:

Foresighting; Strategic Planning; Future Manufacturing Scenarios

1 INTRODUCTION

Our society and environment are changing at an unprecedented rate. Rapid industrial development and economic growth, brought on by staggering advancements in technology, are taking place at the expense of the environment. As we come to understand more about the biophysical constraints of our planet and the impacts of human activities, the growing scale of the challenge ahead is becoming clear.

In particular, the impact of manufacturing activities on the environment has become an area of great focus and concern at all levels, from public through to industry and government. A range of initiatives, investments and regulations have been put in place to mitigate the effects of manufacturing activities, however, at present these are at best just managing to slow down the rate of growth in environmental impact, as opposed to eliminating or reversing the damages caused.

In this context, a great deal of work has been conducted in recent years to better understand the future global requirements. It has been estimated that by 2050 the global population will have risen to over 9 billion [1] and that greenhouse gas (GHG) emissions will have increased by over 50%, driven primarily by a projected 80% rise in global energy demand [2]. When considering that we need to reduce our GHG emissions by 80% (compared to 1990 levels) in order to limit global warming to a maximum increase of 2ºC [3], this predicted rapid increase in future emissions presents serious economic and ecological concerns that require immediate attention.

Furthermore, studies have shown that if everyone in the world consumed at the rate of the average U.S. resident, we would need the resources of 4.5 Earths to sustain this [4] and the world's proven oil reserves would be consumed in less than 10 years [3]. It has also been predicted that current reserves of copper, zinc, lead, nickel, tin, silver, and gold will be depleted by 2050 [5], and a study by Gardner-Outlaw and Engleman [6] states that by 2050 up to 4 billion people could live in areas facing water scarcity or stress.

These predictions give a clear indication that current efforts to reduce impacts are not enough and therefore a radical new approach is needed; as depicted in Figure 1. In order to identify such radical improvements, foresighting and scenario planning approaches are often used by both commercial and governmental organisations to generate strategic insights. In times of high uncertainty, these methods help to understand the challenges and opportunities which lie ahead by enabling complex future scenarios to be visualised through the combination of two key facets, i.e. facts and perceptions [7].

By considering both quantitative and qualitative factors, scenario planning methods go beyond the reach of conventional planning to give a fresh, in-depth perspective. These approaches can be used by companies to systematically identify the most influential factors affecting their industry, and to explore corresponding critical change drivers through informed long term strategic planning activities.

This paper describes one such scenario planning study undertaken with a specific focus on the manufacturing industry. The first part discusses a number of existing foresighting applications and describes the methodology used to generate the 'SMART Manufacturing Scenarios' (SMS). The main section provides an overview of the critical drivers which will shape future industry, and utilises a target year of 2050 to identify four feasible scenarios for future manufacturing.

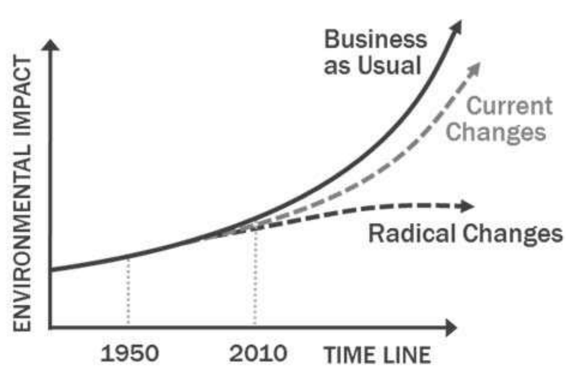

Figure 1: Environmental Impacts Projections.

2 SCENARIO PLANNING IN PRACTICE

Developed in the middle of the twentieth century, scenario planning was firmly established in the corporate world as a 'strategic planning tool' at Royal Dutch Shell by Pierre Wack [8] who stated:

"*Scenario planning aims to rediscover the original entrepreneurial power of foresight in contexts of change, complexity, and uncertainty. It is precisely in these contexts – not in stable times – that the real opportunities lie to gain competitive advantage through strategy*."

To this day, Shell remains world leader in developing scenarios and continues to offer advice to others who wish to conduct their own studies [9]. Their most recent forecasts discuss the effects of governmental and social behaviours on energy supply and put forward two opposing future scenarios [10]. These are utilised internally by viewing each through a set of **'lenses'** which consist of different 'recession and recovery' outlooks based on the effects of the recent global economic crisis. This helps them to be more responsive to change in an uncertain market by accounting for, not only the key drivers directly affecting their industry, but also for globally uncertain factors.

The precedent set by Pierre Wack and Shell has seen a broad uptake of scenario planning activities in recent years. As environmental issues have become a key area of concern and future challenges have become more complex, these methods have been employed by governments and businesses alike to plan for the future, with a particular focus on 2050 as a key milestone year for society's progress. In this context, early examples of these studies were published by organisations such as the World Business Council for Sustainable Development (WBCSD) [11], the World Energy Council (WEC) [12], and the UK Department of Trade and Industry (DTI) [13] amongst others, as a means to identify critical factors which might influence progress in different areas.

More recently, a number of examples have been published through collaborative projects involving a range of stake holders such as consumers, industrial corporations and governing bodies. One such study was conducted through the 'Centre on Sustainable Consumption and Production' (CSCP), a joint venture between the United Nations Environment Program (UNEP) and the Wuppertal Institute in Germany [14]. This project created different 'SPREAD' scenarios for 2050 and used them to generate accompanying roadmaps to sustainable lifestyles in each possible future.

Another group of studies has been conducted by 'Forum for the Future' in partnership with Hewlett Packard Labs, Sony and a number of others. These projects explored different 'Climate Futures' scenarios [15] based on varying responses to climate change, and used these to facilitate crowd sourced discussions about how technology can be leveraged to help guide towards more sustainable lives in the future [16].

In each case stated above, scenario planning methodologies were used to identify the 'critical uncertainties' of each situation. These were then mapped onto two critical axes which allow four contrasting scenarios to be generated. This approach, made famous by Shell and sometimes referred to as the 'two axes method', is one of the most common outputs of these foresighting exercises [17]. It allows organisations to critically assess both quantitative and qualitative information in order to imagine possible futures in specific areas of industry, based on specific drivers and concerns. This offers the flexibility to focus on a broad, or more narrow range of influencing factors, depending on differing strategic concerns.

In this context, one such study was found which related directly to the manufacturing industry. This was conducted by the European Commission (EC) in 2003 and generated a set of 'Scenarios on the future of manufacturing in Europe 2015-2020' (FutMan) which focused on the challenges set by sustainability, and the effects of socio-economic developments and future technologies on the European manufacturing sector [18]. The project discussed various policy and market concerns as drivers for governance decisions and found that the most critical factors affecting the future of manufacturing were 'Integration of Sustainable Development Policies', and 'Public Values and Consumer Behaviour'. The scenarios generated are shown in Figure 2. This study intended to highlight key trends in European manufacturing and to stimulate thinking on policy and technological options by focussing the formation of the scenarios around ten critical socio-economic factors: Global Governance, EU (European Union) Policy Integration, Public Values (consumer behaviour), Innovation Policy, Transport/Energy Infrastructure, Sustainable Development, Education System, Higher Education, Labour Market and Social Security (labour costs).

It should be noted that although the different examples presented above were each developed with a very specific purpose and very specific audience in mind, a clear set of common themes can be observed. The recurring critical factors in each case were often found to be governmental strategies, technological advances and social values. As such, these themes have been explored further as part of the development of the SMS for 2050.

3 DEVELOPING THE SMART MANUFACTURING SCENARIOS

A two axes scenario planning methodology was employed in this study to generate the four SMS. This method required a systematic approach to identify and assess the most critical factors affecting the development of the manufacturing industry over the next four decades with the aim of better understanding possible futures and supporting a range of strategic decisions related to design of future products, development of the next generation of production technologies and a responsible approach to business planning.

The initial stages of the study identified population growth (human impacts), climate change (ecological impacts) and resource depletion (manufacturing impacts) as the three key drivers affecting the environment and the future of manufacturing, depicted in Figure 3. For each of these drivers a range of interdependent and interlocking issues were investigated and analysed in order to identify how they might influence the future of society, governance, and therefore, the manufacturing industry.

Figure 2: EC Scenarios for European Manufacturing 2015-2020 [18].

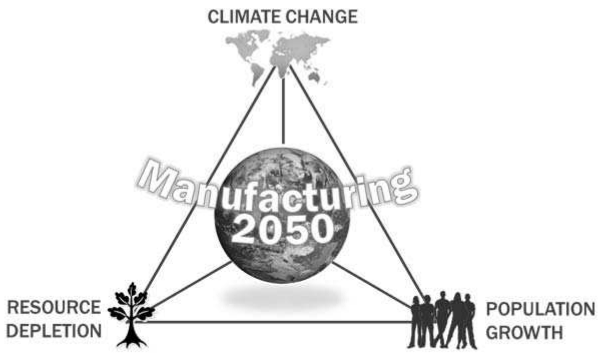

Figure 3: The Critical SMART Manufacturing Factors.

3.1 Population Growth

Human population growth is one of the influential factors affecting the ecosystem, and as global population rises, so does the cumulative impact on the planet. As such, a better understanding of the key issues and global variations in population growth will be required to build a complete picture of the impact of this change driver for the future of the manufacturing industry, and therefore the following four thematic issues related to population growth have been considered.

Rapid Rise of Global Population

Over the last century, global population has quadrupled to a current level of over 7 billion people [19]. Although this rate of increase is expected to slow as fertility rates fall, it is estimated that the global population will surpass 9 billion people by 2050, and exceed 10 billion by 2100 [1]. More importantly, these studies also show that populations in developed countries are set to fall, or at best remain constant supported by steady migration from developing countries. This highlights that almost all of the projected population growth will occur in developing countries, as shown in Figure 4, and as the people living in these areas strive to obtain the lifestyle of the remaining population residing in developed regions, the overall global consumption is set to significantly increase. This presents one of the most significant concerns regarding the level of manufacturing outputs which will be required to meet global demand by 2050.

Shifting Global Demographics

Studies have shown that in 2011, the median age for people living in developed countries was 39.9, whilst for people in developing countries it was just 27.2 years [1]. Over the next four decades, it is projected that the overall global population will age with the percentage of persons over 60 years old increasing by almost 9%, and while the current trend in ageing populations is most prevalent in developed countries, in the future it is expected that populations in developing countries will also begin to age, with the median age in these countries rising at a much faster rate [1]. This will clearly have a significant influence on the range, type, nature and market for specially designed products manufactured to suit the specific needs of aging population in 2050.

Geographic Distribution of Populations

For a number of years, urban populations have been growing rapidly and it is expected that this will almost double by 2050, accounting for 70% of the global population [19]. This will have a substantial effect on required infrastructures, availability of resources, patterns in distribution and consumption, and localised ecological impacts (waste and emissions), as well as a significant, albeit indirect impact on agricultural activities [2]. The other notable consideration regarding the distribution of global populations is the effect of climate change on habitable areas and arable lands which undoubtedly affect our ability to feed the growing population. In 2009, the Food and Agriculture Organization (FAO) of the United Nations (UN) stated that over 1 billion people were already suffering severe food shortage in 37 countries worldwide [21], which is an indicative example of the ever increasing challenges for the manufacturing industry to meet the basic needs of the global population in 2050.

Access to Labour and Skills

The proportion of the global population who are of working age has increased by 40% over the last 20 years [1], with most of this growth occurring in developing countries which now contain 85% of the world's young people. This had led to a phenomenon called 'youth bulge' as persons aged 15-30 years have come to represent over 40% of the total adult population in low income countries [22], resulting in high levels of unemployment and political unrest. This problem is also being compounded by migration of more skilled workers from these areas leading to a phenomenon known as 'brain-drain', and causing social and economic tensions in both developed and developing countries alike. Recent years have also seen a growth in the number of female members of workforces as gender equality is becoming more accepted, and also an increase in older workers due to delayed retirement. These issues related to availability of labour and skills will clearly influence the geographical distribution of different types of manufacturing activities and continue to present complex challenges for future industrial organisations.

3.2 Climate Change

The effects of human activities on the planet can be most clearly seen in the changing global climate of recent years. These present a significant, systemic risk to the manufacturing industry, and society as a whole. Thus, there is a need for a better understanding of the various potential impacts of climate change and to investigate this driver four main thematic issues have been explored.

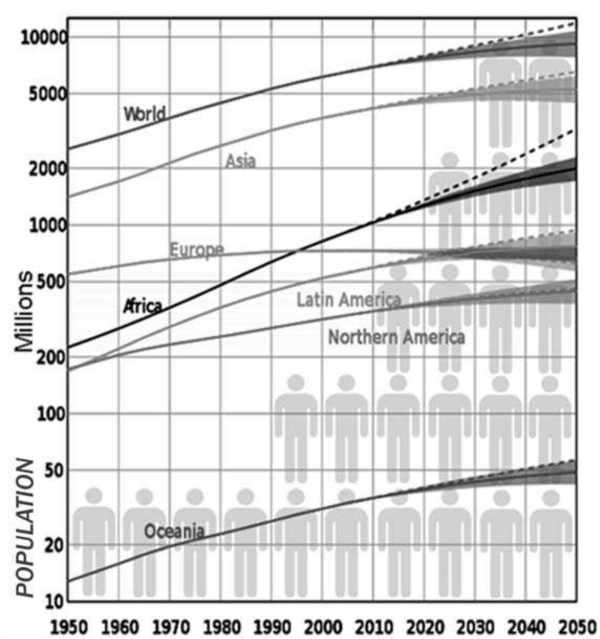

Figure 4: World Population Growth Projection. Adapted from [20].

Implications of Climate Change

In a 'business as usual' scenario, it has been predicted that the global average temperature is likely to be 3-6 °C higher than preindustrial levels by the end of the century [2]. This would go far beyond a large number of ecological thresholds and cause dramatic, irreversible damage to a large number of natural systems seriously affecting global food production, increasing flooding, reducing freshwater supplies and resulting in substantial biodiversity losses [23]. As such, in order to mitigate these effects, the UN set a target to limit global warming to an increase of 2°C [24], however, even a temperature rise at this lower level will affect patterns of demands on manufactured products and access to the resources required to produce them.

GHG Generation

In order to meet the 2°C limit, it has been estimated that GHG emissions will need to peak in 2020, and begin a rapid decline so that in 2050 they should be 53% lower than 2005 levels [25]. At present, the energy sector is the largest producer of GHGs, with industrial activities and transport related emissions coming in second and third place. This highlights the critical contribution of the manufacturing sector to global GHGs through direct emissions from production processes and also through indirect emissions from both consumption of non-renewable energy and excessive requirements for transportation.

Environmental Legislation

In order to enforce change and generate the radical environmental improvements needed in industrial practices, it has been widely acknowledged that holistic global policy mixes are required [2, 26]. Increases in legislation however create a complex legal framework for industry to operate within, often indirectly limiting innovation,

and can also be difficult even for regulators to effectively plan, monitor and enforce. Therefore, it is predicted that by 2050, the environmental regulation framework will play an even more influential role in the way that manufacturing companies can operate in different parts of the world.

Economy of Climate Change

It has commonly been reported that the benefits of strong proactive approaches to mitigate the effects of climate change will far outweigh the costs. A detailed review commissioned by the UK government entitled 'The Economics of Climate Change' [23] found that the cost of limiting global warming at 2°C would slow global GDP growth by only 0.2% per year, costing roughly 1% of global GDP in 2050, if early action is taken. However, the cost of inaction could amount to 5-20% of annual GDP costs, and involve much higher environmental risks [23]. The report also suggested that the costs of adverse weather effects such as flood damage, or loss of crops could have substantial impacts on global markets, for example, a 5-10% increase in hurricane wind speed has the potential to double associated damage costs in the U.S. This not only highlights the benefit of a proactive approach, but also signifies the insurmountable future economic challenges associated with tackling the environmental impacts of the manufacturing industry.

3.3 Resource Depletion

In 1980 we exceeded the ecological capacity of our planet and by 2006 we required 1.4 times Earth's capacity to support human activities [4]. It is expected that ageing populations and increasing quality of life in developing countries are likely to push demand far beyond this in the future, adversely affecting the biosphere's regenerative capacity. Even the most modest estimates, based on slow growth and little improvement to lifestyle, predict that human consumption will be twice the Earth's capacity by 2050 [4]. In this context, it is argued that the availability of resources such as raw materials, water and energy, will have a crucial effect on the operation and economics of the manufacturing industry, and in order to better understand this change driver, four main key resources have been explored.

Energy

By 2050, it has been estimated that global energy demand will be 80% higher than today [2]. Furthermore, it has been predicted that over 90% of this increase in the next 20 years will occur in developing countries where 1.4 billion people have no access to reliable electricity, and more than 2.7 billion people are dependent on traditional bioenergy sources [27]. Of the fuel mix used to meet our current global energy demands, 86% comes from fossil fuels, the most dominant being oil which accounted for a third of total demands in 2008 [27]. This demonstrates a precarious position as estimates predict that our present oil reserves will be severely depleted by 2050 [2]. More concerning however, is the slow growth of renewable energy production which currently only generates 7% of total energy demands due to much higher associated costs [27].

Materials

It is clear that the Earth has a finite amount of material reserves, and it has long been expected that many materials will be in short supply in the near future [5]. The effects of these shortages have already been observed through a rapid rise in the value of scrap steel and other strategically important metals. Furthermore, concerns with supply of rare earths (critical in many renewable energy technologies) are mounting, with a recent U.S. Government report [28] citing that a number of materials are already at high risk, even within the next 5 years. These shifting demands can have significant ramifications as both global supply chains and local economies are greatly dependent upon material availability. The geographic distribution of these materials not only has economic but also political implications, and many countries are critically reliant on trade with others to obtain the materials they require. In order to alleviate the challenges of material shortages, recycling is more frequently being used to recover valuable materials. This however, will not solve the problem as existing technologies are as yet, unable to create a completely closed loop system. A great deal of work is also being conducted into renewable materials such as biopolymers, however, these also need further development to meet existing performance and volume demands [29].

Water

Salt water accounts for 97.5% of the water on Earth, with humans predominantly depending on the remaining 2.5% freshwater, only a fraction of which is readily accessible [30]. At present, around 700 million people live in water stressed areas and 1.1 billion people lack access to safe drinking water. By 2035, it is estimated that these statistics will rise dramatically with 1 in 3 people living in water stressed areas and climate change causing problems with not only access to drinking water, but also production of food. At present, 70% of global water consumption is used for agricultural purposes with 22% for industrial use and 8% for domestic use [31]. However, significant differences can be observed between developing and developed countries, where in some industrialised countries more than half of abstracted water is utilised by industry. This is almost three times the global average, and highlights the challenges which lie ahead when considering manufacturing activities in water stressed areas.

Land

It is estimated that around 30% of global land surface is suitable for crop production, and at present, only 40% of this is being effectively utilised [32]. The availability of land as a resource will become an area of particular concern as unpredictable weather patterns and changing climates take effect. It is projected that droughts, floods and sea level rises will have significant effects on land availability. For example, in Bangladesh, a rise in sea level of 1m could affect 15 million people and submerge 17,000km^2 of land [33]. This highlights the need for a substantial increase in food crop yields to meet the demand of a growing population. This has been exasperated by a rapid growth in use of land for biofuels and biomaterials which are seen as a source of environmentally friendly substitutes for traditional alternatives. In this context, the proposed solution for manufacturing companies to rely on 'solar income' for their energy and material requirements will be a high risk strategy which is highly dependent on land availability.

4 SMART MANUFACTURING SCENARIOS

In line with the scenario planning methodology described in the previous sections, the key drivers identified in Section 3 needed to be consolidated into two axes. In this context, it has been recognised that 'population growth' is directly affecting the scale of 'climate change', which epitomises the most concerning issues relating to human impacts on the environment [19]. Thus, these two factors were broadly considered together for the purposes of this study in order to represent the scale of 'environmental impact' of manufacturing activities. This alongside 'resource depletion', which is believed to be the most influential driver for manufacturing industry, formed the two critical axes used to generate the SMS.

The four scenarios created using this method typify the various possible global conditions that the manufacturing industry may face and be required to operate within by the year 2050. These are depicted in Figure 5 and are labelled as Sustainable Planet (SP), Unsustainable Planet (UP), Technologically Sustained Planet (TSP) and Socio-Economically Sustained Planet (SESP).

The following sections describe each scenario through a number of critical **'lenses'** for the manufacturing industry that are affected by these global societal and governmental conditions, including energy production, material availability, resource demand, consumerism, and eco-efficiency of manufacturing technologies.

4.1 Sustainable Planet (SP)

In this scenario, low consumerism and significant advances in sustainable technologies have created a planet where human life can thrive under sensible conditions. A circular approach to production and a fully closed loop economy have been realised by a combination of a number of factors such as: public and private investment, holistic global policies supported by appropriate international standards and regulations, new business and economic models that encourage growth without environmental degradation, and a societal shift towards responsible and equitable consumption behaviours.

Manufacturing resources (materials, water and energy) are obtained from renewable sources and the planet operates entirely on 'solar income'. Manufacturing activities take place as close as possible to the source of consumption, and environmental impacts of production processes are continuously monitored and mitigated.

Regular training of the workforce provides flexibility in operations and supports adoption of advanced eco-efficient technologies.

Products are designed to meet real needs in the most efficient way, and are built to last or be upgraded as appropriate. GHG emissions are negligible, so the need for specially designed products to combat the impact of global warming has become redundant.

4.2 Unsustainable Planet (UP)

In this scenario, high consumerism and lack of investment in environmental technologies has led to difficult and complex conditions in which manufacturing companies must operate.

Access to all resources (materials, water and energy) is severely limited and fossil fuel reserves have been almost entirely, if not completely, diminished. The cost of access to non-renewable resources and the implementation of severe environmental regulations have created very restrictive, high cost business operating parameters. This significantly influences choices of technologies and pathways to innovation, and means that design, production and marketing of products must be very carefully analysed and planned.

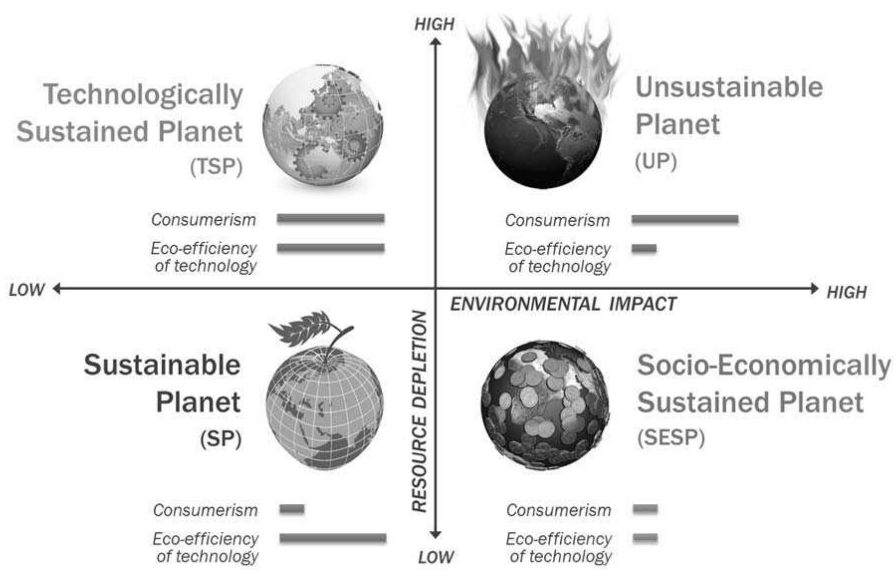

Figure 5: SMART Manufacturing Scenarios.

Due to high demand for access to resources and skills, companies have greater difficulty accessing these from the global market, leading societies to develop more independent strategies for 'self-sufficiency'. Localised production has become necessary, not due to environmental benefits, but because of high transport costs, and a lack of willingness to share scarce resources.

Design of products is strongly influenced by a need to combat the ever increasing effects of climate change that have led to variations in localised weather conditions, food production and changes to infrastructure.

4.3 Technologically Sustained Planet (TSP)

This scenario describes a planet sustained by vast technological growth and advancements, with environmental impacts controlled by high tech, but resource intensive solutions. Consumerism remains high as this advancement in technology has provided capabilities to produce more and more products with fewer resources, and raised the requirement for highly trained and skilled labour.

These advancements have favourably impacted the availability of resources, and recycling is intensively practiced to recover and recirculate even hard to extract materials. Competitive global trade has accelerated development of global infrastructures and local economies, particularly in resource rich countries; with resource poor countries only able to attract production activities through cheap labour.

Technological and product developments have centred on combating the effects of climate change, for example extensive weather control systems to mitigate the impacts of flooding, droughts and high winds, and production systems to ensure access to food and drinking water across the globe.

4.4 Socio-Economically Sustained Planet (SESP)

In this scenario, lack of investment in sustainable technologies has led to the creation of localised insular communities, formed to sustain a lifestyle in which continuous financial crisis has significantly driven down consumption patterns.

Local and/or national coalition groups protect their own resources and look after their own basic needs (e.g. energy and food). Political alliances are strategic to trade specific resources and global trade is highly limited. Production activities take place locally within these small communities, creating large demand for local flexible labour and cooperation. Rationing, reuse, remanufacturing and recycling are employed to preserve resources, and energy production is limited to readily available solutions.

As consumers are more economically aware, companies require significantly more competitive products and must be strategic about product ranges and selected markets in which they operate. Products need to meet specific local needs and enable efficient, recoverable use of resources.

5 APPLICATION OF SMART MANUFACTURING SCENARIOS

Current approaches to lowering the overall environmental impact of a manufacturing company are often built on 'push-based' strategic planning. In such approaches, a number of factors are considered such as regulatory requirements, available investment and skills, consumer pressures, market demand, etc. This aids in development of short term stepwise procedures that deliver modest improvements (e.g. Implementation an Environmental Management System based on ISO14001). The consideration of key drivers (i.e. population growth, climate change and resource depletion) in this paper has made a compelling case that such incremental improvements will not be sufficient to prepare the manufacturing industry for the difficult and complex challenges that will need to be faced in the medium to long term future.

The use of the SMS presents a distinctly different approach built on 'pull-based' strategic planning. This focuses on long term manufacturing objectives in order to deliver and embed the readiness and resilience required to deal with future manufacturing challenges.

While considering long term manufacturing objectives, there are a number of examples (such as improved staff training) that will be beneficial in all four scenarios. However, there are also those that are more supportive for a specific scenario. Figure 6 exemplifies a subset of such objectives for each manufacturing scenarios. Evidently, the range and scope of these objectives will vary depending on the product type, company size, and manufacturing sector.

TSP	UP
• High investment in advanced technologies. • Ability to cultivate a culture for product and process innovation. • High-tech automated manufacturing that relies on global sourcing of skills. • ………	• Securing access to resources. • Ability to adhere to a complex mix of environmental regulations. • Demand for products that withstand and combat the effects of a changing climate. • ………
SP	**SESP**
• Sustainable product design capabilities. • Ability to operate in the context of extended producer responsibility. • Meeting the basic needs of the consumer through a mix of products and services. • ………	• Ability to operate in competitive and restrictive markets. • Ability to source resources locally and operate within insular, smaller communities. • Demand only for commodity products that meet specific, basic needs. • ………

Figure 6: Example Objectives for each of the SMART Manufacturing Scenarios.

One other key consideration with regards to the SMS is the inherent loops that may develop between TSP↔UP and SESP↔UP, as illustrated in Figure 7. The loop between TSP↔UP represents a pattern often referred to as the ‘rebound effect’ in which the ecoefficiency gained through technological advancements and improvements is offset due to significant growth in consumption of the product. This further expands the scope and definition of ‘advanced manufacturing’ to include considerations for the elimination of the rebound effect, so that the pathway from TSP moves towards SP, as depicted by the dashed arrow between the two in Figure 7.

The loop between SESP ↔UP represents the cycle often referred to as a ‘boom and bust’, in which during an economic crisis the frequently proposed solution is to ‘excite the market’ and encourage increased consumption through availability of ‘disposable income’ for consumers. In this context, the improvement in environmental impact during a specific period is wiped out by a period of rapid growth in consumption. The key challenge in such cases is often through sustainable investment in green products and technologies (e.g. renewable energy) and infrastructure improvements that lower environmental impacts (e.g. public transport), therefore producing a path from SESP→SP, as depicted by the dashed arrow in Figure 7.

6 CONCULDING DISCUSSIONS AND FUTURE WORK

Manufacturing industry faces a number of critical challenges due to the societal, economic and ecological impacts associated with its activities. The incremental approach currently adopted to lower these impacts will not meet the requirements for long term sustainability of the manufacturing sector. In this context, there is a need to develop strategies supported by stepwise action plans that provide readiness for upcoming challenges and resilience towards future changes.

The SMART Manufacturing Scenarios presented in this paper provide insights in to a number alternative global conditions that a typical manufacturing company may face. It should be noted that these scenarios do not represent four mutually independent possibilities, instead it is envisaged that the planet could easily shift between these different states as economic crises force lower consumption, or new green technologies improve capabilities to lower the ecological footprint.

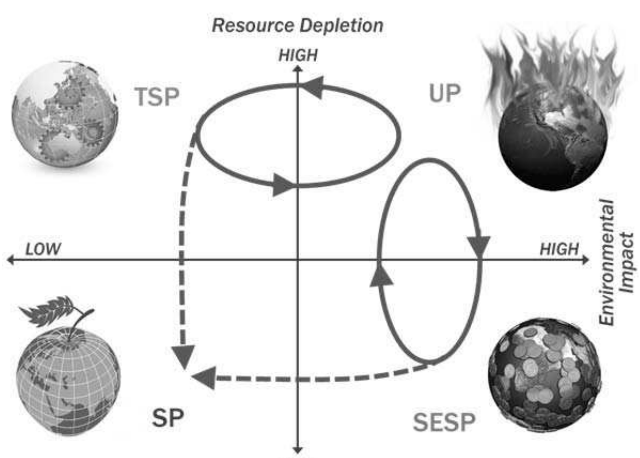

Figure 7: SMART Manufacturing Scenario Loops.

In this scenario planning exercise it has been assumed that lower resource use is linked directly to lower consumption, and that improved sustainability is linked to advances in enabling technologies. Such assumptions may need to be revised as we learn to decouple our ‘economic growth’ from ‘environmental degradation’, however, at present these assumptions very much represent the reality that has been observed throughout recent decades in both developed and developing countries.

In the further expansion of this research, the principal concepts of this scenario planning exercise are utilised to develop a series of SMART strategic planning tools specifically tailored to the requirements of the manufacturing industry. These aid to identify the most relevant long term objectives for companies of varying sizes, sectors and product ranges. The SMART tools focus on five key common factors which influence manufacturing activities. These are referred to as ‘ManuFactors’ [34], and include resources, products, production, labour and markets. The ManuFactors are explored as part of the SMART tools to provide strategic direction in order to achieve resilience within the four scenarios identified as part of the SMS.

Finally, it should be noted that although the SMS are developed for the manufacturing industry, they could further be utilised in a range of complementary sectors that will also need to change dramatically in order to secure their long term survival.

7 REFERENCES

[1] United Nations (2011); World Population Prospects: The 2010 Revision: Highlights and Advance Tables, UN Department of Economic and Social Affairs: Population Division, New York, U.S.

[2] Organisation for Economic Co-operation and Development (2012); OECD Environmental Outlook to 2050: The Consequences of Inaction, OECD Publishing, Paris, France.

[3] WWF (2011); The Energy Report: 100% Renewable Energy by 2050, WWF – World Wide Fund For Nature, Gland, Switzerland.

[4] Ewing, B., Goldfinger, S., Oursler, A., Reed, A., Moore, D., Wackernagel, M. (2009); The Ecological Footprint Atlas 2009, Global Footprint Network, Oakland, U.S.

[5] Halada, K., Shimada, M., Ijima, K. (2008); Forecasting of the Consumption of Metals up to 2050, in: Materials Transactions, Vol. 49, pp. 402-410.

[6] Gardner-Outlaw, T., Engleman, R. (1997); Sustaining Water, Easing Scarcity: A Second Update, Population Action International (PAI), Washington DC, U.S.

[7] Wack, P. (1985); Scenarios: Shooting the Rapids, in: Harvard Business Review, November-December 1985.

[8] Wack, P. (1985); Scenarios: Unchartered Waters Ahead, in: Harvard Business Review, September-October 1985.

[9] Shell (2008); Scenarios: An Explorer's Guide, Shell International BV, The Hague, The Netherlands.

[10] Shell (2011); Signals and Signposts: Shell Energy Scenarios to 2050, Shell International BV, The Hague, The Netherlands.

[11] World Business Council for Sustainable Development (1997); Exploring Sustainable Development: Global Scenarios 2000-2050, WBCSD, London, U.K.

[12] World Energy Council (2007); Deciding the Future: Energy Policy Scenarios to 2050, WEC, London, U.K.

[13] Department of Trade and Industry (2002); Foresight Futures 2020: Scenarios and User Guidance, DTI, London, U.K.

[14] Demos Helsinki (2011); Scenarios for Sustainable Lifestyles 2050: From Global Champions to Local Loops, UNEP / Wuppertal Institute Collaborating: Centre on Sustainable Consumption and Production (CSCP), Wuppertal, Germany.

[15] Forum for the Future (2008); Climate Futures: Responses to climate change in 2030, Forum for the Future, London, U.K.

[16] Sony (2011); FutureScapes: The Scenarios, Forum for the Future / Sony Europe.

[17] Government Office for Science (2009); Scenario Planning: Guidance Note, Foresight Horizon Scanning Centre, London, U.K.

[18] European Commission (2003); The Future of Manufacturing in Europe 2015-2020: The Challenge for Sustainability, EC Joint Research Centre.

[19] United Nations Environment Programme (2012); Global Environment Outlook 5: Environment for the future we want, UNEP & Progress Press, Valletta, Malta.

[20] Wikipedia (2012); File:World population (UN).svg, http://en.wikipedia.org/wiki/File:World_population_%28UN%29.svg, accessed on: 30/01/2013.

[21] Food and Agriculture Organization of the United Nations (2009); More people than ever are victims of hunger, http://www.fao.org/fileadmin/user_upload/newsroom/docs/Press%20release%20june-en.pdf, accessed on: 30/01/2013.

[22] United Nations Educational Scientific and Cultural Organization (2006); Water: A Shared Responsibility: The United Nations World Water Development Report 2, UNESCO & Berghahn Books, New York, U.S.A.

[23] Stern, N. (2007); The Economics of Climate Change: The Stern Review, Cambridge University Press, Cambridge, U.K.

[24] United Nations (2011); Report of the Conference of the Parties on its Sixteenth Session: held in Cancun from 29 November to 10 December 2010, United Nations Framework Convention on Climate Change, Bonn, Germany.

[25] United Nations Environment Programme (2011); Bridging the Emissions Gap, UNEP, Nairobi, Kenya.

[26] United Nations Environment Programme (2012); Global Outlook on Sustainable Consumption and Production Policies: Taking action together, UNEP, Paris, France.

[27] International Energy Agency (2010); World Energy Outlook 2010, OECD/IEA, Paris, France.

[28] U.S. Department of Energy (2010); Critical Materials Strategy, DOE, U.S.

[29] Colwill, J.A., Wright, E.I., Rahimifard, S., Clegg, A.J. (2012); Bio-Plastics in the context of competing demands on agricultural land in 2050, in: International Journal of Sustainable Engineering, Vol. 5, pp. 3-16.

[30] World Resources Institute (2008); Watering Scarcity: Private Investment Opportunities in Agricultural Water Use Efficiency, Rabobank, Utrecht, The Netherlands.

[31] United Nations Educational Scientific and Cultural Organization (2003); Water for People, Water for Life: The United Nations World Water Development Report, UNESCO & Berghahn Books, New York, U.S.A

[32] Nachtergaele, F., Bruinsma, J., Valbo-Jorgensen, J., Bartley, D. (2011) SOLAW Background Thematic Report – TR01: Anticipated trends in the use of global land and water resources, Food and Agriculture Organization of the United Nations.

[33] United Nations Environment Programme (2008); Vital Water Graphics: An Overview of the State of the World’s Fresh and Marine Waters - 2nd Edition, UNEP, Nairobi, Kenya.

[34] Rahimifard, S. (2012); Inaugural Lecture, lborouniversity, http://youtu.be/9iJX0fxys1A, accessed on: 30/01/2013.

On the Potential of Design Rationale for Ecodesign

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Abstract

Ecodesign tools have limited performance, mainly for helping designers in early-design. Design rationale has been explored in many domains, but not yet in ecodesign. The result of a first investigation on design rationale of environmental impacts is presented. The objective is to track the design rationale of the design process and to relate these choices to the environmental impacts of the product, in order to conclude about the usefulness of DR to a redesign. A simple case study done with engineering students is commented.

Keywords:

Ecodesign; Design rationale; Causality network

1 INTRODUCTION

Companies are particularly concerned by environmental issues due to legislations and possible benefits, like cost reduction and new markets [1]. An approach for making the company more environmentally responsible is acting on its services and products. The improvement of product or service environmental performance throughout its whole lifecycle is called ecodesign [2].

For helping designers to consider the environmental aspect, many tools have been created (see section 2.2). Nevertheless, not many of them have actually been used in industry [3]. The obstacle for early-design implementation of the ecodesign dimension pointed here is the fact that even widely used environmental evaluation tools, like life cycle assessment (LCA), require an advanced stage of design to evaluate the product with reduced uncertainty. The problem is that, as seen in figure 1, as more advanced the design, fewer are the possibilities of the designer to influence the product's environmental performance [4]. This means that the designer has access to the product's environmental evaluation when it is too late to make heavy changes on the product.

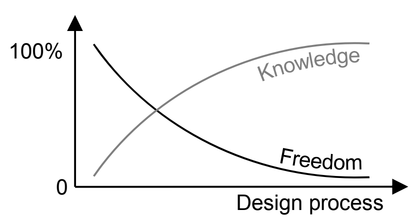

Figure 1: Design paradox. The designer freedom to make changes to the product versus the knowledge about the design problem (adapted from [5]).

The main motivation of this research is to improve efficiency of ecodesign, by helping engineering designers from the early design stages.

To act into the early stages, the idea is to capture the information about the product during its whole lifecycle and use it in the next product's generation, as seen, for example, in the method case-based reasoning (Figure 2). In other words, a design process, rationale and context are documented. Next, if a new product has a similar topic of discussion of a previous design, the designer can look at its consequences throughout the entire life of the previous product. The designer concludes, then, about the options that should be reconsidered for having less environmental impact in the next product's generation.

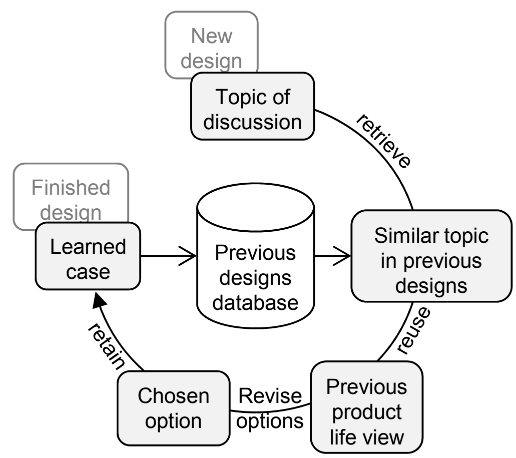

Figure 2: Knowledge use in next product's generation, adapted from case-based-reasoning technique [6].

The focus of this paper consists on demonstrating that a network of topics and the design rationale can result in useful conclusions for eco-redesigning. More precisely, it aims to present a case study of a design process and to analyse the consequences of an argument or a context to the final environmental impact of a product.

The paper is organized as follows. Section 2 provides definitions that are important for the understanding of the paper and a brief state of the art of the main concerned fields. The case study is shown in Section 3. Finally, in Section 4, conclusions and perspectives of future work are commented.

2 DEFINITIONS AND RELATED WORK

2.1 Product Lifecycle

The *product lifecycle* is generically characterized here for stating clear definitions, see Figure 3.

Firstly*, product lifecycle* includes the whole lifespan of the product, starting from the *need* and finishing at the *end-of-life* of the product.

Secondly, *product development process* is “the sequence of steps or activities that an enterprise employs to conceive, design and commercialize a product” [7]. Pugh [8] also calls it the *total design*.

Thirdly, the notions of *early lifecycle* and *late lifecycle* are introduced for making clear that life cycle assessment (LCA) is only possible at *late lifecycle*, after having a physical idea of the product.

Finally, from the *early lifecycle*, the highlighted stages are:

- *needs*: is the impulse to start the design, could be a customer need as well as an internal need (i.e., reducing costs, accomplishing legislation or creating competing products) [9]
- *informal requirements*: informal statement of needs, i.e. the customer demands.
- *product specifications*: translation of the customer requirements to a formal language, tells what the product has to do. [7]
- *product concepts*: generation of forms, functions and features for answering to the product specifications. [7]
- *system-level design*: definition of the product architecture, preliminary design of key components. [7]

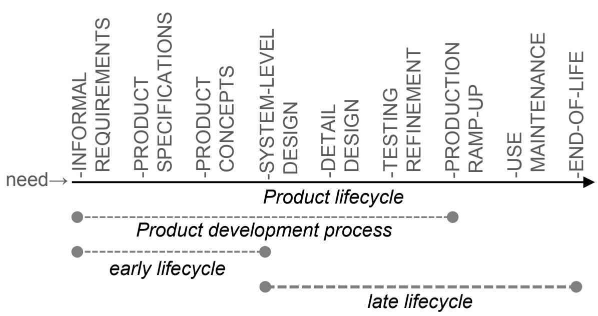

Figure 3: Product lifecycle stages.

The understanding of the structure of the early lifecycle introduces the definition of the early ecodesign tools in the next section.

2.2 Early Ecodesign Tools

Early ecodesign tools are those that come before the product’s architecture is defined (Figure 3). There are different approaches as exposed next.

Guidelines, checklists and rules place environmental issues as constraints of design. The advantages are that they do not require any environmental knowledge from the designer and that they can be applied at the beginning of design. The inconvenience is the need to be customized for each product for not being too general. Lists of harmful materials [10] and The Ten Golden Rules [11] are examples of this ecodesign approach.

Quality-function-deployment (QFD) is also adapted to ecodesign purposes. They aim at ensuring that customer requirements are taken into account by relating them to technical solutions, environmental impacts and often cost [12]. Allocating weights is the main issue of the approach leading to subjectivity.

Simplified or streamlined LCA aims at reducing the amount of data needed to perform LCA, so it could be used earlier in design. One example is to estimate the impact by the parameterization of a product. Therefore, physical parameters are correlated to environmental data (e.g. a certain amount of power, responds with a certain amount of impact) [13]. This approach is more related to changes on scale of very similar products. The idea of simplifying LCA itself needs to be taken carefully for not introducing extra uncertainty to the evaluation.

A more comprehensive review of those previews tools is available at [14], a state of the art of ecodesign tools. The rest of this subsection is about tools that use analogy for ecodesigning.

Analogy for ecodesign is here understood as the estimation of environmental impact of a new product, early in design, based on products with similar characteristics. These products of reference can be the result of a benchmark (i.e. products from the market) or a retrieve among the company’s old versions of products.

Jeong et al. [15] introduced case-based reasoning (CBR) with environmental evaluation purposes. The authors trace the impacts of LCA at the early definitions of the product using the product model FBSe (function-behavior-structure-environment). After, similarity is analyzed between the new product and the products’ cases stored in a database, analogy is used to estimate the impact of the new product.

Devanathan, Bernstein et al. [16] [17] conduct LCA into teardown benchmarked products giving an impact to the bill of materials (BOM). Then, they relate the BOM to product’s functions. Next, those functions are related to customer and environmental requirements (QFD). The redesign is then focused on the functions impacts to support conceptual design and concept selection.

Bohm et al. [18] have used a design repository of environmental evaluated products to automatically generate virtual concepts.

Even if the analogy based approaches here mentioned share close motivation to the work presented in this paper, the novel approach goes further. The reasoning process and the context of the product’s design are considered because they include important information that could have a major impact on shifting products preconceived ideas (see next subsection).

Also, compared to previous research, the purpose of the use of such information is more dependent on the designer's interpretation, meaning that it is out of our interest to replace the designer by automatic generation of LCA results or automatic generation of design concepts. The aim is to present structured information as a support. The final decision is then taken by the designer. In this paper, the focus is to prove that the design rationale information is useful for influencing eco-redesign.

2.3 Design Rationale

What information should be documented so that a past product's design could be useful for making better decisions? This question is initially answered by looking at what influences decision-making in design.

There are several factors that influence the decision-making, and by consequence, the design result, such as: the designers knowledge, ideas and skills [19], the designer’s behaviour, the project’s limited resources of time (Taylor and Ullman call those uncontrollable factors *noise* or *uncertainties* of the decision-making process [20]).

Moreover, a decision can be influenced by prior decisions or prior products. Thus, the act of documenting the design process can impact future decisions concerning the same product or subsequent products [21]. For increasing reflection about the decisions made during a new product's design, strong potential is seen in knowing more than *what* has be done in the past design, but also in knowing *why* it has been done this way.

This *why* of a choice is commonly called *rationale,* i.e. "the principles or reasons which explain a particular decision, course of action, belief, etc." [22]. *Design rationale* (DR) is: the motivations that started design; the stated requirements; the conditions that gave rise to the shape; the struggles and deliberations; the trials and reflections; the tradeoffs; the reasons for doing it or not doing it [23]. DR is a support for:

- Reflection: by incrementally capturing DR, the designer is led to reflect about his choices. “DR schemas can provide a framework with which to carefully reflect upon design decisions” [24].
- Communication: by sharing DR there is a potential for a better understanding in a concurrent design situation. “Explicitly represented rationales can provide common vocabulary and project memories, and make it easier to negotiate and reach consensus.” [25]
- Redesign and maintenance: by looking at the past chain of decisions, the designer can see the cause-effect result. “Design rationale can offer designers useful information about how previous designs evolved and the context in which such evolution happened” [26].

Of course there are also barriers for the application of DR, which include:

- Time for documenting rationale. Structuring the reasons for each choice takes precious time from the designer and it is one of the main reasons for this support not to be largely adopted [27].
- Omission of rationale. “It is possible that DR may unintentionally be omitted because a designer may not be able to explicate their tacit knowledge.” [24]
- Excess of influence. Using DR to identify solutions could result in less thinking, and possibly less innovative solutions. “Research in the field of creativity has shown that the exposure to examples can provoke fixation and reduce the overall creativity of the idea-generation process.” [28]

Research about the capture, storage and retrieval of design rationale information is beyond the scope of this paper. The only notion used was to structure the information so that the reasoning would be more explicit. It is based on the general idea of methods like IBIS (Issued-Based Information System) and QOC (Questions-Options-Criteria) [29], in which a problem, or a topic, leads to options that have arguments pros and cons (see Figure 4).

In sum, the assets brought by DR have a place in ecodesign practice. The relation between DR and the environmental impact of a product could point hotspots with higher level of abstraction. A demonstration is made in the case study of section 3.

3 CASE STUDY

3.1 Description of the Experimentation

The main objective of this case-study is to demonstrate the interest of a network of topics that includes the design rationale.

The case-study is based on a design project for the Shell Eco-marathon competition [30]. This competition is about the designing of an energy-efficient prototype car. The students' team that makes a car that travels the furthest on the least amount of energy wins the competition.

The team chosen for this case-study is a group of seven engineering students of the University of Technology of Troyes. They are motivated by the sustainability challenge, but they do not have any specific ecodesign knowledge.

They were asked to put forward a car for the competition. The project should achieve the *system-level design* phase by the end of the spring semester. The deliverables demanded were the CAD models and a report per person explaining their demarche.

There was not a specific structure for the report. Mostly, they introduced the competition and their own motivations; showed a general picture of the team‘s work and explained more in deep their contribution to the project.

3.2 Analysis Approach

Knowledge Representation

From each report, the topics of discussion (i.e. decision nodes), the options they look at and the arguments were extracted; in reality, only the pros of the chosen decisions were found in the reports. The whole team’s information was fused and the causal links mapped out. This knowledge was represented as showed in Figure 4.

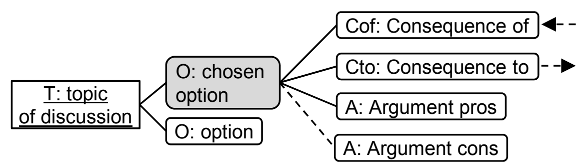

Figure 4: Knowledge representation of the design process.

In Figure 4, *T* stands for Topic of discussion; *O* for Option; *Cof* is an argument that comes from a consequence of a previous Topic; *Cto* is an argument that has a consequence to another Topic; *A* stands for argument, it can be positive if the line is full and negative if the line is dashed.

Interpretation for a Redesign

Based on that schema of topics, options and arguments, the approach used for getting into conclusions is the following:

Firstly, the hotspot topic is identified, by means of the environmental analysis (e.g. a certain lifecycle phase of a part). Then, its options and arguments are analyzed. In general, looking at the options allows having an idea about the time spent and the attention paid by the designers to the topic and the technical solutions they had available at the time; looking at the arguments allows seeing the criteria used for choosing the option and the context of design.

Secondly, the topic that causes this hotspot topic (following the network) is analyzed as in the first step.

3.3 Instantiation

For the purpose of this paper, the body shell has been chosen for the following steps because it is the topic in which the students had more freedom, thinking about material, form, manufacturing and other lifecycle constraints. The other topics like braking system, steering system and security items were mostly about a choice between existing solutions available in the market. As data about those existing solutions was hard to obtain, LCA was conducted only for the body shell.

Knowledge Representation

Figure 5 shows the topics of discussion of the body shell: the body shape leads to the option of tear drop like because of the 3 wheels, the tadpole motion direction and the aerodynamics' knowledge of the designer about the optimal drop shape.

The choices of composites are made using a material's selection software [31] by comparing the parameters: yield strength, density and cost. They decided to choose polyamide with glass fiber reinforcement. The fact that composites are rarely recyclable was pointed out as an issue. Other than end-of-life, this choice has direct consequences on the manufacturing process.

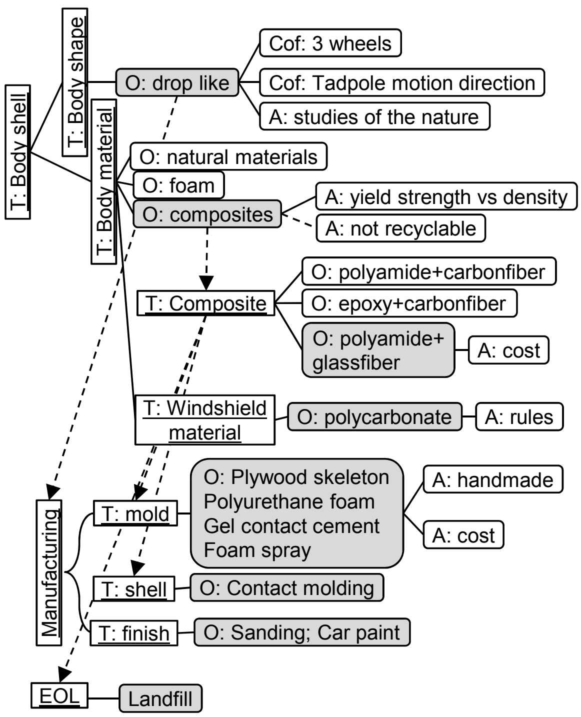

Figure 5: Body shell topics of discussion.

Thus, the result presented by the students is a body shell made of polyamide and glass fiber with the shape of a drop as seen in Figure 6. Usually, a team goes through the whole lifecycle of the car, but as students were asked to go until the system-level design by a matter of time, the rest of the lifecycle of the body shell was only planed.

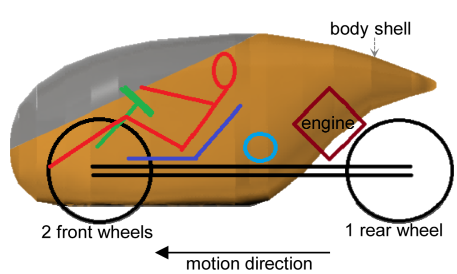

Figure 6: Students CAD model of the prototype's body shell.

Environmental Impact Assessment

For the environmental impact assessment, data was entered using Ecoinvent database [32], ReCiPe and Usetox methods [33] [34] and the Simapro software [35]. The materials and manufacturing of the body shell were assessed, as well as the end-of-life of the parts. The use phase was not considered because the design was not further developed and the performances were hard to predict. It is out of the scope of the paper the details about the environmental evaluation. A simplistic calculation was carried out, mostly based on approximations, the interest being in exemplifying conclusions to enhance the understanding of the main idea.

The comparative impact results between the body shell parts: the windshield (LC_windshield), the shell without the mold (LC_shell) and the mold alone (LC_mold) are shown in Figure 7. The aim by doing this comparison is to show that the mold, from the manufacturing of the shell is a hotspot, from an environmental point of view.

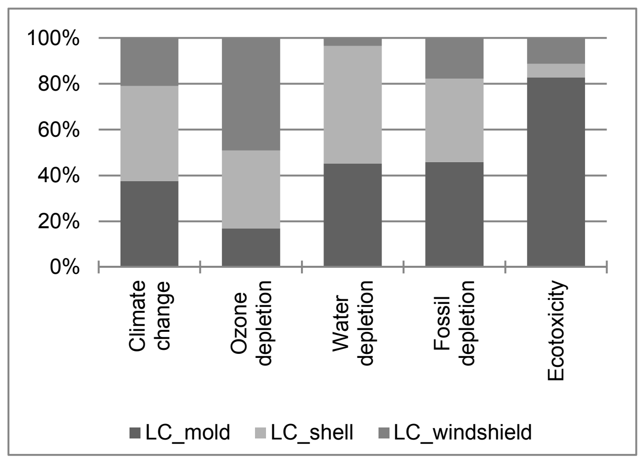

Figure 7: Comparative lifecycle impacts of mold, shell and windshield (read: about 40% of the total lifecycle impact of the car in climate change is due to the mold lifecycle, 40% to the shell lifecycle and less than 20% to the windshield).

Interpretation and Conclusions

Considering that changing the mold is suitable for reducing the environmental impact, the designer could notice that the use of a mold made of foam and plywood was the only option taken into account by the team, consequently concluding about the interest of spending more time finding new options for the mold.

Further, the arguments for choosing this option were: being possible to handmade it and cost. The question is if these arguments are really constraints, i.e. imagine that for the new design, being handmade is not a constraint anymore, so looking for new partners could provide a wider range of manufacturing and material options.

For a next level, the designer could look at the cause of this manufacturing process, which is the material choice: composites. Are there new options of materials? Why did the natural materials and foam were discarded? Which choice would be better when thinking about the whole lifecycle?

In which concerns the methodology, as presented in the introduction of this paper, this team did not have the time to perform LCA and use its results to improve their design, which reflects the real world in the sense that designers do not have time for many feedbacks and loops. Thus, the idea is that the next year's students could access those results for rethinking the design and potentially doing a better prototype.

4 CONCLUSIONS AND RESEARCH PERSPECTIVES

As shown in this paper, the environmental impact comes from design decisions. The product life cycle network with the design rationale helps seeing the reasons and effects of a choice, taking deeper conclusions about the source of environmental impacts and possible improvements for redesigning.

The conclusions about redesign in a relative small chain of decisions do not differ much from conclusions of a normal ecodesign approach. The novel approach is interesting for more complex processes and through a complete product life cycle.

Deeper and more complete rationale is needed for really understanding the past design, for example the reasons for not choosing one option or the arguments related to the organization's strategy.

Ideally, the justifications for each choice should be an input done by the parties involved in the design, the students. Nevertheless, this case-study is an interpretation of reports, which allows following the sequence of choices and often misses deeper arguments. Besides, the experience also showed that the analysis of reports is time consuming and leaves many gaps of information.

In parallel, the fact that students were the object of this case study gave some leads related to the knowledge that they could be taught for achieving a better design.

Finally, two main potential contributions are better seen. One related to the lifecycle view, the network of topics; other related to deeper understanding of decision-making context, the rationale.

The next step of this research is centred on how to technically build, store, retrieve and present the causality network. This will lead to rethinking the knowledge structure and the methodology of interpretation.

5 ACKNOWLEDGMENTS

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6 REFERENCES

[1] A. Veshagh, S. Marval, and T. Woolman (2012): Making the Business Case for Eco-Design and Sustainable Manufacturing, in: 19th CIRP International Conference on Life Cycle Engineering pp. 11–17.

[2] NF E01-005 (2010): Produits mécaniques Méthodologie d'éco-conception,. Association Française de Normalisation (AFNOR).

[3] T. Reyes (2009): Ecodesign trajectories: a strategy for integration of environmental considerations in the design process at SMEs, in: 16th CIRP International Conference on Life Cycle Engineering.

[4] W. Dewulf (2003): A pro-active approach to ecodesign: framework and tools, Katholieke Universiteit Leuven.

[5] D. D. Ullman (1997): The mechanical design process, 2nd ed. McGraw-Hill, p. 340.

[6] I. Watson (1998): Applying case-based reasoning: techniques for enterprise systems, 1st ed. Morgan Kaufmann, p. 289.

[7] K. Ulrich and S. Eppinger (2012): Product design and development, 5th ed. McGraw-Hill, Inc, p. 415.

[8] S. Pugh (1991): Total Design, 1st ed., vol. 38, no. 2 Addison-Wesley Longman Limited, p. 278.

[9] L. Blessing and A. Chakrabarti (2009): DRM, a design research methodology, Springer.

[10] C. Allione, C. De Giorgi, B. Lerma, and L. Petruccelli (2012): From ecodesign products guidelines to materials guidelines for a sustainable product. Qualitative and quantitative multicriteria environmental profile of a material, Energy vol. 39, no. 1 pp. 90–99.

[11] C. Luttropp and J. Lagerstedt (2006): EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development, Journal of Cleaner Production vol. 14, no. 15–16 pp. 1396–1408.

[12] M. D. Bovea and B. Wang (2007): Redesign methodology for developing environmentally conscious products, International Journal of Production Research vol. 45, no. 18–19 pp. 4057–4072.

[13] H. Ostad-Ahmad-Ghorabi and D. Collado-Ruiz (2011): Tool for the environmental assessment of cranes based on parameterization, The International Journal of Life Cycle Assessment vol. 16, no. 5 pp. 392–400.

[14] M. D. Bovea and V. Pérez-Belis (2011): A Taxonomy Of Ecodesign Tools for Integrating Environmental Requirements into the Product Design Process, Journal of Cleaner Production vol. 20, no. 1 pp. 61–71.

[15] M. Jeong, H. Suh, and J. R. Morrison (2010): A Framework for Stepwise Life Cycle Assessment during Product Design with Case-Based Reasoning, in: 6th annual IEEE Conference on Automation Science and Engineering pp. 118–123.

[16] W. Bernstein, D. Ramunujan, and S. Devanathan (2010): Development of a Framework for Sustainable Conceptual Design, in: Proceedings of the 17th CIRP International Conference on Life Cycle Engineering.

[17] S. Devanathan, P. Koushik, F. Zhao, and K. Ramani (2009): Integration of sustainability into early design through working knowledge model and visual tools, in: Proceedings of the 2009 International Manufacturing Science and Engineering Conference pp. 1–10.

[18] M. R. Bohm, K. R. Haapala, K. Poppa, R. B. Stone, and I. Y. Tumer (2010): Integrating Life Cycle Assessment into the conceptual phase of design using a design repository, Journal of Mechanical Design vol. 132, no. 9.

[19] G. Pahl and W. Beitz (1999): Engineering design: a systematic approach, Springer Verlang London, p. 544.

[20] P. Taylor and D. G. Ullman (2001): Robust decision-making for engineering design, Journal of Engineering Design vol. 12 pp. 3–13.

[21] S. Szykman, R. D. Sriram, and W. C. Regli (2001): The Role of Knowledge in Next-generation Product Development Systems, Journal of Computing and Information Science in Engineering vol. 1, no. 1 p. 3.

[22] A. S. Hornby (2010): Oxford Dictionary, 8th editio. .

[23] T. Moran and J. Carroll (1996): Design rationale: concepts, techniques and use, .

[24] J. Horner and M. E. Atwood (2006): Effective design rationale: understanding the barriers, Rationale Management in Software Engineering pp. 1–18.

[25] J. Lee (1997): Design rationale systems: understanding the issues, IEEE Expert.

[26] H. Wang, A. L. Johnson, and R. H. Bracewell (2012): The retrieval of structured design rationale for the re-use of design knowledge with an integrated representation, Advanced Engineering Informatics vol. 26, no. 2 pp. 251–266.

[27] A. Tang, M. A. Babar, I. Gorton, and J. Han (2005): A Survey of the Use and Documentation of Architecture Design Rationale, in: 5th Working IEEE/IFIP Conference on Software Architecture (WICSA'05) pp. 89–98.

[28] D. Collado-Ruiz and H. Ostad-Ahmad-Ghorabi (2010): Influence of environmental information on creativity, Design Studies vol. 31, no. 5 pp. 479–498.

[29] X. Hu, J. Pang, Y. Pang, M. Atwood, W. Sun, C. Science, and W. C. Regli (2000): A survey on design rationale: representation, capture and retrieval, in: ASME Design Engineering Technical Conferences.

[30] Shell Eco-marathon competition http://www.shell.com/home/content/ecomarathon/, .

[31] CES EduPack Software http://www.grantadesign.com/education/software.htm, .

[32] Ecoinvent database http://www.ecoinvent.ch/, .

[33] ReCiPe method http://www.lcia-recipe.net/, .

[34] Usetox http://www.usetox.org/, .

[35] Simapro software http://www.simapro.com/, .

Applying Unit Process Life Cycle Inventory (UPLCI) Methodology in Product/Packaging Combinations

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Abstract

This paper discusses how the UPLCI approach can be used for determining the inventory of the manufacturing phases of product/packaging combinations. The UPLCI approach can make the inventory of the manufacturing process of the product that is investigated more accurate. The life cycle of product/packaging combinations looks different from the life cycle of just a product, because two life cycles are interwoven. A first draft for a possible adaption and extension of the UPLCI framework is described. This is illustrated by examples from case studies. A suggestion for a taxonomy focusing on unit processes for product/packaging combinations is presented.

Keywords:

Product/packaging combination; UPLCI; packaging; LCA

1 INTRODUCTION

The definition of sustainability used in this publication is based on the well-known definition developed by the Brundtland commission [1]. Sustainability is defined here as a balance between the needs of the people, the use of the planet and the continuity of companies. This provides a livable planet for both present and future generations. In this publication the focus is more on the ecologic aspect due to difficulties in assessment.

Sustainability, especially the ecologic aspect, is an important subject in the field of packaging, because packaging is seen as a major contributor to the environmental impact. Waste is remaining after the relative short life cycle of packaging. This creates an imbalance in perception between people, planet and profit; planet is magnified compared to people and profit. The importance of sustainability is reflected by the embodiment of the topic in the mission statements of many large organizations. Dealing with sustainability is difficult for organizations. The procedures of determining the degree of sustainability by life cycle assessments are described in the ISO14000 standards (ISO 14040 and ISO14044) [2][3]. However, many choices need to be made during the execution of a life cycle assessment. If these directions are not communicated clearly, the results can be interpreted incorrectly. Furthermore, life cycle assessments are data sensitive and time-consuming. Because of the data sensitiveness, life cycle assessments are not suitable at the earlier phases of the development process of product/packaging combinations, because during these phases often the data of the product/packaging combination are unknown.

In order to obtain more reliable results from life cycle assessments, the UPLCI methodology has been developed. This methodology splits the manufacturing process into sub processes. This makes the modeling of the manufacturing process more exact and provides more reliable data in the inventory. However, the methodology is explicitly developed for assessing the manufacturing processes of products. This paper describes the applicability of the methodology for product/packaging combinations; it also gives suggestions for an adaption and extension of the methodology for product/packaging combinations. Finally, examples are described by means of a case study.

2 PACKAGING AND SUSTAINABILITY

The environmental concerns regarding packaging are focused on the end of life of the packaging and the high amount of raw materials and energy that are needed for the production of packaging in relation to the relative short life span and low economic value. However, it is not appropriate to assess the packaging as a stand-alone object, because the packaging is closely involved in the life cycle of the content. The packaging preserves and protects the content, conveys formal and informal information to the users and it enables handling and use [4]. The environmental impact of the content is, in many cases, much higher than the environmental impact of the package. Packaging prevents environmental impact from food spoilage and damage of the content by preserving and protecting the content. Spoilage of the content for fast moving consumer goods (FMCG) is in most cases not included in life cycle assessments, while in a study from CREM (2010) it was concluded that eleven percent of the food that is bought was wasted [5]. Four percent of this food waste is inevitable because it is inedible (like bones and shells), but seven percent of the food waste could be avoided. From all food waste that could have been avoided 10 percent was not consumed and was still in its original, unopened packaging. From these contradicting points of view, it can be concluded that a first step in developing a more sustainable product/packaging combination is fulfilling the functional specifications of the packaging. Although a paradox at first sight, adding more packaging material can lead to a more sustainable product/packaging combination.

3 DETERMINING THE ENVIRONMENTAL IMPACT

Companies want to determine the degree of sustainability of their products and processes for different reasons. Many organizations want to know the environmental impact of the products and processes of their suppliers. This makes it possible to compare different suppliers and to choose the supplier with the best ratio between costs, quality and environmental impact. Besides this, the degree of sustainability is needed for communication with the government for getting environmental permits or in order to meet the environmental regulations.

During a workshop with industrial partners, problems regarding determining the environmental impact have been discussed. In this, explicit focus has been on representing different phases in the product/packaging life cycle.

Life cycle assessment is a methodology that is commonly used for determining the environmental impact. The environmental impact is defined by adding the environmental impact of all processes during the life cycle. This methodology could also be used for determining the environmental impact of product/packaging combinations (for FMCG). The result of a life cycle assessment is objective and specific, provided that the calculations are transparent. The reliability of the result is dependent on the reliability of the input. Indeed, industry faces significant problems in executing life cycle assessments because of the reliability of the input. This is also related to the complexity of the overall product/packaging development chain; in essence, every actor in the chain knows their suppliers and their customer (typification). However, connections between other actors are in general not active. A lack of insight in the complete chain, caused by little transparency, can give an unreliable result, because adequate data are missing. Actors need detailed information from their suppliers to obtain a reliable result from any life cycle assessment. A problem described by the companies is that not only the information is not available, but that the format of the information is often not useful for executing a life cycle assessment. Because life cycle assessments can be executed in different ways, the directions that are chosen are important for correctly interpreting the results. A lack of transparency makes this impossible. Life cycle assessments can be used selectively and the desired results can be obtained by 'turning the knobs'. The lack of data is partly solved by collecting general data in a database. Such data can be used if detailed information is lacking. A disadvantage of such data is that it is generic; i.e. it is not specific for a certain process or company.

Determining the degree of sustainability of different concepts during the earlier phases of the development of product/packaging combinations is useful because during these phases consequential decisions will be made. For each of these phases the best solutions regarding aspects as costs, quality and safety could be chosen. During the earlier phases of the development of product/packaging combinations, the data are uncertain or lacking, because the life cycle is not complete. This makes it difficult to use life cycle assessments as decision support tools. Guidelines, scorecards and checklists are developed to guide designers during these phases. The required knowledge for using these tools seems to be low, but that could be deceptive because experience and knowledge is needed to make the right decision regarding the environment. The results of life cycle assessments seem to be more specific and reliable. For this reason, possibilities for executing life cycle assessments during the development phase of product/packaging combinations need to be investigated.

4 LIFE CYCLE OF PRODUCT/PACKAGING COMBINATIONS

4.1 General Life Cycle of Product/Packaging Combinations

The life cycle of product/packaging combinations is different than the life cycle of just products. Because of the mutual dependency as described in section two, both the life cycles of the content and the life cycle of the packaging are important. A general representation of these life cycles is shown in Figure 1. At the left side, the life cycle of the packaging is shown. The right side shows the life cycle of the content (or product). Both general life cycles address similar processes; raw materials are needed to be processed into usable materials or ingredients. These materials and ingredients are used in the manufacturing of the packaging parts and the manufacturing of the content (FMCG) respectively. At the filling line, the packaging is filled with the content or product; here, the life cycle of the packaging and the life cycle of the content start to coincide. The finished product is transported to distribution centers and from there to supermarkets or other distribution points like food service points. Customers or consumers buy and consume the product in most cases. After consumption, the packaging is disposed. The packaging and in some cases (part of) the content are collected and processed into landfill, reusable materials or energy.

Figure 1: Life cycle of product/packaging combinations.

4.2 Actor Network

In most cases, the general chain is almost similar for all product/packaging combinations. The visualization serves as basis for the understanding of the life cycles. However, the representation of the product/packaging life cycle is not complete. Many more (partial) life cycles are involved in the overall life cycle. Every process contains many more sub-processes, like production of ink, machinery, transport packaging, etcetera. A more realistic representation of the product/packaging life cycle is shown in Figure 2. This depiction is referred to as an actor network. It is a more detailed reproduction of the general product/packaging chain. Interconnecting the different processes, presented in the general life cycle, gives the actor network. The actors involved in a product/packaging chain are represented by dots and the relations between these actors are visualized by links. When zooming in on one actor, same processes for all actors can be found. Inputs are coming from the preceding actors in the chain (suppliers), the involved actor converge the inputs and the resulting output is sent to the subsequent actors in the network. In theory, the actor network is

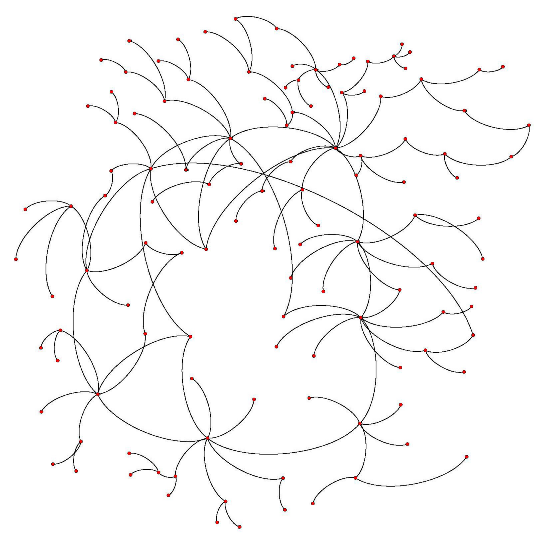

Figure 2: Actor network: the nodes are actors and the lines are relations between actors.

infinite. When using the network as representation of the product/packaging chain, the configuration of the network is dependent of the focus point and case [6].

Using an actor network as a representation of the life cycle provides a more transparent life cycle. Every actor involved in the life cycle describes their part of the life cycle. The combination of all actors gives a transparent overview of the life cycle. This overview can be used to take all important processes into account and to be aware of the parts of the life cycle that are not transparent. Defining the boundaries is essential during a life cycle assessment. By using an actor network, a well-considered decision about the boundaries can be made. For every actor, the necessity of taking this process into account has to be determined. Good argumentation is needed to explain the choices.

5 UNIT PROCESS LIFE CYCLE INVENTORY (UPLCI)

The methodology described by Overcash and Twomey [7] and Kellens et al. [8] gives a framework for systematic inventory analysis of the manufacturing phase. The manufacturing processes that can be found in existing LCA databases is in many cases a combination of many processes like transport, industrial packaging, electricity, etcetera. The UPLCI methodology describes the manufacturing process by these subprocesses. This makes it possible to make a more representative model of the manufacturing process and this can provide more exact and reliable data. The methodology includes two approaches with different level of detail: the in-depth approach and the screening approach.

The screening approach is based on publicly available engineering and industrial data and calculations for energy use and material loss. Sets of equations and tables of data from external sources are used to develop general principles by applying main parameters and energy use. Energy calculation should take both direct energy for accomplishing the unit process task as well as the fixed energy from systems that are active during the idle-mode into account. The other parts of the screening approach are calculations for mass loss. The mass loss might be losses from the basic material (for example the remnant after cutting corrugated plates into the shape of a corrugated box), auxiliary chemicals and interferences that lead to rejection of the product. An example of using the screening approach of UPLCI is described for the use phase of a drilling machine tool in part two of the publication written by by Kellens et al. [9].

The in-depth approach is especially useful for the development and optimization of the applied unit processes. In the in-depth approach, all in- and outputs of the process are measured and analyzed in detail; including time, power consumption, consumables and emissions. The in-depth approach gives more accurate and complete LCI data than the screening approach. During the time study the different production modes and the time span are investigated. Together with measurements on power consumption during these production modes, the total energy consumption can be calculated. Besides an energy study, a consumables study needs to be done. All consumables (materials, components, ancillaries and semi-products) are measured in each production mode. Finally, for every production mode the emissions (gaseous, liquid and solid emissions as well as heat) needs to be indicated and measured. In part two of the publication written by K. Kellens et al. an example of the usage of the in-depth approach for a case study on the use phase of a laser cutting machine tool. [9]

6 USABILITY OF THE METHODOLOGY FOR PRODUCT/ PACKAGING COMBINATIONS

6.1 Manufacturers as Actor

The screening approach of the methodology could be a good starting point for analyzing the activities of the actors involved in the manufacturing of a product/packaging combination on an ecologic perspective. When zooming in on one actor from the actor network, the productivities of this actor could be described by their unit processes (Figure 3). Examples of unit processes are injection molding, cutting, lacquer, etcetera. Public available data from databases as Ecoinvent could be used for these processes, but for a more accurate and complete result, the data should be calculated or measured for every sub process. First, the screening approach can be used to find the major impacts and most efficient optimizations. The in-depth approach could be used to find specific solutions for sub process optimization.

The manufacturing of the packaging is similar to manufacturing processes of other products. Many packages exists of different parts like container, seal foil, closure and label. In many cases, these parts are manufactured by different actors. Unit processes can be determined when zooming in on these actors. Setting the boundaries of these unit processes, or setting the level of detail of these unit processes, is important and needs to be described accurately. The results of the UPLCI gives opportunities to determine the environmental impact by using an impact assessment method (IAM). The results can be used to optimize the processes in an ecologic perspective.

Using the in-depth approach is especially useful for optimization of the manufacturing process. However, it is important to take the consequences regarding the environmental impact of the life cycle into account when changing processes. It could be possible that a change in the manufacturing process decreases the environmental impact of the manufacturing process while increasing the environmental impact of the life cycle of the product/packaging combination.

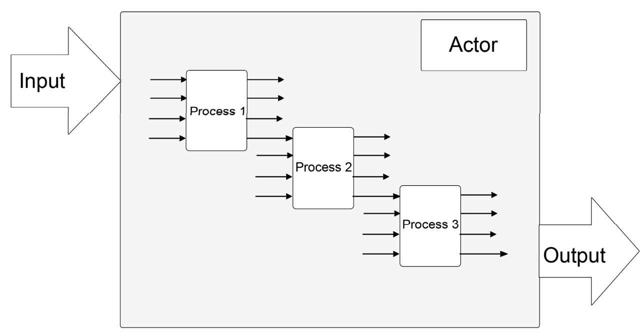

Figure 3: An actor and its unit processes.

6.2 Other Actors

For determining the consequences for the product/packaging life cycle, the complete chain needs to be analyzed. When analyzing the complete chain, publicly available data (with good documentation to assess the reliability) from existing databases can be used to determine the environmental impact of the manufacturing processes. However, it is more accurate and reliable to use the screening approach of the UPLCI methodology to determine the inventory of the manufacturing phase, because it is more product and/or company specific data. It should be possible to adapt variables in the calculation to determine the inventory data. These variables should be variables depending on the product/packaging combination (for example material thickness, size of the cutting line, etcetera).

Analyzing the complete chain is in general done by the packaging designer or the company that produces the content, because these actors have to communicate the sustainability of their products (and thus the product/packaging combination). Other actors than those involved in the manufacturing process cannot use the in-depth approach of the UPLCI methodology, because the data that are needed are not available. It is effortful or even impossible due to intellectual properties to collect or measure the data. The influence on these actors is limited, for this reason the data cannot be retrieved from the manufacturers. Part of the actor network is shown in Figure 4. No actor in the network has complete, detailed data about the whole chain. Data from other actors are black box. However, data that are collected by the manufacturers can be used by other actors involved in the life cycle by using the screening approach. Good documentation is needed to determine the usefulness and reliability of the data.

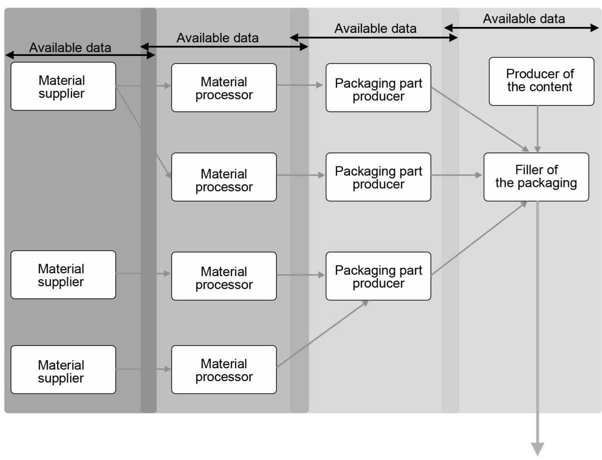

Figure 4: Part of the actor network and the availability of data.

6.3 Describing the Filling System with Unit Processes

During the filling process, the content and the packaging parts are combined into one product. The filling system is dependent on the content and the packaging. Every filling process has other filling machinery. Filling a package can be seen as an assembly process. At the filling line, more assembly processes take place. For example sealing, screwing caps, putting the packages in a corrugated box and palletizing. Every subprocess can be described as a unit process and for every unit process the data can be calculated or measured. However, in many cases different unit processes are combined into one machinery. It is a challenge to determine which part of the energy allocates to which process.

It could be possible to exchange unit processes to describe a filling process, however presumably this description of a filling system is not always realistic. The amount of energy, consumables and emissions are dependent on the types and combinations of machinery. The machinery is dependent on the packaging that needs to be filled and the content of the packaging. The filling process is for example dependent on the viscosity of the product and the techniques that are needed to create a longer shelf life. It seems more accurate to develop an group of unit processes for every filling system. The group of unit processes is dependent on the packaging and on the content.

Many unit processes needs to be collected and combined for describing a filling system. These filling systems are typical for a specific combination of packaging and content. Same filling processes can be used for different sizes of the same packaging and products. For example, it is expected that the differences between filling a one liter milk carton with one liter milk and filling a half liter milk carton with half a liter milk have a linear relationship. All processes are collected in a database. To structure this database a taxonomy is needed to define unit processes suitable to describe the occurring operations during the filling process of packaging with its content.

7 EXTENSION OF THE FRAMEWORK

When creating a database of all the possible processes, a clear taxonomy is needed to classify the processes. The CO_2PE initiative coordinates the (development of the) UPLCI methodology and efforts to collect and improve data for the database [10]. The taxonomy that is used for the database is based on DIN 8580. The processes are classified in primary shaping, forming, separating, joining, coating & finishing and changing material properties. Auxiliary processes are added to the classification of DIN8580. A small extension is needed to include the unit processes that describe the manufacturing and the filling of packaging.

7.1 Manufacturing of the Packaging

The database with the processes that are used for manufacturing products is not complete for describing the manufacturing process of packaging. However, the structure of the database is also useful for the manufacturing of packaging. Several processes for describing the manufacturing phase of plastic packaging are already included in the database: injection molding, extrusion, deep drawing. The same can be done for the other materials. For packaging made of paper and carton, primary shaping is not applicable. The processes that occur during the manufacturing of packaging made of paper or carton are based on forming processes like cutting, creasing and folding. Other processes that are important are printing, gluing, and coating. These processes are classified in coating and finishing. A differentiation between different printing techniques is useful. These printing techniques can also be used to describe the printing process during the manufacturing of plastic packaging. The manufacturing process of packaging made of glass is difficult to subdivide into the processing of raw materials and the production of the packaging. During the processing of raw materials, the bottle is produced. For this reason, unit processes describing the manufacturing of a packaging made of glass do not have to be included in the database. The fourth material that is used for packaging is metal. The unit processes describing the production of metal packaging includes cutting, welding, deep drawing, coating, and printing.

It can be concluded that processes need to be added to the database or specified to make these applicable for packaging. Examples are sealing, co-extrusion, specifying the printing techniques, and specifying the deep drawing for metal and for plastics.

7.2 Filling the Packaging

The filling process is more complex than the manufacturing processes and the database needs to be extended. The filling processes are included in the sub group ‘joining’. It is possible to include all filling processes although many filling processes will be needed to differentiate between the machinery. The database would be an inconvenient arrangement with filling processes, because of the large amount of variables in the filling process. More subtopics are needed to structure the filling processes. However, a good suggestion would be to include a new topic: packing. Every product needs to be packed once. The processes classified in ‘packing’ can be used to describe the filling system.

In the group ‘packing’ a distinction between the different types of packaging could be made to structure the filling processes. The types of packaging can be structured according to the material these are made of: plastics; carton, paper and wood; metal and glass. Besides the packaging, the content also influences the filling process. It should be useful to name the content of the filling process that is described. An example of the structure of the database is shown in Figure 5. The sub processes of a filling system can be used separately and combined to describe a filling system approximately. However, for a more reliable and realistic description and data inventory of the filling system, a group of unit processes need to be created or used.

The methodology is developed for the manufacturing phase. This phase can be described in units easily. This publication shows that the methodology could also be used to describe the filling process. It should also be useful to describe other processes in units, like waste handling, transport and use phase.

9. Packing

9.1 Metal
9.1.1 Can - carbonated beverage: placing cans, filling cans, placing caps, creating sixpack, palletizing
9.1.2 Can - cigars: placing tins, filling tins, closing tins, labelling
9.1.3 Can - paint: placing can, filling can with paint, closing cans, palletizing
...

9.2 Carton, paper and wood
9.2.1 Milk carton - milk placing cartons, folding cartons (1), gluing cartons (2), filling cartons with milk, folding cartons (1), gluing cartons (2)
9.2.2 Corrugated board - primary packaging placing corrugated carton, folding corrugated carton (1), filling corrugated carton, folding corrugated carton (1), gluing corrugated carton
9.2.3 paper bag - sugar gluing paper, filling bag (vertical), gluing paper
...

9.3 Glass
9.3.1 Bottle - noncarbonated beverage placing bottles, filling bottles, placing cap
9.3.2 Bottle - wine placing bottles, filling bottles, placing cork
9.3.3 Jar - apple sauce placing jars, filling the jars, placing caps, placing label
...

9.4 Plastic
9.4.1 Bottle - beverage placing plastic bottles, filling, sealing, placing cap
9.4.2 Tray - cheese placing tray, filling tray, sealing tray, placing cap
9.4.3 Flexible bag - candy sealing bag, filling bag (vertical), cutting and sealing bag
...

Figure 5: Example of the database structure of filling systems.

8 CASE STUDIES

Different case studies are done to describe the manufacturing and filling process of a packaging into unit processes. As discussed, defining the boundaries is difficult, especially for the filling process. Part of an actor network for a bottle made of plastic and filled with a sport drink is shown in Figure 6. The actor network is focused on the manufacturing part of the packaging. Different kinds of plastics are extracted from oil: PET for producing the bottle by injection blow molding, PE for producing the cap by injection molding and PP for producing the shrink sleeve by extrusion. The sleeve has to be printed, ink is needed for printing the sleeve. At the filling line the bottle is filled with the sport drink, a cap is placed on the bottle and a sleeve is sealed and placed on the bottles. An certain amount of filled bottles are placed in a corrugated box. These boxes are placed on a pallet and these pallets are transported to the distribution center. From this point, the products are distributed to different supermarkets or other food selling points.

Applying the UPLCI methodology is useful for the manufacturers of the bottle, cap, sleeve, ink and corrugated box who want to optimize their production processes regarding the environmental impact. It is important to take the consequences for the chain into account when adapting the manufacturing process. The injection blow molding process of the bottle can be described in one unit process. This process can be found in the database in the category primary shaping, primary shaping fibre-reinforced plastic. Calculations in case of the screening approach and measurements in case of the in-depth approach need to be done to determine the inventory. The screening approach is useful for all actors involved in the network, provided that the calculation for the unit processes are set up by the manufacturer. The same is true for the injection molding process for the cap. It is possible to use an existing injection molding process and adapt the variables in the values for the injection molding process of this cap. Manufacturers of the cap can use the in-depth approach for optimizing the process. Consequences for the chain need to be taken into account. The production of the label by extrusion and the printing of the label can be described by unit processes. The extrusion process can be found in the database structure in primary shaping, primary shaping fibre-reinforced plastic and the printing can be found in coating & finishing, printing.

The filling process can be described as unit processes. Examples of unit processes are: placing the bottles, filling the bottles, placing the

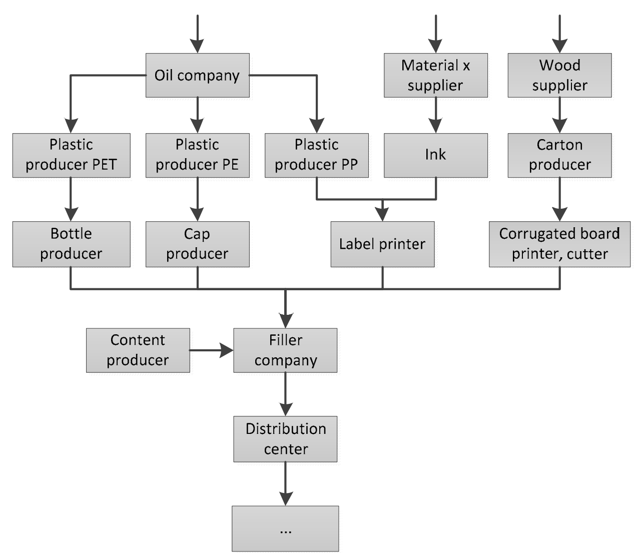

Figure 6: Part of the actor network of a plastic bottle.

caps, filling a box with certain dimensions and palletizing. In many cases placing the bottles, filling the bottles and placing the caps is done at one machine. It is difficult to allocate the energy to the different processes. The filling process can be found in the database: Packing, plastic, bottle – beverage (Figure 5).

9 CONCLUSION

Sustainability is an important topic in the field of packaging, because packaging is seen as a major contributor to the environmental impact. Resources and energy are needed for a 'product' with a relative short life span and low economic value. However, packaging protects the content and prevent spoilage of the content. For actors involved in the life cycle of a product/packaging combination, determining the environmental impact becomes increasingly important. Companies from industry experience problems when determining the environmental impact. Because of a lack of transparency in the chain and a lack of reliable data, difficulties with the reliability of the results of a life cycle assessment occur.

To increase the transparency of the data needed for executing a life cycle assessments the actor network can be used. This network gives a more realistic representation of the product/packaging life cycle. The UPLCI methodology is a useful methodology for systematic analysis of the manufacturing processes of packaging. The methodology is especially useful for analyzing and optimizing the manufacturing processes. The actors involved in these processes have access to the data that are needed to execute the calculations in case of the screening approach or they are able to measure or determine power, time, consumables and emissions.

For other actors involved in the life cycle of product/packaging combinations, the data that are needed to execute the calculations have to be collected and specified by the manufacturers. Other actors cannot use the in-depth approach, because they cannot measure power, time, consumables and emissions of the manufacturing process due to lack of influence. For these actors, the manufacturing data are black box. It is useful to create a database with all unit processes that are investigated. By including a good and transparent documentation, the usefulness and reliability of the data can be determined. When the data are reviewed as useful, the data can be used to describe a manufacturing process and to determine the inventory data.

The filling process can also be called a manufacturing process. In this phase packaging is assembled and filled with its contents. It is useful to use the UPLCI methodology to analyze this process. However, using building blocks to describe the filling system are difficult, because in many cases several unit processes are executed by the same machinery. Allocating an amount of energy to a certain unit process is difficult. The filling system is dependent on the packaging as well as on the content of the packaging. A group of unit processes describe a filling system. The unit processes can be used separately, but it is more reliable to create a new group of unit processes to describe a filling system (unless, same machinery is used).

10 ACKNOWLEDGEMENT

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11 REFERENCES

[1] Brundland ea (1987); World Commission on Environment and Development, Our common future: Oxford University Press, Oxford, England

[2] International Standard ISO 14040. Environmental management - life cycle assessment—principles and framework, 2006.

[3] International Standard ISO 14044. Environmental management - life cycle assessment—requirements and guidelines, 2006.

[4] Lutters, D.; Ten Klooster, R. (2008): Functional requirement specification in the packaging development chain, in: CIRP Annals - Manufacturing Technology, Vol. 57, No. 1, pp. 145 – 148.

[5] CREM: Bepaling voedselverliezen bij huishoudens en bedrijfscatering in Nederland, September 2010.

[6] Lange, J.; Oude Luttikhuis, E.J.; Lutters, D.; ten Klooster, R.; (in press). Towards integrating sustainability in the development of product/packaging combinations

[7] Overcash, M.; Twomey, J.; Unit Process Life Cycle Inventory (UPLCI) – a structured framework to complete product life cycle studies, 19th CIRP International Conference on Life Cycle Engineering; 2012

[8] Kellens, K.; Dewulf, W.; Overcash, M.; Z. Hauschild, M.; Duflou, J.R. (2012): Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI) – CO2PE! Initiative (cooperative effort on process emissions in manufacturing. Part 1: Methodology description, in: International Journal of Life Cycle Assessment, Vol. 17, pp: 69-78

[9] Kellens, K.; Dewulf, W.; Overcash, M.; Z. Hauschild, M.; Duflou, J.R. (2012): Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI) – CO2PE! Initiative (cooperative effort on process emissions in manufacturing. Part 2: case studies, in: International Journal of Life Cycle Assessment, Vol. 17, pp: 242-251

[10] CO2PE (Cooperative Effort on Process Emissions in Manufacturing), 2010, available online: http://www.mech.kuleuven.be/co2pe, last revised 03.12.2012.

Towards an Increased User Focus in Life Cycle Engineering

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Abstract

Traditionally, Life Cycle Engineering has had a limited focus on the use stage of products; also sustainable product design research and education has mainly focused on material and end-of-life aspects. With a new found focus on the use stage, as in the research area of Design for Sustainable Behaviour (DfSB), a better understanding of how a focus on behavioural aspects can reduce life cycle impacts has emerged. Preliminary findings from on-going DfSB research were used as basis for the development of a method to guide designers in selecting promising design principles that can contribute to change user behaviour into more environmentally friendly patterns. This method is presented, and it is reflected upon to what extent this method is suitable and relevant for Life Cycle Engineers to apply. It is concluded that the embedded requirements for designerly thinking may make earlier steps in the method less suitable for engineers to participate in, but collaboration between designers and engineers in the last steps may be key to make the most out of the synergy between designerly and engineerly thinking.

Keywords:

Life Cycle Engineering; Sustainable Design; Design for Sustainable Behaviour

1 INTRODUCTION

The last two decades of research in areas such as life cycle engineering and sustainable product design have resulted in progressing insights on the complexity of the ever broadening topic. The scope has gradually expanded from a product to a systems perspective, from an environmental to a sustainability context, and from a concept development to technology transfer and commercialization perspective [1]. Research focusing on the use phase of products has throughout these transitions mostly focused on technological solutions to achieve resource use (mostly energy use) efficiency. To some extent, in the field of Life Cycle Engineering this is still the case, whereas in Sustainable Product Design a new wave of interest in understanding user behaviour can be observed in recent years. This type of research is increasingly commonly referred to as Design for Sustainable Behaviour.

This paper aims to collect the most relevant developments in this field, highlighting a number of research projects, and to reflect on their applicability in the Life Cycle Engineering research community. It may, as such, serve as an introduction for the Life Cycle Engineering community into Design for Sustainable Behaviour. The Life Cycle Engineering and Sustainable Product Design research communities (if such concepts exist) have always been closely related, with common conferences (such as CIRP Life Cycle Engineering, the Ecodesign, and ICED conference series) and journals (such as Journal of Cleaner Production and International Journal of Sustainable Engineering) and even partly share a common original focus on material and end of-life aspects. However, although many commonalities exist in terms of goals, significant contrasts exist in terms of mind sets, responsibilities, formulation of guidelines, approaches to a problem, work methods, and educational approaches in general [2]. The increased focus on, mostly qualitative, user research in the design community may not be bringing these mind sets closer together either. This paper is written though from a perspective that sharing research perspectives between engineering and design research communities is something that will facilitate reaching common goals.

A central issue in this paper is to consider if knowledge about Design for Sustainable Behaviour approaches has relevance for the design community only, or can be extended in a way relevant for life cycle engineering research. To inform this discussion, Chapter 3 introduces a methodology which, though still under development, proposes a systematic approach for considering behaviour-changing design principles. In Chapter 4, its application in a Life Cycle Engineering context will be discussed.

2 BACKGROUND

Although energy efficiency has been a focus for decades in heavy industries that are major energy consumers, attention for energy efficiency on a product level, in the areas of discrete part and product manufacturing is much more recent and has basically only existed for about a decade [3]. Even there, attention for energy efficiency studies focus mostly on energy consumption of machine tools and process chains in the context of manufacturing processes for products. Within Life Cycle Engineering, attention for sustainability issues related to products is mostly related to the end-of-life phase and focuses on disassembly and recycling processes. Linking Life Cycle Engineering to consumer products in use has received far less attention. Energy metering is however one of few topics that has an interest in addressing opportunities for use phase energy efficiency improvement. Within Life Cycle Engineering, this is mostly addressed from a technical perspective, integrating electronic, mechanical and software design [4] and based on engineering-oriented design for X approaches based on quantitative assessments [5], including Life Cycle Assessment. However the use of Life Cycle Assessment is typically challenging when addressing use related aspects on consumer behavior and preferences [6].

In sustainable design, the use phase of products has traditionally been one of the life stages of products addressed, but mostly from the perspective of reducing energy use using cleaner energy sources. More recently research has suggested that through better understanding user behaviour, and applying that knowledge in design solutions that may make users behave in environmentally preferred

	Lilley et al. 2005 [11]	Elias et al. 2007 [12]	Bhamra et al. 2008 [13]	Wever et al. 2008 [14]	Lockton et al. 2010 [15]	Tromp et al. 2011 [7]	Zachrisson and Boks 2012 [16]
Informing strategies		Consumer education	Eco-information		Thoughtful		Information
	Eco-feedback	Feedback	Eco-feedback	Eco-feedback			Feedback
			Eco-spur				
Persuading strategies	Scripts and behavioural steering	User-centred ecodesign	Eco-choice	Scripting	Shortcuts	Seductive, persuasive	Enabling
							Encouraging
							Guiding
			Eco-steer				Steering
Determining strategies	'Intelligent' Products and Systems		Eco-technical intervention		Pinballs	Coercive, Decisive	Forcing
			Clever design	Forced-Functionality			Automatic

Table 1: An overview of Design for Sustainable Behaviour strategies (based on [16]).

ways, significant additional energy consumption reduction may be achieved . Design researchers increasingly understand their role in investigating such opportunities to influence users to alter their behaviour into more sustainable behaviour and consumption patterns [7]. As a result, we can now observe a young area of research emerging, referred to as Design for Sustainable Behaviour (DfSB) aiming at exploring design strategies for reducing behaviour-related environmental impacts of product and systems as well asmore general applications to persuade users into more socially desirable behavioural patterns [8]. DfSB research incorporates insights from scientific fields including social psychology, persuasive technology, sustainable consumption, stakeholder analysis and interaction design. The current state of the art is one of exploring case studies, identifying design principles and developing guidelines to choose appropriate principles for specific design challenges. Much of this research has been inspired Akrich's [9] concept of scripting. The idea behind a script is to inscribe a kind of user manual into an artefact, in a way that the design of a product guides the way it is being used and as a result reduces the environmental impact caused by its use. Different properties of scripts have been proposed earlier on, including force (how strongly the script prescribes the behaviour), scale (the level of complexity), direction (in which direction the behaviour is being steered), and distribution (how much responsibility and power the user is given) [10]. More recently, elaboration on the notion of scripts, and including weaker and stronger variations of changing behavioural steering, has resulted in the proposition of a range of design strategies by various authors [11-16]. Table 1, an extension of an earlier published table [16], aims to enumerate these strategies. These can broadly be categorised as informing, persuading and determining strategies. This enumeration makes clear that the dimension of control distribution between the user and the product or technology is widely used as a distinguishing factor [7,17]. Very recently, research has proposed additional dimensions that are potentially relevant to consider in forging and choosing relevant design strategies. These include in particular obtrusiveness [7,18], but also empathy (considering collective versus individual concerns) [7], meaning, timing and frequency, have been considered. Our research [16,18] suggests that control and obtrusiveness (the degree of subtlety or amount of attention required) are important ways to distinguish between design principles. Together, control and obtrusiveness have proven to be two main dimensions useful for sorting or categorising design strategies and solutions that may lead to behavioural change. These dimensions can be used to create a landscape for doing so, as depicted in Figure 1. To illustrate how it works: The upper left corner for example depicts a fridge alarm that detects when the door has been left open for more than 30 seconds and reacts by sounding an alarm. The alarm provides mere feedback, leaving the user in control, but is very obtrusive as the alarm is almost impossible to ignore. The lower right corner depicts a modern TV with automatic brightness settings, where the product is in control and the user does not even need to be aware of the technology.

Figure 1: Control-obtrusiveness landscape with examples.

3 PRINCIPLES OF DESIGN FOR SUSTAINABLE BEHAVIOUR

The authors are part of a research group that has adopted Design for Sustainable Behaviour as a key research area. One of the on-going PhD projects in the group aims at providing designers with a means to make informed decisions about which design principles to apply. In the first stages of this project, preliminary guidelines for selecting principles have been proposed [16]. These guidelines propose a way of translating information about human behaviour and insight from social psychology literature to recommendations for design principles. In 2011, these guidelines were developed into an alpha version of a guide in the form of a booklet (Figure 2).

The theoretical basis for the guide is a combination of insights from social psychology regarding the main factors affecting our behaviour, and strategies for behaviour changing design, from design research. The booklet is meant to communicate the results of this research in a form that is suitable for use in a design project. A major emphasis is put on helping designers to translate their understanding of the user and the context into an appropriate selection of design principles. The structure of the booklet is built around a suggested design process (Figure 3), with descriptions of the purpose and activities for each step, and with the help of appropriate examples. Although the figure suggests a linear process, the sequence, number of iterations, or even in- or exclusion of steps may depend on the project and the preferences of the designer, which is clearly explained in the booklet. The steps proposed in the booklet are presented in the next subparagraphs.

Figure 2: Booklet with Principles of Design for Sustainable Behaviour.

3.1 Step 1: Study and Measure the Base-Line Practice

This step explains how to choose the right methods to gather the most relevant information for a specific project, and why that is an important decision. There are numerous different methods and tools to gather information about the user and the situation of using a product. Which tools are most suitable to gather data about user behaviour for a particular project depends on a number of factors, including the time and resources available, the competence available in the team, the accessibility of the target group, and the goal of the research. Although methods useful for a DFSB oriented project are similar to those commonly used in 'regular' user-centred design projects, the methods described in the booklet require some specific information about what goes on in the mind of the user, what goes on around the user and what the user actually does. This is described in more detail in steps 2 and 3. There may also be things the user does or that affect behaviour, which the user is unaware of. To investigate this it is necessary to combine methods or use methods that investigate both aspects, such as applied ethnography or contextual enquiry. This step also highlights the importance of researching previous, similar studies, as user research can be expensive and time consuming; the booklet provides a number of resources to assist in this process.

3.2 Step 2: Identify Which Behaviour Is to Be Changed

Once the information about the user and the context has been gathered, one needs to determine which behaviours to change or maintain. As the goal is to use design to reduce avoidable environmental consequences related to behaviour, it is valuable to identify those behaviours that both cause significant environmental impact and are possible to affect through design; i.e. where a designerly way of thinking can have a contribution. In this context, a designerly way of knowing and thinking refers to the view that designers have a way thinking and communicating that is both different from scientific and scholarly ways of thinking and communicating, and as powerful as scientific and scholarly methods of enquiry when applied to its own kinds of problems [19]. It suggests that design is a process of pattern synthesis, rather than pattern recognition, and that it has to be actively constructed by the designer's own efforts any solution is not simply lying there among the data but has to be actively constructed by the designer's own efforts [20]. The larger the potential impact reduction and the easier it is to affect it through design, the easier it will be to achieve environmental benefit. However, selecting target behaviour is one of the major DfSB research challenges [21]. One logical starting point for selecting appropriate behaviour could be the size of the potential reduction in environmental impact through altering user behaviour. Theoretically, selecting relevant case studies would not be a problem, but systematically ranking all user behaviour that impacts sustainability based on proper life cycle assessments would be an highly impractical and time consuming activity. Moreover, additional relevant considerations would be missing, such as the magnitude of the behavioural component, and the improvement potential from, again, the designerly perspective [21]. In additional, the complexity of the situational context may be a relevant aspect to consider in selecting target behaviours. If quantification is indeed problematic, it may be possible to consider the effects of potential behaviours to be changed relative to each other, in a more qualitative way. The interesting element is to identify how much energy could be saved with a different behaviour while still achieving the goal. It is important to consider the entire practice, as there might be low hanging fruit also outside the core behaviour. If it has been possible to calculate the actual impact of the behaviours, this information can be used after the project to estimate the achieved improvements and thereby the successfulness of the behaviour changes.

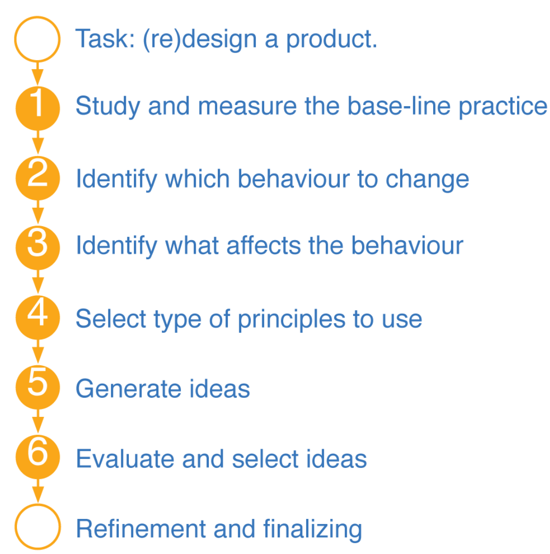
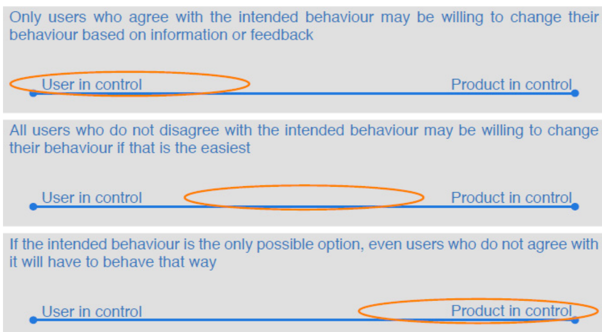


Figure 3: Proposed Design for Sustainable Behaviour process.

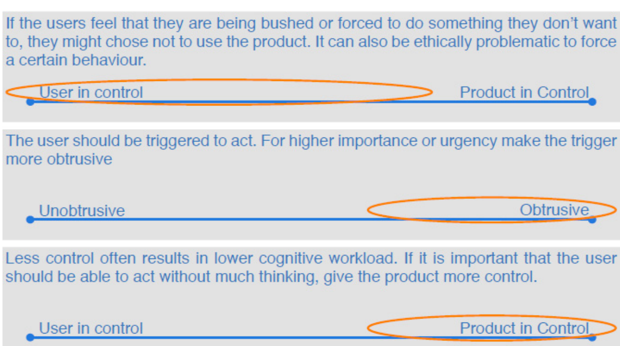
3.3 Step 3: Identify What Affects the Behaviour

When trying to change the behaviour of people related to how they use products, it is important to realize that behaviour can be affected by a number of different factors -- and often a combination of several. The information gathered during the user studies can be analysed to identify the most important factors for your target group, by identifying the main reasons for why users behave the way they do. In the booklet, understanding and structuring the factors is done by dividing them into four different groups and communicating them through diagrams such as illustrated below. These simple diagrams aim to indicate what type of design strategy from the control-obtrusiveness landscape may be most suitable for changing behaviour, based on the insight in what affects the user's behaviour, and based on exploring behavioural psychology models such as the CADM model [16,22].

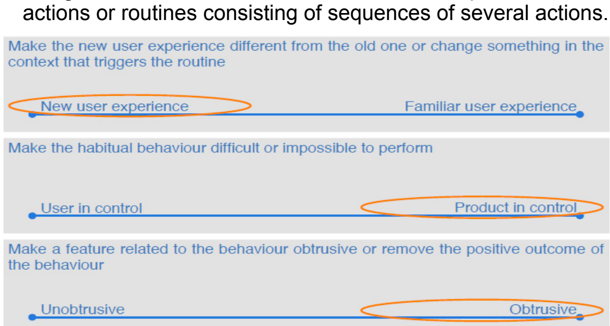
- *What the user wants*: What does the user intend to do? What does the user believe are the consequences of the behaviour? What is the attitude of the user towards these consequences, regarding for instance the environmental impact, the effect is has on other people, the cost, etc.



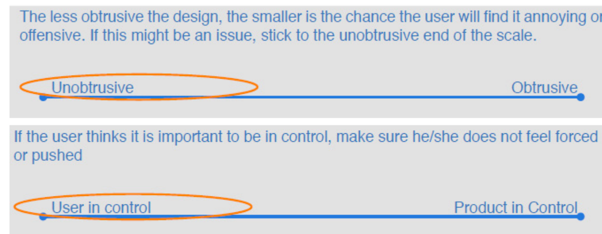
- *The influence of the surroundings:* Which constraints are caused by the context around the use of the product? Do the surroundings make certain behaviour easier or more difficult to do? Does the product itself direct the user towards certain behaviour? Are there elements in the surroundings that affect the behaviour of the user and the interaction with the product?



- *The habits:* Are there things the user does without necessarily being aware of it? These can either be simple, stand-alone actions or routines consisting of sequences of several actions.



- *What the user thinks is right or wrong:* Which values does the user have, and which ones are most important? What does the user think is morally right or wrong to do? Is the user affected by any cultural of community values that may prescribe or forbid certain behaviours?



The factors in these four groups may all affect the behaviour of the user in different ways and may be of importance for how a product should be designed in order to realise the affect that the designer is striving for. It is also possible that the users will have to be divided into groups according to which factors are most important for them or differences in the factors, such as different attitudes towards the consequences. The booklet suggests that one way of doing this is by creating personas that represent the different user groups. Using personas is explicitly suggested for students as they are relatively familiar with using this technique and may be a kind of 'anchor' to them in an otherwise very novel process.

3.4 Step 4: Select Type of Principles to Use

In this fourth step it is explained how numerous design principles exist that can create behaviour change, but that some design principles likely will work better for certain users and in certain situations, than for/in others. To identify which principles may be more successful than others in a specific project, this section of the booklet includes a guide intended to help identify the most promising types of design principles according to the result of the analysis in step 3. This can be done using the control-obtrusiveness landscape introduced in Figure 1. The guide continues with an elaborate discussion on which level of control and obtrusiveness may be appropriate based on the results of the analysis in step 3, using diagrams such as shown in the previous step. It is explained that habits are routine behaviours that are performed more or less automatic, and that because of this, the user is not always aware of the behaviour and it is therefore not necessarily in line with what the user wants, what the user thinks is right or what it is easiest to do. To change a habit, the user should be made aware of the habitual behaviour and be motivated change it. Once the behaviour is no longer automatic, it may be changed according to what the user wants or the influence of the surroundings.

Once it has been decided which principles may be most effective to use, the control-obtrusiveness landscape can be used to summarize the results, in order to get an overview, communicate them and include them in the design process. Figure 4 shows how, based on user research done in previous steps, it can be visualised what solutions on a certain part of the landscape may be most appropriate for affecting the behaviour of various identified personas.

3.5 Step 5: Generate Ideas

Once the requirements for the new design have been identified, idea generation follows. This creative problem solving step is basically the same as in any other design process which may for instance include commonly used methods such as brainstorming, creative workshops or Forced Functions. The purpose is to figure out how the product could be designed to fulfil all requirements, both regarding behaviour change and other requirements the design project might have such as price, durability, aesthetics, ergonomics etc. Whether the idea generation should focus on the identified areas in the landscape, allowing for a focused idea generation process, or whether a more general idea generation process should be the basis for selecting appropriate ideas that fit to the identified areas, is left up to the preferences of the individual designer. We have found that students typically choose the latter way: they do not let themselves be restricted by the confines of the identified search area; they rather select relevant ideas from a broader search.

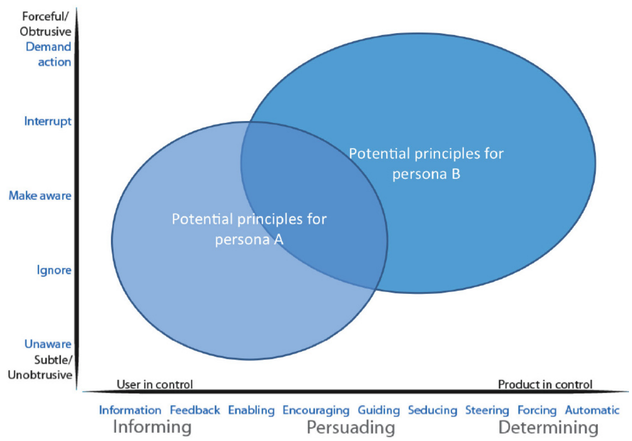


Figure 4: Placing personas on the obtrusiveness-control landscape.

3.6 Step 6: Evaluate and Select Ideas

After ideas have been generated, it is often a challenge to evaluate the ideas in a structured way and actually identify which ideas are most promising. In a regular design project, this is often solved by an assessing how ideas will fulfil a list of requirements, typically formulated as ‘musts, should and coulds’. The same can be done regarding the requirements derived from the desired behaviour change, but to make sure that the ideas actually solve the original challenges it might be useful to evaluate based on the personas and the guide, rather than merely the requirements or design dilemmas derived from these. This may be done by appropriately placing both the personas and the ideas on an empty control-obtrusiveness landscape, revealing which ideas may solve the behavioural change challenges related to individual personas. Once the most promising ideas have been selected a regular user centred design process can be followed, which usually includes concept development, prototype building, user testing and final detailing. The booklet explains how designers should be aware that it can be problematic to test whether changes in behaviour are actually accomplished in a traditional user test and might require more longitudinal testing outside a laboratory context.

4 DISCUSSION: DESIGN FOR SUSTAINABLE BEHAVIOUR IN A LIFE CYCLE ENGINEERING CONTEXT

Researching sustainable behaviour does not seem to have been picked up yet by more engineering oriented research communities. To question why provides an interesting discussion theme. On the one hand, one could argue for the perspective that studying humans, and behavioural issues in particular, are not the responsibility for the engineer and that in fact, research methods required for this are closer to social science than engineering sciences, and perhaps too far away from where design and engineering science overlap. A more positive perspective is to argue from a point of view where synergies between design and engineering communities are necessary to develop successful solutions, and that designers need engineers to help them materialise what comes out of their creativity. For example, if following a design for sustainable behaviour research approach, such as presented in chapter 3, leads to the insight that for a certain persona intelligent, forcing or automatic, unobtrusive design solutions are most likely to result in a desired behaviour change, then designers may need engineers to help make them. Whether engineers could make do with the result of the analysis (as in a list of requirements for a design), or would actually require understanding of the methodology that was fundamental to creating this list of requirements, is an interesting question. The preference for working with overall functionality rather than technical detail is perhaps what separates a designer from an engineer [2]. While engineers see something as a technical artifact, designers, with their aforementioned designerly ways of thinking and knowing, may see the same object as something designed to fulfill a purpose. Designers place more emphasis on qualities that can only be seen when placing the product in a larger context, and they will hence develop the product as an item designed to work with its surroundings. Designers will evaluate their work in terms of whether the concept delivers the intended behavior change, whereas engineers may wonder whether the technology is right and whether the concept works according to prescribed specifications. From that perspective, a broader understanding of the data collection process, gathering elements through behavioural analysis of intended users leading up to these specifications might be unnecessary for engineers to get a grip on – especially if that would frustrate their engagement to the project.

On the other hand, another interesting question is whether the active participation of engineers in brainstorming session may provide idea that designers themselves may never come up with. Through experiences with the method presented in Chapter 3 in an educational setting [23] it was found that students, when setting out to explore concepts in Step 5, seldom explore technology-based concepts beyond app-based solutions, and rather stick typical product based artifacts such as redesigned taps, brushes or detergent dispensers (to change water and detergent consumption behavior), laundry baskets (to change washing behavior). One student group came up with a preliminary concept for a food left-over storage solution based on bacteria sensing technology (to change food waste behavior) but further exploration of the concept was dismissed in favour of simpler, mono-material solutions. This was obviously not only due to lack of time but also due to expected challenges with working with technology; engineering students might have chosen this concept for further development over more aesthetically oriented solutions. This is not to say that our design students only chose to develop simple product-based solutions; another relevant observation has been that the students working with the method presented in this paper, often considered or developed services, product-service systems or integrated solutions as the most promising solution to change behaviour. One example of such a solution was an app designed to interact with an electronic device controlling a heater via Bluetooth: the persona for which this solution was developed cannot be bothered to adjust sleeping room temperature to low, healthy levels, but since the smart phone is used as alarm clock, the app can be left with the responsibility to take care of this task, providing a win-win situation for the user. This example also illustrates the level of interest of design students in detailing the concept: most effort was put in designing the interface of the app, whereas it was basically assumed that the electronic device would be no problem to develop – and thus was not something they chose to focus on.

5 CONCLUSIONS

So, how do these considerations add up? The majority of the steps proposed in Chapter 3 require methods, and a designerly way of knowing and thinking, that may be outside the comfort zone and skills of engineers. Although this may be an overgeneralisation – hybrid professionals do exist --, the ambiguity in terms of structure, which methods to use, which behaviour to change, whether to quantify or not (and if yes, how), and what design strategy to apply are all signs of uncertainty that is more natural for a designer to address, than for an engineer. However, engineers can play an important role in later stages of the process, once the design challenge is defined, and conceptualisation and in particular detailing of concepts is on the agenda. Together, designers and engineers may develop solutions that may not be discovered with a designerly thinking only or with a more traditional engineering approach. To what extent engineers need to be informed about the underlying qualitative user studies before they join a design process is something we would like to collect more experiences about – which is one of the rationales for writing this paper.

6 REFERENCES

[1] Boks, C., McAloone. T. (2009). "Transitions in Sustainable Product Design Research". *International Journal of Product Development* 9(4):429-449.

[2] Gudem, M., Boks, C. (2011). A Study Of Models In Order To Promote Understanding And Interaction Between The Worlds Of Design And Engineering, Proceedings of the International Conference on Engineering Design (ICED2011), 15-18 August 2011, Copenhagen.

[3] Duflou, J. R. Sutherland, J. W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M., Kellens, K. (2012). Towards energy and resource efficient manufacturing: A processes and systems approach. CIRP Annals - Manufacturing Technology 61 (2012) 587–609.

[4] Evrard, D., Brissaud, D., Mathieux, F. (2011). Synergico: a method for systematic integration of energy efficiency into the design process of electr(on)ic equipment. *Glocalized Solutions for Sustainability in Manufacturing - Proceedings of the 18th CIRP International Conference on Life Cycle Engineering* , pp. 148-153

[5] Ingeneer, L.D., Mathieux, F. & Brissaud, D. (2012). A new 'in-use energy consumption' indicator for the design of energy-efficient electr(on)ics. Journal of Engineering Design, Volume 23, Issue 3, 2012

[6] Bright, R., Boks, C. (2008). Mapping LCA Use in Eco-Design: Engineer, Designer and LCA Specialist Perspectives. Proceedings of the 15th CIRP International Conference on Life Cycle Engineering: Applying Life Cycle Knowledge to Engineering Solutions, 17-19 March 2008, Sydney, Australia, pp. 118-123, ISBN 1 877040 67 3

[7] Tromp, N., Hekkert, P., Verbeek, P.P. (2011). "Design for Socially Responsible Behaviour: A Classification of Influence Based on Intended User Experience". *Design Issues* 27(3):3-19

[8] Lockton, D., Harrison, D., Stanton N. (2010). "Design with Intent. 101 patterns for influencing behaviour through design". Windsor, Berkshire, UK

[9] Akrich, M., & Latour, B. (1992). A summary of a convenient vocabulary for the semiotics of human and nonhuman assemblies. In W. E. Bijker & J. Law (Eds.), Shaping Technology, Building Society (pp. 259-265). Cambridge Mass: The MIT Press.

[10] Jelsma, J. (2006). Designing 'moralized' products. In: P.-P. Verbeek and A. Slob (eds.), User Behavior and Technology Development: Shaping Sustainable Relations Between Consumers and Technologies, 221-231.

[11] Lilley, D., Lofthouse, V., Bhamra, T. (2005) 'Towards instinctive sustainable product use', Presented at the *2nd International Conference: Sustainability Creating the Culture*, 2–4 November 2005, Aberdeen Exhibition & Conference Centre, Aberdeen, Scotland.

[12] Elias, E., Dekoninck, E., Culley, S. (2007) 'The potential for domestic energy savings through assessing user behaviour and changes in design', *Proceedings of EcoDesign 2007: 5th International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 10–13 December 2007, Tokyo, Japan.

[13] Bhamra, T., Lilley, D. and Tang, T. (2008) 'Sustainable use: changing consumer behaviour through product design', *Proceedings of Changing the Change: Design Visions, Proposals and Tools*, Turin, Italy.

[14] Wever, R., van Kuijk, J. and Boks, C. (2008) 'User-centred design for sustainable behaviour', *International Journal of Sustainable Engineering*, Vol. 1, No. 1, pp.9–20.

[15] Lockton, D., Harrison, D., Stanton, N. (2012). Models of the user: designers' perspectives on influencing sustainable behaviour. Journal of Design Research, Volume 10, Number 1–2/2012 Pages 7-27

[16] Zachrisson, J., Boks, C. (2012). "Exploring Behavioural Psychology to Support Design For Sustainable Behaviour Research". Journal of Design Research 10(1/2):50-66

[17] Pettersen, I., Boks, C. (2008) 'The ethics in balancing control and freedom when engineering solutions for sustainable behaviour', *International Journal of Sustainable Engineering*, Vol. 1, No. 4, pp.287–297.

[18] Zachrisson, J., Boks, C. (2011). "Obtrusiveness and design for sustainable behaviour", Proceedings of Consumer2011, 18-20 July, 2011, Bonn

[19] Archer, L.B. (1979). "Whatever Became of Design Methodology?". *Design Studies* **1** (1): 17–20.

[20] Cross, N. (1982). Designerly Ways of Knowing, Design Studies 3(4)

[21] Boks, C. (2011). Design for Sustainable Behaviour Research Challenges, in: Matsumoto, M., Umeda, Y., Masui, K., Fukushige, S. (ed.): Design for Innovative Value Towards a Sustainable Society. Proceedings of Ecodesign 2011, Springer Verlag.

[22] Klöckner, C., Blöbaum, A. (2010) 'A comprehensive action determination model', Journal of Environmental Psychology, Vol. 30, No. 4, pp.574–586.

[23] Boks, C., Daae, J. (2012). Design for Sustainable Behaviour in Design Education. Proceedings of the International Conference on Engineering and Product Design Education, 6-7 September 2012, Antwerp, Belgium

Quantitative Design Modification for the Recyclability of Products

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Abstract

This paper proposes a design support method for increasing the recyclability of electrical and electronic products. The method estimates the recyclability rate and the disassembly time of a product based on its material composition and end-of-life scenario. Sensitivity analysis is conducted on the recyclability rate in order to quantify the impact of design changes in the product's material composition, mass of components, and end-of-life treatment processes. For the feasibility check of the design changes, we introduce a structural model of the product, which represents the geometric constraints among components to assess their disassemblability. As a case study, the recyclability of a LCD TV with an end-of-life scenario in Europe was evaluated and sensitivity analysis on the TV generated design alternatives that increase the recyclability rate while keeping the disassembly time of the original design.

Keywords:

Design for recycling; Recyclability rate; End-of-life scenario; Disassemblability

1 INTRODUCTION

The recyclability of waste electronic and electrical products has become a key environmental issue. An effective approach for increasing the efficiency of resources in such products is the quantitative evaluation of their potential for recycling at the design stages. The recyclability of products depends on their end-of-life (EoL) treatment factors (e.g., legislation, recycling technology, recycling processes, etc.) [1] as well as the design of the products. For example, a glass panel of an LCD TV is recyclable only if the printed matters on the glass surface are removed and the clean cullet is collected.

In this study, recyclability rate [2-4] is employed as an index of a product's recyclability estimated by the design parameters and the EoL scenario of the product. This rate is defined as a mass fraction of recyclable materials to total mass of the product. In our previous research, we proposed a recyclability rate evaluation method for electronic and electrical products based on the EoL scenario including the aspects of recycling technologies, regional characteristics, and economical factors [5].

Another aspect of design for recycling is disassembly. It is a fundamental process needed for component reuse and material recycling in all assembled products. Disassembly is often a labor intensive and costly process. This aspect should be included in the recyclability evaluation. In many cases, manual disassembly increases the cost of recycling as well as the recyclability rate of the product [6][7]. The recyclability rate and the disassembly time should be balanced in designing a product.

This paper proposes a design support method for improving the recyclability of electronic and electrical products. The method estimates the recyclability rate and the disassembly time of a product based on the product's structure, material composition, and EoL scenario. In order to generate design alternatives for increasing the rate while maintaining the disassembly time, sensitivity analysis is conducted on the product by changing its material composition and EoL scenario. Based on the analysis, the method suggests candidates for modifying design which have higher effect on the recyclability.

The rest of this paper is organized as follows: Section 2 outlines the concept and procedure of the method. Section 3 describes the architecture of the prototype system. Section 4 illustrates the result of a case study on a LCD TV. After the discussion of the case study in Section 5, Section 6 concludes the paper.

2 DESIGN MODIFICATION METHOD FOR RECYCLABILITY

2.1 Outline of the Method

Modifying the design of products based on quantitative assessment is a promising approach for increasing the recyclability. As described in the previous section, the proposed method supports the design modification that increases the recyclability rate by conducting sensitivity analysis on the rate. The method consists of the following six stages:

(1) The construction of a product model

(2) The description of an EoL scenario

(3) The estimation of the disassembly time

(4) The calculation of the recyclability rate

(5) Sensitivity analysis on the recyclability rate

(6) Design modification of the product and EoL scenario

In stage (1), a structural model of the target product is constructed, which represents connectivity and constraints among components. Based on the product model, disassembly procedure is planned. Next in stage (2), the EoL scenario of the product is described.

In stage (3) and (4), the disassembly time and recyclability rate of the product are estimated based on the EoL scenario, and in stage (5) sensitivity analysis on the recyclability rate is conducted. The analysis quantifies the impact of design changes in the mass of components, their materials, and EoL processes, and suggests candidates for design modification.

Finally in stage (6), based on the analysis in the previous stages, designers change the structure, materials, and the scenario of the product under the allowable limit of disassembly time.

The following subsections describe the details of each stage.

2.2 The Construction of a Product Model

In the method, relationship among the components of a product is structuralized as a topological graph to visualize the disassemblability. The product model is the combination of a connectivity graph and a constraint graph.

The connectivity graph represents the connection network among the components. The edges in the graph denote the connection types of fixation, support, control, power transmission, etc. The edges are disconnected by disassembly process.

For the constraint graph, we employ a precedence constraint graph [8] which represents geometrical constraints among components.

Figure 1(a) shows an example of a product. In this case, disassembly of components C_1 and C_2 precedes that of component C_3 because C_1 and C_2 restrict move of C_3 geometrically. It is defined that C_1 and C_2 have geometrical precedence constraints on C_3. Such constraint can be represented as a directed graph as shown in Figure 1(b). Nodes in the graph correspond to individual components and hold their attributive value such as the constitutional materials, masses and additives. Arrows correspond to precedence constraints between components. In other words, the geometrical precedence in disassembly process is described as an arrow pointing to the nodes of components. In this way, the order of components in disassembly must follow the constraint graph.

2.3 The Description of an EoL Scenario

An EoL scenario is composed of an EoL process flow model and a list of recyclability rates of individual components and material types. The EoL process flow model is formalized as a network of EoL treatment processes, which represents a sequence of the processes including disassembly, sorting, and final treatment of components. Figure 2 shows the basic structure of an EoL process flow for electronic and electrical products.

After the EoL process flow model is determined, in order to represent and manage the relationship between the product and its EoL scenario, we define an integration scheme for the two. To do so, we introduce another edge type of "inter-model" which connects a node in the structural model of the product and an arrow in the EoL process flow model. The inter-model edge denotes which part of the product undergoes which process of the EoL flow as shown in Figure 3.

The recyclability rate of individual components and material types is defined as the ability of the components and materials to be recycled, excluding energy recovery. Even for the same component, the rate may differ depending on the flow of EoL treatment processes for the component due to the quality of collected material. One of the issues in estimating the recyclability rate at design stage in the current practices is that such difference is often omitted, which results in over-estimation of the recyclability rate [5]. In order to include this aspect into the calculation of the recyclability rate, the method classifies each component of the target product into three "process-types" based on the criteria for electronic and electrical products defined by IEC TR62635 [2];

- Type 1: disassembled and sorted manually into an object that requires selective treatment after sorting, such as smelting and depollution. For example, printed circuit boards and fluorescent tubes are categorized in this type.
- Type 2: disassembled and sorted manually into a single material object. For example, the vegetable compartment of a refrigerator, made of polypropylene, is categorized in this type in the current recycling activities in Japan [9].

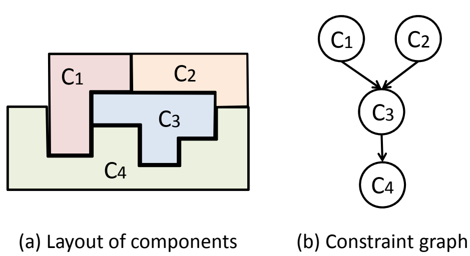

Figure 1: Precedence constraint graph.

- Type 3: shredded and sorted by machines and separated into single material fragments. Steel from waste electronic and electrical products is categorized in this type in Japan.

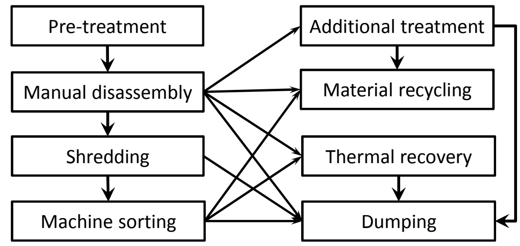

Figure 2: Basic structure of EoL process flow.

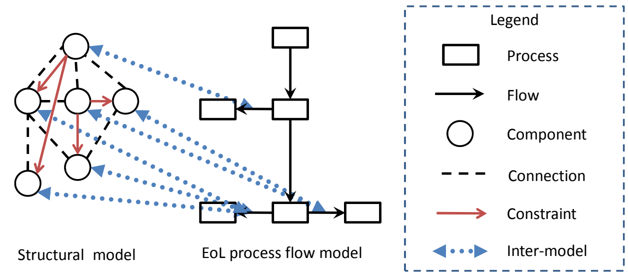

Figure 3: Integration of structural and EoL process flow models.

As an example of Type 1 component, in a recycling scenario of Japan, a Cold Cathode Fluorescent Lamp (CCFL) of a LCD TV is detached by manually and sent to a second recycler for treating mercury. In this way, components requiring special treatment after dismantling and sorting are categorized in Type 1.

Recyclability rate of each component is determined based on the combination of the materials and the type. For example, when a component including iron is shredded by a shredder machine and sorted by magnetic separation processes, the component is classified into Type 3, and the mass of the constituent iron is applied a recyclability rate for iron in this type. In each process-type, if the recyclability rate of a component or material type is zero, this means that the object is impossible to recycle. For example, back cabinet of a LCD TV including flame retardant is not recyclable in EU [10] even if it is disassembled manually. Basically, EoL scenarios are different by regions where the EoL products are treated, based on the legislation, policy, recycling technology, recycling cost and required quality of materials in the region. Therefore, the list of recyclability rates also differs depending on EoL scenarios.

2.4 The Estimation of the Disassembly Time

Disassemblability of the product is evaluated by predicting the disassembling time. In this study, Disassemblability Evaluation Method (DEM) [11] is employed. The DEM is performed when the design details are known. Product designers can predict the ability of disassembly for a given product in terms of time by considering the type, size, weight, connection, and the movement distance of the components. Equations for calculating disassembly time are derived by applying the basis motion status of worker and some information of connection parts, various tools, and different type of assembly structures. The previous researches [5] showed that the actual disassembly time of individual components was well predicted by DEM.

After an EoL scenario is described, the process-types of components are identified and their individual disassembly times are estimated. The disassembly time of each component is allocated to the edge of the connectivity graph in a product model as shown in Figure 4(b). In this example, the disassembly time of the component P_2 from P_3 is 0.26 minutes. The total disassembly time of a product is calculated by summing times allocated to edges between components of process-type 1 and 2. When the components of the same process-type are unified into one module as shown in Figure 4(b), the disassembly time between the components is subtracted from the total disassembly time.

The precedence constraint graph in a product model represents the depth of each component in disassembly process. The time to access and detach a component is calculated by considering all other components constraining the component.

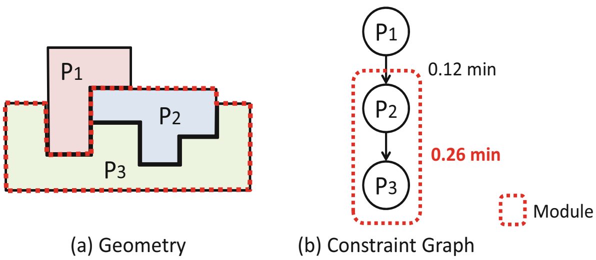

Figure 4: Design change of modular structure.

2.5 The Calculation of the Recyclability Rate

We previously proposed a recyclability rate calculation process [5]. After an EoL scenario is described and the process-type of each component is identified, the recyclability rate of the component is estimated. By summing the rates of the all components, the total recyclability rate (RCR) of the product is calculated by the following equation.

$$RCR\ (\%) = \frac{\sum\left(m_i \times r_{ij}^{cyc}\right)}{M} \times 100 \quad (1)$$

where, M is the total mass of the product and m_i is the mass of ith component. r_{ij}^{cyc} is a recyclability rate of ith component in Type j.

The process-type is determined through the relationship between the product model and the EoL process flow model as described in Section 2.3, and the r_{ij}^{cyc} is acquired from the list of recyclability rates of components materials in the applied scenario.

2.6 Sensitivity Analysis on the Recyclability Rate

As formulated in Equation (1), major parameters affecting the entire recyclability rate of a product are the composition of materials, mass of components, process-types, and the recyclability rates of individual components and material types. The impact of changing these parameters is quantified by sensitivity analysis.

Table 1 is an example of the result of the analysis. The changed parameters are sorted in the order of their positive impact on the entire recyclability rate of the product. For example, when the material of a plastic component is changed from polycarbonate to polystyrene in the same scenario, the difference of the product's recyclability rate is quantified as ΔRCR. The order of the differences represents the priority of the candidates for design changes in the product and the EoL scenario respectively.

Designer can set constraints on the analysis before the calculation of the sensitivity. The constraints restrict the range of the parameters to be changed. For example, the materials of optical sheets in a LCD TV can be constrained not to be changed with materials other than certain plastics for the sheets.

2.7 Design Modification of the Product and EoL Scenario

Based on the result of the sensitivity analysis, the designer selects some candidates of parametric changes (*i.e.*, changes in material, mass, process-type, and recyclability rate) from the sensitivity-order list. In the list, the combinations of components and their changed

	Component	Material Change	ΔRCR [%]
1	Stand Under	Plastic(Others) -> Steel	4.2
2	Stand Under	Plastic(Others) -> PET	4.0
3	Stand Under	Plastic(Others) -> PP	4.0
4	Stand Under	Plastic(Others) -> Aluminum	4.0
5	Power Board Sheet B	PC -> Steel	3.9
6	Stand Under	Plastic(Others) -> Copper	3.8
7	Power Board Sheet A	PC -> PET	3.7
8	Power Board Sheet B	PC -> PP	3.7
9	Power Board Sheet A	PC -> Aluminum	3.7
10	Stand Under	Plastic(Others) -> HIPS	3.7
11	Power Board Sheet B	PC -> Copper	3.5
12	Power Board Sheet A	PC -> HIPS	3.4
13	Stand Head	PC -> PET	2.3
14	Stand Head	PC -> PP	2.2
15	Panel Frame	PC -> Steel	2.0

Table 1: Sensitivity-order list of material changes.

parameters that have higher effect on the entire recyclability rate are prioritized for the selection. Within the candidates, the material and mass changes are independent of the EoL scenario. On the other hand, changes in process-type and recyclability rates include the change in the EoL scenario. In case of changing the process-type of a component from Type 3 to 2, the EoL process flow of the component also changes subordinately from shredding to manual disassembly.

Changing the recyclability rates of components and materials is implemented by changing the EoL processes, such as introducing new sorting technology, increasing workforces for manual disassembly, and improving chemical processes for certain material types. The feasibility of the process changes should be verified with recyclers.

After the selection of candidates for design modification, the feasibility of them should be confirmed on both the product model and the EoL process flow model. As described in Section 2.2, the topological graph represents the physical connectivity and geometrical constraints among components. Disassembly process must follow the constraints indicated by the arrows in the graph. In case of changing a component's process-type, the disassemblability of the component should be confirmed on a constraint graph. In this case, the designers should check the feasibility of the new disassembly process of the product, because the components of Type 1 and 2 should be detached before Type 3 components going to shredding process. However, the geometric constraints may restrict the new disassembly process.

For the material changes of a component, the designers should check the executability of the EoL processes that the component undergoes, because the change of the materials may affect the process behavior and performance. For example, if a machine sorting process cannot separate the certain combination of materials, changing materials into such inseparable materials should be avoided.

Moreover, components made of the same materials have a possibility of composing one module [12]. Such design changes of modular structure may decrease the disassembly time as shown in Figure 4. In this example, modularizing two components of the same material reduces the total disassembly time by 0.26 minutes. Changing materials may lead to such structural change that simplifies the product structure.

3 COMPUTATIONAL ENVIRONMENT FOR RECYCLABILITY ANALYSIS AND DESIGN MODIFICATION

We developed a prototype system based on the proposed method (see Figure 5 for the outline of the system architecture). The system

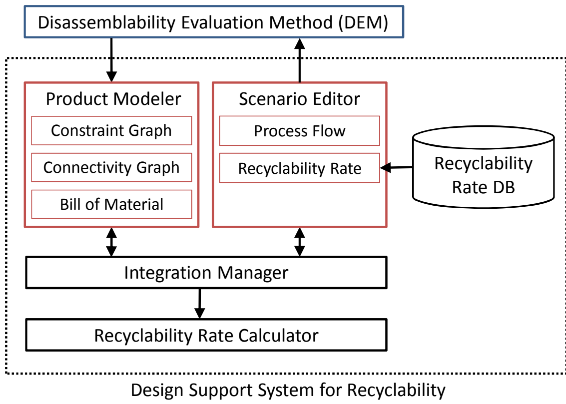

Figure 5: System architecture.

Type	Material	r^{cyc}[%]	Type	Material	r^{cyc} [%]
1	LCD Panel	0	3	ABS	74
	CCFL	80		PC	0
	Cable(High)	33		PC/ABS	0
	Cable(Low)	24		PMMA	0
	PCB(High)	18		PET	90
	PCB(Low)	14		PP	90
2	PET	100		PS	62
	ABS	94		PVC	0
	PP	94		Steel	91
	PS	100		Aluminum	91
	Aluminum	95		Copper	85
	Copper	95		Iron	94

Table 2: Recyclability rates of materials (partial).

supports activities including product structural modeling, describing EoL scenarios, calculating recyclability rates, sensitivity analysis, and modifying design of the products and EoL scenarios.

First, designers construct a structural model of a product and describe an EoL scenario using individual sub-tools including a product modeler composed of two graph editors and a bill of material (BOM) editor, an EoL process flow modeler, and a recyclability rate editor. The data on the recyclability rates of components and material types is managed by a database. The BOM editor also manages the attributive values of each component's materials, mass, and additives, such as flame retardants, paints, and stickers. The attributes correspond to each node of connectivity/constraint graph in the product model.

The product model and the EoL scenario are associated by the integration manager to enable visualization and management of which product's components pass through which processes of the EoL process flow model, and to judge the process-type of each component. If the type of a component is changed to another, the relationship between the node of the component in the product model and the EoL process flow model is also changed.

Second, an evaluation subsystem calculates the recyclability rate of the product and conducts sensitivity analysis by changing the components' attributes and the process-types. The result of the design changes is arranged in a list in order of sensitivity on the recyclability rate.

Disassembly time is estimated by using DEM based on the EoL scenario as an external tool.

4 CASE STUDY

As a case study, we analyzed the recyclability of a LCD TV based on a current EoL scenario in Europe. Then, sensitivity analysis and design modification were conducted.

4.1 EoL Scenario for LCD TVs in Europe

Based on our previous research [5], we described the EoL scenario based on the current TV recycling in Europe. Figure 6 is the EoL process flow model in the scenario, where we insert component names (orange boxes) between the processes (white boxes) in order to visualize the relationship between the components and their process flow. In this figure, the rounded red boxes represent the selective treatment processes for Type 1 components.

Table 2 is the part of recyclable rates of components and material types in this scenario. Note that the items of Type 1 in the list are rates for each component, not for material type, because these components require additional processes for treating their materials after disassembly. The recyclability rates of materials included in Type 2 are higher than those in Type 3, because the materials are collected as single material components through the manual disassembly processes. However, such labor intensive processes may increase the disassembly time and the recycling cost. The data in the table are acquired from the research reports on current recycling activities in Europe [13][14].

4.2 The Construction of the Product Structural Model

To calculate the recyclability rate of the LCD TV, we disassembled the product, and surveyed the components, their weight, and materials. Based on the survey, we made a structural model of the TV, and in each node of the graph, we inputted the attribute values of the component.

4.3 Disassembly Time and Recyclability Rate Estimation

Based on the product's parts number, disassembly sequences, shapes of components, and their connections, the disassembly time of the TV was calculated by using DEM, and the times for disassembling each component were allocated to each edge in the connectivity graph of the product structural model.

Next, the recyclability rate calculation and sensitivity analysis were conducted. The system displayed the result of the analysis in the case of changing the materials and types of components. Figure 7 is the screen capture of the sensitivity-order list in the system.

4.4 Design Modification for the Recyclability

From the list of sensitivity, we selected the Front Cabinet, Stand Head, Stand Under, Panel Frame, and Light Shaping Diffusers as candidate components for design modification, because they have high potential to increase the recyclability rate of the entire product. For example, we selected the combination of the material and process-type changes of the Stand Under from Type 3 plastics to Type 2 steel, because this candidate has the second highest impact on the recyclability rate. The system estimated that the rate will improve by 12.35% from the original design.

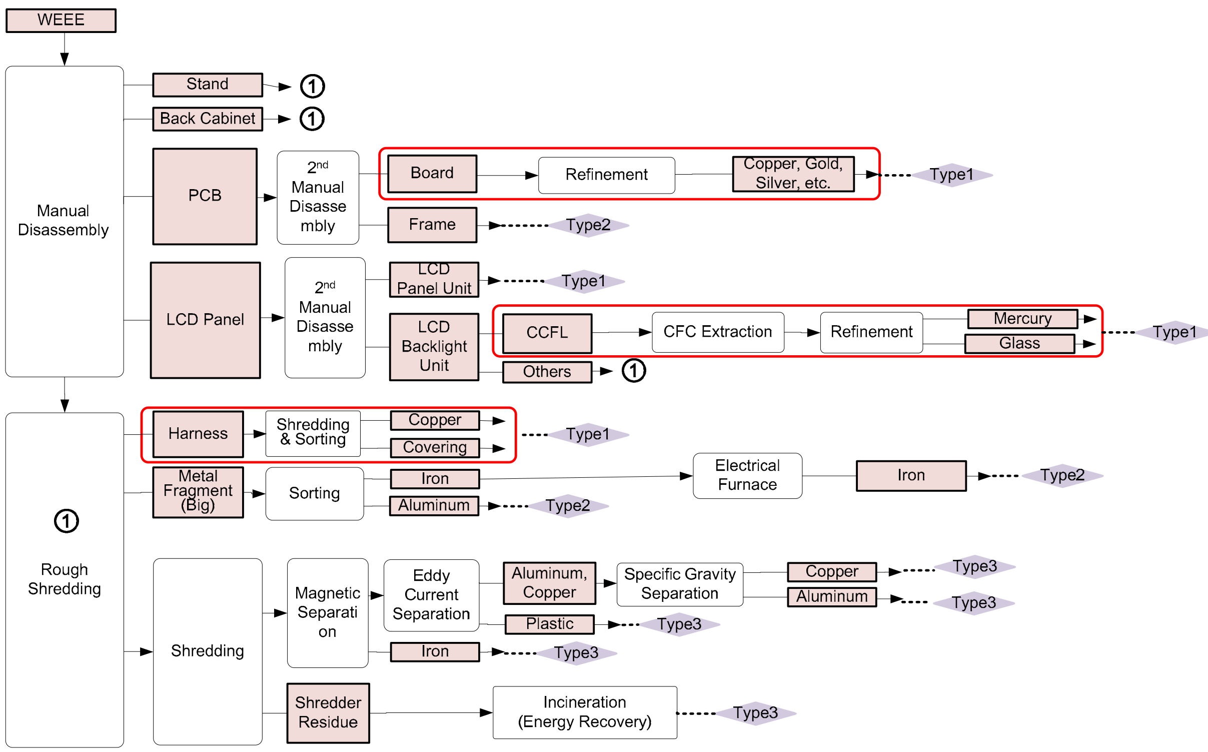

Figure 6: EoL process flow of LCD TVs in Europe.

Name of parts	Material Change	Type Change	ΔRCR[%]
Stand Under	Plastic(Others)→Iron	3→2	12.42
Stand Under	Plastic(Others)→Steel(General)	3→2	12.35
Stand Under	Plastic(Others)→Steel(General)	3→3	12.12
Light Shaping Diffusers	PMMA(Polymethyl Methacrylate)→PMMA(Polymethyl Methacrylate)	3→2	11.38
Front Cabinet	Plastic(Others)→Iron	3→2	9.27
Front Cabinet	Plastic(Others)→Steel(General)	3→2	9.21
Front Cabinet	Plastic(Others)→Steel(General)	3→3	9.04
Stand Head	PC(Polycarbonate)→Steel(General)	3→2	7.26
Stand Head	PC(Polycarbonate)→Steel(General)	3→3	7.12
Stand Under	Plastic(Others)→Iron	3→3	6.63
Stand Under	Plastic(Others)→Aluminium	3→2	6.36
Stand Under	Plastic(Others)→Aluminium	3→3	5.99
Front Cabinet	Plastic(Others)→Iron	3→3	4.94
Stand Under	Plastic(Others)→PET(Polyeythyrene Terephthalate)	3→2	4.65
Front Cabinet	Plastic(Others)→Aluminium	3→2	4.54
Front Cabinet	Plastic(Others)→Aluminium	3→3	4.27
Stand Under	Plastic(Others)→PET(Polyeythyrene Terephthalate)	3→3	4.16
Stand Under	Plastic(Others)→PC(Polycarbonate)	3→2	4.13
Stand Under	Plastic(Others)→ABS	3→2	3.98
Panel Frame	PC(Polycarbonate)→Steel(General)	3→2	3.63
Panel Frame	PC(Polycarbonate)→Steel(General)	3→3	3.56
Stand Head	PC(Polycarbonate)→Aluminium	3→2	3.48
Stand Head	PC(Polycarbonate)→Aluminium	3→3	3.28
Front Cabinet	Plastic(Others)→PET(Polyeythyrene Terephthalate)	3→2	3.27
Stand Under	Plastic(Others)→ABS	3→3	3.17

Figure 7: Screen shot of the system (Result of sensitivity analysis).

	Recyclability rate [%]	Disassembly time [min]
Current design	50.69	17.73
Modified design	71.10	17.29

Table 3: Result of design modification.

After the selection, we verified the candidates on the both models of the product and the EoL scenario. Figure 8 depicts the structural model of the LCD TV. We assumed that the type change (Type 3 -> Type 2) of the Light Shaping Diffuser (P31 in the graph) is difficult to implement, because the component cannot be disassembled within the time of the current design. The minimum time to access the light shaping diffuser is equal to the sum of the times to disassemble the all components from the Front Cabinet (P25) to the Light Shaping Diffusers in line with the constraint arrows in the graph. Therefore, we removed the process-type change of this component from the design candidates.

The material changes were also checked on the EoL process flow model, because process behavior and performance may be affected by the input/output materials. In the case of the Stand Head, the plastics in this component are difficult to separate in the current EoL process. In other words, the machine sorting process cannot separate certain plastic materials such as PC, PVC, and compound plastics. Considering this characteristic of the process, we selected steel as new material for the component.

Table 3 compares the result of the case study. The recyclability rate of the LCD TV was improved 20.4% from the original design. In the new design, the materials of five components and the process-types of three were changed. The feasibility of the new materials was confirmed on the product and EoL flow models, and the modular structure was modified to compose two modules by unifying the same material components of Type 2. As the result, the disassembly time was kept under the current disassembly time.

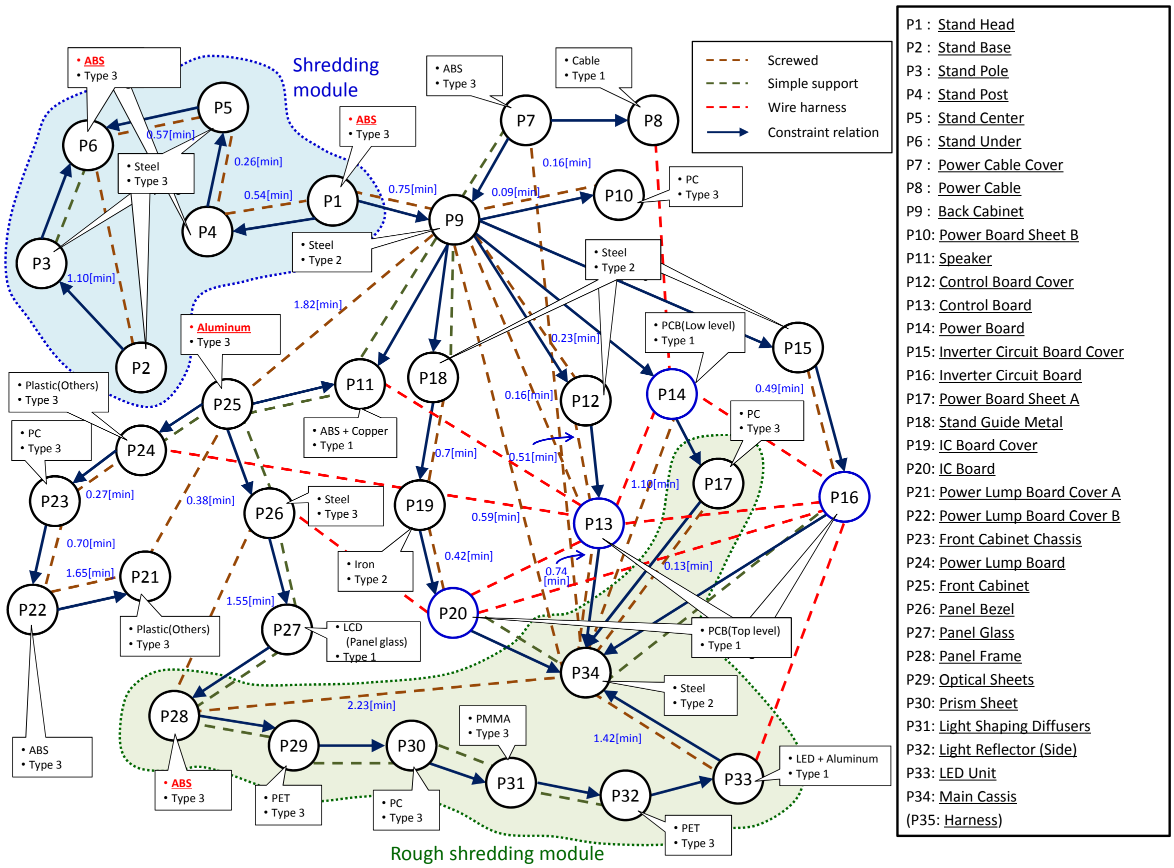

Figure 8: Structural model of the LCD TV.

5 DISCUSSION

We succeeded in increasing the recyclability rate of the LCD TV by changing the materials and the process-types of components, while keeping the disassembly time of the original design. In the design support system, all the combinations of the components and their changed materials, masses, and process-types were evaluated and sorted in order of their impact on the recyclability rate.

Basically, the rates of materials in Type 2 are higher than those of Type 3 due to the quality of the collected materials by manual disassembly in comparison with machine sorting process. However, the process-type switching also changes the disassembly procedure and process flow of related components. In the case study, although we rejected the process-type change in the Light Shaping Diffuser due to the difficulty in the manual disassembling of it, this candidate can be implemented by changing the layout and geometry of the neighboring components. To support such geometrical modification is one of our future issues.

In the sensitivity analysis, although the system quantified impact on the recyclability rates of design candidates, the other effects were ignored. However, for example, material change may have influences on the stiffness, rigidity, thermo tolerance, manufacturability, appearance, and cost of products. If the geometry of a component is constant, material change of the component from steel to plastics drastically may reduce the strength and rigidity to insufficient level. For preventing such side-effects, development of a design support system for keeping the other performance factors constant by adjusting the geometric features (e.g., thickness and volume) of the components to be modified, will be another future work. Applying LC-CAD system [15] to such design is one of promising approaches.

6 CONCLUSION

This paper proposed a design modification method for increasing recyclability of electrical and electronic products. The method evaluates the recyclability of products in terms of their recyclability rate and disassembly time based on their EoL scenario. The scenario is described in an integrated form of an EoL process flow and the recyclability rates of components and materials classified into some process-types. Based on the EoL scenarios, sensitivity analysis clarifies the impact of design changes on the recyclability.

In the case study, we estimated the recyclability rate and the disassembly time of an LCD TV with its recycling scenario in Europe. The sensitivity analysis generated a sensitivity-order list that arranges the candidates for material and process-type changes in the order of their impact on the recyclability rate.

Future works include developing a design modification method for the recyclability of products including the aspects of their functionality and geometry.

7 ACKNOWLEDGEMENT

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8 REFERENCES

[1] Peeters J. R., Vanegas P., Dewulf W., Duflou J. R. (2011): Active Disassembly for the End-of-Life Treatment of Flat Screen Televisions: Challenges and Opportunities, Proceedings of EcoDesign 2011, pp534-539.

[2] IEC/TR 62635 (2012): Guidelines for End of Life information provision from manufacturers and recyclers, and for recyclability rate calculation of Electrical and Electronic Equipment. The International Electrotechnical Commission (IEC), Draft V2: 26/1/2012.

[3] Hiroshige Y., Nishi T., Ohashi T., (2001): Recyclability evaluation method (REM) and its applications, Proceedings of EcoDesign 2001: Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing, pp.315-320.

[4] ISO 22628 (2001): Road vehicles - Recyclability and recoverability - Calculation method.

[5] Mizuno T., Kunii E., Fukushige S., Umeda Y. (2012): Recyclability Evaluation of LCD TVs Based on End-of-Life Scenarios, Proceedings of the 19th CIRP Conference on Life Cycle Engineering (LCE2012), pp. 179-183.

[6] Yi H. C., Park Y. C., Lee K. S. (2003): A study on the method of disassembly time evaluation of a product using work factor method, Proceedings of IEEE International Conference on Systems, Man and Cybernetics, pp1753-1759.

[7] Boothroyd G., Alting L. (1992): Design for Assembly and Disassembly, Annals of the CIRP, Vol.41, No.2, pp.625–636.

[8] Wakamatsu H., Matsuishi M., Morinaga E., Arai E. (2009): Disassembly Support System for Used Products Considering Destruction of Their Parts, Service Robotics and Mechatronics, Springer London, pp.37-42.

[9] Ministry of Economy, Trade and Industry (METI) (2008): Report of the Standards about Recycling the specific household appliance (in Japanese). Available: http://www.meti.go.jp/committee/materials2/downloadfiles/g80922a08j.pdf.

[10] King County Solid Waste Division (2007): Flat Panel Displays: End of Life Management Report. Available: http://your.kingcounty.gov/solidwaste/takeitback/electronics/documents/FPDReport.pdf.

[11] Hiroshige Y., Ohashi T., Arimoto S., Suzuki K. (1997): Development of Disassembly Evaluation Method, Proceedings of the 8th International Conference on Production Engineering (8th ICPE), pp. 175-181.

[12] Fukushige S., Inoue Y., Tonoike K., Umeda Y.(2009): Design Methodology for Modularity Based on Life Cycle Scenario, International Journal of Automation Technology, Vol.3, No.1, pp. 40-48.

[13] Mathieux F., Lescuyer L., Moenne-Loccoz G., Brissaud D. (2008): Design of the Electric Apparatus in Consideration of End-of-life Recovery (in French). Available: http://codde.fr/files/Eco_DEEE_Rapport_final_sept09_codde_bv.pdf

[14] eMaine Department of Environmental Protection (2008): Report Regarding The Recycling of Fluorescent Lamps and Consumer Education Efforts.

[15] Umeda Y., Fukushige S., Kunii E., Matsuyama Y. (2012):LC-CAD: A CAD system for life cycle design, Annals of the CIRP, Vol.61, No.1, pp.175–178.

Evolution in Ecodesign and Sustainable Design Methodologies

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Abstract
The majority of the environmental impact of a product is decided during the design phase, and as such there has been a rapid growth in generation of methodologies and tools that aim to improve design and include sustainability considerations in product development. Although these methodologies and tools have introduced measurable benefits, in most cases they have been incremental in nature as opposed to producing radical 'Factor X' improvements. This highlights the need for a careful analysis of existing sustainable design methods to identify their shortcomings and to enable a greater understanding of how to unlock the full potential of design improvements. This paper provides a brief overview of the evolution of ecodesign and its extension into sustainable design. It assesses the key influencing factors of current practice and identifies a number of future research challenges, promoting the next stage in its development in which sustainability will become a ubiquitous part of the design process.

Keywords:
Sustainable Design; Design for Sustainable Behaviour; Ubiquitous Sustainability

1 INTRODUCTION

Sustainable design is no longer a new concept. It has been shown that a significant proportion of the environmental impact of a product is decided during the design phase [1] and therefore, systematic methodologies and tools for formally embedding environmental concerns into product design have been in development for almost three decades.

One of the earliest examples, Design for Environment (DfE), is now more commonly referred to as 'Ecodesign' and has expanded to be the term given to any design strategies that focus on improving the ecological aspects of a product. Sustainable Design (SD), also known as 'Design for Sustainability' (DfS), builds on ecodesign concepts by additionally taking into account economic and social considerations and aiming to generate solutions that consider the whole life cycle of the product.

SD methods prompt designers and engineers to consider key factors for sustainability, and enable them to modify their designs based on a number of predefined objectives. In most applications, the current methods only generate slightly modified or improved designs and are often applied late in the design process; after many key decisions have been made and when too many constraints are in place. They can also be difficult to implement and to fit within the larger context of product development, requiring a great deal of knowledge to negotiate and offering guidance based on conflicting considerations. Although these SD methods offer a broad set of tools for addressing environmental considerations, they do not yet place the same emphasis on social and economic considerations.

Within Industry there has been a widespread focus on implementing changes to production activities as a first step towards improving environmental performance of manufacturing companies. In this context, many companies have not utilised design as a part of their sustainability effort and do not consider design processes as a strategic approach to organisational improvements. A recent report by the European Commission (EC) highlights that, while the situation is improving, around a third of companies still fail to utilise the full potential of design during product development [2].

With simple products, and in smaller companies, design processes are more agile and implementing change is more feasible. However, in the case of complex products and larger companies, implementing new design practices can provide greater challenges; particularly in applications where the product is developed using a distributed design approach. Such challenges significantly limit the potential impact of sustainable design activities in high volume, high impact sectors which offer the greatest potential for environmental and economic gains.

Therefore, the authors argue that current SD practice is unable to deliver to its full potential. They also highlight a need for better understanding of the shortcomings associated with SD methods and tools in order to be able to integrate sustainability considerations into the initial stages of product development, as opposed to a series of 'afterthought' design improvements.

This paper aims to provide an overview of the evolution of SD, and of the future challenges it will face. The first section of this paper presents a brief overview of the field of SD. The second section critically analyses three key areas of current SD practice and their effect on product development. The final section presents a number of future research challenges for SD. It proposes the next steps towards embedding sustainability into the design process, identifies new opportunities for inclusion of social considerations, and discusses the extension of SD within and beyond product development.

2 BRIEF OVERVIEW OF SUSTAINABLE DESIGN

The first widespread design methods which specifically considered the environment began to emerge during the 1980s and 1990s with the appearance of a number of different 'Design for X' (DfX) methodologies. As awareness of environmental issues grew over the following years, governments enforced a variety of environmental legislations which became the main drivers towards widespread implementation of SD practices. A simplified timeline for a variety of drivers, tools and legislation influencing the evolution of ecodesign and SD practices is shown in Figure 1.

These forerunning DfX methodologies were developed using principles first laid out by Boothroyd and Dewhurst in their Design for Assembly framework (DfA) [3]. This approach enabled systematic incorporation of rising environmental concerns into design activity. As governments and regulatory bodies became more aware of the scale of environmental problems, they began to develop legislations to regulate industry and mitigate impacts. This regulatory influence has resulted in a second wave of generation of environmental design methodologies that are more focused and directed to meet the specific targets of these legislations.

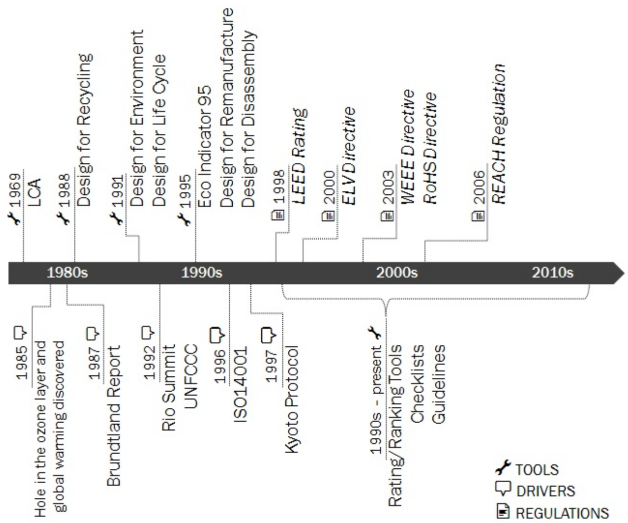

Figure 1: Key milestones and drivers of sustainable design.

However, in recent years the demand for better design solutions has become even more urgent as customer demand, resource scarcity, and energy costs continue to rise. As such, the expectation from SD methods to deliver radical 'Factor X' improvement is gaining momentum, as highlighted in a recent study by Rio *et al.* [4], in which they observe a significant growth in the number of publications on ecodesign methods in the last five years. Despite this growth in research activities, there has been little evidence showing widespread industrial uptake of proposed SD methodologies and tools [5][6][7].

In the cases where environmental design activities have been employed, the main drivers for uptake were found to be either pressure from customer demand, or from imposed regulations and legislation [5][6]. It was observed that the most successful examples of implementation occurred when driven by more conventional business concerns, such as money saving or increased sales from improved customer perception [6][7].

In the cases where environmental design activities were not yet employed and no legislation was in place, it was found that businesses were often unaware of the environmental impacts associated with their products [6] and the significant economic gains that can be achieved through adopting SD methods.

Figure 2 by Lewis *et al.* [8] highlights the cumulative 'lock-in' of the environmental impact of a product over the course of its lifecycle, illustrating that the chances for environmental improvement decrease as a concept is developed, decisions are made and product knowledge increases. This publication, in addition to a number of others, has clearly emphasised that the early stage of the design phase has the greatest influence over the environmental impact of a product. In some cases it was shown that, approximately 80% of the total impact is decided after only 20% of the design activity has been undertaken [1].

The later stages of detail design are the point at which many existing SD methods and tools are typically employed, however, at this stage they provide limited potential to significantly decrease the environmental impacts of the product. Although their overall contribution is minimal, many of these tools directly address the immediate environmental considerations of detail design, such as low impact material choice. As such, a great deal of work has also been done to develop design tools that specifically address challenges with the subsequent lifecycle phases, to try to mitigate the impacts of the product throughout the rest of its life.

Design for Manufacture has been a particular area of focus with the creation of methods such as DfA offering design improvements that are simple to measure and predict, often yielding obvious economic gains in the form of material, energy or production efficiency. Design for disposal or recovery has also seen a large amount of work driven by legislations enforcing end-of-life (EOL) targets for products. This has resulted in generation of a range of methods focussing on specific EOL strategies, for example design for disassembly, remanufacture, reuse or recycling.

The 'use' phase however has seen very little work comparatively, and research in this area is still relatively new despite the fact that the 'use' phase of certain types of products has been found to be particularly environmentally significant. For example, it was found that 90% of life cycle energy consumption of household appliances takes place in the use phase, and of this consumption, up to 90% is determined during design [9]. Research into design for sustainable 'use' has a variety of names including 'Design for Sustainable Behaviour' (DfSB) and 'Design with Intent'. These studies cross the borders between social sciences and design and consider how to include and influence consumer behaviour as part of the early conceptual stages of design activity. The findings however have yet to be integrated into the wider product development process and current studies simply explore the key considerations, offering suggestions and best practices.

The current level of research interest in SD on one hand identifies the potential benefits of wide scale industrial adoption and utilisation, and on the other hand, highlights significant research gaps that require further investigation, such as embedding sustainability consideration into product development from the earliest stages, developing more simple and appropriate tools, or creating methodologies which include environmental, economic and social issues holistically. Existing research also highlights a need to investigate the organisational and social factors of implementing SD as it has been observed that in many cases, the largest barriers to successful uptake were social-psychological issues such as lacking communication or cooperation between actors, organisational complexities, and disparities in language and context [5].

The remaining sections of this paper analyse a number of these research areas in more detail in order to better understand the key factors which have shaped current SD practice.

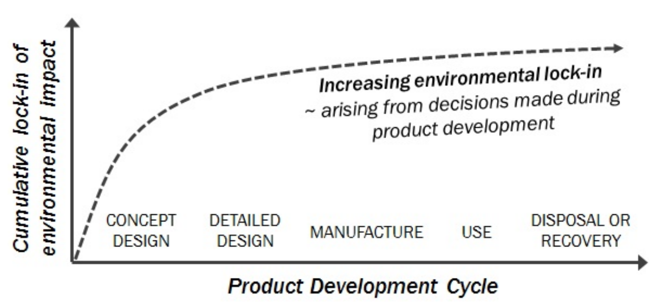

Figure 2: Conceptual representation of environmental lock-in over a product's lifecycle. Adapted from [8].

3 CURRENT EVOLUTION OF SUSTAINABLE DESIGN

3.1 The Driving Factors for Sustainable Design

A broad uptake of SD practices has been encouraged by a rising awareness of environmental issues amongst consumers, the legal requirements of new regulations and the scarcity of materials and other resources, however, many companies have failed to appreciate the full potential of implementing SD activities. In order to maximise the impact of future initiatives, it is important to look at the underlying drivers for uptake that are currently shaping SD.

One of the key influential factors in uptake of SD practices has been the introduction of various industry standards, ecolabels and product certifications. These are all voluntary schemes which enable companies to measure themselves against specific predefined targets and are often used to help market products and clearly communicate that a certain environmental standard is being maintained. This offers a simple way to show customers that the product, and by extension the company, are environmentally conscious.

Industry standards typically provide general supportive information for companies who wish to improve design practice in a certain area. For example, ISO/TR 14062:2002 details the process of integrating environmental aspects into product design and development [10]. Ecolabelling and product certification are similar in nature, however, the information given is more specific and products are required to conform to clearly defined criteria in order to achieve certification, or be awarded an ecolabel. For example, the EPEAT (Electronic Products Environmental Assessment Tool) register is an environmental rating system which uses a number of criteria based on ANSI standards to give gold, silver or bronze status to different products based on a number of characteristics covering their full lifecycle [11].

Additional factors significantly influencing the advancement of SD are environmental regulations and legislations which set specific, compulsory requirements companies must comply with by law. In this context, the most influential recent legislations are those related to 'Extended Producer Responsibility' (EPR). For example, the Waste electrical and electronic equipment (WEEE) directive, and the End-of-life vehicles (ELV) directive. Both of these EU directives require manufacturers to take responsibility for their EOL products, arranging for their collection from the consumer and meeting prescribed recycling targets. In addition to recovery and recycling targets, the EPR legislations aim to encourage environmental consideration related to EOL processing of the products during the design stage. Another example regulation is the Eco-design Directive for Energy-using Products (EuP directive). In this case, guidelines are less prescriptive and instead of quantitative targets, a framework is provided to help manufacturers adopt changes during their design process that will help reduce the energy consumption and other negative environmental impacts of the final products.

These various schemes and legislations undoubtedly offer simple ways for companies to reduce the environmental impacts of their products, however, their effect on the design process is often minimal as the solutions implemented are frequently 'end-of-pipe' and only address the minimum requirements by means of incremental and targeted improvements as afterthoughts [12].

In addition, the targets set by these various schemes can also create confusing trade-off situations. An example of this can be seen in the case of the ELV directive which sets recycling targets based on the weight of a vehicle. Recent LCA studies have highlighted that one of the most influential environmental impacts associated to the lifecycle of a vehicle is the fuel consumption during the use phase, which is largely determined by the weight of the vehicle. This would imply that an automotive manufacturer should try to use lightweight materials, however, these may affect the ability to achieve recovery and recycling targets set by the directive. For example, replacing steel with plastic or composite will have many possible knock on effects such as reducing the quality of waste streams at EOL, and increasing difficulties in separation and recycling of these waste streams.

This illustrates that while these schemes encourage uptake, they may also limit potential for radical improvement and lock companies in to suboptimal solutions [12]. They set targets which can be systematised and do not necessarily require creativity or aid understanding of SD issues by offering prescriptive guidelines and simply requiring compliance.

3.2 Ecodesign Tools for Product Development

There are a wide range of different tools available for the implementation of ecodesign. Although a small number of these take economic factors into account, very few incorporate the social considerations required for true sustainable design and as such, these tools can only be considered as 'ecodesign' tools.

Ecodesign tools utilise a range of approaches that can be broadly categorised [13] as shown in Figure 3. These tools can each be used in isolation, however, many can also be used concurrently with others as each method has a differing scope, a differing stage for application, and a differing environmental focus. For example, Design for Recycling (DfR) provides general guidelines for best practices, is usually applied during the detail design phase and focuses on end of life. In contrast, the MET (Material Energy and Toxicity) matrix provides a framework for structured analysis against guiding criteria and can be used from the initial design stages onwards, to consider the entire life cycle of the product.

A great deal of research exists which offers examples of theoretical or practical applications of ecodesign tools as well as example case study products [4]. In addition, there have been a large number of studies that compare and assess various ecodesign tools against different criteria [4][6], however, little work has been done to evaluate and assess the performance and usefulness of these tools when used in an industrial environment [14]. From the studies available however, a number of conclusions can be drawn about the applicable scope of existing tools and methodologies, as well as their perceived strengths, weaknesses, and potential effectiveness.

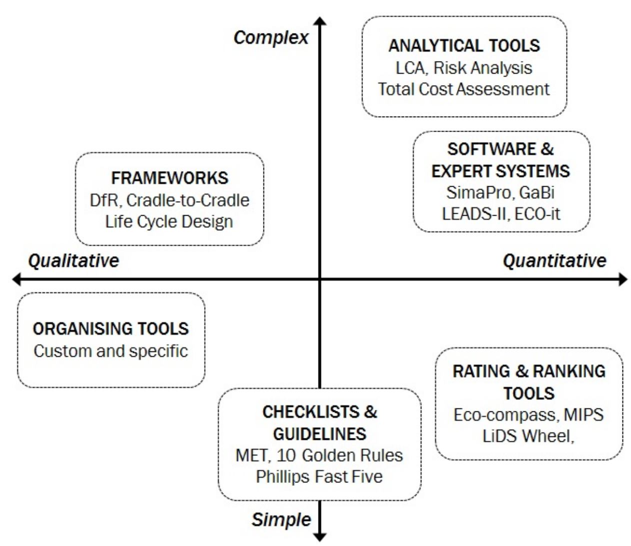

Figure 3: Classification of Ecodesign tools – Difficulty vs. Input type.

It is generally observed that utilising ecodesign tools requires significant of knowledge, demands a lot of data screening, and can become very time consuming [15]. They also present many conflicting considerations and trade-offs with little guidance on decision making, and in the majority of cases they have to be customised prior to implementation to meet the specific needs of a particular company type or product sector [4][7]. Although this adds an extra layer of complication, studies have shown that these specific, customised tools are more successful and more readily taken up by industry [5]. As such, many companies who wish to formalise the consideration of ecodesign within their development process will create their own tools to address their critical issues specifically, and to fit within existing frameworks and procedures.

The use of an ecodesign tool in the early stages of product development is discussed in a recent study of fuel cell design [16]. In this example, LCA software was used to assess early concepts and inform strategic decision making. Data gathered was used to select the most appropriate concepts and materials for the final products based on potential EOL scenarios. In this case the fuel cells were a completely new product for the manufacturer, however, the study required a great deal of prior knowledge to conduct. Even in the early stages it was important to understand both the potential future legislative requirements, and the full composition of at least two initial concepts. This illustrates that although ecodesign tools can be employed in the development of completely new concepts, a large amount of knowledge is required which means a large number of decisions must have already been made before the environmental considerations are taken into account.

Overall, it can be observed that many ecodesign tools currently only offer incremental improvements through preventative measures. This is because they are frequently simply added onto the design process as an afterthought and require a great deal of prior knowledge of the products. In addition, many studies found the tools were difficult to understand and difficult to manage and fit within existing product development processes. These difficulties have dictated the level of uptake and level of effectiveness of the tools and highlighted areas for future improvement.

3.3 The Impact of Product Types and Business Models on SD

Organisational complexities have been found to be a consistent challenge in implementing SD activities [5]. These offer a particularly tough problem as different types of products require very different organisational approaches to the design process, and the structure of the design process will change not only based on the sector and size of a business, but also on the complexity, volume, shelf-life, service-life, and other key characteristics of the products themselves. These different approaches will have a large effect on where and when SD activities will take place. The larger, more complicated and more structured a company and its product development process become, the more difficult it is to make changes during design as 'lock-in' decisions become more firm and more frequent during the development process.

A distributed design approach is usually undertaken in the case of very complex products such as cars which require several subassemblies and components, which themselves consist of many parts. The complex design chain in these companies often involves a number of suppliers with their own embedded levels of complexity. For example, a car manufacturer might purchase their headlamp units from a supplier who in turn purchases the light bulbs from a third company who may simply act as a distributer, and are not involved in the design or production of the light bulbs. An example of this 'V' shaped model against a more simple design model is shown in Figure 4.

This highlights the complications in communication throughout a 'V' shaped model where product development often involves the work of a number of different design teams, both within the parent company itself and at associated suppliers and subcontractors. In addition, products developed in 'V' shaped models often tend to have a larger environmental impact than more simple products as they usually have a longer service life and are available to purchase without upgrades to the design, for a larger number of years.

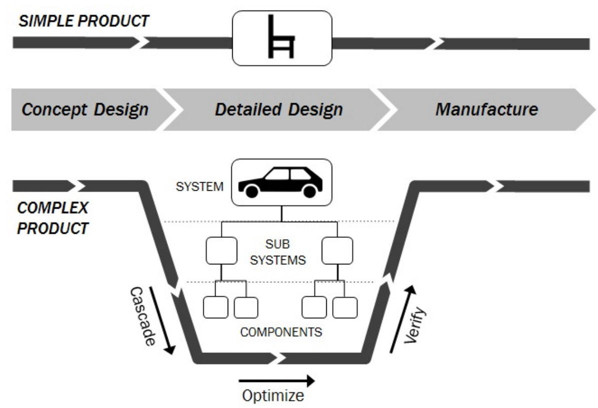

Figure 4: Characterisation of the product development process for a simple and complex product. Adapted from [1].

Due to this, examples of the inclusion of environmental considerations in distributed design models are not uncommon; particularly in vehicle design as the products are governed by the ELV directive. Implementing and controlling environmental considerations at the various levels within a complex design chain can however, present a great number of challenges with communication at each stage, and with collecting, storing and sharing knowledge between all parties. Due to these difficulties, it has been seen that car manufacturers are focussing on 'end-of-pipe' solutions such as recycling and shredder separation [12] as opposed to addressing challenges at the design phase and trying to embed eco considerations throughout the design chain.

The above mentioned organisation structures and product complexities have also had an impact on implementation models for adopting SD practice. Considering who conducts SD activities decides where and when the environment will be considered during the design process and it has been noted that there are three main variations as to how ecodesign can be included in design [4]:

1. Externalised (with a consulting agency).
2. Treated as a distinct department in the company.
3. Integrated into expert activities (such as engineers).

Each situation offers different benefits and drawbacks with respect to agility, information sharing and level of confidence in expertise, however, further investigation is required to identify how each of these scenarios affects the integration of SD from the outset of design activity.

These examples discussed highlight the importance of company structure and the effect it has on SD. In distributed design models, there are large challenges in organisation and communication, as well as in visibility and control over what happens throughout the whole design chain. This, combined with uncertainty over the best methods for implementing SD, can limit uptake and has dictated the extent to which organisations are able to incorporate sustainability in their design activities.

4 FUTURE CHALLENGES AND OPPORTUNITIES FOR SD

In order to maximise the potential for adoption of SD practices, there are a number of areas in need of further investigation, including:

1. The improvement of the design process so that SD is not an afterthought, but is incorporated centrally throughout the design process from its outset.
2. The improvement of SD implementation methods within a company's product development process, particularly in the case of complex organisations and products.
3. The improvement and inclusion of social considerations which are largely underrepresented in current SD practices.
4. The linking of SD practices with other relevant activities within a manufacturing company, such as process and plant design.

4.1 Embedding SD at the Core of the Design Process

Throughout this study it was found that SD activity was frequently applied as an afterthought. This has reduced its effectiveness and prevented it from fulfilling its full potential to make considerable, as opposed to incremental changes. Future SD methods need to offer transformational improvements, to include sustainability consideration from the very beginning of the concept design phase.

To do this, in the first instance, there is a need to create a purposeful overlap between sustainability considerations and the various stages of design. In the long term however, the ultimate goal should be to replace the existing approach of 'design followed by ecodesign', with one holistic, integrated, inherently sustainable design process as shown in Figure 5.

4.2 Improving SD Implementation Models

As discussed, complex **business models** raise a variety of challenges with integrating and implementing SD throughout the whole design chain. There is a large challenge in developing more clearly defined roles and processes for the actors within chain. This highlights a need to better understand the issues with 'V' shaped models and how, and where to integrate SD expertise within different organisational structures

In addition, current SD **tools and methodologies** do not yet encompass all the relevant considerations required to fully address the issues at hand. More actionable, holistic tools are needed which on one hand are simple so that they can be used from the outset of design, and on the other hand can be linked and integrated with other fundamental methods and systems used within the product development process, for example CAD, CAE, FEA, House of Quality.

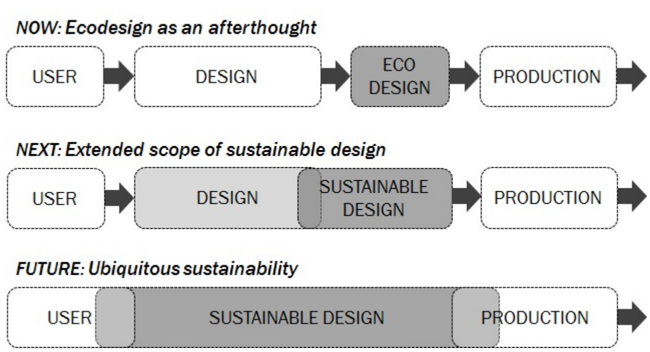

Figure 5: Proposed evolution of the sustainable design process.

In addition to these, a number of other critical success factors for further developing SD and integrating it into product development can be identified as follows:

- **Collaboration:** This needs to be facilitated and encouraged at every level of company activity – across different departments, disciplines, companies, and even sectors.
- **Communication:** Facilitating an open dialogue and establishing a common language will be needed to cross the barriers created by company structures, different disciplines, and different cultures.
- **Improved Metrics**: It is very difficult to measure the success and outputs of design activity. There is a need to not only better understand the value of design, but also have a means by which to more clearly measure progress and establish common ground with the surrounding activities.
- **Knowledge:** Access to appropriate knowledge when and where it is required will be key to facilitating successful implementation of SD activities. Knowledge needs to be properly created, stored, and shared so that it can be readily available to those that need it, and presented in a way that is easily understood.

4.3 Inclusion of Social Factors in SD

It has been well established that social factors are critical to the success, or failure of implementation of SD in product development. In the future, social factors will need to extend beyond company borders in order to realise the full potential of SD.

In this context, the concerning impact of the 'use' phase has highlighted a great potential for improvement of SD practices. This is to be achieved by exploring the application and integration of DfSB further and attempting to directly influence consumer behaviour towards a more sustainable consumption pattern through a series of design features and considerations.

In addition, many organisations are beginning to discuss and explore more collaborative design models which have the ability to address more specific user needs. In relation to this, a recent European design report stated that: "the conventional borders between product design, production and the user are beginning to merge. The internet and the active use of social media not only enable the dissemination of digital works, but also the co-creation of products or services that can engage users from the outset." [2]

Traditional product development is an interdisciplinary task involving many different actors, from designers to mechanical engineers, production technicians and quality officers. Co-creation and participatory design aim to extend this to involve all stakeholders in the process from the outset. Collaboration has long been credited as being a key component of innovation, and the recent socio-technological advances discussed above are creating an environment enabled by ubiquitous computing (ubicomp) that is more conducive to change and to encouraging participation.

In much the same way as these advances have seen sweeping cultural changes in communication, politics and news, similar tools can be used in the future to change consumption behaviours and gather information from more engaged customers. This has the potential to involve all stakeholders and move design activity from interdisciplinary to transdisciplinary practice, as well as to build better relationships for improved stakeholder engagement and embedded sustainable behaviours.

4.4 Integration of Sustainable Product, Process and Plant Design

This paper has so far focused on the product design process, however, there are new and unprecedented scenarios developing which offer unique challenges and opportunities for expanding the scope of sustainable design beyond product development.

A key example of this is the increasing rate of change of manufacturing requirements. In recent years it has become evident that more frequent changes to product designs, rapid progress in manufacturing technologies and ever changing customer demands are highlighting a need to rethink current practice. It is widely recognised that in order to respond to these factors, there is a need for a more flexible, responsive and agile design process which not only considers the products, but also the process and production systems that are used to manufacture them.

In addition to these factors, a set of new challenges in this area are appearing as unprecedented opportunities arise in developing countries. These emerging markets are growing rapidly and offer completely new and different priorities in customer demand, levels of technology, costs of labour, and even local skill levels. The considerations for companies entering these markets will be very different when deciding how to manufacture items and design new plants and supply chains. This offers a vast opportunity to implement change from the outset of designing the whole system and approaching the task from the start with an integrated 'holistic engineering design' approach which considers product, process and plant design together.

5 CONCLUSIONS

The power of design to influence behaviours and transform industries has led to widespread recognition that design will play a key role in helping to achieve more sustainable production and consumption whilst securing and developing economies.

As such, the need for sustainable design is an argument that has been well made and recent developments in ecodesign and SD methods and tools have created significant impact, however, the demands from sustainability are rising. As we become more aware of the scale of the environmental challenges we are facing, the effects of resource shortages, climate change, and energy futures are becoming more prominent. This requires a reassessment of our progress. We need to better understand what has been achieved through current SD approaches, and where we need to be in the future. We can then target research to extend the scope and potential of SD activities.

This study has made a clear case for the need to improve the potential impact of future SD practices and has outlined four key challenges for more effective embedding of sustainability into product development. The next stage of this research will focus on further investigation to develop methodologies and tools to meet the specific requirements and demands of these four areas of opportunity identified for SD.

The ultimate goal of this research is to facilitate a move to a situation where sustainability is inherent and ubiquitous within the product development process – i.e. to move from Design for Sustainability into **'Ubiquitous Sustainability'.** For this, we need better informed designers, better informed engineers, better informed managers, and better informed customers. We need to raise awareness of sustainability issues amongst all involved, requiring better education and a shift in both social and industrial expectations and practices.

6 REFERENCES

[1] Otto, K.N., Wood, K.L. (2001); Product Design – Techniques in Reverse Engineering and New Product Development, Prentice Hall, New Jersey, USA.

[2] European Commission. (2012); Design for Growth & Prosperity: Report and Recommendations of the European Design Leadership Board, European Design Innovation Initiative, Helsinki, Finland.

[3] Kuo, T-C., Huang, S.H., Zhang, H.C. (2001); Design for manufacture and design for 'X': concepts, applications, and perspectives, in: Computers & Industrial Engineering, Vol. 41, pp. 241-260.

[4] Rio, M., Reyes, T., Roucoules, L. (2013); Toward proactive (eco)design process: modelling information transformations among designers activities, in: Journal of Cleaner Production, Vol. 39, pp. 105-116.

[5] Boks, C. (2006); The soft side of ecodesign, in: Journal of Cleaner Production, Vol. 14, pp. 1346-1356.

[6] Deutz, P., McGuire, M., Neighbour, G. (2013); Eco-design practice in the context of a structured design process: an interdisciplinary empirical study of UK manufacturers, in: Journal of Cleaner Production, Vol. 39, pp.117-128.

[7] Knight, P., Jenkins, J., Adopting and applying eco-design techniques: a practitioners perspective, in: Journal of Cleaner Production, Vol. 17, pp. 549-558.

[8] Lewis, H., Gertsakis, J., Grant, T., Morelli, N., Sweatman, A. (2001); Design + Environment: A Global Guide to Designing Greener Goods, Greenleaf Publishing, Sheffield, UK.

[9] Tischner, U. (2001); Tools for ecodesign and sustainable product design, in: Charter, M., Tischner, U. (Eds.), Sustainable Solutions: Developing Products and Services for the Future, Greenleaf Publishing, Sheffield,UK, pp. 263-280.

[10] ISO/TR 14062:2002; Environmental management - Integrating environmental aspects into product design and development, International Organization for Standardization, Geneva, Switzerland.

[11] EPEAT. (2010); Environmental Benefits of 2010 EPEAT Purchasing, Green Electronics Council, Portland, USA.

[12] Gerrard, J., Kandlikar, M. (2007); Is European end-of-life legislation living up to expectations? Assessing the impact of the ELV Directive on 'green' innovation and vehicle recovery, in: Journal of Cleaner Production, Vol. 15, pp. 17-27.

[13] Baumann, H., Boons, F., Bragd, A. (2002); Mapping the green product development field: engineering, policy and business perspectives, in: Journal of Cleaner Production, Vol. 10, pp. 409-425.

[14] Chen, C., Zhu, J., Yu, J-Y., Noori, H. (2012); A new methodology for evaluating sustainable product design performance with two-stage network data envelopment analysis, in: European Journal of Operational Research, Vol. 221, pp. 348-359.

[15] Lofthouse, V. (2006); Ecodesign tools for designers: defining the requirements, in: Journal of Cleaner Production, Vol. 14, pp. 1386-1395.

[16] Wright, E.I., Rahimifard, S. (2012); Strategic decision making for end-of-life management of fuel cells, in: Proceedings of the 19th CIRP International Conference on Life Cycle Engineering (LCE2012), pp.185-190, Berkeley, USA.

Integration of Environmental Aspects in Product Development and Ship Design

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Abstract

Ship recycling is a pressing issue to handle due to bad conditions in South Asian countries. The objective of this paper is to explore how to integrate environmental aspects, especially recycling, in the product development process of ships at Kockums AB by developing and proposing an implementation of a tool, document and/or method. As a result, a Long-term Environmental Action Plan (LEAP) including 18 actions was developed. The proposed way of implementing LEAP was through plan-do-act-check methodology by a systematic integration of ecodesign. LEAP includes tools, documents and methods that are to be used in daily work and product development.

Keywords:

Ecodesign; DFE; Ship industry; Ship recycling; ISO14006; POEMS; LEAP

1 INTRODUCTION

Ship breaking or ship recycling has been conducted ever since ships have been manufactured. This is because there are a lot of assets in terms of valuable material in the ships to manage. However, older vessels contain hazardous materials, such as asbestos, which expose humans as well as nature to danger. Recently, attention has been paid to ships that have been brought up at beaches for dismantling (beaching method) in Bangladesh, India, and Pakistan. Working conditions have been shown to be horrible, and a lot of waste has ended up in the surrounding nature. [1]

There are in general four types of recycling or dismantling methods, where the most common and used is called the beaching method [2]. This method is used in 95% of the cases with key locations in Bangladesh, India, and Pakistan. The ship is driven up on a beach with help of the tidal range and then dismantled on site by cutting. However, in many cases the ships strand on the mudflats before the beach and have to be dragged with winches. In the beaching method it is difficult to ensure human safety and manage hazardous materials. [1] Recycling of ships is carried out in several countries. As mentioned, the beaching method is mainly performed in South Asian countries. Turkey and China are countries where significant recycling of ships takes place as well. [3] The average age of recycled ships is hard to determine, and it is dependent on variables such as ship size and type. In general, ships reach their End-of-Life (EoL) stage after 25-30 years. [4] Even though the average age of ships sent for EoL treatment has increased by seven years from the 1990s until 2007, the amount of recycled ships is growing. This implies that recycling in the ship industry will have a greater focus in the near future. [5]

Requirements concerning ship recycling are increasing along with the awareness of the shocking situations in the countries where the beaching method is performed. At Kockums AB, a Swedish company which designs and builds ships, knowledge on how to design environmentally sustainable and recyclable vessels is not extensive. Hence, eco aspects are not well implemented or integrated, neither in the development of vessels nor in the daily work. However, it is important for Kockums AB to follow international guidelines and regulations when designing ships and selecting components. In addition, it is also of importance to be proactive concerning environmental sustainability to not end up a step behind the law or competitors. Currently, the knowledge within Kockums AB regarding environmental regulations and issues is not vastly spread. In order to increase environmental awareness at the company, Kockums AB has expressed a need for a tool, document, method or similar.

2 OBJECTIVE

The objective of this paper is to explore how to integrate environmental aspects, especially recycling, in the product development process of ships at Kockums AB by developing and proposing an implementation of a tool, document and/or method.

3 RESEARCH METHODOLOGY

Information was collected through qualitative methods, mainly literature study and company staff interviews. The research was divided into four different phases: problem framing, data collection, method development and verification.

4 CONVENTIONS AND REGULATIONS

At the end of the 1990s the International Maritime Organization (IMO) assigned a committee to propose suggestions on how this issue can be dealt with. The IMO, along with other organizations, worked on different documents on better handling of ships after their EoL. Several laws, regulations, and guidelines have been established to deal with the beaching problems in order to find a way for more environmentally sound recycling of ships, as listed in Table 1. The most recent convention is the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (Hong Kong Convention), which includes several previous regulations and deals with ship's whole life cycle. The Hong Kong Convention addresses all issues concerning ship recycling and contains a Ship Recycling Plan. It is expected to be accepted in 2013-2014 at the earliest, since it needs to be ratified by the members of IMO before it enters into force. If this convention is accepted it will mean that more consideration has to be taken when designing vessels, e.g. regarding carefully considered material selection [1].

5 COMPANY DESCRIPTION

Kockums AB is a company, within the marine industry, located in Karlskrona, Malmö, and at Muskö naval base in Sweden. The company was founded in 1679 in Karlskrona as a shipyard for the Swedish navy, and is nowadays the largest shipyard in Sweden. Kockums AB designs, builds, and maintains submarines and ships both for naval and commercial use, and is one of the top submarine manufacturers, regarding advanced technologies, in the world. The company is certified according to ISO 3834-2, ISO 9001, and ISO 14001.

Year	Name	Organization	Content	Ref.
May 1992	Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal	United Nations Environmental Programme (UNEP)	Regulates the transboundary movements of hazardous and other wastes. Adopted in 1989 and entered into force in 1992.	[6]
Aug 2001	Industry Code of Practice on Ship Recycling	The Industry Working Party on Ship Recycl.	Recommendations which would constitute "good practice" in respect to ships destined for recycling.	[7]
Jan 2003	Basel Convention on Technical Guidelines for the Environmentally Sound Management of the Full and Partial Dismantling of Ships	UNEP	Provides guidance to countries that will hold facilities for ship dismantling.	[8]
Oct 2003	Guidelines on safety and health in shipbreaking	International Labour Organization (ILO)	Provides guidance on the safe planning and execution of shipbreaking operations.	[9]
Dec 2003	Resolution A.962(23) IMO Guidelines on ship recycling	International Maritime Organization (IMO)	Gives advice on recycling aspects to all stakeholders in the recycling process and introduced the concept of a "Green Passport".	[10]
May 2007	Green Paper	European Commission	Gives the basic facts on ship dismantling and explains the problems.	[11]
Nov 2008	An EU Strategy for better ship dismantling	European Union	Objective is to ensure dismantling of ships in safe and environmentally sound facilities worldwide, in line with the draft Ship Recycling Convention.	[12]
May 2009	Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships	IMO	Rules covering a ship's whole life cycle, from construction to recycling, and covers previous regulations and guidelines.	[13]

Table 1: A selection of conventions and regulations regarding ship recycling from 1992 until 2012.

5.1 Product Development at Kockums AB

The product development process (PDP) needs to be suitable for the incremental product development (PD) present at Kockums AB. At the moment, Kockums AB is in a transition to update and improve their PDP. This is one step in the KRAFT project that is currently being carried out (KRAFT is a Swedish abbreviation for *"Kockums AB Riktade Ansträngning För Tillväxt"* which can be translated to *"Kockums AB Aimed Effort for Growth"*). KRAFT is an initiative that was introduced as a means to increase the efficiency of processes and facilitate the possibility for continuous improvement.

The maritime industry that Kockums AB is active in is very different from "usual" supply and demand-driven industries, for instance markets for conventional household products. The customer is in control and Kockums AB needs to adjust themselves for their main customers. Consequently, the PD at Kockums AB is conducted in cooperation with the customer. Projects are based on what single customers require instead of a perceived need in the market. Moreover, it is difficult to be innovative and quickly develop new designs. In general, innovation is incremental. In the ship industry, it takes time before innovations are fully implemented. Nevertheless, R&D of naval technology at Kockums AB can be focused on market-pull, just as in a normal market economy. However, the developments will not be rapidly integrated in products. The time perspective of projects at Kockums AB is very long since a ship is a very high-tech and complex product. The design process is a crucial part of the product development process at Kockums AB. This design process is divided into different phases with Design Reviews (DR) after each phase. In the DRs, the ship design is evaluated in order to assure that all necessary requirements for each phase are met.

Environmental aspects that are integrated in the PDP are not apparent. Kockums AB sometimes designs to make specific parts easy to access in order to facilitate updates, maintenance, or replacements. However, design for dismantling, recycling, and reuse is normally not considered to a great extent. Selection of material is where departments can influence and have an effect on environmental impact of the product. However, in most cases military aspects and requirements trump environmental aspects. The environmental aspects that are integrated in commercial projects are mainly requirements to fulfill legal frameworks. Most commercial customers do not have additional environmental requirements since it will be too costly for them. However, the following three positive factors affecting environmental aspects are already in place at Kockums AB:

- Ships are designed to be light-weight and a state-of-the-art carbon fiber solution exists at Kockums AB.
- Expert competence within ship design exists at Kockums AB; there is big potential to realize ecodesign while maintaining the same quality performance.
- Improvement work, KRAFT, is carried out at Kockums AB; there are large opportunities for including changes in environmental attitude and implementing changes in processes.

6 LONG-TERM ENVIRONMENTAL ACTION PLAN (LEAP)

6.1 Development of LEAP

The development phase started with an analysis of the information gained from interviews and literature study. The second step, which consisted of finding solutions for the existing improvement areas, was conducted through brainstorming sessions. Lastly, the solutions were prioritized according to two parameters: how important they were to implement within the nearest future, and how easily the solutions could be implemented without being seen as an obstacle instead of an aid. Consequently, the solutions were prioritized according to complexity. When the solutions were decided upon they were thoroughly described in a Long-term Environmental Action Plan (LEAP) as individual Actions. For each of these Actions, the objective, solution (i.e. how it should be used and/or implemented and when and where it should be implemented), and responsibilities were described. Additional documents were developed according to Kockums AB's existing templates. In this way, implementation and integration of the LEAP was facilitated.

6.2 Contents of LEAP

The LEAP document contains a description of a long-term plan of how to introduce product-related environmental aspects, ecodesign, in Kockums AB's PDP in accordance with ISO 14006. The introduction of LEAP should be incremental, and it contains several Actions which have been prioritized according to the order that the implementations should take place. These Actions are methods, tools, or aiding means that have the purpose of facilitating ecodesign in the daily work, product development, and mindsets' of Kockums AB's employees. The majority of the suggested Actions include worksheets or documents named as LEAP-14XX, where XX are the specific numbers for the Actions' worksheet or document ranging from 1 to 10 (see Table 2). The responsibility for implementing the LEAP should be on an Environmental Management Group, which is suggested to be a part of the KRAFT project.

The Actions are prioritized according to a scale for ranking from 1 to 5, where 1 is of highest priority (Table 2). The prioritization provides guidance on what is suitable to implement initially, but does not prevent work regarding Actions of lower priority from commencing.

Action 1: Environmental Management Group (EMG)

The Environmental Management Group (EMG) consists of representatives from different disciplines within Kockums AB and should be responsible for pursuing, and supporting, environmental issues in the daily work at the departments. By establishing an EMG, work regarding environmental issues can be extensively pursued and environmental aspects can easier infuse the entire organization. The EMG is currently being formed and consists of three people who all work in Karlskrona. However, the group should later be expanded with representatives from Malmö and Muskö. The EMG should continuously pursue environmental work in the daily operation and business. When the LEAP is fully pursued, the EMG will not cease to exist. Instead, the EMG will work as an active and permanent group to where employees can turn with questions and thoughts on environmental issues and ecodesign. Kockum AB's Environmental Manager is responsible for establishing the EMG and for initially directing the work. The intention is that an "Environmental Champion" will be employed to PD departments, in order to unburden the Environmental Manager. If an EMG is instated in KRAFT, environmental issues can be brought up in a clear manner and the status of environmental work can more easily be communicated and mediated to the employees.

Action 2: Revised Environmental Policy

The purpose of the environmental policy is to indicate and show, internally and externally, how Kockums AB is actively working with minimizing the adverse impact on the environment in the company's operation and business. The existing environmental policy has been revised to be clearer, as well as expanded. The environmental policy should be reviewed annually and, at the same time, assessed by the top management. Top management is responsible for making sure that the policy is mediated to all employees who work at and for the company. Through a well-formulated and worked through environmental policy, Kockums AB can show their employees and the public that environmental issues are pursued and that environmental aspects are an important part of their business. This can give competitive advantages and it makes Kockums AB an even more attractive employer.

Action 3: Revised Environmental Objectives and Targets

In order to pursue the environmental work that is described in the environmental policy, measurable objectives and targets are established for relevant disciplines and on suitable levels in the company. The purpose of establishing environmental objectives and targets is to reach an environmentally sustainable development in the long run. Additional environmental objectives and targets should be added in accordance with ISO 14006, which relate to the product and the product development process. It is important that all employees of Kockums AB are well aware of what objectives and targets exist so that they can be fulfilled with joint efforts. Kockums AB should establish all-embracing and detailed environmental objectives and targets from the current situation in which the company is in with regards to what level of ambition that is believed to be suitable. The environmental objectives and targets should be revised and renewed before every new financial year. Top management is then responsible for legitimacy and authorizing the suggested objectives and targets. With product-related environmental objectives and targets, Kockums AB can be a part of and contribute to environmentally sustainable development that reaches outside the walls of the shipyard.

Action 4: Communication Plan

A clear communication plan that is continuously updated makes it easier to avoid inadequate communication, which could otherwise lead to expensive mistakes. Moreover, clear channels of communication can support environmental work, which is dependent on collaboration in order to accomplish a successful result. Several decisions within projects are affecting numerous people; as a consequence of this, changes in for instance procurement processes or design need to be made. It is therefore important to inform and communicate, which is what the communication plan intends to facilitate. A clear communication plan should be established in every project, and it should be visible and accessible for all affected parties. There should be distinct instructions on how communication should take place, and there should also be instructions on who is responsible for what. In this way, who should be contacted if questions arise is made clear. In the beginning of every new project, a clear communication plan should be established, in accordance with the worksheet, and it should be enclosed in the project plan. The Project Manager is responsible for forming, maintaining, and distributing the communication plan throughout the entire project. By clarifying communication channels within projects, insufficient communication can be avoided, ecodesign can be supported, and an efficient project with good quality can be carried out.

#	Action	Responsible	When	Reference	Priority
1	Environmental Management Group (EMG)	Environmental Manager	-	LEAP-1401	1
2	Revised Environmental Policy	Top Management	Annual revision	LEAP-1402	1
3	Revised Environmental Objectives and Targets	Top Management	Annual revision	LEAP-1403	1
4	Communication Plan	Project Manager	Start-up on new projects	LEAP-1404	1
5	Color list of forbidden and restricted substances	Designers and engineers in the EMG	Continuously in the PDP	LEAP-1405, Hong Kong Convention's Appendix 1-2	1
6	Ecodesign Guidelines	Designers	First phase after "Offer" and continuously in PDP	LEAP-1406	1
7	Education and Training	Top Management and EMG	Continuously and before start-up of new projects	-	2
8	Recycling Manual	Integrated Logistics Support (ILS)	Should be completed in the PD's final phase	A customer's recycling manual	2
9	Procurement department's contribution to ecodesign	Employees from Procurement department in EMG	Annual revision	LEAP-1407	2
10	Employment of an environmental champion	ILS's Head of department	-	-	2
11	Prestudy-EEA	Design departments	Design process	LEAP-1408	3
12	Fast Five	Top Management	Strategic product planning of product concepts	LEAP-1409	3
13	Ecodesign Checklist	Design & Engineering and System Manager	Design Reviews in the Design Process	LEAP-1410	3
14	Eco-toolbox	EMG	Continuously in PDP	-	4
15	Further Education and Training	Top Management together with EMG	Continuously and before start-up of new projects	-	4
16	Product-FMEA	Project and System Managers	Early design and as support during PDP	-	4
17	EEA	Same as for Action 16	In connection to Action 16	-	4
18	LCA	Environmental Champion at ILS	Before and during the Design Process	-	5

Table 2: Overview of the 18 Actions in LEAP.

Action 5: Color List of Forbidden and Restricted Substances

A color list of forbidden and restricted substances should be established, in accordance with a customer's criteria document and the Hong Kong Convention's Appendix 1 and 2, making it easier for designers to make environmentally conscious decisions in ship design. The purpose of categorizing substances according to colors is that it makes it easier to make environmentally conscious decisions. Having a color list makes it easier for designers as well as suppliers to see what substances may not be used and hence should be avoided. The color list should be established as soon as possible since this is an important first step to take in ecodesign. The color list consists of:

- A "black list" of substances that can absolutely not be used in ship design (forbidden).
- A "grey list" of substances that should not be used, but can be used if exceptions are given (restricted).
- A "yellow list" of substances that should not be used, but are exceptional cases in naval design and can therefore be used (exceptional cases).

Action 6: Ecodesign Guidelines

The Ecodesign Guidelines is a tool aimed for use throughout the product development process. The guidelines work as guidance so that environmentally conscious choices can be taken when making design decisions. The purpose of using the Ecodesign Guidelines is to support decisions that are taken when designing ships so that the decisions are well thought through from an environmental perspective. This results in a more sustainable design from an ecodesign point of view. The guidelines should be contemplated when making selections for, developing, and/or designing parts, components, systems, or similar during the product development process. The intention is that the guidelines should be used as a compass, or guidance, and it is not necessary that they are meticulously followed through to the last detail. The guidelines are ranked according to how well they are applicable to ship design and to Kockums AB. The ranking is scaled from 1 to 3, where 1 is of highest priority. The Ecodesign Guidelines should also be applied and contemplated continuously throughout the product development process. The Ecodesign Guidelines should be contemplated by every designer as well as other affected employees so that the employees can argue

Success factor	Action #	LEAP #
Commitment and support are provided	1	1401
Clear environmental goals are established	3	1403
Ecodesign is treated on both operational and strategic levels	12	1409
Close supplier relationships are established	18	
Environmental issues are considered at the beginning of the PDP	11 and 17	1408
Environmental issues are integrated into existing PDP	LEAP	LEAP
Environmental checkpoints and reviews are introduced into the PDP	11, 13 and 17	1408 and 1410
Company-specific environmental design principles, rules and standards exist	6	1406
Support tools are applied	14	1404-6 and 1408-10
Education and training are provided to the PD personnel	7 and 15	
An environmental expert supports the PD activities	1 and 10	1401
An environmental champion exits	10	

Table 3: Summary of how success factors are connected to the actions in LEAP.

for how ecodesign has been considered when developing a component, or similar, for the ship. By applying the mindset and inspiration that can take place thanks to the Ecodesign Guidelines, an environmentally conscious ship design will be achieved.

6.3 Success Factors of LEAP

The process of how this LEAP should be implemented has been developed according to the method of how Product Oriented Environmental Management Systems (POEMS) should be introduced. The method of POEMS is based on the concept of Plan-Do-Check-Act, which is a natural part of ISO 14001, where the concept of Plan-Do-Check-Act often is described as continual improvement.

As Ammenberg [14] and Gibson [15] point out, it is not certain that better environmental results will be accomplished if an EMS is implemented. This applies to the LEAP as well, and merely to follow the LEAP as a roadmap will not be enough. The Actions presented in the LEAP are developed according to ISO 14006 with the success factors presented in Johansson's [16] literature review as support. Table 3 below shows how the suggested Actions link to the different success factors and areas of concern. According to the literature review, the three most frequently mentioned success factors are: "commitment and support are provided", "education and training are provided to the product development personnel", and "an environmental champion exists". Support from top management is a significant success factor according to the International Organization for Standardization (ISO) [17] as well. ISO [17] further states that the two most important tasks for top management are strategic planning and managing internal process in order to ensure that ecodesign is well-integrated into processes. Therefore, it is vital that top management addresses these issues as well as gives their full support to the EMG in order for them to be legitimated when pursuing the LEAP. Moreover, it is important to integrate ecodesign in management reporting, practice, and thinking, which is why Fast Five (Action #12) ought to be followed through. The bottom line is that it is significant that ecodesign permeates both at the management and design levels. Hence, the LEAP aims to ensure that actions are taken from top-down, as well as from bottom-up.

The other two of the three most frequently mentioned success factors have shown to be of importance in the empirical findings. Currently, there are no employees at Kockums AB that have striven for environmental issues and can be considered as an environmental champion. However, this is vital in order for employees to motivate each other in ecodesign. A new recruitment, an environmental champion, will contribute to increased knowledge since employees learn a lot from each other. Education was shown to be an important factor, especially when first handling ecodesign [18]. Hence, education and training will also increase the employees' knowledge in product-related environmental areas. As a result, an increased motivation and environmental awareness is aspired.

7 DISCUSSION

The LEAP was developed in order to suit the existing procedures at Kockums AB. Two verification sessions were used to verify that the LEAP was relevant and realizable at Kockums AB. Feedback from both of the sessions was positive, especially regarding the suggestion that the LEAP and the EMG should be a part of KRAFT. However, a potential disadvantage that could occur is that other projects in KRAFT, which are also of high importance, will receive less attention if too much focus is put on the integration of environmental aspects. Moreover, the LEAP contains several Actions which need to be assessed and implemented incrementally in order to be successful and have an impact. It is especially important to do this incrementally because Kockums AB is not used to handling environmental work. If all Actions were to be implemented at once it would be too much to take in and deal with, even though the Actions are developed to suit the existing processes. Additionally, it is important to make sure that employees are motivated to fully implement this environmental work, and that they believe in the LEAP as well as understand why it is important to carry out the environmental work.

There are no environmental and recycling aspects integrated explicitly in the PDP at Kockums AB. In short, interviews at the design departments showed that customer demands and enclosed appendices are requirements that are incorporated in product development and ship design, along with designers' implicit knowledge. Hence, it is necessary to include internal requirements in existing databases, which handle requirements at Kockums AB, and enclose them in project-specific requirements. This means that environmental aspects will be interweaved with the existing process, which is how Jönbrink et al. [19] suggest that ecodesign should be conducted. There exists an environmental handbook at Kockums AB which can support employees in their daily work. It is, just as a design checklist, not used a lot. However, it is accessible when needed. In addition, it includes many different aspects regarding environment, and not only product-related environmental aspects. Empirical findings clearly show that there is a need for tools which can facilitate more environmentally conscious decisions for designers in the product development.

As Jönbrink et al. [19] and the ISO [20] state, environmental aspects need to be included early on in the product development. Freedom of decision making is great in the early stages, and it is important to integrate supporting methods and tools in early PD. Jönbrink et al. [19] argue that environmental aspects should be interweaved with the existing process in order to be successful. The ISO [20] suggests that an analysis of environmental and legal requirements ought to be completed in the planning phase of PDP, and the organization also states that environmental aspects should be considered in design reviews. Hence, several of the suggested Actions are to be included in the existing PDP and DRs. According to Jönbrink et al. [19], environmental requirements need to be included in requirement specifications, a view which was also expressed by staff at Kockums AB and discussed in early stages of conceptual design. These issues have been considered when developing LEAP.

8 CONCLUSIONS AND FURTHER RESEARCH

The proposed Long-term Environmental Action Plan (LEAP) is a leap for Kockums AB to take in the direction of environmentally conscious design. It includes tools, documents, and methods that are to be used in daily work as well as in product development. Consequently, environmental and especially recycling aspects will be included in the product development process at Kockums AB. As a result, the expectation is that employees' environmental awareness and interest will increase, along with their knowledge in ecodesign.

Future research could include how Product-Service Systems (e.g. rental programs) can be applied at Kockums AB. By establishing a Product Service-System, ships can be sold on leases. Consequently, better control during the usage phase of ships will be gained. Moreover, ships will be brought back to the company and money can be earned on taking care of the ships. This would also be a motivation to design ships with regards to how they will be recycled or reused, since the company is responsible for it and can make more profit while also being ecologically beneficial.

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10 REFERENCES

1. Lloyd's Register (2011), Ship recycling - Practice and regulation today. London: Lloyd's Register.
2. Shimizu, K., Nakajo, Y., yaer, X., Kato, K., Kijima, T., Teraoka, I., et al. (2012), Advanced Ship Recycling System – a Pilot Model Project in Muroran. Advanced Materials Research Vols. 356-360, 1827-1830.
3. UNEP (2010), Environmentally Sound Dismantling of Ships. Châtelaine.
4. Mikelis, N. E. (2007), A statistical overview of ship recycling. Athens: International Maritime Organization.
5. Martinsen, K. (2009), Environmentally sound ship recycling. Retrieved January 24, 2012, from DNV - Services for managing risks.
6. UNEP (1992), Basel convention on the control of transboundary movements of hazardous wastes. Châtelaine.
7. The Industry Working Party on Ship Recycling (2001), INDUSTRY CODE OF PRACTICE ON SHIP RECYCLING. London.
8. UNEP (2003), Technical Guidelines for the Environmentally Sound Management of the Full and Partial Dismantling of Ships. Châtelaine.
9. ILO (2003), Safety and health in shipbreaking: Guidelines for Asian countries and Turkey. Bangkok: International Labour Office Geneva.
10. IMO (2003), Resolution A.962(23) - IMO GUIDELINES ON SHIP RECYCLING (Vol. Resolution).
11. EC (2007), GREEN PAPER on better ship dismantling. Communities. Brussels.
12. EU (2008), An EU strategy for better ship dismantling - COM(2008) 767 final. October. Brussels.
13. IMO (2009), Hong Kong international convention for the safe and environmentally sound recycling of ships. Hong Kong: International Maritime Organization.
14. Ammenberg, J. (2003), Do Standardised Environmental Management Systems Lead to Reduced Environmental Impacts? PhD thesis, Linköping University, Sweden.
15. Gibson, K. (2005), Environmental management systems: How successful are they? Environmental Quality Management, 14(3), 25-30.
16. Johansson, G. (2002), Success Factors for Integration of Ecodesign in Product Development - A Review of State-of-the-art. Concurrent Engineering. Linköping.
17. International Organization for Standardization (2002), ISO 14062 Environmental management - Integrating environmental aspects into product design and development (Vol. 2002).
18. Ammenberg, J., & Sundin, E. (2005), Products in environmental management systems: the role of auditors, Journal of Cleaner Production, 13, 417-431.
19. Jönbrink, A. K., Norrblom, H. L., & Zackrisson, M. (2011), Ecodesign – praktisk vägledning (In Swedish). Swerea IVF AB.
20. International Organization for Standardization (2011), ISO 14006 Environmental management systems - Guidelines for incorporating ecodesign (Vol. 2011).

Cradle to Cradle in Product Development: A Case Study of Closed-Loop Design

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Abstract

Cradle to Cradle (C2C) challenges designers to create products with a beneficial impact on environment, society and economy. While existing research has highlighted merits and critical points of the strategy, an understanding of its application -how Cradle to Cradle helps designers to develop such products- is lacking.

This paper analyzes the application of C2C in a 'closed-loop' product development case. Based on in-depth study of the design process and product, the authors identify the effects of specific C2C-elements, and provide tentative conclusions on how designers can benefit from this strategy for developing sustainable products.

Keywords:

Sustainable product development; Closed-loop design; Design methods

1 INTRODUCTION

Taking nature as a model for designing products can help designers in the development of closed-loop products. It is one of the core concepts in Cradle to Cradle[i] (C2C), a strategy that aims for designing products in such a way that, after their useful lives, the products will provide 'food' for new products[ii]. C2C is based on a philosophy, three guiding principles, and a number of application tools [1]. On a philosophical level, the strategy offers a vision that challenges designers to think differently. Instead of trying to make products 'less bad', designers are stimulated to strive for 'eco-effectiveness', designing *good* products that generate a beneficial footprint [1-3]. C2C furthermore identifies "*three key principles in the intelligence of natural systems that can inform human design"*: 'waste equals food', 'use current solar income', and 'celebrate diversity' [1, 2]. The application tools (also referred to as design tools) can help designers to generate solutions for specific design problems.

On C2C in product development, few empirical studies are available, and even fewer studies on the actual use of C2C by professional designers. Rossi et al. [3] studied the development of the Mirra chair by office furniture manufacturer Herman-Miller. They describe the accomplishments of a dedicated Design for Environment (DfE) team that assisted the product team. Bakker et al. [4] discuss advantages and disadvantages of applying C2C in product design, based on literature and student projects. In a preceding study [5], the authors studied the work of student teams applying different sustainable design strategies. Furthermore, Bjørn and Hauschild [6] studied the differences between LCA or eco-efficiency and C2C from an analytical viewpoint.

The objective of the present study is to obtain a better insight in the actual use of C2C by product designers, and to develop an understanding of *how* it helps them (or not) to develop sustainable products[iii]. Based on the results of a case study of a 'closed-loop' design project, this paper aims to assess (1) what specific elements of the C2C strategy have been applied (and what elements not), and (2) how their application has affected the design process and the outcome of the project, with a focus on environmental sustainability. The study is part of a larger research project on the application of nature-inspired design strategies in product development.

2 METHODOLOGY: A CASE STUDY APPROACH

As current empirical knowledge on the application of Cradle to Cradle (C2C) in design practice is tentative, a case study approach was chosen for collecting and analyzing data. Case study research is suited for obtaining an understanding of 'what is happening', for answering 'how' questions in non-experimental settings, and thereby gaining analytical insights on the research phenomenon [7, 8]. The specific case for this study was selected on the basis of the following criteria: a) the project has been executed within a (design) company and actively involves product designers, b) the project addresses environmental (and possibly social) sustainability issues, c) the designers are trained in the use of C2C or assisted by C2C experts, and d) the case can provide rich data, having a diversity of sources available, including the involvement of the designers.

2.1 The Case: Development of the Clps Presentation System

The company selected for this study -Full Circle Design- is a small German design firm, specializing in the development of closed-loop products. Both of the company's designers are trained in C2C design. The case project involved the development of "Clps", a presentation system for fairs and points of sale (figure 1). Such systems are used to present graphic information to people, and typically consist of a frame, onto which printed textile fabric is connected with the use of keder (an elastic cord for fixing the textile onto the frame).

The goal of the project was to develop a modular presentation system that "never becomes waste". According to the designers, such systems are typically disposed of after only days of use, and contribute to the large amount of waste generated at fairs. They retrieved that, for example, the Hannover Messe, a large 5-day industrial trade fair, generated about 1225 tons of waste in 2009.

2.2 Procedure for Data Analysis

In order to understand to what extent the Cradle to Cradle strategy was applied in the design project, a checklist was compiled of different 'strategy elements': philosophical concepts, guiding principles and tools within the Cradle to Cradle strategy (see also Table 1). Three terms have been included to represent the C2C philosophy: 'Do good instead of less bad', 'Creating a beneficial footprint' and 'Eco-effectiveness'. Furthermore, the three C2C principles are included, as well as nine application tools. The tools have been selected based on the contents of the C2C-Designer training at EPEA Hamburg [9], many of which have been described in a positioning paper co-authored by EPEA [1]. The C2C certification criteria have not been included in this study, as they are not intended as design tools, but to support communication and marketing of products that have already been developed [1, 10].

Figure 1: Impression of the Clps closed-loop presentation system by Full Circle Design.

To analyze how, in this particular case, the application of C2C has affected the design process and the final design, data from different sources was used to generate a diagram, showing the observed relations between design steps, C2C elements, and end results.

2.3 Data Collection Procedure

Data was collected during a three-day visit at the design office, each day focusing on a different viewpoint, as shown in figure 2: 1) the product (the physical end result of the project), 2) the design process, and 3) the use of C2C-elements.

The first day, semi-structured interviews were held with both designers individually. The designer was asked to describe the project outcomes, with the aid of the prototype and samples, to obtain knowledge on how the application of C2C may have influenced the final design.

During the second-day session, both designers (together) were first asked to visualize their design process, for which they used their documents, samples, and drawings. They then marked the design steps in which they applied C2C. Figure 3 gives an impression of the results. The marked steps were discussed in detail, to understand how the designers applied C2C and how it affected their design process. During the discussions, the researcher and designers together created a diagram of all major design decisions and applied C2C-elements, to reflect on the effects of applying these elements and incorporate direct feedback from the designers.

Figure 3: Visualization of design process using documents, samples, and drawings.

The last session explicitly focused on the use of C2C elements in the project, as reflected upon by the designers. All C2C elements considered in the study were presented in the form of a stack of cards, each card mentioning one of the elements. The designers were asked to divide the cards into three categories: ‘applied’, ‘known but not applied’, and ‘not known’. Furthermore, for the elements they applied, the designers marked those elements they consider to have been most important in the project. Six elements were discussed in more detail to understand how they were applied, or why they were not applied. During the last part of the third day, the designers were asked to evaluate the outcomes and use of the strategy. Both designers filled-in a five question-questionnaire in which they were asked to assess the outcomes of the project on environmental sustainability, social sustainability, economic feasibility, and functionality as compared to the performance of the solution currently available on the market.

All sessions were audio- and video-recorded. Additionally, project results such as reports, presentations, prototypes, and samples were included in the data collection. The results of the analysis were discussed with the designers via e-mail and Skype-meetings.

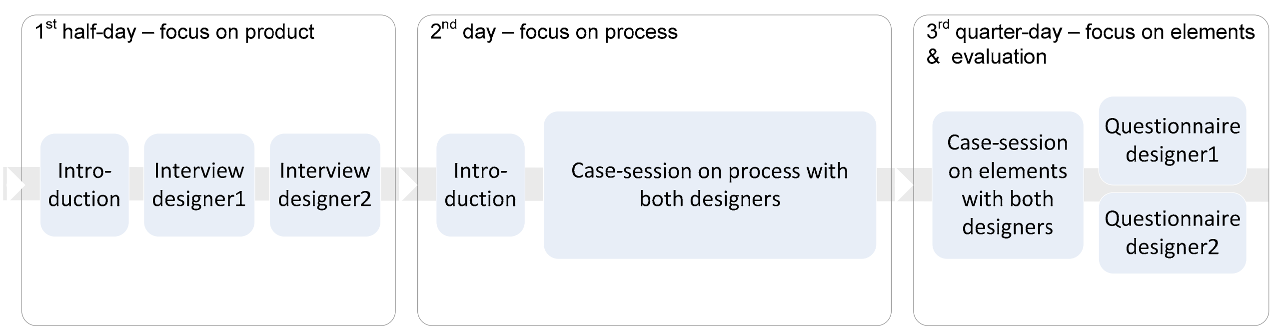

Figure 2: Schematic overview of data collection.

3 RESULTS

Following the aim of the study, this section presents the results on the application of Cradle to Cradle (C2C), and the impact of the C2C elements on both the design process and end results, including results from the evaluation on the sustainability of the final product.

3.1 Application of Cradle to Cradle Elements

The two designers involved in the project completed two Cradle to Cradle courses, including the 2nd C2C-Designer training at EPEA Hamburg (which they entered after their project was well underway). They were familiar with all C2C-elements included in this study, but did not apply all of them in the project. Table 1 lists these elements. The second column shows the elements that, according to the designers, have been applied in the development process. The third column depicts the elements that have been detected in the collected case study data by the researcher.

'Doing good - instead of less bad' was marked as an important driver (by the designers), as well as the principle 'waste equals food' (both by the designers and the researcher). The application tools that were marked by the designers as the most important ones were (in random order) the roadmap, material inventory, define use in bio/tech cycles and design for disassembly.

Elements of C2C considered in the case study	Applied according to designers	Applied according to researcher
Philosophy		
Doing good - instead of 'less bad'	**✓**	✓
Creating a beneficial footprint	✓	✓
Eco-effectiveness	x	✓*
Guiding principles		
Waste equals food	**✓**	**✓**
Use current solar income	x	x
Celebrate diversity	x	✓*
Application tools		
Roadmap	**✓**	✓*
Material inventory	**✓**	✓*
ABC-X classification	x	x
Define use in biological and technical cycles	**✓**	**✓***
Define use period	✓	**✓**
Add value	✓	x*
Cascade use	✓	x*
Design for (dis)assembly	**✓**	✓
Use C2C-elements (materials, processes, ingredients)	✓	✓
Triple-top-line (added by designers)	✓	✓

Table 1: Overview of C2C-elements considered in the case study, based on [1, 2, 9, 11]. ✓=applied, ✓*=applied partially or implicitly, x=not applied; x*=not covered as a tool in the case data; bold markings represent the elements considered to have been most important in the design project.

According to the designers, two C2C-principles: 'Use current solar income' and 'Celebrate diversity' were not considered in this project. The designers could not see a useful application opportunity for these principles within the design project. Considering the 'use of current solar income', the designers argued that there was no practical application of this principle beyond using renewable energy for all processes that require energy. Finding materials that can be fully recycled (related to the first C2C principle) had posed such restrictions, that the designers did not include additional constraints on their selection process regarding the energy sources used for the production. As one of the designers explained:

> "...it's almost as difficult to find the right materials and find the right producers. [...] We can't ask them the first question 'Are you using current solar income? No? Okay then, goodbye', because that's the only opportunity to go further with our project. For example, the fabric company [...] I don't know if they are using this energy."

Within C2C, products do not have to address all elements at once, but to progress towards a fully beneficial result, the transition to renewable energy would be part of the roadmap [9]. Although the designers marked this tool to be important, their roadmaps do not mention such goals. With respect to the third C2C principle, 'Celebrate diversity', the designers expressed difficulty in understanding how to apply it. None of the tools seems to address specifically how designers can implement this principle into their design. However, considering the context-specific solution of their product-system and the modular design, it can be argued that they in fact did include this principle to some extend [9], though not intentionally.

The designers did an extensive material inventory, though not to the level (100 ppm) as described in the tool, as such data is difficult to obtain and cannot be interpreted without the help of a chemist. ABC-X analysis was also omitted, because of the financial constraints (of hiring the required expertise). On the other hand, the designers applied the 'triple-top-line' visualization triangle, a tool not used in the C2C-designer training, but described in the C2C book [11], covering ecology, equity, and economy. This tool made them aware of social aspects of design, and offered an approach to include social considerations into their project.

3.2 The Impact of the C2C Elements on the Design Process and End Results

From the design process that was visualized during the 2nd-day case-study session, it was observed that C2C was blended into the design process and clearly influenced design activities. C2C was not considered or applied in some design tasks, such as market analysis, sketching and detailing of the design. The tasks in which the designers actively involved C2C were analyzed further, based on the detailed visualizations made during the case-study session. Figure 4 shows a schematic summary of these design tasks in relation to the C2C principles and tools.

The C2C strategy was actively used in the projects' preparation phase, which was the result of the companies' ambition to develop products that will 'never become waste'. Already in this phase, the designers decided to design a modular product, allowing different sizes of presentation systems to be constructed with the same frame, whereas currently, each product variant comes with a different frame. Likewise, the basic service-concept was developed in this phase, based on the C2C 'define use period' tool. The designers developed a service and take-back system, which provides value for the customers also after the products' first use, to enable reuse and recycling of the materials.

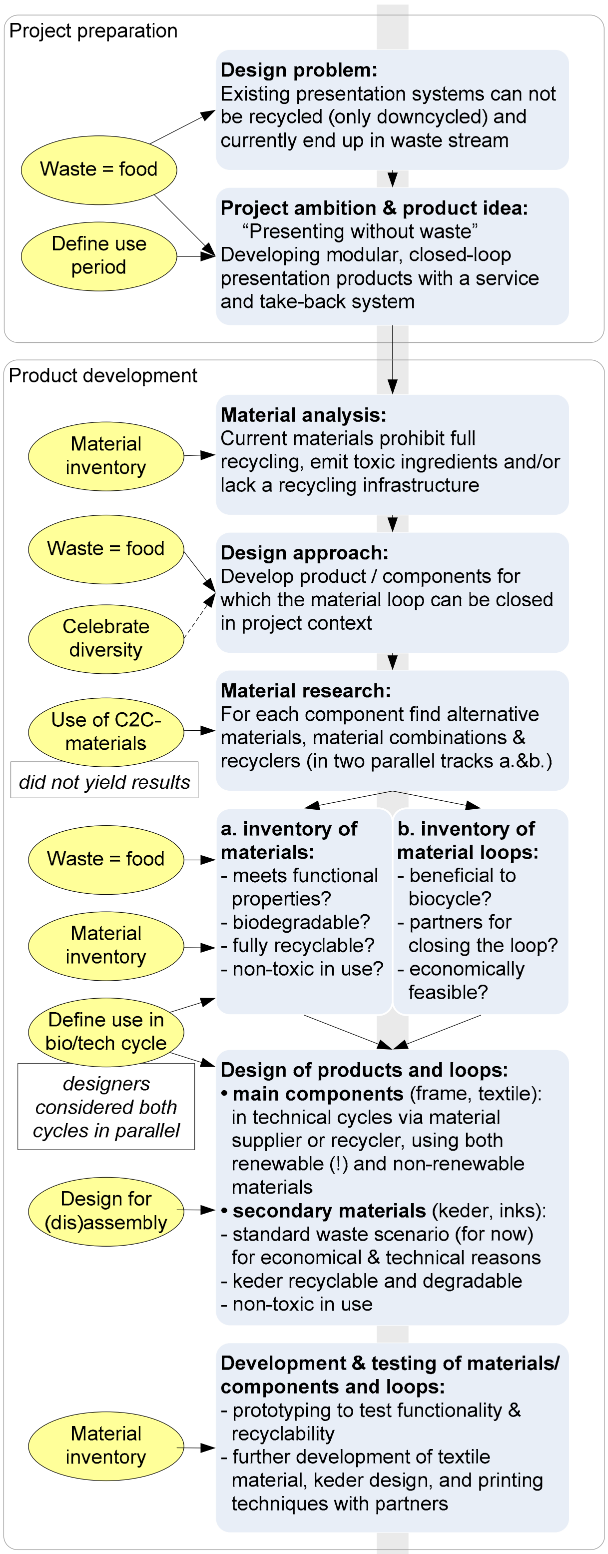

Figure 4: Input of C2C-principles and tools in the design process.

In the product development phase, four Cradle to Cradle tools were used. Their application seems to have triggered the designers to spend considerable time on finding suitable materials and material combinations, on developing closed-loop material systems and on establishing cooperation with value-chain partners. The designers originally intended to replace current materials with alternatives that were already developed using the C2C strategy, especially C2C-certified materials. However, they could not employ such materials because they were either not available (for the frame and keder), or could not be fully recycled yet (printed textile), and the textile company involved could not cooperate in the project.

The designers' ambition to realize a closed loop system seems to have changed their material selection process. Where 'being recyclable' is generally seen as synonymous with being environmentally friendly, the designers went a step further, and for each component also analyzed if and how it would actually *be* recycled. In one of the interviews, the designer explains:

> "Yeah it *could* be recycled, but this is the problem, it *could* be recycled, but the question is *how* could it be recycled? [...] Everyone says 'it could be recycled' like you did. So, if I ask you how would you recycle it, in detail, do you have a clue?"

With respect to renewable materials, the designers were not content with a material being degradable, but instead analyzed whether the material would provide a benefit to the ecosystem. For instance, biodegradable PLA can be applied, but once degraded, the material does not provide ingredients valuable to the soil. This contributed to the designers' choice to apply renewable materials in a technical cycle instead.

As compared to traditional presentation systems, the Clps applies different materials for all product components, including the inks on the textile, as specified in table 2.

Main components	Materials applied in typical presentation systems	Material types applied in Clps
Frame	Aluminium	Grass-fibre composite
Textile	Polyester	PLA
Keder	PVC / Silicone	Biobased elastomer
Inks	Solvent based or UV-curable inks	Water-based inks

Table 2: Material application in presentation systems.

The inks that are generally used for presentation systems, do not allow high-quality recycling of the polyester. Within the project, the designers -together with suppliers- developed an innovative new combination of textile and inks, that allows full recycling of the textile after each cycle of use.

3.3 Sustainability of the Final Product

The design project itself did not include a sustainability analysis. The designers did use an Ecodesign checklist [12] during the project, because they felt the need for "having a complete picture" of sustainability issues involved. Furthermore, they analyzed external LCA-data of PLA and grass-fibre composites to check for possible environmental impacts that might influence their material selection.

In this study, a qualitative evaluation of the final product was made with respect to environmental sustainability, complemented with the designers' considerations on social and economic sustainability.

Environmental Sustainability

Environmental aspects have played a dominant role in the project. The designers implemented many changes to develop a product that is environmentally sound. To what extent the new design influences the overall environmental sustainability could be assessed with a quick-scan LCA. However, according to C2C-proponents, LCA cannot be used to capture the environmental benefits of C2C-products. As described by [1, 6, 13] there are several 'basic contradictions' or differences between the two. Where LCA calculates the context-independent environmental impact under current conditions (i.e. typical energy production and recycling scenario's), C2C strives to work towards context-driven new scenarios that enable a fully beneficial impact. Bjørn and Hauschild [13] have illustrated how LCA can be adapted and used to assess a product's performance in a 'near future' C2C scenario. The complexity of such an analysis makes it unsuitable for the scope of this paper. Instead, a qualitative assessment has been made, using a checklist with eight Life Cycle Design Strategies, as identified by Van Hemel [14]. Table 3 lists the strategies, which allow evaluation of different parts of the product life cycle and different types of environmental impacts.

Qualitative assessment of the product on Life Cycle Design Strategies (LiDS):
1. Selection of low-impact materials: - 80% renewable materials, 20% fossil-fuel based materials, reduced amount of toxic ingredients, including use of non-toxic solvent; the textile still contains flame-retardants, and the inks contain toxic ingredients.
2. Reduction of materials usage: - no change in product weight.
3. Optimization of production techniques: - optimization was not considered; the textile still requires chemically optical brightening; however, one of the suppliers produces more solar energy than they consume.
4. Optimization of distribution system: - energy *efficiency* of distribution was not considered; instead a *local* production and recycling network (Western Europe) is being created; packaging will be recycled together with textile.
5. Reduction of impact during use: - the product does not consume energy or materials during use.
6. Optimisation of initial lifetime: - the use period of the frame increased from days (duration of an exhibition) to 2-5 years, due to modular design and ease of repair; reuse or recycling of components via take-back system.
7. Optimisation of end-of-life system: - full recycling of the textile (back to feedstock); frame recyclable into new frames for four times (material can thus be used 8-20 years for this application); the keder is recyclable, but at the time of the study not foreseen to be recycled due to economic constraints; inks are treated as waste materials.
8. New concept development: - not considered.

Table 3: Qualitative assessment of environmental impacts, using the Life Cycle Design Strategies [14].

Following the assessment in Table 3, the product seems to have superior environmental properties on three Ecodesign strategies: 1. 'Selection of low-impact materials', 6. 'Optimization of initial lifetime' (reuse of components), and 7. 'Optimization of end-of-life system' (recycling of materials). Three strategies were not followed. 'Reduction of material usage' (no. 2) was not addressed, as the goal of C2C is not to *reduce* the use of materials but instead to fully recycle all materials used. However, no adverse effects are anticipated, as the designers did consider product weight. As the user has to carry the product, the weight has been kept comparable to that of existing presentation systems. Strategy 3 'Optimization of the production processes' was not considered as the production techniques were directly coupled to the materials. Production techniques seem comparable to the ones currently used, and part of the energy from production originates from solar energy, but data to assess the overall impact of production are lacking. A change of the basic concept -Strategy 8 'New concept development'- was (deliberately) not included. The designers wanted to maintain the current primary function of the product, because they aim for high market acceptance. Making a radical change in the design of the current concept was deemed unrealistic for maintaining acceptance.

Social Sustainability

The designers paid (some) attention to social aspects, using the triple-top-line visualization tool. This led them to consider and include a producer that employs handicapped people. Furthermore, the use of local suppliers may contribute to the strengthening of the local community, although this was not an explicit aim of the project. Other social sustainability aspects, such as social impacts associated with material extraction, or the active development of 'fair-trade' practices, were not considered.

Economic Sustainability

With respect to economic sustainability, the designers paid considerable attention to building a sound business-case for their product and the service system. This focus was chosen to ensure the viability of the product and to facilitate the return of the components for reuse and recycling. Equal material and production costs for the projected production volume are combined with increased modularity of the product.

4 DISCUSSION

The design activities performed in the project differ in many aspects from a conventional design project. The material selection process was dominant in the embodiment of the design, and resulted in the development of innovative material solutions. Apart from the ink, all materials applied in the product can be recycled. Additionally, a recycling system for the main components (the frame and textile) is included in the design solution.

The designers, though not anticipating this at the start of the project, went into cooperation with material suppliers to overcome major barriers in recycling. They could not 'simply' employ materials that have already been developed according to the Cradle to Cradle (C2C) strategy. Their search for suitable 'C2C' materials proved an ineffective task, in the sense that no such materials met their requirements for closing the loop. This may change with the increasing availability of certified materials. However, having data available on the actual performance of certified materials with respect to the C2C-principles, may greatly contribute to the effective selection of materials.

Cradle to Cradle was applied from the preparation phase of the project, resulting in a challenging ambition of a fully closed-loop system. Aiming for this absolute end goal, instead of analyzing and aiming to reduce the impacts of current products, may have yielded the designers both time and creative freedom to develop innovative solutions. Their 'closed-loop ambition' led the designers to go beyond traditional steps of product design into the domain of material development. The C2C philosophy, principles, and tools in this project clearly aided the designers in achieving this result.

The project focused on the application of the principle 'waste=food'. This principle, supported by the application tool 'define use in biological and technical cycles', seems effective in helping designers to develop a product concept, which corresponds to our findings in a previous study with student projects [5]. On the other hand, the designers left aside the second principle 'use current solar income' to not further limit the amount of materials available for designing their product. As no goals were included in the roadmap for a transition to renewable energy, environmental impacts from energy consumption may continue to exist. In our prior study [5], the design students did include energy aspects in their design process, but the Herman-Miller case study [3] illustrated a similar focus of the designers on the material-side of the design. Accordingly, our current findings support criticism that C2C may divert focus away from addressing energy aspects [4, 6], despite the presence of the C2C principle 'use current solar income' and the roadmap tool.

The case study showed that the designers did not explicitly aim to create beneficial social impacts, or to incorporate 'diversity' into their design. This coincides with the absence of concrete tools for these topics, hinting to the importance of application tools for product designers that wish to apply Cradle to Cradle to its full potential. Further research may address the reasons why designers do not consciously include all principles of C2C in their projects.

5 CONCLUSIONS

The objective of this study was to provide a better insight on the use of Cradle to Cradle (C2C) by product designers, to develop an understanding of *how* it helps them (or not) to develop sustainable products. This case shows how the application of C2C activated the designers to adopt a 'systems approach', by engaging them in the actual design of 'the product loop'. Furthermore, the case illustrated how the fields of product and material development may converge when applying C2C. This approach helped the designers to overcome recycling barriers in the development of their closed-loop product.

Cradle to Cradle, with its three principles, in theory offer designers the possibilities to incorporate environmental, economical, as well as social benefits in the design of products. In this case, however we observed that the project focus was on the materials and environmental aspects of the design. The results indicate that new application tools, specifically aimed at incorporating renewable energy and diversity into the design project, may help designers to integrate all three C2C-principles into their design process.

The designers involved in this case study, work at a small, independent design firm, allowing them to apply C2C as they see fit. Further research, analyzing designers in larger firms, may broaden the insight on the use of C2C in product development.

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7 REFERENCES

[1] Bor, A.-M., et al.): Usability of Life Cycle Assessment for Cradle to Cradle purposes. NL Agency: Utrecht.

[2] McDonough, W., et al., (2003): Applying the Principles of Green Engineering to Cradle-to-Cradle Design, in: Environmental Science & Technology, Vol. 37, Issue: 23, p. 434A-441A.

[3] Rossi, M., et al., (2006): Design for the Next Generation: Incorporating Cradle-to-Cradle Design into Herman Miller Products, in: Journal of Industrial Ecology, Vol. 10, Issue: 4, p. 193-210.

[4] Bakker, C. A., et al., (2009): Designing cradle-to-cradle products: a reality check, in: International Journal of Sustainable Engineering, Vol. 3, Issue: 1, p. 2 - 8.

[5] de Pauw, I., Karana, E., and Kandachar, P. (2012): Nature-Inspired Design Strategies In Sustainable Product Development: A Case-Study Of Student Projects, in: Proceedings of the 12th International Design Conference DESIGN 2012, 787-796.

[6] Bjørn, A. and Hauschild, M. Z. (2011): Cradle to Cradle and LCA – is there a Conflict?, in: Glocalized Solutions for Sustainability in Manufacturing: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, J. Hesselbach and C. Herrmann, Editors. Springer Berlin Heidelberg. p. 599-604.

[7] Yin, R. K., (2009): Case Study Research: Design and Methods, Applied Social Research Methods Series, Vol 5, Applied social research methods, ed. Thousand Oaks: SAGE Publications, Inc.

[8] Thomas, G., (2011): How to Do Your Case Study: A Guide for Students and Researchers, London: Sage Publications Ltd.

[9] Hansen, K., (Nov. 2012): Personal communication on C2C-tools included in the C2C-Designer training at EPEA Hamburg.

[10] Braungart, M., (Nov. 2012): Personal communication on research findings.

[11] McDonough, W. and Braungart, M., (2002): Cradle to cradle: remaking the way we make things, New York: North Point Press.

[12] Internationales-Design-Zentrum-Berlin. Kriterienmatrix zum Bundespreis Ecodesign. Access date 26-11-12; Available from: http://www.bundespreis-ecodesign.de/downloads/859/Kriterienmatrix_A3.pdf.

[13] Bjørn, A. and Hauschild, M. Z., (2012): Absolute versus Relative Environmental Sustainability, in: Journal of Industrial Ecology, Vol. Early view.

[14] van Hemel, C. and Cramer, J., (2002): Barriers and stimuli for ecodesign in SMEs, in: Journal of Cleaner Production, Vol. 10, Issue: 5, p. 439-453.

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i Cradle to Cradle® and C2C® are registered trademarks held by EPEA Internationale Umweltforschung GmbH and McDonough Braungart Design Chemistry, LLC.

ii EPEA refers to 'continuous loops' instead of 'closed loops', to emphasise that the materials do not necessarily need to be applied for the same products in the same company, but can be used again at a similar quality level for different purposes as well.

iii In this paper, sustainable product development is defined as design aimed at the development of products that are beneficial to people, planet and profit.

Aligning Product Design Methods and Tools for Sustainability

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Abstract

More thorough evaluation of energy and material efficiency of manufacturing operations are needed to face advancing environmental requirements and to maintain competitiveness. For evaluation, the design of a product and its manufacturing operations need to be considered simultaneously. This paper will discuss how design for environment approach can be used in integrating these phases of the product lifecycle for improving sustainability. For effective application of design for environment tools, more company-specific key goals and process knowledge are needed in addition to generic set of good practices Life cycle analysis based on simulation enables a designer to compare different design alternatives with higher accuracy. Also the needed data to perform the evaluations is discussed.

Keywords:

Design for Sustainability; Life cycle engineering; Product lifecycle management

1 INTRODUCTION

Minimizing negative environmental impacts and environmental awareness as essential parts of business practices require insight how to achieve the set targets in practice. Products should be designed by considering their life cycles and by understanding the wide effects that a product will have over its life cycle. The key aspect of sustainable design is the notion that design-related environmental factors can be externalized only rarely, and that they should always be considered while designing the product. As designing a manufactured product and considering its life cycle impacts in wide context, thorough understanding of the external effects of the product is needed, and the question turns to how design methods can be useful when designing more sustainable products. As discussed in this paper, there are no simple solutions for a complex question, such as how to become more sustainable, in terms of economic, environmental and social performance.

The purpose of this paper is to show how the goal of sustainable manufacturing cannot be reached without considering multiple other problems as well. The aim is not to cover all environmentally design related knowledge into one, but to demonstrate through literature review how different components are necessary especially when trying to develop and design more sustainable products and estimate their impacts through manufacturing and lifecycle.

2 SUSTAINABILITY PRESSURES IN PRODUCT DESIGN

Business impacts of resource depletion and ever-increasing competitiveness pressures motivate the search to understand and even to control all resource flows in a systematic way over defined product lifecycles. Whether the pressure is imminent or likely to emerge in the foreseeable future, aligning product development efforts with the business interests are joined tasks. It is certain that sustainability issues can't be avoided, but as sustainability may not yet have been defined clearly enough for it to be useful in the context of product engineering, motivating design efforts calls for appropriately defined targets and sustainability indicators.

Environmental aspects of design activities range from the view of absolute limit of resources as a wall, to the view that limits can be avoided by innovation, and that new technologies may even eliminate the need for any specific scarce resource [1,2]. Sustainability efforts aiming to maintain the current state of resource use, or applying measures to prolong it, can't be seen as sufficient design targets for absolute sustainability. Instead, further efforts to conserve resources, and the goal of advancing the sustainability of technical systems for the good of humans and the environment, should be included in design efforts as well [3]. Absolute sustainability, which should be the ultimate goal of production, represents a massive leap in business models, in comparison with the rational continuous improvement. Regardless of the paradigm on what the limits of growth are based, it can be agreed that continuing with the current snapshot of industrial activities and resource usage, some form of a limit in growth will be reached within the perceivable future.

As the limits of sustainability are always more or less arbitrary and artificial, total sustainability based on comparison to limit values is not a feasible solution. Formulating the question whether a given product is sustainable in an absolute way, or if it is sustainable when produced and used in limited numbers, will point the question to relative sustainability. Tanzil & Beloff [4] remind that the terms “indicators” and “metrics” should not be mixed but used appropriately with the proper scope in mind. However, as an engineering solution, product life cycle analysis, added with verifiable impact metrics, is the only way to measure and compare the sustainability performance on localized scale. As every company operates with different set of limitations and goals, the interesting metrics are also specific for every individual company [4].

Sustainability as an emerging megatrend [5] and a buzzword has gained quick public attraction due to reports on human imposed climate change. Environmental resources in general are at the core of sustainability, but other aspects need to also be considered to keep the term sustainability valid. Labeling products as environmentally beneficial or sustainable is certainly appealing for manufacturers, but differences in assessment methods and unknown uncertainty often make such claims invalid [6,7]. Single measures to manage sustainability issues will lose their credibility if they are unable to show and prove tangible and specific results, and more specific claims are now required in US consumer-targeted product labels [8]. As Lippiat [9] puts it, “a product is claimed to be “green” because it has recycled or bio based content, or criticized of not being green because its manufacture contributes to air pollution. These single-attribute claims may be misleading because they ignore the possibility that other life cycle stages, or other environmental impacts, may yield offsetting impacts."

To achieve a sustainable product, it is necessary to define the goal and methods in separate ways. When trying to evaluate the sustainability performance of a product, the question is that how a metric can be compared to other internal processes, then how with other identical sectors, and ultimately, how can it be made sure whether the number indicates sustainability at all? Umeda et al. [10] note that even though there are a lot of studies to address environmentally conscious product design, such as design for recycling, remanufacturing/reuse, maintenance etc., such methods concentrating on specific targets instead of the whole product life cycle do not necessary help a product to be more sustainable. DfX aims to incorporate environmental considerations into product and process design, and Design for Environment (DfE) can be particularly applicable to remanufacturing as seen through developments including the design for recyclability or reuse [11]. These DfE approaches, as a single target, usually will not support the holistic aspects of product life cycles [12]. Various concepts and Design for X methodologies have been proposed to support life cycle design, as described by [12].

Design for Sustainability should be seen as discipline in which known methods and knowledge of impacts are used to assist informed design decisions through knowledge aggregating analysis, and as capturing and leveraging relevant information flows within and between organizations. However, as discussed in this paper, not enough of the goals is understood or considered to make DfS attractive yet. Many of environmental issues are not isolated, but are rather interconnected in complex ways, and integrating different aspects is challenging [13]. The problem is combining a set of narrow tools to the extremely wide scope of environmental impacts. Complexity, uncertainty and ambiguity are inherent features in sustainability domain, and without commonly set guidelines, claims about sustainability are not adoptable. To date, lack of efficient consensus about sustainability goals makes also the development of standard reference methods either insufficient or unpractical for wide industry adoption. Useful sustainability indicators should also be viewed as dynamic due to continuous change in operating environment, materials supplies, recyclability solutions and integration issues.

The objective of life cycle design is to maintain corporate profits and social welfare while minimizing resource consumption and waste generation during the entire life cycle [14]. Concept of Systems engineering calls for understanding enough about a problem and its context before trying to solve it. Life cycle engineering must be able to confront complex issues, such as avoiding the increased use of resources in a more efficient way, as known as the rebound effect [14] or Jevons' paradox [16]. In order to establish the sustainable product life cycle systems, resolving such conflicts and trade-offs among numerous design aspects is required [10].

To help getting the most benefit of sustainability efforts, the best ways to contribute the development of more sustainable products that have been found needs to be communicated better. Design and engineering as the root source of competitiveness should not be wasted or incapacitated by giving burdensome ambiguous tasks, but rather problem-specific solutions work the best. Therefore, the question of what design methodologies are applicable is more of a question of how to use and to align design efforts in the most efficient way to target the most efficient improvement opportunities, and how to align the existing business model with environmentally neutral or positive impacts.

3 DESIGN METHODS SUPPORTING SUSTAINABILITY

Environmental management methods, supported by standards, such as the ISO 14000 –series [17, 18, 19], help to view sustainable products as a result of process excellence, rather than a design task that can be added into design process as a new layer. The view of design as a part of total sustainability, instead of sustainability as a part of design [20, 21], makes it necessary to understand sustainability in its proper context of product life cycle impacts. Successful efforts towards sustainability call for engineers' skills and supporting education and professional development [22]. The proper level, at which an engineer must understand sustainability, depends of the product category context. The basic concepts that engineers must consider, such as life cycle impacts and interdependence of systems, reflect the need to formalize these requirements in accordance to company-specific variables.

Environmentally aware design of products means that engineers need to be able to make decisions involving value judgments. Corporate policies should guide making such tradeoffs, but as Groche et al. [21] point out, the conventional ways to introduce design solutions are still based strongly on experience-based approaches. As in the context of configurable systems designs, and arguably also in sustainable design, most practitioners look for tools rather than theories, even if the phenomenon is ill defined [23]. Small and verifiable steps towards sustainable products are the most appealing, but the key is to find such measures that can effectively improve product sustainability.

3.1 Targeting Sustainability with Design Processes

Sustainability considerations affect all phases from need recognition to production, as, for example, in the integrated product development process described by Andreasen and Hein [24]. Transition towards sustainability should not affect product design processes themselves, such as VDI 2221, or a stage-gate –approach [25], but the changing design criteria influence design decisions in detailed way.

Design for Sustainability (DfS) differs from other DfX methods as a way to understand the product design in the context of wider systems, instead of clearly defined target. Seeing design as a cyclic process becomes the cornerstone of understanding the limits of design efforts for sustainability. As the overall sustainability of a product can be analyzed only as the product acting as a part of a larger system, iterations based on life cycle analysis that is made after a system is designed will be very difficult. Therefore, DfS can't be seen as additional layer of design evaluation screen, unlike perhaps as in design for assembly or design for manufacturability. Design for sustainability is related to broadening of the design paradigm from total quality systems and lean product development. Simulations based design analysis may be the only way to validate the sustainability of design decisions throughout the intended lifecycle of the product. Sustainability will continue to highlight the need and importance of adequate goal definition and to include the design of the life cycle in the early phase of design processes.

As design quality can be improved by increasing the inputs available for each individual designer, as well as the knowledge available for all design team members, sustainability related questions will benefit from team efforts. Individual knowledge about sustainability at conceptual and practical level is prerequisite for aggregation of useful knowledge from information exchanges between people within and between organizations. Therefore, random pieces of information and information exchange that in general support innovation will not be useful in improving product sustainability.

Creativity is needed in sustainable design, and a wider understanding of business opportunities, such as service-oriented approach, must also be kept in mind [26]. Sustainability innovation may occur outside the product and its design features to form new sustainable business models for more efficient product and resource use. Design constraints and innovation as a source of sustainable design will not always reflect the position of the control that engineering has over product lifecycles. It is also premature to state that innovation can act as basis for both economic competitiveness and sustainability [27], as it is difficult to point exact areas where efforts should be focused. However, complex life cycle design expands the impacts beyond the design department, and can lead to complicated interactions, which also need to be understood within product design.

Formalized design methodologies seem to be more useful for inexperienced product developers than for experienced, which could also be caused by unique nature of every development project [28, 29]. Reinertsen [30] notes that repetitive product development processes should in general be avoided to maintain learning which will make future developments better. This leads to notion that checklist-based design methods can be used only for a limited number of goals. Overall lifecycle impact assessment will require extensive efforts for creating an appropriate checklist, and as such, checklists based methods have only limited use.

Design efforts attempt at hitting a moving target, and as a design methodology should help in allocating design resources to adequate part of product design, in lifecycle engineering this should translate into manageable design tasks. In sustainability, the changing of design targets and goals over long period is also certain, as, for example, more information about different materials becomes available and the business scenarios develop. Environmentally conscious design struggles with the complexity and ambiguity mix of environmental science, business practices and political (regulatory) views of what things should be considered at a given period of time. Although ultimate constraints are guided by regulations and consensus standards, these developments do not represent the favorable business opportunity scenarios of incorporating sustainability into core business practices.

Within the total sustainability paradigm, informed decisions must be made also on other aspects than design or manufacturing related attributes. Therefore, short term product redesign projects for sustainability can only help to achieve limited or temporary results, such as material substitutions or gaining sustainability improvements resulting from the use of other DfX methods. The question of where to focus on depends on individual products in their individual operating scenarios. Remanufacturing, for example, may be a great business model for some type of products, but in others some other way of material and/or energy recovery may be better suited. In order to achieve cradle to cradle cycles for materials, the materials should be technically or biologically viable [31], and this depends on the business model of the product. Some industries can choose only the minimal negative effects, while some may develop even further to creative positive trade-offs.

The complexity of the problem of sustainability leads to balancing of manageability of design efforts with Life cycle impact assessment including considering the whole supply chain and location of operations. Sustainability at the level of local impact analysis and the social context of product life cycle impacts are beyond design process related feasibility, even if they are at least partially affected by design decisions. However, design for sustainability as combination of operational excellence and proven design processes is the basis for successful generation and adoption of design goals that lead to sustainable products. Manageable ways to incorporate these opportunities and limits of full life cycle analysis into design process have not yet been introduced.

3.2 Metrics and Tools Approach

Several tools and indicators have been developed to assist environmental performance evaluations, ranging from checklists to complex life cycle assessment, as listed, for example, in [32, 33]. There are no commonly approved aggregated metrics that can be implemented accurately and universally. Statements and indicators of the sustainability of a product, such as its ecological footprint, is merely a means to draw attention for the problem [34]. Reliability of source data used for indicators becomes a major issue when metrics are based on large amount of data, as the source data itself is variable [3]. Better allocating of data of environmental impacts is also needed to support reliable lifecycle assessments [35], which in turn should reflect into more accurate design evaluation practices.

The use of metrics calls that different companies use same metrics in identical way, and therefore requires a governing authority. The need of regulatory bodies is twofold, as they might give the impression that the underlying problems could be externalized [34]. Validated standards based approaches should help compiling large amount of data into sustainability analysis. As life cycle is unique for every batch of products, the support of IT depends on models that can be compiled in standardized way.

For analyzing lifecycle impacts, the lifecycle needs to be described or even designed in documented manner. Product lifecycle management (PLM) provides support for collecting and retaining sustainability related data, but wide adoption and effective operation depend on developing sustainability based requirements, as well as ways to process collected data. Material substitution and recycling requirements are examples of steps where IT can support design decisions. Further scenarios might include materials that are engineered for specific use. [36] Choice of material is also benefitted by more detailed knowledge exchange between manufacturing and design processes at the materials science level [37] Sustainability calls for more detailed documentation of design decisions, in order to enable more efficient reuse of existing design features. To realize any methodology for designing sustainable products, PLM tools are necessary, but not sufficient by themselves.

It should be noted that gathering and analyzing data is not enough or helpful in itself for solving ways how to improve the sustainability of any product, process or activity. Major issue when performing lifecycle analysis is that their results come at a too late phase and too much effort for effective design revisions before product launch. Accurate data about the environmental impacts of production can be gathered after a product is finished. The amount of detailed data and the uncertainty of statistical manufacturing or materials data is useless a reference point is defined, which in itself is the key of any metrics based approach.

As sustainability analysis can be done at relatively late phase of the design process, and considering that it is practically impossible to capture all life cycle aspects of sustainability, design optimization by simulation may prove to be useful. Complexity makes it unlikely that an alternative design option is better by all desired metrics, but rather it is an effort to balance trade-offs between systems and can act as guidance in helping to optimize desired metrics. When searching for methods to incorporate product lifecycle sustainability into an existing product design process, one of the key decisions is decision of what level of optimization is searched for.

Design for sustainability will benefit from further development of decision guidance tools and metrics, once their functionality and databases can be considered to be transparent enough. Similarly to design analysis tools, such as Finite Element Method or Computational Fluid Dynamics, the science behind these tools or metrics must be understood for being able to use the tools for valid results. In many cases an experienced engineer can use such analysis tools to verify experience and skills based design decisions. Any tool intended to help designing more sustainable products should be accepted for use in their targeted context and the use of sustainability analysis tools should be documented as a part of the design documentation.

It is difficult to analyze or check the context related life cycle impacts and complex interdependencies of different sustainability aspects, as systematical approach of how to set reference values for sustainability metrics or indicators is not defined. Because of lack of reference data, even with elaborate and exhausting collection and analysis of product environmental performance data, the dynamic nature of the concept sustainability will make it necessary to evaluate used metrics and tools continuously.

3.3 Linking Sustainability with Manufacturing

In the context of manufacturing, sustainability means the ability to produce specific product endlessly, considering the wide impacts of operations and the circulation of resources at the rate of production. Incorporating manufacturing-induced properties into product design is a potential opportunity to improve also profitability [21]. Other sustainability improvement measures made in parallel with manufacturing optimization include assembly analysis and detailed view of component ingredients. Manufacturing operations related material and energy flows can potentially be measured to help decision-making process, but a method to transfer knowledge from manufacturing optimization needs to be developed. Instead of a set of feasible design goals, which are transferred to product design, product and process design become more interconnected.

Manufacturing process optimization itself will require detailed models and simulations, and this is the key to provide valuable information for design solutions, and makes simulations based analysis possible. In this sense, sustainability is parallel and gains support with manufacturing operations competitiveness efforts, as pointed in [38]. For simulation to be a realistic solution, a way to gain other improvements as well is necessary. Improved energy and material use efficiency can contribute to competitive advantage and life cycle analysis should also help to estimate total production costs more accurately, which is often complicated at early design phases [39].

Although improving sustainability through manufacturing process optimization is far from simple, it is appealing because of manageable number of variables, and as relatively low uncertainty can be achieved by measurements of local manufacturing operations. Therefore simulation can be used effectively to validate design requirements in the scope of manufacturing requirements instead of full life cycle optimization based business case. Manufacturing analysis through simulation can help solving decisions whether the use of a specific material needs to be balanced out through its lifecycle, or if it should be eliminated completely. Work in the field of improving the sustainability of manufacturing is active and ongoing research at the National Institute of Standards and Technology [NIST], USA, targets also to promote the feasibility of sustainability analysis through participating in standards development activities.

Assembly analysis and manufacturing process optimization may be parts of full life cycle simulation that can be managed, but in order to be able to simulate life cycle impacts, various assumptions must also be made to be able to run the simulations. Estimates of energy and material flows will become more accurate as design process is completed. Context-specific production cases, which reflect the need to design parts exploiting the optimum processing capabilities of planned production equipment, require that manufacturing process planning is connected with engineering design tools. Usable knowledge about possible manufactured product sustainability improvements is limited before the characteristics of manufacturing equipment can be formulated in a uniform way.

4 CONCLUSIONS

From high-level talk about improving the sustainability of a product, it is hard to derive direct recommendations for actions how to design more sustainable products. It is also hard to act upon those recommendations, if the economic reasoning behind actions is not solid. Engineering decisions require reasoning and argumentation that is valid, and contributions to sustainability should be also within the domain of engineering. The ultimate goal of absolute sustainability is not achievable without significant change also in consuming habits. Changes in product preferences are reflected to design decisions over time, but without external pressure, feasible engineering changes are limited in number and scope. As sustainability goals are disputed, it is difficult to claim one design technique to be better than another. This does not make development of design methods wasted effort, but it emphasizes the need to understand and collect information of interrelated life cycle phases of a product.

In product design science, seeking completely new methodologies is not necessarily the right way to go to improve the environmental performance of products. Whatever the path is to minimizing negative environmental impacts, the overall environmental performance depends upon the ability to understand actions within their larger contexts, and the ability to optimize the flows within product lifecycle. Existing and proven design processes can be used, and any chosen design method should be linked with the designed life cycle of a product. Product development activities need to be more tightly coupled with overall business decisions and the social environment of the physical locations of the product manufacturing company. Any single product development methodology is not sufficient to solve or to contribute significantly to the environmental performance of a product or product category. It must also be remembered that it is unlikely that the designing and production of any given set of products is in itself responsible for significant environmental impacts or hazards in total. An environmentally sustainable product cannot be designed in separation of knowledge about the wider part of the lifecycle of the whole product system, and therefore a larger portion of analysis tools should be integrated to share and contribute to same sustainability metrics.

A product design process that aims to minimize environmental impacts will absorb the boundary between design and manufacturing, making it necessary to design the manufacturing operations in parallel with the product features. Understanding, comparing and communicating the detailed activities and outcomes of a factory is a key factor for comparing the environmental performance of manufacturing operations. Currently factory operations are mostly viewed as a black box by most environmental models, but as simulations based impact analysis of factory operations make it possible to base environmental impact metrics on analysis instead of estimations, the detail level of simulation models could be increased to benefit sustainability. Further development of ways to represent and optimize manufacturing operations will also help to design products that utilize the capabilities of available machinery in the most efficient way.

Tools supporting design tasks require integration of information also from areas outside of traditional design interests. Integrating supply chain as part of product life cycle is not yet supported by common tools. Further research is needed to understand interactions in the whole supply chain. Together with life cycle consideration, the common design processes and Design for X methodologies can incorporate sustainability views as extension of design requirements. With the combination of supporting tools and standardized ways to interpret and allocate impacts, the existing iterative design processes remain the basis for environmentally benign design efforts, as tools function as decision guidance systems. Existing tools and metrics, supported by various analysis tools complementing PLM systems, must also be developed further in parallel with the harmonized descriptions how to use them consistently. Further development of different metrics is also needed, even if full life cycle control of materials can be achieved. The dynamic nature of sustainability should also encourage reviewing the used metrics and the validity of data collection periodically.

Even though different tools that help making design processes aiming for sustainability more manageable, engineers still need to understand the underlying mechanisms of environmental issues before using any methodology, tool or metric. Principles that make more sustainable designs possible can’t be externalized from engineering routines, to functions such as environmental management units. Setting up environmental management policies help to target and track activities appropriately, but the proactive tasks will remain among product and production engineers. Deep understanding of materials and production must be found within engineering department, and design tools and processes can be leveraged usefully only after sufficient definition of goals. As the question of sustainability is complex and relative, key definition is to determine the level of appropriate but adequate targeted measures, whether minimizing negative effects or aiming for overall positive trade-offs.

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6 REFERENCES

[1] Meadows, D. (1972) The Limits to Growth. A Report for the Club of Rome's Project on the Predicament of Mankind, Universe Publications.

[2] Rees W. & Wackernagel M. (1996) Urban ecological footrprints: Why citiescannot be sustainable – and why they are a key to sustainability. Environmental impact assessment review 1996;16;223-248

[3] Graedel T. E. & Klee R. J. (2002) Getting serious about sustainability. Environmental Science and Technology 36, 523-529.

[4] Tanzil D. & Beloff B. R. (2006) Assessing Impacts: Overview on Sustainability Indicators and Metrics. Environmental Quality Management, Summer 2006, 41-56.

[5] Lubin D. A. & Esty D. C. (2010) The Sustainability Imperative. Harvard Business Review, May 2010

[6] Kral C., Huisenga M., & Lockwood D., (2009) Product Carbon Footprinting: Improving Environmental Performance and Manufacturing Efficiency. Environmental Quality Management, pp. 13–20.

[7] Campanelli M., Berglund J. & Rachuri S. (2011) Integration Of Life Cycle Inventories Incorporating Manufacturing Unit Processes. Proceedings of the ASME 2011 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference. IDETC/CIE 2011. Aug. 28-31, 2011, Washington, DC, USA

[8] US Federal Trade Commission (2012) FTC Issues Revised “Green Guides”. Available at: www.ftc.gov/opa/2012/10/greenguides.shtm.

[9] Lippiatt B. C. (2012) Science-Based Metrics for Product Sustainability Assessment. NIST Publications (USA). Available at http://www.nist.gov/manuscript-publication-search.cfm?pub_id=907286

[10] Umeda Y., Fukushige S., Kunii E. & Matsuyama Y. (2012) LC-CAD: A CAD system for life cycle deisgn

[11] Ijomah W. L., McMahon C. A., Hammond G. P. & Newman S. T. (2007) International Journal of Production Research, Vol. 45, Nos. 18–19, 15 September–1 October 2007, 4513–4536

[12] Niemann J., Tichkiewitch S. & Westkämper E. (editors) (2009) Design of Sustainable Product Life Cycles. Springer. 210p

[13] Kleindorfer P.R., Singhal K. & Wassenhove L.N.V. (2005) Sustainable operations management. Production and Operations Management. Vol. 14, No. 4, pp.482–492.

[14] Umeda Y., Nonomura A., Tomiyama T. (2000) Study on life-cycle design for the post mass production paradigm. AI EDAM Vol. 14, Iss 2 April 2000, pp 149-161

[15] Herring H. (2006) Energy efficiency—a critical view. Energy 31 (2006) 10–20

[16] Jevons, William Stanley (1866). The Coal Question (2nd ed.). London: Macmillan and Co..

[17] ISO 14001 (2004) (standard) Environmental management systems - Requirements with guidance for use

[18] ISO 14040 (2006) (standard) Environmental management - Life cycle assessment - Principles and framework

[19] ISO 14044 (2006) (standard) Environmental management - Life cycle assessment - Requirements and guidelines

[20] Dewberry, E. & Fletcher, K. (2001), Demi: Linking Sustainability with Design. Proceedings of the European Round Table on Cleaner Production, Lund, May 2001.

[21] Groche P., Schmitt W., Bohn A., Gramlich S., Ulbrich S. & Gunther U. (2012) Integration of manufacturing-induced properties in product design. CIRP Annals - Manufacturing Technology 61 163–166

[22] Huntzinger D. N., Hutchins M. J., Gierke J. S. & Sutherland J. W. (2007) Enabling Sustainable Thinking in Undergraduate Engineering Education. Int. J. Engineering Education Vol. 23, No. 2, pp. 218-230.

[23] Pulkkinen A. (2007) Product Configuration in Projecting Company: The meeting of Configurable Product Families and Sales-Delivery Process. Publication 712, Tampere University of Technology. 201p

[24] Andreasen M. M. & Hein L. (1987) Integrated Product Development. IFS Publications Ltd. / Springer-Verlag, London. 1987.

[25] Copper R. G. (2001) Winning at New Products- Accelerating the Process from Ideas to Launch. New York, Perseus Publishing. 425p.

[26] Rachuri S., Sriram R. D., Narayanan A., Sarkar P., Lee J. H., Lyons K. W. Srinivasan V., Kemmerer S. J. (2011) Summary of the NIST workshop on sustainable manufacturing: metrics, standards, and infrastructure. Int. J. Sustainable Manufacturing, Vol. 2, Nos. 2/3, 2011

[27] Coenen L. & Lopez F. J. D. (2008) Comparing systemic approaches to innovation for sustainability and competitiveness. DIME International Conference "Innovation, Sustainability and policy" 11-13 September 2008, GREThA, Univ Motesquieu Bordeaux IV, France.

[28] Ringen G. & Holtskog H. (2011) How enablers for lean product development motivate engineers. International Journal of Computer Integrated Manufacturing, 2011, 1–11, DOI:10.1080/0951192X.2011.593046

[29] Repenning, N.P., 2001. Understanding fire fighting in new product development. The Journal of Product Innovation Management, 18, 285–300.

[30] Reinertsen, D.G. (1997) Managing the design factory. New York: The Free Press

[31] McDonough. W and M. Braungart. Cradle to Cradle: Remaking the Way We Make Things. New York: North Point Press, 2002

[32] Bovea M. D. & Wang B. (2003) Identifying environmental improvement options by combining life cycle assessment and fuzzy set theory. International Journal of Production Research, 2003, vol. 41, no. 3, 593–609

[33] Feng S., & Joung C. B., (2009) An Overview of a Proposed Measurement Infrastructure for Sustainable Manufacturing. The 7th CIRP Global Conference on Sustainable Manufacturing

[34] Moffatt I. (2000) Ecological footprints and sustainable development. Forum: the ecological footprint. Commentary, Ecological Economics 32, 359–362

[35] Sutherland J. W., Rivera J. L., Brown K. L., Law M., Hutchins M. J., Jenkins T. L., Haapala K. R. (2008) Challenges for the manufacturing enterprise to achieve sustainable development. 41st CIRP Conference on Manufacturing systems, Tokyo, Japan, 26-28 May 2008

[36] Shipp S. S., Gupta N., Lal B., Scott J. A., Weber C. L., Finnin M. S., Blake M., Newsome S., Thomas S. & Samuel T. (2012) Emerging Global Trends in Advanced Manufacturing. Institute For Defense Analyses. 248 p.

[37] Lenau T. & Alting L (1996) The Missing Element in Design for Manufacture. CIRP Annals – Manufacturing Technology 45(1):105.

[38] Järvenpää E., Lanz M. (2011) KIPPcolla - Knowledge Intensive Product and Production Management from Concept to Re-cycle in Virtual Collaborative Environment. Tekes Digital Product-Process Programme Final Report.

[39] Mauchand M, Siadat A, Bernard A, Perry N (2008) Proposal for Tool-based Method of Product Cost Estimation During Conceptual Design. Journal of Engineering Design 9(2):159–172.

Managing Eco Design and Sustainable Manufacturing

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Abstract

This paper studies the principles of eco-design and sustainable manufacturing and alternative strategies to change course towards sustainability and sustainable development by reviewing and evaluating the main drivers, barriers, benefits and risks involved such strategies and their implementation in UK manufacturing industry. This paper also examines the application of sustainable practices in manufacturing industry for eco design and sustainable manufacturing in the food and drink sector. A questionnaire based survey was conducted with 258 manufacturers in the UK to examine the business case for eco design and sustainable manufacturing in terms of the drives, barriers, advantages and risks associated with the move towards sustainability and sustainable development and the business case for implementing sustainability strategies. In terms of the findings, compliance with regulations and risks reduction were the most important drivers and benefits amongst the manufacturing companies as a whole. The survey results also showed that the main barriers faced by the overall manufacturing industry were most importantly high implementation costs, followed by weak justification for investment and lack of stakeholder and customer awareness. On the other hand, concerning the findings of food and drink sector, there is more regard and consideration for the regulation compliance in this sector compared to the rest of the manufacturing areas, also, there is a higher legal and financial risk in the business environment for this particular sector; in addition, market opportunities is considered one of the most important drivers for the food and drink sector.

Keywords:

Eco-design; Sustainable Manufacturing; Drivers; Barriers; Food and Drink

1 INTRODUCTION

There is a significant growth in the manufacture, technology and development of products alongside with a decrease of the resources and degradation of the earth, so, in recent years it has been an awareness increase on the environmental impact. There are numerous aspects that have to be taken into consideration in order to regulate and preserve the earth such as pollution, energy use, resource use, waste disposal and reduction, among others, thus the earth necessitates sustainable solutions.

This paper will address the aspects regarding the manufacturing and design within a sustainable approach and the reality that UK manufacturers are facing. Eco Design and Sustainable Manufacturing have a great reliance in different principle that have to be considered as the primary framework to deploy properly their different strategies, alongside with a set of techniques to carry out the tasks involved. These sustainable approaches are aided by different drivers that allow a higher level of interaction between their line of work and the environmental aspects; however, the implementation needs to overcome a set of barriers affianced in the performance towards an eco-design and sustainable manufacturing.

In addition, in the development of the research will be investigated the state of art of the different enablers and barriers through the manufacturing industry in order to set background knowledge of the current practices. Hence, surveys will be conducted in the different sectors of the industry for further analysis of the current practices in order to disclose the perspectives, welfares or the difficulties encountered in the industrial performance in UK, with a special regard of the food and drink sector in order to establish a comparison with the other sectors. In the followings it will be given an overview of eco-design and sustainable manufacturing.

2 ECO-DESIGN: DEFINITION AND PRINCIPLES

Eco-design is a philosophy based on the concern of the environmental and economic performance of a product over its lifecycle (Basile, 2002). According to Fiksel (1996), eco-design could be defined as “the systematic consideration of design performance with the respect to environment, health and safety objectives over the full product and process life cycle”. The conception of Eco-design is embedded in the practices related to sustainability; and also, it is focused is the enhancement of the product development approaches in the way that the environmental loads are considerable reduced (Karlsson R., Luttropp C., 2006). There is no blue-print or any establishment of specific set of principles that entirely define eco-design practices. In the followings some principles will be illustrated in order to disclose just to offer an overview. Some of those principles applied for Eco-design are:

Meet the society requirement, respect the culture and believes.
Consider reusability, recycle and remanufacturing at the early stage of the design.
Conscious material selection with less environmental impact.
Optimisation of energy.
Reduce the material use.
Contemplate the recycled and the recyclable materials.
Design for durable and quality product.
Ethics and policies
Design for satisfaction efficiency
Innovation

2.1 Eco-Design Strategies

In the past decades eco-design strategies could be considered as reactive, since they aimed to tackle the “effects” rather than "causes", with the main premise of rigorously comply with guidelines and reducing burdens, and not being able to accomplished a significant impact-reduction (Olsen). The following strategies have aided from a proactive approach, focusing mainly to look at the root cause of the unsustainable aspects in organizations and the impacts from the whole product life; some of the strategies briefly explained below come from the manufacturer's survey responses:

2.1.1 Selection of Materia

Several variables has to be taken into account in the design process, the material selection should not only consider the environmental aspects, it also must recyclability, consider the configuration of the final product, the context in which it will be used, its end-life states, and the how profitable it could be.

2.1.2 Resource Use Reduction

The definition of an ideal proportion of the material use and the supply of renewable or non-renewable materials regardless on its nature (mineral or biotic) are crucial to control and manage the environmental impact regarding the materials employed in the creation of products (EspDesign, 2004). The resource consumption is not only about the physical materials employed, but total ecosystems and cycles that control the conditions of the earth (Esty and Winston, 2006)

2.1.3 Design for 3R

Researchers are taking a new dimension regarding the involvement of the design in the life cycle of the product. Since sustainable design has come as a basic procedure throughout the product's supply chain, its practices must be strongly focused in a wider view where the end of life phase gets a great deal of thought using reduce reuse and recycle as means towards sustainability (Fiksel, 2009) (Ljungberg, 2007).

2.1.4 Modularisation

Often at the design stage, products are considered as a set of segments conceived to join together in order to deploy several functions. This approach permits the creation of customised products from the combination of modules, and also allows the upgrade and alteration to fulfil the consumers' changing requirements (Tsenga, 2008).

2.1.5 Design Research

This strategy primary intent is the production of research that leads to innovations and sustain the development of such products and find the most suitable manner to low the environmental impact. Design research comes across with findings that are fed back into further cycles of innovation within the design process (Ljungberg, 2007). (Bereiter, 2002).

2.1.6 Develop a Safe and Healthy Working Environment

By the creation of a safe and healthy working environment it minimizes work-related health risks for employees, society, customers and suppliers; which will translate into more productive and sustainable results (Selinger, 2008)

2.1.7 *Design for Energy Efficiency*

Design for Energy Efficiency aims to consider the energy required by the product, not just during its use, but in all phases of the product lifecycle, such as the extraction of raw materials, product manufacturing, use and disposal (Birkeland, 2002).

3 SUSTAINABLE MANUFACTURING: DEFINITION AND PRINCIPLES

Sustainable Manufacturing can be defined as the creation of goods or services that satisfy customer needs while respecting the environment and communities' wellbeing (Badurdeena, 2010). Sustainable manufacturing goes beyond the product view and plant perimeters, from extraction to disposal and recovery. This manifests itself in terms of, waste, energy use, employee and customer health and safety, community involvement, supplier development, transport or materials used for packaging, among many other areas (Hitchcock, 2006) There a several principles embedded in sustainable manufacturing; according to Alwood (2009) the principles for sustainable manufacturing are:

"Use less material and energy"
"Substitute the input material, based in the replacement of toxic for non-toxic and non-recyclable for recyclable"
"Reduce unwanted outputs: waste and pollution by the use of cleaner production technologies"
"Convert outputs to inputs in manufacturing: recycling, reuse and remanufacturing"
"Change structure of ownership and production: move from manufacturing products to providing services, reorganising supply chain structure"

3.1 Sustainable Manufacturing Strategies

Several strategies could be addressed to approach optimisations and low the environmental burden alongside with obtaining of financial benefit, some UK manufacturers have this strategies in common:

3.1.1 Waste Minimisation

This is one of the most common strategies mentioned in the literature, which basically consist in the commitment of minimisation of waste. Managing has to be taken into account to reduce the waste within the sustainable manufacturing structure. Disproportionate waste generation is a clear sign of inefficiencies inside the production procedures (Epstein, 2008).

3.1.2 Material Efficiency

Efficiency is the proportion of the output to the input out of the system. In this particular matter material efficiency could be defined as the proportion between the materials used against the raw material necessary to manufacture the product (Epstein, 2008) (Salwa, et al, 2008).

3.1.3 Resources Efficiency

This is a strategy that seeks the productive utilisation, decrease of movement and consumption of resources extract from nature. The efficiency of the resources can be measured, it can be expresses as the amount of goods or outcomes that come as a consequence of the spending of item resources (Salwa, et al, 2008)..

3.1.4 Eco-Efficiency

The main focus of Eco-efficiency is the development of the economy with a minimum effect in economy. With the utilisation of this strategy, sustainable manufacturing is able to adopt and achieve competitive prices of goods and fulfilling the community necessities with the enhancement of their living quality (Hendrik and Bidwell, 2000).

3.1.5 Clean Production

This strategy seeks the avoidance of pollution rather than end of pipe, cleaning or remediation tasks namely, the avoidance of toxic materials, usage of more clean sources of energy such as renewable energy, waste minimization among others (Epstein, 2008)

3.1.6 6R (Reduce, Reuse, Recycle, Recover, Redesign and Remanufacturing)

Since sustainable manufacturing is the basic procedure throughout the product's supply chain, its practices must be strongly focused in a wider innovation-based "6R methodology", where not only aspects like reduce, reuse and recycle but aspects such as recover, redesign and remanufacture must be considered and deployed through multiple product life cycles (Arthur, 2010) (Jayal, et al, 2010).

3.1.7 Supply Chain Integration

Due to the impact that sustainable practices has through the entire life cycle, it is imperative to deploy tactics in order to include the suppliers he cooperation and in formation collection about the effects associated with the sustainability settlements, and also, assisting the improvement in controlling all aspects of the supply chain (Epstein, 2008).

4 DRIVERS, BARRIERS, RISK AND BENEFITS OF ECO-DESIGN AND SUSTAINABLE MANUFACTURING

In the followings it will be illustrated the relevant characteristics to manage Eco-Design and sustainable manufacturing such as the knowledge of their barriers and enablers. Also, when these sustainable approaches are implemented they are capable of delivering several benefits to the organisations, although, there are some risks inherent to the application and development of these sustainable tasks.

4.1 Drivers

The motivation for the application and control of a corporate strategy that includes the three bottom line features should be driven by internal aspects, such as management commitment towards sustainable development as a main principle or by the acknowledgement that sustainable activities will derive in financial welfares for the organisations. However, usually the incentive for sustainability and eco-design operations come from external pressure from government regulations, market demands, competetors' engagements, organisation name and reputation among others. In this paper the main drivers for Eco-design and sustainable manufacturing that will be addressed are: regulations, competitiveness & brand name, market opportunities, financial benefits and environmental awareness.

4.2 Barriers

Although there are several reasons and aspects that promote the implementation of sustainable manufacturing practices and economic/ecologic design, there are also numerous obstacles that impede the proper application of such activities and strategies, therefore, this work will approach the obstacles that UK manufacturing industry are facing such as: high implementation cost, weak justification as investment, lack of know-how and stakeholders awareness of the benefits.

4.3 Benefits and Risks

A result of sustainable practices is the achievement of cost reduction by the usage of recycled materials, proper usage of raw material, energy efficiency improve logistics among others; more specifically, this lessening are clear outcomes from the optimisation of the main aspects inside the product life cycle (Plouffe, et al, 2011) Moreover, environmental products provide greater satisfaction to customers who are progressively concerned about the impact on nature, in addition, it is not always just about the reducing the environmental effects but it also simplify and prolong the life cycle, therefore, assisting in the standing out from the competitors (Borchardt, et al, 2010). In the same manner, when sustainable strategies are performed properly they generate better relations with the stakeholders, promoting fidelity, acceptance and trust. All these bring benefits whereby government licensing, contract settlement, employee involvement and community acceptance (Laszlo, 2003). However, not accomplishing in the identification of these variables will result in the decrease of stakeholder support and important consequences in the bottom line. If the environmental practices and the social responsibilities are not well addressed it might constitute a risk for investors, which could turn the back on conceding financial support or the increase of insurance expenses (Berns, et al, 2009). Furthermore, the expectation from the community in general regarding the company's behaviour is suffering changes; if a company abuses the local environment could lead to difficulties to grow operations (Esty and Winston, 2006).

5 SURVEY OF MANUFACTURING INDUSTRY

In order to analyse the Uk reality regarding eco-design and sustainable manufacturing, a survey was conducted among various manufacturing businesses in the UK during the year 2012. The survey also aimed to provide an insight into the changes needed and implementation plans for more sustainable design and manufacturing, as well as areas where business may need external. In addition, the food and drink industry will be extracted from the overall data in order to compare and contrast with the rest of the sectors. The number of manufacturing companies participating was 258, thus, the UK Office of National Statistics reported 153,510 VAT registered manufacturing business in the UK in 2008; representative of the total population. A confidence interval for the following percentage proportions found in the survey was calculated as ± 6.1% at a 95% confidence level.

Companies' Sizes: 40% of the companies surveyed had between 51 to 250 employees, 28% had less than 50 employees and 21% between 251 to 1000 employees. Companies with more than 1000 employees were the lowest proportion participating, 11%.

Responses by sector: About industry sectors represented companies that manufacture machinery, equipment and instruments is the sector with the biggest collaboration to the research with 33% of answers; in second place comes Food and Drink sector with 26% of participation. The companies out of the options we had when designing the survey were defined as others and those companies had a participation share of 16%, while Materials/Metal products had a 8% of collaboration. Energy suppliers participation were about 6%, before Consumer products sector which account for 5% of the participation share, followed closely by Petroleum/Chemical/Rub with 4%. Motor vehicle and transport has a 2% of participation, while, Wood/Furniture/Paper had a 1%. Textile and Clothes had no contribution to this survey.

5.1 Drivers for Eco-Design and Sustainable Manufacturing

Figure 1 shows that 70% of the companies surveyed claimed that legislation compliance was the most important driver. In the second place is Company brand, even though Market opportunities and Financial benefits with a 47% of answers, Company reputation with 44% comes third.

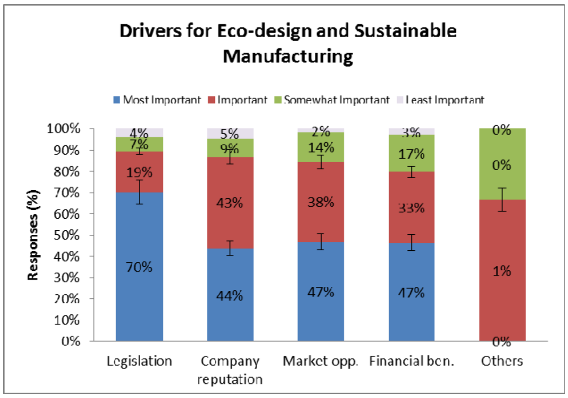


Figure 1: Drivers for eco-design and sustainable manufacturing.

5.2 Barriers for Eco-Design and Sustainable Manufacturing

Regarding the results for barriers of eco-design and sustainable manufacturing, High implementation cost/long payback time was accounted as the most important barrier with 32% of the answers; the second most important barrier identified by the companies was Weak justification as investment with 25% of votes.

In the third place, comes lack of customer stakeholder/long playback with 23% of respondents assuring that this barrier was the most important; finally, lack of in house expertise/know how came as the least relevant aspect to consider as a barrier with only 10% of interviewed companies positing that this lack of know how is the most important barrier.

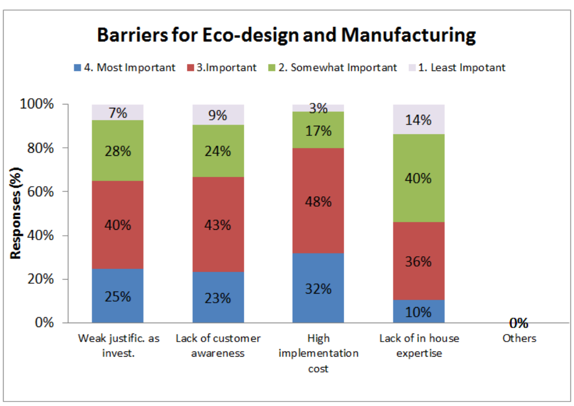


Figure 2: Barriers for eco-design and sustainable manufacturing.

5.3 Benefits of Eco-Design and Sustainable Manufacturing

Regulation compliance and risk reduction were the most important benefit identified by the companies with 57% of those responses corresponds to the most important benefit option. As the second best ranked benefits comes long term financial benefits with 39% of respondents account this benefit as the most important one.

The third place is the accomplishment of competitive advantage/ innovation with 38% followed closely by the achievement of the improvement of the reputation/stakeholder relationship with 34%.

5.4 Risks of Eco-Design and Sustainable Manufacturing

In terms of the risks from environmental and social concerns, the companies most of the companies participating agreed that the most relevant risk they undertake is the legal/financial risk and liabilities with 44% within the general responses with the perception of being the most important risk. The second place is for damage to reputation with 26% of the responses saying that this risk as the most important.

Being close to certain markets is regarded as the third most significant risk with 24% of the responses trailed by raw materials and energy supply problems with 16%.

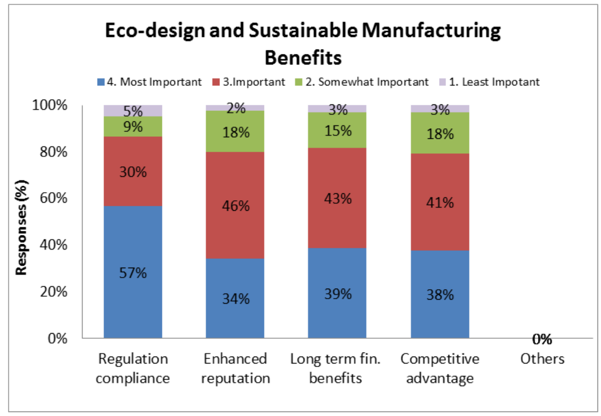


Figure 3: Benefits of eco-design and sustainable manufacturing.

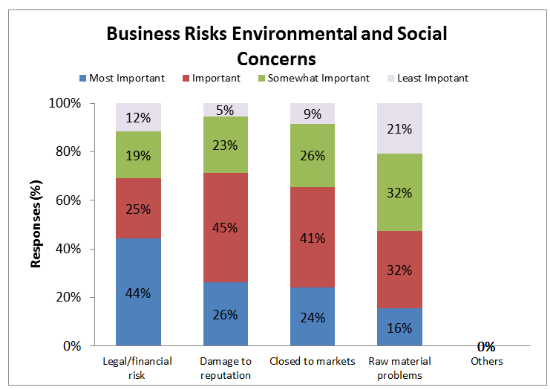


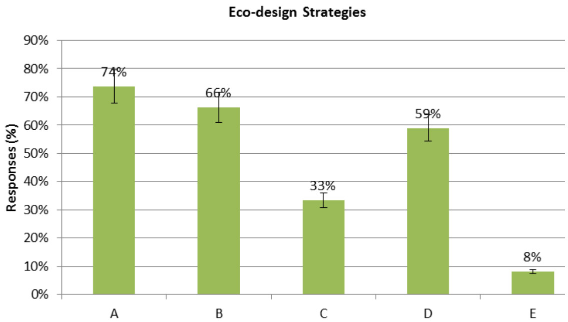
Figure 4: Risks of eco-design and sustainable manufacturing.

5.5 Eco-Design Strategies

As figure 5 illustrates the strategy most used was Design for reduce resource use with 74% of utilisation, followed by the designing for recycle/reuse/remanufacturing with 66% of usage. The third most extensively used was design for longer life holding a 59% of use. In the fourth place of the different strategy option chosen by the participants was the reduction of pollution/emission with 33%. Finally, other strategies not listed here as alternative are being used by the industry with 8% of share.

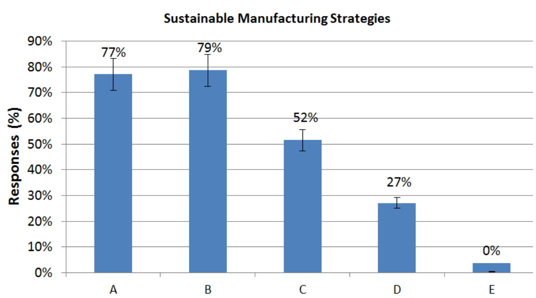
5.6 Sustainable Manufacturing Strategies

Same as the previous eco-design approach, various sustainable manufacturing were taken from the literature review and presented to the companies to collect their current practices. The most broadly used strategy was the reduction of waste and cleaner production with 79% of utilisation; in the second spot comes the usage of less raw material, water and energy with 72% of companies implementing it. Accounting 52% of strategy employment there is product stewardship, reverse logistics/close loop; no other strategy was specified by the companies participating.



A	Design for reduced resource use
B	Design for Recycle/Reuse/Remanuf.
C	Design for Longer Life
D	Reduce pollution/emission
E	Others

Figure 5: Eco-design strategies.



A	Use less raw material, water and energy
B	Reduce waste, cleaner production
C	Use sustainable, renewable materials
D	Product stewardship, reverse logistics/closed loops
E	Others

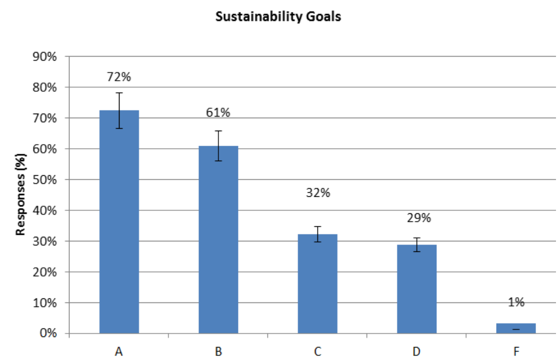
Figure 6: Sustainable manufacturing strategies.

5.7 Sustainability Goals and Objectives

In terms of the objectives in which sustainable activities are been carried, as it can be seen in the figure 7 the most common goal/objective of the companies surveyed was the measurement of the environmental footprint of Products and processes with 72%, followed by the training of employees, suppliers, clients on sustainability showing a 61% of agreement among the participants. In third place, as the most widespread objective is verifying supply chain social performance with 32% and very closely is the movement towards a service business model as a mayor goal showing a 29% of convergence. Only one per cent of the participants had a different goal among the overall responses.

5.8 Supplier Selection Criteria

Regarding the most significant factor to considering when outsourcing or choosing a supplier, the first is cost with and importance average of 3.39 and an amazing 62% of votes as the most important. Secondly, flexibility to meet new needs had a 3.12 of importance average from the participating companies but a 45% of most important votes. Thirdly, building long-term relationship comes as third with 30% of votes as most important although this strategy had more "important" selections (47%) than the second ranked (flexibility to meet new needs with 41%), and last sustainability performance as fourth and last with 16% of the votes as most important.



A	Measure the environmental footprint of Products and processes
B	Train employees, suppliers, clients on sustainability
C	Verifying supply chain social performance
D	Move towards a service business model
F	Other

Figure 7: Sustainability goals and objectives.

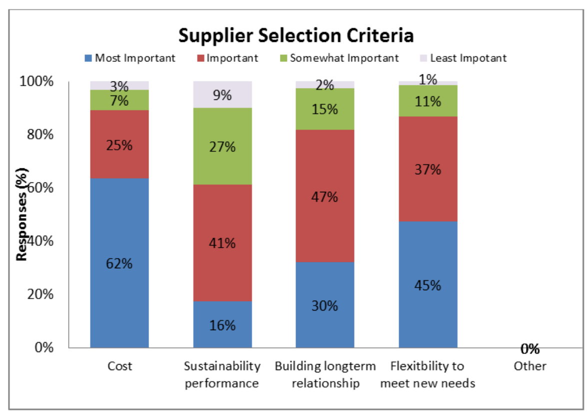


Figure 8: Supplier selection criteria.

5.9 Implementation Plan

The 45% of companies interviewed claimed to have been planning to implement sustainable strategies, the total of responses came from 107 companies; therefore, regarding the answers, 24% fitted into the group which was aiming to implement the design of cleaner and energy efficient products, in the second place is the improvement of the processes within the company with 15% of share, followed very closely by seeking ISO14000 certification with 14%.

Suppliers or partner collaboration were ticked by 13% of the companies and 11% of participant converge that they are planning to utilise lifecycle assessment. Ten our of 107 companies that represent approximately 9% of the organisation's opinion said that they were defining the sustainability strategies, while, the companies that were planning taking into account social sustainability consideration represented the 7% of the responses. Other environmental assessment got 6% of companies' usage.

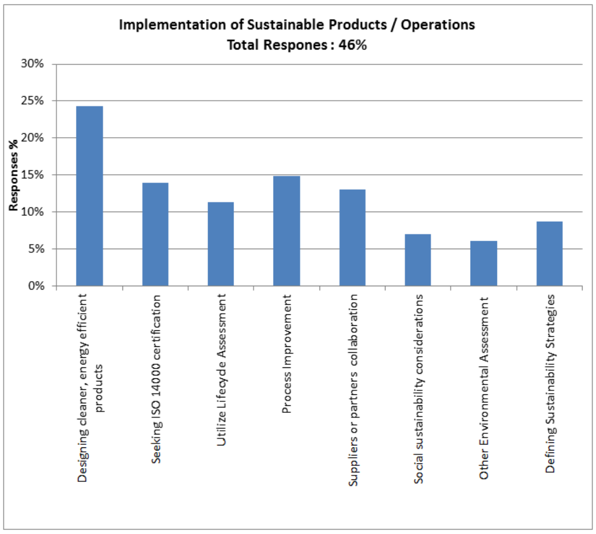


Figure 9: Implementation plan.

5.10 Internal Changes Needed for Implementing Sustainability

The rate of responses was considerably small, only 26% of the companies responded this question which is the representation of 68 companies. Regarding the responses, 41% of the companies' responses claimed requirement for changes in the process, infrastructure and technology, while, changes referring to the employees, suppliers and partner training with a 28% of companies considering this types of changes or planning to implement them. On the other hand, 19% of the companies are focusing in changes regarding research and development, whereas, customer awareness are the change requirements of the 7% of the companies interviewed. Finally, four per cent of the companies already have changes in their products or processes towards sustainability in place.

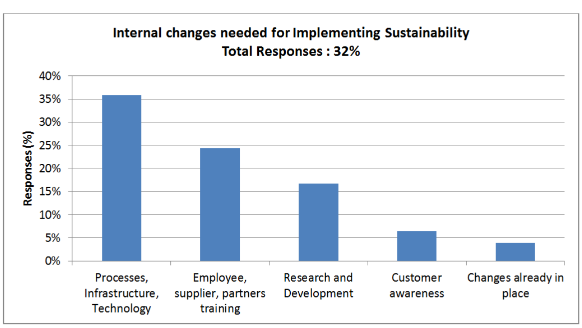


Figure 10: Internal changes needed for implementing sustainability.

5.11 External Advice and/or Collaborative Work

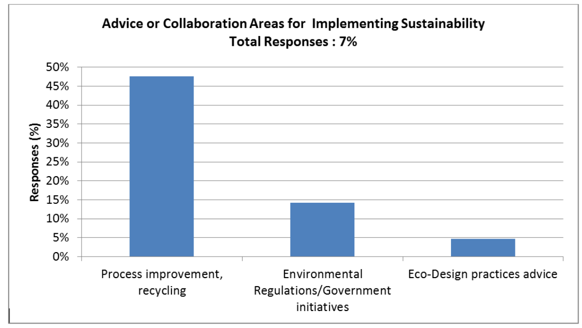


Figure 11: External advice and/or collaborative work.

6 SURVEY RESULTS AND ANALYSIS FOR FOOD AND DRINK SECTOR

In order to compare and contrast the food and drink data from the overall, the information gathered was filtered and illustrated in graphs to realise the key differences between both groups. In the followings it will be summarised the most significant aspects of the food and drink sector that differ and diverge from the other manufacturing groups.

6.1 Drivers Comparisons

In summary, the most relevant differences regarding the drivers are related to the compliance with legislation and market opportunities; first, the percentage of food and drink companies that accounted legislation as most important increase from by 6% (69% overall to 75% F&D); and market opportunities, which in the overall importance average increase considerably.

6.2 Barriers Comparisons

In terms of the barriers The most important barriers that food and drink sector in the UK manufacturing is the high implementation cost, followed this time by weak justification of investment, on the contrary, the second most important of the rest of the sector was lack of stakeholder and customer awareness.

6.3 Benefits Comparison

On the benefits results, The most relevant benefit perceived by the UK food and drink companies participant was compliance with regulation, moreover, the second most important benefit of food and drink was competitive advantage, which contrasts with the findings of the rest of the company sectors, being long term financial benefits the second most beneficial fact perceived for them.

Eco-Design Strategies Comparisons

There is no noteworthy variation when comparing food and drink with the rest of the sectors, although, design for longer life was more regarded and utilised by the food and drink sector with 60% of the companies claiming to use this strategy, meanwhile, 46% of the other sectors stated to be using design for longer life as one of their activities. In addition, there is a considerable gap difference of 11% more food and drink companies utilising the pollution reduction strategies.

6.4 Sustainable Manufacturing Strategies Comparison

First, reduce waste and cleaner production increased is higher for food and drink with 82%, while 77% of the rest of the sectors used this strategy. On the other hand, in product stewardship, reverse logistics and closed loop the utilization of the food and drink sector is higher than the rest sectors together by 12% (36% vs. 24%).

7 DISCUSSIONS, COMPARISONS AND CONCLUSIONS

7.1 Overall Discussions

Due to the results of the aspect that drive the most the sustainable practices it would be fair to say that, even when it is widely understood that companies' common goal and priority is the establishment of an economic growth, also, the importance of compliance with legislation and accountability presumably has risen during the years, being nowadays the most significant encourager for the implantation of sustainable strategies. Also, to reinforce this result, compliance with regulation was identified as the most important benefit as well, which suggests that coping with external or internal regulation proved to be advantageous to UK manufacturing industry because it provides direction and guidelines to the companies towards a safer social, economic and environmental friendly activities.

In the same manner, the translation of sustainable strategy practices comes as a real challenge, therefore, several organisations have been using ISO 14001 which is considered an Environmental Management Systems (EMS) in order to be provided with direction to the design and application of the environmental strategies. This shows that UK manufacturers not only are highly complying with legislation, but also, are seeking alternatives and frameworks to reinforce their activities towards a sustainable approach.

Furthermore, regarding the clear trend of the obedience and compliance of sustainable parameters, regulation and industry codes of conduct claim the growing address to sustainability; the non-compliance with these rules has a direct impact in the costs that organisations have to deal with several menaces such as, penalties and fines infringement, legal costs, diminish in the productivity because of additional inspections, possibility of operation closure, among others; all these represent big risks to companies, therefore, there is a great deal of congruency between the literature and the survey findings, where, the biggest risk identified by the respondents was the legal and financial threats. Therefore, this hazard encourages companies around the UK to comply with the regulations to avoid monetary and legal drawbacks.

In the same sense, companies identified financial benefits in the survey as one of the important drivers, also, high implementation cost and long-time payback was the most important barrier, which, suggest that under the UK manufacturing perception the benefits and the return of investment are perceived as a long term basis matter, and it implies that companies with no strong financial muscle might struggle when implementing sustainable strategies.

It is relevant to posit that, weak justification of investment and lack of support of customer/stakeholder support and benefit awareness are seen by UK manufacturers as the survey reveals as equally important and it would be fair to say that due to the nature of both issues they are directly related one to the other. This suggests that several companies might not be feeling a real burden to change their current practices into a more sustainable strategies being also consistent with the literature; exhibiting a reality where, although there is a real growth of the environmental conscious customers, it is also likely that they will not be prone to pay high prices or change their product/services preferences to a more sustainable focused ones, weakening the purpose for devoting money to this cause. This has a direct impact in the suppliers' involvement resulting in an overall lack of support from the stakeholders.

More precisely, it gives the impression that these obstacles might be seen with doubt by manufacturers under the fact that they could provide weak financial incentive; it seems that difficulties are likely when it is intended to set a balance between the initial investment to establish the strategy and translate that in positive economic performance in the short term, resulting in a lack of full support to endorse such sustainable activities due to the common focus on short term goals.

Alternatively, regarding the eco-design and sustainable manufacturing strategies survey outcomes the most utilised eco-design strategy from UK manufacturers is design for reduced resource use (materials and energy), therefore UK manufacturers are attempting to preserve the earth and at the same time guarantee cost savings due to the considerations made for the proper administration of the resources required at the design stage, which impact positively the whole life-cycle. Nevertheless, the second most voted strategy was design for recycle, reuse, remanufacturing. The application of all these criteria does not vary the assets of the products, so, the cost and the environmental enhancement are mutual in terms of focusing in diminish the impact to nature related to the whole life cycle and competitive costs. Presumably from the result, UK manufacturers are actually requiring smaller amount of end-of-life resources and recuperating them through the recycling, reuse and remanufacturing, also, this suggest a clear intention to upgrade the products and consequently extend the life cycle. Furthermore, the third position on the eco-design strategies went to reduce pollution/emission. The climate change was in a certain way the stepping stone of the environmental considerations.

Regarding the sustainable manufacturing strategies the two most popular strategies were use of less raw material, water and energy and reduce waste/cleaner production. It seems that UK manufacturers are attempting to control and separate the link between the resources utilised namely raw material, water and energy and the impact of their consumption. As it was stated earlier, with these strategies the environmental impact is highly reduced, alternatively, there is a clear economic advantage in the implementation of these strategies.

When evaluating the plans towards sustainability, supplier selection, organisational change and sustainable goals, the trend of the accountability for economic and environmental issues is very clear; there is not a significant contemplation for social aspects, since the classification of social sustainability consideration was nearly not part of their plans.

7.2 Key Findings and Conclusions about Food and Drink Sector

In summary, compliance with legislation was regarded as the most important motivator for sustainable strategies in all sectors; however, the proportion of organisations that accounted this particular issue as main driver was greater in the food and drink sector. This difference could be explain by the fact that, as food and drink are mainly focus for the human being consumption, then the code of practice and statutes are more tight when manufacturing and distributing the products to the general public. As it has been said before the non-compliance with this rules and obligation would not only harm the company financially by lawsuits and penalties but it will also add the risk of harming the society in general, therefore, the obedience to guidelines in this sector is paramount, which validates the higher regard for legislation compliance in this sector. All the above is confirmed when assessing the principal benefits perceived by food and drink industry, which place compliance with regulation and risk avoidance as the most important benefit.

Food and drink sector regarded market opportunities and pressures as the second most important driver. It is important to highlight that the margin of variance when comparing the market influence of food and drink sector with the rest of the sector is quite significant. Nowadays, due to the increasing environmental awareness, people are asking for green based products and sustainable consumption. Generally, food and drink products are focused to reach the general public as the main end user; the appeal for organic and environmental friendly based products is rising so manufacturers around UK seem to be aiming to find gaps and/or gain market share by providing green conscious product to them. These issues are strongly aligned with the highest benefit behind the regulation compliance, which is the competitive advantage and innovation, which suggests that, being motivated by the pressure of the market and the opportunities engendered.

Also, considering the results it seems that for food and drink the costs associated to move towards into a most sustainable approach is higher than the other sectors; this could be because several considerations should be put in place due to the several regulations and restrictions of the food and drink sector, therefore more resources, research and consideration should be made when applying eco-design and sustainable manufacturing to aliments.

Regarding the eco-design strategies comparisons, the greatest difference comes in the third most used strategy which for the rest of the sectors was reduction of pollution, but for the food and drink sector was designing for longer life. This suggest that companies are attempting to create product that last for longer, which is quite obvious when assessing food and drink industry. Food and drink has the particularity that their products tend to have short life after it is distributed, therefore, it seems organisation are aiming to design products with longer expire dates, which will end up improving the product life and consequently their profit, since the probability of selling the product increases due to the higher length of exhibition time.

On the other hand, the sustainable manufacturing strategies comparisons the most utilised strategy regarding sustainable manufacturing in the food and drink sector is the reduction of waste and cleaner production, which differs from the rest of the other groups. The fact food and drink utilise the reduction of waste and cleaner production authenticates the literature review; the manufacturing area of the food and drink sector generates 3.2 million of waste per annum, and as an overall from the 7.2 mt/year just 4.4 mt/year are avoidable, consequently, manufacturers are looking for ways to reduce the waste production, minimise the environmental footprint, and also cope with some legislation such as the WRAP agreement or Climate Change Agreement (CCA). Furthermore, food and drink sector produce a considerable amount of GHG, so manufacturers are quite driven by decreasing this emissions produced by their chain process.

8 CONCLUDING REMARKS

- The UK manufacturing industry is highly driven by the compliance regulation is perceived as beneficial and as a risk avoidance practice.
- The account for regulation compliance of the food and drink sector is higher compared with the other sectors.
- Eco-design and sustainable manufacturing are means to achieve competitive advantage, market opportunities and financial benefits for all the sectors of the UK manufacturing industry.
- Barriers for eco-design and S.M. the high implementation cost was the most important obstacle
- The most important risks that companies are facing is the legal and financial risks.
- The two most popular strategies of eco-design are designing for reduce use and 3R
- The most utilise sustainable manufacturing strategy is the clean production followed closely by the resource efficiency.
- When selecting a supplier the most important criteria is cost by a high margin of difference.
- The most popular goal among the UK manufacturing industry is the measurement of the environmental footprint.
- Process improvement is distinctly considered in the UK manufacturers plans.
- UK manufacturers are not deploying a balanced approach towards the three bottom line, having no sufficient consideration for social factors.
- The implementation cost and long-time payback time when investing in sustainable strategies is a major hurdle for SME's than large size companies.

9 REFERENCES

[1] Allwood, J.M and Cullen, J.M. (2009) The efficient use of energy: tracing the global flow of energy

[2] Arthur, D., et al.(2010). Sustainability: The “Embracers” Seize Advantage. Boston: Boston Consulting Group. Boston: MIT Sloan Management

[3] Badurdeena, F., et al. (2010). Sustainable Manufacturing: Modelling and Optimization Challenges at the Product, Process and System Levels. CIRP Journal of Manufacturing Science and Technology, 2, pp. 144-152.

[4] Basile, G., et at. (2002). Strategic Sustainable Development: Selection, Design and Synergies of Applied Tools. Journal of Cleaner Production, 10, pp. 197–214.

[5] Berns M., Townend A., Khayat Z., Balagopal B., Reeves M., Hopkins M.S., Kruschwitz N., 2009, Sustainability and Competitive Advantage . MIT Sloan Management Review, 51(1), pp.18-26.

[6] Birkeland, J.(2002). Design for Sustainability: a Sourcebook of Integrated, Eco-logical Solutions. London : Earthscan Publications Ltd.

[7] Borchardt, M., Wendt, M.H., Peirera, G.M., Sellitto, M.A., 2010, Redesign of a component based on ecodesign practices: environmental impact and cost reduction achievements. Journal of Cleaner Production. Volume 19, Issue 1, January 2011, Pages 49–57

[8] Boret, D, (2012), Managing eco-design and sustainable manufacturing, MSc Dissertation, WMG, University of Warwick.

[9] Deif Ahmed, 2011, A System Model for Green Manufacturing, Advances in Production Engineering and Management, Volume 6, (2011) 1, 27-36

[10] Epstein M.J., 2008, Making sustainability work: best practices in managing and measuring corporate social, environmental and economic impacts, Berrett-Koehler Publishers, Ilustrated Edition, 288 pages

[11] Esslinger H., 2011, Sustainable Design: Beyond the innovation-Driven Business, Journal of production Innovation Management, Volume 28 (3) (2011), 401-404 May 2011

[12] Esty, D., Winston, A. 2006, Green to Gold. 2nd Edition New Haven: Yale University Press.

[13] from fuel to service, Energy Policy (in press)

[14] Haanaes H., Teck Hong N., Hopkins M., Reeves M., Velken I., Arthur, D., 2010, Sustainability: The “Embracers” Seize Advantage. Boston: Boston Consulting Group. MIT Sloan Management Review.

[15] Hitchcock, D., Willard, M. (2006). The Business Guide to Sustainability. London: Earthscan Publications Ltd.

[16] Jayal A.D., Badurdeen F., Dillon Jr, O.W., Jawahir I.S., 2010, Sustainable manufacturing: Modeling and optimization challenges at the product,process and system levels, Journal of Manufacturing Science and Technology, Volume 2 (2010) 144–152

[17] Joshi, K., Venkatachalam, A., Jawahir, I.S., 2006, A New Methodology for Transforming 3R Concept into 6R Concept for Improved Product Sustainability, in: Proceedings of the IV Global Conference on Sustainable Product Development and Life Cycle Engineering

[18] Karlsson R., Luttropp C., 2006, EcoDesign: what’s happening? An overview of the subject area of EcoDesign and of the papers in this special issue, Journal of Cleaner Production 14 (2006) 1291-1298

[19] Kernbaum, S., Seliger, G., Zettl, M. (2008). Approaches to Sustainable Manufacturing. International Journal of Sustainable Manufacturing, 1, pp. 58-77

[20] Laszlo, C., 2003, The sustainable company: How to create lasting value through social and environmental performance. Washington: Island Press.

[21] Marval, S. (2011) Eco Design and Sustainable Manufacturing, MSc Dissertation, WMG, University of Warwick.

[22] Plouffe S., Lanoie P., Berneman C., Vernier M., 2011, Economic benefits tied to Eco-design, Journal of Cleaner Production 19 (2011) 573-579

[23] Review (Winter 2011 Research Report).Consulting Group (Fall 2009 Report).

[24] Salwa H. Abdul R, Evans S., Longhurst P., 2008, A comparison of four sustainable manufacturing strategies, International Journal of Sustainable Engineering, Vol. 1, No. 3, September 2008, 214–229

[25] Tseng H., Chang C., Li J., 2008, Modular design to support green life-cycle engineering, Expert Systems with Applications, Volume 34, Issue 4, May 2008, Pages 2524–2537

[26] Veshagh, A., Brown, C. (2008). Sustainable Manufacturing in the UK Industry, in Proceedings of 15th CIRP International Conference on Life Cycle Engineering, Sydney, Australia, 17-19 March 2008.

[27] Veshagh, A., Loannou, K. (2011) Managing Sustainability in Product Design and Manufacturing in: Proceedings of 18th CIRP International Conference on Life Cycle Engineering, Braunschweig, Germany, May 2011.

An Evaluation Scheme for Product-Service System Models with a Lifecycle Consideration from Customer's Perspective

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Abstract

The product-service system (PSS) is a business system in which its integrated products and services jointly fulfill customer needs. This research proposes an evaluation scheme for PSS models. The PSS model evaluation scheme consists of evaluation criteria and methods. The current paper mainly focuses on the introduction of the evaluation criteria and their application. The set of evaluation criteria has a four-layered hierarchical structure which has 2 perspectives, 5 dimensions, 21 categories, and 94 items in total. They are designed to consider the provider and customer perspectives, and all 3P (profitability, planet, and people) dimensions. They cover various stages of a PSS lifecycle, namely, design, production, sales (or purchase), usage as well as disposal. To illustrate the usefulness of the proposed evaluation scheme, a few PSS cases are first modeled using an existing PSS visualization tool, and then evaluated using the scheme. Case studies show the proposed evaluation scheme is workable to assess the potential value of the PSS models in question; it provides an extensive knowledge base for PSS evaluation, thereby serves as an efficient and effective aid to practitioners for successful PSS development.

Keywords:

Product-service system (PSS); PSS model; Evaluation scheme; Evaluation criteria

1 INTRODUCTION

With the commoditization of many products, product-based companies now face various challenges in innovation. Getting ahead of competitors in terms of cost and technology leadership in production is becoming more difficult. Furthermore, global environmental regulations are becoming more rigid. With more intense product-led competition, many product-based companies have begun to adopt a service-led competitive strategy to distinguish themselves from competitors [1, 2].

Recent studies have defined such value proposition, in which its integrated products and services "jointly fulfill" customer needs, as product–service system (PSS) [3, 4, 5]. Representative examples of PSS include the precise farming solution, car-sharing scheme, and document management solution [6].

PSSs have enabled the win-win situation for both customers and providers. Customers become able to perform specific tasks in product consumption process faster, better, or cheaper than before [6, 31]. Literature has categorized what providers benefit from PSS into 3P values, namely, profitability, planet, and people [5, 11]. From profitability (i.e., economic) point of view, greater customer satisfaction contributes to arrive bigger gain. Furthermore, building closer relations based on customer process management enables companies to anticipate future businesses and to stabilize the profit mechanism [2, 8]. From planet (i.e., environmental) point of view, providing PSSs dematerializes product offering and taps the potential to alleviate material production surplus and consumption [3, 5, 9]. From people (i.e., social) point of view, the balanced consumption propensity achieved through the use of PSSs encourages people to streamline their product consumption routines with more mature choices. Meanwhile, the products consumption related-social cost decreases [10, 11]. In short, PSS could be an alternative solution in achieving sustainable growth affording the stakeholders grins.

A generic process of PSS development consists of iterative two phases (van Halen et al., 2005): alternatives design and evaluation. For any PSS development project, either developing brand new PSSs or improving existing PSSs, to be successful, the evaluation of PSS should be done in a proper manner.

Despite its importance, PSS evaluation has not received as much attention as it deserves in literature [3, 29, 30]. In this regard, this paper proposes an evaluation scheme for evaluating PSS. The evaluation scheme should include evaluation criteria, evaluation methods, and an evaluation procedure. This paper focuses on the introduction and use of evaluation criteria. The evaluation criteria cover not only the provider perspective but also the customer perspective. The results of this research can support the development of PSS. This paper presents an extension of the authors' previous work [7] by emphasizing the lifecycle consideration from the customer's perspective with the support of a PSS visualization tool, called PSS Board [6].

2 LITERATURE REVIEW

Existing studies related to the PSS evaluation can be classified into five categories according to the focus of evaluation: profitability, planet, and people which refer to economic, environmental, and social value, respectively; all the 3P (profitability, planet, and people); and customer value created from the customer needs fulfillment. This section introduces some of the reviewed studies. Although some of the introduced studies are not specifically targeted for the PSS evaluation, their approaches or insights can be employed for the purpose of the evaluation.

For profitability value, Mannweiler et al. [13] proposes a methodology to assess the costs arising throughout the whole lifecycle of PSS, while Kimita et al. [14] proposes a methodology to evaluate service activities, employing activity based costing.

For planet value, Vogtlander et al. [15] proposes the EVR (eco-costs/value ratio) model to measure ecological burden over added value of a product, a service, or a product-service combination. Park and Tahara [16] proposes a methodology to evaluate eco-efficiencies of product using data envelopment analysis (DEA) and life cycle assessment (LCA).

For people value, Rothenberg [2] provides insights extracted from the three PSS case studies (Gage, PPG, and Xerox). This research proposes six key success factors of the PSS development regarding organization's structural and cultural changes. The author mentions the true change in the PSS development is overcoming cultural inertia that employees and customers have. Labuschagne et al. [17] proposes a framework to evaluate the sustainability of operations in the manufacturing sector.

For all the 3P values, van Halen [9] proposes methodology for PSS innovation (MEPSS) that is developed based on the authors' consulting experience on PSS development over time. The methodology consists of various tools and a PSS development process. The tools, such as Inventory of Sustainability Indicator, E2 Vector and Sustainability Design-Orienting, support evaluating the 3P values of a PSS and interpreting the results. Omann [10] proposes a PSS evaluation tool. The tool includes a set of 59 evaluation criteria reflecting the 3P values.

For customer value, Garvin [18] proposes eight dimensions of product quality, namely, performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality, while Parasuraman et al., [19, 20] proposes five dimensions of service quality, namely, reliability, assurance, tangibles, empathy, and responsiveness. Womack and Jones [21] argues the importance of streamlining the customer's consumption process, while Frei [22] identifies the five types of customer-introduced variability affecting the service outcomes, namely, arrival, request, capability, effort, and subjective preference.

Based on the literature review, we propose three requirements for successful PSS evaluation as follows. First, the customer perspective to experience a PSS should be considered in the PSS evaluation. This is because the essence of PSS is to focus on customer's fundamental goal rather than the product concept [3, 23]. However, most works have considered only the provider perspective.

Second, a spectrum of the PSS lifecycle in time needs to be thoroughly investigated in the PSS evaluation, since the value of a PSS is continually created throughout its entire life rather than at a single point in time. Without a complete understanding of the contextual relationships, the PSS evaluation could be limited. Brissaud and Tichkiewitch et al. [24]; Mannweiler et al. [13]; and Lim et al. [6] define the steps of PSS lifecycle (or PSS process) from the customer perspective for its effective analysis, while Aurich et al. [25]; Hepperle et al. [26]; and Geum and Park [27] define the steps from the provider perspective. In summary, a PSS lifecycle consists of five phases, namely, design, production, sales (or purchase), usage as well as disposal.

Third, for a sustainable growth of a PSS or eventually the PSS provider, the evaluation should be done in a balanced manner, which covers all the 3P values. However, few works have considered 3P for sustainability.

3 PROPOSED PSS EVALUATION SCHEME

The PSS evaluation scheme consists of evaluation criteria, evaluation methods, and an evaluation procedure. This paper focuses on the introduction and use of developed evaluation criteria. The proposed evaluation scheme pursues a general evaluation model. It attempts to evaluate PSS in a comprehensive manner. First, it considers both customer and provider (company) perspectives. Second, the evaluation scheme considers all phases of PSS lifecycle by including the PSS lifecycle-dependent criteria. Third, all the 3P (profitability, planet, and people) dimensions are considered in the provider perspective.

Table 1 shows the structure of the evaluation criteria. The framework of evaluation criteria has a four-layered hierarchical structure. The uppermost level of the structure is the perspective level. The perspective refers to the evaluator's point of view. In the perspective level, two levels exist. One is sustainability and the other is customer value. Sustainability and customer value represent the provider (company) and the customer perspectives, respectively. Each perspective has several dimensions, and each dimension has categories as shown in Table 1. A dimension is a particular part of perspective. Categories refer to "the broad areas or groupings of social, environmental or economic issues of concern to the company stakeholders [9]." A brief explanation of each category is also given in Table 1. Each category has several items. Items refer to "the general types of information related to a given category [9]." A category and an item need specific adaptations since they depend on a specific context considered.

The wide coverage over both process lifecycle dimension and value dimension (i.e., the 3P and customer values) is the main advantage of the proposed set of 94 criteria. This enables a comprehensive and balanced understanding on the weaknesses and strengths of the PSS. On the other hand, all the proposed criteria may not be relevant in evaluating a particular PSS process. Thus, in an actual evaluation, only the criteria relevant to the given PSS can be selected as appropriate to the evaluation purpose. The user, definitely, can adapt the criteria or add her own ones as needed.

The process of arriving at the 94 evaluation criteria is as follows. First, we collected the evaluation criteria and perspectives proposed by existing studies related to the PSS evaluation. Section 2 introduces some of the studies reviewed. Second, we examined their relevance with lifecycle and value dimensions. In this examination, some of the criteria proposed by existing studies are adopted, while some are distilled from the implicit expertise related to evaluation criteria. As a result, experts in existing studies related to the PSS evaluation had been re-defined as evaluation criteria considering lifecycle and all the 3P values dimension of PSS.

Third, some evaluation criteria, which the existing studies related to the PSS evaluation (shown in Table 1) could not cover, were newly identified and added to the library in the present work, based on our understanding on PSS and general system evaluation. Finally, we examined the collection of criteria if it provides enough diverse viewpoints to evaluate all the three types of PSS [28]. We also modified (e.g., combined, divided, or renamed) some of them as required. Then, we repeated this refinement process several times. As a result, the set of 94 evaluation criteria, specifically related to the lifecycle and all the 3P values of PSS, finally came through.

Perspective	Dimension	Category	Item
Sustainability	[10000] Profitability	[10100] Fixed cost	Fixed cost for offering PSS [10101] Fixed cost for designing PSS [10102] Fixed cost for producing PSS [10103] Fixed cost for supporting the use of PSS [10104] Fixed cost for supporting the disposal of PSS
		[10200] Operational cost	Variable cost for operating PSS (4 items)
		[10300] Revenue	Financial benefits from PSS (8 items)
		[10400] Ecosystem Structure	Efficiency/Effectiveness of Ecosystem Structure (4 items)
		[10500] Macroeconomic effects	Ripple effects resulting from PSS (2 items)
	[20000] Planet	[20100] Product usage	Intensity of product use (2 items)
		[20200] Material usage	Amount of material use (4 items)
		[20300] Energy usage	Amount of energy use (3 items)
		[20400] Emissions of toxic substance	Amount of toxic substance discharge (8 items)
		[20500] Environmental management	Observance of environmental standards (3 items)
	[30000] People	[30100] Capability of employees	Level of employees' capabilities (3 items)
		[30200] Profit sharing	Sharing profit among stakeholders (2 items)
		[30300] Working environment	Working environment and conditions (5 items)
		[30400] Employment equity	Providing equal opportunity of employment (8 items)
		[30500] Acceptability	Level of acceptance by people and society (3 items)
		[30600] Influence on society	Impact on society and culture (6 items)
Customer Value	[40000] Quality	[40100] Product-related quality	Quality of product component of PSS (7 items)
		[40200] Service-related quality	Quality of service component of PSS [40201] Tangibles of service component [40202] Reliability of service component [40203] Responsiveness of service component [40204] Assurance of service component
		[40300] Customer support	Customization and support for customers (5 items)
		[40400] System convenience	Convenience and flexibility of PSS (6 items)
	[50000] Cost	[50100] Cost	Costs to customers (3 items)

Table 1: Structure of PSS evaluation criteria.

The complete list of the 94 evaluation criteria can be found at "http://thome.postech.ac.kr/user/quality/PSS_Evaluation/Complete_list.pdf." We do not present the set of 94 evaluation criteria as an exhaustive listing of the PSS evaluation criteria. Different researchers addressing this issue may build the library in which owns more or different criteria. Our effort is an initial one to emphasize the lifecycle-oriented and all the 3P values-considered PSS evaluation.

4 CASE STUDY

We conducted various case studies to test the applicability of the proposed scheme. In this paper, we introduce the evaluation of a car-sharing model in Korea. A number of companies in Korea provide cars to be shared by citizens and visitors in various cities. These companies also provide services to take care of all the troublesome duties related to cars. As a result, car-sharing users need only to reserve, unlock and drive the cars, a process which costs less than buying the cars. The massive environmental load caused by cars is expected to decrease since a portion of these vehicles is shared. The power of car-sharing model is evaluated in comparison with conventional car selling, car leasing, and car-pooling models.

First, we visualized three models using a PSS process visualization tool. Essentially, gaining a complete view of the As-Is is the first step towards its evaluation, and visualization of PSS is a useful method accomplish this purpose. PSS is a complex system which consists of various components; and its value creation mechanism and power are characterized by the system components and their relationships. With rough understanding of the system architecture, companies can neither analyze the mechanism of PSS nor achieve a precise evaluation.

In particularly, a PSS process visualization tool is advantageous because: 1) it supports the decomposition of process architecture and thus helps to outline the evaluation scope, and 2) it facilitates the association of components and customer activities of the PSS with evaluation criteria.

Considering the three requirements proposed in Section 2, PSS Board (Lim et al., 2012) is employed as a basis for the PSS evaluation in this research. This tool is capable to decompose PSS process showing how the four components of PSS, namely,

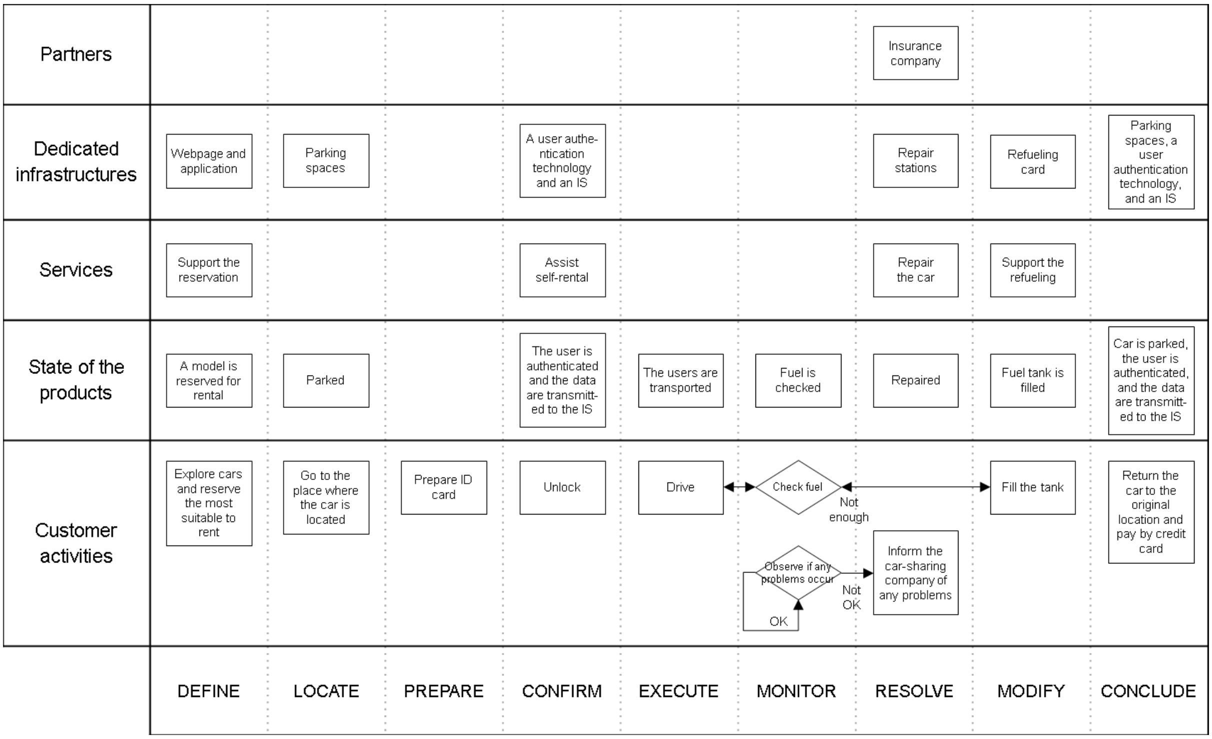

Figure 1: A car-sharing model visualized on PSS Board.

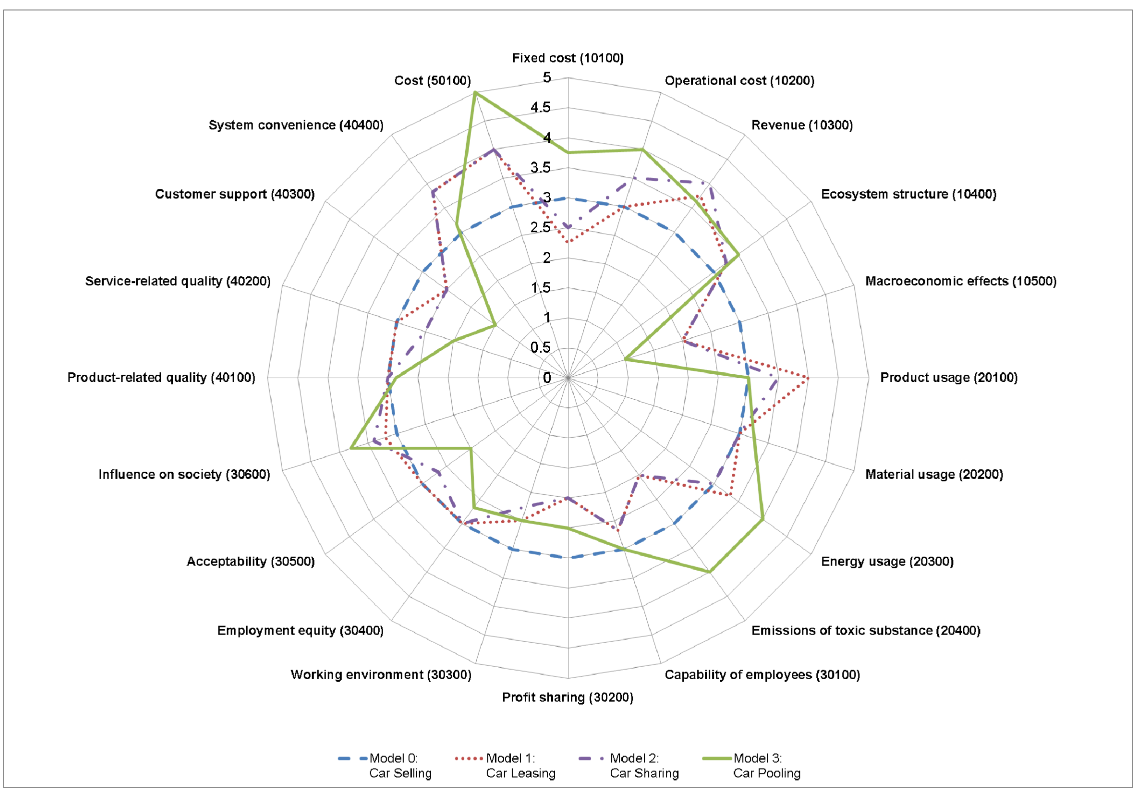

Figure 2: Evaluation results of automobile-related PSS models on the category level.

products, services, dedicated infrastructures, and provider network, support customer's goal achievement process in a very structured and complete manner. In particularly, this tool can show a PSS with a full consideration of its lifecycle from customer perspective. In fact, PSS Board was originally developed for the systematic PSS design and evaluation considering the system mechanism. Figure 1 shows the visualized car-sharing model on PSS Board.

From the evaluation criteria shown in Table 2, only the criteria relevant to the specific case study are selected. As a result, 20 out of 21 categories, and 82 out of 94 items are selected and actually used in this study. The three models are evaluated against a reference model. The conventional car selling model is set as the reference model, denoted as Model 0. For each evaluation item, a five-point scale is used for scoring. That is, each model is evaluated either as much worse (1), worse (2), same (3), better (4), or much better (5) compared with Model 0. The evaluation is done based on the information gathered from various sources, including an existing study on PSS models in the automobile industry [30] and the internet (Website of the company, customer reviews in blogs, and news), besides our experience on the car-sharing model. Figure 2 shows evaluation scores in the category level. The relative weaknesses and strengths of car-sharing model to others are clearly illustrated.

From case studies, we could validate the practicability and power of the proposed PSS evaluation scheme. In comparison with existing studies, the scheme is distinguished by its rich knowledge base. In particular, the evaluator can fully utilize the wisdom from prior experiences in order to evaluate PSSs instead of starting from scratch.

5 CONCLUDING REMARKS

Product-service system (PSS) is a collection of inter-dependent components, namely, products, services, infrastructures, and provider network organized as a whole in order to accomplish customer's goal. These components are realized over PSS lifecycle, namely, design, production, sales (or purchase), usage as well as disposal.

A requirement to an effective PSS evaluation is the consideration of the structure of PSS lifecycle from customer perspective. This is because the value of a PSS is continually created throughout its entire life rather than at a single point in time. With the exception of Waltemode et al. [31], however, our review of the literature revealed a surprising lack of work directed at arguing the necessity of considering its lifecycle structure for analyzing PSS quality.

A contribution of the current research is that it breaks new ground in the field of PSS evaluation, proposing a novel scheme to evaluate PSS with a full consideration of its lifecycle structure. The proposed PSS evaluation scheme consists of evaluation criteria, evaluation methods, and evaluation procedure. The focus of this paper is on the introduction and use of the evaluation criteria.

The proposed framework of evaluation criteria has a four-layered hierarchical structure. The four layers refer to perspectives, dimensions, categories, and items. Two perspectives are considered, namely, sustainability and customer value. The sustainability perspective consists of 3Ps (i.e., profitability, planet, and people) dimensions, while the customer-value perspective consists of quality and cost dimensions. The sustainability and customer-value perspectives represent the provider (company) and customer perspectives, respectively. Each dimension is further classified into categories, and finally into more detailed items. The framework has 5 dimensions, 21 categories, and 94 items in total.

With the proposed scheme, evaluators can utilize the wisdom from rich experience in PSS evaluation in the past, rather than starting from scratch. The proposed scheme is comprehensive enough to cover the provider and customer perspectives as well as all phases of the PSS lifecycle. Although the proposed scheme is not complete at this moment, it has a potential to grow as a generic platform for PSS evaluation in the future.

There are several issues for future research to improve the evaluation scheme. First, the comprehensiveness of the proposed 94criteria should be continually checked and updated over time. Second, more PSS cases should be evaluated using the evaluation criteria. Third, the usage of the evaluation criteria for the PSS evaluation considering its composition should be investigated.

Effective system engineering, including system design, evaluation, realization, and operation, can never be achieved without clear definition and understanding of the system composition. In this regard, Cavalieri and Pezzotta [32] argue the necessity of a system perspective on PSS engineering, based on a wide review of studies on PSS. As such, consideration of the composition of PSS as well as its lifecycle would be very useful to effective PSS evaluation.

Fourth, evaluation procedure should provide a step-by-step guide to conducting an evaluation. Finally, the feedback mechanism after an evaluation needs to be developed. The evaluation result should be reflected upon and utilized in devising a PSS improvement plan. A detailed guideline on which characteristic of the PSS should be refined or revised when evaluation scores are unsatisfactory should be created.

6 REFERENCES

[1] Baines, T. S.; Lightfoot, H.W.; Evans, S.; Neely, A.; Greenough, R.; Peppard, J,; Roy, R.; Shehab, E.;Braganza, A.; Tiwari, A.; Alcock, J.R.; Angus, J.P.; Bastl, M.; Cousens, A.; Irving, P.; Johnson, M.; Kingston, J.; Lockett, H.; Martinez, J.; Michele, P.; Tranfield, D.; Walton, I.M.; Wilson, H. (2007): State-of-the-art in product-service systems, in: Journal of Engineering Manufacture, vol. 221, pp. 1543-1552.

[2] Rothenberg, S. (2007): Sustainability through servicizing, in: MIT Sloan Management Review, vol. 48, pp. 83-91.

[3] Tukker, A.; Tischner, U. (2006): Product-services as a research field: past, present and future. Reflection from a decade of research, in: Journal of Cleaner Production, vol. 14, pp. 1152-1156.

[4] Goedkoop, M.; van Haler, C.; te Riele, H.; Rommers, P. (1999): Product Service-Systems, ecological and economic basics, in: Report for Dutch Ministries of Environment (VROM) and Economic Affairs (EZ).

[5] Mont, O. (2002): Clarifying the concept of product-service system, in: Journal of Cleaner Production, vol. 10, pp. 237-245.

[6] Lim, C.; Kim, K.; Hong, Y.; Park. K (2012): PSS Board: A Structured Tool for Product-Service System Process Visualization, in: Journal of Cleaner Production, vol. 37, pp. 42-53.

[7] Kim, K.; Lee, D.; Lim, C.; Heo, J.; Hong, Y.; Park, K. (2011) : Development of an Evaluation Scheme for Product-Service Systems, in : Functional Thinking for Value Creation: Proceedings of the 3rd CIRP International Conference on Industrial Product Service Systems, pp. 255-260.

[8] Reinartz, W.; Ulaga, W. (2008): How to sell services more profitably, in: Harvard Business Review, vol. 86, pp. 91-96.

[9] van Halen, C.; Vezzoli, C.; Wimmer, R. (2005): MEPSS Innovation, Van Gorcum.

[10] Omann, A. (2006): Multicriteria tool for Evaluating the impacts of Product Service Systems on Sustainable Development: An application in Austrian companies, Sustainable Europe research institute.

[11] Tukker, A.; Tischner, U. (2005): New Business for Old Europe, Suspronet.

[12] Kang, M.; Wimmer, R. (2008), in: Journal of Cleaner Production, vol. 16, pp. 1146-1152.

[13] Mannweiler, C.; Siener, M.; Aurich, J.C. (2010): Lifecycle Cost oriented Evaluation and Selection of Product-Service System Variants, in: Proceedings of the 2nd CIRP Industrial Product-Service Systems (IPS2) Conference, pp. 21-26.

[14] Kimita K.; Hara, T.; Shimomura, Y.; and Arai, T. (2009): Cost Evaluation Method for Service Design Based on Activity Based Costing, in: Proceedings of the 1st CIRP Industrial Product-Service Systems (IPS2) Conference, pp. 224-228.

[15] Vogtlander, J. G.; Brezet, H. C.; Hendriks, C. F. (2001): The virtual eco-costs '99 A single LCA-based indicator for sustainability and the eco-costs-value ratio (EVR) model for economic allocation, A new LCA-based calculation model to determine the sustainability of products and services, in: International Journal of LCA, vol. 6, No. 3, pp. 157-166.

[16] Park P.; Tahara K. (2008): Quantifying producer and consumer-based eco-efficiencies for the identification of key ecodesign issues, in: Journal of Cleaner Production, vol. 16, No.1, pp. 95-104.

[17] Labuschagne, C.; Brent, A. C.; van Erck, R. P. G. (2003): Assessing the sustainability performances of industries, in: Journal of Cleaner Production, Vol. 13, No. 4, pp. 373-385.

[18] Garvin, D. A. (1984): What does ''Product Quality'' really mean? in: MIT Sloan Management Review, vol. 26, pp. 25-43.

[19] Parasuraman, A.; Zeithaml, V. A.; Berry, L. (1985): A conceptual Model of Service Quality and Its Implications for Future Research, in: Journal of Marketing, Vol. 49, pp. 41-50.

[20] Parasuraman, A.; Zeithaml, V.; Berry, L. (1988): SERVQUAL: A Multiple-Item Scale for Measuring Consumer Perceptions of Service Quality, in: Journal of retailing, vol. 64, pp. 12-40.

[21] Womack, J.; Jones, D. (2005): Lean consumption, in: Harvard Business Review, vol. 83, pp. 58-68.

[22] Frei, X. (2006): Breaking the Trade-Off Between Efficiency and Service, in: Harvard Business Review, vol. 84, pp. 1-11.

[23] Mont, O. (2000): Product Service-Systems. Final report, IIIEE, Lund University.

[24] Brissaud, D.; Tichkiewitch, S. (2001): Product models for life-cycle, in: CIRP Annals-Manufacturing Technology, vol. 50, pp. 105-108.

[25] Aurich, J.; Schweitzer, E. (2007): Life cycle management of industrial product-service systems, in: Advances in life cycle engineering for sustainable manufacturing businesses, pp. 171-176.

[26] Hepperle, C.; Orawski, R. (2010): An integrated lifecycle model of product-service-systems, in: Proceedings of the 2nd CIRP Industrial Product-Service Systems Conference, Linköping-Schweden, Linköping University.

[27] Geum, Y.; Park, Y. (2011): Designing the sustainable product-service integration: a product-service blueprint approach, in: Journal of Cleaner Production, vol. 19, pp. 1601-1614.

[28] Tukker, A. (2004): Eight types of product-service system: eight ways to sustainability? Experiences from SusProNet, in: Business Strategy and the Environment, vol. 13, pp. 246-260.

[29] Tasaki, T.; Hashimoto, S.; Moriguchi, Y. (2006): A quantitative method to evaluate the level of material use in lease reuse systems of electrical and electronic equipment, in: Journal of Cleaner Production, Vol. 14, No. 17, pp. 1519-1528.

[30] Williams, A. (2007): Product service systems in the automobile industry: Contribution to system innovation? In: Journal of Cleaner Production, vol. 15, pp. 1093-1103.

[31] Bettencourt, L. (2010): Service Innovation: How to Go From Customer Needs to Breakthrough Services, McGraw-Hill Professional.

Life-Cycle Oriented Decision Support for the Planning of Fleets with Alternative Powertrain Vehicles

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Abstract

Corporate fleets are responsible for a large number of economic and environmental impacts. At the same time especially the introduction of alternative powertrain vehicles requires new life-cycle oriented approaches in corporate fleet planning. Here the complexity increases significantly as the vehicle characteristics are much more diverse compared to having only conventional vehicles. Furthermore, their economic and environmental impacts are related to different life-cycle phases of fleets. Thus, this paper provides a systematic decision support that allows for a life-cycle oriented evaluation of vehicle concepts according to the requirements of corporate fleet applications. To this end, the research background, the general approach and a case study are presented. The results are discussed comprehensively and suggestions for further research are given.

Keywords:

Life-cycle oriented Decision Support; Fleet Planning; Alternative Powertrain Vehicles; Simulation-based Evaluation

1 INTRODUCTION

Corporate fleets are responsible for a lot of economic and environmental impacts [1]. Moreover about 60% of the annual new vehicle registrations (in Germany) can be allocated to companies and self-employed persons [2]. For this reason corporate fleets are an attractive first market for the introduction of new alternative powertrain vehicles, such as hybrid (HEV) and battery electric vehicles (BEV) or those suitable for alternative fuels [3]. However, the related economic and environmental characteristics of these new vehicles are different in comparison to conventionally powered vehicles. For example, the purchase prices of BEVs are higher in comparison to diesel vehicles whereas the energy costs are lower [4]. Moreover, today environmental impacts of fleets result mainly from the use phase of vehicles (up to 80%) [5]. But as shown by [6] the share of Greenhouse Gas (GHG) emissions from manufacturing will become much higher with the introduction of BEVs (up to 40%). Thus, the introduction of alternative powertrain vehicles requires life-cycle oriented approaches to determine the economic and ecological break-even points and to support corporate fleet planning. Here, corporate fleet planning refers to the decision situation when a fleet manager has to decide, which alternative vehicles to purchase for and operate in different fleet applications.

In the following this paper provides decision support for the fleet planning with a focus on alternative powertrain vehicles under consideration of a life-cycle perspective. To this end, the remainder is structured as follows: chapter 2 gives more detailed insights into life-cycle considerations in fleet planning. Chapter 3 provides an overview on recent research in this field and concludes that currently no framework exists that enables to elucidate the described decision situation while incorporating an explicit life-cycle perspective. Based on the derived research demand, chapter 4 presents the approach for the life-cycle oriented decision support. It relies on a simulation-based evaluation of promising vehicle concepts with respect to different fleet applications using economic, environmental and operational life-cycle evaluation criteria. In chapter 5 a case study is elaborated in order to clarify the framework and chapter 6 finally gives a conclusion and a short outlook.

2 LIFE-CYCLE PERSPECTIVE IN FLEET PLANNING

Typically, corporate fleet planning has been approached from the operational management perspective with a focus on the use phase of fleets [7] [8]. In fact, when purchasing vehicles for corporate fleets they are today mostly assessed against financial and operational requirements [9]. On the one hand vehicles must fit to their expected tasks within daily business (e.g. carrying capacity). On the other hand the related costs must be minimized or may not exceed a certain value given by strategic management. However, the decision situation in corporate fleet planning has become much more complex due to the introduction of alternative powertrain vehicles and an increasing awareness in society. This is why a life-cycle oriented fleet planning is required as shown in Figure 1.

The main goal of fleet planning is to match the available alternative vehicle concepts with the relevant fleet characteristics (Figure 1). Here, the new concepts (e.g. BEVs) lead to a higher diversity in available vehicle options compared to having only conventional vehicles [1], [10]. Still, the planning objective is necessarily focused on the use phase of fleets while technical, environmental and economic evaluation criteria are relevant. However, with the introduction of alternative powertrain vehicles environmental and economic impacts, such as GHG emissions and costs, cannot be captured when the usage characteristics of the vehicles are considered alone. Rather a holistic view is required in which a fleet manager has to question which up- and downstreams should be

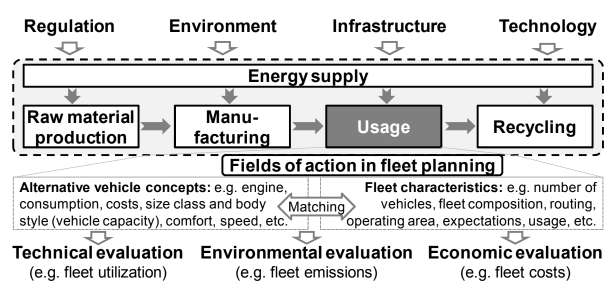

Figure 1: Life-cycle perspective on fleet planning.

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included in an evaluation. When evaluating the environmental performance of fleets, for example, local (e.g. smog), regional (e.g. acid rain) and global (e.g. climate change, resource extraction) impacts must be considered as many companies dedicate themselves to corporate social responsibility [1] [9]. However, for BEVs this means that also emissions resulting from the electricity production need to be accounted for [3] [11]. Furthermore, as mentioned in the introduction the relative importance of manufacturing becomes more important when GHG emissions of BEVs are evaluated [6]. From the economic perspective it is of crucial importance that the related costs of fleets are considered from a life-cycle perspective using at least the Total Cost of Ownership (TCO) approach. This allows for evaluating all relevant cost factors of vehicles (e.g. purchase or leasing, maintenance, or usage costs, etc.) to identify forefront costs.

Besides the necessary integration of a life-cycle perspective into the economic and environmental evaluation, fleet planning becomes more influenced by external factors due to the introduction of alternative powertrains. Here, the infrastructure availability, technology developments as well as regulatory measures or the environmental awareness of customers must be respected. As a result especially mid-to-long-term cost factors are difficult to predict, e.g. energy costs, purchase costs [9]. Thus, a strategic evaluation of different vehicle concepts requires a detailed analysis and should include different scenarios, e.g. for the technology development.

As shown above the evaluation of alternative propulsion vehicles in fleet planning has become more complex and requires the integration of a life-cycle perspective, especially in the economic and environmental evaluation. In the following a short literature review shows that such holistic approaches are scarce.

Approach	Aim
Fleet Routing (FRO)	Optimal routing of vehicles in a known network; fulfilling customer requirements
Fleet Size (FS)	Optimal number of vehicles; the type of vehicle is assumed to be fixed
Fleet Composition (FC)	Optimal composition of a fleet; the number of vehicles is assumed to be fixed
Fleet Replacement (FRP)	Creating an optimal replacement schedule
Other (O)	Non OR-approaches; general strategic considerations; comparative technological and economic analyses in fleet context

Table 1: Approaches in fleet planning and management.

3 RESEARCH BACKGROUND

Current approaches in the context of vehicle fleet planning and management come from Operations Research (OR) and have a focus on combinatorial optimization problems [7]. Here existing approaches can be classified into the groups given in Table 1. In fleet-related OR, FRO approaches are the biggest group and include research concerned with the problem of optimal routing of vehicles in a known network with homogeneous and heterogeneous fleets [12]. FS and FC approaches determine the optimal number, and composition of vehicles in a fleet. Typically FRO, FS, and FC problems are integrated in some way, such as in [13]. Even though the approaches differ in the single or combined models, their aim is to determine the number and / or type of vehicles while optimizing primarily the economic objective, i.e. minimizing the costs [14]. A few examples exist, where the economic dimension is complemented by further objectives, such as the quality of service in [1]. A further adaptation is the Pollution-Routing Problem [15] where the target is to minimize CO_2 emissions resulting from the usage of vehicles. In [16] different alternative powertrain vehicles are considered explicitly. As fourth OR category FRP problems pursue the objective of creating an optimal replacement schedule while costs are minimized. Thus, the question of when and which vehicles should be replaced or renewed is answered [17]. Finally, Other (O) non-OR approaches focus on more general considerations with respect to implications on fleet planning and management. [9] consider sustainability and risk management in fleet planning. Also comparative technological and economic analyses are available that look at different vehicle types in the fleet context such as battery electric vehicles [10], biodiesel vs. diesel vehicles [18] or gasoline vs. E85 vehicles [19]. Stakeholder views on fleet-related policy implications are considered in [20] and (expert) surveys focusing on commercial fleet demand are addressed in [21]. [22] focuses on the decision process for new vehicle technologies and [3] present an interim assessment of a voluntary ten-year fleet conversion plan in a case study.

The mentioned categories and approaches do not provide an exhaustive list but a good overview on the current directions in research on fleet planning and management. A further overview can be found in [1]. In Table 2 the current state of research is illustrated systematically whereas the approaches have been categorized into the mentioned five groups and investigated with respect to different criteria. In detail, it was analyzed whether the approaches consider economic (e.g. costs), environmental (e.g. GHG emissions) and further (e.g. capacity) evaluation criteria of fleets. Further, it was checked, if alternative powertrain vehicles are considered explicitly and if the approaches include a life-cycle perspective. The review shows that only a few approaches consider alternative powertrains and that no approach contains an explicit life-cycle perspective. Instead most approaches focus on fix and variable fleet costs in a costing analysis whereas the costs are not explicated in most cases. So to the best of our knowledge no framework yet exists that allows to structure and elucidate the decision making process in fleet planning while incorporating a life-cycle-perspective including the manufacturing stage as suggested in Figure 1.

4 APPROACH FOR THE LIFE-CYCLE ORIENTED PLANNING OF FLEETS WITH ALTERNATIVE POWERTRAIN VEHICLES

Within the previous sections the necessity of a life-cycle oriented planning of fleets was illustrated – especially for those including alternative powertrain vehicles. Developing a generic planning procedure is a challenging task due to the extensive diversity of fleets. Actually there is no same service, no same product delivery and different fleets typically do not operate in the same manner. There can be fleets for the transport of goods and

		[13]	[17]	[23]	[24]	[25]	[26]	[27]	[28]	[1]	[8]	[14]	[31]	[29]	[12]	[15]	[16]	[30]	[10]	[18]	[19]	[20]
Research approach		FS/ FR	FRP	FRP	FRP	FS	FS	FS	FS/ FC	FS/ FC	FC/ FS/	FC/ FS/	FC/ FS/	FC/ FR	FR O	FR O	FR O	FR O	O	O	O	O
Criteria	**Economic (e.g. costs)**	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	◐	●	●	●	○	○
	Environmental (e.g. GHG)	○	○	◐	○	○	○	○	○	●	○	○	○	○	○	●	●	○	◐	○	○	●
	Further (e.g. capacity)	●	○	○	○	○	○	○	○	○	●	●	○	●	●	○	●	○	●	●	●	○
Alternative powertrains		○	◐	○	○	○	○	○	○	○	○	○	○	○	○	○	●	○	◐	◐	◐	●
life-cycle perspective		◐	◐	◐	◐	◐	○	○	◐	◐	◐	◐	○	◐	◐	◐	○	○	◐	◐	◐	○

Legend: FRO - Fleet Routing Problem, FS - Fleet Size Problem, FC - Fleet Composition Problem, FRP, Fleet Replacement Problem, O - Other; ● considered, ◐ partly considered, ○ not considered

Table 2: Overview on the state of research.

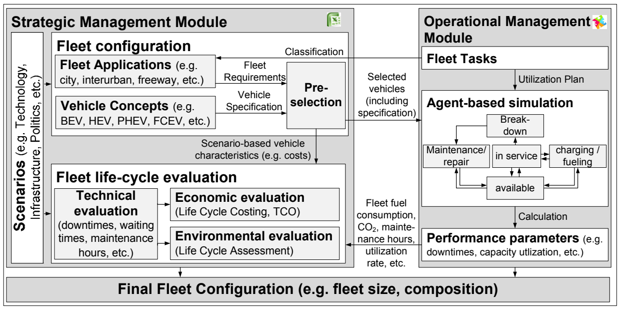

Figure 2: Conceptual framework for life-cycle oriented decision support for fleet planning.

personnel, fleets operating mainly in city traffic or mainly in sub-urban traffic, etc. Actually, the only analogy of different fleets is that their operation is based on vehicles [22]. Additionally, no knowledge and experience exist regarding the integration of alternative powertrain concepts and their potential benefits and drawbacks within fleet applications. Against the background of this planning challenge, Figure 2 illustrates the developed conceptual framework which aims at providing life-cycle oriented decision support for the planning of fleets with alternative powertrain vehicles.

Within this concept two important modules are distinguished. The Strategic Management Module focuses on the selection and life-cycle evaluation of potential fleet configurations with respect to scenarios and different target parameters. However, a crucial and innovative cornerstone of the concept is the Operational Management Module. Here, the performance and behavior of the fleet with all its individual vehicles can be simulated based on the specifications of the fleet configuration. Therewith, relevant performance indicators can be calculated that are key inputs for the evaluation of alternative fleet configurations.

4.1 Strategic Management Module

As shown in Figure 2 the Strategic Management Module consists of three parts – fleet configuration, life-cycle evaluation and scenarios.

Within the fleet configuration the relevant *fleet applications* are consolidated with available *vehicle concepts*. Fleet applications can be distinguished according to diverse variables as already indicated in Figure 1. The operating area with its specific characteristics (type of area, average speed, distances) plays an important role but also e.g. expectations of users. To build up the fleet different vehicle concepts can be applied. This became increasingly complex in the last years since – caused by environmental discussion and connected political pressure – alternative powertrain vehicles strongly gained importance. As indicated before, all those different vehicle concepts differ according to their technical, economic and environmental characteristics.

As an intermediate evaluation, a pre-selection takes place which integrates requirements from fleet applications as well as the benefits and drawbacks of different vehicle concepts into a potential fleet configuration in terms of size and composition of vehicles. This preselected fleet is analyzed in detail with the help of a simulation based-evaluation in the Operational Management Module.

Important performance indicators are fed back to the Strategic Management Module and used for the *life-cycle oriented evaluation of the fleet*. Therefore, three dimensions are considered:

- Technical evaluation which assesses data on downtime, waiting time or necessary maintenance
- Economic evaluation in the sense of life cycle costing (LCC) or at least TCO
- Environmental evaluation, e.g. with a (simplified) life cycle assessment (sLCA) and a transfer into impact categories such as global warming potential (GWP in kg $CO_{2,eq}$)

Finally, in order to be able to evaluate the overall performance of fleets different *scenarios* – e.g. regarding the development of technology, the existence of infrastructure or possible political decisions – need to be taken into account. This allows for a strategic evaluation of different fleet configurations with mid-to-long-term planning horizons.

4.2 Operational Management Module

Existing approaches for fleet planning try to capture the operational perspective by developing operations research based optimization problems. However, they typically lack to consider the time based dynamics, system interactions and the flexibility to a transparent evaluation of different fleet configurations. Instead only one single solution is presented that is optimal with respect to the constraints of the problem. This impedes broad applicability and leads to a limited consideration of real economic and environmental impacts. Studies from other technical systems underline that the simulation of TCO has benefits – major cost blocks (e.g. energy, maintenance) are dynamically depending on individual behavior over the use phase and are hard to predict statically [32] [33]. Simulation also enables to consider stochastic effects and uncertainty which allows for incorporating risk management into business decisions [34] [35].

Therefore, a simulation based approach is used here for assessing the operational performance of fleet concepts. The core is an agent-based simulation: practically this means that each vehicle is modeled as separate entity which behaves individually based on pre-defined state-charts and certain trigger events (Figure 2). If the vehicle is available (not on duty, in maintenance or charging/fueling) it draws individual tasks (distinguished by fleet parameters, e.g. distance, type of area, customer service time) from a fleet order book. Based on those fleet parameters the operation performance of each vehicle and the fleet as a whole can be dynamically calculated and relevant performance indicators (e.g. utilization) are transferred to the fleet evaluation. To address the issue of uncertainty Monte-Carlo simulation can be applied – a sufficient number of simulation runs with varying parameters leads to a distribution of resulting variables. This data can be very valuable since not just a single value but rather a range of values (e.g. min/max, standard deviation) is available. Thus, probabilities can be considered as the base for a conscious risk management.

The simulation approach was implemented in AnyLogic™ 6 – Figure 3 shows the graphical user interface (GUI) of the tool. The GUI eases the configuration of fleets and gives a live view on the fleet behavior of vehicles and the development of performance indicators during the simulation runs.

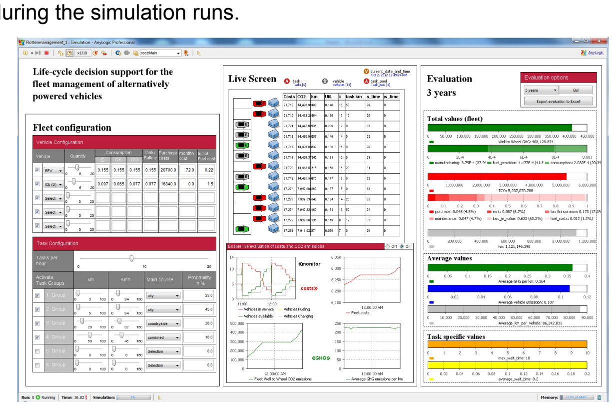

Figure 3: Screenshot from the graphical user interface of the developed simulation tool.

5 CASE STUDY

The aim of the case study is to illustrate how the developed framework can be used to support life-cycle oriented decision-making in fleet planning and to underline why a simulation-based approach bears advantages. To this end, the decision situation, the basic assumptions and data as well as exemplary results are discussed whereas the focus is set on the fleet evaluation.

5.1 Decision Situation

Starting point of the case study is the fleet of a small craftsman company that serves customers by installing sanitary equipment. The company is willing to purchase new vehicles as a replacement. Due to the present discussion about the introduction of Battery Electric Vehicles (BEVs) into corporate fleets, the fleet manager wants to evaluate the advantages and disadvantages of BEVs to know if he should purchase BEVs and if yes, how many. To this end operational, economic and environmental criteria are of interest.

5.2 Basic Assumptions and Data

Table 3 provides an overview on the case study. According to the developed framework, the tasks of the fleet have to be analyzed as a first step in order to derive *fleet applications* and *requirements*. The fleet applications stem from unknown future customer requests. One approximation approach is to assume a probabilistic occurrence of requests based on past data. Thus, in the case study fleet tasks are grouped to four different task groups each of which has a certain probability to occur. The groups are characterized by task-specific variables, such as the distance to drive to the customer, the average speed, the customer service time and the main course which will be driven to get to the customer. It is assumed that the task-specific variables of future requests each follow normal distributions, with the mean values given in Table 3. It is further assumed that the company has to serve five customer requests per hour in average and that vehicles are allocated to tasks based on availability. Thus, a worker can take every vehicle of the fleet to serve a certain request if the remaining range of the vehicle is sufficient to meet the required distance to the customer.

Based on the fleet applications, fleet requirements can be derived. First the vehicle capacity must provide enough space to carry tools and the sanitary equipment. Second, the fleet must be configured so that at best no waiting times occur for customers. Here, the number of fleet vehicles and their range could have significant influence. Besides the fleet is connected with environmental and economic impacts which need to be evaluated for different fleet configurations. Here, TCO and GHG emissions from manufacturing, energy provision and fuel consumption are considered as the three phases form up to 90 % of life-cycle fleet GHG emissions [6].

The *vehicle concepts* of interest are electric and diesel vehicles. For simplicity further vehicles are not considered. The vehicles are specified by the fuel consumption, the tank capacity, the purchase price and operating costs (i.e. fuel costs, maintenance, tax, insurance, battery rent and loss in value). For simplicity, scenarios (e.g. technology, fuel price developments, etc.) are not considered.

Within the *Pre-Selection*, city utility vehicles are of interest to the fleet manager due to the capacity requirement resulting from the fleet tasks. The Renault Kangoo is the only city utility vehicle which is available as BEV and diesel vehicle. Thus, the Kangoo has been chosen for a comparison and vehicle specific data (e.g. purchase price, consumption, tank and battery capacity, etc.) comes from [36]. Estimations have been made regarding the life-cycle GHG emissions based on [6]. Fuel and electricity costs are based on [37] [38]. Tax, insurance and maintenance are based on [39] [40] [41]. The loss in value is estimated to be 20% per year based on [42] for both vehicles as the battery is lent from Renault.

Decision situation						
Small craftsman company wants to evaluate the advantages and disadvantages of BEVs in order to know if to purchase BEVs or not and if yes, how many						
Fleet applications						
Fleet demand	unknown future demand: probabilistic occurrence of requests based on past data; five customer requests per					
Fleet tasks (task-specific variables)	Group	Distance	Speed	Customer service time	Main course	Prob. in %
	1	3	24	30	city	20
	2	5	24	30	city	30
	3	20	28	30	countryside	25
	4	50	45	30	combined	25
Fleet requirements	vehicle capacity; at best no waiting times; low environmental and economic life-cycle impacts					
Vehicle Concepts						
Vehicles to evaluate	electric vehicles and diesel vehicles					
Scenarios						
No scenarios are considered (for simplicity)						
Pre-Selection						
City utility vehicles; Renault Kangoo and Renault Kangoo Z.E.						
Operational perspective						
Vehicle allocation to fleet tasks	random allocation based on availability; range must be sufficiant					
Evaluation						
Evaluation approach	Simulation-based evaluation approach, agent-based simulation					
Operational criteria	waiting times					[Min.]
Economic criteria	fleet TCO (purchase, fuel, rent, tax, insurance, maintenance, loss in value)					[Euro]
Environmental criteria	life-cycle GHG emissions (manufacturing; energy provision;					[CO_2 eq]

Table 3: Overview on the case study.

5.3 Exemplary Results

As suggested above three criteria are used to evaluate the fleet of the craftsman company: waiting times of the customers to be served, TCO and life-cycle GHG emissions of the fleet. As a first step a fixed seed simulation (i.e. a constant utilization plan, see Figure 2) was applied. Figure 4 provides an overview on the average waiting times as a function of the fleet size (left side) and fleet composition (right side). The waiting times can only be determined in a simulation-based approach due to the dynamics which result from the operation of multiple vehicles in the fleet.

The left graph shows that at least five vehicles are required so that customer requests can be served on the same day they occur. Seven vehicles are required so that the average waiting times are less than five minutes. However, to be sure that all customers can be served in time at any time, eleven vehicles would be required given the probability distributions of the task-specific variables. The right side of Figure 4 shows the influence of the fleet composition on the average waiting times for the fleet size of seven to nine vehicles. For eight and nine vehicles the average waiting times remain nearly unchanged with respect to different fleet compositions, i.e. different shares of BEVs in the fleet. However for seven vehicles, a fleet composition of more than two BEVs has a notable influence on the waiting times which rise to more than five minutes. Thus, the limited range of BEVs has an influence on the operational requirements depending on the fleet size.

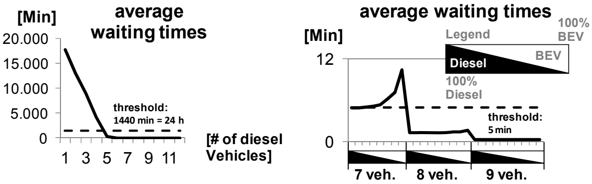

Figure 4: Waiting times with respect to fleet size and composition.

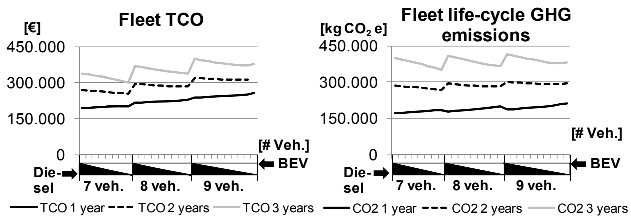

Figure 5: Fleet TCO and GHG emissions.

In Figure 5 fleet TCO and life-cycle GHG emissions are shown depending on the fleet size (from seven to nine vehicles), the fleet composition (from solely diesel vehicles to solely BEVs) and the years the vehicles are operated in the fleet (from one to three years). For the case BEVs should be operated more than one year to be economically and environmentally feasible. This is due to the GHG emissions coming from manufacturing and the purchase costs. It is crucial that this picture is strongly dependant on the vehicle utilization parameters. With less driven km per year, e.g. due to a different fleet application scenario, BEVs might not be a good solution from a cost and environmental perspective also for three years of operation (at least at the moment).

Also, trade-offs between the operational, economic and environmental requirements can be identified depending on the fleet size and composition. This is most obvious for three years of operation. From a TCO and environmental perspective a fleet composition of seven BEVs is the best option in the case due to the high driven km per year, and the relatively low costs as well as emissions per km of BEVs. However, a composition of two BEVs and seven diesel vehicles could be preferable to achieve a lower average waiting time of five minutes (see Figure 4). However, eight BEVs would result in lower GHG emissions and waiting times (1.6 minutes in average) in comparison to five diesel vehicles and two BEVs.

In Figure 6 the TCO and GHG emissions are shown in more detail for the two latter cases. The distribution of the cost factors and emissions is shown and the results of a Monte-Carlo simulation are illustrated in the box-blots. Interpretations are as follows: First, the share of purchase costs and manufacturing emissions rise with a higher share of BEVs in the fleet. Second, five diesel vehicles and two BEVs result in a higher economic risk than eight BEVs due to the higher costs of diesel vehicles per km and the randomly generated fleet tasks. But it is likely that eight BEVs are economically less feasible. Third, the environmental risk is comparable due to slightly lower emissions per km of BEVs compared to diesel vehicles but it is likely that GHG emissions are lower for eight BEVs.

To give a final conclusion to the case, BEVs could have benefits from a life-cycle oriented cost and environmental perspective. However, especially the high investment at the beginning (high purchase costs) and the high environmental impacts of manufacturing might be an obstacle for the fleet manager of the craftsman company. The benefit of BEVs holds only true for the high utilization that is assumed in the specific case with high total

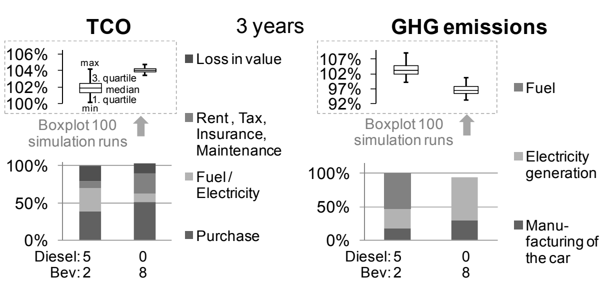

Figure 6: TCO and GHG emissions for two fleet compositions.

driven km per year. Thus, in case of a decline in customer requests the high investment and the high initial environmental impacts due to the manufacturing of the BEVs might not be compensable. This is why a recommendation could be to buy two BEVs and five diesel vehicles although the economic risk was higher in the case. Still, a high utilization of the BEVs can be guaranteed then.

6 CONCLUSION AND FURTHER RESEARCH

In this paper a life-cycle oriented decision support for the planning of fleets is presented – especially for fleets including alternative powertrain vehicles. To this end the necessity to include life-cycle thinking in fleet planning and a brief literature review were the basis for illustrating the developed concept. The concept consists of two modules: The Strategic Management Module focuses on the selection and life-cycle evaluation of fleet configurations. In the Operational Management Module, the performance and behavior of the fleet with all its individual vehicles can be simulated. Finally, a short case study serves to show the application of the concept and underline the benefits of a simulation.

As for now the concept has been illustrated within a small case study while considering a small fleet of a craftsman company. Next steps are the following: first, larger heterogeneous fleets and more heterogeneous fleet applications must be considered. Here, it is expected that especially the simulation approach can bring new insights into the behavior of real fleets and the resulting fleet life-cycle emissions and costs. Second, the allocation of vehicles to fleet applications was very much simplified as it was based on availability. Here, more sophisticated allocation approaches must be considered. Third, more elaborated Monte-Carlo Simulations must be applied so that the risk evaluation can be improved. Finally, no scenarios were considered and sensitivity analysis is due so far. This can result in insights on the sensitivity of life-cycle emissions and costs on the variability of single parameters, e.g. fuel costs.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] Bae, S. H.; Sarkis, J.; Yoo, C. S. (2011): Greening transport-tation fleets: Insights from a two-stage game theoretic model, in: Transport. Research E, Vol. 47, pp. 793–807.

[2] Bundesministerium für Verkehr, Bau und Stadtentwicklung (Hrsg.) (2009): Verkehr in Zahlen 2009/2010, Hamburg.

[3] Haller,M. et al. (2007): Economic costs and environmental impacts of alternative fuel vehicle fleets in local government: An interim assessment of a voluntary ten-year fleet conversion plan, in: Transport. Research D, Vol. 12, pp. 219-230.

[4] Urbschat, M. V.; Bernhart, W. (2009): Powertrain 2020 – The Future Drives Electric, Roland Berger Strategy Consultants.

[5] Hill, N. et. al (2012): EU Transport GHG: Routes to 2050 II. The role of GHG emissions from infrastructure construction, vehicle manufacturing, and ELVs in overall transport sector emissions, **www.eutransportghg2050.eu**, last upd. on Nov. 12.

[6] Helms, H.; Jöhrens, J.; Hanusch, J.; Höpfner, U.; Lambrecht, U.; Pehnt, M. (2011): UMBReLA. Umweltbilanzen Elektromobilität, Ergebnisbericht. Heidelberg.

[7] Bielli, M.; Bielli, A.; Rossi, R. (2011): Trends in Models and Algorithms for Fleet Management, in: Procedia Social and Behavioral Sciences, Vol. 20, pp. 4-18.

[8] Jabali, O.; Gendreu, M.; Laporte, G. (2012): A continuous approximation model for the fleet composition problem, in: Transport. Research B, Vol. 46, pp. 1591-1606.

[9] Nurminen, M. A.; Pojasek, R. B. (2012) - Driving Sustainability and Risk Management: How Companies Can Improve Fleet Vehicle Purchasing, in: Environmental Quality Management.

[10] Neubauer, J.; Brooker, A.; Wood, E. (2012): Sensitivity of battery electric vehicle economics to drive patterns, vehicle range, and charge strategies, in: Journal of Power Sources, Vol. 209, pp. 269-277.

[11] Herrmann, C. et al. (2012): The Transition to Alternative Powertrains - Concept for the Life-Cycle-oriented Symbiosis of Technology, Product and Product Portfolio Planning, in: International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (ASME 2012), Chicago, August 12-16, 2012.

[12] Li, X.; Leung, S. C. H.; Tian, P. (2012) - A multistart adaptive memory-based tabu search algorithm for the heterogeneous fixed fleet open vehicle routing problem, in: Expert Systems with Applications, Vol. 39, pp. 365-374.

[13] Liu S.; Huang, W., Ma, H. (2009) - An effective genetic algorithm for the fleet size and mix vehicle routing problems, in: Transport Research E, Vol. 45, pp. 434-445.

[14] Repoussis, P. P.; Tarantilis, C.D. (2010): Solving the Fleet Size and Mix Vehicle Routing Problem with Time Windows via Adaptive Memory Programming, in: Transport. Research C, Vol. 18, p. 695-712.

[15] Bektas, T.; Laporte, G. (2011): The Pollution-Routing Problem, in: Transport. Research B, Vol. 45, pp. 1232-1250.

[16] Erdogan, S.; Miller-H., E. (2012): A Green Vehicle Routing Problem, in: Transport. Research E, Vol. 48, pp. 100-114.

[17] Parthanadee, P.; Buddhakulsomsiri, J.; Charnsethikul, P. (2012) - A study of replacement rules for a parallel fleet replacement problem based on user preference utilization pattern and alternative fuel considerations, in: Computers & Industrial Engineering, Vol. 63, pp. 46-57.

[18] Shrake, S. O. et al. (2010): A comparative analysis of performance and cost metrics associated with a diesel to bio diesel fleet transition, in: Energy Pol., Vol. 38, pp. 7451-7456.

[19] Corts, K. S. (2010): Building out alternative fuel retail infrastructure: Government fleet spillovers in E85, in: J. of Env. Economics and Management, Vol. 59, pp. 219-234.

[20] Michiels, H.; Beckx, C.; Schrooten, L.; Vernaillen, S.; Denys, T. (2012) - Exploring the transition to a clean vehicle fleet: From stakeholder views to transport policy implications, in: Transport Policy, Vol. 22, pp. 70–79.

[21] Golob, T. F.; Brownstone, D.; Bunch, D. S. (1997): Commercial fleet demand for alternative-fuel vehicles in California, in: Transpn. Res.-A, Vol. 31, No. 3, pp. 219-233.

[22] Nesbitt, K.; Sperling, D. (2001) - Fleet purchase behavior: decision processes and implications for new vehicle technologies and fuels, in: Transport. Research C, Vol. 9, pp. 297-318.

[23] Stasko, T. H.; Gao, H.O. (2012): Developing green fleet management strategies: Repair/retrofit/replacement decisions under environmental regulation, in: Transport. Research A, Vol. 46, pp. 1216-1226.

[24] Simms, B. W.; Boudreau, A. (1984): Optimal buy, operate and sell policies for fleets of vehicles, in: European Journal of Operational Research, Vol. 15, pp. 183-195.

[25] Li, Z.; Tao, F. (2010): On determining optimal fleet size and vehicle transfer policy for a car rental company, in: Computers & Operations Research, Vol. 37, pp. 341-350.

[26] Song, D.-P.; Earl, C. F. (2008) - Optimal empty vehicle repositioning and fleet-sizing for two-depot service systems, in: European Journal of Operational Research, Vol. 185, pp. 760-777.

[27] George, D. K.; Xia, C., H. (2011): Fleet-sizing and service availability for a vehicle rental system via closed queueing networks, in: European Journal of Operational Research 211, pp. 198-207.

[28] Couillard, J. (1993) - Decision support system for vehicle fleet planning, in: Decision Support Systems, Vol. 9, pp. 149-159.

[29] Lima, C. M. R. R.; Goldbarg, M. C.; Goldbarg, E. F. G. (2004): A Memetic Algorithm for the Heterogeneous Fleet Vehicle Routing Problem, in: Electronic Notes in Discrete Mathematics, Vol. 18 pp. 171-176.

[30] Topaloglu, H. (2006) - A parallelizable dynamic fleet management model with random travel times, in: European Journal of Operational Research, Vol. 175, pp. 782-805.

[31] Salhi, S.; Rand, G. K. (1993): Incorporating vehicle routing into the vehicle fleet composition problem, in: European Journal of Operational Research, Vol. 66, pp. 313-330.

[32] Herrmann, C.; Kara, S.; Thiede, S. (2011): Dynamic life cycle costing based on lifetime prediction. International Journal of Sustainable Engineering.

[33] Thiede, S.; Spiering, T.; Kohlitz, S.; Herrmann, C.; Kara, S. (2012): Dynamic Total Cost of Ownership (TCO) Calculation of Injection Moulding Machines, In: Proceedings of the 19th CIRP Conference on Life Cycle Engineering, Berkeley, USA, Springer, 2012, pp. 275-280.

[34] Fleischer, J., Wawerla, M., Niggeschmidt, S. (2007): Machine life cycle cost estimation via Monte-Carlo simulation, in: Proceedings of the 14th CIRP conference on life cycle engineering 2007, Tokyo. Springer, pp. 449–453.

[35] Kleyner, A. and Sandborn, P. (2008): Minimizing life cycle cost by managing product reliability via validation plan and warranty return cost, in: International Journal of Production Economics, Vol. 112, No. 2, pp. 796–807.

[36] Renault (2012): **www.renault.de**, last updated on Nov. 2012.

[37] Mineralölwirtschaftsverband (2012): Statistiken - Preise, Monatliche Verbraucherpreise für Mineralölprodukte, **http://www.mwv.de**, last upd. on Nov. 12..

[38] Eurostat (2012): Strompreise für industrielle Verbraucher EUR je kWh, **http://epp.eurostat.ec.europa.eu/**, last upd. on Nov. 12.

[39] Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie (NOW) (Hrsg.) (2010) - Ein Portfolio von Antriebssystemen für Europa, **www.now-gmbh.de**, last upd. on Nov. 12.

[40] Bundesministerium der Justiz (2010): Kraftfahrzeugsteuergesetz, **www.gesetze-im-internet.de**, last upd. on Nov. 12.

[41] Der Autokostencheck - wie teuer ist mein Auto im Unterhalt?, available: **www.autokostencheck.de**, last upd. on Nov. 12.

[42] ADAC (2012): ADAC Autokosten 2012, available: **www.adac.de/_mmm/pdf/autokostenuebersicht_m-r_47088.pdf**, last upd. on Nov. 12.

A Case-Based Reasoning Approach to Support the Application of the Eco-Design Guidelines

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Abstract

The product eco-sustainability is recognized as a key factor for competitive products and recently, lots of international directives (guidelines) have been issued. However, in literature does not exist research on the practical application of the guidelines during the design phase. The paper aims to define a new approach to support the product design, applying the most common eco-design guidelines integrated with the designers past experiences. This approach consists in a Case-Based Reasoning tool containing a repository of eco-design guidelines and knowledge relative to the past designers experience. The approach has been tested during the re-design process of a cooker hood.

Keywords:

Eco-sustainability; eco-design guidelines; CBR

1 INTRODUCTION

In the last years, the environmental problem has become very serious due to the vertiginous growth of the world population and to the increase of the discard rate of goods. In this troublesome global context, it is necessary to consider the concept of sustainability, which was defined for the first time twenty-five years ago [1]. Only applying the eco-design approach it is possible to design and manufacture “green” sustainable products, but usually these important concepts are not applied by companies which tend to follow the classical criteria of the design process, such as costs or technical requirements.

Recently, International organizations have issued an high number of normative, standards and technical reports about the environmentally conscious design [2][3][4]. This highlights the extreme importance of the environmental issues. However, all these documents only suggest to companies some general indications and guidelines about the aspects which is necessary to take into account. The most critical matter is that they do not clearly provide a strategy to easily integrate eco-design in the traditional product design and development processes. For these reasons, designers cannot implement an efficient strategy to improve the sustainability of their products. The result is the unavoidable lack of application of the eco-design approach in manufacturing companies.

The present paper aims to provide a contribution to this topic. The proposed approach allows designers to consider the indications given by the well-known eco-design guidelines in a rapid and efficient way. In fact, the link between the general guidelines and the knowledge about past design choices, obtained by the use of a Case Based Reasoning approach, permits to guide the designer in the choice of the most proper solution. Only in this way it is possible to implement an effective eco-design approach, without increasing the product development time which is always limited.

2 STATE OF THE ART

As reported in the Chambers' English Dictionary, a guideline is "*an indicator of a course that should be followed, or of what future policy will be*". From the literature it is possible to notice that eco-design guidelines often provide general indications related to different stages of the design process and to different phases of the product life cycle. Recent research works aims to contextualize the general eco-design guidelines to specific design phases, as the material choice [5], or to specific products, as rail vehicles [6], in order to facilitate their implementation during the product development process. The importance of developing specific guidelines and checklist for product typology is also highlighted in [7]. Even if the general guidelines are valid for a wide number of products, they really do not provide a tangible support to the designer which has to take decisions.

Even if lots of researches have been done to contextualize the general guidelines, transforming them in specific ones, the further challenge consists in their practical implementation during the Product Development Process. The medicine was one of the first field where the problem of the guidelines implementation has been recognized [8]. *Wensing et al.* [9] write how “*It is crucial that research findings are implemented in general practice…*”. In [10] are presented the most common barriers during the guidelines implementation, for the medical sector (i.e. changing current practice model lack of trust in evidence or research).

In the industrial sector, the literature proposes different methods to foster the guidelines implementation. *Regazzoni et al.* [11] present a structured set of eco-guidelines based on TRIZ theory with the aim to support designer improving a product, a process or a service according with eco-parameters. Each eco-TRIZ guideline has been structured as a set of questions followed by a set of operative rules. Even if this method is a step beyond the traditional methods for the eco-design guideline, it doesn’t consider the knowledge the designer acquire during the development of new products. The past experience is useful for the designers to estimate how the product eco-sustainability changes after the implementation of the suggestions proposed by the guidelines. In [12] the CBR (Case-Based Reasoning) and TRIZ methods have been linked defining a new model to acquire innovative ideas more easily to design eco products. A CBR system connects the innovative idea to the cases located in a database to accelerate the product innovation process. The proposed method, even if it provides tangible benefits for the development of innovative products, doesn’t provide a strong support to the eco-design guidelines. CBR is historically a very useful method for the knowledge management. Its application ranges among different fields, such as the workflow exception management [13][14] and manufacturing cost estimation [15].

In the field of the knowledge management, the knowledge elicitation and modeling phase is crucial during the definition of a method or a tool. Houe and Grabot [16] propose a tool to verify the compliance of a product with a set of norms and standards. It is also presented how the knowledge contained in standards and norms in textual form can be translated into constraints which can be propagated through the product structure in order to identify the inconsistencies between the present design and a given norm.

According to the proposed literature review, a method or tool to manage the eco-design knowledge to support the implementation of the specific eco-design guidelines, during the design/re-design of a product, is lacking. Using this kind of method, the designer is able to develop eco-friendly products knowing in advance the improvements to implement in respect to a standard product, and the relative environmental impacts.

3 METHODOLOGY AND IMPLEMENTATION

The methodology is based on the definition of an eco-design tool which helps designers during the design phase of a product, through the consultation of a set of eco-design guidelines and eco-knowledge, considering all aspects related to the environmental impact of products in order to improve their eco-sustainability.

3.1 Eco-Design Guidelines and Eco-Knowledge

Modular Analysis and Definition of Standard Components

With the aim of describing products through a schematic structure, a preliminary modular analysis for different product categories, is proposed as starting point of this work. In particular the analysis is realized for different mechatronic product families in order to define for each of them a list of standard components, that can be defined as all those components that can be found in different modules of a specific product family. They have general validity for the particular product families to which are related and can be considered representative for them. This approach allows to describe a product as a set of standard components to which designers refer in the design process of different models of the same product family. Considering the cooker hood, which is the case study of this research, the modular analysis identify the following modules: motor/impeller, blower, cover, electricity supply, electronic control board, filters, lamps, supports, others. The standard components identified for the cover module are, chimney, cover and aesthetic panel.

Eco-Design Guidelines and Their Classification

The analysis of the literature related to this topic shows that exists a high number of eco-design guidelines and that they often provide to designers general indications related to different stages of the design process and to different phases of the product life cycle [17].

This generality makes from one side the eco-design guidelines referable to a lot of different product families, but on the other side, do not guarantee an efficacious consultation of them by designers, and above all an effective translation of them into design choices.

For these reasons, in order to facilitate the guidelines consultation and to make them useful for designers, each specific eco-design guideline retrieved from the state of the art [18][19] is classified on the basis of the life cycle phase to which it is related, the objective that it aims to reach and the standard component to which it is connected. Eco-design guidelines can be at first subdivided in guidelines related to products and to components.

Eco-design guidelines related to products are all those indications that can be associated to different product families, and that provide general recommendations valid for different products. By the consultation of these general eco-design guidelines, designers can have a first overall vision of the best design choices for the product under analysis and can reflect on its general criticalities. This typology of guidelines is not referred to a specific life cycle phase, but can concern different specific stages of product life cycle and different phases of the design process. Table 1 shows some example of general guidelines related to products.

General eco-design guidelines related to components, instead, can be divided further on general and specific indications. The general ones are referable to almost all components of different product families and provide suggestions about specific components of a product. Designers can use these advices to understand how to improve components, in terms of environmental sustainability. General eco-design guidelines related to components are referred to different life cycle phases of the product, from material selection, to end of life. An important consideration is that not all these guidelines can be related to all the components, in fact the suggestions concerning the use phase, like for instance "Prefer high efficiency components" can be referred only to energy using components (e.g. electronic motor, lights) and not to the others (e.g. covers, supports, etc..). In Table 2, some examples of general guidelines related to components are shown.

GENERAL GUIDELINE	LIFE CYCLE PHASE	OBJECTIVE
Minimize component number	Material selection, Production process, End of life	Improve product recyclability, Minimize disassembly time
Minimize material types used in the product	Material selection, End of life	Improve product recyclability, Minimize disassembly time
Optimize product functionality	All life cycle phases	Increase product life time
Prefer simply, easily dismountable and reparable parts	Material selection, Production process, End of life	Improve product reparability, improve disassemblability of the product, Improve product reparability

Table 1: General guidelines related to products.

GENERAL GUIDELINE	LIFE CYCLE PHASE	OBJECTIVE
Prefer high quality materials	Material selection, Use, End of Life	Minimize component weight, Reduce wear in the use phase, increase product lifetime.
Avoid toxic substances	Material selection	Minimize component toxicity
Use a low number of material and prefer the use of the same material in different parts of the product	Material selection	Increase product recyclability
Avoid the use of alloy and composite materials	Material selection	Increase product recyclability, Minimize disassembly operations

Table 2: General guidelines related to components.

Specific eco-design guidelines related to components derive from EuP directives and are associated to the specific components of the specific product family (e.g. cooker hoods, washing machines, refrigerators, etc…). These specific guidelines are referred principally to the use phase and aim to minimize the energy consumption of the energy using components and as a consequence of the whole product.

Knowledge Definition

The knowledge is composed by all the choices made by designer during the design process of a product and its components. In particular during the design process, designer registers all the design choices related to a specific component into the tool database, by recording choices correlated to all the different life cycle phases of the product. These choices can be related to material selection, dimensions, chemical and physical properties, production processes, transportation and end of life strategies adopted. Another important tool functionality is that designer can memorize also information related to the environmental impact of the choices made (that can concern all the different life cycle phases above mentioned), through the annotation of impact indicators related to each of them and obtained from the realization of an LCA analysis.

Due to the possibility to consult the correlation between design choices to their environmental impact, designers, by examining data stored in the CBR tool, have in fact the capability to rapidly understand how to modify a component or a product to improve its performances. It is important to underline that the tool functionalities can become a valid support for designer if a significant quantity of data is stored in it; in this a high number of information are available for designers, allowing to compare different options in order to choose the most environmental sustainable one.

3.2 Approach: Application of the Eco-Design Guidelines through the Use of Past Design Choices

The proposed approach is oriented to promote the use of the well-known eco-design guidelines during the design process of a product. The main features is to link the guidelines with the knowledge about past design choices done in similar cases. For this reason a Case Based Reasoning approach has been used to consider and easily retrieve the company know-how. In this way, the designer is guided in the product modification with the aim of improving the sustainability.

The starting point of this approach is an analysis of the environmental impact of a product, which allow to assess the sustainability of the current design solution. Depending on the scope of the study, a designer can perform a full LCA, if he has all the huge amount of required information, or a simplified LCA, if he does not know some aspects of the product lifecycle. The results of these analysis can be used to clearly identify the “hot spots” which have to be considered for the product redesign.

The designer focuses his attention on a particular component or functional group, such as the aesthetical panel of a cooker hood, the electric motor or the cover panel of a washing machine. The general purpose of the designer is to improve the environmental performance of the chosen component. The chosen component can be linked to one of the standard component which has been classified in this work (see section 2.1). This assignment permits to retrieve and use all the past design solutions from the knowledge database. In this way the approach and the related tool can suggest to the user only the choices related to similar components or functional groups.

Frequently the designer is mainly interested in a particular life cycle phase. In fact, for the different components of a product not all the life cycle phases are critical in terms of environmental impact. For example, if we consider an electric motor the most critical phase is certainly the use phase due to the electrical energy consumption. Instead, if we consider a moulded plastic component or a sheet metal component, probably the most important phases to take into account are the material selection and the manufacturing phase, while the use phase can be neglected. Given that both the eco-design guidelines and the past design choices are classified specifying a life cycle phase which they are referred to, the tool can easily filter the database in order to retrieve only the information which is interesting to help designer in solve his problems. This is the first important link between the well-known guidelines and the know-how acquired by the company.

Together with the life cycle phase which has to be improved, the designer usually consider an objective that wants to reach with the redesign of the chosen component or functional group. As reported above in this section, for all the knowledge stored in the CBR database, one or more objectives are specified. This is the second important link between the guidelines and the company knowledge. Thanks to this, another important filtering operation can be performed by the tool in order to provide to the user only the necessary and most interesting indications to improve the product performances. In this way, the user can be effectively guided in the redesign operations of a product component or functional group. The approach presented in this paper is depicted in Figure 1 which represents the workflow and the filtering operations which permit to orientate the designer choices through the link between eco-design guidelines and past design solutions.

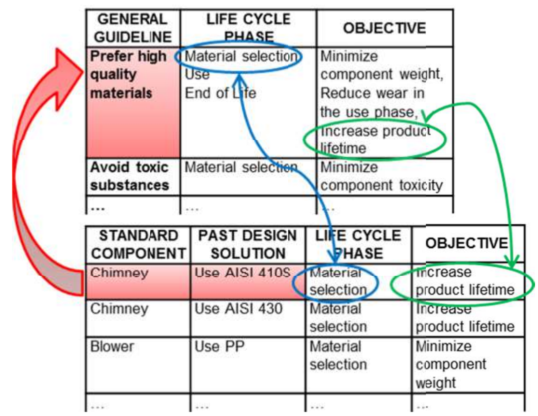

Figure 1: General workflow of the approach.

Therefore, the described approach is based on the CBR methodology. The process of solving design problems about environmental issues is implemented with the application of the four classical steps:

1. Retrieve phase: the designer chooses a component which wants to improve. He also has to specify a phase of the life cycle of which directs the attention and a particular objective that wants to reach. In this way the knowledge stored in the database can be filtered to provide to the designer only solutions related to past similar cases.
2. Reuse phase: the designer analyzes the proposed solutions and chooses the most interesting for its particular case. Obviously he has to take into account not only the environmental problems but also all the design constrains such as performances, manufacturing issues, technical and aesthetical requirements, costs and so on. In this phase the designer can also partially modify the chosen solution in order to apply to the present case.
3. Revise phase: the designer verifies the effect of the application of the chosen solution. In the context of eco-design, the verification can be performed by an S-LCA analysis in order to compare the previous and the new design solutions. Usually this is an iterative process which permits to reach the best compromise between the sustainability of the product and all the other constrains considered during the design.
4. Retain phase: after the best solution has been found, the CBR system is able to automatically store the design choices as a new successful case. The designer has to specify the objective which was reached by the application of these choices. He can also enhance the knowledge specifying the values of the environmental impact indicators which was obtained for the component or functional group under analysis. In this way, during future redesign of similar products, the designer will have a quantitative result for the application of each particular choice.

However, the presented CBR approach does not consider only the design choices made by company designers in the past, but it also involves the eco-design guidelines. The link between them and the knowledge about past solutions, realized thanks to the attributes objective and life cycle phase in which they are both classified in the database, allows the designer to easily apply the well-known guidelines. In fact, when the designer decides to apply a particular choices, retrieved from the database, at the same time he applies one or more eco-design guidelines which are linked to the chosen solution (see Figure 1). This is a very important characteristic of this approach because permits to know how to apply a particular guideline. Mostly designers know very well the eco-design guidelines but have difficulty to apply them. For this reason, eco-design requirements are usually ignored during the design process, when time is limited and designers have to satisfy many other design constraints. This approach, instead, is able to drive the designer choices in the correct way, helping him in the application of an effective eco-design strategy.

3.3 Implementation

In this paragraph the CBR implementation is described and the proposed architecture is examined though the identification of the different modules and the interaction among them. Figure 2 shows the CBR tool architecture, which is composed by connected modules having the function of acquire/manage the knowledge and the guidelines in order to give to the user indications for the product eco-design process.

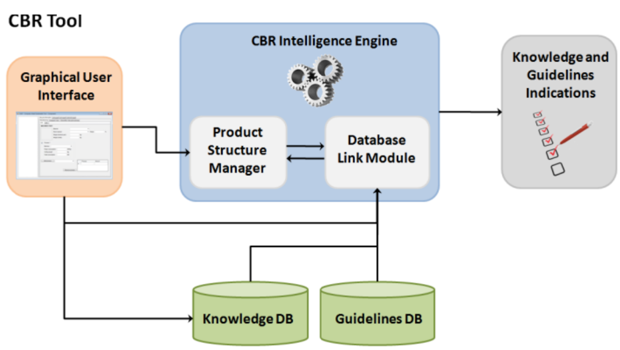

Figure 2: CBR tool architecture.

The core module of the CBR tool is the “CBR Intelligence Engine” which include two sub-modules, the “Product Structure Manager” and the “Database Link”. The first has the aim of managing the product structure, composed by assemblies, sub-assemblies and components, the second has the role of connecting the knowledge and guidelines databases and manage these information.

The information used to perform the output of the tool are stored in the mentioned databases, the eco-design guidelines identified in the previous paragraph are contained in the database with all the attributes already described. The knowledge database stores the past choices made in the product design process for all the lifecycle phases, for its nature these data cannot be embedded in the tool but needs to be loaded by the user basing on the experience.

The “Graphical User Interface” (GUI) module allows the user to insert all the information required to perform the output of the CBR tool, the product structure can be compiled by the user and made available to the CBR intelligence engine. Also the knowledge database can be populated through the user interface, by the input of the choices made for all the lifecycle phases of the product. The GUI is structured in two different sections: a product structure section which allow to create a new structure or edit an existing one from a CAD model, the other section is dedicated to the knowledge compilation, allowing to select the choices made in the product design process for the different lifecycle phases. This information regards the material, the manufacturing processes, the transportations, the energy demand and other flows concurring in the product use phase and the final end of life treatment, which can be recycling, incineration, reuse and others.

The knowledge as already mentioned in the previous paragraph, can include as attributes the environmental impact associated to the product and its components. The environmental impact is represented by different indicators coming from an LCA analysis. These optional information can be manually added to the knowledge by GUI using data coming from LCA analysis conducted with specific tools.

The product knowledge compilation as already described is, at this stage of implementation, completely manual using the GUI except the possibility to import the product structure form a CAD model. The knowledge can also be retrieved from the tools used in the product design process, CAD model contain the product structure, component materials and other useful information. PLM tools store product lifecycle data, form material choice to commercial components and other useful information which can be helpful in the redesign of a new product or component. In the product design process a wide range of dedicated tool are used to assist the engineer in the definition of the product and component data, from these tools is possible to extract these data and store them in the knowledge database. Some examples of tools used in the design process are those specific for material selection, for the calculation of cost and environmental impact, for the management of product information and others. Also the environmental information, which comprise the results of the LCA analysis of products and components, as obtained by means of specific tools can be automatically extracted by these tools and stored in the knowledge database together with the other attributes that make up each database record.

The last module of the CBR tool is the “Knowledge and Guidelines Indications”, this is the module which show the output of the tool in terms of helpful indications for the user to be taken into account in the eco-design process. The output is composed by guidelines classified by lifecycle phase and the stored knowledge for each standard component of the product to be designed, the user can organize and show this information by different ways in order to understand and retrieve helpful data for the improvement of the environmental performances.

4 RESULTS DISCUSSION

In order to test the effectiveness of the tool, its application on a redesign of a cooker hood is proposed in this paragraph. Cooker hood represents a basic house hold appliance, with simple components that can permit to completely valid the experimentation. The proposed work-flow for the tool application is composed by these several steps: a preliminary environmental analysis of the product examined, an evaluation of its major criticalities and finally, the modification of the product by following the suggestions provided by the tool.

The analysed cooker hood is a basic model product, made by an Italian company, with these principal characteristics: Maximum air flow: 660 m^3/h, Maximum power consumption: 230W, Lighting devices: 2 x 20 W halogen lamps.

The cooker hood environmental analysis is realized by the use of an S-LCA commercial tool, CES Selector 2012, (ECO-AUDIT module by Granta Design Ltd), and its environmental impact in terms of Energy and CO2 Footprint of the whole life cycle (subdivided in

Material, Manufacturing, Transport, Use and End-of-life phases) is determined. The S-LCA Analysis results are useful to understand where the major environmental impacts are located and as a consequence the environmental criticalities for the analysed cooker hood. In this case, the results, shown in the Figure 5 and 6 allow to individuate the lifecycle phases and components where it is necessary to focus the attention:

- Use Phase: Electric motor (Single-phase AC asynchronous motor) and halogen lamps. These are the energy using components, responsible of energy consumptions in the hood;
- Material Selection Phase: Chimney, cover, aesthetic panel, which are the components which represent the most relevant amount in weight of the whole product.

From these criticalities, the suggestions provided by the general guidelines related to the use phase and the specific eco-design guidelines for the cooker hood, suggest to use motor and lamps with high efficiency. Brushless motor and led lamps can be considered as components with a higher efficiency than the components currently installed in the hood (Single-phase AC asynchronous motor and halogen lamps), and can be taken as possible alternatives of them. In this case also the company knowledge stored in the tool, suggests that the use of brushless motor and led lamps typology, that company installs on higher class model of hoods, determines a smaller environmental impact if compared with the impact of Single-phase AC asynchronous motor and halogen lamps. The proposed modifications, if analysed in terms of environmental impact, determine a significant reduction both in energy consumptions and CO_2 emissions as shown in Figure 3, where with "current solution" the existing cooker hood, and with "alternative solution" the redesign hypothesis are indicated.

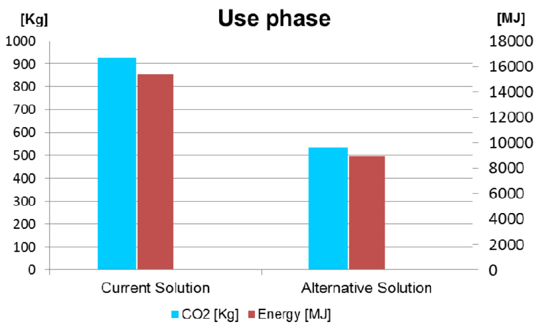

Figure 3: Environmental impact comparison for the use phase.

Concerning components with a high environmental impact on the material phase, general eco-design guidelines related to material selection phase are considered and the modification on materials is proposed for chimney, cover, and aesthetic panel. All of these components, which represent the most relevant amount in weight of the whole product, are now realized in Anodized Steel AISI 430. Related to materials, also in the company knowledge, are stored different solutions, each of them characterized by a precise environmental impact. By considering many characteristics, such as chemical, physical and mechanical properties, cost, energy consumption and emission during the manufacturing processes, energy consumption during the dismantling processes, the alternative material chosen is the Wrought Annealed AISI 410S.

If its use is hypothesized for the analysed components, it will guarantee a lower environmental impact if compared with the material of the hood current solution, as it is shown in Figure 4.

A further environmental impact analysed is that determined by the transport phase, which even if, do not represent a significant term if compared with the impact of the use phase, can be drastically reduced. In this case, general eco-design guidelines for the transport phase and company knowledge related to the environmental impact associated to different suppliers are followed, and the improvement of the product is realized by the selection of local suppliers. In particular Italian suppliers are chosen for electric motor and lamps, which, before the redesign analysis were bought from China. All the modifications proposed for the cooker hood and related to the application of the eco-design guidelines and company knowledge stored in the tool, are summarized in Table 3.

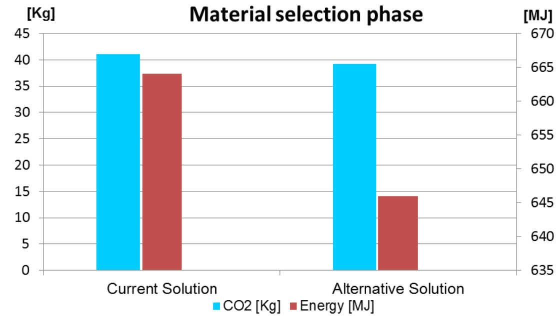

Figure 4: Environmental impact comparison for the material selection phase.

Component	Modification	Description of modifications
Chimney, cover and aesthetic panel	Material	From Anodized Steel AISI 430 to Wrought Annealed AISI 410S
Motor	Typology	From Single-phase AC asynchronous motor to Brushless typology
	Supplier	From Chinese to Italian
Light	Typology	From Halogen to LED
	Supplier	From Chinese to Italian

Table 3: Summary of the applied modifications.

Figure 5 and Figure 6 show the S-LCA analysis results for the current hood solution and for the redesigned one.

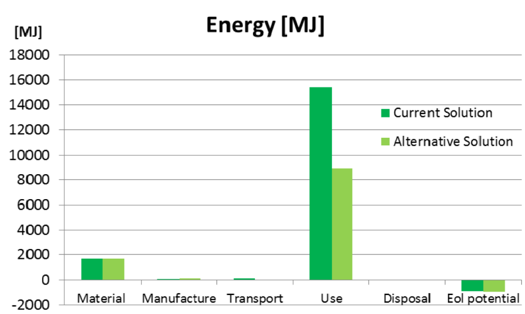

Figure 5: Energy consumption indicator comparison.

The redesign process of the cooker hood is performed following the proposed approach. The implementation of these suggestions has determined a significant reductions in the environmental impact of the cooker hood. Analysing the reduction for the use phase, which is the phase with the highest environmental impact of the whole product, we can notice that it is about of 44%, both for the CO_2 emissions and the Energy consumption.

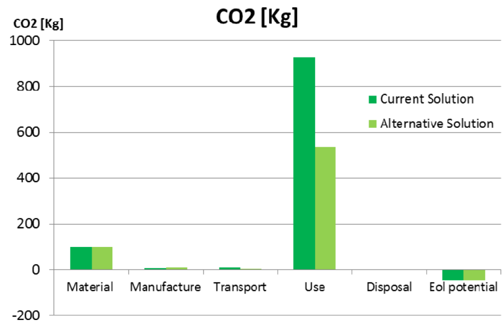

Figure 6: CO2 emission indicator comparison.

5 CONCLUSIONS

This paper presents a new approach to support the product design, applying the most common eco-design guidelines integrated with the designers past experiences. This approach has been implemented through CBR methodology, developing a tool which allows to support the environmental aspects in the design process.

The proposed approach allows to overcome the difficulty to apply ecodesign guidelines in the design process, giving to designers a tool which supports this task.

The tool has been tested in the redesign of a cooker hood. The results shown highlight a significant reduction of the environmental impact, in particular for the use phase.

Since this research work is part of a larger project (G.EN.ESI), the main improvement for the proposed tool will consist in its integration in an ecodesign platform, which allows to automatically retrieve the company knowledge and environmental impacts from other platform tools used in the design process. Further works will deal with the definition of new and more specific guidelines and applying the approach for other mechatronic product families.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] United Nations – World Commission on Environment and Development, 1987. Our Common Future. Oxford University Press, London, United Kingdom.

[2] International Standard Organization: Environmental management - Integrating environmental aspects into product design and development (ISO/TR 14062:2002).

[3] International Standard Organization: Environmental management systems - Guidelines for incorporating ecodesign (ISO 14006:2011).

[4] Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products (Text with EEA relevance).

[5] Pierini, M., Schiavone, F. (2006): From Life Cycle Assessment to Systematic Integration of Eco-Design Criteria Inside Product Development Process: Experience at a First Tier Automotive Supplier, in: XIII CIRP International Conference Life Cycle Engineering (LCE2006), pp. 201–206, Leuven – Belgium.

[6] Lagerstedt, J., Luttropp, C. (2006): Guidelines in ecodesign: a case study from railway industry, Innovation in Life Cycle Engineering and Sustainable Development, D. Brissaud, S. Tichkiewitch, and P. Zwolinski, eds., Springer Netherlands, pp. 245–254.

[7] Vezzoli, C., Sciama, D. (2006): Life Cycle Design: from general methods to product type specific guidelines and checklists: a method adopted to develop a set of guidelines/checklist handbook for the eco-efficient design of NECTA vending machines, Journal of Cleaner Production, Vol. 14, No. 15-16, pp. 1319–1325.

[8] Wallace, M., Shorten, A. (2005): The challenge of implementing clinical guidelines, Evidence-based Healthcare and Public Health, Vol. 9, No. 4, pp. 276–277.

[9] Wensing, M., Van Der Weijden, T., Grol R. (1998): Implementing guidelines and innovations in general practice: which interventions are effective?, The British journal of general practice: the journal of the Royal College of General Practitioners, Vol. 48, No. 427, pp. 991–7.

[10] Spallek, H., Song, M., Polk, D. E., Bekhuis, T., Frantsve-Hawley, J., Aravamudhan, K. (2010): Barriers to Implementing Evidence-Based Clinical Guidelines: A Survey of Early Adopters, Journal of Evidence Based Dental Practice, Vol. 10, No. 4, pp. 195–206.

[11] Regazzoni, D., Rizzi, C, Russo, D. (2009): TRIZ-Driven ECO-Design and Innovation, in: International Conference on Research into Design, ICoRD'09, pp. 105-112, Bangalore, India.

[12] Yang, C. J., Chen, J. L. (2011): Accelerating preliminary eco-innovation design for products that integrates case-based reasoning and TRIZ method, Journal of Cleaner Production, Vol. 19, No.9-10, pp. 998–1006.

[13] Weber, B., Wild, W., Breu, R. (2004): CBRFlow: Enabling adaptive workflow management through conversational case-based reasoning, in: Proceedings of the 7th European Conference for Advances in Case Based Reason (ECCBR'04), Vol. 3155, pp. 434-448, Madrid, Spain.

[14] Mengoni, M., Graziosi, S., Mandolini, M., Peruzzini, M. (2010): A knowledge-based workflow to dynamically manage human interaction in extended enterprise, International Journal on Interactive Design and Manufacturing, Vol. 5, No. 1, pp. 1–15.

[15] Duverlie, P., Castelain, J. (1999): Cost estimation during design step: parametric method versus case based reasoning method, International Journal of Advanced Manufacturing Technology, Vol. 15, pp. 895-906.

[16] Houe, R., Grabot, B. (2007): Knowledge Modeling for Eco-design, Concurrent Engineering, Vol. 15, No. 1, pp. 7–20.

[17] Bonvoisin, J., Mathieux, F., Domingo, L., Brissaud, D. (2010): Design for energy efficiency: proposition of a guidelines-based tool, in Proceeding of International Design Conference, France.

[18] Active Disassembly Research, Design for Disassembly Guidelines, http://www.activedisassembly.com (January 2005).

[19] Austrian ECODESIGN Platform, http://www.ecodesign.at (November 2012).

Integrated Software Platform for Green Engineering Design and Product Sustainability

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Abstract

Nowadays, industrial products, particularly household appliances, are strongly related to environmental issues. Due to high levels of uncertainty regarding design embodiments at the early design phase, new methods and tools are essential to provide designers a basis to determine the degree of sustainability of a given product. The paper aims to integrate eco-design activities within the traditional flow of the product design process through the development of an integrated software platform which supports the decision-making task for product sustainability in the early phase of product design.

Keywords:

Eco-design; Design for Environment; Product Development Process

1 INTRODUCTION

Nowadays, industrial products, particularly household appliances, are strongly related to environmental issues. Energy consumption in the residential/domestic sector makes up about 20% of world consumption, and furthermore greenhouse gas emissions coming from this sector exceed 35%.

Currently, there is an increasing worldwide need for products and services which are qualified in terms of Environmental Sustainability. This need can be satisfied if environmental impact considerations become an integral part of the product design process. Decisions made during the design phase of a product can have a significant effect on the product environmental impact. It is estimated that 80% percent of the environmental impact of a product is determined during the design stage.

During the past years, several eco-design methods and tools have been proposed and developed. Generally these solutions are either too qualitative or too detailed in terms of needed input data. For instance, the tools based on checklist are easy to use, but they do not provide quantitative results which support the designer in choosing the best product solution, from an environmental point of view. On the other side, the existing quantitative tools are mainly based on LCA methodology which requires a huge amount of data (manufacturing processes, suppliers, transportations, end of life strategies, etc.) which are difficult to retrieve during the design phase. For these reasons, these tools are far from a practical day-by-day application within the engineering departments, because they are not well integrated into the design process.

In this context many further improvements can be achieved through a rethinking of the design process, integrating the eco-design activities (and the related tools). The environmental considerations have to be integrated with the other classical design aspects, such as performances and cost. From the environmental point of view, the objective is to stimulate the designers to apply the Life Cycle Design paradigm, in order to consider the entire product life cycle. This idea can favour the creation of a new generation of design tools where environmental considerations become a key factor when decisions on product are taken.

The paper wants to make up for this lack and develops an eco-design methodology and a related software design tool able to help product designers in ecological design choices, without losing sight of cost and typical practicalities of industry. This research is a part of an European Project aiming to develop a platform of integrated software tools, to support the design of eco-friendly mechatronic products.

The paper is structured in order to provide a state of the art and the limitations of the existing methods and tools, which will be overcome by the proposed eco-design approach which has been implemented in a platform of software tools. Section 2 presents an overview of the eco-design methods, tools and methodologies; section 3 describes the proposed methodology, to integrate the eco-design activities into a traditional Design Process of a mechatronic product, which is supported by a software platform, explained in section 4. The evaluation of the improvements given by the proposed approach will be presented in future papers, since this work is related to the first results of a larger project, called G.EN.ESI.

2 STATE OF THE ART

The increasing interest in environmental issues led to the development of several methods aimed at measuring and assessing the environmental impacts of specific products [1]. In this part, the paper presents and analyse different ways of integrating eco-design in the design process: firstly tools and methods, and secondly methodologies. Tools and methods refer to any structured activity which aids a designer in the completion of a part of a design process and methodologies refer to an overall system containing certain tools, principles and rules selected to aid designers in completing the eco-design process.

2.1 Eco-design Tools and Methods

During past years, many methods and tools for eco-design were developed; Baumann et al. [2] found in their literature review near 150 eco-tools.

Some authors have already proposed classifications. For example, Baumann et al. [2] classified eco-tools in six categories: frameworks, checklist and guidelines, rating and ranking tools, analytical tools, software and expert systems and organizing tools; whereas Knight and Jenkins [3] chose only three categories: guidelines, checklists and analytical tools. In a more recent work, Hernandez Pardo [4] proposed a usage-oriented classification of eco-tools realised according to three properties: complexity (resources required to use the tool: amount of time, amount of input information and level of expertise required), type (analytical, guiding and information tools), and main function (life cycle assessment, simplified life cycle assessment, life cycle inventory, life cycle costing, life cycle work environment, impact assessment, eco-design support and product evaluation).In addition, Kortman et al. [5] and Lenox and Ehrenfeld [6] identified three dimensions to characterise a tool used in the development of a product: the design phase in which the tool can be used, the life cycle stages upon which the tool is focused, and its “degree of decision support”.

The following paragraphs show the main classes of eco-design tools. The types of tools presented below are limited to assessment and improvement tools, other types (eco-innovation, communication, etc) are not listed here.

LCA, Simplified-LCA, Streamlined LCA, MFA

Life cycle assessment is a tool that was developed for evaluating environmental impact of systems along their life. Eco-designers use these as an evaluation tool of the current state of environmental pressure generates by their product design. Since performing a full LCA is time and resources consuming, industry and research has proposed various solution to simplify it.

Simplified LCA aims at simplifying the assessment by reducing the number of data to process. Streamlined LCA decreases the number of indicators to manage. Finally, Matrix LCA proposes a semi-quantitative assessment that can be performed with little information on product shape and lifecycle.

Matrix Approaches

The matrix approaches represent a group of qualitative or semi-quantitative eco-design tools with the form of table or matrix to be filled in by intended users. Most of those approaches derive from LCA and can be regarded as somewhat simplified LCA. Due to its relative simplicity, they have potential to be accepted by enterprise, especially by small and medium enterprise.

Standards/Directives/Regulations

We can find major regulations and directives that are carrying out in the European Unions. Those law and regulations play an important role to enforce industries to internalize their environmental externality into their product particularly through product design activities.

Check-List

According to Janin [7], checklists refer to a list of questions that can help to have a quick evaluation on the environmental profile of the product under design. The list has been established based on the experience and does not necessarily take into account the whole life cycle for the product.

Guideline, Spider Diagram, Design for X Guideline

Design for Environment (DfE) guidelines are widely used as a mean to adapt products to environmental demands, and the literature is full of various DfE rules. Those rules tend to focus on a specific issue, e.g. material reduction or on a specific phase of a product’s life cycle. They are generic for different companies but can also be very product-specific, and require different levels of knowledge and education.

Design for X Tool

Design for “X” concept was proposed due to the ever increased pressure on the competitiveness of product. Products are required not only to meet the traditional requirements (e.g.. functionality) but also other aspects that may increase customer or stakeholder’s satisfaction, e.g. safety, reliability, serviceability, maintainability, recyclability, disassemblability, etc., So, tools called design for “X” paradigm, with each X representing a product property have been developed.

CAD Integrated Environmental Feedback, Adapted Design Tools

Some Computer-aided design (CAD) tools consist of an environmental module but it is not yet very used in the companies. Some others classical design tools were adapted to environmental issues as Quality functional deployment for environment (QFDE) [8], [9] or Environmental Failure Mode Effect Analysis (EFMEA) [10].

Analysis of These Tools

Tools and methods for environmental impact assessment of products are widely regarded as tools reserved for environmental experts due mainly to the complexity of environmental sciences on which those tools are based. Therefore, those tools are by nature not designers friendly and also are not designed promptly for being used by SMEs or companies starting with eco-design approaches.

For tools aiming to improve environmental performance of products, they are generally designed to be adapted to designers compared to the environmental impact assessment tools. Thus, they are thought as less complicated to be employed by both large company and SMEs. However, the problem is that those tools cannot play alone because in that case, they do not address the main environmental issues for the product. Then, they generally fail to optimise the overall environmental performance [11].

Furthermore, as each eco-design tool has a particular function and a specific use, several tools can be used to eco-design a same product. However, the compatibility between tools is not guaranteed [12] and there is a lack of information about how to use the tools [13].

2.2 Eco-design Methodology

Some issues were therefore raised and one solution to remedy the problem of environment integration within a company and specifically in the design process is to develop a methodology meeting different requirements. The first methodology to note is the one given in the ISO/TR 14062 document which looks at the issue of integrating environmental aspects into design from an environmental management perspective. This standard offers a broad methodology that covers topics of business structure, management and specific design activities but it is too general and not sufficiently specific to be applied to the design process.

A number of authors offer eco-design processes that fit within the definition of the methodology previously developed. following, three main papers have been reviewed considering partially the expectations of the G.EN.ESI methodology developed in section 3.

Hauschild et al. [11] tackled the issue of getting the focus right, i.e. addressing the most important environmental impact, in introducing a hierarchy of focusing. The G.EN.ESI methodology uses principles of this paper to identify the environmental hot spots and the potential improvements in order to optimize the environmental performance of the product.

Fargnoli and Kimura [13] presented a new design process for the development of sustainable products, supported by a series of indications providing information on how to apply the most common eco-design tools. A particular attention was paid to the integration of environmental legislation requisites into the traditional design activities. The G.EN.ESI methodology uses tools different of those used by Fargnoli and Kimura. Moreover the role of the different actors and the links between them are not highlighted.

Le Pochat et al. [12] proposed a method to facilitate integration of eco-design devoted to the problem encountered by SMEs: the EcoDesign Integration Method for SMEs (EDIMS). The method they propose is addressed not to the enterprise itself but to the external organisations that provide assistance to it at the time of an eco-design pilot project.

On the contrary, the G.EN.ESI methodology, which will be presented in the next section, is dedicated to the company designing products. Sure a consultant can be sought if an environmental expertise is not available in the company but the methodology is specifically dedicated to the actors within the company. In addition, it is necessary to ensure the success of the eco-design integration.

3 METHODOLOGY

Within the G.EN.ESI project, a methodology was developed aiming to guide the designers, first of all, to link eco-design activities with traditional design activities and secondly to entirely integrate eco-design in the design process. This methodology supports the software platform described in section 4.

The G.EN.ESI methodology consists of six main phases:

1. Functional analysis
2. Determination of environmental hot spots
3. Determination of the environmental strategies and deployment in indicators
4. Guidance
5. Sustainability check
6. Impacts of the decisions in the long term company objectives

The phases are described in the following paragraphs and in the Figure 1. The needed elements to support the different steps are highlighted after each phase description.

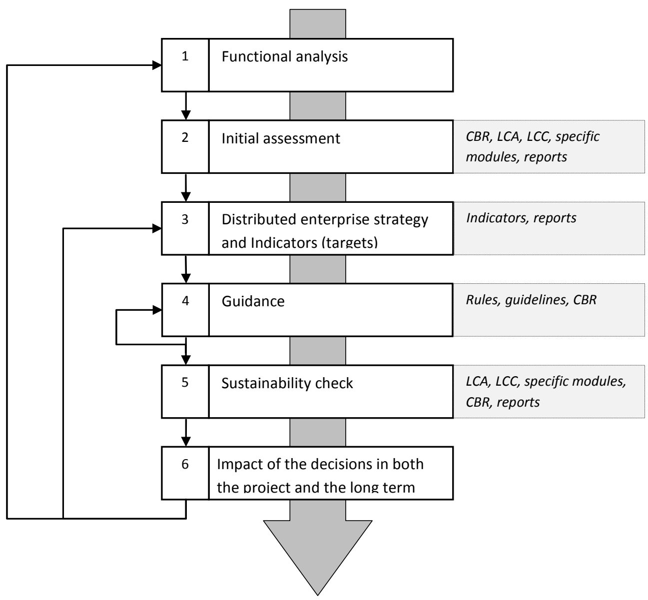

Figure 1: Steps of the methodologies and the linked elements.

3.1 Functional Analysis

The first step of the methodology is to carry out a functional and a modular analysis for an existing product. This approach is useful either for the realization of a new product and for the optimization of an existing product. The modular analysis concerns only the redesign of an existing product; it consists in defining sets of components in modules. Each module corresponds to a specific function of the product. This step enables also to define a functional unit useful to carry out a life cycle assessment (LCA).

This is a necessary step because with eco-design the goal is to maintain functionality whilst minimising environmental impacts and using resources efficiently. For this step, a product model, integrating at least functional aspects is needed. This phase of the methodology is not supported by the platform, since it is a preliminary analysis of the product.

3.2 Determination of Environmental Hot Spots

The second step of the methodology is to realise an initial environmental assessment of an existing product. It consists also of identifying the most environmental critical points, called “environmental hot spots”, during the life cycle of the product. The environmental hot spots represent the worst environmental impacts in the product life cycle, for example the energy depletion or the waste production during a specific life cycle stage. Different ways are used to find them; the designer will carry out this step based on:

- The literature and legislation. The literature is useful to find similar case studies already analysed. One objective of this step is to determine the legislation and standards to which the product is submit, with the aim to determine some priorities to improve the environmental performance of the product;
- Previous experience. Designers use their own experience about previous products to guide them in their task;
- An initial assessment phase. In cases where the product is well defined (e.g. in the case of redesign), the initial assessment is done by a simplified life cycle assessment (S-LCA) of the existing product. A more qualitative LCA or life cycle approaches can be used to identify potential environmental hot spots when the product is not sufficiently well defined [11]. Other aspects of the product can be assessed, such as the cost, the recyclability or the disassembly. A simplified life cycle cost (LCC) evaluation can thus be carried out to highlight cost problem.

Once the environmental hot spots are defined, they are reported in documents to inform all the members of the design team.

Some elements are needed to realise this step:

- A case-based reasoning (CBR) tool can be a solution to use previous experience. Indeed, the concept of this tool is based on the adaptation of previous solutions to solve the current problems [14]. It contains a data base which lists the previous design solutions;
- A simplified LCA tool for the environmental evaluation if necessary;
- A simplified LCC tool for the cost evaluation if necessary;
- Specific modules to calculate other criteria of the products, such as recyclability rate or disassembly rate;
- Reports that are generated to show the results of the assessment and to highlight the defined environmental hot spots.

3.3 Determination of the Environmental Strategies and Deployment in Indicators

The next step enables the company, and specifically the design team, to establish the environmental strategy, according to the environmentally critical points highlighted in the second phase. The strategy is then translated into indicators levels: the designers’ team set design targets translated in values for the chosen indicators. The design targets depend on different criteria mainly the environmental hot spots, the company objectives and the product. Reports are then sent to designers to provide them objectives for redesign.

Important elements used at this step are indicators. They come from the LCA results but they can be also costs indicator or engineering indicators: energy efficiency, recyclability rates, disassembly rates, etc.

3.4 Guidance

Step 4, called the guidance step, aims to help the designer to improve the product environmental performance, using guidelines, and checklist, with the respect of the standards. The product is optimised according to the priorities and targets established in the previous steps [11]. It is a continuous and iterative phase of assessment, advice and action.

Specific elements are thus needed to help the designer in the advising activity:

- Eco-design rules and guidelines;
- A Case Based Reasoning (CBR) tool that can also be used at this step to assist the designers improving the environmental performance of the product through the utilisation of existing knowledge.

3.5 Sustainability Check

During this step, the final sustainability check is carried out. This evaluation highlights the potential points where the design still does not reach the targets. The evaluation phase is based on a collection of data from experts and contributes to the establishment of the different reports.

The S-LCA and LCC tools, as well as specific calculation modules are used for the final evaluation and thus the final check. These calculation modules allow the designers to take into account all the phases of the product life cycle (from manufacturing to End of Life). In order to perform an analysis of the whole product as accurate as possible, without asking the designers specific information, a module linked to the Supply Chain Management is required.

Reports are generated presenting applied solutions to improve the product in order to supply the CBR tool.

3.6 Impacts of the Decisions in the Long Term Company Objectives

The last step is to assess the impacts of the previous decisions from two perspectives. The first one is about the project itself in order to redefine the strategic indicators if needed. The second one concerns the impacts of the decisions on long term company objectives.

Some feedbacks are thus generated from the last step towards previous steps in order to improve the global policy of the design in the company.

4 DESCRIPTION OF THE PLATFORM ARCHITECTURE

The G.EN.ESI platform architecture (Figure 2) consists of various tools integrated in the same structure. G.EN.ESI tools will be synergistic and communicate to each other to support the whole product design process. Each tool is dedicated to a specific life cycle phase and their integration allows to control the environmental and economical aspects along the entire product lifecycle. The integration of the different tools will allow a flow of information in a quick and automatic way. The designers will be always conscious of their choices and the consequences on the product.

An additional tool has been thought to support designers in the implementation of the eco-design guidelines, using a CBR (Case-Based Reasoning) approach. Even if this tool is not fully integrated within the platform, it is required to follow all the methodology steps.

Having in mind the Extended Enterprise concept, an additional web-based tool (Supplier Web Portal) has been designed to exchange product related information. This allows the lead company to consider the exact data for all the components of their products.

The platform is interfaced with a 3D CAD and a PLM system, in order to retrieve the information required by each single tool. In addition to the product structure, geometric (i.e. weight, volume, dimensions, etc.) and no geometric data (i.e. materials, tolerances, surface finishing, working machines, cost of components, etc.) will be extracted from these systems.

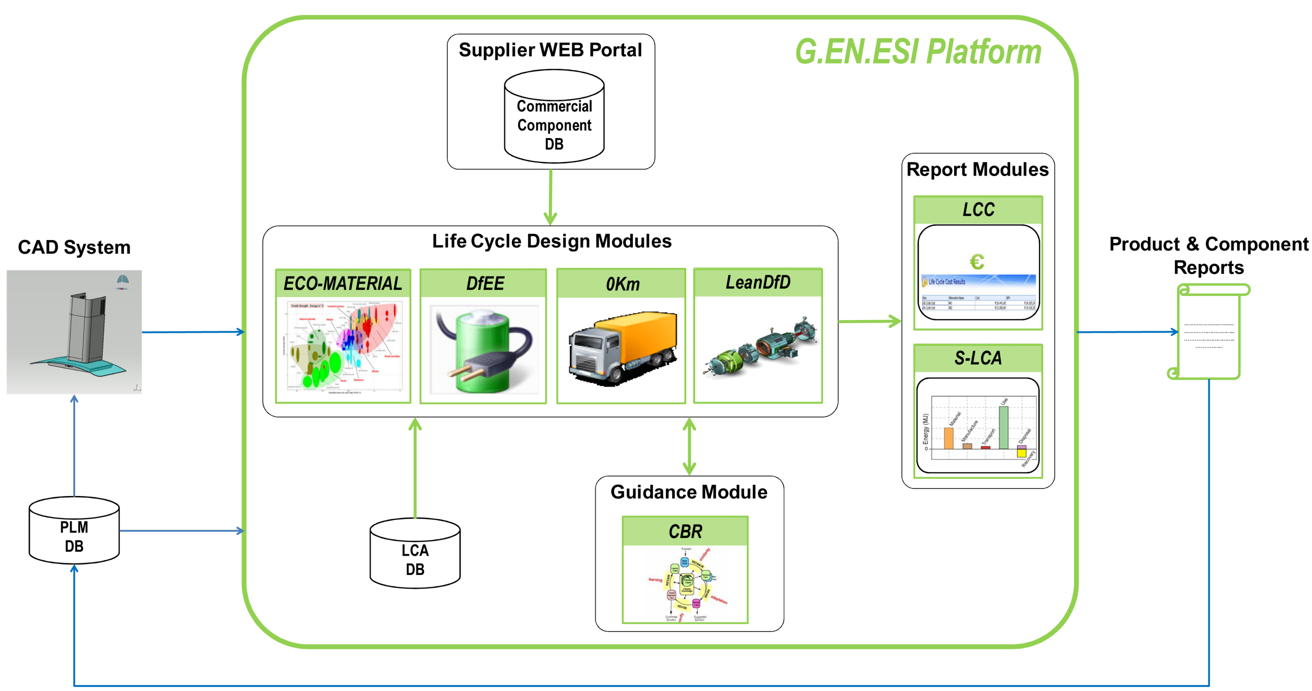

Figure 2: G.EN.ESI Platform architecture.

4.1 G.EN.ESI Platform Functionalities

The platform is mainly based on a specific database containing a large set of engineering materials (over 4000) with the relative manufacturing processes. Each of them is characterized by multiple environmental indicators (energy consumption, CO_2 emission and water consumption) and by its unitary cost. This database is accessed by each specific tool, described below.

Eco-Material is a tool of the G.EN.ESI Platform dedicated to the management of the material selection and manufacturing phase, supporting the designer in the choice of the most sustainable material. The Eco-material tool evaluates the most sustainable materials on the basis of embodiment energy needed for primary extraction and production, the exploitation of resources and minerals, the quantity of greenhouse gases emitted and the possibility of recycling. According to the selected material, the tool allows the selection of the manufacturing processes to finish a component.

The *DfEE (Design for Energy Efficiency)* is a tool for the evaluation of the environmental impact and Life Cycle Cost of the energy consuming components. For instance, it provides an useful support during the design phase of electric motors. To obtain an accurate assessment of the environmental impact during the use phase, the tool gives to designers the possibility to define multiple working points for the energy using components.

0km is a tool dedicated to the management of the transport phases along the product life cycle, from component supplying to dismantling. Considering the geographic positions of the suppliers, producers and dismantlers, the tool is able to provide the transport links necessary to move a component during its lifecycle, with relative environmental and economical impacts.

LeanDfD is a tool dedicated to the product End-of-Life (EoL) management. The tool permits to evaluate disassembly times and relative costs of the entire product or of a specific component (or subassembly). LeanDfD is also able to calculate some EoL indices which permit to evaluate the most convenient EoL strategy for each component (or subassembly), considering the disassembly cost. For the chosen EoL scenario, the environmental impact is calculated.

S-LCA and *LCC* are reporting tools which collect the information calculated by each tool in order to generate a report containing the environmental and economical data referred to a single product component and to a single life cycle phase. In addition, also the overall evaluation for the entire product in all the life cycle phases is provided.

CBR is a tool which represents the knowledge and the “best practices” for mechatronic products. It helps the designer in the design process through the acquired company knowledge on these products and the well-established eco-design guidelines. The knowledge is represented by all the choices made from the designer during the development of other similar products. Using this knowledge, the design process can be assisted and guided in the selection of the best material, geometry, commercial components and so on.

The *SWP* (*Supplier Web Portal*) allows suppliers to upload products, components, processes and logistics data within a specific database. Thanks to this information, the designers can choose a particular component that will be used by the platform in the product life cycle analysis. Therefore, this module is used at first by suppliers, that input data related to components they sell, and then by designers to choose those components from a list of different options. The Supplier Web Portal database is supervised by the company where the G.EN.ESI platform is deployed. Only suppliers which receive authorization from the lead company can upload their products into the Supplier Web Portal. It is the company that certifies its suppliers. The SWP provides to each analysis tool some necessary information related to commercial components. For example, in case of an electric motors, such information are:

- Energy consumption for different working points used by DfEE;
- Production site of the supplier used by 0Km to calculate the necessary transportation links;
- Cost used by LCC during the report generation and by LeanDfD for the calculation of some End of Life indices.

4.2 G.EN.ESI Platform Use

G.EN.ESI Platform can be accessed by two different types of users: suppliers and designers (or environmental experts) of a company. The first can use the platform to provide essential information about commercial components. The second, instead, is the main user of the platform which uses it as a system to easily integrate an eco-design approach in the product design process.

Supplier Web Portal is the module of the platform dedicated to suppliers. Thanks to the web-based interface, this type of users can upload all the necessary data about commercial components. All this information is stored in the Commercial Component DB and can be used by designers to perform an S-LCA/LCC analysis. Therefore, suppliers are “provider” of data necessary to designers to assess the environmental and cost impacts of their products, and permits to consider components that the company does not manufacture internally.

Designers can use the G.EN.ESI Platform to rapidly estimate the impacts of products, during the product development process, when the available information about the life cycle and the time are limited. Thanks to the link with the company CAD System and with the PLM DB, the platform is able to retrieve the necessary data (geometric and no geometric) to start an analysis. Using the platform tools, designers are able to build a model of the whole product life cycle performing the following actions:

- Selection of materials and processes for each component which is manufactured internally by the company (Eco-Material tool);
- Selection of the necessary commercial components (from Supplier Web Portal);
- Modelling and evaluation of the use phase of energy using components (DfEE tool);
- Modelling and evaluation of the transport phases required in the entire product life cycle (0Km tool);
- Evaluation of the disassembly and EoL phases of each product component (LeanDfD tool).

The product model definition is guided by the CBR tool which is able to suggest to the designer the most convenient choice from an economical and environmental point of view, using at the same time the eco-design guidelines and the company knowledge about past design choices done in similar products. The platform is able to automatically update the product and component reports in order to provide to the user a “live” estimation of his choices. When the designer reaches the pre-established objectives the reports can be saved in the PLM DB as an attribute of components or products.

4.3 Platform Advantages

Once the software tools integrated in a common platform are deployed within a technical office, several meaningful advantages can be reached:

- Designers are able to compare different design solutions, considering environmental and economical aspects. The S-LCA is a simplified assessment tool which does not require detailed information. The designer can choose the best design solution, even if the tool does not allow a full assessment. The LCA analysis is done quickly without harness the design process. Same considerations can be outlined for the LCC tool;
- The proposed platform includes also a specific web portal where suppliers can specify LCA and LCC data related to their own products. This information is used by each platform tool, providing to designers a quite accurate assessment, without asking them to input this information;
- The platform is integrated with the CAD system in order to create a single workbench where perform environmental and economical analyses. Also the integration with the PLM system is proposed, in order to retrieve those information required during the analysis. This solution avoids data duplication;
- The integration of an S-LCA and LCC tools within the same platform allows the designer to have a single and modular report where the meaningful results are highlighted.

5 CONCLUSIONS

The paper presents an innovative eco-design approach which can be easily integrated within the Product Development Process. Even if the focus is on mechatronic products (i.e. household appliances) the methodology can be also applied to other industrial products.

The methodology is supported by a set of software tools thought to be used also by inexperienced designers (in terms of environmental sustainability issues) during the early design phases. The main idea leading the platform development was to guarantee its ease of use. To reach this objective, the integration with the other enterprise software tools and databases has been necessary. In this way, the designer, can develop new components/products and assess both the economical and environmental sustainability, using a single workbench.

This paper does not present any experimental results since the platform is under development. This research work is part of a larger project (G.EN.ESI) and further papers will highlight the quantitative advantages and drawbacks related to the use of the G.EN.ESI methodology and platform.

Future works will consist in the platform experimentation during the design phase of cooker hoods and electric motors for household appliances. In this way, it will be also possible to evaluate the relationships within the supply chain, in terms of eco-design data exchanging, since the electric motor is one of the most important household appliance component, from an environmental point of view.

For the test phase, the platform will be also deployed within companies with low or none experience on eco-design. Doing so, at the end of the experimentation, will be evaluated the effectiveness of the proposed approach. It consists of measuring how the products will be improved in terms of eco-sustainability and how and how fast the designers are able to acquire the eco-design expertise.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] Bovea, M. D., Wang, B. (2007): Redesign methodology for developing environmentally conscious products, International Journal of Production Research, Vol. 45, No. 18–19, pp. 4057–4072.

[2] Baumann, H., Boons, F., Bragd, A. (2002): Mapping the green product development field: engineering, policy and business perspectives, Journal of Cleaner Production, Vol. 10, No. 5, pp. 409–425.

[3] Knight, P., Jenkins, J. O. (2009): Adopting and applying eco-design techniques: a practitioners perspective, Journal of Cleaner Production, Vol. 17, No. 5, pp. 549–558.

[4] Hernandez Pardo, R. J., Brissaud, D., Mathieux, F., Zwolinski P. (2011): Contribution to the characterisation of eco-design projects, International Journal of Sustainable Engineering, Vol. 4, No. 4, pp. 301–312.

[5] Kortman, J., van Berkel, R., Lafleur, M. (1995): Towards an environmental design toolbox for complex products; preliminary results and experiences from selected projects, pp. 35–40.

[6] Lenox, M., Ehrenfeld, J. (1997): Design for Environment: A new framework for strategic decisions, in: Moving ahead with ISO 14000, Chap 22, pp 211-225.

[7] Janin, M. (2000): Demarche d'eco-conception en entreprise un enjeu : construire la coherence entre outils et processus, PhD thesis, ENSAM Chambéry.

[8] Masui, K., Sakao, T., Inaba, A. (2001): Quality function deployment for environment: QFDE (1st report)-a methodology in early stage of DfE, in: Proceedings EcoDesign 2001: Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing, pp. 852–857.

[9] Zhang, Y., Wang, H.-P., Zhang, C.: (1999): Green QFD-II: A life cycle approach for environmentally conscious manufacturing by integrating LCA and LCC into QFD matrices, International Journal of Production Research, Vol. 37, No. 5, pp. 1075–1091.

[10] Lindahl, M. (1999): E-FMEA-a new promising tool for efficient design for environment, in: Proceedings EcoDesign 1999: First International Symposium on Environmentally Conscious Design and Inverse Manufacturing, pp. 734–739.

[11] Hauschild, M. Z., Jeswiet, J., Alting, L. (2004): Design for Environment — Do We Get the Focus Right?, in: Annals of the CIRP - Manufacturing Technology, Vol. 53, No. 1, pp. 1–4.

[12] Le Pochat, S., Bertoluci, G., Froelich, D. (2007): Integrating ecodesign by conducting changes in SMEs, Journal of Cleaner Production, Vol. 15, No. 7, pp. 671–680.

[13] Fargnoli, M., Kimura, F. (2007): The Optimization of the Design Process for an Effective Use in Eco-Design, Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses, pp. 59–64.

[14] Janthong, N., Brissaud, D., Butdee, S. (2010): Combining axiomatic design and case-based reasoning in an innovative design methodology of mechatronics products, CIRP Journal of Manufacturing Science and Technology, Vol. 2, No. 4, pp. 226–239.

Integrating Information in Product Development

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Abstract

The amount of product and process related information in the engineering industry is large and constantly growing. Methods and tools are therefore needed to effectively leverage the information, ensuring that it is readily available, contextually understandable and usable for the activity at hand. This paper presents findings from two cases performed at manufacturing companies and an approach for how information effectively can be utilized during the development and lifecycle of a product. The approach primarily addresses the lack of up-to-date information, free of redundancies and accessible from the context where it is needed or will be captured.

Keywords:

Information Management; Product Development; Product Lifecycle Management (PLM)

1 INTRODUCTION

The information available within an organization is an asset that can and must be leveraged in order to be competitive. Over time, the amount of product and process related information has increased dramatically. Products are at the same time becoming increasingly diverse and complex, as is the way in which information is exchanged in concurrent product development. This has led to an increased demand for purposeful information, which in turn needs to be efficiently managed during the lifecycle of a product. A large percentage of the product development lead time is spent on acquiring information, information which is a part of the organizational memory. As argued by Kim et al. [1],

"... approximately 90% of organizational memory exists in the form of text-based documents."

Sherman et al. [2] found that the degree to which information from past related product development projects is effectively recorded, retrieved, and reviewed is an contributing factor to new product performance. Sherman et al. [3] concludes that achieving effective R&D integration of information from past projects is the single most important integration factor in reducing development time. Making sure that information is readily available to those who need it could reduce the time spent on searching for, waiting for and translating information. It could in addition reduce the time spent on working with out-of-date information and recreating old information. The time spent searching for information accounts for about 60% of the total operational time in most businesses [4].

Being able to find and acquire supposedly known information is one issue. Research [5] shows, however, that designers may not even be aware of existing information, or for that matter, be willing to disrupt their work in search for relevant information. These findings are strengthened by the studies conducted within the confines of the research presented in this paper, and therefore further underline the need to ensure that the right information is readily available.

Product development decisions, specifically early design decisions, have a significant impact on sustainability [6]. Consideration to the effects decisions will have on later stages in the product lifecycle should enable the development of sustainable products. Efficient information management would allow manufacturers to take a greater responsibility for the sustainability of their products.

Product lifecycle information is to a large extent managed using Product Lifecycle Management (PLM) systems. These PLM systems are a part of a company's total PLM solution, which often consists of several tools and methods. PLM is a product-centric approach to support information flow throughout a product's lifecycle, and enables the gathering of a substantial amount of product lifecycle information. Stark [7] states that,

"*PLM is the business activity of managing, in the most effective way, a company's products all the way across their lifecycles; from the very first idea for a product all the way through until it's retired and disposed of.*"

The product lifecycle can be divided into three phases: beginning of life, middle of life and end of life [7]. PLM manages the product development process by gathering and making information available for everyone involved in the process. Information managed in the early stages of the lifecycle can be used in the later stages, just as information related to downstream stages can be fed to the earlier stages. This bidirectional flow of lifecycle information could also cross product, project and business boundaries.

Information integration is a major subject within computer science and a lot of work has been done to enable integration of heterogeneous information sources. Approaches include for example canonical data models and ontologies that allow semantic interoperability of information.

Ontology approaches for the integration of various lifecycle information through PLM has also been researched [8–13].

The product information needs differ among various actors involved in the development of a product. This variation in need can be addressed by providing multiple views of the information, each view catering to the specific needs of the actor in question. Research related to multiple views includes, but are not limited to [14–16]. Bouikni et al. [14], presents a multiple views management system capable of generating different views of the product information based on to the need of the actors. Demoly [15] presented a modeling framework for multiple views that supports assembly oriented design. Ding et al. [16] presented an approach to multiple views using multi layered lightweight product representations.

The objective of the ongoing research behind this paper is a proposed, implemented and evaluated approach to the integration of information in product development, with the purpose of effectively leveraging available information assets based on the end users' needs. Research efforts include investigations of information utilization at two industrial manufacturers and the development of a conceptual approach. The approach addresses principle information integration, assuming an integrated PLM solution as the master source of information. The main contribution lies within how information is contextually represented, utilized and captured during product development, thus removing static and redundant representations. The conceptual approach presented, aim to ensure contextual information representation for an arbitrary end user in the development of a product. Integrating information into the everyday activities, environments and tools of the end users, should serve to make retention and retrieval into intuitive and natural parts of daily activities. This should in turn ensure awareness of available information, what it means, where it came from and how it can and should be utilized. Integrating relevant and up-to-date information from a PLM solution within the tools used during product development should ensure that users make informed decisions within their everyday tasks.

2 METHODOLOGY

The underlying investigation for this paper is part of a research project and has been conducted as two independent and concurrently executed studies. Both studies have been conducted in close collaboration with industry, with the initial objective of acquiring an accurate representation of processes, information flows and information (re)use. The investigations presented have been conducted during the course of three years, and have included company representation ranging from customer relations, order acquisition and delivery to design, automation, simulation and downstream product and process consideration.

2.1 Data Collection

Insight into and an understanding of each case company and their development process has primarily been ensured through data collection of a qualitative nature. The qualitative nature of this research stems from the difficulties of clearly quantifying needs and influencing factors within the product development process. There is a need to understand the development process as a whole and how each individual contributes. Sources included archived documents, workshops, observations and in-depth interviews, all to ensure an accurate view of the cases based on multiple and potentially biased sources of evidence [17]. The interviews have been guided and directed just enough to stay relevant. The respondent were allowed free reins to describe their situation and everyday challenges in a way similar to what Bell [18] refer to as semi-structured interviews. Observations were then used to witness the process first hand, in part to corroborate any information gained from interviews and in part to uncover aspects and issues respondents simply had not reflected upon, forgot to mention or perhaps intentionally left unsaid. Workshops could for the purpose of these investigations be described as group interviews and discussion forums, and was during initial stages used to inform involved personnel of the nature and aim of the research. Workshops did also provide a platform for information exchange over divisional borders and an environment for questions and discussions over diverse perspectives and competences. Interviews, observations and workshops have been planned in terms of purpose and general procedure, once execute however, they did have a more open nature. User involvement has been essential, as it has been and will continue to be used throughout the entire process of investigation, development, implementation and evaluation.

3 INDUSTRIAL CASES

This paper is based on studies carried out at two industrial product developers and manufacturers in Sweden. One is a supplier to the automotive industry and the other a tool supplier for the metal cutting industry. This section describes the current state-of-practice and the issues uncovered.

3.1 Case A

Case A focus on an R&D center that provides sheet metal safety components for the automotive industry. Finite element simulation of product performance is a driver in the product development. The products are often of complex shapes that require forming simulations to verify and develop manufacturing processes. The center uses a standardized product development process that is common to all R&D centers within the company. Product development for both quotation and serial production is included in this process. The process is managed by documents in which product information is stored and revised. Information is manually duplicated from the product definition (CAD file) into specification documents. These documents are later used as information sources for other activities, activities such as design reviews and pricing. There is a risk that information in these documents is out-of-date or faulty.

There is currently no system implemented for storing and managing product data such as CAD files and documents. All data storage is confined to files managed in folder structures on file servers. Metadata is in turn stored inside files, and to some extent in file names and folder structures respectively, which makes finding the right information using queries difficult. Information available in documents could be searched using full-text searches, but there is no such system implemented. There is an ongoing project within the company to implement a PLM system for management of product data, workflows and other aspects of the products lifecycle. However, the simulation-driven approach currently used is highly iterative and does generate large amounts of data. This has led to the conception of an in-house simulation data management system, which store and archive simulation data associated with a project. The information flow in between design and simulation activities is not managed in a central location. Design generated data is manually exported to the simulation environment, where it is tracked by the simulation data management system. Simulation results are analyzed, which in turn is the foundation for design decisions in product development. The information base for these changes is, however, not captured. A homogeneous product data environment where design and simulation data is managed by the same or integrated systems would allow for a better information flow and, allow decisions based on simulation results to be captured. This is crucial, since the simulation-driven approach used means that a lot of the decisions in the product design are based on information from simulation results. Simulation data management is, according to Fasoli et al. [19], an area that more companies will focus on in the future to complement the management of the design information.

Product information is exported and imported to and from customers and internally within the company several times during the product development process. Although the information often has a high impact on design decisions there is no effective way to track and manage these import/export operations. This makes it hard to ensure that the right information has been sent, but also to track which information has been sent and to whom. The company has in recent years acknowledged that there is a need to capture and make information and experiences accessible in future development. Efforts have been made to achieve this. One example of efforts made is a wiki, where information about available tools and methods is documented. Manufacturability properties for materials, such as draft angles, are one example of information documented within the wiki. But to keep the wiki updated, it requires that the users continuously add and revise the information. Experience from previous development projects are saved in a database that is managed by in-house developed software. This software allows search capabilities in terms of projects similar to the one performed, based on requirements, dimensions and markets. This would in turn allow the use of lessons learned, and potentially, design and feature reuse.

3.2 Case B

Case B focus on the early stages of product family development, at a company which develops and manufacture tools and tool holders for the metal cutting industry. The early stages do, for the purpose of this study, correspond to the point of pre-study up to, but not including, manufacture. Product applications range from milling, turning and drilling to the interfaces in between tools and machine. An important part of the product portfolio is the customizable product spaces in which customers, through a sales person, can specify a product based on their particular requirements. The company develops product families. They do, however, still develop and provide standard product assortments in the traditional sense, if there is a market for it. Each product family has its own applicable range. This range is governed by a set of parametric components, and in extension, their range of application and the way in which these can be combined. The company in question utilizes an automated generative process, a process which at run time, selects, modifies and combines product modules accordingly. The process generates a complete CAD model as if it was created interactively. In addition, it is also capable of generating 2D and 3D representations for sales and customer evaluation, respectively, along with complete manufacturing documents and programs for subsequent manufacture, validation and marking. This automated process is an essential aspect in realistically providing customers with an entire product space to choose from, as developing each unique product instance on demand would not be feasible in many cases, given the variety and amount of unique orders.

The company in question has a strong foundation in modular reuse. A majority of modules does, however, show signs of being confined to a particular product family, even though efforts are made to ensure that components are generally applicable. The reason for this is that modules, in practice, tend to be built to incorporate more and more properties that are specific to a particular family, in addition to being challenging to locate and understand. All components are, once ready for automation, stored in a module repository, which can be searched using an in-house application. There are, however, ongoing efforts to move over to a combination of ERP (Enterprise Resource Planning) and PLM, where the PLM system would replace the modular repository and the search application. The future aside, components can at this time, as with most documentation, be found over a variety of repositories. Repositories include local repositories, department repositories, company-wide repositories and repositories connected to a project portal for past and present projects. The project portal is usually navigated manually, and user has concerns about the ease of finding what they need. Participation within a project grants access as long as that project is active. Specific access, however, has to be assigned to most users after a project is completed. Most project-related documentation is, however, also stored in a large and unstructured repository, accessible given the appropriate authorization and the keywords to find it. There are also a variety of supporting databases containing best practice, training documents and formal design instructions. Support ranges from general descriptions of tools, modules and how these should be developed, to regulations such as naming conventions. The company produces a considerate amount of documentation, documentation which essentially is static representations of what at the time of conception hopefully was up-to-date information. There are, to a certain extent, requirements as to what documentation should be generated and when. There are, however, few requirements in terms of what these documents in fact should contain, not to mention the extent and format of the information within. Altogether, this has inevitably resulted in multiple copies and restricted means of attaining what could be usable elsewhere. Efforts are therefore made to enable search over the variety of databases currently used.

The concurrent nature of the product development process, the inherent complexity of development and verification of an entire product space and continuous downstream consideration, naturally require much in terms of informational exchange. Geographically collocated functions within development and synchronous communication are what ultimately ensure that what is needed, is in fact delivered, after a few iterations if need be. One of the major issues today is finding and accessing required information, not necessarily the document where it resides, but the information itself. Access is generally accomplished by limited keyword searches and manual browsing, a time-consuming process that holds no guarantee of finding what is in fact available and relevant for the task at hand. What it all comes down to is providing the right support at the right time, based on the context and needs at hand.

3.3 Issues Common in Both Cases

The following section includes the issues found during analysis of the industrial cases.

- The companies produce a considerable amount of product information. This information is spread across several disconnected heterogeneous sources, including the mind of the developer, personal disks, divisional disks and company common disks. Information on disk is primarily confined to static documents. Those involved in the development process do not need, nor do they desire the static representation (document) wherein the information they need resides. They simply want the information itself, the relevant and up-to-date information presented in the, for all intents and purposes most suitable context at that time.
- The lack of centralized product information sources makes finding the right information using queries difficult. It also makes it hard to share information internally as well as externally without creating copies of information that lacks relation to the original.
- The tools for information capture and sharing require manual entry of information that might already exist in, and is disconnected from, the product representation where the information is acquired. They also require separate interfaces and that the information is continuously updated and revised.
- The same fundamental information could potentially be passed on and rewritten in different documents during essential parts of the product development process. Instead of being continuously reused and extended, information is rewritten and formalized for the particular purpose at hand. The challenge lies in ensuring that information, once stored, can be used and reused by systems and individuals, under anticipated and presently undefined circumstances.

- Aside from issues in terms of reuse, such as actually finding what is required, what currently restricts users is that they may not understand the work that has been done, nor do they have the rationale behind its conception. It is therefore, generally easier to start from scratch, rather than trying to figure out what they are dealing with and what they actually can change without risking problems downstream. Additional information that may be vital for reuse includes information related to traceability, ownership, searchability, purpose, application, rationale, relations and associations.
- Users desire association and relation among product, process and resource information. This includes visual association and contextual communication of information, related not only to the product itself but to specific geometric properties of the product in development. Information tends to only make sense in a specific context. Information could in one case be specific to the individual component geometry, whereas information in another case could describe the relations in between geometric component properties in a larger system, requiring associativity on a number of levels. This is currently achieved through annotated snapshots of the product representation, embedded in text-based documents.
- Investigation shows that designers have to maintain proficiency in a variety of applications and systems in addition to continuously having to switch between them, making them reluctant to add additional applications for the sake of acquiring more information. Some of the tools for information capture and exchange have any connection to the designers other interfaces that are used during product development, such as CAx or Office applications. These tools require the designer to disrupt work to access or capture information.
- There are several downstream product lifecycle aspects that need consideration during product development, including aspects such as performance, manufacturability, cost, customer-specific requirements, reliability, availability and use. Design verification and optimization in terms of these aspects requires a lot of time. Changes made in favor of one aspect often impact another aspect of the product lifecycle, potentially requiring further optimization or process iterations. Information about these interdependencies is not readily available, making the designer reliant on experts downstream to evaluate the impacts of design decisions made.

The core issue, derived from the investigations performed, is the lack of up to date, redundancy free and contextual information, integrated in product development.

4 INTEGRATING INFORMATION IN PRODUCT DEVELOPMENT - A CONCEPTUAL APPROACH

This section presents the authors vision of how information should be exchanged and utilized during product development.

The vision for the integration of information in product development is based on performed investigations and identified issues. Documents, the static representation of what at the time of conception was considered relevant information, are broken down into its basic building blocks (objects) and stored in a PLM solution. Much of the document content is in many cases already available in the product definition stored in a PLM solution. An issue when disassembling documents in the traditional sense, is that the objects left are stripped of the context these had within the document. Contexts such as their relation to other data and information, for example in association to a product, project or lifecycle stage. Each information object would therefore require metadata to govern how and when it is to be used. Every single data or information object should be retained together with the metadata necessary to ensure; traceability (author, version/revision, time stamp), ownership, search ability (name, ID, tag, keyword) as well as understanding and proper use (access/rights, purpose, application, rationale, relations, description). As much metadata as possible is pulled from the authoring context, i.e. the user function, author environment, stage, activity and so on. What cannot be directly derived from the authoring context, should be provided by the user an integrated and natural part of the current activity. The benefits of decomposing the traditional document into its basic components and storing these in a central repository are; (1) each information object can now be associated individually, for instance, to specific aspects of the products geometry; (2) and data and information, once retained, could potentially be formalized and assembled to accommodate new circumstances, and would not have to be rewritten.

Instead of associating an entire document to a product or product family, complemented by annotated static snapshots, information such as a specific requirement can now be associated and if required, be visually connected to everything from system arrangements and components to specific geometrical aspects of a component in development. This would allow for information to be compiled in different views, including view points on the product model as defined by Ding et al. [16]. Information can consequently be created, modified and presented within adapted interfaces or be generated as documents, all based on the current activity and context as illustrated in Figure 1.

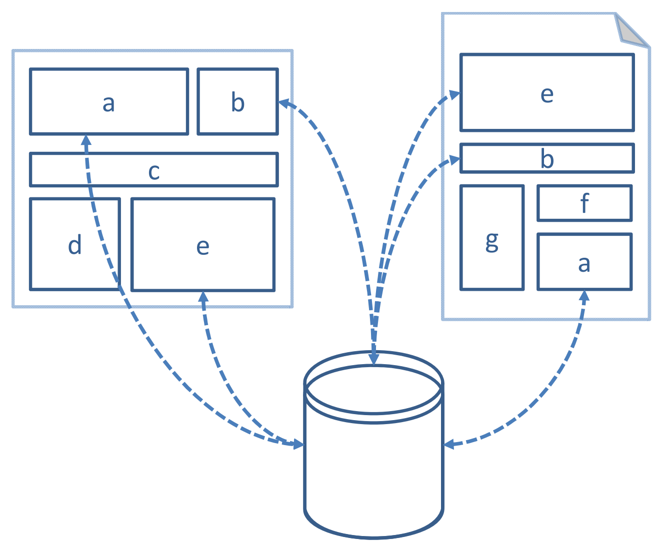

Figure 1: Information created and presented in different views.

Information is stored in a main source, a PLM solution, while information requiring storage elsewhere is tightly integrated to ensure that it is up-to-date and free of redundancies. Information flow between activities and the PLM solution is enabled by both commercial-off-the-shelf (COTS) and custom integrations. These integrations are enabled by a service-oriented architecture (SOA) provided by the PLM system. SOA enables loosely-coupled systems that are extensible, flexible and fit well with existing legacy system [20]. An overview of this approach is illustrated in Figure 2.

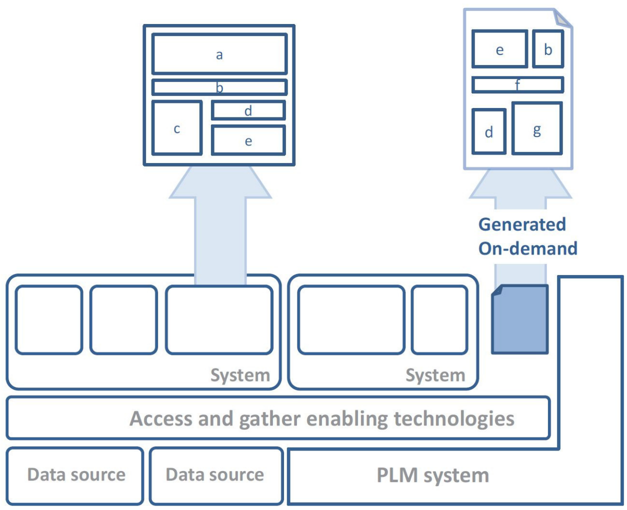

Figure 2: An approach to integration of information in product development.

Retained data and information are upon manual or automated query retrieved and assembled, all based on current needs and context. Contextual consideration could include aspects such as the function, activity, decision and environment at hand. Information from one or multiple repositories is always presented in the, for all intents and purposes, most suitable format or interface in order to maximize understanding and utilization.

The document or static representation, albeit a natural part of daily activities, should ideally be avoided. Static representations could be used if there is no way to ensure access to the actual repository or provide such information in an adapted interface, for instance, in the case of business-to-business exchange. Static representations could, if required, be generated on-demand, as illustrated in Figure 2, and preferably not be stored. All retrieval of said information should, at any given time, be a direct representation of the up-to-date source.

One of the underlying issues with reuse, is that it requires an understanding of the information/object and the rationale behind its conception. The potential of capturing and representing information, such as design rationale [21], to specific aspects of a products geometry should ensure a natural and more streamlined process of retention, while at the same time ensuring awareness, access and contextual representation downstream.

5 DISCUSSION

It is desirable to gather all information needed for and created during any given stage of the product's lifecycle in a way that makes it readily available, contextually understandable and usable for the specific activity at hand. Information retention is in the light of performed investigations rarely considered value-adding, as it is essentially reproduced from what has already been done. Information, once retained, should not need to be rewritten, and the retention itself should be a natural and contextually integrated aspect of continuous development. Appropriate tools that enable information search and presentation are central to achieve this. To enhance the utilization of product information, it should be made available in the interfaces in which it will be used. For example, information that can aid a design decision should be presented in the authoring tools used to implement this decision. Information can be requested when a need arises (pull) or be presented based on the context of the current situation (push). Both manual (pull) and automatic (push) searches can be used to integrate information into the activities during the product development process. Informational reuse is limited by access and awareness [5]. Making the information readily available, searchable and presented within the interfaces used should provide the needed support to leverage existing information in the product development process. This should also allow capture of design decision and design intent together with the information that was used as a basis for that decision.

If the information about requirements, and the impact of design decisions on the fulfillment of these requirements, are readily available during design, the need to rerun verifications is reduced. Automatic checks, based on requirements, within the authoring tool can be used to verify the impact of design decisions. In the approach presented, there is no need to send copies of information for validation and optimization. A reference to the actual product definition can be used instead. This would also allow storage of the results from validation or optimization with a relation to the product definition. Managing and presenting the relations between product definition and the requirements enables the users to better understand the interdependencies between different requirements and the design.

Companies that can integrate information from their PLM solution in their product development process will be able to leverage the information throughout the product lifecycle. It is, however, important to realize that tools and methods developed to effectively enable and support information integration is not enough. User involvement throughout the entire process of finding and integrating product information is important both for actually finding and correctly describing all product related processes and information. It is also important in order to establish an understanding of changes in information management for the users involved. Efforts must be made to ensure that the tools and methods developed are in fact accepted, used, used properly and constitute a valuable addition to the intended users in their everyday activities and the product lifecycle.

6 FUTURE WORK

With the conclusions drawn from the cases in this paper it should be possible to begin implementing the approach described and to develop method and tools that can be used to address the issues presented. Future work should include identification of specific cases where tools and methods can be implemented and evaluated. In a longer perspective, identifying and investigating cases at other companies is required in order to ensure that the findings are generally applicable.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] Kim, S., Bracewell, R. H., and Wallace, K. M. (2007): Answering engineers' questions using semantic annotations, Artificial Intelligence for Engineering Design, Analysis and Manufacturing , Vol. 21, pp. 155–171.

[2] Sherman, J. D., Berkowitz, D., and Souder, W. E. (2005): New Product Development Performance and the Interaction of Cross-Functional Integration and Knowledge Management, Journal of Product Innovation Management , Vol. 22, pp. 399–411.

[3] Sherman, J. D., Souder, W. E., and Jenssen, S. A. (2000): Differential Effects of the Primary Forms of Cross Functional Integration on Product Development Cycle Time, The Journal of Product Innovation Management , Vol. 17, pp. 257–267.

[4] Ameri, F., and Dutta, D. (2005): Product Lifecycle Management: Closing the Knowledge Loops, Computer-Aided Design & Applications , Vol. 2, pp. 577–590.

[5] Kim, S., Bracewell, R. H., and Wallace, K. M. (2007): Improving design reuse using context, in: 16th International Conference on Engineering Design, (ICED'07).

[6] Ramani, K., Ramanujan, D., Bernstein, W. Z., Zhao, F., Sutherland, J., Handwerker, C., Choi, J.-K., Kim, H., and Thurston, D. (2010): Integrated Sustainable Life Cycle Design: A Review, Journal of Mechanical Design , Vol. 132, pp. 091004.

[7] Stark, J. (2011): Product Lifecycle Management: 21st Century Paradigm for Product Realisation., Springer London, London.

[8] Monticolo, D., Lahoud, I., Bonjour, E., and Demoly, F. (2012): SemKnow: A Multi-Agent Platform to manage distributed knowledge by using ontologies, in: IMECS 2012 - the International MultiConference of Engineers and Computer Scientists.

[9] Assouroko, I., Ducellier, G., Eynard, B., and Boutinaud, P. (2011): Semantic-based approach for the integration of product design and numerical simulation, in: International Conference on Product Lifecycle Management.

[10] Sudarsan, R., Fenves, S. J., Sriram, R. D., and Wang, F. (2005): A product information modeling framework for product lifecycle management, Computer-Aided Design , Vol. 37, pp. 1399–1411.

[11] Chen, Y.-J., Chen, Y.-M., and Chu, H.-C. (2009): Development of a mechanism for ontology-based product lifecycle knowledge integration, Expert Systems with Applications, Elsevier Ltd , Vol. 36, pp. 2759–2779.

[12] Matsokis, A., and Kiritsis, D. (2010): An ontology-based approach for Product Lifecycle Management, Computers in Industry, Elsevier B.V. , Vol. 61, pp. 787–797.

[13] Rachuri, S., Subrahmanian, E., Bouras, a, Fenves, S., Foufou, S., and Sriram, R. (2008): Information sharing and exchange in the context of product lifecycle management: Role of standards, Computer-Aided Design , Vol. 40, pp. 789–800.

[14] Bouikni, N., Rivest, L., and Desrochers, a. (2008): A Multiple Views Management System for Concurrent Engineering and PLM, Concurrent Engineering , Vol. 16, pp. 61–72.

[15] Demoly, F., Monticolo, D., Eynard, B., Rivest, L., and Gomes, S. (2010): Multiple viewpoint modelling framework enabling integrated product–process design, International Journal on Interactive Design and Manufacturing (IJIDeM) , Vol. 4, pp. 269–280.

[16] Ding, L., Davies, D., and McMahon, C. A. (2009): The integration of lightweight representation and annotation for collaborative design representation, Research in Engineering Design , Vol. 20, pp. 185–200.

[17] Yin, R. K. (2009): Case study research: design and methods, Essential guide to qualitative methods in organizational research (Bickman, L., Ed.), Sage Publications.

[18] Bell, J. (2005): Doing your research project: a guide for first-time researchers in education, health and social science, British Journal of Educational Technology, p xv, 267 p., Open University Press.

[19] Fasoli, T., Terzi, S., Jantunen, E., Kortelainen, J., Sääski, J., and Salonen, T. (2011): Challenges in Data Management in Product Life Cycle Engineering, in: Glocalized Solutions for Sustainability in Manufacturing: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering (Hesselbach, J., and Herrmann, C., Eds.), pp 525–530, Springer Berlin Heidelberg, Berlin, Heidelberg.

[20] Wu, Q., Zhou, C., and Jing, T. (2008): Research on SOA Based Framework of Collaborative Design System for Complicated Product, 2008 International Conference on Computer Science and Software Engineering, Ieee pp. 400–403.

[21] Lee, J. (1997): Design rationale systems: understanding the issues, IEEE Expert , Vol. 12, pp. 78–85.

Life Cycle Oriented Evaluation of Product Design Alternatives Taking Uncertainty into Account

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Abstract

Product planning activities do not only have to consider the wants and needs of the costumers, they also must meet the requirements coming up during development and manufacturing, while providing maximum economic benefit throughout the life cycle. When deciding what design alternatives to realize, these requirements have to be considered as to their long-term impacts on the entire product life cycle. On the top of that, it is necessary during the early stages of product planning to consider uncertainties arising from the fact that the available information is often incomplete, uncertain and vague. The approach discussed in this paper combines different methods of processing uncertain information on product planning alternatives including the evaluation of economical as well as technical and environmental aspects. While traditional evaluation tools mainly focus on a restricted selection of hierarchical aspects and consider uncertainty as part of sensitivity analysis, this approach allows for an enlarged evaluation of product realization alternatives in the early stages of product development in conjunction with process planning as well as product assessment. This paper describes the theoretical background and explains the developed model in order to support evaluation activities during product planning. In addition, possibilities for the practical implementation are described.

Keywords:

Decision support; Product design for resource efficiency and effectiveness; Life Cycle Engineering and Assessment

1 INTRODUCTION

The early stages of product design and development are characterized by the effort of involved engineers as well as managers to create and select those products that satisfy customers' wants and needs as a basic input and in the same time come up with technical and ecological requirements while providing maximum economic benefit throughout the life cycle. All these requirements have to be considered in terms of their long-term impacts on the entire product life cycle.

An engineering design should not only transform a need into a description of a product but should ensure the design's compatibility with related physical and functional requirements. Therefore, it should take into account the life of the product as measured by its performance, effectiveness, producibility, reliability, maintainability, supportability, quality, recyclability, and cost [1].

Designers are in a position to substantially influence the life cycle performance of the product they design by giving due consideration to life cycle implications of the design decision they make. In an attempt to improve the design of products, reduce design changes, the incurred life cycle cost as well as the environmental impacts, the approach of life cycle oriented evaluation as discussed in this paper combines decision support tools with approaches for product assessment. The latter include quality and value-driven tools as well as methodologies of Life Cycle Assessment and Life Cycle Costing. The approach has been developed considering the perspective of a decision taker acting in the triangle of conflicting priorities between technical, ecological and economic requirements. It describes an integrated methodology of life cycle oriented evaluation and decision support for the product planning processes and helps considering the above-mentioned requirements in terms of their long-term impacts on the entire product life-cycle.

The results of product assessment provide the input for the decision support that is based on the Analytic Network Process. In order to come up with the uncertain and fuzzy judgments of the human decision-maker the traditional ANP-model has been enhanced to an approach that considers on the one hand statistical based judgments of decision makers, on the other hand fuzzy-based judgments where the vagueness of the human thinking is expressed by fuzzy sets.

2 CONCEPT OF LIFE CYCLE ORIENTED EVALUATION OF PRODUCT DESIGN ALTERNATIVES TAKING UNCERTAINTY INTO ACCOUNT

The developed concept of life cycle oriented evaluation for product alternatives is intended as an instrument for facilitating the effective identification of a product concept fulfilling existing restrictions within a given time period and the selection of the most appropriate product alternative coming up with the requirements set. More over the approach supports the optimization of life cycle design decisions. It enables both, to obtain a design satisfying customers' needs and wants expressed as requirements in a technical-ecological profile as well as cost optimization. Moreover it makes proposes for use of engineering process technology to reduce life cycle cost. The approach of life cycle oriented evaluation for product design alternatives enhances the traditional concepts of decision support and design to life cycle and helps to integrate life cycle costs, functions and value aspects of the product into the decision during the very early product planning phase. In order to give the decision makers quick and accurate estimates of the life cycle consequences of design decisions the approach includes a process based evaluation of resource consumption. The procedures to determine the optimal design are deduced from the value-oriented optimization module.

2.1 The Basic Concept of Life Cycle Oriented Evaluation

The approach of life cycle oriented evaluation aims to identify and select those cost-efficient product concepts without compromising quality, eco-efficiency or schedule constraints. Its object is to consider the life cycle implications of design decisions and to reduce life cycle costs while complying with a defined technical-ecological profile. This profile is deduced from life cycle considerations as well as from customer and market requirements. The modules comprised in the approach are illustrated in figure 1.

2.2 The Evaluation Modules

The evaluation process considering the product life cycle is part of the function and process analysis module pictured in figure 1. It comprises in a first step the prioritization of customer demands and customer needs as well as their translation into product related technical features. The implementation is based on the approach of Quality Function Deployment (QFD). With help of the QFD methodology a technical-ecological profile of the product can be established, which has to be translated into product features. The requirements resulting from the life cycle considerations are also input for the QFD methodology and as far as they are not customers' requirements, they are deduced on the one hand from precedent products with similar functions, which have been in the market. On the other hand the information is provided by historical data on processes used for manufacturing, maintenance and service activities as well as recycling and recovery activities.

The function and process analysis module of the life cycle oriented evaluation approach for decision support are similar to the requirements specification of a traditional design to life cycle model. The life cycle requirements are regarded as restrictions and have to be considered in the subsequent evaluation phases. In the next steps of the evaluation process the performance specification for the product concept and the design specification for the conceptual design are considered. In order to facilitate the next evaluation steps the product functions are determined on a rough level. In parallel the product breakdown structure is established including the functional product modules to be realized as well as the related product features.

In a third step the product design solutions developed in the product concept phase are assessed. The evaluation is based on the methodologies of Life Cycle Costing and Life Cycle Assessment. The technical solutions for the product design which are in line with the product profile defined have to be optimized with regard to the life cycle cost. In order to realize product improvements Value Analysis is integrated into the evaluation process.

The cost evaluation uses a resource based and process oriented estimation. Based on the product structure, the processes during the life cycle and the corresponding resource consumption are included [2] (figure 2).

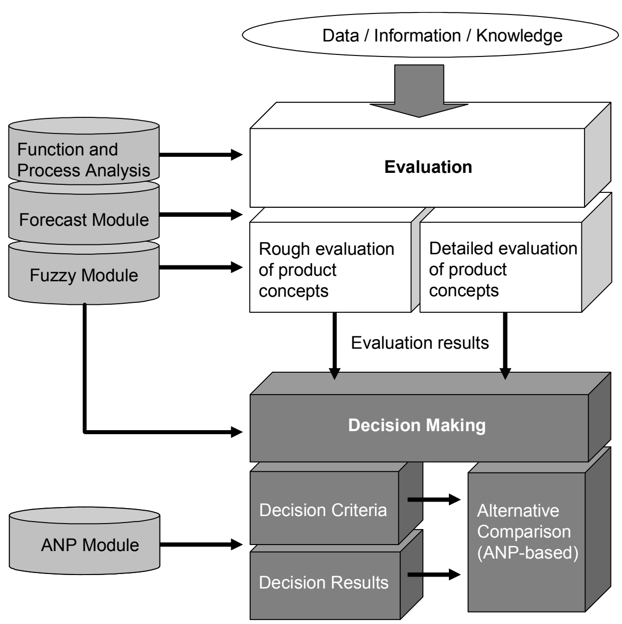

Figure 1: Evaluation and decision modules of the elaborated approach.

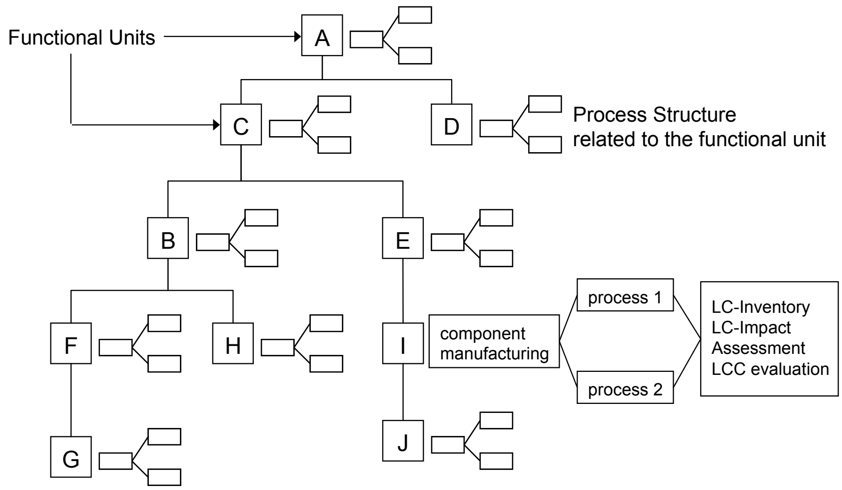

Figure 2: The optimization approach includes already existing as well as new functions.

2.3 The Economic and Ecological Evaluation

While the life cycle cost is the aggregate of all the costs incurred in the product's life, it must be pointed out that the developed approach focuses on the cost that can be influenced by designer. Some of the costs incurred in the life of the product are not a result of the design. These costs are related to the "way we do things" [3]. Classifying life cycle cost into management related costs and design related costs we are focusing on the latter component. One cost category for example, that may not be of interest to the designer when thinking about life cycle cost is the research and development cost. This cost is not related to the actual design of the product but rather to the kind of product being developed, the resources committed to the process and the manner in which these resources are used to arrive at a design solution. The cost determination in the current approach is based on the method of resource oriented Activity-Based Costing.

The organization's resource costs are assigned through activities to the products and services provided to the customers. The quintessence of the resource model is provided by the functional description of the coherences between the cost relevant product features and the resource cost with help of consumption and cost functions [2] [4]. The consumption functions quantify the resource consumption whereas the cost functions describe the functional relation between resource consumption and the cost induced by this consumption. The mathematical determination of resource consumption functions is based on the method of multiple linear regression, a statistical procedure for the identification of functional relationships.

For the implementation of the resource oriented Activity-Based Costing all activities and processes of one company have to be listed which are related to at least one resource and one cost driver. The dependency of processes from the individual quantity of cost drivers and the flexible linkage of processes to resulting process chains provide the ability to adapt easily to changing company structures. The current approach of evaluation of solutions for design to life cycle looks at the cost issues in the production, usage and disposal phases of products. The production cost consists of manufacturing cost (fabrication, assembly, test), process development, production operations, quality control, and initial logistic support requirements (e.g. initial consumer support, the manufacture of spare parts, the production of test and support equipment, etc.).

The primary focus in this phase is on determining the optimal design of the product and sequences of processes to produce and assemble the constituent parts into a complete product. Increasingly, this component is becoming a large proportion of the total production costs. Another concern in this phase is the effect of the activities on the environment [5] [1]. The operation and support cost comprises consumer or user operations of the product in the field, product distribution (marketing and sales, transportation and traffic management), and sustaining maintenance and logistic support throughout the system or product life cycle (e.g. customer service, maintenance activities, supply support, test and support equipment, transportation and handling, technical data, facilities, system modifications, etc [6] [7] [8].

Operating and support costs are the most significant portion of the Life Cycle Cost and yet are the most difficult to predict. The cost of operating and supporting an industrial machine tool for example may exceed the initial purchase price of that tool as much as five times [9]. A product which is reliable and easily serviceable leads to maximum availability and maximum customer satisfaction. To improve customer satisfaction, it is important to address the issue of making products which can be maintained in the least time, at the least cost and with a minimum expenditure of support resources, without adversely affecting the product's performance or safety characteristics. Support resources are manpower utilization, spare parts, tools, test equipment, services, and support facilities. The larger and more complex a system, the greater is the capital investment it will represent and the greater its likely revenue-earning capacity. Each minute out of service is therefore going to result in considerable financial loss to the system user [4] [10].

Development, use and retirement of products require the use and conversion of material and energy resources. These activities cause waste to be released into the environment. Energy consumption, air pollution and waste management currently dominate public discussions. The legislation in EU countries is guided by the "originator principle": the one who inflicts harm on the environment has to pay for cleaning up the damage [11] [1]. This together with other factors such as corporate image and public perceptions, consumers' demand for green products and rising waste disposal costs, has led to a increasing importance of retirement and disposal cost.

Life Cycle Assessment (LCA) is the framework that has been proposed for the evaluation of the impact products and processes have on the environment. LCA is known as an environmental and energy audit (accounting procedure) that focuses on the entire life cycle of a product from raw material acquisition to final product disposal of environmental emission [12] [9]. The approach described in this paper uses the LCA method in order to determine the environmental impact of the design solution regarded. Because of the insufficient data in the early stages of product planning and design, databases are used to get the information needed from similar products or processes. The assessment of the cost components bases on similar data and expert knowledge.

2.4 The Decision Support Modules

The decision support is based on two main components: a decision field and a target system.

The decision field includes the product alternatives and the so called 'state space' with knowledge about the business environment and about factors that influence the results of a product alternative but at the same time being independent from the different activities of the decision maker. Furthermore, the decision field includes the information system and the decision logic. The information system contains all the available information on the decision conditions as well as related parameters whereas the decision logic describes the reasoning for the alternative choice.

The second main component of the decision support is the target system containing the definition of the different target parameters as well as the preference values, as illustrated in figure 3. The approach is based on the likelihood specifications of the involved decision makers. Both, subjective as well as objective probability values are supported and handled in the forecast module of the evaluation approach (see figure 1). The objective specifications are based on empirical data, whereas subjective specifications are derived from the numerical values a decision maker uses to describe the different future conditions. The subjective specifications are characterized as 'subjective likelihood' or 'certitude level'. The uncertainties deduced from risk and ambiguity of the future conditions are integrated in the evaluation approach by means of distribution functions (objective specifications) as well as with help of conditional probabilities based on Bayes-statistics (subjective specifications).

The deduction of subjective likelihood is done based on a subjective a priori estimation and a test distribution. The evaluation approach provides for uncertainties derived from the fuzziness and incompleteness of available data by using fuzzy logic [13]. To express the preference judgments as fuzzy sets or fuzzy numbers is a natural way to cope with the incorporated vagueness of the human thinking [14].

Fuzzy-parameters are integrated in the evaluation model as 'possibilistic information' and are used for the interpretation of linguistical specifications and assessments done by experts and decision makers. Fuzzy based computations are done within the Fuzzy-module of the evaluation approach. The design and process analysis allows for an allocation of product components to necessary manufacturing processes and process steps as well as to resource consumptions and costs. The evaluation within the three modules is based on selected technical, ecological and economic criteria (e.g. reliability, maintainability, functional capability, emissions, environmental impacts, resource consumption, recyclability, life cycle costs, efficiency, cost-performance ratio, etc.).

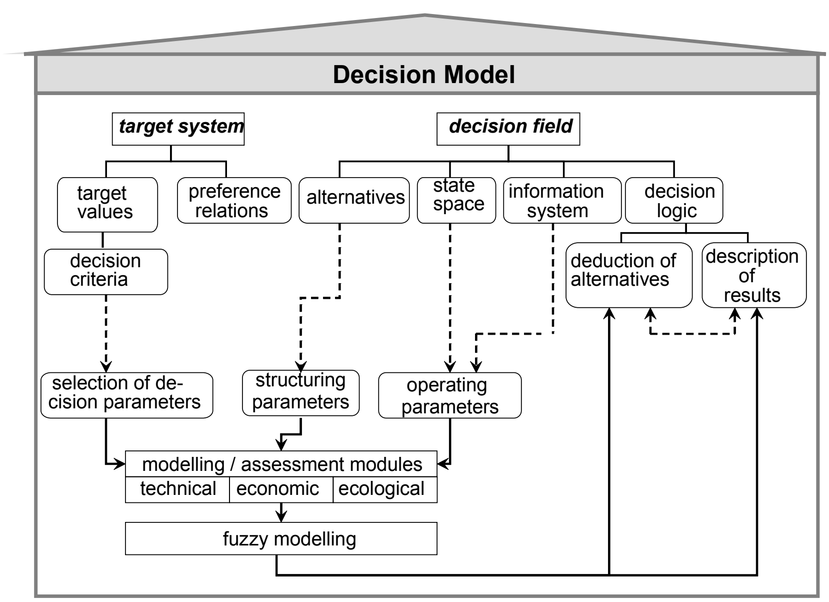

Figure 3: Structure of the decision support module.

The criteria evaluation and comparison between the different parameter values is done by means of paired comparison matrices. They allow for a determination of the priority vector as well as the control hierarchy or network of objectives and criteria that control the interactions in the evaluation system based on the ANP-method. This provides ANP [15] [16] a way to input judgments and measurements to derive ratio scale priorities for the distribution of influence among the factors and groups of factors in the decision for the most appropriate product alternative. In this approach, the ANP can be also used to allocate resources according to their ratio-scale priorities.

In the approach described in this paper the decision-maker's vague judgments are represented by a specific form of normal fuzzy sets, which are called triangular fuzzy numbers. The reason for this is the better mapping within the ANP network. However the specific form of the fuzzy sets does not restrict the applicability of the approach.

The conventional ANP method is modified by use of the Preference Programming Method [17], which supports the transformation of fuzzy judgments into interval-based judgments by using so called α-cuts (see figure 4). For each α-cut a crisp value can be determined that corresponds to the crisp priorities derived from the interval judgments, thus eliminating the need for any additional fuzzy ranking procedure. A simple aggregation is than used to obtain overall values of the priorities in the ANP network. Priorities are derived from fuzzy pairwise comparison judgments and there is no need for the construction of fuzzy comparison matrices of skewed reciprocal elements. More over the adapted method allows for prioritization from an incomplete set of judgments and can easily be applied for group decision making (see further explanations in [17]).

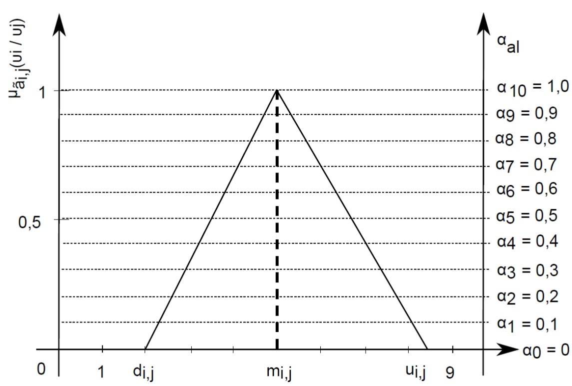

Figure 4: α-cuts transforming initial fuzzy judgments into a series of interval judgments [17].

In order to combine probability data with possibility data (expressed by fuzzy-sets) λ-fuzzy-measures are used. The latter are integrated into the Fuzzy Preference Method as a new component. Hereby λ-fuzzy-measures are defined as δ-algebra and provide the adequate mathematical framework to convert and combine the likelihood data with the fuzzy-based data.

The traditional ANP-method is substantially enlarged by two items:

- The Fuzzy Preference Programming Method is used. That allows for accurate results and faster computations,
- Using additionally comprehensive fuzzy-measures not only likelihood or fuzzy-based information is used, but both sources of information are integrated: probabilities as well as vague information represented by fuzzy sets.

An algorithm has been created in order to realize the transformation and combination of data as well as to conduct the computations necessary to implement the modified ANP-method (see also [18]).

3 IMPLEMENTATION

The implementation of the above described model requires the formulation of some requirements that should be fulfilled before conducting the application to practice:

Definition of the most important target values and determination of relevant decision criteria: For the calculation of values in the assessment modules as well as for mapping of different interdependent relationships in the ANP-network it is important to keep the number of considered parameters to a manageable level.

Gathering of necessary data to conduct the assessments in the three assessment modules: That includes forecasts based on expert judgments expressed as fuzzy sets as well as learning from experiences with similar products available as statistical data.

Combination of the gathered data under consideration of uncertainty: This step includes a conversion of statistical data and fuzzy sets into λ-fuzzy-measure. This way a combination of likelihood data with uncertain information expressed by fuzzy sets is possible.

Construction of an ANP-network: In general, this can be done with help of software-tools (e.g. Super Decisions Software – ANP software for dependence and feedback [19]. As the current approach modifies the traditional ANP method, an algorithm has been created based on MatLab in order to enlarge the basic functionality of ANP. The conduction of paired comparisons within the ANP-network has been realized based on fuzzy sets. The further computations have been done under consideration of the Fuzzy Preference Programming method and the adaptations described in the aforementioned chapter.

The early evaluation of product alternatives for a product during preliminary planning activities are characterized by a high variety of influencing factors linked with each other by interacting dependencies as well as by a high uncertainty of available data. The developed ANP-based approach helps describing the decision alternatives as well as the influencing factors and facilitates the representation of dependence and feedback. The model has been implemented in a pilot project for the early evaluation of product alternatives relevant for ceiling-mounted supply units. Three alternatives have been considered:

- Ceiling supply units as compact configurations of strong rigid arms,
- Ceiling supply units with modular design for better space management,
- Ceiling supply units with compact but motorized design.

Considering the targets short time to market, low life cycle costs, high compatibility with already existing products and the achievement of significant market share within a given time period, the 2nd alternative yielded the best results. Using the ANP-based model made visible the high influence of know-how transfer from operations on the development of enhanced functionalities that determine the compatibility with existing products. The interdependent relationships could be integrated in the evaluation of the alternatives and facilitated the decision making. This feature represents one of the main advantages of the developed approach.

4 SUMMARY

The design of industrial products considering their entire life cycle must satisfy technical and ecological requirements while providing maximum economic benefit. The approach of life cycle oriented evaluation for product alternatives taking uncertainty and vagueness into account discussed in this paper acts in the triangle of conflicting priorities between technical, ecological and economic requirements.

It describes an integrated methodology of life cycle oriented evaluation and decision support for product design alternatives and helps considering the above-mentioned requirements in terms of their long-term impacts on the entire product life-cycle. In order to achieve an efficient and effective decision considering the product life cycle the methods of Quality Function Deployment and Value Analysis are aligned with the methods of Life Cycle Costing and Life Cycle Assessment to be integrated into a comprehensive evaluation approach. The life cycle oriented evaluation approach for product alternatives taking uncertainty and vagueness into account includes an analysis identifying and reducing costs by evaluating the most economic way of satisfying customer's needs and specified requirements. What drives or triggers costs, how these costs can be reduced, and how resources can be utilized more effectively and efficiently are very important issues to be considered.

The described evaluation methodology comprises two assessment levels, which are implemented for the purpose of facilitating a differentiated evaluation based on the content of the available data. The developed fuzzy-based evaluation model enhances, on the one hand, the ANP approach in order to consider uncertain and vague data. On the other hand, a supplementary transformation of statistical and fuzzy data into fuzzy-measures is conducted, in order to be easier integrated into the comprehensive decision network.

5 REFERENCES

[1] Raar, j., (2004), Environmental and Social Responsibility: a Normative Financial Reporting Concept, Fourth Asia Pacific Interdisciplinary research in Accounting Conference, Singapore

[2] Emblemsvag J., (2003), Life-Cycle Costing: using Activity-based costing and Monte Carlo Methods to Manage Future Costs and Risks, John Wiley & Sons Inc.

[3] Asiedu, Y., Gu, P., (1998), Product Life Cycle Cost Analysis: State of the art Review, International Journal of Production Research, Volume 36, Number 4.

[4] Goldbaum, J., (2000), Life cycle cost Analysis Stateof-the-Practice, springfield, Denver

[5] IEC 56/655/CD, (2000), Supporting information to IEC 60300-3-3: Dependability Management – Part 3-3 Application Guide – Life Cycle Costing, Beuth, Berlin

[6] Frangopol, D.M., furuta, H., (2001), Life Cycle Cost analysis and Design of Civil Infrastructure Systems, Structural Engineering Institute of the American Society of Civil Engineers, Reston

[7] Bernardi, M.; Bley, H.; Schmitt, B., (2003), Restructuring Service of Repair Capable Products to Optimize Useful Life, Cirp Life Cycle Engineering Seminar 2003 – Engineering for Sustainable Development, Copenhagen, Denmark

[8] Warnecke, H.-J., Bullinger, H-J., Hichert, R., Voegele, A. A., (1996), Kostenrechnung Für Ingenieure, Hanser, München

[9] Ulmschneider, (2004), Life Cycle Costing (LCC) Und Life Cycle Assessment (LCA) – EINE Übersicht Bestehender Konzepte Und Deren Anwendung Am Beispiel Von Abwasserpumpstationen, Dresden

[10] Coenenberg, A.G.; Fischer, T.M.; Günther, T., (2009), Kostenrechnung Und Kostenanalyse, Stuttgart: Schäffer-Poeschel

[11] Züst, R., Troxler, P., (2006), No More Muddling through. Mastering Complex Projects in Engineering and Management. Dordrecht: Springer

[12] Hendrickson, C.T., (2006), Environmental Life Cycle Assessment Of Goods And Services: An Input-Output Approach, Washington, D.C.: Resources for the Future; Chichester: John Wiley

[13] PARDALOS, P. M., (2008), Fuzzy Multi-Criteria Decision Making: Theory and Applications with Recent Developments, Boston, MA : Springer

[14] Roso, M., (2009), Kosten- Und Erlösrechnung Unter Unscharfer Sicherheit: Fuzzifizierung Der Grenzplankostenrechnung, Baden-Baden : Nomos

[15] Saaty, T.L., Vargas, L.G., (2006), Decision Making with the Analytic Network Process: Economic, Political, Social, and Technological Applications with Benefits, Opportunities, Costs And Risks, New York, NY: Springer

[16] Peters, M. L., (2008), Vertrauen In Wertschöpfungspartnerschaften Zum Transfer Von Retentivem Wissen: Eine Analyse Auf Basis Realwissenschaftlicher Theorien Und Operationalisierung Mithilfe Des Fuzzy Analytic Network Process Und Der Data Envelopment Analysis, 1. Aufl., Wiesbaden: Gabler

[17] Mikhailov, L., Singh; M.G., (2003), Fuzzy Analytic Network Process and Its Application to the Development of decision support systems. IEEE transactions on Systems, Man & Cybernetics – Part C: Applications & Reviews, Vol. 33 (2003), No. 1, 33-41

[18] Rossi, D., (2012), Modell Zur Unterstützung Von Entscheidungen Bei Unsicherheit in Der Lebenszyklusorientierten Produktplanung, Dissertation, Tu Wien

[19] Superdecision (2011); The Analytic Network Process for Decision-Making, 2011, Www.Superdecisions.Com

Environmental Impact of Body Lightweight Design in the Operating Phase of Electric Vehicles

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Abstract

Against the background of dwindling resources and increasing emission regulations powertrain electrification seems to be the future for individual mobility. In this context lightweight design is a promising enabler to reduce energy consumption in the operating phase. Considering higher efforts within production and recycling for lightweight solutions this paper aims to conduct a life cycle assessment for the operating phase of electric vehicles to evaluate the ecological advantages of a lightweight car body in comparison to a conventional steel concept. At this, the outperformance of the lightweight concept extremely depends on the chosen use pattern and mix of charging current.

Keywords:

Life cycle assessment; electric vehicle; lightweight design

1 INTRODUCTION

Politics and society are more and more concerned about an anthropogenic climate change. In times of a beginning energy revolution especially automotive companies are urged to develop new driving concepts to meet the challenge of limited oil reserves and strict pollutant emission levels defined by law for the future [1]. Therefore, innovative driving concepts are required. Using an electric drive in combination with an energy-efficient lightweight design can be considered as a promising alternative to conventional vehicle driving systems.

1.1 Goal and Scope

A common approach to modify a vehicle's driving system is to replace the components of the conventional drive by an electric engine including the required energy storage without considering the changing circumstances and technical requirements of the used electric drive system (Conversion Design). Due to the overall heavier electric system (electric motor, battery etc.) without altering the structure of the car body this procedure causes an increase in the vehicle´s weight. Therefore, an alternative approach is to integrate the battery as a load-bearing element in the body structure and additionally use a weight-optimized multi-material design of the body (Purpose Design). By these weight savings, resource-savings and an energy-efficient design of the entire vehicle can be achieved. Certainly the lightweight design is an enabler to significantly reduce the total energy consumption of a moving vehicle since it contributes to the rolling, gradient and acceleration resistance whereas only the air resistance is unaffected.

Considering higher efforts within production and recycling for lightweight solutions this paper aims to conduct a life cycle assessment (LCA) for the operating phase of electric vehicles to evaluate the ecological advantages of a lightweight multi-material car body in comparison to a conventional steel concept.

1.2 Environmental Impact throughout the Lifecycle

The operating phase is an important stage when conducting a LCA of an automobile. According to other studies, it accounts for the majority of the environmental impacts in a car's life cycle [2, 3]. The significance of this phase does mainly arise from direct and indirect emissions from fuel or electricity production and consumption. Other factors, i.e. maintenance and tire abrasion represent only a minor part of the emissions and will be neglected in further considerations. Beside the energy efficiency of an electric vehicle it is also important to analyze the supply chain of the electricity used as it has a huge influence on the car's overall lifetime emissions.

Recent studies state that lightweight materials are more energy-intensive than conventional steel during production and recycling, thus directly increasing the environmental impacts of a lightweight car body in these phases [4]. However, the operating phase is the life cycle stage where a lightweight concept gains ground compared to a concept based on conventional steel due to decreased energy consumption caused by the reduced mass. The assumed progression of the environmental impacts for both vehicle designs along the lifecycle are displayed in Figure 1. In this figure it is initially assumed that the advantages during the operating phase outweigh the disadvantages of a lightweight car body in the other phases. In the further course of this paper these postulated advantages will be quantified.

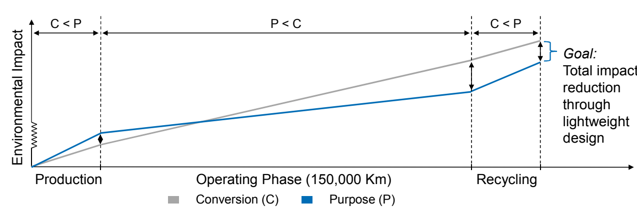


Figure 1: Environmental impact throughout the lifecycle.

2 RELATED WORK: LIFE CYCLE ASSESSMENT OF LIGHTWEIGHT ELECTRIC VEHICLES

Our research methodology is based on DIN EN ISO 14040 et seq. [5] and the ILCD Handbook [6]. Those are the official and international accepted guidelines of conducting a LCA.

As the influencing factors and surrounding conditions for the use of electric cars may vary in the future and cannot be predicted precisely, a variety of scenarios have to be designed to cover a wide range of potential developments and aspects. The three studies described below focus on a similar topic and their results will serve as input for this paper.

"EMPA"[1] focuses on analyzing different drive systems, i.e. gasoline, liquid natural gas, hybrid and electric vehicles [7]. Therefore, each system is analyzed separately and different European electricity mixes are applied. The "Öko-Institut"[2] analyzes the interaction of electric vehicles with the electricity sector [8]. Different scenarios, based on the time of charging and the use of a charging management are defined to analyze the charging electricity and green house gas (GHG) emissions that are caused. The "IFEU"[3] applies a similar approach but neglects the influence of daytime or nighttime charging. Instead the emissions of a lightweight vehicle based on an aluminum car body are examined for an "innovative" scenario in 2030 [9]. The ecological consequences of these vehicles are only evaluated using an average electricity mix in 2030. Moreover, the influence of a lightweight car body in combination with different charging strategies and user profiles is not considered yet. An overview of the studies is given in Table 1.

All aforementioned studies provide useful results for the ecological assessment of compact-class electric vehicles. But they do not achieve to evaluate the potential advantages of a lightweight vehicle concept under various realistic scenario assumptions, such as differentiated driving cycles and varying charging electricity composition.

Institution	Main Focus	Time Horizon	Fuel Efficiency* [kWh/100km]
EMPA	LCA of different drive systems	2015	14.8
IFEU	LCA of EV. Consider charging strategies and lightweight scenarios**	2030	12.8
ÖKO	Interaction of EV with electricity sector and connected GHG-emissions	2030	16.0

LCA = Life Cycle Assessment
EV = Electric Vehicles
GHG = Green House Gas

* Fuel efficiency means consumption in the New European Driving Cycle without consideration of auxiliary consumers
** The lightweight vehicle ist only analyzed using an average electricity mix and not examined under the assumption of different charging strategies

Table 1: Overview of analyzed studies.

3 CONVENTIONAL AND LIGHTWEIGHT BODY CONCEPTS USED FOR THE LCA

3.1 Technical Requirements

To carry out valid results for two vehicle concepts the comparison of both approaches has to be based on the same assumptions and circumstances. Therefore, the assumed start of production and use of the car is 2016 and the total lifetime mileage is expected to be 150,000 km. Moreover, the 5th generation of the VW Golf (1247 kg empty weight) serves as the basis for both concepts, Purpose Design and Conversion Design (air drag coefficient, front wheel drive etc.). The range of both vehicles is set to 150 km by using a battery system of 130 Wh/kg. The operating power of the electric engine is assumed to be 42.5 kW, the peak power to be 85 kW. The additional load is 500 kg. The vehicle's safety requirements have to comply with the requirements of the Euro-NCAP crash test valid in 2016.

[1] "Eidgenössische Materialprüfungs- und Forschungsanstalt", Zurich, Switzerland

[2] "Institute for Applied Ecology", Freiburg, Germany

[3] "Institut für Energie- und Umweltforschung", Heidelberg, Germany

3.2 Purpose and Conversion Design

By removing the relevant components of the combustion drive and vice versa adding components required for an electric drive the VW Golf V is theoretically modified into an battery electric vehicle (BEV). All components not directly connected to the drive, like chassis, shell or interior remain the same. To ensure the comparability to the Euro-NCAP crash test and furthermore to protect the battery cells in case of crashes the existing steel body (282 kg) has to be reinforced at several critical points increasing the body's weight by 32.1 kg, finally adding up to 314.1 kg [10].

By replacing the conventional combustion engine (265.1 kg) by an electric drive (314.3 kg) and due to the structural reinforcements the final weight of the Conversion Design including the driver (75 kg) is 1403 kg. The calculated weight of the battery (187.5 kg) is based on a battery capacity of 24.36 kWh in combination with 150 km driving distance in the New European Driving Cycle (NEDC) and 85% maximum depth of discharge [10].

The Purpose Design employs a lightweight car body with a battery system that is integrated into the car body's structure as a load-bearing element and thus contributes to the safety and stability of the vehicle. All in all, the lightweight measures aim at a reduction of the body's weight by 25%. A lighter body lowers the car´s empty weight and therefore induces further potentials for secondary weight reductions [11]. Further investigations only consider secondary weight savings of the battery since the focus of the study lies on the lightweight measures concerning the body in which the battery is meant to act as a load-bearing element. Considering the presettings of the Conversion Design the aspired 25% body weight reduction counts up to 78.5 kg. Since the battery capacity can be lowered to 23.53 kWh while maintaining a distance of 150 km in the NEDC a 6.5 kg battery reduction can be assumed. Due to these measures the lightweight car sums up to 1318 kg (driver included), meaning 6% less weight compared to the Conversion Design.

4 ASSESSMENT OF THE ENVIRONMENTAL IMPACT OF A LIGHTWEIGHT CAR BODY IN THE OPERATING PHASE

4.1 Methodology

A scenario analysis will be performed as various factors having multiple specifications are influencing the ecologic performance of an electric vehicle. A detailed analysis will then be performed for each scenario to identify the impacts under the defined assumptions. A "Well-to-Wheel"-approach which includes the complete fuel or electricity supply chain is applied meaning that all relevant steps from mining to transportation up to conversion in plants are covered [12]. To model the system and calculate the environmental impacts the LCA software "Ganzheitliche Bilanzierung" (GaBi) with its connected databases will be used. The results will be calculated per km driven for each vehicle, thus the vehicle-kilometer (vkm) serves as the functional unit. In the further process of scenario definition it is distinguished between an "average" and a "marginal" approach to cover a wide range of possible developments by varying the boundary conditions. "Average" in this context means standardized or average conditions whereas "marginal" takes into account individual preferences and behavior of the vehicle owner, i.e. when to refuel the vehicle or usage habits.

4.2 Environmental Impact of an Electric Vehicle

The first step while evaluating the environmental impacts derived from the operating phase of a vehicle is to identify the key drivers of the ecological performance. On the most aggregated level it can be distinguished between consumption and the used charging electricity as the determining factors (see Figure 2). The consumption is influenced by the technical characteristics of the vehicle but also by the conditions under which it is operated. For building scenarios in the average approach standardized driving cycles, like the "New European Driving Cycle" (NEDC) will be considered [13]. The NEDC is mandatory for manufacturers in Europe when assessing fuel consumption and emissions of new vehicles and therefore is also used for the present study. The NEDC is often criticized for being based on unrealistic driving conditions. Therefore other driving cycles have been developed, such as the "Common Artemis Driving Cycle" (CADC) [14]. It has a more dynamic speed profile which is derived from real world driving experiments. The higher shares of acceleration result in an additional consumption of 16% compared to NEDC values [2].

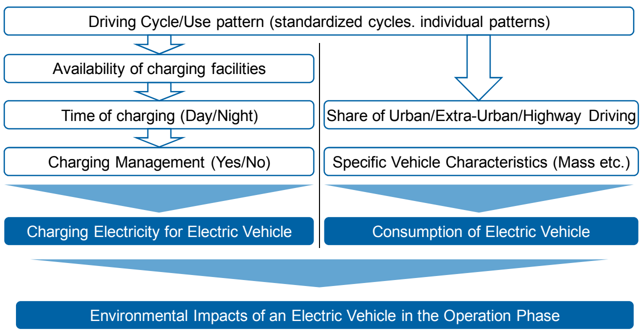


Figure 2: Main influencing factors of an electric vehicle.

Although the CADC tries to depict a real life driving cycle it is still an average cycle and may not resemble the individual use pattern of vehicle owners. Therefore, the marginal approach takes this into account by defining three user profiles, "Homemaker", "Commuter" and "Businessman", with varying shares of urban, extra-urban and highway driving. Table 2 displays the three profiles with their distinct share of driving time for each environment. Due to their constant engine efficiency electric vehicles have the lowest energy consumption in an urban environment with low velocities [9].The higher the average speed, the higher the consumption of the vehicle. This results in the "Homemaker"-profile being the most fuel-efficient while the "Businessman" has the highest energy consumption.

Profile	Urban	Extra-Urban	Highway
Homemaker	70%	20%	10%
Commuter	30%	40%	30%
Businessman	10%	20%	70%

Table 2: Individual user profiles in the marginal approach.

Beside the velocity further specific vehicle characteristics influence the vehicle's consumption. In the present study it is assumed that both vehicles, the Conversion and the Purpose Design, are identical as to air drag coefficient or gear ratio. Only the design of the car body and battery system results in a vehicle mass reduction of 85kg which in turn leads to reduced fuel consumption.

The second key driver is the charging electricity. The environmental impacts may differ significantly if different sources of electricity production are used for charging the vehicle. For instance, nuclear power plants or renewable energies have close to zero green house gas emissions (GHG) whereas coal fired power plant's GHG emissions tend to be much higher. As the geographical scope of this study is Germany, the German electricity mix is considered for this analysis in the average approach. Since the assumed Start-of-Production of both concepts is in 2016, this year is also chosen as the starting point of the analysis. Since no reliable predictions are available for this year the values for 2016 are linearly interpolated between 2011 an 2020. Official values of the Renewable Energies Agency [15] are used to represent the mix in 2011. For 2020 multiple studies on the development of the German electricity market are available [16]. As all of these studies are based on different assumptions and used different modeling approaches, the arithmetic average of those results is calculated and used as an objective input for the present study (see Table 3).

Shares in [%]	Nuclear	Lignite	Hard coal	Gas	Oil	Water	Solar	Wind	Geoth.*	Biomass	Other
Mix 2011	18.0	25.0	19.0	14.0	2.0	3.0	3.0	8.0	3.0	6.0	0.0
Mix 2016	10.4	22.7	19.2	16.9	1.2	2.8	3.8	13.5	3.3	6.2	0.2
Mix 2020	4.4	21.0	19.3	19.2	0.5	2.7	4.5	17.9	3.5	6.4	0.4

* Geothermal Energy

Table 3: German electricity mix in 2011, 2016 and 2020.

The assumption that electric cars will be charged with the average German electricity mix can be seen as inappropriate for a realistic use context and therefore is only applied in the average approach [9]. Thus, for the marginal approach the individual behavior has to be taken into account when evaluating the charging electricity.

Depending on the particular point in time and the location of recharging the car will be charged with electricity supplied from different sources. The most important factor in this context is the "merit order" [22]. It determines that demanded electricity is supplied from the power plant with the lowest marginal costs and free capacities at any time.

As a fluctuating amount of power is required throughout the day the last called power plant, the so-called "marginal power plant", may vary. Thus, the environmental impacts caused by charging electricity generation are influenced by the particular daytime of charging as the supplying power plant in the morning might be different from the one in the evening.

But the exact time of charging does not only depend on when the car is plugged in. It can also be controlled by a price-based charging management which moves the charging process to hours with low electricity costs, thus influencing the composition of charging electricity. Based on these assumptions, it can be distinguished between four different charging strategies: charging during daytime or nighttime combined with or without using a charging management.

The "Öko-Institut" simulated the impact of electric cars on the German electricity production [8]. As a result they reveal possible compositions for charging electricity in the aforementioned charging strategies respectively for the years 2020 and 2030, resulting in a total of eight possible compositions. A similar study has been conducted by the "IFEU" [9]. Their temporal focus is the year 2030 and they consider three different scenarios with no particular distinction between daytime and nighttime charging: (1) recharging directly after the last trip of the day, (2) recharging using a charging management and (3) recharging using charging management with an increase of regenerative energy capacities to supply the vehicle. In total, eleven different compositions can be adopted from the studies conducted by the "Öko-Institut" and "IFEU". In combination with the three use patterns 33 potential scenarios have to be analyzed in the marginal approach. In the average approach two driving cycles (NEDC and CADC) are combined with the German electricity mix in 2011, 2016 and 2020 respectively to build up 6 scenarios in total.

4.3 Scenario Preparation

For evaluating the potential outperformance of a lightweight vehicle in the operating phase the five most relevant scenarios will be discussed, two of the average and three of the marginal approach.

The consumption for the average scenarios in the NEDC amounts to 13.80 kWh/100km for the Conversion Design and 13.33 kWh/100km for the Purpose Design which equals a consumption saving of about 3.4%. As mentioned before 16% can be added to obtain the CADC values.

For calculating the consumption in the marginal scenarios, the CADC consumption is split into urban (factor 0.865) and extra-urban (factor 1.087) according to the EMPA study [7]. To create an additional value for highway driving the extra-urban result is duplicated and additionally increased by 23% [23]. The tractive energy in each profile of the marginal approach ("Homemaker", "Commuter", "Businessman") is calculated by multiplying the energy demand for urban, extra-urban and highway driving by their respective shares (see Table 2) and adding them up.

In contrast to the average approach, the marginal approach does also account for auxiliary consumers to resemble common or more realistic driving conditions. The power demand is supposed to be 1 kW constantly [9], thus the additional energy consumption depends on the average speed or the time needed to drive the distance of 100 km. The assumed average speeds for urban, extra-urban and highway driving are 28, 65 and 110 km/h respectively. Again the average speed in the three defined profiles is calculated by multiplying these speed values by the shares of urban, extra-urban and highway driving and adding them up. This results in an average speed of 43.6 km/h for the "Homemaker", 67.4 km/h for the "Commuter" and 92.4 km/h for the "Businessman" leading to an auxiliary energy consumption per 100 km of 2.29 kWh, 1.48 kWh and 1.08 kWh respectively. To conclude the calculation of consumption in the marginal scenarios the required tractive and auxiliary energy are added. This leads to the following values, as shown in Table 4.

Consumption [kWh/100km]	NEDC	CADC*	Homemaker**	Commuter**	Businessman**
Conversion Design	13.80	16.01	17.61	19.03	20.95
Purpose Design	13.33	15.46	17.09	18.44	20.27

* 16% increased energy consumption compared to NEDC
** 16% increased energy consumption compared to NEDC plus auxiliary consumers

Table 4: Consumption in the five selected scenarios.

The second important factor is the charging electricity. As mentioned before, the German electricity mix for 2016 and 2020 is used in the average approach for both vehicles in the NEDC and CADC. For the marginal approach the composition of charging electricity considers the time of charging, the use of a charging management and the possibility of additional regenerative energies. The assumptions for each scenario are marked in Figure 3.

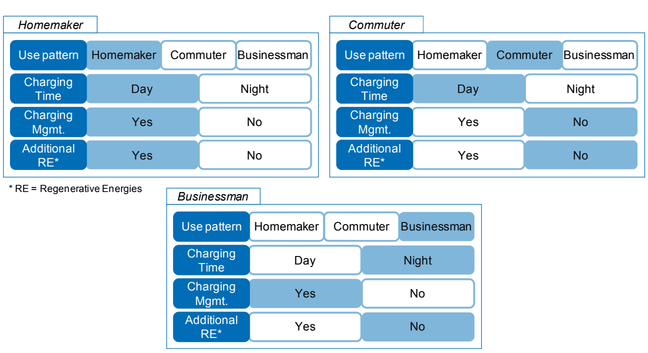


Figure 3: Characteristics of the scenarios in the marginal approach.

It is assumed that additional capacities of renewable energies that cover the additional electricity demand caused by electric vehicles are only provided in the "Homemaker"-scenario. The charging process takes place during the day. These two assumptions lead to the vehicle being charged almost exclusively from regenerative energies, such as wind, water and solar power. In combination with the high share of urban driving and low energy consumption it is supposed to be the most eco-friendly scenario.

For the "Commuter"-profile it is assumed that the vehicle can be charged during the day, i.e. at charging stations during working time, without being a charging management employed. Thus the vehicle will start charging as soon as it is plugged in. In this scenario charging electricity will mainly be supplied by coal-fired power plants.

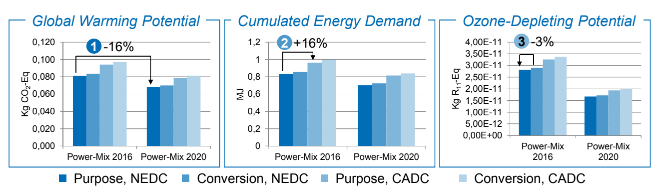
Consumption is highest in the "Businessman"-scenario due to the high share of highway-driving. As the vehicle is parked in different places almost every day, a charging station is not assumed to be available in most cases which results in nighttime charging while using a charging management. It shifts the composition to a greater share of electricity from lignite-fired and nuclear power plants with low marginal costs. In turn, the share of hard-coal is lowered compared to the "Commuter" scenario. For the exact composition of the different kinds of charging electricity see Table 5.

Composition of Charging Electricity in [%]	Power-Mix 2016	Power-Mix 2020	Homemaker	Commuter	Businessman
Non-Regenerative	**73.2**	**67.4**	**2.0**	**99.2**	**97.9**
Nuclear	10.4	4.4	0.0	1.5	5.9
Lignite	22.7	21.0	0.0	25.5	46.3
Hard-Coal	19.2	19.3	2.0	62.8	44.3
Gas	16.9	19.2	0.0	8.0	1.4
Oil	1.2	0.5	0.0	1.4	0.0
Other	2.8	3.0	0.0	0.1	0.2
Regenerative	**27,0**	**32.7**	**98.0**	**0.7**	**2.0**
Water power	3.8	4.5	9.7	0.0	0.0
Wind power	13.5	17.9	70.5	0.6	1.6
Solar power	3.3	3.5	17.8	0.0	0.0
Biomass	6.2	6.4	0.0	0.1	0.4
Geoth.Power	0.2	0.4	0.0	0.0	0.0

Table 5: Composition of charging current in the chosen scenarios.

4.4 Discussion of Results

For further discussions the common impact categories Global Warming Potential (GWP), Cumulated Energy Demand (CED) and Ozone-Depleting Potential (ODP) are chosen. At first, the results will be presented per vehicle-kilometer (vkm) before the cumulated savings throughout the complete operating phase are calculated in a second step.



(a) (b) (c)

Figure 4: Results of the average approach per vkm.

Three major findings can be obtained from the average approach. The first is the decrease of environmental impacts, i.e. 16% in case of Global warming potential, from the year 2016 to 2020 (see Figure 4 (a)). The main reason for this effect is the expansion of renewable energies. It is assumed that the share of renewable energies in the German electricity mix will increase by about 6.6% in this four year span. But this effect is also partly related to the improvements in conventional power plant efficiencies as they will rise with the building of new plants and repowering older ones [24]. The second effect is based on the different driving cycles (see Figure 4 (b)). As the CADC has a more consumption-intensive speed profile, more energy is required to cover the same distance, thus resulting in higher emissions. Finally, due to lower weight, energy consumption decreases and the car's ecological performance improves by 3.4% regarding GWP,CED and ADP. The advantages of a lightweight design in the operating phase are exemplarily shown for the Ozone-Depleting Potential (see Figure 4 (c)).

Putting the 3.4% in a life cycle context reveals the relevance of this value. Table 6 presents the total lifetime results in the three chosen categories for the NEDC charging the vehicle with the electricity mix in 2016.

Lifetime Emissions and Savings	Global Warming Potential (GWP)	Ozone-Depleting Potential (ODP)	Cumulated Energy Demand (CED)
Unit	Kg CO_2-Eq	Kg R11-Eq	MJ
Conversion Design	12,542,39	4.35E-06	128,528,27
Purpose Design	12,160,57	4.22E-06	124,615,55
Savings	381.82	1.33E-07	3,912,73

Table 6: Total lifetime savings in the NEDC in 2016.

The total savings amount to 381.82 kg of CO_2-equivalents over the course of a 150,000 km lifespan in the NEDC. To grasp the significance of this number it has to be evaluated against the emissions of the production and recycling stage. An analysis of a conventional steel car body production conducted by WZL of RWTH Aachen University revealed that during production an amount of approximately 2,000 kg of CO_2-equivalents is emitted. Against this background, a buffer of about 19% would be gained in the operating phase which could be consumed during production and recycling of the commonly more energy-intensive lightweight materials [4]. The lifetime savings of all scenarios in the average approach are summarized in Table 7. It can be seen that the savings decrease from 2016 to 2020 because of the higher share of renewable energies, in particular wind power. Comparing the driving cycles, the savings rise from the NEDC to CADC as the total emissions are higher in the CADC.

Total Lifetime Savings	GWP	OPD	CED
Unit	Kg CO_2-Eq	Kg R11-Eq	MJ
NEDC-Power Mix 2016	381.82	1.33E-07	3.912.73
NEDC-Power Mix 2020	319.67	7.86E-08	3.303.21
CADC-Power Mix 2016	449.38	1.56E-07	4.605.08
CADC-Power Mix 2020	376.24	9.25E-08	3.887.71

Table 7: Lifetime savings in the average scenarios.

The environmental impacts for the Purpose Design and Conversion Design derived from the marginal scenarios can be found in Figure 5. To additionally compare them to the average approach, the values for the Purpose Design in the NEDC in combination with the 2016-electricity mix are also displayed. Again the values are presented per vehicle-kilometer (vkm).

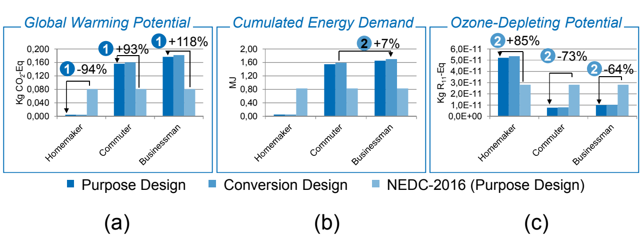


Figure 5: Results in the marginal approach per vkm.

The first finding in the marginal approach are the massive disparities in GWP compared to the NEDC values in the different scenarios (see Figure 5 (a)). When analyzing the "Homemaker"-scenario a 94%-decrease of GHG emissions compared to the NEDC results from the average scenario using the 2016 electricity mix is revealed. This is due to the 98%-share of renewable energies in contrast to about 27% in the 2016 electricity mix. The picture changes when looking at the "Commuter" (+93%) and "Businessman"-scenario (+118%). The emissions increase drastically due to the high share of coal-based energy.

The second effect is based on the different use patterns (see Figure 5 (b)). When comparing the "Commuter"-scenario against the "Businessman" an increased energy demand of 7% can be observed although both scenarios only slightly differ in terms of their used energy composition (mainly coal-based energy).

The third finding is displayed in the diagram about Ozone Depleting Potential (ODP) (see Figure 5 (c)). The impact measured in ODP is diametrically opposed to the previous findings. The results show a massive increase (+85%) in ODP if the vehicle is charged with "green" electricity compared to the average scenario using the electricity mix in 2016. A more thorough analysis of the results reveals that solar energy is the main driver for this phenomenon as the production of solar panels has high impact in this category [25]. On the contrary, charging electricity in the "Commuter" and "Businessman"-scenario has a lower ODP, -73% and -64% respectively, as emissions from conventional power plants are lower for this impact category.

Putting these results into the life cycle background reveals the following findings. Again, the focus is on GHG-emissions as it is the politically most relevant category. The left side of Figure 6 shows the values in the NEDC and the three chosen scenarios of the marginal approach as well as the savings, the total difference between the two values of the Conversion and Purpose Design.

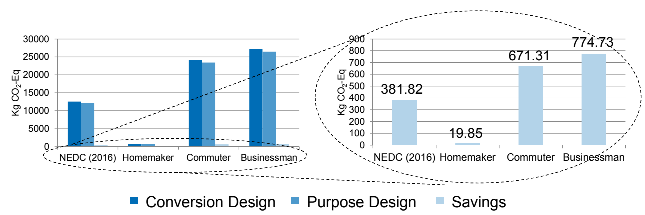


Figure 6: Total lifetime savings in the marginal approach.

In the different scenarios, the total emissions range from about 730 kg (Homemaker, Purpose Design) to approximately 27,200 kg (Businessman, Conversion Design). In relative terms, the savings remain constant around 3% between Conversion and Purpose Design. But as the total emissions sum up over 150,000 km, remarkable differences can be found. Looking at the "Homemaker" profile, the savings amount to less than 20 kg. Compared to the assumed production emissions of about 2000 kg, the buffer would be about 1%. In this scenario no environmental benefit is gained from a lightweight car body which is expected to be much more energy-intensive in production than 20 kg CO_2-Equivalents. The savings are increased to 671.31 kg (Commuter) and 774.73 kg (Businessman) which results in a buffer of 34% and 39% respectively against the aforementioned 2000 kg emissions of the production phase. A buffer above 30% represents an ample cushion for production and recycling so that over the complete life cycle the ecological outperformance of a lightweight concept in comparison to a conventional steel design becomes very likely.

To summarize the results, three major findings can be derived: Using electric cars makes most sense in an urban environment where they have the lowest energy consumption. Second, with respect to a legislative limit for CO2-emissions it is vital for electric mobility that additional regenerative power plants are constructed to power the vehicles in the long term future. Otherwise, there is only a limited probability for electric vehicles to become a sustainable mobility concept. Third, in the foreseeable future it is unlikely that electric vehicles can be charged exclusively from regenerative resources [8, 26]. Thus, lightweight offers great opportunities for improving an electric vehicle's ecological performance as it will mostly be charged with CO_2-intensive electricity from coal-fired power plants. Under this assumption, the energy and emission savings amount to a high share of the production emissions which is assumed to result in decreased total lifetime emissions over the whole lifecycle of the vehicle.

5 SUMMARY

This paper evaluates the advantages of a lightweight car body in the operating phase. Therefore, an innovative lightweight Purpose Design is compared to a conventional steel based Conversion Design. The assumed 25% body weight reduction leads to a 3.4% decrease of energy consumption. To quantify the advantages, average scenarios, using standard driving cycles and average electricity mixes, and marginal scenarios, constructed from individual user profiles and charging currents, are analyzed. The results show that lightweight car body design can be seen as an investment with low payback if electric vehicles can mainly be charged from regenerative energies. But especially considering the forecasted electricity mixes, it is very likely that electric vehicles will be charged from fossil power plants in the foreseeable future. Thus, lightweight design presents a promising contributor to the sustainability of electric mobility.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] Pehnt, M., Helms, H., Lambrecht, U., Dallinger, D., Wietschel, M., Heinrichs, H., Kohrs, R. et al. (2011): Elektroautos in einer von erneuerbaren Energien geprägten Energiewirtschaft, in: Zeitschrift für Energiewirtschaft, Vol. 42, No.3 , pp.230-231.

[2] Helmers, E. (2010): Bewertung der Umwelteffizienz moderner Autoantriebe - auf dem Weg vom Diesel-Pkw-Boom zu Elektroautos, in: Umweltwissenschaften und Schadstoff-Forschung. Vol. 22., No.5 , pp.564-578.

[3] Kolke, R. (2004): Vergleich der Umweltverträglichkeit neuer Technologien im Straßenverkehr, Dissertation, Otto-von-Guericke-Universität Magdeburg, Magdeburg, Germany.

[4] Warsen, J., Krinke, S. (2012): Das Lebenszykluskonzept von Volkswagen,. In: ATZ - Automobiltechnische Zeitschrift, Vol. 114, no.8, pp.560-565.

[5] EN ISO 14040:2006 (2009): Environmental management - Life cycle assessment - Principles and framework, Beuth Verlag GmbH, Berlin, Germany.

[6] European Commision - Joint Research Center - Institute for Environment and Sustainability (2010): International Reference Life Cycle Data System (ILCD) Handbook, Publications Office of the European Union, Luxembourg.

[7] Althaus, H.-J., Gauch, M. (2010): Vergleichende Ökobilanz individueller Mobilität: Elektromobilität versus konventionelle Mobilität mit Bio- und fossilen Treibstoffen, Dübendorf, Switzerland.

[8] Hacker, F., Harthan, R., Kasten, P., Loreck, C., Zimmer, W. (2011): Marktpotenziale und CO_2-Bilanz von Elektromobilität - Arbeitspakete 2 bis 5 des Forschungsvorhabens OPTUM: Optimierung der Umweltentlastungspotenziale von Elektrofahrzeugen, Berlin, Germany.

[9] Helms, H., Jöhrens, J., Hanusch, J., Höpfner, U., Lambrecht, U., Pehnt, M. (2011): UMBReLA Umweltbilanzen Elektromobilität - Wissenschaftlicher Grundlagenbericht, Heidelberg, Germany.

[10] Institut für Kraftfahrzeuge (ika) (2012): unveröff. Zwischenbericht Light-eBody

[11] Eckstein, L., Göbbels, R., Goede, M., Laue, T., Wohlecker, R. (2011): Analyse sekundärer Gewichtseinsparungspotentiale in Kraftfahrzeugen, in: ATZ, Vol. 113, No. 3, pp. 68-77.

[12] European Commision - Joint Research Center (2007): Well-to-Wheels analysis of future automotive fuels and powertrains in the european context, Version 2c.

[13] Richtlinie des Rates 70/220/EWG vom 20. März 1970 zur Angleichung der Rechtsvorschriften der Mitgliedstaaten über Maßnahmen gegen die Verunreinigung der Luft durch Abgase von Kraftfahrzeugmotoren mit Fremdzündung.

[14] André, M. (2004): Real-world driving cycles for measuring cars pollutant emissions - Part A: The ARTEMIS European driving cycles.

[15] Renewable Energies Agency (2012): Der Strom-Mix in Deutschland in 2011, http://www.unendlich-viel-energie.de/de/wasserkraft/detailansicht/article/95/der-strommix-in-deutschland-im-jahr-2011.html, accessed August 09 2012.

[16] Dürrschmidt, W., Nestle, U., van Mark, M., Nitsch, J., Wenzel, B. (2009): Langfristszenarien und Strategien für den Ausbau erneuerbarer Energien in Deutschland - Leitszenario 2009, Berlin, Germany.

[17] Fahl, U., Blesl, M., Voß, A., Achten, P., Bruchof, D., Götz, B., Hundt, M. et al (2009): Die Entwicklung der Energiemärkte bis 2030 - Energieprognose 2009.

[18] Renewable Energies Agency (2009): Stromversorgung 2020 - Wege in eine moderne Energiewirtschaft, Berlin, Germany.

[19] Matthes, F.C., Harthan, R.O., Groscurth, H,-M., Boßmann, T. (2007): Klimaschutz und Stromwirtschaft 2020/2030 - Technologien, Emissionen, Kosten und Wirtschaftlichkeit eines klimafreundlichen Stromerzeugungssystems, Berlin/Hamburg, Germany.

[20] Hoffschmidt, B., Lanz, M., Peter, S., Fricke, B., Warerkar, Shashikant, Anthrakidis, A. (2010): Struktur und Dynamik einer Stromversorgung mit einem hohen Anteil erneuerbarer Energieerzeuger - Energiestudie, Aachen, Germany.

[21] Schlesinger, M., Lindenberger, D., Lutz, C. (2010): Energieszenarien für ein Energiekonzept der Bundesregierung, Basel/Köln/Osnabrück, Switzerland/Germany.

[22] Pehnt, M. (2010): Erneuerbare Energien und Elektromobilität, in: Müller, T. (2010) 20 Jahre Recht der Erneuerbaren Energien, Nomos Verlag, Baden-Baden, Germany.

[23] Helms, H., Pehnt, M., Lambrecht, U., Liebich, A. (2010): Electric Vehicle and plug-in hybrid energy efficiency and life cycle emissions, in: 18th International Symposium Transport and Air Pollution - Proceedings, pp.113-124, Dübendorf, Switzerland.

[24] Nitsch et al. (2010): Langfristszenarien und Strategien für den Ausbau erneuerbarer Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global - "Leitstudie 2010".

[25] Marheineke, T. (2002): Lebenszyklusanalyse fossiler, nuklearer und regenerativer Stromerzeugungstechniken, Dissertation, Universität Stuttgart, Stuttgart, Germany.

[26] NDR (2012): Warum der Netzausbau stockt. http://www.ndr.de/info/programm/sendungen/reportagen/energiewende279.html, accessed: 09 August 2012.

Combining Five Criteria to Identify Relevant Products Measures for Resource Efficiency of an Energy Using Product

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Abstract

Product recovery at end-of-life (EoL), initially focusing on the reduction of residual (hazardous) waste, is currently being enlarged and now link with emerging issues such as "resource efficiency" and "use and management of Critical Raw Materials". However, for many environmental aspects, product's measures considered by current policies and industry practices are not always consistent, nor optimized. It can be concluded that there is currently no systematic and consistent integration of EoL and resource efficiency measures in product design practices and in product policies and this should be improved. The paper proposes a new integrated method to assess the resource efficiency performances of products and to derive relevant product's measures for improvement. The assessment is based on five different criteria: reusability/recyclability/recoverability - RRR - (per mass and per environmental impacts); recycled content (per mass and per environmental impact); use and management of hazardous substances. The paper briefly describes the assessments methods proposed for each of these criteria. The methods are based on existing literature and technical documents, and have been adapted to this particular aim. The proposed method is presented and discussed on the basis of a Energy using Product (EuP) case-study: a LCD-TV.

Keywords:

Ecodesign; Energy using Products (EuP); Design for recycling; Recyclability; Recycled content; LCA, policy

1 INTRODUCTION

In 2011 the European Commission (EC) published its "Roadmap to a Resource Efficient Europe" indicating objective, strategies, milestones and actions to be undertaken in order to improve the resource efficiency of the European Union (EU) [1]. Among the others the EC will "*stimulate the secondary materials market and demand for recycled materials through economic incentives and developing end-of-waste criteria*" and "*assess the introduction of minimum recycled material rates, durability and reusability criteria and extensions of producer responsibility for key products*" [1].

Some principles of the EC roadmap have been already put into practice in several pieces of legislations as, for example, in the setting of minimum recycling and recovery rates (in mass) for Waste of Electrical and Electronic Equipment (WEEE) [2], limitation of use of hazardous substances [3], improvement of durability of Energy Using Products (EuP) [4] or in the setting of minimum thresholds for some Ecodesign criteria as reusability / recyclability / recoverability (RRR) in mandatory [5] or voluntary [6] policies. Analogously, ecodesign practises addressing some of these principles have been discussed by academics and are being applied by industries [7; 8]

However, for many environmental aspects, product criteria considered by these policies and practices are not always consistent. Furthermore, it has been evidenced the need to develop tools to help designers make better decisions while designing a product, following a multi-criteria approach [9; 10; 11]. This is in particular the case for EoL performances of products. It can be concluded that currently there is no systematic and consistent integration of EoL and resource efficiency criteria in product design practices and in product policies (e.g. EU Ecodesign Directive or Ecolabel) and this should be improved.

The paper introduces a new integrated method to assess the resource efficiency of EuP based on a multi-criteria analysis and to derive relevant product's measures for the improvement. Based on a review of the scientific literature (see for example, [8;12]) some relevant criteria have been identified. Among these the following five criteria have been considered currently as the most robust and applicable for the purpose of the analysis and have been embodied in the method: reusability / recyclability / recoverability - RRR (per mass and per environmental impacts); recycled content (per mass and per environmental impact); use and management of hazardous substances. Some other potentially relevant criteria for the analysis have been identified, including: durability, design for source reduction (dematerialisation) and design for the use of renewable materials. However, indexes to quantitatively assess these criteria are still to be developed. Therefore these criteria have been not considered in the method but could be potentially introduced in future developments.

Section 2 presents the general method while Section 3 introduces the indices used for the assessment. Section 4 illustrates the implementation of the method on an exemplary product, an LCD-TV, so that hot-spots of the product can be identified. Section 5 discusses, based on the results of the case study, the identification and assessment of product's measures, in particular for potential use in product policies.

2 METHOD FOR THE IDENTIFICATION AND ASSESSMENT OF PRODUCT'S MEASURES

We introduce a new method for the identification and assessment of measures, against a set of five selected criteria, to improve the resource efficiency of products at the EoL. The method is composed of the following steps (Figure 1):

Step 1. Selection and characterization of the product(s), including the collection of data (Bill of Materials, disassembly information) and the calculation of lifecycle impacts.

Step 2. Assessment of the product against a selected set of criteria. This is further subdivided in:

2.1 Definition of EoL scenario(s). EoL scenario(s) for the case-study product(s) are defined, representative of the current or future EoL treatments.

2.2. Calculations and assessment of qualitative and quantitative indices for the selected criteria.

Step 3. Identification of product's 'hot spots' for resources efficiency, meaning product's components that are relevant for some criteria and for the considered EoL processes. This step is further subdivided in:

3.1.a Identification of key components (for hazardous substance).
3.1.b Identification of losses for the selected indices. 'Losses' occur when product's parts can grant high benefits at EoL (in terms of reused/recycled/recovered masses or in terms of environmental benefits) but this potential is only partially exploited due to the current EoL treatments.

3.2. Identification of hot spots. Results of the previous steps identified key components for some of the considered criteria. This new step combines these results to identify 'hot spots' at the product level.

Step 4. Identification of potentially relevant measures at the product level, which could contribute to the improvement of the product performances (e.g. contributing to the reduction of the losses) Measures are therefore tested to assess if and how they can produce, at the case-study level, some relevant lifecycle benefits.

Step 5. Assessment of policy measures at the 'product group' level. The last step consists in the extension of the analysis from the 'case-study' level to the 'product group' level. Performances of products representative of the considered product category are assessed over the considered EoL scenario(s).

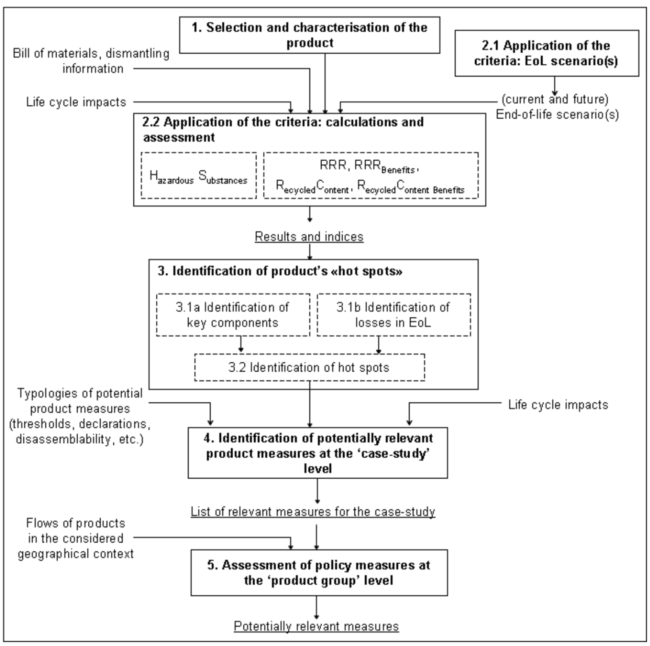

Figure 1: assessment of product's resource efficiency measures.

3 INDICES FOR THE ASSESSMENT OF SELECTED CRITERIA

The present section presents a set of qualitative and/or qualitative indices for each criterion selected for the analysis of resource efficiency of products at the EoL (a more detailed description of the indices is illustrated in [13]).

- *Reusability/Recyclability/Recoverability (RRR) rates* (in mass)

The three Reusability/Recyclability/Recoverability (RRR) indexes in terms of mass rates can be calculated as:

$$RRR = \frac{\sum_{i=1}^{P} m_i \cdot X_{RRR,i}}{m} \cdot 100$$

where:

- RRR = Reusability / Recyclability / Recoverability rates [%];
- m_i = mass of the i^{th} part of the product [kg];
- $X_{RRR,i}$ = Rates of the i^{th} part of the product that is potentially reusable / recyclable / recoverable [%];
- P = number of parts of the product [dimensionless];
- m = total product's mass [kg].

This equation summarizes the structure of the three indices. Their structure is consistent with the formulas of the standard IEC/TR 62635 [14].

- *Reusability/Recyclability/Recoverability (RRR) rates (in terms of environmental impacts/benefits)*

The RRR rates (in terms of environmental impacts/benefits) are based on the RRR rates previously introduced with the inclusion of the lifecycle impacts about: production of virgin materials, manufacturing of the product, recycling and production of secondary materials, transport and disposal. These indexes have been named 'RRR Benefit Rates'. For example the rate for the Re

$$R_{cyc,n} = \frac{\sum_{i=1}^{P}\left(m_{recyc_i} \cdot X_{recyc,i} \cdot D_{n,i}\right) + \sum_{i=1}^{P}\left[m_{recyc_i} \cdot X_{recyc,i} \cdot \left(k_i \cdot V^*_{n,i} - R_{n,i}\right)\right]}{V_n + M_n + U_n + D_n} \cdot 100$$

where:

- $R_{cyc,n}$ = 'Recyclability benefit' rate (for the "n" impact category) [%];
- $m_{recyc,i}$ = mass of the i^{th} recyclable part of the product [kg];
- V_n, M_n, U_n, D_n = impacts (for the "n^{th}" impact category) due to the production of virgin materials, manufacturing, use and disposal of the product [unit][1];
- $V^*_{n,i}$ = impact (for the "n^{th}" impact category) due to the production (as virgin) of the material assumed to be substituted by the i^{th} recyclable material of the product [unit/kg];
- $R_{n,i}$ = impact (for the "n^{th}" impact category) due to the recycling of the i^{th} recyclable part [unit/kg];
- k_i = downcycling factor [dimensionless][2].

Similar equations can be developed for the 'Reusability benefit' and the 'Recoverability benefit' rates (for further details see [13]). These indexes are based on several scientific works (e.g. [8]).

- *Recycled content rate (in mass)*

The method for the calculation of the recycled content is substantially consolidated and standardised in the technical literature (e.g. by [15]). It accounts for the rate of recycled masses (overall or of certain materials) in the product's mass.

- *Recycled content rate (in terms of environmental impacts/benefits)*

The "Recycled content benefit" rate calculates, in a lifecycle perspective, the environmental benefits (for certain impact categories) that can be achieved by introducing some recycled materials during the manufacturing of the product:

$$RCB_n = \frac{\sum_{i=1}^{P} m_{r,i} \cdot \left(V_{n,i} - R^*_{n,i}\right)}{V_n + M_n + U_n + D_n} \cdot 100$$

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1 The unit of measure depends on the selected impact category.

2 The downcycling factor 'k' takes into account factors that "depreciate" the quality of the materials after their recycling (e.g. contamination among materials and loss of physical performances due to the treatments). For further details see [12].

Where symbols previously not introduced are:

- RCB_n = recycled content benefit rate of the product (for the "n^{th}" impact category) [%];
- $R^*_{n,i}$ = impact (for the "n^{th}" impact category) of the recycled material used for the i^{th} product's part [unit/kg];
- $m_{r,i}$ = mass of the i^{th} recycled material in the product [kg].

  - *Use of hazardous substances*

The use of hazardous substances (HS) can largely affect the EoL treatments of products. However this influence is related to several issues (including safety, environmental impacts and legislation in force) and cannot be translated into a simple formula. The use of HS can be assessed qualitatively, according to the following method:

Step 1. Definition of the set of substances to be considered for the analysis. The set shall include regulated substances and components and others substances and components as suggested by feedback from manufacturers and/or recyclers as potentially dangerous (as also suggested by the IEC 62635 [14]).

Step 2. Identification of parts of the product that contain the considered substances (quantities and typologies).

Step 3. Identification of current treatments for the EoL of these parts. It is necessary to identify the recovery treatments that the components will undergo at EoL and potential related impacts for workers and the environment.

Step 4. Identification of 'hot spots'. These are components that have a content of HS that is critical for the identified EoL treatments.

4 ANALYSIS OF A CASE-STUDY PRODUCT: LCD-TV

The objective of the analysis is the testing of the proposed method and indices to a EuP case-study: a LCD-TV (20.1 inches) with an integral Cold Cathode Fluorescent Lamp (CCFL) backlight system. Performances of the product have been analyzed in order to identify hot spots of the product and to identify potentially relevant policy measures to improve resource efficiency.

Data about the Bill of Materials (BOM) of the product have been collected in a WEEE recycling plant, while data concerning the dismantling and further recycling treatments have been collected from various recyclers. Product mass is largely composed by plastics (about 50%, mostly constituted by HI-PS frames and Polymethilmetacrylate – PMMA – board), metals (steel and aluminium, around 30%), electronic parts (around 15%, including LCD screen, Printed Circuit Boards – PCBs, capacitors), and other parts (CCFL, cables, fan, speakers).

A complete description of the product is provided in [16]. The EoL treatments that the product undergoes are based on two EoL scenarios (set in accordance to [14] and based on information collected from 4 representative European recycling plants):

- "Manual dismantling" scenario: the product is fully manually dismantled in order to separate potential hazardous components (e.g. CCFL, LCD screen, PCBs, capacitors) and other parts (mainly metals and plastics) for further treatments.
- "Mechanical Treatment" scenario: the product is mainly treated by special shredders (in a controlled environment). Shredded parts are subsequently mechanically sorted for recycling/recovery. Mercury is supposed to be sorted to avoid contamination of other parts and of the environment. Before the shredding, recyclers also implement some minor dismantling operations for a few key components, when economically viable or required by legislation.

Results of the indexes previously introduced are illustrated in Table 1, for the two EoL scenarios presented. The next step of the analysis consists in the interpretation of the results to identify product's 'hot spots'. Some identified 'hot spots' are discussed in the following sections and summarised in Table 2.

Indexes for resource efficiency			EoL scenarios	
			Dismantling	Mechanical treatment
Reusability	(in mass)	[%]	0%	0%
Recyclability	(in mass)	[%]	75.3%	34.5%
Recoverability	(in mass)	[%]	79.7%	49.0%
Reusability benefit	(for all impact categories)	[%]	0%	0%
Recyclability benefit	(Climate change)	[%]	6.6%	2.7%
	(Acidification)	[%]	19.5%	5.9%
	(Photochemical oxidant)	[%]	12.7%	4.2%
	(Ozone depletion)	[%]	1.2%	0.8%
	(Respiratory effects)	[%]	18.6%	6.2%
	(Eutrophication freshwater)	[%]	15.9%	5.5%
	(Eutrophication marine)	[%]	10.9%	3.5%
	(Human toxicity)	[%]	65.7%	32.1%
	(Aquatic Ecotoxicity)	[%]	47.9%	17.9%
	(Terrestric ecotoxicity)	[%]	50.4%	23.7%
	(Abiotic Depl. - element)	[%]	95.2%	24.8%
	(Abiotic Depl.- fossil)	[%]	8.3%	2.5%
Energy Recoverability benefit	(Abiotic Depl.- fossil)	[%]	2.8%	1.9%
Recycled content	(in mass)	[%]	0%	0%
Recycled content benefit	(Abiotic Depl.- fossil)	[%]	0%	0%
Use of hazardous substances			o CCFL (for the content of mercury) o LCD (for the content of heavy metals) o Capacitors (for the potential content of polychlorinated biphenyl) o PCBs (for the content of hazardous substances)	o CCFLs (for the content of mercury), which request a shredding treatments in a controlled environment o LCD (for the content of heavy metals), which requires preventive separation before shredding o Capacitors (for the potential content of polychlorinated biphenyl) which request 'hand picking' after shredding o PCBs (for the content of hazardous substances)

Table 1: Results of resource efficiency analysis.

Criteria	Hot spots
Reusability (in mass)	(none)
Recyclability (in mass)	LCD; large plastic parts (HI-PS frames; PMMA board)
Recoverability (in mass)	(none)
Reusability benefit (environmentally based)	(none)
Recyclability benefit (environmentally based)	PCB; PMMA board
Recoverability benefit (environmentally based)	(none)
Recycled content	large plastic parts (HI-PS frames;
Recycled content benefit (environmentally based)	(none)
Use of hazardous substances (HS)	CCFL; LCD; PCB

Table 2: LCD-TV's 'hot spots' for resource efficiency.

4.1 Hot Spots for Reusability

According to the interviewed recyclers, parts of LCD-TVs are currently not reused, both for economic and technical reasons. Although all the product's parts could be potentially reusable, current EoL treatments do not allow separation for reuse. Furthermore, special design alternative of the product would not have the effect of improving the reusability. For these reasons, it is assessed that the LCD-TV has no hot-spots for the reuse, both in terms of mass and environmental benefits.

4.2 Hot Spots for Recyclability (In Mass)

The analysis of the recyclability (in mass) showed a large discrepancy between the two EoL scenarios. This is due to the performing processes (for the yield) in the “dismantling” scenario for the sorting of recyclable parts, mainly circuit boards and other electronics, large plastic fractions (HI-PS frames and the PMMA - board). On the other hand, the Recyclability rate in the “mechanical treatment” scenario is much lower. The shredding with mechanical sorting is, in fact, characterized by lower recycling percentages for common metals and, especially, for precious metals and plastic parts.

Hot spots for recyclability in mass therefore concern large plastic parts (HI-PS and PMMA board): they have been assumed as recyclable in the dismantling scenario while will be largely lost in the mechanical treatment, especially the PMMA that is not sorted by current mechanical treatments.

A large loss of mass during the EoL treatments is due to the LCD screen, which is also considered as a product hot spot. According to consulted recycling companies, LCDs are currently landfilled or, in some cases, temporary stored in prevision of the availability of future recycling technologies. In particular LCDs are relevant for their content of indium. Small amounts of indium are currently recycled due to lack of infrastructures and low prices of the metal [17]. However some exemplary recycling processes are currently under research and development (see for example [18]).

4.3 Hot Spots for Recyclability (Environmentally Based)

The analysis of the Recyclability benefit indexes confirmed the large discrepancy between the two considered scenarios. In particular, the analysis focused on losses of the potential environmental benefits due to different recycling rates of materials in the different EoL treatments.

It is observed that large losses of efficiency between the two scenarios occur for almost all the considered impact categories. In particular the most significant loss (over 70%) is related to the ‘Abiotic Depletion – element’ (ADP-Elements) category. Other relevant losses (from 20% to 30%) regard also the ‘Human Toxicity’, ‘Freshwater Aquatic Ecotoxicity’ and ‘Terrestric ecotoxicity’.

The further analysis of the results shows that losses are mainly due to the lower recycling rates of metals in PCBs in Scenario 2, which are rich in precious metals (gold, silver, and platinum group metals). Manual dismantling allows to increase the recycling rates of precious metals, otherwise largely dispersed in the dusts during the shredding.

PCBs are therefore assessed as TV’s hot spots for the environmentally based recyclability. Furthermore, the PMMA board, already identified as relevant for the recyclability in mass, is also here assessed as relevant in term of potential environmental benefits achieved by its recycling. The loss in the recyclability of the PMMA in the mechanical treatment scenario causes, in fact, a loss of benefits from 2% to 4% for various impact categories.

4.4 Hot Spots for Recoverability

Concerning the Recoverability (in mass), it is observed a similar behaviour as observed for recyclability in mass. Manual dismantling scenario is generally optimized for the additional energy recovery of not recyclable fractions. The mechanical treatments scenario is instead affected by larger losses of plastics in the shredding residuals, which are only partially recovered.

Concerning the Energy Recoverability benefit, the manual dismantling scenario has still higher performances, mostly due to the selective sorting of plastics. In terms of ‘Abiotic Depletion – fossil’ (ADP-Fossil) impact category, the energy recovery of plastics of the products allows a benefits of 2.8% of the lifecycle impact of the product. The loss of benefits during the treatments in the two scenarios is however limited (less than 0.9% for ADP-Fossil). It is further highlighted that product’s measures would not have the effect of increasing product recoverability. Furthermore according to the European waste hierarchy [19], energy recovery of products has lower priority. Therefore, no product’s hot spot is identified as relevant for the energy recoverability criteria.

4.5 Hot Spots for Recycled Content (in Mass and Environmentally Based)

According to the analysis of the scientific literature, the analysis of the recycled content focused to some specific materials (especially polymers). The present section analyzes if the introduction of recycled polymers in the manufacturing process could produce relevant benefits. First of all the attention was focused on large HIPS parts, heavier than 200g (back cover, front cover and support). According to studies in the literature [20], primary HI-PS used for the frames of EEEs can be substituted by recycled materials without interfering with its functionality. By changing the potential content of HI-PS large parts from 10% to 70%, the recycled content (in mass, formula) of the product varies from 2% to 16%. Large plastics parts are therefore considered as ‘hot spots’ for the recycled content in mass.

Subsequently, the potential environmental benefits associated to these percentages have been calculated. The calculation has been related to the “ADP-Fossil” impact categories (assumed as most relevant for the analysis of this criterion). The analysis demonstrates that, for example, a 20% recycled content of HI-PS can allow a 0.2% saving of the overall lifecycle ‘ADP-fossil’. A percentage of 70% of recycled HIPS in the TV would allow a 1.5% benefit for the same impact category. Being these benefits much lower that benefits achievable through e.g. the reduction of the consumption in the use phase (see e.g. [21]), it is concluded that, for the moment, there are no product’s hot spots relevant for the Recycled content benefit criterion.

4.6 Hot Spots for the Use of Hazardous Substances (HS)

According to communications from recyclers, the main criticality for HS in LCD-TV is represented by the mercury in CCFL potentially dangerous if spread during both the dismantling scenario [22] and the shredding scenario [23].

In particular in the dismantling scenario, the major risk is represented by the breakage of the lamps during the dismantling, with potential high impacts for the health of workers and releases in the environment. Risks could be minimized by a careful design of the lamps (and their casing) to facilitate their extraction. The mechanical treatment scenario allows minimizing the risks for the workers, but on the other hand, it is affected by larger risks of contaminating other recyclable parts. Special shredders in a controlled environment are requested [22]. CCFL are therefore assessed as ‘hot spots’.

Other potentially relevant parts for the content of HS (especially heavy metals) are the LCD screens, PCBs and capacitors. According to current legislation [2; 3], these parts have to be removed from any separately collected WEEE. According to the EoL scenarios, this can be performed manually (by dismantling and sorting) or after the shredding by mechanical sorting or hand-picking. LCD screen and PCBs are therefore assessed as ‘hot spots’ for HS. Instead, according to communications from manufacturers, modern capacitors are nowadays free of polychlorinated biphenyl, and therefore these parts are not considered as relevant for the analysis.

5 PRODUCT'S MEASURES FOR THE IMPROVEMENT OF RESOURCE EFFICIENCY

5.1 Identification of Product's Measures

This step of the analysis focuses on the identification of product's measures that can contribute to improve the performances of the product at its EoL for each criterion. Selected measures could be applied as mandatory requirements (set by legislation the in force, as e.g. the achievement of minimum thresholds for performances [4] or by the declaration of information, see e.g. [24]), voluntary approaches based on mandatory requirements (as environmental labelling systems, e.g. [25]) or voluntary actions (as environmental claims and declarations [15]).

The starting point is the result of Table 2. It is observed that some recurrent components of the product are relevant for one or more studied resource efficiency criteria and, in particular:

- PCBs are 'hot spots' for Recyclability benefits and the content of HS. Manual dismantling of these parts should be improved (e.g. by thresholds for the time for dismantling). The proposed measure could in the future help both EoL scenarios: dismantling scenario will be more economically viable and the mechanical treatments scenario can implement pre-dismantling stages in order to reduce losses. This measure can regard both mandatory and voluntary tools.
- LCD is a hot spot for Recyclability (in mass) and the content of HS. According to current treatments, LCDs are landfilled, causing large environmental burdens [26] but, also, the loss of relevant materials (e.g. indium). According to communication from recyclers, the recycling of LCD could be fostered by measures to improve its dismantlability and by the communication of some key information [16].
- Large plastics parts (e.g. HI-PS frames in the case-study) are 'hot spots' for Recyclability (in mass) and Recycled content (in mass). Marking of some large plastic parts has been identified as a possible measure to support sorting during the manual dismantling by recyclers. Concerning the improvement of Recycled content, this could be fostered by measures to communicate the content of recycled materials in the product (e.g. via standardized self-claims [15]) or by the setting of minimum thresholds of recycled plastics.
- PMMA board represent a special case among large plastic parts. It is assessed as a hot-spot for Recyclability (in mass and environmental benefits). Analogously to LCD and PCBs, measures to support dismantlability of PMMA part should be developed to support manual and mechanical EoL treatments.
- Finally CCFL are 'hot spots' for the content of HS. The treatment of mercury in lamps represents one of the biggest difficulties faced in the treatment of LCD-TV. Measures should be set in order to improve the design for the disassembly of such a component containing HS, supporting the 'dismantling' scenario and minor dismantling operations before the 'mechanical treatments'. Due to the high relevance of this issue, measures should be preferably set via mandatory requirements.

According to previous considerations, one exemplary measure targeting these components could be formulated:

"*The time for the dismantling of product's key components (i.e. PCBs, LCD, PMMA and CCFLs) shall be less than 240 sec*[3]".

[3] This threshold is only exemplary, based on preliminary observations at the recycling plants. The threshold should be further discussed together with recyclers and manufacturers, and should be also adapted to LCD-TV with different dimensions and to automatic dismantling initiatives (when developed).

This measure could be set via mandatory requirements as proposed in [4]. The threshold should be derived from an analysis of products currently available in the market.

5.2 Assessment of Product's Measure for the Case-Study

According to communications from stakeholders (manufacturers, recyclers, NGOs) [16], the full dismantling scenario is currently economically viable and extensively applied in the EU for the treatments of LCD-TVs. However there is plenty of evidence of technological progresses moving towards mechanical systems for the EoL treatments of LCD-TV, including open air shredders or 'encapsulated units' (i.e. sealed shredders operating in a controlled environment) [27]. It is estimated that the mechanical treatment scenario will be improved and installed in the EU in the next future, mostly because of its higher economic efficiency and reduced risks for workers [16].

According to interviewed stakeholders, the dismantling scenario will become less competitive in the near future unless actions to support this scenario will be undertaken [28: 16]. The previously introduced measure is intended to contribute in this sense to the improvement of product's dismantlability.

The next step of the analysis consists in the calculation of potential environmental benefits related to the application of the selected measures to the case-study. In particular, the calculation aims at assessing the potential environmental benefits when the LCD-TV is treated in the dismantling scenario instead than in the mechanical treatment scenario.

The benefits have been calculated in terms of masses of additional recyclable materials by comparing the recycling yields of the two EoL scenarios. Successively, the related lifecycle environmental benefits have been estimated and compared to lifecycle impacts of the product for 12 impact categories (cf. Table 2).

Environmental impact category	Climate change kg $CO_{2\text{-eq.}}$	Acidification kg $SO_{2\text{-eq.}}$	Photochemical oxidant kg $NMVOC_{\text{-eq}}$	Ozone depletion kg $CFC_{11\text{-eq.}}$	Respiratory effects kg $PM_{10\text{-eq}}$	Eutroph. freshwater kg $P_{\text{-eq}}$
A. Estimated benefits	15.12	0.40	0.08	3.3E-07	0.08	0.011
B. Lifecycle impacts LCD-TV	397.4	3.5	1.0	8.8E-05	0.75	0.1
(A / B) [%]	3.8%	11.5%	7.8%	0.4%	10.5%	9.9%
Environmental impact category	Eutroph. marine kg $N_{\text{-eq}}$	Human toxicirty kg $DCB_{\text{-eq.}}$	Acquatic Ecotoxicity kg $DCB_{\text{-eq.}}$	Terrestric ecotoxicity kg $DCB_{\text{-eq.}}$	Abiotic Depl. - element kg $Sb_{\text{-eq.}}$	Abiotic Depl.- fossil MJ
A. Estimated benefits	0.022	26.43	0.87	0.26	0.009	241.92
B. Lifecycle impacts LCD-TV	0.3	116.8	3.1	1.2	0.0	4195.6
(A / B) [%]	7.3%	22.6%	28.2%	21.7%	71.6%	5.8%

Table 3: Environmental benefits (A_n) brought by the product's measure, compared to life cycle performances (B_n) of LCD-TV.

It is possible to observe that most relevant benefits concern the ADP-Elements. Relevant are also the benefits related to several other categories, including Human toxicity, Terretric Ecotoxicity and Acquatic Ecotoxicity.

5.3 Assessment of Product's Measures at the 'Product Group' Level

The last step of the analysis is the assessment of the potential benefits brought by product's measures for the whole 'product group', so that the measure can be compared to other potential measures. Benefits can be also normalized (e.g. to the impacts of the product group or the overall impacts of some geographical context) in order to assess their relevance for the considered scope of the analysis.

For the LCD-TV case-study, the product-level benefits (see Table 3) have to be multiplied by the number of televisions currently introduced in the market. The analysis should also determine how the measure would potentially affect their EoL of the LCD-TV flows (see [13]). For the case study, it is expected that the implementation of the proposed product's measure would have the effect of supporting the economical and technical convenience of the dismantling scenario, by diverting a portion of waste flow from the 'mechanical' to the 'dismantling' scenario and hence obtaining higher recycling yields. Due to large uncertainties for these assumptions concerning future scenarios, it is recommended the set of different scenarios for the assessment of the benefits.

6 CONCLUSIONS AND PERSPECTIVES

The paper discussed a new integrated method to assess the resource efficiency of products and to derive relevant product's measures for improvement. The assessment has been based on a multi-criteria approach focused on the following: reusability / recyclability / recoverability (per mass and per environmental impacts); recycled content (per mass and per environmental impact); use and management of hazardous substances. Indexes for each criteria have been derived by the scientific literature, and adapted to the scope of the method.

The method has been tested and illustrated on a EuP case-study: an LCD-TV. An exemplary product's measure has been discussed, including the related potential benefits achievable. The method reveals to be applicable and relevant, although some key robust input data (dismantling information of the product and lifecycle inventory data for some materials and processes) is needed.

In the future, it is planned to further investigate the potential applicability of the methodology for various EU mandatory and voluntary product policies, as well as exploring further additional resource efficiency criteria such as Durability and use of renewable resources.

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8 REFERENCES

[1] European Commission. Roadmap to a Resource Efficient Europe. Brussels, 20.9.2011. COM(2011) 571 final.
[2] Directive 2012/19/EU on waste electrical and electronic equipment (WEEE) (recast)
[3] Directive 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment
[4] Directive 2009/125/EC establishing a framework for the setting of ecodesign requirements for energy-related products.
[5] Directive 2005/64/EC on the type approval of motor vehicles with regard to their reusability, recyclability and recoverability and amending Council Directive 70/156/EEC.
[6] Regulation (EC) No 66/2010 of the European Parliament and of the Council of 25 November 2009 on the EU Ecolabel.
[7] Froelich, D., Haoues,N., Leroy,Y., Renard,H., Development of a new methodology to integrate ELV treatment limits into requirements for metal automotive part design. Minerals Engineering, 2007. 20: p. 891-901.
[8] Mathieux, F., Froelich,D., Moszkowicz,P., ReSICLED: a new Recovery-Conscious Design method for complex products based on a multicriteria assessment of the recoverability. Journal of Cleaner Production, 2008. 16(3): p. 277-298.
[9] F. Ardente, G. Beccali, M. Cellura. Eco-sustainable energy and environmental strategies in design for recycling: the software "ENDLESS". Ecol.l Mod. 163 (2003)101–118.
[10] A. Gehin, P. Zwolinski, D. Brissaud. A tool to implement sustainable end-of-life strategies in the product development phase. Journal of Cleaner Production 16 (2008) 566-576.
[11] Lelah, A., Mathieux,F., Brissaud, D, 2011. Contributions to eco-design of machine-to-machine product service systems: the example of waste glass collection. Journal of Cleaner Production (19) 1033-1044.
[12] Huisman, J., Boks, C.B., Stevels, A.L.N., 2003. Quotes for environmentally weighted recyclability (QWERTY): concept of describing product recyclability in terms of environmental value. Int. Journal of Prod. Research. 41(16), 3649 - 3665.
[13] F. Ardente, F. Mathieux. Refined methods and Guidance documents for the calculation of indices concerning Reusability / Recyclability / Recoverability, Recycled content, Use of Priority Resources, Use of Hazardous substances, Durability. JRC Technical Report. September 2012.
[14] The International Electrotechnical Commission (IEC). Technical Report IEC/TR 62635. "Guidelines for End of Life information provision from manufacturers and recyclers, and for recyclability rate calculation of Electrical and Electronic Equipment". June 2012.
[15] ISO 14021 - Environmental labels and declarations — self-declared environmental claims (Type II environmental labelling). 1999.
[16] F. Ardente, F. Mathieux. Application of the project's methods to three product groups. European Commission. Joint Research Centre. Institute for Environment and Sustainability. Report n° 2. September 2012.
[17] U. S. Geological Survey – USGS. "Mineral commodities summaries: Indium". Statistics and Information (http://minerals.usgs.gov/minerals/pubs/commodity/indium/ Access October 2012).
[18] K. Takahashi, A. Sasaki, G. Dodbiba, J. Sadaki, N. Sato, T. Fujita. "Recovering Indium from the Liquid Crystal Display of Discarded Cellular Phones by Means of Chloride-Induced Vaporization at Relatively Low Temperature". Metallurgical and Materials Transactions A. April 2009, 40 (4), pp 891-900
[19] Directive 2008/98/EC of the European parliament and of the council of 19 November 2008 on waste and repealing certain Directives.
[20] Waste and Resource Action Programme (WRAP). Demonstration of recycled content in electrical products. (http://www.wrap.org.uk/sites/files/wrap/Demonstration%20of%20recycled%20content%20in%20electrical%20products%20summary%20report.pdf ; access November 2012).
[21] Fraunhofer Institute - IZM. EuP Preparatory Studies "Televisions" (Lot 5) Final Reports on Tasks 1-8. Berlin. August 2007. (http://www.ecotelevision.org/: access September 2012).
[22] Stena Metall Group. http://corporate.stenametall.com/News-and-media/News-archive/Stena-launches-a-unique-process-for-recycling-LCD-screens/ (access September 2012).
[23] T J McDonnell, K S Williams. The location and character of mercury in waste LCD backlights. Summary research report. September 2010.
[24] Directive 2010/30/EU on the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products.
[25] European Commission. Commission Decision of 9 June 2011 on establishing the ecological criteria for the award of the EU Ecolabel for personal computers. (2011/337/EU)
[26] Robinson, B.H. 2009. E-waste: An assessment of global production and environmental impacts. Science of the Total Environment (408), 183–191.
[27] EMPA. Disposal of Flat Panel Display Monitors in Switzerland. Final Report. March 2011 (www.swicorecycling.ch/downloads/497/344539/swico_schlussbericht_e_2010.pdf; access June 2012)
[28] B. Letcher. Old and new LCD Television Assemblies. Disassembly differences. Report of HÅPLA project. 8/11/2011. (http://extra.ivf.se/hapla/Default.asp; access November 2012).

Structure for Categorization of EcoDesign Methods and Tools

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Abstract

EcoDesign methods and tools play an important role in assuring that environmental aspects are considered in the product development process. However, despite the large number of EcoDesign methods and tools in the literature, they are rarely implemented and used in product development. The objective of this paper is present a structure for how to categorize different EcoDesign methods and tools, or more specifically, a structure that can work as guidance for, depending on the context and need, selecting EcoDesign methods and tools. Based on a literature review, a structure for categorization of EcoDesign methods and tools is presented, and a total of 28 EcoDesign methods and tools are mapped. These EcoDesign methods and tools include benchmarking tools, tools for investigating customer needs, concept generation and elimination tools and evaluating and assessment tools.

Keywords:

Design for Environment (DfE); Product Development; Evaluation; Engineering Designer

1 INTRODUCTION

Engineering designers can do much for the environment by considering the environmental aspects of the products they are developing. By considering the product's entire life cycle in the early phases of product development, money can be saved, as well as the environment.

EcoDesign is not a specific method or tool, but rather ***a way of better design through analyzing and synthesizing*** in order to reduce ***environmental impacts*** throughout the ***product's entire life cycle***. In short, do more with less – and be more resource-effective and efficient.

Most of a product's total life cycle cost is determined early in the design process, and this is related to economic as well as environmental concerns [1]. Decisions made in the early phases are therefore very important, and it is beneficial to use proven methods and tools to assure that the result is the best possible.

EcoDesign methods and tools play an important role in assuring that the environmental aspects are considered in the product development process. However, despite the large number of EcoDesign methods and tools in the literature (see e.g. [2, 3]), they are rarely implemented and used in product development [4]. Could it be that they have been designed mainly with environmental issues in focus, neglecting the potential users' requirements on methods and tools?

Lindahl concludes that an EcoDesign method/tool as well as a common method or tool must exhibit the following [4]:

(1) *be easy to adopt and implement* – whether a method or tool fulfills the three following requirements is of lesser importance if it is due to a problem with adoption and implementation and becomes seen as having a low degree of usability, and therefore is not utilized by the designers in their daily work. This requirement is the key for a method or tool to become actively used.

(2) *facilitate designers to fulfill specified requirements* on the presumptive product and at the same time

(3) *reduce the risk that important elements in the product development phase are forgotten*.

Both of these two latter requirements relate to a method or tool's degree of appropriateness. The second and third requirements are related to the fourth requirement, which is considered by the author to be the most important, that the use of the method or tool:

(4) *must reduce the total calendar time (from start to end) to solve the task.* If the method or tool helps designers to fulfill specified requirements, it will also most likely help them to reduce the calendar time as well as the number of working hours needed to accomplish the product development. This is also something that enables designers to introduce changes in early phases of the product development when changes still are easy to make. Likewise, if the method or tool reduces the risk that important moments in the product development are forgotten, it will most likely have a positive effect and reduce the calendar time and number of working hours needed.

2 OBJECTIVE

Based on the above, this paper's objective is to present potential criteria that can be used for selecting EcoDesign methods and tools: criteria that can also be used when developing new or modifying existing ones. The objective is also to present a structure for how different EcoDesign methods and tools can be categorized. This structure can work as a guidance for, depending on the context and need, selecting EcoDesign methods and tools.

3 METHOD

A literature review was conducted in order to identify potential criteria on methods and tools for product development, with special focus on EcoDesign methods and tools. The literature study is based on the keywords *criteria, requirements, utilization,* and *usability*, together with *methods* or *tools* and *product development*. The results are compared and evaluated in order to answer the question of what criteria could be used.

In order to develop and evaluate a structure for how different EcoDesign methods and tools can be categorized, a literature review was done to identify a number of EcoDesign methods. The article databases accessible through Linköping University's library were used (e.g. *Scopus* and *Academic Search Primer*) in combination with the university library for research on published books on the subject. The encountered results were crosschecked on Google in order to investigate if they are easy to access and find on the Internet. Keywords used were e.g.: *Design for Environment, DFE, EcoDesign, Sustainable Design, Environmentally Conscious Design,* and *"Miljöanpassad Produktutveckling" (keyword in Swedish for "Environmentally Adopted Product Development").*

References in books and articles describing and listing many different methods were tracked one step, and the original sources were listed as references as extensively as possible. When the original source was not available at the university library or on the Internet, the reference to the method was given "*original source*" according to "*source where it is found*". Different sources describing approximately the same methods that could be considered close variants to the same method were linked together as one method, but referred to several sources.

4 THEORETICAL FRAMEWORK

4.1 Product Development Models

In order to make their product development more efficient and effective, companies use various forms of product development models. These are, especially at small companies, more or less formalized and documented. According to ENDREA [5], product development is defined as: *"all activities in a company aiming at bringing a new product to the market. It normally involves design, marketing and manufacturing functions in the company"*.

The rate of market and technological changes has accelerated in the past decade. This implies that companies must be pro-active in the sense that they must be able to rapidly respond to fluctuations in demand [6]. Central to competitive success in the present highly-turbulent environment is the company's capability to develop new products [7]; to improve, further develop and optimize old products; and to do so faster than competitors [8]. Designers must develop and proceed faster, while at the same time covering an increased number of different demands on the product.

When developing new products, designers typically follow a general procedure, a so-called product development model. A product development model is a process description of the sequence of activities in a company aiming at bringing a new product to market. It normally involves design, marketing and manufacturing activities. An extensive number of prescriptive models for performing product development have been developed to make product development more effective and efficient; some examples are provided by Ulrich and Eppinger [9], Andreasen and Hein [10], Olesen [11] and Roozenburg and Eekels [12].

These product development models often divide the product development into several phases. For example, Ulrich and Eppinger [9] divide it into six phases: ***Planning***, ***Concept Development***, ***System-Level Design***, ***Detail Design***, ***Testing and Refinement***, and ***Production Ramp-Up,*** as shown in Figure 1. The process is described as linear, but is actually iterative.

The product development process could have different focuses depending on the objectives of the projects. There are many considerations that the designer needs to implement simultaneously and that might need to be in focus for the success of the product; examples include optimizing the manufacturing process, assembly, customer satisfaction or environmental aspects [13, 14].

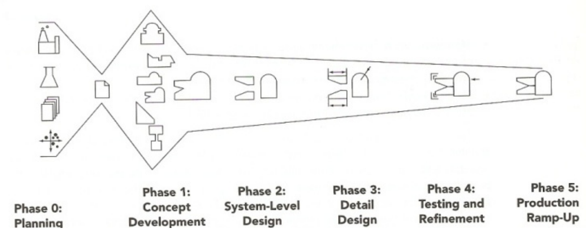

Figure 1: Ulrich and Eppinger's Product Development Model [9].

4.2 Product Development Methods and Tools

Methods and tools are important in product development, as they help in structuring the work, aid in communication and contribute with integrated knowledge and experience [4]. There are methods and tools for almost everything that is encountered in the product development process, ranging from creativity tools to structuring tools to evaluation and decision tools. A company's product development model often describes ***which*** methods and tools are used, and ***when*** and ***why*** they are used during the product development process. Thus, the existence of a product development model may give some indication of the formal use of methods and tools among designers.

4.3 EcoDesign

Environmental considerations in product development could be beneficial in several ways; minimization of resource usage, optimization manufacturing processes and reuse of materials and products are efforts that benefit the environment as well as the economy of the company.

EcoDesign is an approach to product development that focuses on minimizing the environmental impact of all the product's life cycle stages. EcoDesign is a word commonly used to describe this approach, while other words meaning slightly the same thing are also used; for example, *environmentally conscious design*, *Design for Environment (DfE)* and *green design* are other commonly-used expressions meaning the same thing [15]. A broader approach is *sustainable design,* that along with the environmental sustainability also considers the social and economic aspects [16].

The life cycle perspective, which is central when performing EcoDesign, considers the entire life cycle of a product, from *cradle to grave*. To improve the environmental aspects of a product, not only one part of the product life cycle could be studied; such an approach could result in an improvement in that part of the life cycle, but a worse overall environmental impact. The life cycle phases of an ordinary product could be e.g. material extraction, manufacturing, use, and end-of-life (EOL) treatment [17].

It is important that the EcoDesign process is built into the existing product development model in order to achieve the environmental goals that are set in the organization [18]. The EcoDesign process should therefore be constructed by carefully studying the current product development model [18].

4.4 EcoDesign Methods and Tools

Many methods and tools exist to facilitate an EcoDesign approach in product development. Methods and tools available for EcoDesign purposes range from simple checklists and guideline tools, to supporting software tools, to material selection tools, to complex life cycle assessment tools [3].

The EcoDesign method or tool in this paper refers to *any specific procedure with a specified desired outcome that could be performed in a product development process in order to support the work towards an environmental goal*.

5 POTENTIAL CRITERIA FOR SELECTING ECODESIGN METHODS AND TOOLS

Methods and tools that could be used in the early design phases have greater potential to affect the environmental impacts of the product [4, 18].This is also referred to as the design paradox, and could be applied in environmental life cycle aspects as well as the costs of the project that usually are considered.

According to Ryding [16], useful methods and tools must meet certain criteria. For example, the methods and tools must be: easy to use and review; standardized so that results can be compared; universal, flexible and fast; and enable sensitivity analyses. Further, the use of the methods and tools needs to give easily interpreted and comparable results as well as provide basic data for environmental product declarations and long-term environmental planning [16]. The criteria are presented in a textbook for industry, and describe the requirements for methods and tools in order to correctly accommodate the demands of industry in determining the environmental impact of the products.

As described in the introduction of this paper, Lindahl [4] has concluded that there are four basic requirements on methods and tools for them to be useful. Those are that the method or tool must be "*be easy to adopt and implement*", "*facilitate designers to fulfill specified requirements", "reduce the risk that important elements in the product development phase are forgotten"* and most important *"reduce the total calendar time (from start to end) to solve the task"*. Based on an interview study at an international Swedish industrial equipment company, the same author [19] concludes that important criteria are: the method/tool must be valuable for the purpose; the customer requires that the method is used; it covers relevant and common problems; and it is not experienced as too complex or complicated to use.

According to Lofthouse, industrial designers have special demands on EcoDesign methods and tools [20]; she divides designers' requirements for useful EcoDesign tools into five categories: service, content, time, style and culture. The study is based on four surveys, a pilot study and semi-structured interviews with industrial designers at different competence levels and at different sizes of companies. The study showed that designers often were either overwhelmed by the information given in the methods, or that the tools were too general and hard to use. They also had the belief that the tools did not focus on design, but only on analysis of existing products, and that in general they were too time consuming. The designers asked for quick and easy guidance together with information and education that could support their learning. Another requirement was the use of examples and images to illustrate results, because that fits better into how designers work. They were often requesting more specific information, and methods that could be used by individuals. The designers often did not understand or read complicated technical explanations; they would rather appreciate less technical approaches with visual communication and minimal text, presented in an understandable language [20].

Handfield *et al.* [21] describe the problems with incorporating EcoDesign in product development; according to these authors, the problems identified are strongly correlated to requirements that could be set for the methods and tools to fulfill. The study was based on interviews with managers and engineers in ten companies, and focused on implementation of environmentally conscious manufacturing in the product development process. The study found that design engineers often were negative to the implementation of environmental concerns, for the reasons that the results are often hard to prove, they did not think that it was included in the primary job, and it is often hard to motivate trade-offs towards ordinary technical requirements. They also believed that the environmental aspects would have negative impacts on costs, lead time and quality. In addition, they were not comfortable with the tools that were available, as they required education and were too time consuming [21]. The authors of this paper interpret the problems encountered in the study [21] as the methods and tools available not being sufficiently satisfying. In order to satisfy the design engineers the methods and tools used for EcoDesign must be easy to use, reduce the time of work, require short or no setup-time or education, be incorporated in daily work, support trade-off decisions and have a clearly visible result and purpose.

The requirements found in the literature study are summarized in Table 1. The most frequent requirements were narrowed down to the following four categories: **Expected Result** (could give information on: whether the method is inspiring, if the result is measurable, a foundation for decision-making, comparable results, if there is interpretable data, and the method's reliability). **Product Development Process Phase**, **Considered Life Cycle Stages** (and life cycle perspective, yes/no), **Time** and **Difficulty** (complexity, accessibility and expertise knowledge needed).

	Criteria	Ryding [16]	Lindahl [4]	Lofthouse [20]	Handfield *et al.* [21]
	User friendly				
1	Easy to implement and use	✓	✓	✓	✓
2	Reduce the total calendar time to solve a task (time efficient)		✓	✓	✓
3	Short set-up time		✓	✓	✓
4	Computer-based		✓	✓	
5	Universal and flexible	✓	✓		
6	Fast	✓		✓	
7	Based on low quality data		✓		
8	Does not require education				✓
9	Easy to access			✓	
10	Easy to incorporate in daily work				✓
11	Facilitate designers to fulfill specified requirements		✓		
12	Not require excessive simultaneous collaboration		✓		
13	Presented in appropriate language			✓	
14	Providing guidance, information and education			✓	
15	Visually presented				
16	Reduce the risk that important elements are forgotten		✓		
17	Inspiring			✓	
	Reliability				
18	Accepted valuation methods	✓			
19	Consistent and standardized	✓			
20	Industrially established	✓			
21	Enable uncertainty and sensitivity analyses	✓			
22	Interpretable and comparable results	✓			
23	Objective assessment (competition neutral)	✓			
24	Reliable and relevant outcome		✓		
	Purpose and Results				
25	Be a foundation for environmental product declarations	✓			
26	Direction towards a target area rather than a road map to the target		✓		
27	International environmental considerations, adaptable to local problems	✓			
28	Support long-term environmental planning and risk assessment	✓			
29	Support trade-off decisions				✓
30	Clearly visible result and purpose				✓

Table 1: Identified criteria for EcoDesign methods and tools.

6 ECODESIGN METHODS AND TOOLS

This section lists some of the EcoDesign methods and tools found in the literature review. Identified methods and tools can be divided into different types aimed at e.g. Investigating Customer Environmental Needs, Benchmarking, Idea and Concept Generation and Concept Eliminations.

In order to bring structure, identified EcoDesign methods and tools were categorized according to Table 2, which is based on the criteria found in Section 5.

Phase of development process	*Planning/ Concept Development/ System-Level Design/ Detail Design/ Testing and Refinement/ Production Ramp-Up*
Expected results	*Describes what outcome the user could expect when using the tool*
Time	*Fast/Somewhat time consuming/Time consuming*
Difficulty	*Very Easy/Easy/Medium/Hard*
Life Cycle Perspective	*Yes/No / Resource extraction/ Product Manufacturing / Product Use/ End-of-Life (EOL)*
Sources	*References where methodology and more information can be found*

Table 2: Template for describing EcoDesign methods and tools.

In Table 3, some of the identified EcoDesign methods and tools are presented. Symbols, which are explained below, are used to make the table easier to read. The table summarizes the methods and tools in alphabetical order and indicates the phase of the product development process, life cycle perspective, time, difficulty, and accessibility on the Internet.

Symbol Explanations:

Phase of Product Development Process:

The bar, [0 | 1 | 2 | 3 | 4 | 5], shows the phase of the product development process where the method is useful. The reference is Ulrich and Eppinger's Product Development Model [9].

Life cycle perspective:

- ✓ The method or tool has a life cycle perspective.
- ✗ The method or tool has no life cycle perspective.
- ✓/✗ The method or tool has no built-in life cycle perspective, but the product developers can implement a life cycle perspective if they like.

Time:

The time has been estimated from information in the literature and comparisons on the work burden between the different methods. Many methods could be performed with different scopes; therefore, the amount of time that would be needed to complete a useful and reliable result has been approximated.

- Not time consuming – less than 1 person-days.
- Somewhat time consuming – 1-5 person-days.
- Time consuming – more than 5 person-days.

Difficulty:

The difficulty has been evaluated by the authors, with help from information found in the literature. Some method descriptions mention that environmental specialists are needed, and that the classification is therefore a difficulty level of "medium". The methods marked "very easy" were understood by the author without reading the descriptions and methodology, while the ones marked "easy" were understood and possible to perform by the author with help from the provided manual or step-by-step descriptions. The methods marked "hard" require expert knowledge in both how to perform the method and environmental concerns.

- Very easy – Could be performed intuitively.
- Easy – Can be performed with help from a manual.
- Medium – Needs some education on method or extensive knowledge in environmental concerns.
- Hard – Requires expert knowledge.

Accessible on the Internet:

- ✓ Yes
- ✗ No
- (money icon) Not free – license or costly

Method	Product development process	Life cycle perspective	Time	Difficulty	Accessible on the Internet
Cumulative energy demand [22]	1, 2		Not time consuming	Easy	✓
Checklist for environmentally conscious electronics [23]	1, 3	✓	Not time consuming	Very easy	✓
Contingent valuation [24]	1	✗	Somewhat time consuming	Easy	✓
Cleaner Technologies Substitutes Assessment [25]	1	✓	Somewhat time consuming	Medium	✓
Design for Environmental Compliance Workbench Tool [26]	3	✓	Somewhat time consuming	Medium	✗
Disassembly analysis [23]	1, 2	✗	Not time consuming	Easy	✓
Dominance Matrix [22]	0, 1	✗	Not time consuming	Easy	✗
Eco Strategy wheel [23]	1	✓	Not time consuming	Very easy	✓
Eco Compass [22]	0, 1	✓	Not time consuming	Easy	✓
EcoDesign PILOT [27]	1	✓	Somewhat time consuming	Easy	✓
EcoPaS [28]	1, 2, 3	✗	Somewhat time consuming	Medium	✓
Environmental Effect Analysis (EEA) [29]	1	✓	Somewhat time consuming	Medium	✓
Environmental Objectives Deployment [30]	1	✓/✗	Not time consuming	Easy	✗
Environmental Benchmarking (EPAss) [31]	0, 1	✓/✗	Somewhat time consuming	Easy	✓
The Environmentally Responsible Product Assessment Matrix [32]	1	✓	Somewhat time consuming	Medium	✓
Function analysis [23]	1	✓/✗	Not time consuming	Easy	✓
House of Environmental Quality [32]	1	✓	Not time consuming	Easy	✗
IdeMat [33]	1, 2, 3	✓	Somewhat time consuming	Medium	✓
Life Cycle Assessment (LCA) [34]	0, 5	✓	Time consuming	Hard	✓/(not free)
Life-Cycle Design Strategies (LiDS) Wheel [35]	0, 1	✓	Not time consuming	Easy	✓
Materials-Energy-Chemicals-Other (MECO) Matrix [36]	1, 2	✓	Somewhat time consuming	Medium	✓
Material, Energy Consumption and Toxic discharge (MET) matrix [23]	1, 2	✓	Not time consuming	Medium	✓
Material Input Per Service unit (MIPS) [22]	1, 2	✗	Not time consuming	Easy	✓
Product Ideas Tree (PIT) [37]	1	✓	Somewhat time consuming	Easy	✓
Quality Function Deployment for Environment (QFDE) [38]	0, 1	✓	Not time consuming	Easy	✓
Ten Golden Rules [39]	1, 2, 3	✗	Not time consuming	Very easy	✓
TRIZ used in EcoDesign [40]	1, 2	✓/✗	Somewhat time consuming	Medium	✓
EDIP (Environmental Design of Industrial Products) [36]	0, 5	✓	Time consuming	Hard	✓/(not free)

Table 3: Summary of EcoDesign methods and tools.

7 DISCUSSION AND CONCLUSIONS

7.1 Criteria on EcoDesign Methods and Tools

The objective was to present potential criteria that can be used for selecting EcoDesign methods and tools, and this has been done through the literature study of criteria for choosing EcoDesign methods and tools. Only a few studies have been made in this field, and they showed quite different results; one reason could be that the studies have had different approaches and interpretations on what is important when utilizing methods and tools. For example, Lindahl [4] focused on the requirement the engineering designers have for using methods and tools, and he does not consider if the results of the method are appropriate from an environmental perspective. Ryding [16], on the other hand, specifies criteria that the methods should fulfill in order to produce appropriate results from an environmental perspective. Lofthouse [20] analyzes the industrial designers' special demands on EcoDesign methods and tools that are quite different since their technical knowledge in general is much lower than that of engineering designers. It seems like most EcoDesign methods and tools are developed for the use of engineers and few tools exist for industrial designers. However, those criteria described by Lofthouse could be important to consider whenever industrial designers are participating in the EcoDesign work.

Many different criteria could be used for selecting EcoDesign methods and tools. The most common criteria mentioned in the literature and in the interview study are that the methods must be useful, provide help for the user to reach the goal, and have a clearly defined purpose and measurable results. Also, it is important that the tools not are too complex and time consuming compared to the benefit.

7.2 EcoDesign Methods and Tools

A second objective was to present a structure for how different EcoDesign methods and tools can be categorized – a structure that can work as guidance for, depending on the context and need, selecting EcoDesign methods and tools.

In order to do that, 28 EcoDesign methods and tools were identified through a literature review and later used to test the proposed categorization structure. They included benchmarking tools, tools for investigating customer needs, concept generation and elimination tools, evaluating and assessment tools, as well as checklist and guideline tools.

It should be noted that the aim of gathering the methods and tools is not to claim that this paper covers all existing EcoDesign methods and tools. Instead, the purpose is to provide an illustration on how environmental methods and tools could be categorized in order to support selection of suitable ones depending on the actual context. Nevertheless, an interesting note is that many of the identified EcoDesign methods and tools are derived from methods and tools used in other purposes in product development, for example the functional analysis and the morphological box that is redesigned to incorporate environmental requirements as well. Other EcoDesign methods derived from other product development methods and tools are for example Environmental Effect Analysis (EEA) and Quality Function Deployment for Environment (QFDE). Those methods and tools could be easy to learn and implement if the user is already familiar with the original method.

7.3 Structure for Categorization of EcoDesign Methods and Tools

The second objective was to present a structure for how different EcoDesign methods and tools can be categorized, and this is done in the previous section. This structure is tested by using the identified EcoDesign methods. The conclusion is that this structure can be used as guidance for companies, engineers, etc. when selecting suitable EcoDesign methods and tools. It can be used both as a way to structure EcoDesign methods and tools, as well as used as categories when trying to describe the actual context in which the EcoDeign method or tool is supposed to be used.

8 REFERENCES

[1] Billatos, S.B. and Basaly, N.A., Green Technology and Design for the Environment, 1997: Taylor & Francis Inc.

[2] Simon, M., Evans, S., McAloone, T.C., Sweatman, A., Bhamra, T., and Poole, S., Ecodesign Navigator - A Key resource in the Drive towards Environmentally Efficient Product Design, 1998, Manchester, UK: Manchester Metropolitan University, Cranfield University & EPSRC.

[3] Mizuki, C., Sandborn, P.A., and Pitts, G., Design for environment-a survey of current practices and tools. Electronics and the Environment, 1996. ISEE-1996., Proceedings of the 1996 IEEE International Symposium on, 1996: p. 1-6.

[4] Lindahl, M., Engineering Designers' Requirements on Design for Environment Methods and Tools, in Industrial Engineering and Management, 2005, KTH: Stockholm, Sweden.

[5] ENDREA, ENDREA nomenclature, ENDREA - Engineering Research and Education Agenda, 2001: Linköping, Sweden.

[6] Collaine, A., Lutz, P., and Lesage, J.-J., A method for assessing the impact of product development on the company. International Journal of Production Research, Taylor & Francis, 2002. 40(14): p. 3311 - 3336.

[7] Gonzalez, F.J.M. and Palacios, T.M.B., The effect of new product development techniques on new product success in Spanish firms. Industrial Marketing Management, 2002. 31(3): p. 261-271.

[8] Stalk, G.J. and Hout, T.M., Competing Against Time - How Time-Based Competition is Reshaping the Global Markets, 1990, New York, USA: The Free Press, A Division of Macmillan Inc. 285.

[9] Ulrich, K.T. and Eppinger, S.D., Product Design and Development, 2000, New York: McGraw-Hill Higher Education.

[10] Andreasen, M.M. and Hein, L., Integrated Product Development, 1987, Bedford, UK: IFS Publications Ltd.

[11] Olesen, J., Concurrent Development in Manufacturing - based on dispositional mechanisms, in Institute for Engineering Design, 1992, Technical University of Denmark: Lyngby, Denmark. p. 154.

[12] Roozenburg, N.F.M. and Eekels, J., Product Design: Fundamentals and Methods, 1995, West Sussex, UK: John Wiley & Sons, Ltd.

[13] Graedel, T.E. and Allenby, B.R., Design for Environment, 1998, Upper Saddle River, New Jersey: Prentice Hall.

[14] Luttropp, C., Design for Disassembly, in Department of Machine Design, 1997, Royal Institute of Technology: Stockholm, Sweden.

[15] van Hemel, C.G., EcoDesign Empirically Explored - Design for Environment in Dutch Small and Medium Sized Enterprises, 1998, Delft University of Technology: Delft, Netherlands.

[16] Ryding, S.-O., et al., Miljöanpassad produktutveckling (in Swedish), 1995, Stockholm, Sweden: Industrilitteratur AB.

[17] Rydh, C.J., Lindahl, M., and Tingström, J., Livscykelanalys - en metod för miljöbedömning av produkter och tjänster (Life Cycle Assessment - a method for environmental assessment of products and services). 1st ed 2003, Lund, Sweden: Studentlitteratur AB. 228.

[18] Kutz, M., ed. Environmentally conscious Mechanical Design. 2007, John Wiley & Sons, Inc: New Jersey.

[19] Lindahl, M., Engineering designers' experience of design for environment methods and tools - Requirement definitions from an interview study. Journal of Cleaner Production, Elsevier, 2006. 14(5): p. 487-496.

[20] Lofthouse, V., Ecodesign tools for designers: defining the requirements. Journal of Cleaner Production, 2006. 14(15): p. 1386-1395.

[21] Handfield, R.B., Melnyk, S.A., Calantone, R.J., Curkovic, S., Integrating environmental concerns into the design process: the gap between theory and practice. Engineering Management, IEEE Transactions on, 2001. 48(2): p. 189-208.

[22] Charter, M. and Tischner, U., eds. Sustainable Solutions - Developing products and services for the future. 2001, Greenleaf Publishing Limited: Sheffield, UK.

[23] Norrblom, H.L., Jönbrink, A.K., and Dahlström, H., EcoDesign - Praktisk vägledning, 2000, Göteborg, Sweden: Institutet för Verkstadsteknisk Forskning.

[24] Thurston, D., L. and Hoffman, I.W., F. Integrating Customer Preferences into Green Design and Manufacturing. in Proceedings of the 1999 IEEE International Symposium on Electronics and the Environment. 1999. Danver, Massachusetts.

[25] Kincaid, L., Davis, E., Allen, G., and Jed, M., Cleaner Technologies Substitutes Assessment - Executive Summary (http://www.epa.gov/dfe/pubs/tools/ctsa/exsum/exsum.htm.), 2010.

[26] Roche, T., The Design for Environmental Compliance Workbench Tool in Product Engineering; Eco-Design, Technologies and Green Energy, D. Talabă and T. Roche, Editors. 2004, Springer: Dordrecht.

[27] Wimmer, W. and Züst, R., ECODESIGN PILOT, Product-Investigation, Learning- and Optimization-Tool for Sustainable Product Development, 2003, Dordrecht: Kluwer Academics Publishers.

[28] Duflou, J.R. and Dewulf, W., Eco-Impact Anticipation by parametric screening of machine system components: An Introduction to the EcoPaS Methodology, in Product Engineering; Eco-Design, Technologies and Green Energy, D. Talabă and T. Roche, Editors. 2004, Springer: Dordrecht.

[29] Lindahl, M. and Tingström, J., A small textbook on Environment Effect Analysis (EEA), 2000, Kalmar, Sweden: Dept. of Technology, University of Kalmar.

[30] Byggeth, S. and Hochschorner, E., Handling trade-offs in Ecodesign tools for sustainable. Journal of Cleaner Production, 2006. Vol. 14: p. 1420-1430.

[31] Stevels, A., Adventures in EcoDesign of Electronic Products - 1993-2007, 2009: VSSD.

[32] Graedel, T.E. and Allenby, B.R., Industrial Ecology. 2nd ed2003, Upper Saddle River: Pearson Education, Inc.

[33] Design for Sustainability Program. Delft University of Technology IdeMat Product Info - IdeMat (http://www.idemat.nl/Product/pi_frame.htm). 2005 [cited 2012 10th of September].

[34] Baumann, H. and Tillman, A.-M., The Hitch Hiker's Guide to LCA - An orientation in life cycle assessment methodology and application, 2004, Lund, Sweden: Studentlitteratur AB.

[35] Brezet, H. and Hemel, C.v., eds. Ecodesign - A Promising Approach to Sustainable Production and Consumption. 1997, Delft University of Technology: Delft, Netherlands.

[36] Wenzel, H., Hauschild, M., and Alting, L., Environmental Assessment of Products - Volume 1: Methodology, tools and case studies in product development, 1997, London: Chapman & Hall.

[37] Jones, E., Stanton, N., and Harrison, D., Applying structured methods to Eco-innovation. An evaluation of the Product Ideas Tree diagram. Design Studies, 2001. Vol. 22: p. 519–542.

[38] Sakao, T., Watanabe, K., and Shimomura, Y. A Method to Support Environmentally Conscious Service Design Using Quality Function Deployment (QFD). in EcoDesign 2003. 2003. Tokyo, Japan.

[39] Luttropp, C. and Lagerstedt, J., EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development. Journal of Cleaner Production, 2006. Vol. 14: p. 1396-1408.

[40] Chang, H.-T. and Chen, J.L., The conflict-problem-solving CAD software integrating TRIZ into eco-innovation. Advances in Engineering Software, 2004. Vol. 35: p. 553–566.

RFID Integrated Adaption of Manufacturing Execution Systems for Energy Efficient Production

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Abstract

An emerging challenge for manufacturing companies is to increase the energy efficiency of their manufacturing systems in order to reduce both energy costs and overall environmental impact. Modern manufacturing execution systems must cope with the new requirements of sustainable manufacturing in addition to the conventional focus on production management. This approach shows how the digital network of manufacturing execution systems can be used to eliminate non-value adding energy consumption in the manufacturing system. Therefore, an integrated use of workstation-related information from production schedules as well as the availability of product, operator and manufacturing equipment was developed. In particular, the advantages of the radio frequency identification technology is considered, as a decentralized information source for the manufacturing execution system for product and operator induced idle and stand-by times of production machinery.

Keywords:

Energy management and efficiency; manufacturing execution system; RFID

1 INTRODUCTION

This day's resource and energy efficiency is a key-driver for innovations in technologies and products [1]. This fact is becoming increasingly important since customers are aware of the ecological impact of their machinery in the utilization phase during the product life cycle. Furthermore the European legislation already forces manufacturers to increase the energy efficiency of their products as well as the reduction of the energy consumption during the manufacturing process [2]. Upcoming technical standards and rising energy costs indicate that in future manufacturing systems and their machinery have to be reengineered to increase energy efficiency in manufacturing [3].

Especially manufacturing companies are characterized by a high consumption of energy and resources, as well as by a causing, heterogeneous plant structure. Consequently, companies have to face the challenge of controlling the continuously weight gaining proportion of energy costs of product manufacturing. This pushes for appropriate energy efficiency related reengineering measures on manufacturing equipment. Furthermore, companies have to cope with the practical issue of identifying the right equipment for energy-efficient optimization among the existing manufacturing system and to develop economically viable solutions [4].

In parallel to the activities of energy efficiency improvement, a trend for information technology (IT) oriented manufacturing equipment reengineering, like controlling migration, i.e. replacing or supplementing existing control technology by current, state of the art systems, prevails in manufacturing companies. Through the informational system integration via industrial digital networks, such as industrial Ethernet, almost all systems can be linked to modern production management software. The enabled virtual integration of manufacturing equipment extrapolate especially unused rationalization reserves through accelerated provision of information, process data recording, calculation of key performance indicators and the subsequent data analysis for continuous improvement activities [5].

This paper presents an approach on how to use existing IT company infrastructure and the horizontal and vertical information availability to establish an energy management system for the shop floor. For this purpose the architecture for an energy efficiency module within Manufacturing Execution Systems (MES) is introduced to improve resources and energy consumption situation of the manufacturing system. Through the use of wireless RFID (Radio Frequency Identification) systems, required information signals can be developed in manufacturing, which extend the scope of the system and increase their impact.

2 ENERGY CONSUMPTION AND PRODUCTIVITY

2.1 Characteristic Energy Consumption of Manufacturing Equipment

The energy consumption of manufacturing equipment during the utilization phase is based on different operating states in compliance to ISO 14955 [6]. Figure 1 shows the schematic profile of the overall energy consumption of manufacturing equipment taking into account four different operating states. A further differentiation in value adding processes, e.g. like the actual processing operation, and not value adding processes, e.g. the work piece handling task, is derived.

According to the ISO-standard a machine consist of the following component groups, which are separately analyzed according their energy consumption: Peripheral units, machine control, machine processing unit and machine motion unit. The group elements of peripheral units include the following components like units for machine cooling, process cooling, work piece and tool handling, recyclables and waste handling.

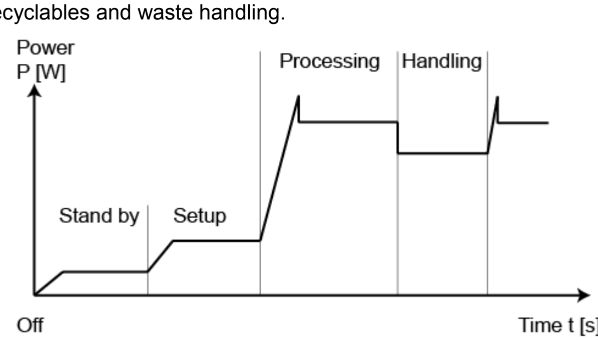

Figure 1: Schematic power profile of discrete manufacturing process.

Machine processing units are e.g. main spindle of a turning machine, tool spindle of a machining centre, slide of a press, draw cushions of a press machine. Motion units are e.g. linear axes of a turning machine, linear and rotary axes of a machining centre, mechanical, electrical, hydraulic, or pneumatic device of a machine tool, or a combination thereof.

In compliance to the ISO-standard, table 1 shows an application of the system using a metal-cutting machine tool. The matrix includes a recommendation of the component activity regarding the operation state condition and a further subdivision in value and not value adding tasks.

Operation state / Component	Off / not value adding	Setup / not value adding	Stand by with peripheral units on / not value adding	Ready for operation and idle / not value adding	Processing / value adding
Mains	Off	On	On	On	On
Machine control (PLC)	Off	On	On	On	On
Peripheral unit (cooling system)	Off	On	On	On	On
Machine processing unit (main spindle)	Off	On no machining	Off	Hold	On, machining
Machine motion unit (rotary axis)	Off	On	Off	Hold	On

Table 1: Machine state and component matrix.

This structure allows a consumption-based analysis of energy input of individual manufacturing equipment and serves as a starting point for component-related measures of reengineering.

For evaluating the energy efficiency of an entire system in discrete manufacturing, the equation listed in Formula 1 is used [7]. It indicates how much energy for the product manufacturing is needed.

$$E_{eff} = \frac{Processed\ piece}{Energy\ input} \quad (1)$$

Recent studies show that a remarkable proportion of the total energy consumption of manufacturing equipment is caused during non-value-added machine states like idle and stand by [8]. These consumers are often process-independent peripheral components such as the cooling system and material or chip conveyor [9]. The actually required energy consumption for machining on factory level represents 12 % compared to the total power [10].

2.2 Productivity of Manufacturing Equipment

The productivity of manufacturing equipment is defined as the ratio of produced parts to the related time of production [11].

$$Productivity = \frac{Processed\ pieces\ per\ period}{\text{Operation time per period}} \quad (2)$$

The effectiveness of manufacturing equipment is reflected in ensuring the required availability and its optimal utilization and an optimum in the use of resources and energy.

In practice the equipment productivity, enabled by the energy consumption described in section 2.1, is limited by several factors. Losses in the productivity are possibly connected with the machinery itself, caused by technical malfunctions or in correlation with organizational disturbances like failures in the production order schedule or material shortages. Both are resulting in equipment downtimes [12]. The connection between the technical feasible productivity and the actual produced quantity of parts is shown schematically in figure 2. The typical progress of productivity increases continuously during ramp-up until the manufacturing equipment reaches its predetermined value. During downtimes the productivity goes back to zero.

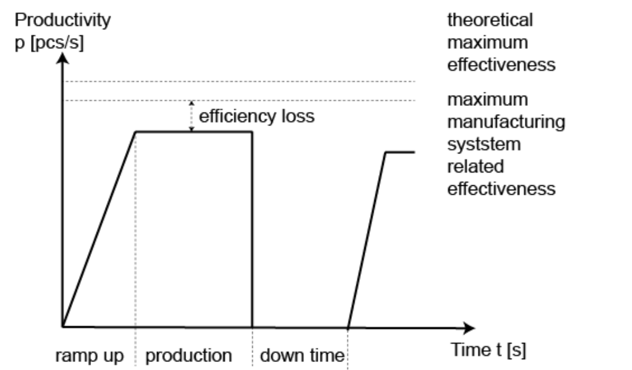

Figure 2: Schematic productivity profile of a discrete manufacturing process.

Besides the aim of increasing energy efficiency of manufacturing equipment the effort considering an increased effectiveness as well as the reduction of technical and organizational losses in efficiency are dominating the measures of reengineering [5].

3 FRAMEWORK FOR THE MES INTEGRATED ENERGY EFFICIENCY OPTIMISATION

3.1 Initial Power and Productivity Profile Analysis

To evaluate the applicability related control measures for reducing not value adding energy demand, a simultaneous analysis of both power consumption as well as the associated manufacturing equipment productivity is performed as shown in Figure 3.

Therefore two assessment criteria Q_1 and Q_2 are established which evaluate the energetic behavior of each component j with respect to prioritize the non-value adding operation states i. Initially, the condition Q_1 is checked. It indicates whether in a downtime of the equipment a power consumption of the analyzed system component j is present.

$$Q_{1_{i,j}}: p_{(t1)} = 0 \land P_{i(t_1)} > 0 \quad (3)$$

If condition Q_1 is valid for the component j, the indicator Q_2 will be assessed subsequently. Q_2 describes the ratio of the average energy consumption of a non value adding operation state of the component j to the average energy consumption during a processing operation.

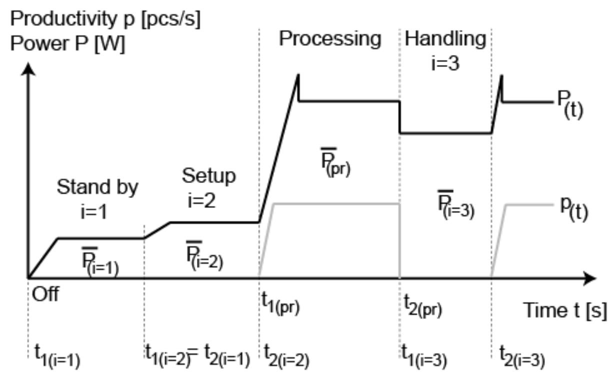

Figure 3: Productivity and power profile analysis.

$$Q_{2_{i,j}}: \frac{\overline{P_i} = \frac{1}{t2(i) - t1(i)} \int_{t1(i)}^{t2(i)} P_{(t)_i} dt}{\overline{P_{pr}} = \frac{1}{t2(pr) - t1(pr)} \int_{t1(pr)}^{t2(pr)} P_{(t)_{pr}} dt} \quad (4)$$

To ensure the comparability, the value Q_2 is normalized to the range [0, 1]. If the value of the criteria Q_2 approaches 1, the difference between the average energy consumption during the value adding process and the average energy consumption of related non-value added states i is high. This indicates a high potential for optimization and thus a high priority based on the underlying condition before.

However, if Q_2 is close to 0, the difference between the average energy consumption during the production process and the average energy consumption of related non-value added states i is low. This indicates a modest potential for optimization and thus a low priority based on the underlying condition before.

The assessment factors Q_1 and Q_2 serve as decision support criteria for the selection of the components with high efficiency potential.

3.2 Architecture of the Energy Efficiency Module

A Manufacturing execution system (MES) is defined as a shop floor control system which includes either manual or automatic labor and production reporting as well as online inquiries and links to tasks that take place on the production floor [5]. MES creates a vertical integration of information by connecting manufacturing equipment with its sensor-based process data at the lowest hierarchical level all the way up to the business divisions and their ERP systems. Figure 4 shows the MES embedded IT infrastructure. The horizontal integration of information is the exchange of data at the manufacturing equipment level. This data is transmitted via the related digital shop-floor network, which is also connected to the MES [13].

The implementation of the described approach increases the energy efficiency based on immediate real-time control of electrical manufacturing equipment including the equipment's components connected to the MES. The control consists of a unit to turn a device or process on or off and for more complex processes, advanced multivariable control functions are applied.

Since a large proportion of the energy consumption of production equipment is connected with non value adding operating states, e.g. product handling, relevant conditions, which exclude a value adding operation, will be evaluated in a logical interpreter unit.

Therefore a centralized information deployment in relation to the operation state-specific energy consumptions and the differentiation in value adding processes is established. In general, a work station with manually operated manufacturing equipment cannot be in the value adding operation state if one of the conditions listed in Table 2 (A, B, C, D or E) is present. If the system is part of a manufacturing line and depending on other equipment, the available information provided through horizontal integration about the equipment connected before and after is included as additional conditions into the interpretation process.

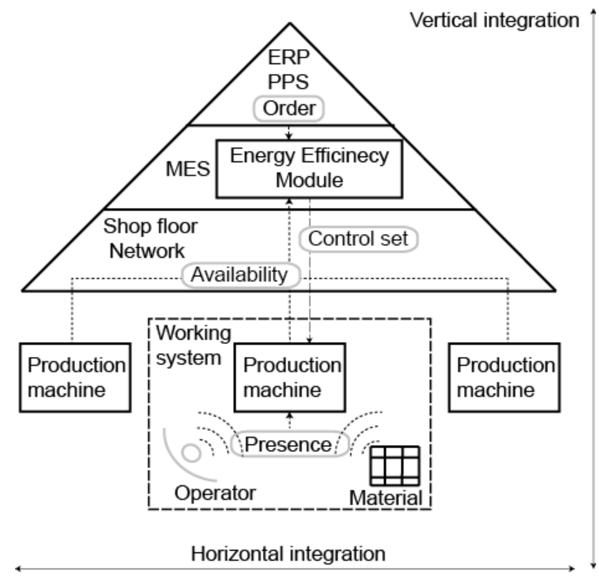

Figure 4: Energy efficiency MES Module.

The information on the conditions A, B and E can be achieved as an integral part of MES and must not be additionally provided. While the presence information of the machine operator and the material or work piece has to be taken additionally to the System.

Condition	Information source
A: No production order	PPS; vertical integration
B: Machine down time (planned or unplanned)	Machine control; vertical integration
C: No operator present	Presence; RFID
D: No material or work piece present	Presence; RFID
E: No availability of connected production equipment	Machine control; horizontal integration

Table 2: Conditions and related information source.

In this context the following logical condition will be checked by the MES energy efficiency module:

$$IF \quad A \vee B \vee C \vee D \vee E \quad THEN \quad \overline{Production} \quad (5)$$

According to the interpretation the second step of the energy efficiency module is preceded immediately. This includes an energy-oriented control of the connected manufacturing equipment and their individual components in form of customized control functions f_i.

The control function will be individually adapted to the triggering condition A, B, C, D or E to specifically regulate the equipment components or to fully switch them on and off. The selection of control measures will be individually set up for each component in order to obtain no influence on plant productivity.

To keep the implementation effort for the control functions manageable a pre selection of relevant components considering the criteria $Q_{1_{i,j}}$ and $Q_{2_{i,j}}$ is recommended.

For forwarding of control commands to individual manufacturing equipment control the system makes use of the Object Linking and Embedding for Process Control (OPC) standard.

3.3 Presence Detection and Information Generation through the Use of RFID

In order to generate information signals depending on the presence of a machine operator (condition C) or the absence of material (condition D), RFID systems can be applied. RFID systems use radio waves to identify items or people automatically. These systems consist of RFID tag and a transceiver. The latter emits a field of electromagnetic waves by an antenna, which is absorbed by the tag. The absorbed energy is used to power the tag's microchip. A signal including the tag identification number is sent back to the reader. Those passive RFID tags work on the basis that they absorb the power from the reader and use this to empower the microchip and re-emit a signal. Active tags contain a battery, which powers the chip and transmits to the reader [14].

RFID is an automatic identification technology which is already used in the supply chain of many companies but is also gradually applied to the core of manufacturing processes [15]. By adopting the technology on the shop floor, the exact real-time presence information that is obtained from RFID systems, can be integrated seamlessly into the energy efficiency module of the manufacturing execution system [16]. In particular, the electromagnetic field of a 13.56 MHz system with passive RFID tags will be used for the presence detection. Depending on the antenna and the production environment these systems can achieve a reading distance up to 7 meter. This fits the specifications for the work station.

In order to generate the information for the energy efficiency module the machine operator as well as the used material respectively the work piece conveyor have to be equipped with a transponder. The reading device for this transponder has to be positioned close to the related production machinery. By means of the electromagnetic field (generated by the antenna of the reading device) a presence area around the work system is created. If the transponder enters this area, a signal is generated by the reading device. The presence area size depends on the response field strength. The response field strength is the minimal value, at the maximum distance between transponder and reading device, when the supply voltage is still enough to power the transponder. The supply voltage has to be adjusted depending on the production environment to reduce interference. The switching limit respectively the response field strength is set by the reading device [14].

The information about presence of a machine operator or the absence of material, acquired with the RFID system is sent through the equipment MES interface via the network infrastructure to the energy efficiency module and can be used for the condition interpretation described in section 3.1.

4 ASSESSMENT OF THE ENERGY SAVING POTENTIAL OF AN INDUSTRIAL CLEANING MACHINE

The initial power and productivity analysis and the derivation of the achievable savings potential were carried out on industrial cleaning equipment. The system includes a washing process by the three cleaning steps, spraying, flooding and ultrasonic adding up to a total nominal power of 91 kW.

For measurement of the electrical consumption of selected components in the various operating states, a data acquisition system with single-ended analog input, and a sampling rate of 10 ms per channel was applied.

The analog current signals were generated by inductive current sensors. The used devices are in the measuring range of 10, 25, 50, 75 ampere. The voltage was recorded via a conventional voltage divider. To determine the component-based energy consumption, the energy data was recorded by the following system components with the specified sensors:

1: Ultrasonic cleaning device, nominal power: 2 kW; Sensor: 10 A

2: Cleaner treatment, nominal power: 1 kW; Sensor: 10 A

3: Vacuum pump, nominal power: 2.5 kW; Sensor: 10 A

4: Heating, nominal power: 9 kW; Sensor 50 A

5: Hot air heating, nominal power: 20 kW; Sensor: 75 A

6: Flood-injection pump1; nominal power: 3 kW; Sensor: 10 A

7: Flood-injection pump2; nominal power: 3 kW; Sensor: 10 A

8: Flood-injection pump3; nominal power: 7.5 kW, Sensor: 50 A

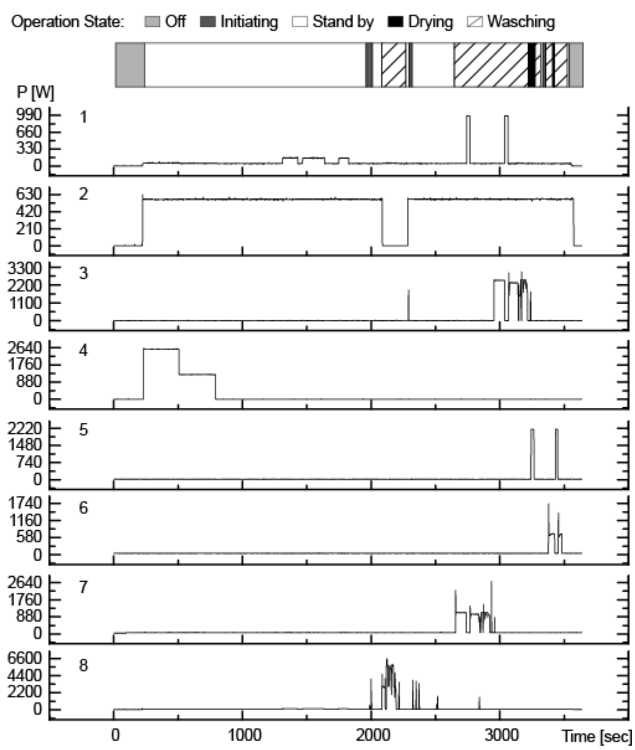

Figure 6: Component related energy consumption of an industrial cleaning machine.

Component \ Operation state	Off / not value adding	Initiating / not value adding	Stand by / not value adding	Drying / not value adding	Washing / value adding
					Q1
1: Q2	0,01	0,09	0,12	0,09	1
2: Q2	0,04	0,99	0,99	1,00	1
3: Q2	0,08	0,08	0,08	0,41	1
4: Q2	0,01	0,01	0,01	0,01	1
5: Q2	0,03	0,03	0,03	0,78	1
6: Q2	0,02	0,06	0,02	0,60	1
7: Q2	0,02	0,14	0,14	0,14	1
8: Q2	0,08	0,16	0,20	0,15	1

Table 3: Analysis results.

The component related energy consumptions as shown in Figure 6 are used to determine the quality criteria Q_1 and Q_2 introduced in Section 3.1. In this application, the washing process is defined as the value adding operation due to the fact, that this step fulfills the requirements of the customer and increases the rewarded product value. All other operation states are defined as not value adding. The determined values for the quality criteria are shown in table 3.

Then, for each component their control function f_i was defined. The achievable relative energy savings, based on the total energy consumption of the system was calculated.

For the considered components a resulting total stand by energy saving potential of 60 % can be achieved by implementing the MES module and the selective component control. The control conditions for the stand by state are: 1: turn off; 2: power reduction up to 50 % according used cleaning media; 3: turn off; 4: power reduction to 50 %; 5: turn off; 6: turn off; 7: turn off; 8: turn off. To avoid extending the response time from stand by state to washing, the heating and cleaner treatment is not fully turned off.

In this use case, the RFID transponder can be attached to the cleaning basket. This requires a special transponder type resistant to temperature and chemical- cleaning agents.

5 CONLUSION AND FUTURE WORKS

The developed procedure represents an approach to use the MES related IT infrastructure of manufacturing companies for a continuative reduction of non value adding energy consumption of connected manufacturing machinery. Furthermore the effectiveness of the system can be increased by integrating RFID technology as a related decentralized presence information source. Therefore this work supports manufacturing companies to increase their energy efficiency with manageable efforts. The introduced machinery analysis based on the energy demand in different operation states, indicates the effectiveness which can be achieved by connecting it to the system.

A first practical check of the potential energy savings on an industrial cleaning machine showed that at least 60 % of the non value adding energy consumption during the stand by state can be avoided by connecting the machine to the introduced MES energy module.

A next step is to improve the performance of the interpretation and control system of the MES energy module by integrating knowledge based decision making system. The task of this system is to predict the duration and impact of the non value adding operation states regarding the available information sources. For instance such a system extension would support to classify machine break downs based on the interpretation whether it’s a serious failure like a bearing damage or just an inadvertently checked photoelectric barrier. The MES energy module can individually decide which energy mode should be initiated with respect to the machine availability both on the broke down equipment and all inter-connected machines.

Finally the implementation of the procedure in further use cases will additionally optimize the procedure especially regarding its portability and significance on various manufacturing processes.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] Lang-Koetz, C.; Pastewski, N.; Schimpf, S.; Heubach, D. (2010): Resource efficiency as a key-driver for technology and innovation management: Dealing with an emerging trend in technology intelligence, in: International journal of technology intelligence and planning 6, No.2, pp.164-184.

[2] European Union (2009): Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products.

[3] Steinhilper, R.; Slawik, S.; Pentzlin, F.; Boehner, J. (2011): Increasing energy efficiency by remanufacturing and reengineering, in: Proceedings of Eco Design 2011 International Symposium, Kyoto, Japan, pp.206-212.

[4] Steinhilper, R.; Freiberger, S.; Kübler, F.; Boehner, J. (2012): Development of a Procedure for Energy Efficiency Evaluation and Improvement of Production Machinery, in: Leveraging Technology for a Sustainable World: Proceedings of the 19th CIRP Conference on Life Cycle Engineering, Dornfeld, D. A. and Linke, S. B. (eds.), Berkeley, USA, pp. 341-346.

[5] Cottyn, J.; Landeghem, H.; Stockman, K.; Derammelaere, S. (2009): A Method to Align a Manufacturing Execution System with Lean objectives, in: International Conference on Production Research, Wang, G. and Wong, T. (eds.), Shanghai, China, pp. 211-217.

[6] Objectives ISO 14955-1 (2011): Design methodology for energy-efficient machine tools, working draft commented, comments discussed, committee draft until 2011-05-15.

[7] Thiede, S. (2012): Energy Efficiency in Manufacturing Systems, in: Sustainable Production, Life Cycle Engineering and Management, Herrmann, C., Kara, S. (eds.), Berlin, Germany.

[8] Linke, B.; Overcash, M. (2012): Life Cycle Analysis of Grinding, in: Leveraging Technology for a Sustainable World: Proceedings of the 19th CIRP Conference on Life Cycle Engineering, Dornfeld, D. A. and Linke, S. B. (eds.), Berkeley, USA, pp. 293-298.

[9] Brecher, C.; Bäumler, S.; Jasper, D.; Triebs, J. (2012): Energy Efficient Cooling Systems for Machine Tools, in: Leveraging Technology for a Sustainable World: Proceedings of the 19th CIRP Conference on Life Cycle Engineering, Dornfeld, D. A. and Linke, S. B. (eds.), Berkeley, USA, pp. 239-244.

[10] Quilligan, F.; Upton, C. (2012): Visual Decision Support for Energy Aware Production Planning, in: Towards Implenting Sustainable Manufacturing: Proceedings of the 10th Global Conference on Sustainable Manufacturing, Seliger, G. and Kiliç S. E. (eds.), Istanbul, Turkey, pp. 453-458.

[11] Zandin K., Kjell B., (2001): Maynard's Industrial Engineering Handbook.

[12] Garcia, M.; Santos, J.; Arcelus, M.; Viles, E. (2011): A Framework Based on EWW and Wireless Technology for Improving Overall Manufacturing Operations, in: Proceedings of the International Conference on Advances in Production Management Systems, Stavanger, Norway, pp. 132-139.

[13] VDI, Richtlinie 5600 (2007): Manufacturing Execution Systems, Beuth Verlag, Berlin.

[14] Keskilammi, M.; Sydänheimo, L.; Kivikoski, M. (2003): Radio Frequency Technology for Automated Manufacturing and Logistics Control. Part 1: Passive RFID Systems and the Effects of Antenna Parameters on Operational Distance, in: International Journal of Advanced manufacturing Technology, pp. 769-774.

[15] Dirk H. (2004): Mapping and localization with RFID technology, in: Proceedings of the 2004 IEEE International Conference on Robotics & Automation, New Orleans, USA, pp. 1015-1020.

[16] Jiwei, H.; Hexu, S.; Tao, L.; Zhaoming, L. (2008): The Design of Manufacturing Execution System Based On RFID, in: Power Electronics and Intelligent Transportation System, pp. 8-11.

Optimising Compressed Air System Energy Efficiency – The Role of Flow Metering and Exergy Analysis

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Abstract

Compressed air is a widely used power source in modern manufacturing and is therefore responsible for a large portion of factory energy usage. For this reason, there has been increased attention from the research community into the measurement of air consumption in machines, assessments of energy efficiency and optimisation of devices and systems. This paper provides an overview of the technology used for compressed air flow measurement, including a survey of commercially available flowmeters. Some guidance on sensor selection and installation is also provided. A number of industrial case studies are used to illustrate the dynamics of individual pneumatic consumers and larger demand production machines. In addition a standardised approach is proposed for the analysis of energy efficiency in manufacturing compressed air systems.

Keywords:

Compressed air; energy efficiency; measurement

1 INTRODUCTION

Recent research into the energy consumption and efficiency of manufacturing has highlighted the importance of taking a holistic approach that involves a consideration of compressed air (CA) and other media such as steam and vacuum, in addition to electric energy [1]. This is particularly important for discrete manufacturing facilities where air compressor energy use is larger than the direct electrical energy use of production machines. This is the case in the production of inkjet and toner printer cartridges for example. From an industrial point of view, the distribution of energy costs by unit process or value stream is an essential aspect to driving awareness to energy losses, and saving opportunities. As a prerequisite to local level energy use accounting, the quantification of different types of energy flows to production machinery is necessary. In the CIRP and related literature, there have been a number of reviews of the state of the art in electric power and energy metering, which usually also provide case studies of industrial implementation [2,3]. According to Radgen and Blaustein [4] increasing the visibility of compressed air costs to all levels of management is key factor in overcoming the organisational barriers to improving compressed air system energy efficiency. Unlike energy consuming units such as electric motors that are located in the production toolset, air compressors are generally arranged in a centralised station with extensive distribution to multiple consumers. This means that power consumption, due to air compression for individual production machines, is not easily measured but estimated based on measured compressed air consumption instead. However, since the medium to be measured is a compressible gas, its measurement is subject to inherent measurement error.

In addition to measurement complexity, an assessment of the energy efficiency of pneumatic production machines, and its comparison with alternative power sources, is often required. However, in previous assessments it if often unclear how the energy losses were determined. It is important therefore that the measurement methods and limitations for monitoring compressed air flow are understood, and also that the energy efficiency of pneumatic systems are assessed in a consistent manner.

The objective of this paper is twofold: 1. To provide an overview of measurement technology for compressed air flow with insight into the dynamics of CA demand 2. To propose a standardised approach for the assessment of energy efficiency in compressed air systems, which will allow for a comparison with alternative energy sources. A number of industrial case studies from multinational (MNE) manufacturers, ranging from bio-medical to consumer electronics, will be used to support the discussion. The specific focus for this paper is on the energy consumption and efficiency of compressed air systems used in manufacturing. Additional factors such as maintenance costs and (non-energy related) environmental impacts are outside the scope of the study.

2 SENSORS FOR COMPRESSED AIR FLOW

2.1 Sensor Technology

The main technologies used in the measurement of compressed air flow include: thermal mass, differential pressure (orifice plate), vortex and ultrasound. It is important to note that only flowmeters employing the thermal mass technology directly measure mass flow. The other measurement technologies measure volumetric flow and require additional hardware, pressure and temperature sensors, for computation of mass flow rate. For the measurement of compressed air demand in production environments, thermal mass based flow meters are considered state-of-the-art. In addition to the direct measurement principle employed, thermal mass flow meters have a number of key advantages over competing meter technologies, with the principle being the provision of large turndown ratio. Accuracy over a wide range of flow rates is important in many industrial situations. In particular for the measurement of air flow to production machine or lines, the magnitude of flow can range from small leakage rates during machine idling to a maximum measurable during production mode. Additional advantages of thermal mass flow sensors include no moving parts and a largely unobstructed flow path, which results in only small energy losses across the meter. Minimising pressure drop is a priority as otherwise meter installation, in itself can negatively impact on machine performance e.g. cycle time.

The two most common types of thermal flow sensors are the hot-wire and hot film type, which measures the effect of a flowing fluid on a hot body, and the calorimetric sensor type, which measures the asymmetry of the temperature profile around a heater [5]. The transducing principles employed for temperature measurement in thermal mass flow sensors includes thermoresistive, thermoelectric and thermoelectronic types. In addition to the physical principles of sensing employed, there are two primary alternative design variants, shown in Figure 1: 1) In-line and insertion type (ITMF) or 2) Capillary with laminar bypass design (CTMF). In the context of pneumatic applications, the immersible type design is used for larger pipe lines, typically DN15-DN300, while the capillary type is used for the measurement of smaller flow rates e.g. leakage of pneumatic components or consumption of individual actuators.

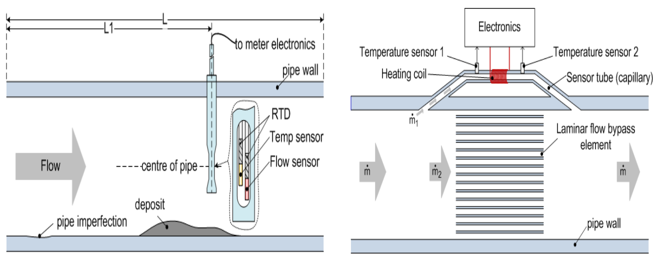

Figure 1: Immersible (left) and Capillary (right) TMF sensors.

2.2 Meter Selection

As with power meters, flow meters are available for three levels of application [2], though with slightly different functions (Table 1). Flow meter uncertainty and repeatability are given as a percentage of full scale (F.S.) or percentage of measurement value (m.v.) depending on supplier, so care must be taken in comparing the two [6]. In addition to traditional selection criteria such as uncertainty and repeatability, factors such as range, response time and bi-directional measurement capability are important considerations during the sensor selection stage, and requirements will vary depending on specific applications e.g. bi-directional measurement is only a requisite for ring main installations. The rangeability of the flow meter, referred to as turndown ratio is an important selection criteria, as outside the specified range the measurement error increases exponentially.

Monitoring level	Function
Factory	Compressors metrics
	Compressor control
Value stream (Prod. line)	Energy accounting
	Transparency of energy flows
Unit Process (Prod. Machine)	Condition monitoring
	Machine efficiency assessments

Table 1: Monitoring levels and functions for flowmeters in CAS.

The time constant of the flow meter is also an important consideration, as depending on the dynamics of process to be measured, it can lead to major systematic error if not carefully selected [7]. This is particularly relevant for production machines where a significant portion of CA demand is due to highly dynamic consumers i.e. pneumatic cylinders. The response time of a flow meter depends on fluid inertia, component inertia and electrical damping [6]. Generally the response time increases with increasing pipe measurement size. Additional selection issues include robustness, to withstand pressure, temperature, and ease of installation. A benefit of using an ITMF sensor is that it can be inserted into a pipeline, using 'hot tap' methods, without process interruption.

3 GUIDELINE FOR METERING COMPRESSED AIR IN MANUFACTURING ENVIRONMENT

3.1 Installation Issues

There are a number of factors that can significantly impact on the performance of an installed flow meter. These include orientation, condensation of moisture on temperature sensors and the variation of ambient temperature, which causes a change in gas properties. Automatic temperature compensation is included on most modern thermal mass flow meters [8]. The quality of compressed air is specified according to ISO8573 in to six quality classes for solids, water and oil contaminants. The accuracy of thermal mass based sensors is sensitive to the quality of the air. A typical example is that the measurement uncertainty is 3% m.v. for an air quality class of 1-4-1 and rises to 6% m. v. for class 3-4-4 air (5 µm particle size, 3˚C pressure dewpoint, 5 mg/m3 oil). This can be a concern, since in many factories the air is only pre-filtered at compressor station and filtered to required levels at point of use. However, the measurements of flow rate to a machine are usually made on the supply line before any further conditioning.

3.2 Reference Standards for Normalised Flow

Normalised volume flow refers to volumetric flow at a standard reference condition. The most common international standards used in pneumatics are shown in Table 2. While the reference standard employed is typically not quoted with measured flow data, incorrect assumptions as to the referencing standard can lead to an additional **3% to 80%** error due to density differences, increasing overall measurement uncertainty. Care must therefore be taken when making comparisons across flow meters using different standards. Many flow sensor suppliers offer adjustable outputs or conversion between reference conditions via software.

	ISO 6358	DIN 1343	ISO 2533
Relative humidity, %	65	0	0
Pressure, bar	1	1.01325	1.01325
Temperature, ˚C	20	0	15
Density, kg/m^3	1.185	1.292	1.225

Table 2: International Standards for reference CA conditions.

3.3 Survey of Commercial Flow Meters (Thermal Mass)

A survey of a sample of commercially available ITMF meters is shown in Table 3. The meters shown are for 1" pipe diameter, a common supply line size for many production machines. Most OEM's offer a variety of pipe sizes (typically 1/2" to 2") within a product family to cater for varying flow measurement ranges and with performance characteristics similar to those shown in Table 3. The uncertainty of a typical 'off-the-shelf' ITMF meter today is 2% m.v. within the specified range of the sensor. The uncertainty values are also quoted for the recommended air quality class. According to manufacturers literature, turndown ratios of 300:1 are not uncommon for ITMF meters. Typical response time is of order 200ms. This is usually adjustable by changing the damping settings for the meter's integrated digital filter. Power supply voltage is 12-30 VDC or 230VAC for mains supply, and all meters provide 4-20mA, 0-5/10V or pulse output options.

OEM & model	Range, NL/min*	Uncertainty, %	Repeatability, %	Response time, ms	Additional Comm. options
CS ins. VA420	8 to 4,800	1.5 m.v.	-	200	USB
Endress + Hauser Proline	25 to 2580	1.5 m.v.	0.5 m.v.	<2,000	RS485,Profibus,Modbus
Testo 6442	12 to 3,750	3 m.v.	-	100	-
VP ins. Flowmate	15 to 3,330	<0.5 F.S.	-	100	RS232
Festo SFAM-90	50 to 5000	3 m.v.	0.8 m.v.	60	-
SMC PF2A703H	150 to 3000	± 5 F.S.	± 2 F.S.	1000	-
IFM Electronic SD8000	12.5 to 3750	3 m.v.	± 1 m.v.	<100	-
Fluid Components ST75	9.9 to 3962	1 m.v.	± 0.5 m.v.	-	RS232
AZBIL MC0151	0 to 3000	± 3 F.S.	± 1 F.S.	50 to 1500	-
Bronkhorst Hitech CTA T15	10 to 5000	± 1 F.S.	± 1 F.S.	2000	RS232
M&W Mass Stream D6380	10 to 5000	± 2 F.S.	< ± 0.2 F.S.	<2000	RS232,Profibus,Modbus

Table 3: Survey of commercial inline thermal mass flowmeters -1” pipe diameter (*Reference standards vary between manufacturers).

4 CASE STUDIES

Pneumatic consumers such as linear cylinders, rotary actuators, motors and nozzles have found widespread application in manufacturing for a range of functions including automation, tooling, sealing, cooling, material removal and bearings. While compressed air is mainly used as a power source in discrete manufacturing, it is also sometimes used as a feedstock in the process industries. In addition to the core compressed air consumers in production machines, other consumers such as drain and pilot valves, and desiccant driers (purge air) also contribute to the CA system load. Compressed air demand is defined as the flow rate required by a device in operation and air consumption is the total amount of air consumed in cycle or operation. It is common practice to treat consumption, and the required flow rate of a pneumatic drive in cycle, as equivalent terms. However, for the purposes of sizing pneumatic circuits, supply lines and compressors, the distinctions between the two are important. For all consumers, the consumption is a monotonically non-decreasing function. This terminology is similar to electrical power measurement, where the power demand, measured in kW, is equivalent to CA flow and energy usage is equivalent to CA consumption. The following industrial examples are taken from two MNE manufacturing facilities in Ireland engaged in the manufacture of printer inkjet cartridges and medical device stents respectively. The combined rated power of all compressors in the two factories totals approximately 3MW. In both cases, production activity is a mix of material removal, joining and quality testing functions.

4.1 Component Air Demand

Pneumatic components can roughly be categorized into two consumer groups: passive and active based on their characteristic demand for compressed air [9]. Passive refers to those consumers with a relatively steady demand for compressed air, once activated. Such consumers include nozzles and air guns with upstream pressure regulation. Leakage is also included in this category, though if occurring at network pressure, the flow demand can be subject to fluctuations with system pressure. In general though, it is uncommon in modern factories to use compressed air at network supply pressure at the point of use. Active consumers such as linear and rotary drives, cause an unsteady flow demand. This is similar to the pulsating flow generated by piston compressors on the supply side of the system. In both cases, most flow meters are sensitive to the measurement of unsteady flow and receivers must be used to dampen the pulsations.

Industrial surveys indicate the majority of linear cylinders used in production equipment, around 90% in Figure 2, are less than 100mm in length. Cyclic rates of 100 cycles per minute (CPM) are common for such mid-size actuators [10]. The cycle time is the total time for the extension and return stroke and dwell time on each end. At an average stroke velocity of 800 mm/s, most linear actuators will have traversed the stroke in less than 200ms. This analysis also holds true for rotary type actuators. However, this is not an issue for positive displacement air motors due to their high rotational speed, which results in quasi-steady flow demand. Figure 2 also shows the characteristic demand for a linear cylinder. The cylinder consumes air, beginning when the control valve opens, until the pressure in the cylinder chamber equalizes with the supply pressure. In the case of Figure 2, this occurs in 350ms. While CTMF sensors are available with response times of 10ms, range is usually limited to 100 NL/min. It is therefore difficult to achieve high resolution in temporal and mass flow frames due to the combination of range and response sensor limitations. The installation of a receiver is also impractical for industrial measurements. An additional restriction with commercial flow meter software is a limited sampling rate of usually 1s. This means that custom data logging solutions are necessary to accurately capture the full dynamics of drive systems e.g. National instruments PXI. Due to the current economic cost of individual consumer metering and DAQ, it is mainly done for research purposes e.g. development of optimal pneumatic circuits.

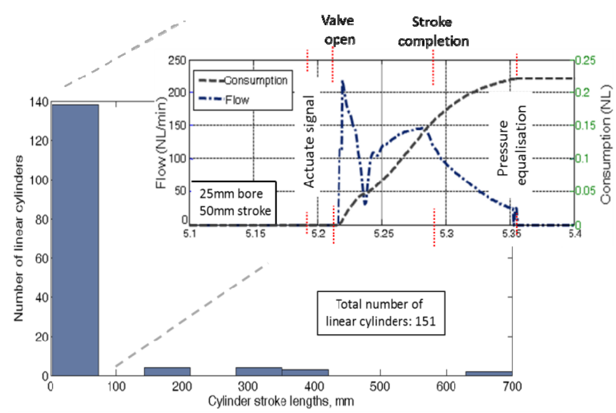

Figure 2: Cylinder stroke lengths for biomedical production line and simulated CA flow to a pneumatic linear cylinder.

4.2 Machine Air Demand

A machine consists of an assembly of CA consuming devices, with typically a mix of pneumatic drives and open jet type consumers. The majority of CA consumer devices are automatically controlled by programmable logic control (PLC) on the machine, with the exception of operator activated components such as air guns and hoists. Figure 3 shows the measured compressed air flow demand for a typical production cycle. The measurement point was the supply line to the machine and the sampling rate for the data logging software was 2Hz, the maximum possible. The compressed air demand due to air nozzles and knifes used in cleaning and drying purposes can be seen at the start of the cycle. When the machine is in 'ready for production' state, the flow demand due to leakage is also visible. While in theory, pneumatic devices do not consume energy when holding position, in practise due to poor maintenance and/or lack of detection tools, the air demand due to leakage can account for up to 30% of overall consumption. These losses are equivalent to the idle power draw of electrical consumers. It can also be seen from the figure that continued use of air nozzles during machine idling is a large (and common) source of waste. In addition to leakage flow during idle states some pneumatic consumers, such as nozzle flapper actuated process valves, have static demand when not in use. Therefore care must be taken when assigning losses based on idle demand rates. Another experience from industrial investigations is that the compressed air requirements of production machines are often not clear from OEM documentation. For example it is not usually stated whether the specified air flow requirements represent peak or average demand, or additionally what air reference conditions or ISO standard is being utilised. The methods for determining such air requirements are also not provided. In the case of Figure 3, the specified flow demand for the machine appears larger than necessary. These issues can obviously lead to a large amount of uncertainty in the air supply sizing process. However, as highlighted in the preceding section, the direct measurement of CA demand for production machines may not be possible with sufficient accuracy. The uncertainty of the measurement is influenced by the breakdown between active and passive consumption for a machine. In the case of machine tools for example, where the main pneumatic components (air bearings, sealing control cabinets, cooling or chip removal) are characteristically steady state consumers, the CA requirements can be directly measured. However, for highly automated processes, such as assembly, where active consumers represent a significant portion of CA demand, model based approaches are recommended.

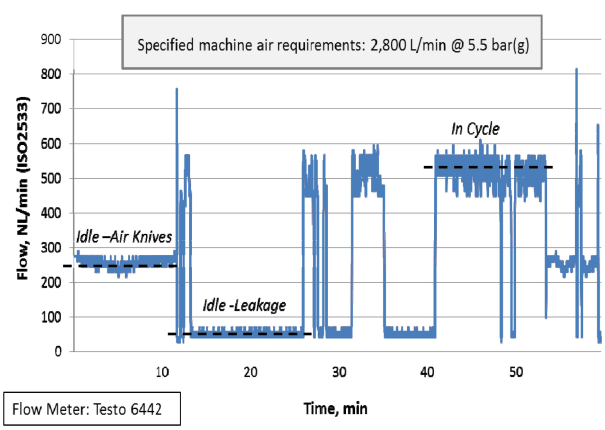

Figure 3: Compressed air demand profile for inkjet automated assembly machine.

4.3 Factory Air Demand

The measurement of factory CA demand is done at the supply side of the system and usually after air treatment (drying/purification). Figure 4 shows the result of an industrial survey detailing the flow capacity of the factory's compressors, and both average and peak demand over a year. It is clear from the figure, that there is large excess capacity built into the factory's CA system. This is in-part to ensure redundancy. The back-up capacity ensures no disruption to production and factory output during periods of planned or unplanned maintenance. If the CA system is managed in an optimal manner, the additional compressors are shutdown when not in use. However, it can be seen in the figure, when considering only online compressors, the required CA demand is still significantly less than available capacity. This oversizing negatively impacts the energy efficiency of the system, as larger compressors obviously require large prime movers i.e. electric motors. One of the factors underlying the oversizing of CA generators is the lack of knowledge regarding machine CA demand, and the larger-than-necessary flow demand requirements specified by machine developers. It would therefore be useful for a standardised approach for testing and specification of production machine CA requirements in order to aid end users in minimising compressor size. In addition to understand the scale/size of CA demand, it is also important to understand the type of demand i.e. fluctuating or steady. For example, since the specific power of variable speed drive (VSD) compressors is greater than equivalent fixed speed units, it only makes sense to install VSD's when the load ratio of the system is below a certain threshold, typically given as 70%. A common configuration therefore allows for a combination of fixed speed compressors for base load loads demands, and variable speed for fluctuating. One novel concept arising from the industrial investigations could be to use the excess compressor capacity, with additional storage, to schedule the CA generation, such that electrical power demand is weighted toward off-peak times with lower energy tariffs. Since major excess capacity is a practical reality in most industrial facilities, and cost of production likely to outweigh energy considerations for some time to come, this method could be a useful way of reducing electrical energy bills without the complexity of production scheduling. This may be applicable where multi-rate tariffs are available or to avoid penalties due to peak electricity use.

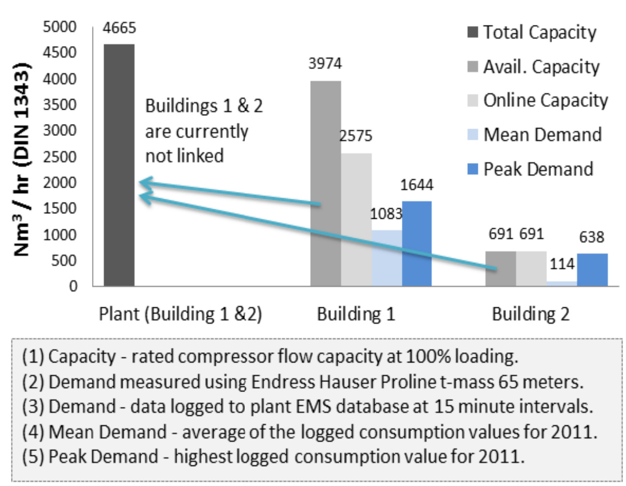

Figure 4: Compressed air capacity and demand for biomedical manufacturing facility.

5 ENERGY EFFICIENCY

5.1 Electrical Energy Usage

The electrical energy consumed in the generation of compressed air for production machines can be easily measured using power meters. It is important to also consider the electrical energy usage of refrigerant driers and pumps for external cooling circulation where applicable. If the compressor and after-cooler are air-cooled, the electric fan usage will be captured along with usage due to air end compression. If combined with flow measurements, the specific power of the system can be assessed. The theoretical lower limits for specific power are shown in Table 4 for range of common factory pressure levels. The isentropic efficiency of modern twin-screw rotary air compressor is around 90% [11]. It is important to note that compressors attain their highest efficiency, in terms of specific power, at the rated design point. While capacity control strategies for part-load conditions such as 'unload' or variable speed reduce power demand, they also reduce the efficiency of generation. An average specific power figure can be used to determine the compressor power attributable to the air demand of a particular machine.

Pressure, bar(g)	**Adiabatic specific power,** kW/(Nm3/min)	**Isothermal specific power,** kW/(Nm^3/min)
7	4.73	3.46
8	5.10	3.66
9	5.44	3.83
10	5.75	3.99

Table 4: Minimum specific power requirements for common factory supply pressures (ISO6358 reference conditions).

5.2 Efficiency Assessments

It is widely stated in the literature that the energy efficiency of compressed air systems is low, but the methods for determining energy losses are often unclear and the potential gains from utilizing best practice and leading edge technology unknown. The first law energy efficiency definition applied to a compression process is given by equation 1, see Bader et al [12] for derivation and further details. Where η1 is energy efficiency, $\dot{W}$elec is electric power, $\dot{m}$ is mass flow, Cp is specific heat at constant pressure for air, T is temperature and $\dot{Q}$ is heat recoverable.

$$\eta_1 = \frac{\dot{m}C_p\,(T_2-T_1)+\dot{Q}_{rec}}{\dot{W}_{elec}} \quad (1)$$

Since the air is cooled to near ambient temperature (T1=T2), the efficiency according to eq. 1 is then totally dependent on the amount of heat recovered. If no heat is recovered, the compression process is then 0% efficient. However, if 100% heat is recovered, as is possible with latest compressor heat recovery technology under certain operating conditions, and utilised, the efficiency increases to 100%. The first law definition of energy efficiency is evidently inadequate for assessing compressed air systems as it does not consider the large amount of potential work available in the pressurised gas. An exergy based approach is therefore required and the exergy efficiency can be determined using equation 2 where P is pressure.

$$\eta_2 = \frac{\dot{m}C_p\,(T_2-T_1)+\dot{m}T_0\left[R\ln\left(\frac{P_2}{P_1}\right)-C_p\ln\left(\frac{T_2}{T_1}\right)\right]+\dot{Q}(1-\left(\frac{T_0}{T_s}\right))}{\dot{W}_{elec}} \quad (2)$$

Note the last term in the numerator of equation 2 accounts for the fact that heat is a disorganised energy, of which only a fraction is recoverable e.g. via a heat engine, and can be converted to do useful work. A simplified version of the numerator in equation 2 can also be used to determine the air power of a flowing stream of compressed air, downstream of generation and treatment [13]. Using this type of approach the exergy efficiency of the basic compression process, and aftercooler, process has been estimated to between 46% to 53% for typical manufacturing compressor conditions [12,14]. However, even with reduced energy consumption during unloading, the exergy efficiency of the compression process drops significantly during this (idle) state because no useful exergy is generated. The reduction in efficiency will depend in the type of part-load capacity control employed. In the case of [12] a load ratio of 33% resulted in 50% decrease in exergy efficiency. An estimated optimal exergy efficiency of 60% is attainable with properly sized compressors, minimal leaks and the use of heat recovery. The exergy losses in CA treatment, storage and distribution are mainly due to pressure drop across components and pipelines, and can account for efficiency reduction of up to 14% [14].

From a production engineering perspective, the efficiency of the end-use side of the compressed air system or pneumatic consumers is directly influenced in the machine design stage. At this point in the system, it is mainly the device conversion efficiency which is of relevance. In order to clarify the different exergy efficiency levels, it is proposed that when discussing compressed air efficiency, three main definitions are used, see Table 5. Electrical power input includes all relevant electrical energy inflows to the system i.e. compressor, drier, pump, fans.

Efficiency level	**Definition**	**Typical values**
Consumer (η_{con})	Mechanical power output/ Air power in	1 - 75%
Support system (η_{sps})	Air power at point of use / Electrical power input	20% - 60%
Overall system ($\eta_{sy} = \eta_{sps} * \eta_{con}$)	Power output/ Electrical power input	<1% - 45%

Table 5: Exergy efficiency definitions for compressed air systems.

Traditional pneumatic consumers used in manufacturing have relatively low conversion efficiencies. Linear cylinders have an estimated exergy efficiency of 14% [15]. The use of compressed air nozzles for cleaning at relatively low pressure also leads to considerable exergy destruction of high quality air. Pressure regulators decrease the air power by 40%, when reducing pressure from 6 bar(g) to 2 bar (g) for example. Such low conversion efficiency at a device level drastically reduces the exergy efficiency of the overall system. It is therefore essential to maximize the use of expansion energy of compressed air. Recent research efforts to achieve this, for example with pulsed nozzles, actuators with inter-chamber crossflow and scroll motors, has been reviewed in [16]. In the case of production tools with mainly low pressure consumers, a low pressure compressor, either centrally or locally located, would help improve exergy efficiency.

In terms of energy efficiency comparisons, it is clear that in general the energy efficiency is less than that of electric drive motors whose exergy efficiency (η2) is around 85% in the small power range, since pneumatic actuators are generally used for moving small loads. However, electric actuators have additional energy requirements that must also be considered: Controllers, brakes and cooling requirements, which are particularly onerous e.g. in the case of high power spindles. The efficiency of the entire electric system including supporting components also needs to be considered. Two other points may favour pneumatic technology from an energy perspective: 1. for low actuation rates Cai et al [13] has shown that pneumatic actuation is more efficient as it does not require continuous holding energy. 2. For very fast machining processes, air motors offer very high rotational speeds and are self-cooling. A number of authors have shown that increased material removal rate can also lead to decreased specific energy on a per part basis. Further research is required to allow for a holistic comparison of the technologies. The above discussion does not consider additional selection criteria such as overall life cycle costs and environmental impact, which will obviously impact design decisions. In fact it is also reasonable to propose that pneumatic technology is generally used for reasons other than energy efficiency, therefore its continued improvement is essential for improving overall factory energy performance.

5.3 Optimisation Approaches

Previous energy assessments of CA systems have focused on the inefficiencies in the supply and distribution sub-systems. However, the exergy approach shows that in many cases, the major limiting factors for efficiency of the system are compressor over-sizing, and the low conversion efficiency of pneumatic consumers. Both of these factors are directly influenced in the development stage of production machines. Additionally, many of the best practice guides overestimate savings due to reduction of inlet temperature and/or outlet pressure reduction at the compressor. In particular while low grade heat recovery offers good potential energy savings, its applicability in manufacturing is often limited due to the lack of available heat sink. The exergy approach illustrates, that the focus for improving energy efficiency in compressed air systems should not just be limited to the supporting infrastructure, but should also consider the impact of end-use production machines and devices.

6 SUMMARY AND OUTLOOK

There are a number of issues that inhibit the uptake of flow meters in the industrial context including substantial cost, non-interruption in 24/7 production environments and quality/verification issues in highly regulated biomedical and pharmaceutical facilities. Nevertheless, due to a growing awareness of the energy costs of compressed air, there is a general trend toward their adoption in order to improve consumption visibility and identify waste. Practical experience within industrial facilities suggests that flow meter performance parameters and flow referencing standards are poorly understood or overlooked. Future meters for compressed air systems may allow for the integration of multiple sensors and data fusion, to allow exergy assessments and advanced condition monitoring. In terms of energy, this paper has highlighted the merits of an exergy analysis approach to determining CA system efficiency, and detailed the considerable efficiency improvements that can be made with the engagement of production machine developers. Finally, some potential areas for future research have also been highlighted and include:

Holistic comparisons of energy use for alternative power transmission technology in production machines.

Standardised approach for the determination and presentation of production machine air flow requirements.

Further investigation of potential use of excess compressor capacity to shift factory electrical load via storage, with a view to application in the MNE context.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

[1] Hesselbach J, Herrmann C, Detzer R, Martin L, Thiede S, Ludemann B Energy efficiency through optimised coordination of production and technical building services. In: 15th CIRP Conference on Life Cycle Engineering, Sydney, Australia 2008.

[2] Kara S, Bogdanski G, Li W (2011) Electricity Metering and Monitoring in Manufacturing Systems. In: 18th CIRP International Conference on Life Cycle Engineering, Braunschweig, Germany, May 2nd-4th 2011.

[3] O'Driscoll E, O'Donnell GE (2013) Industrial power and energy metering - a state-of-the-art review. Journal of Cleaner Production 41 (0):53-64.

[4] Radgen P, Blaustein E (2001) Compressed Air Systems in the European Union: Energy, Emissions, Savings Potential and Policy Actions. Fraunhofer ISI, Stuttgart.

[5] Nguyen NT (1997) Micromachined flow sensors - a review. Flow Measurement and Instrumentation 8 (1):7-16.

[6] Baker RC (2000) Flow Measurement Handbook: Industrial Designs, Operating Principles, Performance, and Applications Cambridge University Press, Cambridge, UK

[7] Sosna C, Walter T, Lang W (2011) Response time of thermal flow sensors with air as fluid. Sensors and Actuators A: Physical 172 (1):15-20.

[8] Olin JG (1999) Industrial Thermal Mass Flowmeters. Measurements & Control (193).

[9] Harris P, O'Donnell GE, Whelan T (2012) Predictive Consumption Models for Electropneumatic Production Systems. IEEE/ASME Transactions on Mechatronics PP (99):1-8.

[10] Fleischer H (1995) Manual of Pneumatic Systems Optimisation. McGraw-Hill, New York, NY.

[11] Barber A (1997) Pneumatic Handbook. 8th edn. Elsevier Advanced Technology, Oxford, UK.

[12] Bader WT, Kissock JK Exergy Analysis of Industrial Air Compression. In: 22nd National Industrial Energy Technology Conference, Houston, TX, April 5-6 2000.

[13] Cai M, Kagawa T, Kawashima K Energy conversion mechanics and power evaluation of compressible fluid in pneumatic actuator systems. In: 37th Intersociety Energy Conversion Engineering Conference (IECEC), 2002. pp 438-443.

[14] Krichel S, Hulsmann S, Hirzel S, Elsland R, Sawodny O (2012) Mehr Klarheit bei der Druckluft. O+P Ölhydraulik und Pneumatik (1-2):28-32.

[15] Eret P, Harris C, De Lasa T, Meskell C, O'Donnell GE Industrial Compressed Air Usage - Two Case Studies. In: 7th International Fluid Power Conference, Aachen, Germany, 22-24 March 2010. pp 355-366.

[16] Harris P, O'Donnell GE, Whelan T Energy efficiency in pneumatic production systems: state of the art and future directions. In: Proceedings of the 19th CIRP Conference on Life Cycle Engineering, University of California, Berkeley, California, USA, May 23-25 2012.

Benchmark of Existing Energy Conversion Efficiency Definitions for Pneumatic Vacuum Generators

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Abstract

To offer an ideal design solution for vacuum handling systems, taking energetic aspects into account is essential. Therefore the energy conversion efficiency has become a commonly used parameter for describing the efficiency a system. In Literature there are already a few definitions of the energy conversion efficiency of de Laval nozzles respectively pneumatic vacuum generators. This paper shows a benchmark of the existing energy conversion efficiency definitions with respect to vacuum handling, the practical usage in industry and the possibility for comparison with other generation forms. In the end, an approach for a generally applicable exergy based definition is given. In addition, the measurement of an example vacuum system is shown and analyzed.

Keywords:

Energy conversion efficiency; vacuum generator; ejector; venturi nozzle

1 INTRODUCTION

1.1 Motivation

Due to rising energy costs [1], benchmarking through carbon footprint and an increasing social demand for sustainable orientation of companies, efficient energy usage is a more and more important issue for producing companies [2]. The strategic roadmap leads from energy efficient products towards energy efficient production. In this process especially the selection of appropriate components for production but also the right system design plays a central role. In the European Union (EU) 10 % of the industrial used electrical energy is allocated to compressed air generation [3]. Therefore, the energy efficiency of pneumatic components is an important issue in the development of sustainable and efficient manufacturing processes. At the moment an increasing trend of substitution of pneumatic components with electrical components is recognizable. The reason is that compressed air generation is generally assumed to be very inefficient and thus an expensive energy form [3]. Latest investigations refute this claim partially, however [4].

Harris et al. [5] investigated the state of the art of energy efficiency in pneumatics and gives a detailed statement about possible energy saving potentials in manufacturing. To improve energy efficiency of pneumatic systems a detailed knowledge of the dynamic behavior of a component during the process is needed [6].

1.2 Vacuum Handling

Efficient usage of energy in vacuum handling technology is also an important topic, as it is often a non-value-added process [7]. For vacuum handling negative pressure is generated to grip objects [8]. For that purpose, an active vacuum generator is mostly necessary. This can be done either electrically or pneumatically. The pneumatic vacuum generation usually uses the Venturi effect. Compressed air is admitted to a convergent-divergent nozzle, also called Venturi or de Laval nozzle, to generate a lower static pressure level at the end of the nozzle than the ambient pressure level, which causes a suction effect. These vacuum generators are also called ejectors and they are often used for vacuum handling systems. Because of their little weight they can be mounted directly on the end of arm tooling and they are very wear-resistant.

1.3 Aim of Investigation

Because of tightening environmental regulations and rising energy costs, energy assessment of different concepts during the design phase of pneumatic systems is essential. To offer an energy optimal solution with regards to the respective requirements, a method shall be developed to measure the energy consumption of an ejector and suction cups systematically and as easy as possible. Hereby, the direct comparison of competing solutions with respect to energy consumption in industrial applications shall be enabled. Within this investigation, existing approaches for description of energy consumption and energy conversion efficiency of pneumatic vacuum generators (ejectors) are gathered and examined regarding their applicability to compare energetically with other components. For selection of the method the comparison with other handling systems e.g. electrical-driven components is decisive.

Based on the results of the investigation an appropriate method is chosen and if necessary modified for the current application. Thereby, especially the applicability in practice is taken into account.

2 STATE OF THE ART

2.1 Energy Conversion Efficiency

Energy efficiency is defined by Müller et al. [9] as the ratio of utility to energy input for a specific task. The goal is to achieve as much as possible utility out of the inputted energy respectively to need as less as possible energy input for a certain task.

$$\text{enegy efficiency} = \frac{\text{utility}}{\text{energy input}} \tag{1}$$

For description of the efficiency a process converts energy or power into another energy form, the energy conversion efficiency has established. Usually the energy conversion efficiency is defined as the relation of desired output power to total input power.

$$\eta = \frac{P_{out}}{P_{in}} \tag{2}$$

The difference between input and output power is defined as power loss.

In more complex systems a comparison of alternative processes or technologies is difficult, because balance boundaries for a direct comparison of energy consumption cannot be determined. For example, if a lifting procedure, which can be realized both electrically and pneumatically, shall be assessed energetically to estimate the energy costs for that lifting process, the system boundaries have to be defined in a way, that comparable processes are formed. Therefore the electrical energy, which is inputted on the beginning of the process, is a suitable base. For a pneumatic process, the energy input of the air compressor is taken into account and set into relation with the required energy used for the handling process. In practice it is not possible to assign the energy consumption of single consumers directly to the electrical energy input used for the system of the compressed air supply network. Accordingly, the energy conversion efficiency of every component along the process chain has to be determined. With these energy conversion efficiencies the energy loss for every component up to the lifting process can be determined.

2.2 Power Determination in Pneumatics: The First Law of Thermodynamics

Most of the technical systems in pneumatics can be assumed as open systems. Open systems allow inputting and outputting mass and energy throughout the system boundaries during a change of state. For a general, energetic consideration of open systems, which the ejector belongs to, an energy balancing equation for a control volume shall be set up. For the description the first law of thermodynamics for a steady flow is used. The first law states that the energy of a closed system remains unchanged. Different energy forms can solely transform into another, but energy can neither be created nor destroyed [10]. With the simplifying consideration of steady flows follows that the mass flow is not only over time constant but also constant in every flow cross-section regarding to the law of conservation of mass. This is also valid for the amount of entering and exiting mass flows m_{in} and m_{out} of a control volume. Consequently, the depending state variables are also constant. The equation of the first law of thermodynamics for steady flows is shown in Eq. (3). The heat flow, which emits over the system boundary, is named $\dot{Q}$. P marks the mechanical power which enters the system over the system boundary. The specific power, which is entering the system by the fluid, is displayed on the right side of the equation by the summation of the specific energy portions, consisting of the enthalpy *h*, the kinetic energy and the elevation energy and is multiplied by the mass flow.

$$\dot{Q} + P = \sum_{out} \dot{m}_o \left(h + \frac{c^2}{2} + gz\right)_o - \sum_{in} \dot{m}_i \left(h + \frac{c^2}{2} + gz\right)_i \tag{3}$$

The enthalpy is composed of the internal energy of the fluid and the work done by the system on its surroundings, $p \cdot v$. Since there is no crucial height difference on the ejectors, the elevation energy can be neglected. Furthermore the components can be assumed in good approximation as adiabatic, thus the heat flow over the system boundary can be neglected. Besides the measurement of the heat flow seems to be impracticable. Hence it follows the simplified Eq. (4).

$$P = \sum_{out} \dot{m}_o \left(h + \frac{c^2}{2}\right)_o - \sum_{in} \dot{m}_i \left(h + \frac{c^2}{2}\right)_i \tag{4}$$

As the main application field of ejectors and suction cups is in vacuum handling, there are lower temperature changes to be expected than in refrigeration technology (where Venturi nozzles are also used). This allows a simplified description of the equation of state with ideal gas equation instead of real gas equation, which makes it more usable in practice. As a result the specific enthalpy h from Eq. (4) can be described with the ideal gas law in Eq. (5). It solely depends on the temperature, because the calculation of the enthalpy difference with the isobaric heat capacity is also valid for different pressures. Due to the low temperature change, it can be calculated with a constant c_p. The calculation of the isochoric heat capacity c_v can be done with $c_p = c_p + R$.

$$h(t) = u + pv = u(T) + RT = c_p T + u_0 + RT \tag{5}$$

To get a complete description in dependency of measured variables, the flow velocity c has to be determined. Based on the law of conservation of mass, for every flow cross-section with constant pressure and constant temperature of a steady flow, the flow velocity can be determined as follows:

$$\dot{m} = c \cdot \rho \cdot A = c \cdot \frac{p}{RT} A \Leftrightarrow c = \frac{\dot{m}RT}{p} \tag{6}$$

Thereby all necessary variables for the power balancing can be determined by measurements. In summary the power balancing used for a common referencing point results in:

$$P = \sum_{out} \dot{m}_o \left(c_v T + RT + \frac{1}{2}\left(\frac{\dot{m}_o RT}{p}\right)^2\right)_o - \sum_{in} \dot{m}_i \left(c_v T + RT + \frac{1}{2}\left(\frac{\dot{m}_i RT}{p}\right)^2\right)_i \tag{7}$$

2.3 Application of the First Law to a Vacuum Ejector

A vacuum ejector is an open system and can be described with Eq. (7). Energy and mass is inputted by the inlet connection. Depending on the state of the ejector mass is also led in through the vacuum port. Both mass flows are merged in the mixing chamber and exit through the outlet into the surroundings.

Obviously, direct application of Eq. (7) to vacuum ejectors is not practicable, because the ejector has no interface for output of mechanical power. Therefore, direct application of the first law of thermodynamics to an ejector with the system boundary showed in Fig. 1 is not suitable for determination of the energy conversion efficiency.

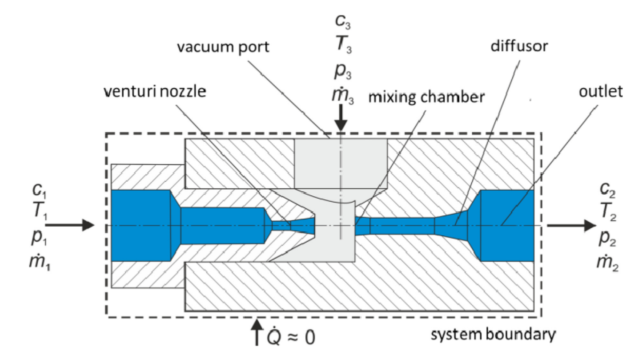

Figure 1: Composition and system boundary of an ejector.

To create a possibility for energy conversion efficiency determination, it is necessary to find substitution models for describing the mechanical equivalent power.

3 ENERGY CONVERSION EFFICIENCIES OF EJECTORS

3.1 Assessment of Existing Energy Conversion Efficiency Definitions

Especially for ejectors in the field of refrigeration technology there are several different definitions of the energy conversion efficiency. These are shown below and assessed for their application to vacuum ejectors. In addition to the applicability, it has to be ensured that the measurement of the physical variables is feasible. In theoretical investigations the energy conversion efficiencies are often defined with the energy conversion efficiencies of the single components like venturi nozzle, mixing chamber and diffusor as well as the flow processes in between [11] [12]. A metrological acquisition of these energy conversion efficiency variables is impossible in practice, which is why they are not considered in this investigation.

In literature there are a few energy conversion efficiency definitions for application to ejectors in refrigeration systems that are only valid under certain assumptions. Thus, in some cases the compression of the vacuum flow is assumed to be isothermal [13].

For vacuum ejectors the company Festo has defined a practice-orientated energy conversion efficiency [14]. For the calculation the evacuation time multiplied with the normed compressed air consumption is set into relation with the volume to be evacuated and used as follows:

$$\eta(\Delta p)=\frac{1}{1+\frac{t(\Delta p)\cdot Q_N}{V\cdot 60s/min}} \quad (8)$$

An example diagram of the energy conversion efficiency against the pressure difference is shown in Fig. 2.

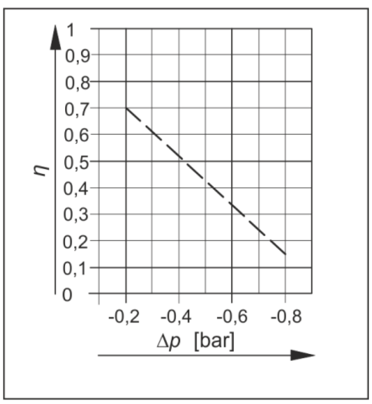

Figure 2: Energy conversion efficiency for ejectors by Festo [14].

This energy conversion efficiency definition is useful for comparison of different ejectors in a certain application. But a general statement about the energy requirement cannot be given. In addition the volume to be evacuated can be chosen arbitrarily but influences the energy conversion efficiency enormously.

Another widely-used definition, which is described in literature as very purposive [15], makes the ratio of the input power of the suction medium in relation to the outlet pressure divided by the input power of the compressed air on the inlet of the venturi nozzle also in relation to the outlet pressure.

$$\eta=\frac{P_{32}}{P_{12}} \quad (9)$$

Because the kind of the state change within the ejector is unproven and difficult to predicate, in many cases an isentropic state change is assumed. An advantage of this method is that the flow state within the ejector doesn't have to be known. Therefore, all relevant flow variables can be determined within the connection ports of the ejector. Like it is shown above, a direct power determination is not possible. Instead a corresponding model is used [16] [17]. The corresponding model, as shown in Fig. 3, consists of a turbine, on which the inlet flow relaxes to outlet pressure and a compressor, which compresses the vacuum flow to the outlet pressure. In this model it is assumed that the power P of the turbine is completely transformed by the compressor without losses.

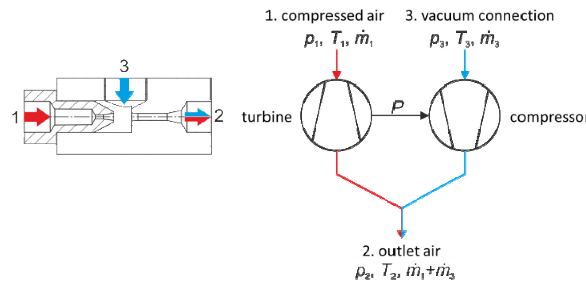

Figure 3: Corresponding model.

The specific work, which is outputted by the turbine in an isentropic state change with κ = 1.4, is given in Eq. (10) and can be determined with the first law of thermodynamics.

$$w_{12}=\kappa\frac{p_1 v_1}{\kappa-1}\left(\left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}}-1\right)=\frac{\kappa}{\kappa-1}RT_1\left(\left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}}-1\right) \quad (10)$$

Equation (10) is also valid for the compression from state 3 to 2 with substitution of the concerning indices. With known mass flows at the connections 1 and 2 the energy conversion efficiency of an ejector results in:

$$\eta_{ejector}=\frac{\dot{m}_3}{\dot{m}_1}\cdot\frac{w_{32}}{w_{12}}=\frac{\dot{m}_3}{\dot{m}_1}\cdot\frac{T_3\left(\left(\frac{p_2}{p_3}\right)^{\frac{\kappa-1}{\kappa}}-1\right)}{T_1\left(\left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}}-1\right)} \quad (11)$$

With the energy conversion efficiency of Eq. (11) an example of a characteristic diagram of an ejector as in Fig. 4 can be determined.

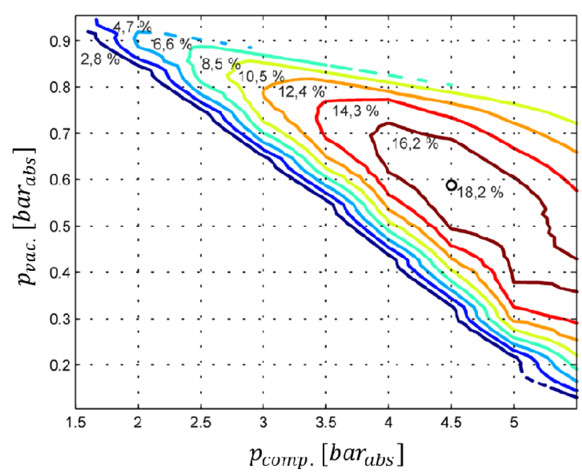

Figure 4: Characteristic energy conversion efficiency diagram of an ejector.

As mentioned before, in this definition, like in many others, it is assumed that the flow within the nozzle is isentropic [18]. Indeed this can be assumed with good approximation, however, in literature an energy conversion efficiency of the venturi nozzle of 92 to 99 % is given [19] [15]. The energy conversion efficiency is calculated by the ratio of the real enthalpy change of the entire enthalpy h_{i0} of the unaccelerated flow before the nozzle and the highly accelerated flow on the exit of the nozzle h_i to an equivalent isentropic process. The energy released by the decrease of enthalpy is transformed according to the first law of thermodynamics into kinetic energy. Hence, the exit velocity of the venturi nozzle u_1 in relation to the theoretical exit velocity $u_{1,\mathrm{isen}}$ can be determined as follows:

$$\eta_{\mathrm{nozzle}} = \frac{h_{10} - h_1}{h_{10} - h_{1,\mathrm{isen}}} = \frac{u_1^2}{u_{1,\mathrm{isen}}^2} \tag{12}$$

Thus, for a physically based, as precisely as possible definition of the energy conversion efficiency of ejectors the assumption of isentropic state change is not reasonable. An alternative that is independent of the state change has to be found.

3.2 Exergetic Approach of Conversion Efficiency Definition for Vacuum Ejectors

With introduction of exergy the problem of assumption of different state changes which the correspondent model uses, can be avoided. This advantage is originated in the definition of exergy. In contrast to energy balancing not two arbitrary states like the energy difference between the venturi nozzle and the air outlet are compared. For exergy the reference is ambient condition by definition. Baehr [10] defines the exergy and anergy as follows: “exergy is energy which can be completely transformed into any other energy form with contribution of certain ambient conditions. Anergy is energy, which is not transformable into exergy. The exergy of an energy form is the maximal producible work of this energy under certain ambient conditions.” That means in all reversible processes the amount of exergy of the participating energy sources stays the same. The conversion from anergy into exergy is impossible [10]. Because the exergy is characterized as the maximum useful work, it follows that the surrounding itself has to be in thermodynamic equilibrium to fulfill the demand of an exergyless reference state. For the surroundings only the temperature is defined by ISO 6358 [20] with the technical standard reference conditions of T_0 = 293.15 K. The ambient pressure p_0 is determined by measurement, because it influences the suction behavior of the ejector.

Calculation of Exergy

For determination of an exergetic conversion efficiency of fluid-flow machines, the description of physical exergy of a fluid flow is of great importance. Which is why below the consideration is limited to this. From the definition above follows, that in a nonreversible state change a part of the exergy is transformed into anergy. To detect this part quantitatively and thus enable the allocation of energy to anergy and exergy, the entropy S has been established in thermodynamics. The entropy allows a quantitative statement about the grade of irreversibility of a process. For example, the transformation of electric energy into heat is simple to realize. The reversion of this process from heat into electric energy isn’t directly possible. This unsymmetrical behavior is considered in the second law of thermodynamics. The entropy balancing equation is given in Eq. (13). Detailed explanations of entropy and its application in thermodynamics are given in further literature [10] [21].

$$\frac{dS}{dt} = \dot{S}_Q(t) + \dot{S}_{\mathrm{irr}}(t) = 0 \tag{13}$$

The calculation of specific entropy change of an ideal gas is done with Eq. (14) [21].

$$s^{\mathrm{ig}}(T_2,p_2) - s^{\mathrm{ig}}(T_1,p_1) = \int_1^2 \left(\frac{1}{T}du + \frac{p}{T}dv\right)$$
$$= \int_1^2 \left(\frac{1}{T}dh + \frac{v}{T}dp\right) = \int_1^2 \frac{c_p^{\mathrm{ig}}}{T}dT - R \cdot \ln\frac{p_2}{p_1} \tag{14}$$

The exergy of a fluid flow can be determined with application of the first and second law of thermodynamics (derivation given in [10]). With respect to the surroundings and the kinetic energy, the specific exergy e of a fluid flow results in Eq. (14).

$$e = h - h_0 - T_0(s - s_0) + \frac{1}{2}c^2 \tag{15}$$

In Fig. 5 the non-dimensional exergy $\varepsilon^* = E/(mRT)$ is plotted against the temperature ratio and the pressure ratio with neglect of kinetic energy.

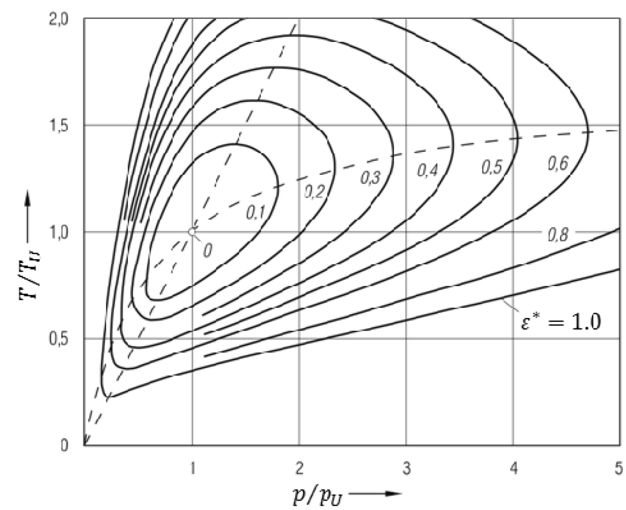

Figure 5: Lines with constant exergy ε^* [10].

Figure 5 shows that the exergy is also clearly defined for the vacuum range where $p/p_U<1$.

To get a formula with measurable variables, Eq. (15) can be transformed into:

$$e(T,p) = (T - T_0) \cdot c_p^{\mathrm{ig}} \cdot \ln\frac{T}{T_0} + T_0 R \cdot \ln\frac{p}{p_0} + \frac{1}{2}c^2 \tag{16}$$

With known mass flow and flow cross-section, the velocity *c* can also be determined with temperature and pressure under the assumption of an ideal gas. In extensive form the exergy of a mass flow is calculated as follows:

$$\dot{E}(T,p) = \dot{m}\left[(T - T_0) \cdot c_p^{\mathrm{ig}} - T_0 \cdot c_p^{\mathrm{ig}} \cdot \ln\frac{T}{T_T} + T_0 R \cdot \ln\frac{p}{p_0} + \frac{1}{2}\left(\frac{\dot{m}RT}{pA}\right)^2\right] \tag{17}$$

Exergetic Conversion Efficiency of a Vacuum Ejector

The exergetic conversion efficiency in thermodynamics is generally defined as the ratio of output exergy to input exergy [21].

$$\zeta = \frac{\dot{E}_{out}}{\dot{E}_{in}} \quad (18)$$

For jet pumps there is another conversion efficiency definition found in literature [22], because there the requested process variable is on the outlet (2) of Fig. 3:

$$\zeta_{\text{jet pump}} = \frac{\dot{E}_2}{\dot{E}_1+\dot{E}_3} \quad (19)$$

This definition, however, is inappropriate for vacuum ejectors, because there a medium on the vacuum connection is compressed.

If Eq. (18) is applied to the ejector of Fig. 3, the input exergy comes from connection (1). The exergy output is the vacuum flow, which is sucked in at connection (3), as the vacuum is the desired state. Because a typical vacuum ejector boosts the outlet air directly into the surrounding, the outlet air is in equilibrium with the surrounding and therefore it is pure anergy. It follows from Eq. (5) that the conversion efficiency of a vacuum ejector is:

$$\zeta = \frac{\dot{E}_3}{\dot{E}_1}$$

$$\zeta = \frac{\dot{m}_3\left[\left(T_3 - T_0\right) \cdot c_p^{ig} - T_0 \cdot c_p^{ig} \cdot \ln\frac{T_3}{T_0} + T_0 R \cdot \ln\frac{p_0}{p_3} + \frac{1}{2}\left(\frac{\dot{m}_3 R T_3}{p_3 A_3}\right)^2\right]}{\dot{m}_1\left[\left(T_1 - T_0\right) \cdot c_p^{ig} - T_0 \cdot c_p^{ig} \cdot \ln\frac{T_1}{T_0} + T_0 R \cdot \ln\frac{p_1}{p_0} + \frac{1}{2}\left(\frac{\dot{m}_1 R T_1}{p_1 A_1}\right)^2\right]} \quad (19)$$

With this formula a complete exergetic conversion efficiency description of an ejector with simple measurable variables is possible.

Example of Exergetic Conversion Efficiencies of an Ejector

With the definition of Eq. (19) a sample ejector can be measured and calculated. For that reason an ejector was equipped with different sensors on the supply and vacuum connection to measure all the variables needed to calculate the exergetic conversion efficiency. The ejector was admitted with different supply pressures from 3 to 5 bar relative. The exergetic conversion efficiency is plotted against the produced vacuum level as shown in Fig. 6.

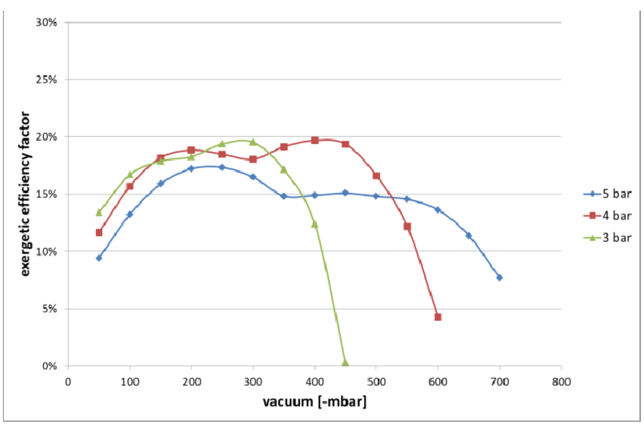

Figure 6: Exergetic conversion efficiency diagram for different supply pressures.

As it can be seen in the figure, for this ejector a maximum exergetic conversion efficiency of ca. 20 % can be reached.

4 SUMMARY

In this benchmark literature was investigated for existing energy conversion efficiency definitions and their applicability to vacuum ejectors. It became apparent that the existing definitions have several constraints. This is originated from the application of these definitions in the field of refrigeration technology where other assumptions are given. To these assumptions belongs the isentropic state change, which is only valid for special ejectors and under special boundary conditions. To get a conversion efficiency definition which is on the one hand easy to measure and on the other hand independent of the kind of state change, the exergetic conversion efficiency was defined.

With the help of this conversion efficiency, now the operating point of highest efficiency of an ejector can be determined. If this point is known, a vacuum handling system can then be designed that way that the ejector is mostly working in this operation point. This helps to increase the energy efficiency of the whole handling system.

5 REFERENCES

[1] German Federal Statistical Office: Daten zur Energiepreisentwicklung, www.destatis.de, 2012-11-72.

[2] Duflou, J.R.; Sutherland, J.W.; Dornfeld, D; at al. (2012): Towards energy and resource efficient manufacturing: A processes and systems approach, In: CIRP Annals - Manufacturing Technology, Elsevier Ltd., Volume 61, Issue 2, pp. 587-609.

[3] Radgen, P.; Blaustein, E. (2001): Compressed Air Systems in the European Union: Energy, Emissions, Savings Potential and Policy Actions. Fraunhofer ISI, Stuttgart.

[4] Kirchel, S. et al. (2012): Exergy Flow Diagrams as Novel Approach to Discuss the Efficiency of Compressed Air Systems, 8th International Fluid Power Conference, Dresden.

[5] Harris, P.; O'Donnell, G.E.; Whelan, T. (2012): Energy efficiency in pneumatic production systems: State of the art and future directions, In: Leveraging Technology for a Sustainable World, Proceedings of the 19th CIRP Conference on Life Cycle Engineering, Berkeley, USA, pp. 363-368.

[6] Herrmann, C.; Thiede, S. (2009): Process chain simulation to foster energy efficiency in manufacturing, CIRP Journal of Manufacturing Science and Technology 1 (4): 221-229.

[7] Hermann, C. (2009): Ganzheitliches Lifecycle Management, Springer, Berlin.

[8] Hesse, S. (2011): Greifertechnik: Effektoren für Roboter und Automaten, Hanser, München.

[9] Müller, E. et al. (2009): Energieeffiziente Fabriken planen und betreiben, Springer, Berlin, Heidelberg.

[10] Baehr, H.; Kabelac, S. (2009): Thermodynamik: Grundlagen und technische Anwendung, Springer, Berlin, Heidelberg.

[11] Watanawanavet, S. (2008): CFD optimization study of high-efficiency jet ejectors, Dissertation, Texas A&M University, TX, USA.

[12] Kornhauser, A. (1990): The use of an ejector as a refrigerant expander, Proc. Of USNC/IIR-Purdue refrigeration conference, pp. 10-19.

[13] Butrymowicz, D. (2003): Improvement of Compression Refrigeration Cycle by Means of two-phase Ejector, Proc. of International Congress of Refrigeration, Washington D.C.

[14] Festo AG & Co. KG (2012): Grundlagen der Vakuumtechnik, http://www.festo.com/net/de_de/SupportPortal/Downloads/10106/9916/Grundlagen_Vakuumtechnik_de.pdf

[15] Bauer, B. (1966): Theoretische und experimentelle Untersuchung an Strahlapparaten für kompressible Strömunsmittel (Strahlverdichter)", VDI-Forschungsheft 514, Deutscher Ingenieur-Verlag, Düsseldorf.

[16] Bou Lawz Ksyer, E. (2007): Etude et conception de systemes a efficacite energetique amelioree fonctionnante au CO2 comme fluide frigorifene, Dissertation, Paris Tech, Paris.

[17] Fiorenzano de Albuquerque, R.; Tischendorf, C.; Lemke, N.; Köhler, J. (2010): KI Kälte Luft Klimatechnik, KI – 06/2010, Hüthig GmbH, Heidelberg.

[18] Matsuo, K. et al. (1982): Investigation of Supersonic Air Ejectors, JSME, 25, Paper 210-7.

[19] Flügel, G. (1951): Berechnung von Strahlapparaten, VDI-Forschungsheft 395, Deutscher Ingenieur-Verlag, Düsseldorf.

[20] ISO 6358 (1989): Pneumatic fluid power; components using compressible fluid; determination of flow-rate characteristics, Beuth, Berlin.

[21] Lucas, K. (2008): Thermodynamik: Die Grundgesetze der Energie- und Stoffumwandlung, Springer, Berlin, Heidelberg.

[22] Bauer, B. (1965): Auslegung von Strahlapparaten für beliebige Medien, Dissertation, Technische Hochschule Stuttgart.

A Model for Predicting Theoretical Process Energy Consumption of Rotational Parts Using STEP AP224 Features

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Abstract

Energy efficiency in manufacturing has become a key concern due to the increased awareness of the adverse effects of global warming. First step for increasing energy efficiency is to quantify the energy consumed for manufacturing processes. This study presents a prediction model for the theoretical energy that is consumed during the manufacturing processes of a rotational part and resulting CO_2 release. Theoretical energy is the tool tip energy required to remove the given volume of chip. Prediction model is based on the volume removed for each STEP AP224 feature and the specific cutting energy for the given material.

Keywords:

Process Energy Prediction; Energy Efficient Manufacturing; Carbon Footprint

1 INTRODUCTION

Population increase and industrialization across Turkey give rise to a continuous increase in the demand for energy. Based on the report of Turkish Electricity Transmission Company [1] the gross electrical energy demand of Turkey is 229,395 GWh in 2011 (Figure 1). According to The Turkish Ministry of Energy and Natural Resources there is 20% improvement potential for energy savings in production industry [2].

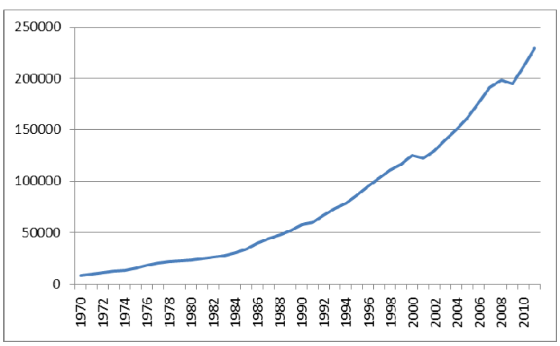


Figure 1: Gross Electrical Energy Demand of Turkey (GWh) [1].

In order to use this potential and pursue energy efficiency, Energy Efficiency Law [3] and the Regulation on Increasing Efficiency in the Use of Energy Sources and Energy [4] were enacted by the Ministry. 8e, 8f and 8g clauses of the latter define the tasks that are expected to be undertaken by the energy management departments of enterprises:

- Monitoring and evaluating the energy consumptions and costs; preparing periodical reports.
- Acquiring and installing the necessary meters for tracking energy consumptions.
- Tracking the relation between products and energy consumption and preparing proposals for the reduction of energy intensity of the enterprise.

In terms of manufacturing industry, monitoring of energy consumption is only possible during the manufacturing stage after the design stage of the part is completed. Hauschild et al. [5] emphasizes that the knowledge of the product is increased as the design stage progresses from idea generation towards detailed design. On the other hand, most of the product properties are fixed by design decisions, decreasing the possibility of improving the energy consumption and environmental properties of the product. By the time the production starts, most of the design decisions are already made and there is a little improvement potential for the properties of the part. This scenario is presented in Figure 2. Therefore, a tool is needed which can estimate the energy consumption in the early design stages, providing designers the information about the energy consumption and environmental impact of the part and enabling them to make energy aware and environmentally conscious design decisions.

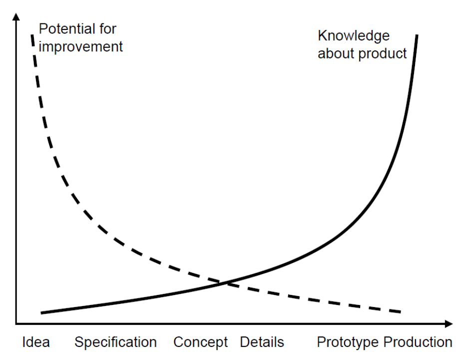


Figure 2: Knowledge about the product vs. improvement potential for environmental performance throughout the design phases [5].

This paper aims at developing a model to predict the tool tip energy consumption which is referred as theoretical energy in this paper and corresponding carbon releases for manufacturing processes of a rotational part. Prediction model for theoretical process energy is implemented in a feature modeler software which was developed in previous studies [6].

After implementing the auxiliary energy consumption model to the prediction model which is planned as a future work, the model and software will be used as a tool supporting design for environment (DfE) efforts for rotational parts. Besides, final version of the design tool can be used for providing energy and carbon release estimates for the facilities where energy consumption values are not monitored.

2 FEATURE BASED APPROACH AND STEP

Most CAD systems utilize geometric modeling techniques which provide an incomplete definition of the product. Despite their power of representation of product model, due to the lacking high level information they cannot be used alone for downstream applications such as process planning, manufacturing, CNC programming, inspection, etc. [7]. There is always a need for another system to translate the implicit geometric data into explicit process planning and manufacturing information adding the design intent of the product.

In order to eliminate this need and be able to supply geometric tools with a higher level of information, feature modeling was introduced in 1980s. Lacking information elements in geometric modeling were introduced and named as “features” to create a link between geometric models and downstream applications. This means features make possible understanding the design intent and manufacturing information besides geometric information by providing engineering attributes such as materials, dimensions, tolerances, surface finish, etc [6].

There are several techniques used to create features, either directly or indirectly. The direct creation case named as “design by features” is using the predefined features in design stage and creating geometry from the feature definitions. The indirect case is “feature recognition” where features are derived from the geometry of a product created by CAD software. The software used in this study uses “design by features”.

2.1 Design by Features

Product data and its geometric model are created by selecting among predefined features named “feature library”. This gives the opportunity of adding the functional design intent and explicit manufacturing information into the product data as well as the geometric modes. This property of design by features makes the high-level communication between design and manufacturing possible without any additional process after the design phase. If there is a complete feature library for product definition the only limit is the creativity of the designer and competence of the feature based design software in using the pre-defined generic features [8].

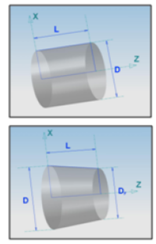
2.2 STEP

A standardized product data model is required for representation and exchange of information about a product allowing the seamless integration of CAD/CAM systems. In order to address this need, the International Standards Organization (ISO) proposed a “Standard for the Exchange of the Product data” (STEP). Prior to STEP all standards developed for product data representation and exchange failed to supply high-level information for CAPP and CAM systems and only dealt with geometric aspect of design data. Introduction of STEP enabled exchanging not only geometric design data but also the high-level information.

ISO 10303 is an international standard for the computer-interpretable representation and exchange of product data, STEP. The objective is to provide a mechanism that is capable of describing product data throughout the life cycle of a product, independent from any particular system. The nature of this description makes it suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases and archiving [9].

STEP is organized as a series of parts, each published separately. These parts fall into one of the following series: description methods, integrated resources, application protocols (APs), abstract test suites, implementation methods, and conformance testing [9].

STEP uses a formal specification language, EXPRESS, to specify the product information to be represented. The use of a formal language enables precision and consistency of representation and facilitates development of implementations (Figure 3).



```
ENTITY outer_diameter
 SUBTYPE OF (outer_round);
 diameter : numeric_parameter;
 feature_length : numeric_parameter;
 reduced_size : OPTIONAL taper_select;
END_ENTITY;

TYPE taper_select = SELECT (diameter_taper, angle_taper);
END_TYPE;

ENTITY diameter_taper;
 final_diameter: numeric_parameter;
END_ENTITY;

ENTITY angle_taper;
 angle: numeric_parameter;
END_ENTITY;
```

Figure 3: Sample EXPRESS Specification.

In this study, AP224 (Mechanical Product Definition for Process Planning using Machining Features) [10] and its feature library is used after refining for the rotational features. For the lacking information in AP224, AP238 (Application Interpreted Model for Computerized Numerical Controllers) [11] is referred. STEP AP224 contains all the information needed to manufacture the required part. Features and corresponding parameters used in the feature library of this study is given in Table 1.

OUTER ROUND	
Outer Diameter	D, L
Tapered Outer Diameter	D, D_F, L
Outer Diameter to Shoulder	D, R, L, α, β, r
REVOLVED FEATURE	
Revolved Flat	R, R_F, L
Revolved Round	R, α, r
Spherical Cap	R, $\alpha=90$, $r=R$
Groove	
Partial Circular	R, α, r
Rounded U	R, W
Square U	R, W, α_1, r_1, α_2, r_2
Vee	R, α, β, r
MUTIAXIS FEATURE	
Hole	
Round Hole	D, L, Bottom Condition
Tapered Round Hole	D, D_F, L, Bottom Condition
Counterbore Hole	1st Hole, 2nd Hole
Countersunk Hole	1st Tapered Hole, 2nd Hole
TRANSITION FEATURE	
Edge Round	1st and 2nd feature, r
Fillet	1st and 2nd feature, r
Chamfer	1st and 2nd feature, D_1, α

Table 1: Feature list.

A simple design is demonstrated in Figure 4 with three Outer Diameter features and 1 Tapered Outer Diameter feature.

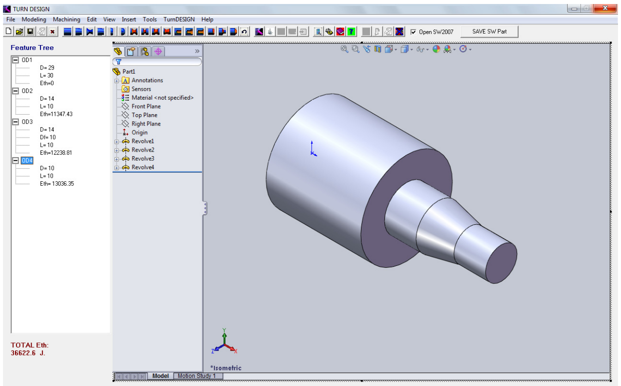


Figure 4: Feature modeler.

3 ESTIMATION METHODOLOGY

Energy consumed for production of a part can be broken down by using the following equation. E_{part} represents the energy consumption at line level for production point of view.

$$E_{part} = \sum E_{process} + \sum E_{handling} + \sum E_{indirect} \quad (1)$$

where $E_{process}$ is the energy consumed by the manufacturing processes, $E_{handling}$ is the energy consumed by the automated material handling equipment such as robots and conveyors and $E_{indirect}$ is the allocated indirect energy consumed by the services to maintain the environment for the production activities of the part.

Energy consumption for manufacturing processes of a rotational part ($E_{process}$) has two components as given in the Equation 2 [12]:

$$E_{process} = E_{th} + E_{aux} \quad (2)$$

where E_{th} is the theoretical energy which is consumed during the actual metal removal processes and E_{aux} is the energy which is consumed during the operation of the auxiliary equipment such as pumps or cooling media.

Auxiliary energy can also be broken down into variable ($E_{aux\text{-}var}$) and constant ($E_{aux\text{-}const}$) components.

$$E_{aux} = E_{aux-\mathrm{var}} + E_{aux-const} \quad (3)$$

Variable auxiliary energy is time dependent and may change during the operation of the machine tool. Energy consumed by servo motors, spindle motor or the energy consumed by the automatic tool changer for each tool change action are examples of variable auxiliary energy.

Constant auxiliary energy is due to the auxiliary components of the machine tools which consume energy even if the machine is in standby mode. Lighting and the embedded computer for the CNC machine tools are two examples for constant auxiliary energy.

Li et al. [13] identified and classified the electrical components of machine tools into several systems. Adoption of a similar classification will enable the further breakdown of variable and constant parts of auxiliary energy into their components. A preliminary study on the breakdown of auxiliary energy into its components gives:

$$E_{aux-\mathrm{var}} = E_{servo} + E_{spindle} + E_{ATC} + E_{cool} + E_{chiller} + E_{clamp} \quad (4)$$

$$E_{aux-const} = E_{computer} + E_{light} + E_{fan} + E_{misc} \quad (5)$$

Estimation of the energy consumed by the auxiliary equipment of the machine tools (E_{aux}) is planned as a future study and it will be estimated based on the operation time, power rating of the corresponding motor and volume of the chip removed.

3.1 Theoretical Energy Estimation Model

In order to estimate the theoretical energy consumed by the manufacturing processes (E_{th}), features of the part are determined in accordance with the STEP AP224 standard [10]. Since theoretical energy is the energy required to remove a given volume of chip form the material, it can be calculated for each feature by using the equation:

$$E_{th} = k_c \cdot V_{rem} \quad (6)$$

where k_c is the specific cutting energy (J/mm^3) and V_{rem} is the volume of the material removed (mm^3).

Removed volume for each feature is formulated parametrically by using the theorem on volume of a body of revolution. This theorem states that the volume of a body of revolution is equal to the generating area times the distance traveled by the centroid of the area while the body is being generated. Therefore:

$$V_{rem} = 2\pi \cdot \bar{r} \cdot A_{rem} \quad (7)$$

Specific cutting energy is the energy required to remove a unit volume of material and is calculated by:

$$k_c = (1 - 0.01 \cdot \gamma_0) \cdot \frac{k_{c1.1}}{a_c^{mc}} \quad (8)$$

where γ_0 is the cutting rake angle, $k_{c1.1}$ is the specific cutting energy for an uncut chip thickness of 1mm, mc is an exponent and a_c is the uncut chip thickness for the given feature and machining process combination. Uncut chip thickness is given by:

$$a_c = a_f \cdot \sin \kappa_r \quad (9)$$

κ_r is the cutting edge angle and is determined by the tool geometry. a_f is the feed engagement (also referred as the feed per tooth) which is defined as the instantaneous engagement of the cutting edge with the workpiece in the direction of feed motion. For manufacturing processes using a single point cutting tool a_f is equal to the feed (f). But for processes using multi point tools feed is calculated by:

$$f = a_f \cdot N \quad (10)$$

where N is the number of teeth on cutting tool.

Specific cutting energy for an uncut chip thickness of 1mm ($k_{c1.1}$) and exponent mc depends on the material being cut; cutting edge angle (κ_r) and cutting rake angle (γ_0) depends on the selected tool geometry. Feed (f) is selected based on the desired surface roughness value and tool properties. Tool catalogues provide a range of feed values according to the chip breaker design of the cutting tool.

3.2 Carbon Footprint Estimation Model

According to the GHG protocol [14], in order to achieve emission reduction goals, first organizational boundaries should be set and then operational boundaries should be determined. Operational boundaries encompass scope 1, scope 2 and scope 3 emissions (Figure 5). Scope 1 covers direct emissions from sources owned or controlled by a company. Scope 2 covers indirect emissions from the creation of purchased electricity used by a company. These emissions occur at the facility where electricity is generated. Scope 3 are indirect emissions resulting from the activities of a company, but occurs from sources not owned or controlled by a company. Scope 3 emissions include both upstream and downstream emissions and represent the largest opportunity for GHG reductions.

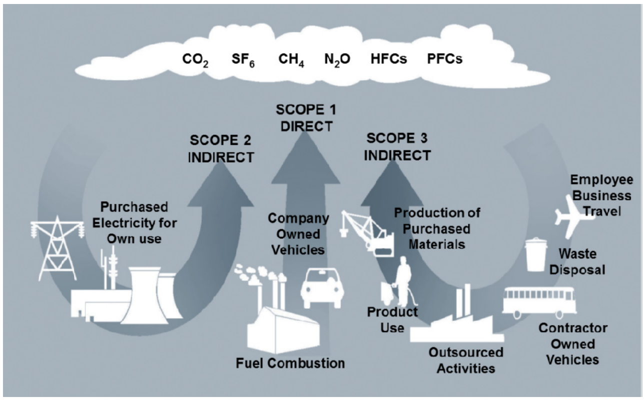


Figure 5: GHG Emission Sources [14].

According to 2010 data of Turkish Statistical Institute [15], 75.3% of the GHG in Turkey is originated from the fossil fuel combustion in energy sector and 39.61% of those emissions are the result of electricity production. It is evident that, if a manufacturing enterprise seeks to decrease its environmental impact through sustainable manufacturing, the company should reduce its electricity dependency by increasing the energy efficiency of its manufacturing processes. Therefore this study focuses on Scope 2 indirect GHG emissions resulting from the purchased electricity used by the company.

Jeswiet and Kara [16] have proposed a method for estimating carbon footprints in a system that uses electric power grids. This method proposes a Carbon Emission Signature (CES^{TM}) that has a unit of kg CO_2/GJ. CES^{TM} depends on the primary energy supplies of a power grid. The carbon emitted for manufacturing processes of a single part ($CE_{process}$) can be estimated by multiplying the electrical energy consumed for manufacturing that part ($E_{process}$) by the Carbon Emission Signature (CES):

$$CE_{process} = E_{process} \cdot CES \tag{11}$$

The CE for a finished good can be used as a carbon label, if it can efficiently rolled up from parts to components to a product.

CE_{th} which is the amount of carbon emitted as a result of the theoretical energy consumption can be found by:

$$CE_{th} = E_{th} \cdot CES \tag{12}$$

CES can be calculated by the following equation:

$$CES = \eta \cdot (112 \cdot \%C + 49 \cdot \%NG + 66 \cdot \%P) \tag{13}$$

where C (coal), NG (natural gas) and P (petroleum) are the fractions of primary energy sources; coefficients 112, 49, and 66 are the kilograms of carbon released per gigajoule of heat in each case and finally η is the conversion efficiency.

Based on the Turkey's electricity generation by primary resources data (2011) which is obtained from the Turkish Electricity Transmission Company [1] fractions for C, NG and P are 28.9%, 45.4% and 0.2% respectively. Using a conversion efficiency of 0.34, CES for Turkey can be calculated as 160.85 kg CO_2/GJ.

4 CASE STUDY

A part with 7 STEP AP224 features is designed to demonstrate the developed model (Figure 6). Features which are used to design the part, corresponding parameters and the volume removed to manufacture those features are listed in the second, third and fourth columns of Table 2 respectively.

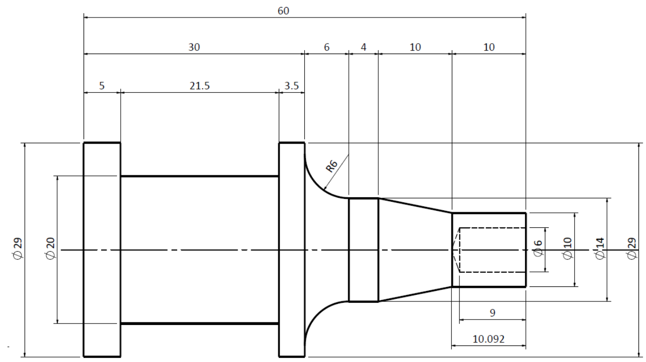


Figure 6: Sample part.

Two design alternatives are created by selecting two different raw materials: Steel (AISI 1040) and Aluminum (6013). Part designs are restricted to a stock size of ϕ30mm by 60mm. In order to make realistic calculations, proper turning, grooving and drilling tools are selected from SECO Tool Catalogues [17], [18]. Feed (f), cutting edge angle (κ_r), cutting rake angle (γ_0), specific cutting energy for an uncut chip thickness of 1mm ($k_{c1.1}$) and exponent mc which are required to calculate the specific cutting energy (k_c) are based on the tool selection and the corresponding data given in the same catalogues. Calculated specific cutting energy values are given in the fifth and eighth columns of Table 2 for AISI 1040 and Aluminum 6013.

Theoretical energy consumptions (E_{th}) are calculated using Equation 6 and the corresponding carbon emissions are estimated using Equations 12 and 13. The negative sign in theoretical energy columns for fillet features is because some volume of material is recovered with the addition of fillets which was considered as being removed in the previous design steps.

Other than the material removed for the features which are set during the design stage, there will be three operations during the manufacturing stage of the designed part. Those are facing, stock removal where the stock diameter (30 mm) is reduced to the maximum diameter of the part (29 mm) and cut-off operations. Theoretical energy consumed for those three operations constitute 19.3% of total theoretical energy for both AISI 1040 and Aluminum 6013.

According to the results of the case study, part which is machined out of an aluminum 6013 stock will consume a lower amount of theoretical energy (30574.8 J) and has a lower carbon footprint (4.9 g) compared to those of AISI 1040 (65556.8 J and 10.5 g). However, at this stage it cannot be concluded that aluminum part consumes lower energy and has a lower carbon footprint in total compared to the steel part since the model of this study does not take the auxiliary energy consumption into consideration. The final decision can only be made after the auxiliary energy consumption module is implemented to the prediction model which is planned as a future work.

No	Feature	Parameters	V_{rem} (mm^3)	$k_{c\text{-}Steel}$ (J/mm^3)	$E_{th\text{-}Steel}$ (J)	$CE_{th\text{-}Steel}$ (g)	$k_{c\text{-}Al}$ (J/mm^3)	$E_{th\text{-}Al}$ (J)	$CE_{th\text{-}Al}$ (g)
1	Outer Diameter (OD)	D = 29 mm L = 30 mm	0.0	2.24	0.0	0.0	1.05	0.0	0.0
2	Outer Diameter (OD)	D = 14 mm L = 10 mm	5065.8	2.24	11366.6	1.8	1.05	5304.4	0.9
3	Tapered Outer Diameter (ODT)	D = 14 mm L = 10 mm D_F = 10 mm	5463.8	2.24	12259.5	2.0	1.05	5721.1	0.9
4	Outer Diameter (OD)	D = 10 mm L = 10 mm	5819.8	2.24	13058.4	2.1	1.05	6093.9	1.0
5	Square U Groove (SQRUGRV)	R = 10 mm W = 21.5 mm (α_1, r_1) = 90°, 0 (α_2, r_2) = 90°, 0	7446.8	2.24	16703.2	2.7	1.05	7794.8	1.3
6	Round Hole (RNDHOL)	D = 6 mm L = 9 mm BC = Conical Bottom α = 140°	264.8	1.63	430.3	0.1	0.69	182.4	0.0
7	Fillet (FILLET)	1st Feature (OD) 2nd Feature (OD) r = 6 mm	-404.8	2.24	-908.4	-0.1	1.05	-423.9	-0.1
No	**Operation**	**Parameters**	**V_{rem} (mm^3)**	**$k_{c\text{-}Steel}$ (J/mm^3)**	**$E_{th\text{-}Steel}$ (J)**	**$CO_{2th\text{-}Steel}$ (g)**	**$k_{c\text{-}Al}$ (J/mm^3)**	**$E_{th\text{-}Al}$ (J)**	**$CO_{2th\text{-}Al}$ (g)**
1	Facing	D_{stock} = 30 mm L_{facing} = 1 mm	706.9	2.34	1652.2	0.3	1.09	771.0	0.1
2	Stock Removal (Dstock – Dmax)	D_{stock} = 30 mm L_{max} = 60 mm	2780.3	2.24	6238.4	1.0	1.05	2911.3	0.5
3	Cut-off	D_{stock} = 30 mm L_{cutoff} = 3 mm	2120.6	2.24	4756.5	0.8	1.05	2219.7	0.4
TOTAL			**29263.8**		**65556.8**	**10.5**		**30574.8**	**4.9**

Table 2: Results of the case study.

5 CONCLUSION AND FUTURE WORKS

This study will provide design engineers a tool for considering the energy consumptions and the environmental impacts of the parts before proceeding to the manufacturing stage. By this way, users can work on designs by taking energy consumption and carbon footprint of the products into account which will lead to decreased costs as well as carbon releases.

The study presented in this paper is a part of a broader research effort which aims at developing a model to predict the total energy consumption for manufacturing processes of a rotational part i.e. involving both of the components in Equation 2. Therefore, future works for the complete study involves the following items:

- Development of a model for predicting the auxiliary energy consumption model for rotational parts.
- Verification of the compete model by taking measurements from CNC Turning Center (Anatool TP 32) at the Department of Mechanical Enginering in Middle East Technical University. Energy measurements which will be used to verify the components of consumed manufacturing energy will be based on the measurement methodology explained in Uluer et al [19].

6 REFERENCES

[1] Turkish Electricity Transmission Company (TEİAŞ), available at: http://www.teias.gov.tr/ [Accessed 09.12.2012].

[2] Republic of Turkey, Ministry of Energy and Natural Resources (2011): Energy Efficiency, available at: http://www.enerji.gov.tr/index.php?dil=en&sf=webpages&b=enerjiverimliligi_EN&bn=217&hn=&id=40719 [Accessed 09.12.2012].

[3] Republic of Turkey, Ministry of Energy and Natural Resources (2007): Energy Efficiency Law, available at: http://www.enerji.gov.tr/tr/dokuman/5627_Sayili_Enerji_Verimliligi_Kanunu.pdf [Accessed 09.12.2012].

[4] Republic of Turkey, Ministry of Energy and Natural Resources (2008): Regulation on Increasing Efficiency in the Use of Energy Sources and Energy, available at: http://www.enerji.gov.tr/tr/dokuman/Enerji_Kaynaklarinin_ve_Enerjinin_Kullaniminda_Verimliligin_Artirilmasina_Dair_Yonetmelik.pdf [Accessed 09.12.2012].

[5] Hauschild, M., Jeswiet, J., Alting, L., (2005): From Life Cycle Assessment to Sustainable Production: Status and Perspectives, in: CIRP Annals – Manufacturing Technology, Vol. 54, No. 2, pp. 1-21

[6] Akkuş, K., Kılıç, S.E. (2012): STEP AP224 Based Feature Modeller with Automatic NC-Code Generation for Rotational Parts, in: Proceedings of the 15th International Conference on Machine Design and Production (UMTIK2012), Vol. 2, pp. 763 - 777, Pamukkale, Denizli, Turkey.

[7] Shah, J.J., Rogers, M.T., (1988): Functional Requirements and Conceptual Design of the Feature-Based Modelling System, in: Computer-Aided Engineering Journal, Vol.5, No.1, pp. 9-15.

[8] Amaitik, S.M., Kılıç, S.E., (2005): STEP-based Feature Modeler for Computer-aided Process Planning, in: International Journal of Production Research, Vol. 43, No. 15, pp. 3087-3101.

[9] International Standards Organization, (1994): ISO 10303-1 Industrial automation systems and integration - Product data representation and exchange - Part 1: Overview and fundamental principles, Geneva, Switzerland.

[10] International Standards Organization (2006): ISO 10303-224 Industrial Automation Systems and Integration - Product Data Representation and Exchange - Part 224: Application Protocol: Mechanical Product Definition for Process Planning Using Machining Feature, Geneva, Switzerland.

[11] International Standards Organization, (2007): ISO 10303-238 Industrial automation systems and integration - Product data representation and exchange - Part 238: Application protocol: Application interpreted model for computerized numerical controllers, Geneva, Switzerland.

[12] Rahimifard, S., Seow, Y., Childs, T. (2010): Minimising Embodied Product Energy to Support Energy Efficient Manufacturing, in: CIRP Annals – Manufacturing Technology, Vol. 59, pp. 25-28.

[13] Li, W., Zein, A., Kara, S., Herrmann, C. (2011): An Investigation into Fixed Energy Consumption of Machine Tools, in: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering (LCE2011), pp. 268-273, Braunschweig, Germany.

[14] Greenhouse Gas Protocol Initiative, 2004. A Corporate Accounting and Reporting Standard, Revised Edition, http://www.ghgprotocol.org/files/ghgp/public/ghg-protocol-revised.pdf [Accessed 09.12.2012].

[15] Turkish Statistical Institute (2012): National Greenhouse Gas Inventory Report 1990 - 2010.

[16] Jeswiet, J., Kara, S. (2008): Carbon Emissions and CES™ in Manufacturing, in CIRP Annals – Manufacturing Technology, Vol. 57, pp. 17-20.

[17] SECO Tools (2012): MN2012 - Turning in: Machining Navigator Catalogue

[18] SECO Tools (2012): MN2012 - Holemaking in: Machining Navigator Catalogue

[19] Uluer, M.U., Ünver, H.Ö., Kılıç, S.E. (2012): An Eco-Tracking System for Environmentally Conscious Manufacturing, in: Proceedings of the 15th International Conference on Machine Design and Production (UMTIK2012), Vol. 2, pp. 845 - 855, Pamukkale, Denizli, Turkey.

Developing Unit Process Models for Predicting Energy Consumption in Industry: A Case of Extrusion Line

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Abstract
Energy efficiency has become a critical concern for manufacturing industries due to the increasing cost of energy, the associated environmental impacts and perceived social awareness. Global efforts have been directed towards improving transparency, e.g. developing energy consumption models for manufacturing processes. However, most of the existing models were developed in laboratories, whilst developing models in industry faces multiple challenges, such as cost, interruption of current production, limited process flexibility, etc. Therefore, a modified methodology is essential for the practical implementation in an industrial environment. A sheet extrusion line in a biomedical company was selected as the test case.

Keywords:
Energy Consumption; Empirical Model; Extrusion

1 INTRODUCTION

Energy efficiency has become a critical concern for manufacturing industries due to the increasing cost of energy, the associated environmental impacts and a perceived social awareness. In Australia, the price of electricity for industry has been steadily increasing in the last few years. Moreover, most of Australia's electricity is produced using coal, which accounts for 77 per cent of total electricity generation in 2008-09 [1]. Obviously, the consumption of electrical energy is strongly related to greenhouse gas emissions. The introduction of the carbon tax legislation has resulted in even greater pressure on manufacturers. Owing to the increasing customer awareness, manufacturers are receiving greater scrutiny from the general public to reduce their environmental impact. Therefore, reducing electrical energy consumption of manufacturing processes not only benefits the manufacturers economically and ecologically, but also improves their image in the society.

To reduce electricity consumption, it is essential to understand exactly how energy is being used. In the last ten years, global efforts have been directed towards improving transparency in manufacturing; hence, different approaches have been developed at multiple levels from unit process to the entire factory. Since manufacturing processes cross over a wide range of types and feature a dynamic behaviour, the studies at the unit process level contribute to the fundamental knowledge of the energy efficiency of manufacturing processes. However, previous research was mainly conducted in a laboratory environment where the types of machine tools were generally limited. Alternatively, the developed methodology can be implemented in industries where a great variety of manufacturing processes and machine types can be investigated.

This paper discusses the challenges of model development in an industrial environment, and presents a modified methodology to improve its practicality. A sheet extrusion line in a biomedical company was selected to demonstrate the proposed methodology.

2 RESEARCH BACKGROUND

Traditionally, the energy consumption of a machine tool or manufacturing process has been overlooked and poorly documented. As a result, they can only be estimated roughly based on the nameplate power or cutting force models, suggesting either the worst case scenarios or the minimal energy requirements respectively. The traditional methods were inevitably unreliable. Fortunately, the situation has been improved in the last ten years, since energy efficiency has become one of the most intensively researched topics in the field of manufacturing. Several methods have been developed by different researchers in order to improve the transparency of energy efficiency in manufacturing.

In 2006, Gutowski et al. used an exergy framework to develop a theoretical model which showed a generic trend of energy consumption behaviour among different manufacturing processes [2]. The model revealed that the process rate (e.g. throughput rate, material removal rate, etc.) was a critical factor for the specific energy consumption. However, this approach lacked a clear definition for deriving values of model coefficients and thus did not account for machine to machine variation.

A screening approach was favoured by different researchers. For example, Dietmair and Verl proposed a state-based energy consumption simulation for use in the study of energy-efficiency [3]. Doflou et al. further developed this approach under the initiative-Cooperative Effort on Process Emissions in Manufacturing (CO_2PE!) [4]. In this approach, power consumption of a machine tool was recorded under different states such as ramp up, standby, processing, ramp-down, etc. This method emphasised the dynamics of machining processes in the sense of containing discrete operational stages but did not account for variable machine loads.

Alternatively, an empirical approach of developing unit process models has been developed recently, which has proven to be accurate and reliable in the prediction of energy consumption among different manufacturing processes, such as turning, milling, grinding and injection moulding [5-8]. In a similar study for milling machine tools, the empirical approach has been further validated [9].

Despite the different focuses of the aforementioned approaches, most of the research has been done in a laboratory environment. In particular relation to the empirical approach, only a limited number of machine tools were tested compared to the machine variety in industries. Since the model coefficients vary from machine to machine, it is necessary to investigate as many types as possible. In other words, the benefits of the empirical approach can be magnified once the methodology is adapted to an industrial environment. However, the procedure of developing empirical models involves a large number of experiments. Hence, it is important to first discuss the challenges to develop such a model in industries.

3 INDUSTRIAL CHALLENGES

The empirical approach of developing energy consumption models for manufacturing processes requires series of experiments to filter different process parameters, as well as to characterise the relationship between process parameters and the energy consumption. More importantly, each tested parameter has to be varied in a relatively wide range, in order to capture the trends. Since the machine tools used in laboratories were highly flexible, researchers find little problem either to conduct a large number of experiments or to reach the limit of certain process parameters. However, it is unlikely to find this level of flexibility in industries.

First of all, experiments directly result in a significant expense, including operational costs, material costs, energy costs and labour costs. Prior to any experiments, an energy metering and monitoring system needs to be set up which normally requires a certified electrician to connect the meters to the tested machine tools. Disconnecting the metering system also needs to be done by the electricians. During the experiments, the output products might not be acceptable when changing the original process parameters. Consequently, the experiments become a waste of raw materials and production time. It is even worse for the process which requires a long time to reach production readiness, such as injection moulding, extrusion, etc. Thus, the cost of experiments has to be considered with cautions.

In laboratories, machine tools can be isolated and studied individually. By contrast, the majority of machine tools or processes in industrial processes are closely related to the other ones in a production line. In other words, additional experiments on one process may have a significant impact on the whole process chain or even the entire factory, especially for the case of bottleneck processes. Hence, an appropriate schedule for the experiments is critical to obtain the approval from the industrial side.

The other important aspect for model development is the possibility to change process parameters. In industry, some machine tools are purpose built and run under specific process conditions. In these cases, it is preferable to apply the screening approach to obtain the energy profile of the machine tools. Conversely, industries commonly use one machine tool to produce different parts; corresponding, to different loads and cycle time result in different energy consumptions. These processes provide the opportunity to develop energy consumption models regarding dynamic loads but the process parameters are generally configured according to the quality requirements which limit the range of varying process parameters. Testing the extreme cases also places machine tools at risk of costly breakdowns. Therefore, the levels of variance for the process parameters need to be defined properly in order to meet the industrial requirements as well as to provide a sufficient range for model development.

Apart from the technical constraints, it is essential to obtain the management support. Ideally, the model development activities can be coupled with energy efficiency projects, since the models provide valuable information. Previous studies have revealed the important relationship between the energy intensity of the process (i.e. energy consumption per unit volume/mass of processed materials) and the productivity of the process (e.g. throughput rate or material removal rate) [4-8]. The models also offer an accurate estimation and prediction of energy consumptions, which benefit the energy accounting activities in industries. Moreover, the energy efficiency aspect can be introduced to the stage of configuring process parameters. It is also possible to reduce the energy consumption whilst remaining at the same level of quality performances. Besides the benefits, industry support can be enhanced by minimising the experimental costs and the interruption of the production. Therefore, the original methodology needs to be modified to meet industrial requirements.

4 METHODOLOGY

The original empirical modelling approach consists of four stages, namely Design of Experiments (DoE), physical experiments, statistical analysis, and model validation [5]. Firstly, DoE aims to filter all the possible variables, to eliminate insignificant factors, and to determine the levels of variance for the significant factors. Different experimental approaches can be used during this stage, such as One-Factor-at-a-Time (OFAT), fractional factorial experiment design or Response Surface Methodology (RSM) design. The outcome of this stage is a full schedule of experiments with different combination of significant factors or design factors. Secondly, experiments were performed through the implementation of these experimental designs, each combination of which normally needs to be repeated multiple times to provide sufficient samples for statistical analysis. Thirdly, statistical software, SPSS® and Minitab®, can be used to conduct statistical analysis for model development, such as regression analysis, curve-fit estimation, multiple linear regression, etc. Finally, model validation is performed through the use of lack-of-fit testing and trial runs in order to evaluate the accuracy of the derived model.

As suggested by Montgomery, DoE is the critical stage for any experimental work, but it is also time- and resource- consuming to filter out the insignificant factors [10]. Previous empirical modelling on different processes (e.g. turning, milling, grinding, and injection moulding) has proved that the production rate (e.g. material removal rate or MRR, throughput rate or ṁ) is the decisive factor for specific energy consumption (SEC), as shown in equation 1 [4-9]. The empirical models also agree with the form of exergy framework [2].

$$\mathbf{SEC} = \boldsymbol{c_0} + \frac{c_1}{MRR}\ or, = \boldsymbol{c_0} + \frac{c_1}{\dot{m}} \quad (1)$$

In fact, both MRR and throughput rate are dependent variables. For example, the MRR of a turning process is the product of cutting speed, feed rate and depth of cut. The types of raw materials also affect the selection of MRR. Obviously, these independent factors have significant impacts on the energy consumption, and are normally classified as design factors during DoE stage. However, it is a tedious procedure to statistically prove the significance or insignificance of each factor on energy consumption. Alternatively, the conclusion obtained from previous work can be adapted for the similar manufacturing processes. Instead of testing the significance of each factor on energy consumption, the qualitative relationship between process parameter and production rate can be easily observed. For instance, drilling is similar to other conventional machining processes, such as turning and milling; and, the MRR is a function of driller diameter, feed rate and RPM (rotation per minute); other factors like workpiece materials and driller materials have an indirect impact on the MRR; so, these factors can be directly concluded as design factors for model development. As a result, the number of experiments can be reduced considerably.

Regarding the industrial challenges discussed in section 2, other issues need to be taken into account for experiment planning. The first question which needs to be answered is whether this process is suitable for empirical modelling or not. If all the process parameters of one process remain constant, a screening approach is more suitable for that process. Otherwise, the process can be considered for empirical modelling. Then, each factor is closely observed in conjunction with the production rate. If one factor has a significant impact on production rate, that factor needs to be targeted as design factor. Afterwards, the operational constraints need to be considered, which leads to an addition planning step prior to all the modelling work. Cost analysis, initial setup, scheduling issues and management support needs to be obtained during this step. Once the experiments are approved by industry, the remaining stages are similar to the original empirical approach, including physical experiments, statistical analysis and model validation. Therefore, the methodology can be modified as shown in figure 1.

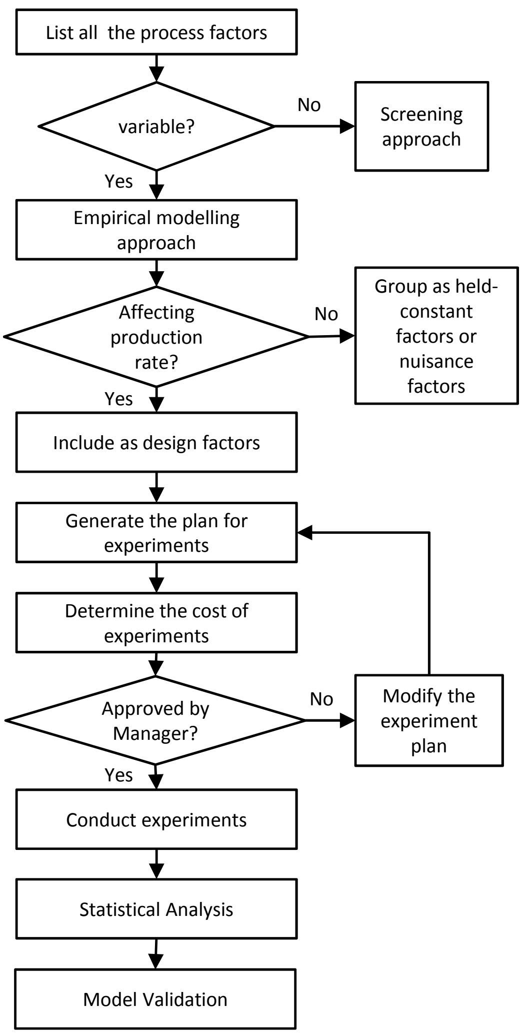


Figure 1: Flow chart of the modified methodology.

5 CASE STUDY: AN EXTRUSION LINE

5.1 Case Overview

The presented case is derived from a biomedical products and services company in Australia. This company is continuously looking ways to improve their processes with environmental awareness. The company has strategic targets for substantially reducing energy and resource consumption as well as reducing its carbon foot-print. To achieve that goal, the company has invested on improving the transparency of its energy flows. Projects were formed to develop energy consumption models or to obtain energy profiles at unit process level.

The manufacturing plant in western Sydney specialises in producing sterilised IV and renal dialysis fluids. One of the key processes is the sheet extrusion line, which produces plastic sheeting to construct containers for IV solutions. Figure 2 shows a typical sheet extrusion line, which consists of an extruder, die, three roller stack, conveyor, pull rollers, and a winder. In general, the plastic pallets or powders are firstly melted and forced through the die by a screw. As the film is drawn out of the die, it passes through the roller stack which controls the cooling rate, final thickness and the surface of the sheet. The pull rollers are set to provide a uniform pressure, ensuring that the plastic does not slip between the rollers. At the end of the sheet line, a winder is normally used where the sheeting is stored [11].

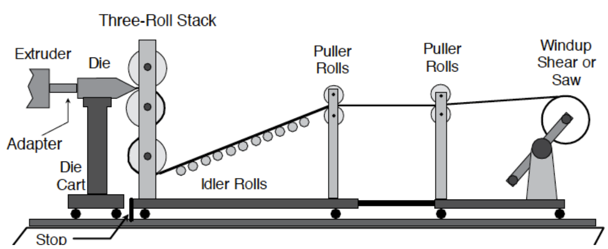


Figure 2: Schematic of a typical sheet extrusion line [11].

5.2 Design of Experiments

According to the proposed methodology, a complete list of factors was first identified for this plastic sheet extrusion line. The factors were categorised into four groups as shown in Figure 3. Some factors, such as air humidity and temperature, can be concluded as uncontrollable factors. Other factors were further investigated in terms of their variance and impacts on production rate.

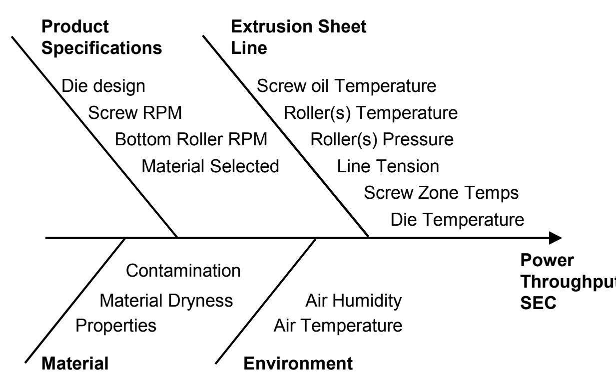


Figure 3: Flow chart of the modified methodology.

According to the production record, the tested sheet extrusion line produces different types of plastic sheets. Two types of raw materials are used, PVC and HDPE. The thickness of the plastic sheets also varies according to the size of the IV bag, which requires different settings for the process parameters. Therefore, it is useful and valuable to develop empirical models for this process.

The production rate of the process is measured by throughput rate, which is the mass of produced plastic sheet per unit time. There are two methods to measure the throughput of the tested process. The first method is to use the sensor which gauges the thickness. The material mass flow can be calculated in conjunction with the width and speed of the plastic sheet as well as the material intensity. The second method calculates an average throughput rate, dividing the total mass of one roll of plastic sheets by the production time. The first method is used to monitor the throughput rate during production. Figure 4 shows the throughput rate trend during the start-up period (after changing the filter). The results suggest that it requires at least 120 seconds for the mass flow to stabilize.

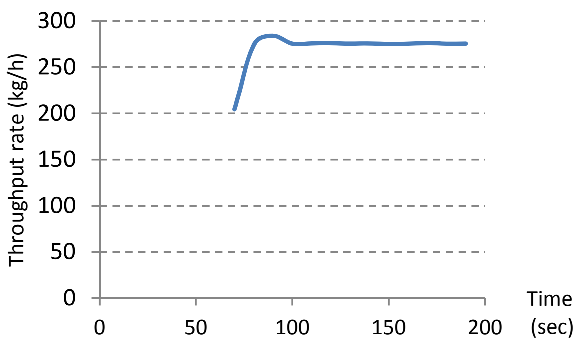


Figure 4: Throughput rate change after filter change.

Figure 4 also suggested that the change of throughput rate is due to the increase of screw RPM from 6 to 100. The bottom roller RPM is adjusted accordingly to maintain the level of line tension. According to the operators, the screw RPM is normally set between 80 and 104. However, the theoretical range is much greater from 0 to 120. The production schedule also suggests that once the RPM is lower than 50, the demand cannot be met even if the process is running continuously. Therefore, the screw RPM was targeted and grouped as a design factor, the range of which is limited between 50 and 104.

Although different raw materials are used in production, the experiments with HDPE were rejected by the plant management, since the scrap of HDPE is not recycled onsite. Consequently, the tested material was limited to PVC, which is cheaper than HDPE. The production of PVC sheets accounts for a considerably higher proportion of the total output of this extrusion line. More importantly, the PVC scraps are shredded and reused for extrusion, which resulted in minimal material waste. Since the experiments were solely conducted with PVC, the temperatures were also held constant. Therefore, the design factors were narrowed down to the screw RPM.

In order to precisely characterise the relationship between power consumption and screw RPM, it is important to test multiple levels of this single design factor, since 2-level experiments initial assume the relationship would be linear. After discussion with the operators and plant manager, 6 levels of screw RPM would be used in the experiment allowing an increment of 10 RPM between each step from 50 to 100.

As discussed in Section 3, it is important to minimise the cost of experiments as well as the interruption of the normal production. Figure 4 suggests that the machine takes at least 120 seconds to stabilise. It was safe to allow 5 minutes for process stabilisation, and another 10 minutes for data collection. The mass throughput can be manually recorded every 30 seconds, so 10 mins experiments offers 20 samples at each level. The material cost was also estimated based on an average throughput rate. Since the machine is running 6 days a week, 24 hours per day, the experiments were scheduled during one weekend, resulting in additional labour and operational cost. In addition, electrician was also ordered to connect the metering device. The overall cost was under the project budget with the highest proportion due to labour costs. Finally, the experiment plan was approved by the plant manager and the project manager.

5.3 Experiment Details

Developing an effective metering system has been proven as a challenging task especially in manufacturing industries [12]. The tested extrusion sheet line is connected with different distribution boards and these distribution boards supply other processes. Thus, the extrusion line was separated into heating unit, screw unit, and the driving train unit (including the rollers, conveyer and the winder) and three Chauvin Arnoux®, C.A.8335 portable power analysers were used to meter these units simultaneously with 1 second resolution.

Figure 5 shows the power consumption measurements of the screw unit. It clearly indicates the steps of the experiments, including an unexpected filter change during the process. The experiments steps were:

1. Once the process was at normal operating conditions the screw RPM was set to 50 and the drive train was set to keep the required tension on the line;

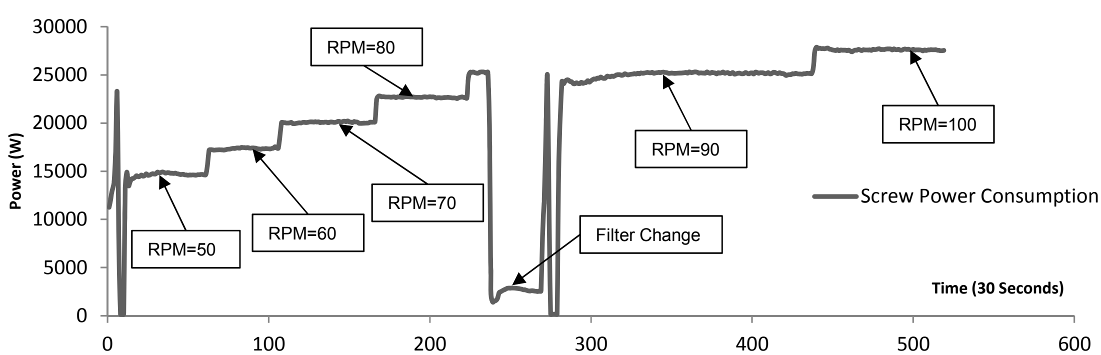


Figure 5: Observed power consumption of screw unit.

2. The throughput of the process was observed for 5 minutes unit the process had stabilised;
3. At the beginning of the experiment, the initial mass was measured. The throughput was recorded every 30 seconds for the duration of 10 minutes;
4. After 10 minutes had elapsed, the total mass was measured again to calculate the average throughput rate;
5. The screw RPM was increased to 60 and the drive train was adjusted accordingly;
6. Step 2 to 5 were repeated and the screw RPM was increased to 70, 80, 90 and 100.

5.4 Statistical Analysis

A series of statistical analyses were conducted with a statistical package, MiniTab® V16.

The distributions of observed data at different levels were first analysed. The heating unit power curve showed a similar pattern over the entire experiment. Two groups of measured heating power (screw RPM 50 and 100) were processed with a two-sample t-test. The null hypothesis had a p-value of 1.000, which suggests that both sets of observations belong to the same group and there is no variation present in the population. Another t-test was conducted on the variances between these two populations, which resulted in a p-value of 0.94. These two tests demonstrated that the power consumption of the heating unit remains constant during the operation. Therefore, the power consumption of the heating unit can be written as equation 2.

$$P_{heating}(kW) = 4.8699 + \epsilon \tag{2}$$

Unlike the power consumption of heating unit, other observed data shows an obvious difference when the screw RPM changes. At each level of screw RPM, the data sets were found to follow a normal distribution. The means of all the observed responses were listed in the Figure 6 a).

The observed responses were then processed using linear regression. Figure 6 b-d) shows the fitted linear model against screw RPM for power consumption of screw unit, power consumption of the drive train unit, and throughput rate ($\dot{m}$) respectively. The models can be written as equations 3-5.

$$P_{screw}(kW) = 1.479 + 0.2571(RPM) + \epsilon \tag{3}$$

$$P_{drive\ train}(kW) = 9.352 + 0.00456(RPM) + \epsilon \tag{4}$$

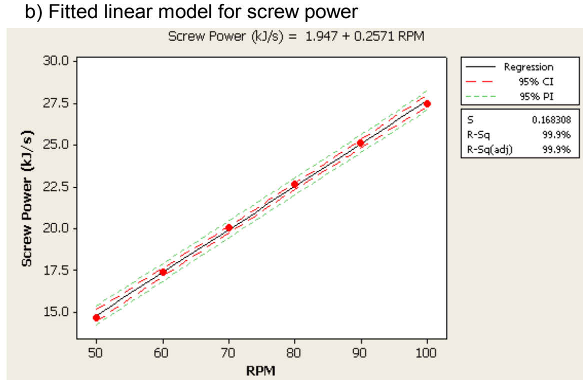
$$\dot{m}\left(\frac{g}{s}\right) = 5.063 + 0.7562(RPM) + \epsilon \tag{5}$$

All of the derived linear models resulted in a high R-square value which indicates a high level of correlation between the observed responses and screw RPM. Notably, the lower R-square value for drive train power consumption is believed to be the lack of control of the process parameters at the related units. During the experiments, the drive train was adjusted to maintain the required line tension. The relationship between the roller speed and the screw RPM may not necessarily be linear. Nevertheless, the variance of drive train power consumption (from 9575 to 9856) is less significant than for screw power consumption (from 14636 to 27458). Hence, the linear model for the drain train power consumption is acceptable in this case.

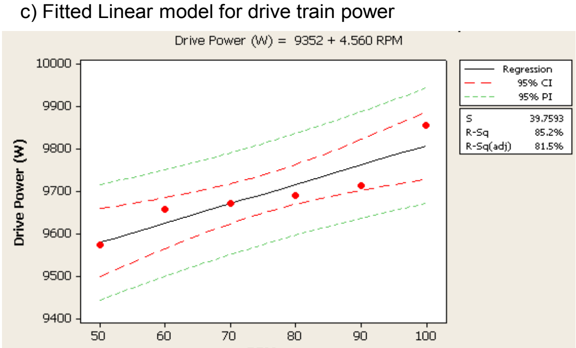
a) Summary of observed data

Design Factor	Response means		
Screw RPM	Screw Power (W)	Drive Train (W)	Throughput (g/s)
50	14636	9575	45
60	17385	9657	48.6667
70	20085	9671	56.6667
80	22663	9691	65.6667
90	25151	9714	73.3333
100	27458	9856	81.3333

b) Fitted linear model for screw power



c) Fitted Linear model for drive train power



d) Fitted Linear model for throughput rate

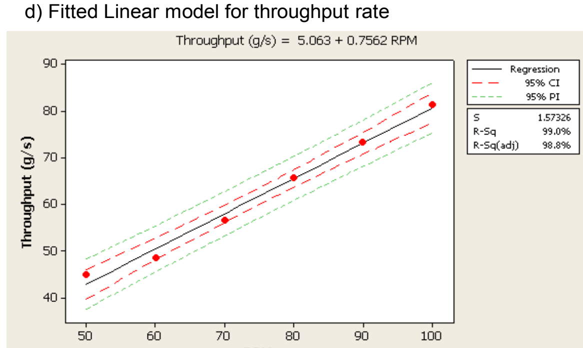


Figure 6: Results of statistical analysis and model regression.

The total energy consumption of the extrusion line can be then written as equation 6.

$$P_{total}(kW) = 16.169 + 0.2617(RPM) + \epsilon \quad (6)$$

5.5 Model Discussion and Validation

Specific Energy Consumption (SEC) is a more favourable, since it enables the comparison on the basis of producing same amount of product [6]. The power consumption model can be further converted into SEC model as shown in equation 7 and figure 7. The SEC model also agrees with the ones for other manufacturing processes, which enables comparison among different manufacturing processes.

$$SEC = \frac{P_{total}}{\dot{m}} = \frac{16.169}{\dot{m}} + \frac{0.2617 \cdot \left(\frac{-5.063}{0.7562}\right)}{\dot{m}} + \epsilon$$
$$= 0.3461 + \frac{14.416}{\dot{m}} + \epsilon \quad (7)$$

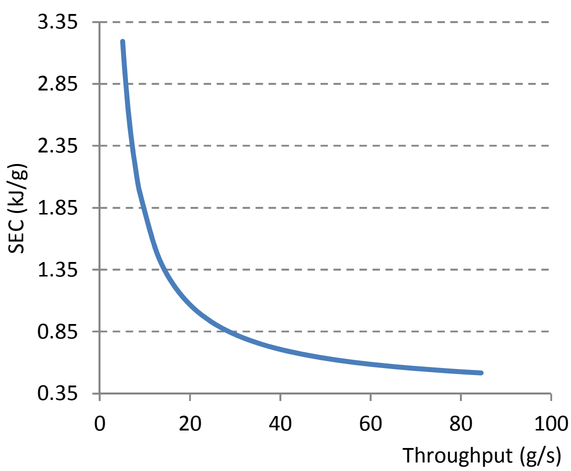


Figure 7: SEC trend of the tested plastic sheet extrusion line.

A further validation run was conducted for 16 minutes at 85 screw RPM, the value of which was not used for model development. According to equation 5 and 7, the predicted throughput rate was 0.069g/s and the estimated SEC was 0.5501kJ/g. Under this setting, the process took 962 seconds to product 69 kg of plastic sheet. The measured energy consumptions during this period were 23861 kJ for the screw unit, 9334 kJ for the drive train unit and 4685 kJ for the heating unit. So the actual SEC was 0.5489. Comparing the predicted SEC with the actual value, the difference is around 2 precent of the real SEC. Therefore, the derived SEC model is safe to use for estimating the energy consumption of the tested sheet extrusion line.

6 SUMMARY

This paper proposes a methodology for deriving energy consumption models of manufacturing process in industries. The planning stage (DoE) plays a critical role for model development, where industrial requirements and practicality need to be considered with caution. An extrusion line was used to demonstrate the methodology. The resultant model shows great ability to accurately predict energy consumption in this tested case. Further validations on different manufacturing processes and industrial environments are recommended as future work.

7 ACKNOWLEDGEMENT

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8 REFERENCES

[1] Department of Resources and Energy and Tourism (2011): Energy in Australia 2011, available online: http://www.ret.gov.au/energy/Documents/facts-stats-pubs/Energy-in-Australia-2011.pdf, last visit 20/11/2012

[2] Gutowski, T., Dahmus, J., Thiriez, A. (2006): Electrical Energy Requirements for Manufacturing Processes; *Proceedings of the 13th CIRP International Conference on Life Cycle Engineering*, Leuven, Belgium.

[3] Dietmair, A., Verl, A. (2009): A generic energy consumption model for decision making and energy efficiency optimisation in manufacturing, *International Journal of Sustainable Engineering*, 2: 2, 123-133.

[4] Kellens, K., Dewulf, W., Overcash, M., Hauschild, M. Z., and Duflou, J.R. (2012): Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI) – CO2PE! Initiative (Cooperative Effort on Process Emissions in Manufacturing). Part1: Methodology Description, *The International Journal of Life Cycle Assessment*, 17(1), 69-78

[5] Li, W., Kara, S. (2011): An Empirical Model for Predicting Energy Consumption of Manufacturing Processes: A Case of Turning Process, *Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture*. 225(9), 1636-1646.

[6] Kara, S., Li, W., (2011): Unit process energy consumption models for material removal processes, *CIRP Annals-Manufacturing Technology*, 60(1), 37-40.

[7] Li, W., Winter, M., Kara, S., Herrmann, C. (2012): Eco-efficiency of manufacturing processes: a grinding case, *CIRP Annals-Manufacturing Technology*, 61(1), 59-62.

[8] Qureshi, F., Li, W., Kara, S., and Herrmann, C., (2012): Unit process energy consumption models for material addition processes: a case of the injection moulding processes, *Proceeding of the 19th CIRP International Conference on Life Cycle Engineering*, Berkeley, USA..

[9] Diaz, N., Redelsheimer, E., Dornfeld, D., (2011), Energy consumption characterization and reduction strategies for milling machine tool use, *Proceedings of the 18th CIRP International Conference on Life Cycle Engineering,* Braunschweig, Germany.

[10] Montgomery, D.C., (2008): *Design and Analysis of Experiments*, 7th ed., Wiley, New York.

[11] Giles, H.F., Wagner, J.R., Mount, E. M., (2004). *Extrusion: The Definitive Processing Guide and Handbook*, William Andrew.

[12] Kara, S., Bogdanski, G., Li, W., (2011), Electricity metering and monitoring in manufacturing systems, *Proceedings of the 18th CIRP International Conference on Life Cycle Engineering*, Braunschweig, Germany.

Advanced On-Site Energy Generation towards Sustainable Manufacturing

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Abstract

The manufacturing industry is under pressure due to escalating energy costs and environmental legislation. On-site energy generation technologies such as cogeneration systems, with higher resource consumption efficiencies, provide a feasible alternative to address these concerns. However in practice, on-site energy system configuration is done without taking into account the dynamic nature of the manufacturing plant's energy demand. This paper extends the identification of the key indicators of energy systems to enhance their performance. Final results provide an appropriate methodology to develop onsite energy systems, based on each plant's characteristics to reduce operational cost and increase resource consumption efficiencies.

Keywords:

Cogeneration; Energy management; Manufacturing industry; Energy monitoring

1 INTRODUCTION

Manufacturing plants consume different forms of energy resources to run machines and complete the material transformation processes to final product. In the past, energy costs were considered as overhead costs rather than resources to be managed. However escalating costs of energy resources such as electricity and gas have changed energy's role to a key element for any manufacturing company. For instance, the cost of electricity has increased around 28% over the past three years for manufacturing plants in Australia. In addition, environmental legislation such as carbon tax reduction schemes are forcing manufacturers to come up with less energy intensive solutions towards sustainability. Consequently energy management solutions are becoming a key issue for every manufacturing company that has the fundamental goal of manufacturing with the least cost and environmental impact [1]. Several approaches such as retrofitting, waste energy recovery, operation management of machines and fuel switching are identified as practical solutions to achieve the aforementioned objectives [2-4].

One of the existing technologies, which has the potential of energy cost and environmental impact reduction is Combined Heat and Power generation (CHP). These systems would supply both electrical and thermal energy by recapturing and utilizing the waste energy from a single fuel source. Thus their application can result in energy efficiency improvement of around 10-40% in comparison with separated power and heat generation (SPH) [5]. Moreover, in addition to higher level of energy supply independence, considerable energy cost and environmental impact reductions have been reported in several industrial case applications [2][6].

However, appropriate configuration of these systems is a complex task as there are multiple factors from different perspectives due to the plant's energy supply and demand characteristics. In this case CHP type, size, number, operation strategy and power to heat ratio are identified as the main factors that should be identified by the system designers [7]. In addition, other objectives such as economical, environmental and primary resource consumption must be taken into account [8].

Review of the published literature illustrates that optimal machinery sizing is the most critical factor for onsite energy generation systems since it will have an impact on the economic return as well as the efficient utilisation of energy resources [9].

Consequently, interest towards the economic feasibility and the optimal sizing of the on-site energy generation options has grown during recent years. This has been the main focus of several studies for residential, commercial and industrial applications to develop methodologies that can determine the most appropriate configuration of the on-site energy generation systems. Ren et al. have modelled a system based on assumptions of seasonal and hourly energy demand fluctuations throughout the year. This was used to study optimal system sizing and investment [10]. Chad et al. [11] also presented a methodology to identify the economical effectiveness of CHP application for industrial facilities by analysing the project payback time, net present value (NPV) and internal rate of return. This was conducted based on different factors such as cost of electricity, fuel purchase and annual operating hours. The study was performed based on monthly utility bills and minimum energy demand. Moreover, optimal economical combination of CHP systems for district heating facility was studied by Sanaye et al. [12] to achieve annual benefit maximization by thermodynamic analysis of prime movers based on hourly electrical and heat demand data over the course of one day.

More recent energy optimization approaches take into account operational strategy development as well. These studies aim to achieve annual revenue maximization by proposing economic load dispatch and operation scheduling solutions for optimal power and heat supply. Marshman et al. [13] provided a solution for economic improvement in industrial application of CHP systems. This was achieved through operation scheduling of CHP machineries over the course of one day and one week based on hourly energy demand. The results illustrate additional profit of 10-50%. In addition Ashok et al. [14] developed an optimal operation strategy for an industrial application based on time of use power charges to achieve operational cost reduction. In this case 16% saving is reported by peak demand reduction over one month planning horizon with hourly energy demand time intervals.

Although the existing studies identify practical solutions for on-site energy system configuration and operation management, they focus exclusively on the economic viability and cost reduction of these systems. However, energy cost reduction doesn't guarantee optimal resource consumption and higher energy efficiency. Therefore, appropriate energy consumption indicators need to be identified and evaluated for the CHP applications.

In the literature, proposed methodologies are mainly based on the average power and heat demand or a short time horizon of the system operation. As a result, these assumptions eliminate the impact of energy demand fluctuations during operation of a system. Consequently an efficiency gap, which is the discrepancy between, expected improvements and actual level of energy efficiencies, will result [15-16]. Insufficient energy flow information has been identified as one of the main factors which can contribute to this [17-18]. Therefore, this paper aims to identify indicators such as primary energy resource consumption and surplus energy generation in order to integrate both economical and energy resource consumption objectives more precisely and effectively. In addition the role of time aggregated energy metering for onsite energy system configuration is evaluated to help facility managers and system designers to come up with enhanced onsite energy system design. The remainder of this paper will give an overview of manufacturing energy systems followed by proposed methodology and reviewed case-study at section three. Finally, the analysed indicators are evaluated.

2 OVERVIEW OF MANUFACTURING ENERGY SYSTEMS

2.1 Energy Flow in Manufacturing Industry

In general, industrial sites are major consumers of electricity and heat with different specifications such as process temperature, electricity to heat demand ratio, timing of peak energy demands and seasonal rates. In addition individual plants have unique design, operating protocols and regulations. Moreover the nature of production is dynamic based on the market behaviour and each organization's strategic planning. As a result, production environments are highly dynamic with unique energy demand patterns compared to residential and commercial sectors. Their energy demand is believed to be in correlation with their manufacturing type and production planning. For instance, continuous manufacturing plants such as petrochemical plants or pulp and paper industries, which consist of material processing without interruptions, are usually categorized as high energy intensive with more stable and predictable energy demand trends [14]. On the other hand, batch production is usually categorized as low energy intensive industry which might have more agile energy demand trends than other types of manufacturing due to their dynamic production planning.

Moreover there are other factors on the shop floor that give energy demand a highly dynamic nature. These can be categorized as:

Dynamic/Unpredictable factors:

- Shut-downs
- Unscheduled maintenance
- Daily changes of production plans
- Ageing of machines

Controllable/Predictable factors:

- Weekdays/weekends
- Seasonal changes
- Scheduled shut-down days
- Scheduled maintenance
- Long term production plans (Automations-Production capacity increase)
- Retrofitting

Figure 1 illustrates the dynamic characteristics of both electricity and heat demand of a manufacturing plant, which is based on 15 minutes aggregation time intervals for one day.

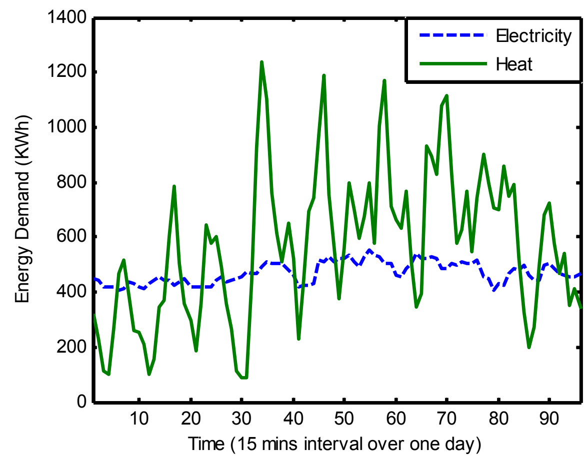


Figure 1: Electricity and heat demand of manufacturing plant.

Despite this, most of the existing studies cover initial system configuration based on the average energy demand patterns disregarding the illustrated dynamic characteristic of energy systems in course of their operation. Consequently these approaches do not take into account agile characteristic of electricity and heat demand at manufacturing plants properly. As stated before, this shortage can result in an efficiency gap and unsatisfied economic objectives during the lifetime of the system.

So far, to the best knowledge of the authors, there is no single solution, which can provide unique design or operational strategy of on-site energy generation systems for every potential site. The collection and integration of the factory level electricity and heat demand data can add value in terms of optimal sizing and operational strategy selection that can be matched with each plant's unique energy demand pattern. Integration of these data sets with proper analysing methodologies can assist facility managers and designers with more realistic and appropriate configuration of onsite energy generation systems.

2.2 On-Site Energy Generation System Description

Any on-site energy generation system can be divided into two sections, namely supply and demand sides. Figure 2 illustrates the general schematic of an energy system for two different scenarios, one as the baseline, which consists of the boiler for heat supply and grid connection for power as well as other onsite energy generation systems that can potentially consist of CHP systems, renewable energy sources such as photovoltaic system integrated with boiler and grid connection to guarantee energy supply in case of CHP failure or lack of capability to supply peak demands. In order to evaluate the potential efficiency and resource consumption improvement of these systems existing performance indicators are identified and analysed at the next section.

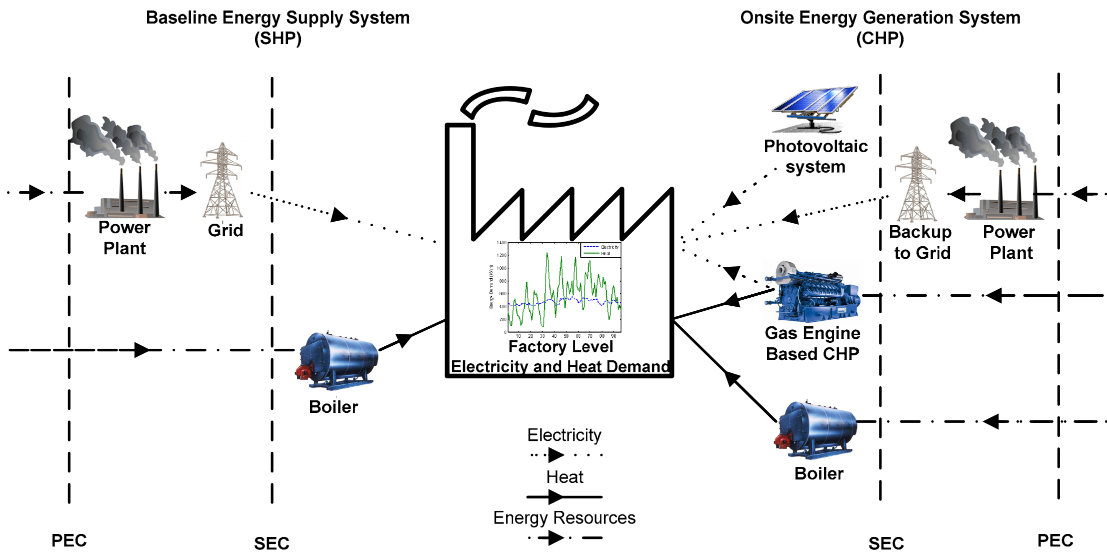


Figure 2: Baseline and onsite energy generation system.

2.3 Energy Resource Consumption Indicators

In order to guarantee the sustainable operation of on-site energy generation systems, there is a necessity to integrate the energy resource consumption indicators into the design stage of these systems. This approach should lead to systems with minimal energy waste and operation at nominal efficiencies. In this case Fumo et al. [19] have reviewed site energy consumption (SEC) in presence of CHP application, which can be defined as the amount of the purchased energy in terms of BTU for an industrial site. Moreover, primary energy consumption (PEC), which is the SEC plus energy loss at the generation, transmission and distribution stages is evaluated. The results illustrate PEC reduction while there is an increase of SEC by CHP application for customers, which is not properly stated by machinery suppliers.

As a result, optimal energy dispatch algorithms have been developed to generate operational strategies which can achieve not only the operational cost reduction but also PEC savings based on simulated hourly electric, cooling and heating load of an office building [20]. However, none of these studies take into account the energy resource consumption indicators at the design stage. This necessitates more detailed resource consumption study of the CHP systems and integration of the appropriate indicators at the initial stage [17] [21]. One of the key indicators for determining the efficiency improvement of a cogeneration system in relation to the baseline scenario is primary energy saving ratio (PESR). This is defined as

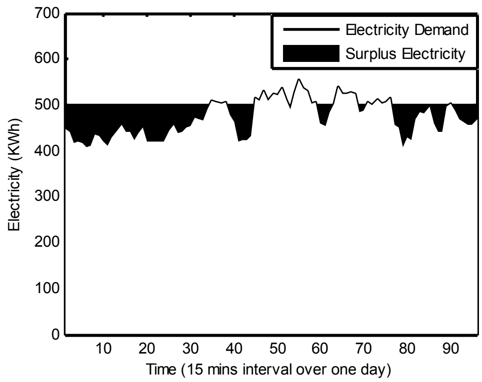
$$\mathrm{PESR} = \left[1 - \frac{1}{\frac{\mathrm{CHPHeff}}{\mathrm{RefHeff}} + \frac{\mathrm{CHPEeff}}{\mathrm{RefEeff}}}\right] \times 100\%$$

Where CHPHeff is the heat efficiency of the cogeneration system, RefHeff is the heat efficiency in case of SHP, CHPEeff is the electrical efficiency of the cogeneration system and RefEeff is the electrical efficiency in case of SHP.

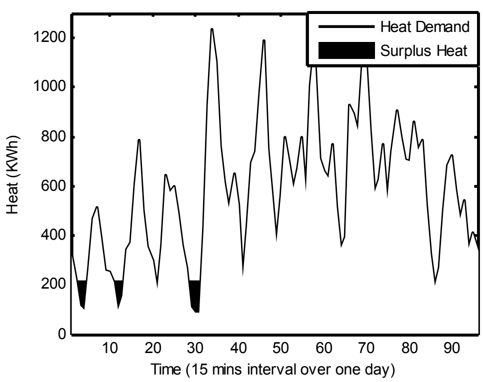
The calculation methodology of this factor is based on the annual fuel consumption, generated electricity and heat. Based on the existing studies and directives, an acceptable cogeneration project should lead to at least 10% PESR. Although this factor give an insight into the potential improvement of energy efficiency of the cogeneration process, it disregards the fact that the amount of generated energy by the CHP system might not be totally utilized in each site due to the energy demand fluctuation [22-23].

In general, simultaneous electricity and heat output of the on-site energy generation systems makes their sustainable operation a complex task as this might not be matched to the transient demand of electricity and heat at the manufacturing plant. As a result, although an on-site energy generation system might guarantee primary energy saving ratio, the generated energy might not be matched to the demand if it is not generated at the appropriate time or magnitude when it is required.

The indicator, which can be monitored to identify the magnitude of the utilizable generated energy during the course of the system operation, is the surplus electricity and heat. This can be defined as the amount of generated energy, which cannot be utilized due to the lack of energy demand and operational constraints of these machineries such as their minimum load. For instance a CHP machine might have minimum operational constraint of 50% with respect to its rated capacity. There will be times that this system is working although the demand is lower than the generated electricity, known as surplus electricity. Similarly there might be periods at which the production of the electricity is economical but there is no demand for the cogenerated heat, which should be dumped so the system can continue the operation, known as surplus heat. These are illustrated for a continuous operation of a CHP system with 2-MW capacity in a manufacturing plant in the Figure 3 over the course of one day. This can account for 5.19×10^6 KWh of surplus electricity and 8.48×10^5 KWh of surplus heat per year in case of continuous operation. This has the financial saving potential of around 800,000 AUD per annum. To this end, considerable impact of integrating energy resource consumption indicators for further improvements and the lack of appropriate methodology at the design stage of the onsite energy generation systems is stated. In order to improve the sustainability of the onsite energy generation system, more awareness is required in relation to the energy flows of manufacturing plants at factory level. This can lead to useful information generation for optimal selection of system components and their operational strategy.



a) Surplus electricity



b) Surplus heat

Figure 3: Surplus energy generation over the course of one day.

3 METHODOLOGY

3.1 System Modelling

A methodology for analysing integrated onsite energy generation system sizing and operational strategy development has been developed. It encompasses both economical and resource consumption indicators by using mathematical models of involved components. The advantage of using mathematical models in this case is their capability to illustrate the performance of the CHP machineries and their operational constraints at different loads for further studies. Moreover, the integration of economical study is facilitated for different sizes of CHP machineries. The problem is stated as a linear programming (LP) problem, which facilitates setting up objective functions and constraints and is sufficiently accurate in presenting the partial operation of the components and their fuel consumption [13] [24]. Baseline scenario with SHP is modelled as well to give more insight regarding potential improvement. MATLAB is used as a software tool to simulate different decision alternatives.

3.2 Case Study

An Australian manufacturing site is used in order to demonstrate the application of the methodology. Factory level energy demand profiles of a manufacturing plant were generated for this purpose. In general the studied site has a high share of steam demand for the sterilization processes and the electricity as the main driver of machineries. The generated data set covers the time horizon of one year based on 15 minutes sampling interval and integrates both electricity and heat demand in the form of steam. Additional data sets with different aggregation times namely hourly, daily, weekly, monthly and annually are subsequently generated based on 15 minutes interval data set. Figure 4 illustrates the value of power demand with different aggregation times in the course of two days. The value of the detailed aggregation time in covering the dynamic nature of the demand side is clear in this case. For instance although the average annual power demand for the studied site is around 1.4 MW, the base load is 1.2 MW and the maximum demand is 2.9 MW. The aforementioned methodology for different sizes of CHP system is applied to each of these data sets for the course of 20 years based on the lifetime of the machinery.

In general, PEC and NPV are the main analysed variables for different CHP sizes between 800 to 2200 KW. Figures 5 (a) and (b) illustrate the impact of using data with different aggregation times for these two indicators. The results illustrate that more reliable and realistic behaviour of the onsite energy generation systems can be achieved by system simulation and use of detailed aggregation time data. In this case, based on the Figure 5 (a) using monthly data indicates much lower PEC in comparison with 15 minutes data. On the other hand Figure 5 (b) indicates the maximum NPV of 1.5×10^7 AUD regarding baseline scenario based on monthly energy demand data although 15 minutes energy demand data indicates

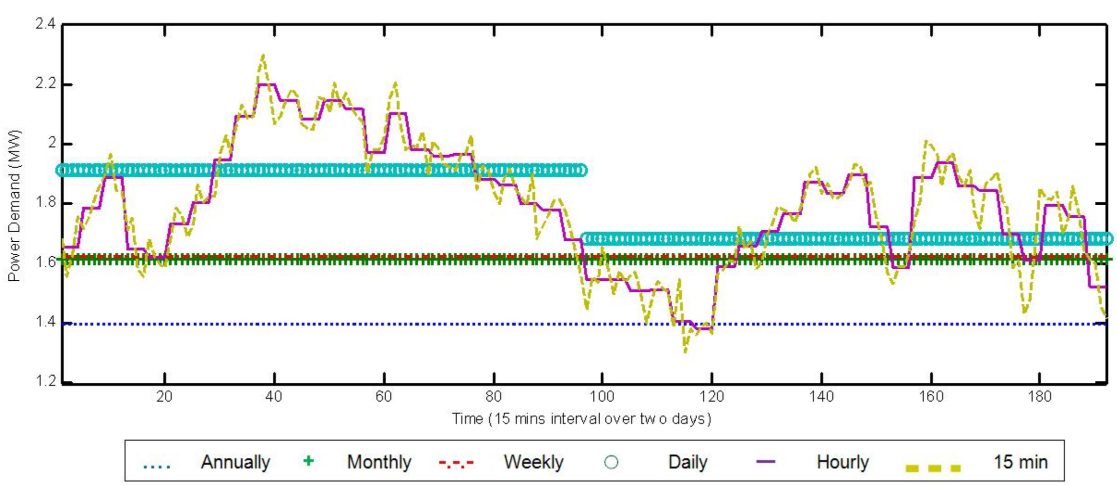
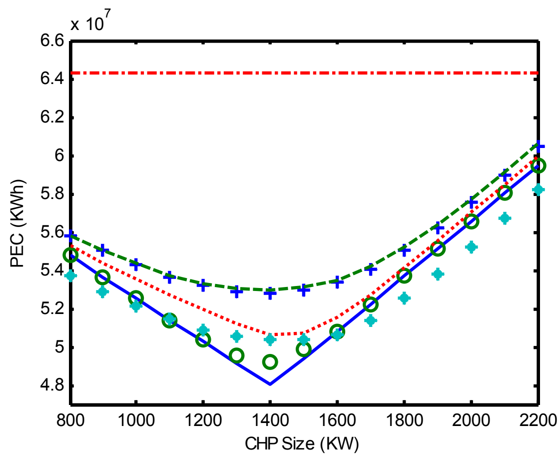


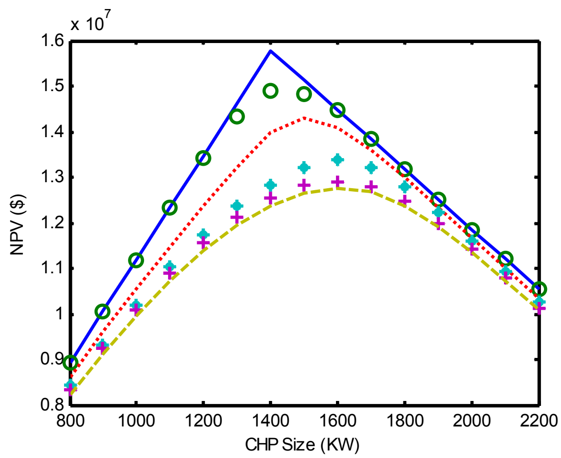
Figure 4: Power demand regarding different aggregation times.

lower NPV around 1.25×10^7 AUD. This is 16.6% lower than expected NPV.

In addition, this can be misleading when it comes to the point of CHP size selection to guarantee least operational cost and highest NPV. In this case monthly data indicates a CHP system with 1.4 MW as the best economical option in comparison with 1.6 MW based on the 15 minutes data. This discrepancy can be seen in case of system selection to minimize PEC. In this case, 1.5 MW CHP is the optimal option to guarantee minimum PEC, which might not be matched to the assumptions during the design stage based on annual or monthly data.



a) Primary energy consumption



b) Net present value

Figure 5: Analysis of PEC and NPV with different data resolutions against the CHP sizes.

On the other hand, the simulation results show that PESR increases by the size of the CHP machineries as it is illustrated in Figure 6. This is due to the reduction of the fuel to power output rate as the size of the CHP increases. In reality, this is in contrast with waste energy and real usage of output energy.

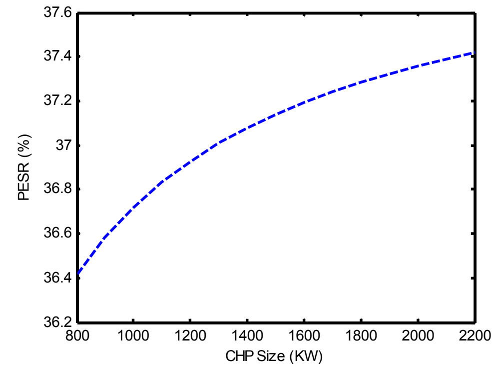
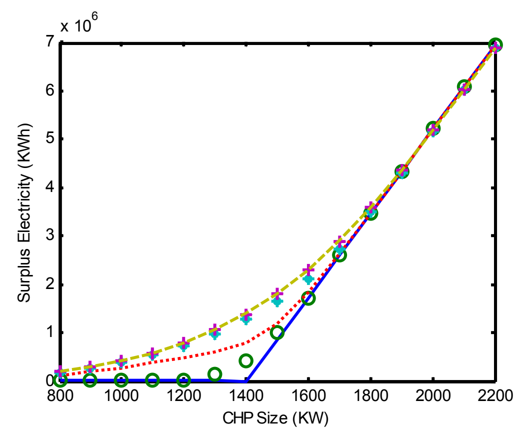
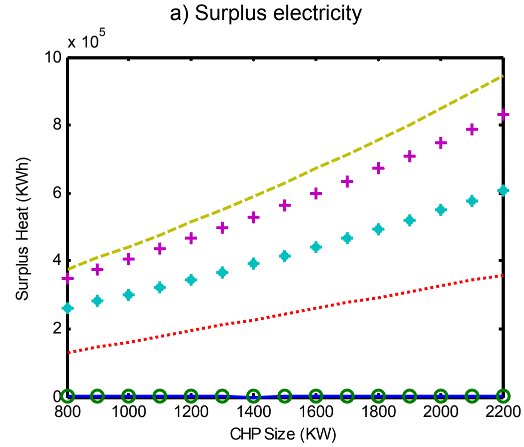


Figure 6: Primary energy saving ratio against the CHP sizes.

Figure 7 illustrates the surplus electricity and heat in case of continuous operation of CHP machineries, with the same legends as presented in Figure 5, which is ignored by the PESR indicator. From the surplus electricity graph, we can conclude that using annual or monthly data does not show the surplus electricity and heat generation during the lifetime of these machineries as it is assuming average constant demand. In addition, use of detailed aggregation time data can evaluate the hidden value of these factors, which can give more insight into the system configuration.



a) Surplus electricity



b) Surplus heat

Figure 7: Surplus energy against the CHP sizes.

4 CONCLUSION

In this paper a methodology, which can contribute to more sustainable application of onsite energy generation systems, was developed. In addition analysis of the energy resource consumption at manufacturing plants in presence of onsite energy generation system was carried out. This was accomplished by the simulation of CHP systems operation with different sizes over the time horizon of one year based on the electricity and heat demand historical data of a manufacturing plant. The proposed methodology is capable of encompassing the fluctuations of energy demand at any manufacturing plant. This can give more realistic evaluation of onsite energy generation systems. In addition, energy resource consumptions indicators and appropriate energy metering strategy were investigated.

Results demonstrated that although average data can give an approximate idea of the potential improvements and are easy to be generated but they eliminate the real impact of the system and can lead to erroneous decisions. Finally, usage of more appropriate energy resource consumption indicators is evaluated. In this case, although PESR is an appropriate performance indicator for a general overview of the onsite energy generation systems but it doesn't cover the dynamic nature of energy demand in manufacturing plants. Moreover it does not reflect the existing potential of different operational strategies.

In this case, future work should be carried out to evaluate conjunction of the system sizing and different operational strategies such as electricity or heat following to improve both energy resource consumption and financial returns, which will be the future work of the authors.

5 ACKNOWLEDGMENTS

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6 REFERENCES

[1] Turner, W.C., 2004. Energy Management Handbook. Marcel Dekker.

[2] Petursson, G., Turner, W.C., (2001). Reducing facility operating costs through on-site generation of electricity. Energy Engineering, 98, 65.

[3] Arenas Guerrero, C., Wang, J., Li, J., Arinez, J., Biller, S., Huang, N., Xiao, G., (2011). Production system design to achieve energy savings in an automotive paint shop. International Journal of Production Research, pp.1–17.

[4] Herrmann, C., Thiede, S., Kara, S., Hesselbach, J., (2011). Energy oriented simulation of manufacturing systems - Concept and application. CIRP Annals - Manufacturing Technology In Press, Corrected Proof.

[5] Madlener R., Schmid C., (2003). Combined Heat and Power Generation in Liberalised Markets and a Carbon-Constrained World. GAIA - Ecological Perspectives in Science, Humanities, and Economics 12, pp. 114–120.

[6] Christian, G.S., (2011). Environmental report for Danish electricity and CHP (summary of the status year 2010).

[7] Wheeley, C., Mago, P.J., (2011). A Methodology to Conduct a Combined Heating and Power System Assessment and Feasibility Study for Industrial Manufacturing Facilities. ASME, pp. 631–639.

[8] Salgado, F., Pedrero, P., (2008). Short-term operation planning on cogeneration systems: A survey. Electric Power Systems Research 78, pp. 835–848.

[9] Midwest CHP Application Center, (2003). Combined Heat and Power(CHP) Resource Guide (No. Edition 2). University of Illinois at Chicago, Energy Resources Center.

[10] Ren, H., Gao, W., Ruan, Y., (2008). Optimal sizing for residential CHP system. Applied Thermal Engineering 28, pp. 514–523.

[11] Wheeley, C.A., Mago, P.J., Luck, R., (2011). A Comparative Study of the Economic Feasibility of Employing CHP Systems in Different Industrial Manufacturing Applications. Energy and Power Engineering 3, pp. 630–640.

[12] Sanaye, S., Shokrollahi, S., (2004). Selection and Sizing of Prime Movers in Combined Heat and Power Systems. ASME, pp. 613–621.

[13] Marshman, D.J., Chmelyk, T., Sidhu, M.S., Gopaluni, R.B., Dumont, G.A.,(2010). Energy optimization in a pulp and paper mill cogeneration facility. Applied Energy 87, pp. 3514–3525.

[14] Ashok, S., Banerjee, R., (2003). Optimal operation of industrial cogeneration for load management. IEEE Transactions on Power Systems 18, pp. 931 – 937.

[15] Jaffe, A.B., Stavins, R.N., 1994. The energy-efficiency gap What does it mean? Energy Policy 22, pp. 804–810.

[16] Koopmans, C.C., te Velde, D.W., (2001). Bridging the energy efficiency gap: using bottom-up information in a top-down energy demand model. Energy Economics 23, pp. 57–75.

[17] Kara, S., Bogdanski, G., Li, W., (2011). Electricity Metering and Monitoring in Manufacturing Systems, in: Hesselbach, J., Herrmann, C. (Eds.), Glocalized Solutions for Sustainability in Manufacturing. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 1–10.

[18] Rohdin, P., Thollander, P., (2006). Barriers to and driving forces for energy efficiency in the non-energy intensive manufacturing industry in Sweden. Energy 31, pp. 1836–1844.

[19] Fumo, N., Mago, P.J., Chamra, L.M., (2009). Analysis of cooling, heating, and power systems based on site energy consumption. Applied Energy 86, pp. 928–932.

[20] Cho, H., Mago, P.J., Luck, R., Chamra, L.M., (2009). Evaluation of CCHP systems performance based on operational cost, primary energy consumption, and carbon dioxide emission by utilizing an optimal operation scheme. Applied Energy 86, pp. 2540–2549.

[21] Bogdanski, G., Spiering, T., Li, W., Herrmann, C., Kara, S., (2012). Energy Monitoring in Manufacturing Companies – Generating Energy Awareness through Feedback, in: Dornfeld, D.A., Linke, B.S. (Eds.), Leveraging Technology for a Sustainable World. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 539–544.

[22] Frangopoulos, C.A., (2012). A method to determine the power to heat ratio, the cogenerated electricity and the primary energy savings of cogeneration systems after the European Directive. Energy 45, pp. 52–61.

[23] Directive 2004/8/EC of the European Parliament and the Council on the promotion of cogeneration (2004), Official Journal of the European Union, L 52/50-L 52/60.

[24] Savola, T., Keppo, I., (2005). Off-design simulation and mathematical modeling of small-scale CHP plants at part loads. Applied Thermal Engineering 25, pp. 1219–1232.

Impact of Process Selection on Material and Energy Flow

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Abstract

Within the four-wall of a manufacturing plant, different resources including material and energy are consumed across process chains in order to fabricate their raw materials into a finished product. The increased efficiencies will enhance their productivities by reducing their production cost from either consuming less resource, or increasing outputs through improving the performance of their processes and systems. Therefore, this research aims to demonstrate the impact of process selection towards the material and energy flow of a product by comparing two different process flows of a compression terminal. A material and energy flow model was developed and the material and energy hot spots were identified. The improvement of the reduction of the associated environmental impact was also demonstrated.

Keywords:

Material and Energy Flow; Process Flow; Carbon footprint

1 INTRODUCTION

As commodities prices keep rising and the competitiveness of a market continue to increase, many industries have been putting significant effort to improving their material and energy efficiencies of manufacturing processes and systems. Their main targets are often increasing productivity, reducing the production cost by consuming less resources and improving the manufacturing efficiency. This is owing to the fact that within the four-wall of a manufacturing plant, various resources are consumed across process chains in order to transform raw materials into a finished product.

Resources include different materials, energy sources, labour, machines and infrastructure such as supporting system and facilities. To improve the efficiencies of these resources, various factors have to be systematically monitored in a holistic view for the manufacturing system. The system generally starts from purchasing raw materials from suppliers until manufacturing processes a finished product is produced and delivered to customers.

Many studies provided the methods and techniques to increase the energy and resource efficiencies in a manufacturing plant as systematically reviewed by Duflou et al [1]. Different approaches can be employed in different levels; namely a unit process, multi-machine, factory, multi-facility and supply chain levels. Herrman et al [2] proposed an energy oriented simulation model that can be used for planning a manufacturing system to improve its energy efficiency in both unit process and factory levels. Wen et al [3] developed a prediction approach of eco-efficiency at a unit process level by focusing on energy consumption and carbon emission of a grinding process.

Obviously, such models and predictions require monitoring the material and energy flow within the manufacturing plant in order to identify the hotspots which are the high consumption processes. Thus, a number of studies investigated material and energy flows of many products and processes. For instance, Rodríguez et al [4] proposed a methodology to detect and suggest a solution to improve hotspots found in material and energy flows. Smith and Ball [5] qualitatively mapped material, energy and waste flows for a machining cell and identified the opportunities to improve environmental impact. Herva et al [6] employed the energy and material flow and evaluated an ecological footprint for a tailor factory. The investigation was also observed the improvement of the attempts to minimise the energy consumption during a cutting stage and using low power energy consumption lights and regulating the use of heating. Torres et al [7] analysed energy and material flow for the storage stage of clay used in making a roof tile. They found that the transportation caused the highest environmental impact due to the high fuel consumption from a lorry.

Consequently, energy consumption is strongly connected with greenhouse gases (GHG) including carbon dioxide and therefore it is a common variable to assess environmental impact with CO_{2eq} as a unit. As a result, several studies have analysed the carbon emissions within the manufacturing industry. Laurent et al [8] suggested that carbon footprint should be used as an environmental performance indicator on a case-by-case basis. This is due to the fact that for some industries sector, other environmental impacts such as human health and toxicity may have higher damages.

For example, Kara and Manmek [9] demonstrated the impact of supply chains towards the embodied energy of different types of products. Jeswiet and Kara [10] demonstrated that a manufacturer can estimate the carbon emitted by their manufacturing processes and their products. The energy consumed in making a part is the summation of energy consumed by each manufacturing process and the ancillary energy used by supporting systems such as pumps and cooling media.

Much research tends to observe an existing process flow and attempted to identify the improvement opportunities. However in practice, an identical product may go through different process flows. Often, manufacturing system behaviour dynamically depends on customer demand and resource availability.

Therefore, this paper presents the impact of process selection towards material and energy flows of a manufacturing plant using the compression terminal as a case study. An overview of the methodology and a background of two process flows are provided in the next section. Results and discussion are presented by portraying the developed model, identified hot spots and compared carbon footprint results.

2 METHODOLOGY

2.1 Overview

The material and energy models of two different process flows of a product called a compression terminal produced by Preformed Line Products (Australia) Pty Ltd (PLP) were developed by three main steps. These steps are data collection, data conversion and model development as shown in Figure 1.

First, the data collection involved visiting PLP manufacturing plant and collect related data sources such as plant layout, bills of materials (BOM), production schedule and utility bills. Second, the collected raw data were then processed by mapping all process flows. All inputs and outputs of each process were identified such as types of consumed materials and energy as well as released wastes. Subsequently, the quantities of the inputs and outputs were calculated based on an annual production of a compression terminal in 2010. Finally, the models were developed using the converted data.

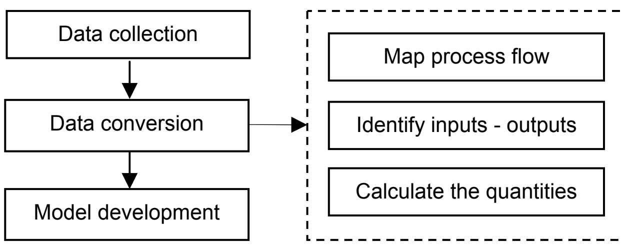


Figure 1: Model development.

2.2 Background of a Product and the Two Process Flows

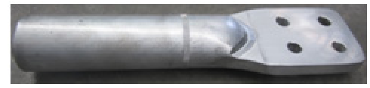
Aluminium compression terminals in Figure 2 are used as fittings for a power transmission. The geometries include two main sections which are a tube and a flat section with holes for fasteners. These compression terminals can be manufactured by using two different approaches namely:

- Forged compression terminal (Forged CT)
- Welded compression terminal (Welded CT).

These two approaches are currently used by the company to accommodate two different production volumes. The Forged CT is used when the large order is received while Welded CT is used for a small order to avoid the high set-up time of the forging process.

Materials and processes involved in these two approaches are summarised in Table 1. The actual process flows can be viewed in the next section. Both approaches are made from an aluminium tube. Generally, Forged CT is manufactured by cutting, heating and forged aluminium tube while Welded CT is made by welding two pieces of a flatten aluminium tube and a flat aluminium piece together.

There are common processes that both approaches used such as cutting the aluminium tube into a desired length and punching holes. Main different processes are also provided in the table. They are the forming process namely the heating and forging processes for Forged CT as well as flatten tube and welding processes of Welded CT.



Forged CT

Welded CT

Figure 2: Forged and welded compression Terminals [11].

Description	Forged CT	Welded CT
Materials	Aluminium tube	Aluminium tube
Example of common processes	Such as cutting, punching and deburring holes	
Main different processes	Heating and forging	Flatten tube and welding
Supporting system	Transport	Transport
Energy sources	Electricity and natural gas	Electricity and welding gas

Table 1: Input data summary.

Based on the readily available data, the methodology included only transport as the supporting system while technical building service (TBS) such as air compression and water used by cooling tower were excluded. In addition to electricity being their main energy source, natural gas is used for Forged CT and welding gas is used by Welded CT.

After the raw data was collected from PLP, the data conversion was carried out by obtaining raw material types and quantities from BOM. The inputs for each manufacturing process were quantified by direct measurement of its material weight and the multiplication of nominal power consumption and its estimated operating hours.

2.3 Material and Energy Flow Model Development

Two material and energy flow models of the Forged CT and Welded CT were developed using Umberto 5.5 software [12] as presented in Figure 2 and 3 respectively in the following section. The square symbol represents the processes where the green and red circles represent inputs and outputs of the processes respectively. To simplify the presentation of the model, a subnet (double square symbol) was created to model the detailed processes such as Process 1 to 3. The energy supplies were modelled distinctively. An example of the electricity supply is shown in Figures 2 and 3.

2.4 Carbon Footprint Assessment

Once the models were developed, the carbon footprint of the two approaches was analysed based on the functional unit of the production of 100 pieces of Forged CT and Welded CT. The Umberto 5.5 software [12] was used to assess the carbon footprint assessment. The ecoinvent 2.2 database [13] was employed as the Life Cycle Inventory (LCI) database and the CML2001 method [14] was applied as the life cycle impact assessment (LCIA) method.

The IPCC GWP 100a results obtained from CML2001 was used as the carbon footprint results to represent GHG emissions. This environmental impact category was selected to highlight the electricity in Australia which largely consumes coal as the main energy source. Moreover, aluminium is also an energy intensive material as it uses high energy during the extraction process. The hotspot analysis was conducted by reviewing the materials and energy distributions for each process.

3 RESULTS AND DISCUSSION

This section presents the results of the developed material and energy flow models in the following subsections. The subsections are divided into the material and energy flow models and the electricity distribution, the hotspot analysis and the carbon footprint results.

3.1 Material and Energy Flow Models

Due to the confidentiality of data, Figure 2 depicts the material and energy flow model for Forged CT as process 1 to 12 which are presented in four subnets. The main raw material is the aluminium tube which is transported from a supplier to a storage location. Then, the tube is gone through process 1 to 12 (purple line) and the compression terminal is produced and ready for delivery. Other raw materials are named as component 3 and 4. Figure 3 shows another material and energy flow model developed for Welded CT. In this case after process 1 to 3, two main flows of aluminium tube go

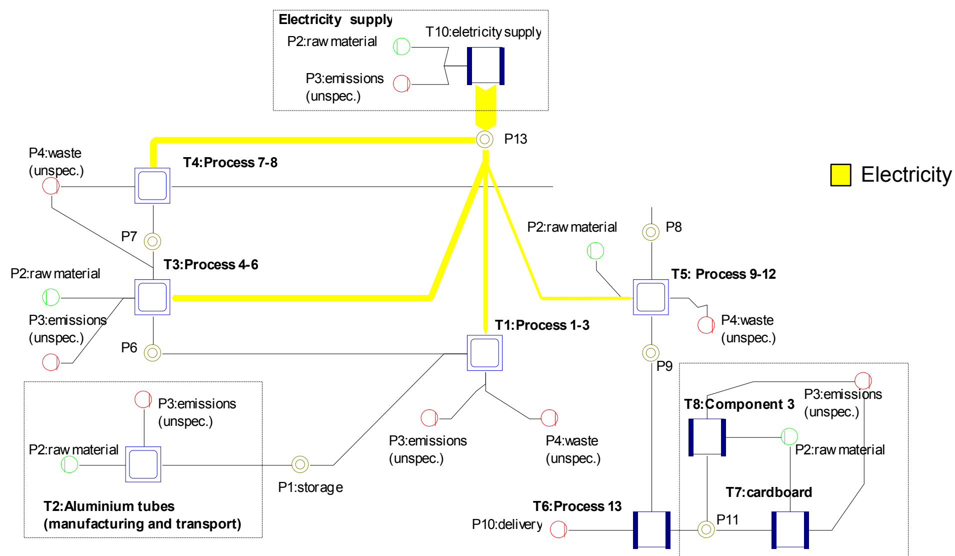


Figure 2: Forged CT material and energy model with a displayed of electricity flow.

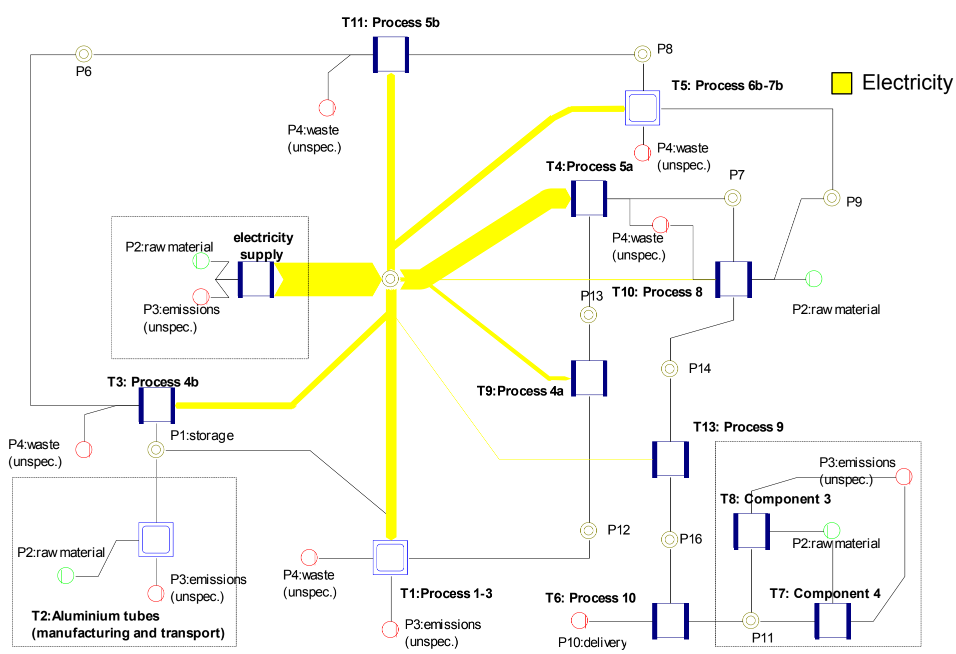


Figure 3: Welded CT material and energy model with a displayed of electricity flow.

through process 1) 4a to 5a and 2) 4b to 7b (grey line). Then, the two main flows are joined together at process 8 and continued with process 9 to 10.

3.2 Hot Spot Analysis

Figures 2 and 3 also show a Sankey diagram where the width of the yellow line represents the contribution of an electricity distribution to different processes [12]. According to the diagrams, electricity hot spots are observed. The main hot spots In Figure 2 are highlighted in two subnets of process 4 to 6 and process 7 to 8 for Forged CT. On this occasion, process 6 and 8 were the main contributors. Likewise, Figure 3 reveals that process 5a has consumed the highest electricity followed by the subnet of process 1 to 3 and process 5b.

In terms of the hot spots for the material consumption, the aluminium waste was analysed. Most aluminium waste (red line) is produced during process 1 for both forged and welded approaches as presented in Figure 4. This is owing to the cutting process of the aluminium tube (grey think line) into a desired length. The next contributors are process 9 for Forged CT and process 6b to 7b for Welded CT.

The comparisons of energy and material consumptions of Forged CT and Welded CT are demonstrated in Figure 5. Forged CT consumes less electricity than Welded CT by 13%. Forged CT is the only approach that uses significant amount of natural gas to support the heating process. The weld gas has a minimal impact for the welded CT due to the short welding time. The impact from the fuel consumption is similar for both approaches. For the aluminium waste, Welded CT produced less amount of waste than Forged CT by up to 70%. This is due to the cutting process of Forged CT that removes significantly higher amount of aluminium waste than Welded CT.

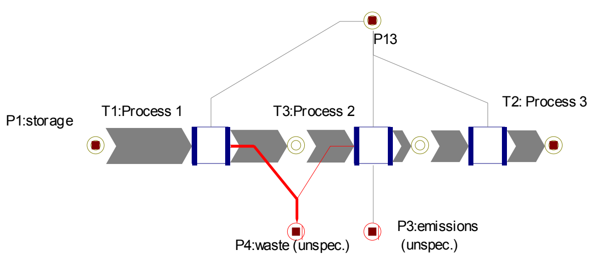


Figure 4: Hot spots of aluminium waste.

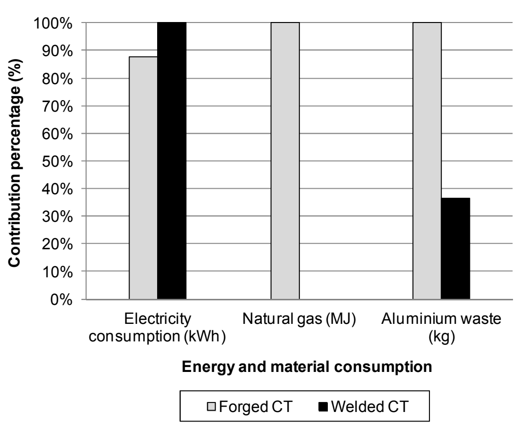


Figure 5: Comparison of the contribution percentage for the energy and material consumptions of the forged CT or welded CT.

The findings of the hotspots provide were validated and agreed with an expert at PLP. These results encourage the company to investigate further the root causes of the identified hotspots.

3.3 Carbon Footprint Results

The carbon footprint results for Forged CT and Welded CT are presented in Figure 6. Although, Forged CT consume less electricity than Welded CT as shown in Figure 5, forged CT results in 20% higher GHG emission than Welded CT. This is largely due to the high consumption of natural gas during the heating process. According to Figure 6, there are approximately 65% of GHG contributed by the pre-chain of the aluminium tube and another 35% is produced within the manufacturing plant. The carbon footprint of the compression terminal can be reduced further by reducing the amount of aluminium waste.

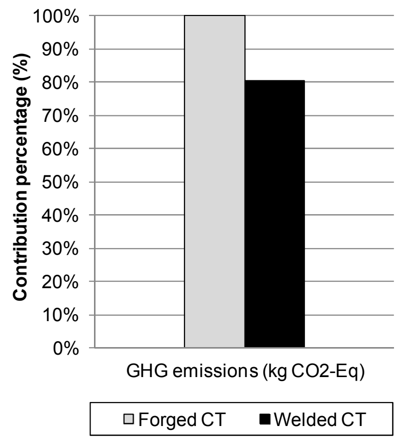


Figure 6: Contribution percentage for the carbon footprint results.

3.4 Uncertainties and Limitations

There are a number of uncertainties that can be discussed for the two material and energy models. Firstly, the models base on estimations of the electricity consumption of the machines used for each process. This estimation was calculated based on the nominal power consumption from the machine's asset plate and the operating hours. This nominal consumption represents the maximum power consumption and is normally used for dimensioning the electricity grid. However, in reality the actual electricity consumption could be significantly less than the estimation. A simple test was made by an actual measurement of a cutting process. It was found that the actual power consumption could be 80% to 90% less than the estimated calculation. However, this limitation is true for all processes which still allow a valid relative comparison.

Secondly, the operating hours were estimated using the work order database and engineering reports. Certainly, this database just provides a selected extract for a specific period of time and data may vary depending on production program, utilisation et cetera. Additionally, theoretical, planned time is used for operation machines which may not reflect the actual operation in the manufacturing plant.

Lastly, the material and energy consumptions of the TBS such as air compression, cooling water, lighting and the HVAC system are currently excluded. This is due to the limitation of the data which was a challenge to allocate the consumptions of each TBS item into a particular product. TBS is generally used for an entire manufacturing plant which is also concurrently manufacturing other products.

According to the mentioned uncertainties and limitations, the results of the findings in this paper are limited to a theoretical calculation which may be varied in practice. Nonetheless, they provide reasonable guidance for further improvements.

4 SUMMARY

The research has investigated the material and energy flows of a product, a compression terminal which is made by two process chains – the first one focuses on forging whereas the second one uses welding. Two material and energy flow models were developed which were used to identify the hot spots of both energy and material consumptions. As a result, it was found that the forging approach used less electricity the welding approach.

The main energy hotspot was found in the heating process where significantly high amount of natural gas is used. The main material hot spot was found in the cutting process which resulting in creating higher amount of aluminium waste in the forging approach. The carbon footprint was also analysed to show that the forged CT is 20% higher than the welded CT. This is substantially due to the high consumption of the natural gas.

Currently, there are a number of uncertainties that could alter the results due to the lack of technical data for the actual production and the TBS. Future work can be carried out further by carrying out actual measurements of the electricity consumption of each machine and also including the cost and production volume data to identify the optimal trade-off and threshold for the production parameters between these two approaches.

5 ACKNOWLEDGMENTS

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6 REFERENCES

[1] Duflou, J.R., Sutherland, J.W., Dornfeld, Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M., Kellens, K. (2012): Towards Energy and Resource Efficient Manufacturing: a Processes and Systems Approach, CIRP Annals - Manufacturing Technology, Vol. 61, Iss.2, pp. 587-609.

[2] Herrmann, C., Thiede, S., Kara, S., Hesselbach, J. (2011): Energy Oriented Simulation of Manufacturing Systems – Concept and Application, CIRP Annals - Manufacturing Technology, Vol.60, Iss.1, pp. 45-48

[3] Li, W., Winter, M., S., Kara, Herrmann, C. (2012): Eco-Efficiency of Manufacturing Processes: A Grinding, CIRP Annals - Manufacturing Technology, Vol.61, Iss.1, 2012, pp. 59-62.

[4] Rodríguez, T.M.T., Andrade, C. L., Bugallo, B. P.M., Long, C.J.J. (2011): Combining LCT Tools for The Optimization of an Industrial Process: Material and Energy Flow Analysis and Best Available Techniques, Journal of Hazardous Materials No.192, pp.1705– 1719.

[5] Smith, L., Ball, P. (2012): Steps Towards Sustainable Manufacturing through Modelling Material, Energy and Waste Flows, International Journal of Production Economics, No. 140, pp. 227–238.

[6] Hervaa, M., Álvarezb, A., Roca, E. (2012): Combined Application of Energy and Material Flow Analysis and Ecological Footprint for the Environmental Evaluation of a Tailoring Factory, Journal of Hazardous Materials, No. 237–238, pp. 231– 239.

[7] Torres, T.M., Barros, C.M., Bello, P.M., Casares, J.J., Rodrı´guez-Blas, M.J. (2008): Energy and Material Flow Analysis: Application to the Storage Stage of Clay in the Roof-Tile Manufacture, Energy No.33, pp. 963–973.

[8] Laurent, A., Olsen, S.I., Hauschild M.Z. (2010): Carbon Footprint as Environmental Performance Indicator for the Manufacturing Industry, CIRP Annals - Manufacturing Technology, Vol.59, Iss.1, pp. 37-40

[9] Kara, S., Manmek S. (2010): Global Manufacturing and the Embodied Energy of Products: CIRP Annals - Manufacturing Technology, Vol. 59, No. 1, pp. 29-32.

[10] Jeswiet, J., Kara, S. (2008): Carbon emissions and CES™ in manufacturing, CIRP Annals - Manufacturing Technology, Vol.57, Iss.1, pp. 17-20.

[11] Malewski, A. (2012): Material and Energy Flow Modelling of a Manufacturing Plant: Preformed Line Products (Australia) Pty Ltd, Technical report, Joint German Australia Research Group.

[12] www.umberto.de: access date: 23/November/2012.

[13] Ecoinvent Centre. 2010. The life cycle inventory data version 2.2.

[14] Centre of Environmental Science. 2001. Life Cycle Assessment – An operational guide to ISO Standards, Leiden University.

Generic Energy-Enhancement Module for Consumption Analysis of Manufacturing Processes in Discrete Event Simulation

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Abstract

Customer demands for eco-friendly goods, energy supply bottlenecks or consumption/emission restrictions in many countries, as well as the current economic situation demand a conscious use of energy in industry. Manufacturers and suppliers need to increase efficiency of their products, processes and resources dramatically in order to reach agreed energy targets. To achieve substantial reductions it becomes necessary to establish predictive assessments of the energy demand for new production systems and whole manufacturing sites as standard operating procedures in systems engineering. This paper discusses a newly developed, generic energy-enhancement module, which renders resource consumption analyses within material flow simulation software possible.

Keywords:

Energy efficiency; Simulation; Production planning; Digital factory

1 INTRODUCTION

Expected supply shortages for raw materials and energy carriers (i.e. oil) do not just propagate the inflation on international markets, they also influence customer's and manufacturer's consciousness toward sustainable production. Hence, the demand for eco-friendly goods is increasing. Especially larger manufacturing companies have developed an intrinsic motivation to realise environmentally benign production processes. Apart from the afore-mentioned customer demands, major motivators for this are regulatory mandates, competitive economic advantages, and the desire for proactive green behaviour [1]. In order to reach such ecological aims, the conscious use of energy in production processes is vital.

The shift towards regenerative (e.g. solar) and away from conventional (e.g. nuclear) energy sources, as decreed in Germany and Japan, is another promoter for environmentally benign manufacturing. Concerns regarding energy supply bottlenecks are already being reported with increasing frequency in these countries. Especially German manufacturers become anxious about their economic advantages provided through the stable energy supply net. Regarding these circumstances, it is all the more important for manufacturing companies around the world to consciously utilise natural resources and energy in particular. Hence, the improvement of energy-efficiency whilst retaining productivity is of supreme interest in R&D. For this purpose different levels of analysis can be considered [2]. The hereafter discussed approach focuses on multi-machine system as well as facility level.

Predictive assessment of energy demands for new or replanned production systems is of considerable importance in this regard. However, holistic studies can only be conducted if all energy flows, as well as their sources and drains are considered. While it is common practice, to examine and predict material flows in existing or planned manufacturing systems with specific tools following a discrete event simulation (DES) approach, energy flows are usually disregarded. This paper discusses a newly developed, generic energy-enhancement module, which enables resource consumption analyses using a material flow simulation software system.

For this purpose, a set of requirements is formulated partially based on preliminary publications by other researchers (section 2). Their implementation is outlined in section 3. Afterwards, various use cases employing the developed generic module illustrate the potential it promises for industry and research alike.

2 TOWARDS A GENERIC ENERGY-ENHANCEMENT MODULE

The introduction of energy-related considerations into DES tools has been investigated by a considerable number of researchers in recent years. However, none of the published efforts focused on the users of such software or their workflows. The approach discussed in this paper aims at closing this gap by combining ideas from existing approaches with common user requirements, both of which are elaborated hereafter.

2.1 Categorising the Features of Existing Approaches

Due to the diversity of published approaches on this matter, a multitude of ways for categorising them exists. A selection of these is elaborated hereafter. One attempt at categorising approaches has been made by Thiede, who distinguished the individual contributions by their general setup [3]. Accordingly, the three identified paradigms are:

- Coupling of DES and external evaluation layer,
- (dynamic) coupling of DES and further simulation approaches plus internal or external evaluation layer, and
- DES and evaluation in one application.

These paradigms already imply certain benefits and disadvantages of the corresponding approaches. More particularly, coupling different pieces of software is usually associated with a more complex experimental setup as well as the necessity to define and implement interfaces for the interaction of individual tools. Hence, planning work flows need to be adjusted considerably in order to incorporate energy considerations.

With respect to their intended purpose, the existing approaches differ in the level of detail for the modelling of energy consumption. The most fundamental method is to define operation states and assign a constant consumption for the time an operation state is active (e.g. [4][5]). A more refined approach has been developed by Rager, who split complex processes with varying energy demand into sub-processes, so that the temporal overlay of highly consumptive tasks became apparent [6]. With special regard to the load profile of moving industrial robots, M-profiles have been employed in [7]. Junge aimed for a higher level of detail and metered the consumption of existing machines and linearised the results as a piecewise function [8]. The most flexible approach, on the other hand, has been published by Weinert et al., who use generic EnergyBlocks that emulate the consumption during a certain operation state [9].

A major concern is the acquisition of data for the determination of necessary parameters. Although first approaches for metering energy consumption exist (e.g. [10]), the data acquisition process becomes more complex the more complex the modelled profile is. Hence, a "dilemma of the level of detail and necessary effort in terms of time and costs" exists [11].

Another difference between existing approaches becomes apparent with respect to the regarded energy carriers. While some authors only model the consumption of electricity (e.g. [6][9]), others highlight the importance of including all energy carrying media and infrastructure services (e.g. [3][5]). Considering all forms of energy provisioning fundamentally increases the level of detail and thus the potential for improvements. However, at the same time more effort has to be invested in the afore-mentioned data acquisition process. Further application of thermal building simulation software has also been demonstrated [8], although it required the combination of different simulation tools.

Extensibility is another important issue for the development of a ready-to-use solution that is applicable across different companies and industries. Most published approaches are either not very generic or their enhancement requires a considerable amount of know-how and effort. Two different general approaches can be identified in this regard. On the one hand there are very specific approaches tailored for a defined use case [6][7][8][12], on the other there are those that aim to be extensible frameworks [3][9][13][14][15]. The latter are generally better suited for the application in different use cases, however, data acquisition is a major concern. In case of Thiede's approach TBS (technical building structure) modules need to be created for each type of TBS [14], which increases the necessary effort for new extensions.

2.2 Requirements from a User's Point of View

The previous subsections already discussed shortcomings and issues of existing approaches. Keeping these in mind, requirements for the development of a novel energy-enhancement module, which pay heed to common industry workflows and user concerns, are discussed hereafter.

Following the general aim of the 'Digital Factory', all relevant flows within a production facility should be modelled and considered. This includes the flow of materials as well as that of electric energy or other process media (e.g. compressed air, cooling water etc.). In addition, other production prerequisites such as lighting and ventilation need to be considered for a holistic study of the energy consumption. Some other authors already identified the importance of this matter [3][5]; hence, it is the first requirement to be taken into account.

A major concern for manufacturing companies when altering their planning processes is the ratio of additional benefit to increased costs [7]. Collecting detailed information on load profiles of equipment and parameterising these into a simulation is a tedious and thus expensive task. Accordingly, a simple approach shall be followed in this work. More specifically, the user should be free to define an arbitrary number of operation states. For each of these a specific input and output has to be be defined. Figure 1 exemplarily depicts this connection between the operation states of a piece of equipment and its energy consumption, i.e. input. This fundamental approach has also been suggested in [16], although for sake of simplicity and performance, static consumption and provisioning are assumed. Individual states further need to be either set by a controlling instance or – in order to be able to correctly model a consumption increase while processing material – triggered by entering material. It is further necessary that these state transitions can be parameterised to require a certain time. Bearing these requirements in mind it is possible to limit the necessary effort for parameterisation as well as the simulation time while allowing for maximum flexibility.

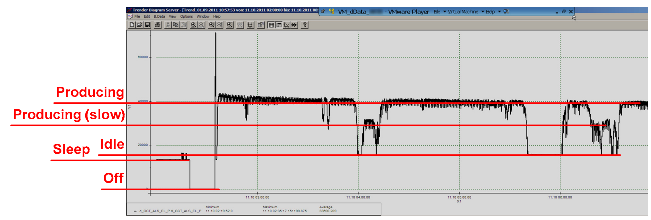

Figure 1: Exemplary equipment energy consumption with corresponding operation states (source: InnoCaT®, 2011).

In order to retain efficiency in planning processes, it is vital that an energy-enhancement module integrates seamlessly into existing tools, models and workflows. Siemens Tecnomatix Plant Simulation has a dominant role in the automotive sector but is also being used in other industries. Hence, the new module shall be implemented in this software in a way it may also enhance the VDA Automotive Toolkit (see [17]). According to Thiede's classification, the paradigm is to integrate DES and evaluation into a single tool so that no additional interfaces are necessary for basic functionality.

Following a system theory approach, both energy consumers as well as suppliers can be described using a formal component model, as depicted in Figure 2. Consequently, only one module should be used for modelling energy sources and drains, creating a fully generic enhancement for the simulation of energy or other media flows. These should enhance existing modules providing material flow related functionalities.

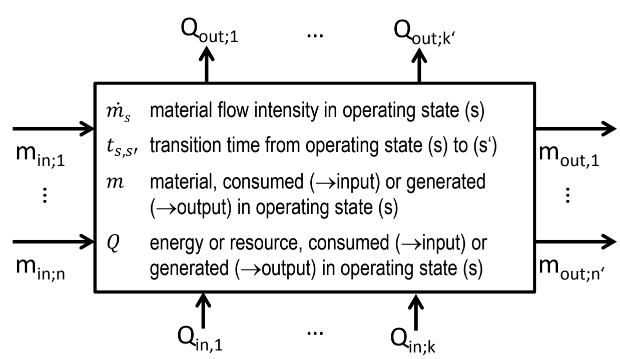

Figure 2: Characterised components of production, production infrastructure and building infrastructure.

Another requirement is that the developed module can be used to validate new approaches to production control and energy aware software tools. These kinds of studies are important for increasing the energy-efficiency of new or existing production systems and decreasing development costs for new methods, strategies and solutions.

3 IMPLEMENTING A GENERIC ENERGY-ENHANCEMENT MODULE

Previously, a number of requirements for the development of a novel energy-enhancement module have been defined. This section discusses how these were implemented in Plant Simulation.

First of all, the hereafter described approach consists of three basic module classes, one for collecting and evaluating data, one for configuration purposes as well as one for providing actual energy related functionalities – the generic energy-enhancement module or eniBRIC. While the latter has to be instantiated once for any regarded component, the earlier two only need to be instantiated once per model. Either of these is a frame with specific methods and information objects (i.e. tables, lists, or variables) which provide the necessary functionality. eniBRIC instances can exist just by themselves as components of infrastructure or along with material flow objects (e.g. SingleProc) as components of production. Independent of this difference, all methods realising energy related functionality remain unchanged. In order to enhance an existing material flow object, some of its sensor method calls (e.g. for entering material) have to be relayed to specific methods of eniBRIC.

Figure 3 depicts how the three basic modules interact with one another. For this purpose, the focus is set on an instance of the generic module for a component of production. The arrows indicate what kind of information is being transmitted during run time. In particular, the data collection and evaluation module receives information concerning which resources or media are considered from the configuration module. It further receives information on consumed media and energy from each instantiated component. Collected data can be evaluated from within the Plant Simulation model or be exported for further processing and analysis.

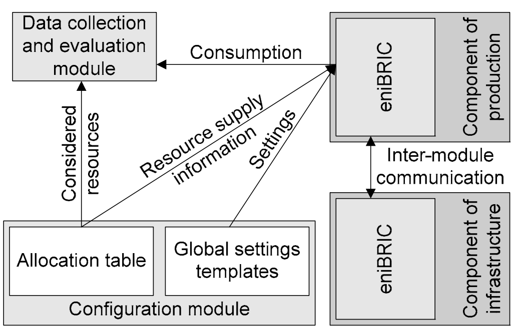

Figure 3: Interaction of the various modules.

The configuration module provides both global settings templates and an allocation table. On model initiation the earlier are utilised to centrally configure a variety of flags influencing the behaviour of all instantiated generic modules during run time. Additionally, the allocation table allows for defining which consuming component obtains any regarded resource or media from which supplier. Hence, its descriptive function is similar to that of a transport matrix. By means of this table it is possible to easily and dynamically configure supplier-consumer-relationships in a central place.

Individual instances of the generic module communicate with one another (inter-module communication) in order to determine whether the remaining capacity of a regarded resource is sufficient for a state transition and to report a change of demand. The amount reported and required is defined by the current operation state or the one to be transitioned into. For this purpose, each instance of eniBRIC needs to be configured with a set of operation states. These are defined by their transition times (see below), resource demand and – if applicable – resource supply capacity as well as material in- and output. The number of regarded resources or media and operation states is unlimited. In order to be able to distinguish the demand between states such as ‘ready for production’ (‘idle’) and ‘producing’, it is possible to pair any two states. This allows for the active state to transition into the higher consuming one as soon as material enters the corresponding material flow station. When material departs the component, i.e. after a work on a part has concluded, the operation state is reverted back to ‘idle’.

Any other change of operation state is induced by either external control systems (via interfaces) or control mechanisms within the model. Either has to call a defined interface method which initiates the actual operation state transition. The latter is only processed entirely, if the necessary process requirements, i.e. resources, are available. Otherwise, a transition will only commence after all requirements have been fulfilled. Once it is started, it requires a parameterised amount of time to complete. During the time of transition (t_{down} & t_{up}) the higher demand is required and the lower output is available (see Figure 4). Other authors use a greater level of detail for modelling warm up processes and other specific effects of transitions (e.g. [14]), however, this increases the necessary effort for the data acquisition and is not always exact. For instance, warm up processes are highly dependent on the difference between initial and targeted temperature of the machine which, in turn, is dependent on the building temperature, time since last and time of last operation etc. Accordingly, the approach described here favours ease-of-use over maximum level of detail.

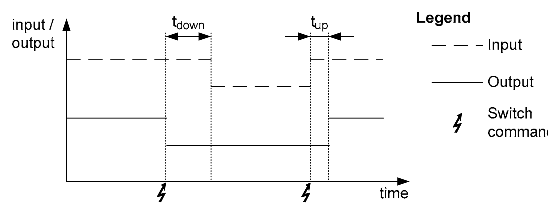

Figure 4: Input and output during transitions.

In addition to the afore-mentioned switching capability for operation states, each instance of the generic module holds capability to collect and evaluate data. This allows for a localised view of consumed and supplied resources in addition to the global view provided by the data collection and evaluation module.

4 EXEMPLARY APPLICATIONS OF ENIBRIC

One of the requirements for developing eniBRIC was to create a fully generic module which can be utilised in a multitude of ways. In order to demonstrate this capability, the following subsections present different exemplary use cases that make use of eniBRIC.

4.1 Validating Approaches to Energy-Sensitive Production Control

The validation of new approaches for production control is difficult and expensive, if conducted in real manufacturing systems. Hereafter, the utilisation of DES and eniBRIC for this purpose is elaborated. The object of study is a shop floor containing multiple work groups (each consisting of multiple industrial robots) as well as multiple manual work stations. Figure 5 depicts the general structure of the regarded production system along with the considered ventilation (green) and lighting zones (yellow). This system is a clocked flow production where car bodies with either three or five doors are assembled.

Individual work groups are clustered to a total of eight complex subsystems. Each of these is set in an individual lighting zone and pairs of two supply the four work stations (WS1 to WS4) in the main line via conveyors (C1 to C8).

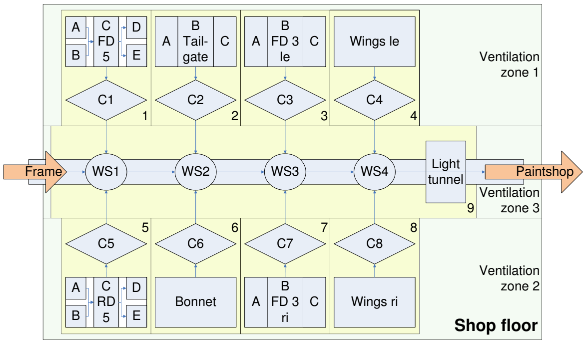

Figure 5: Structure of the simulated production system.

In order of the work stations the following parts are produced and mounted doors for vehicles with five doors front (FD) and rear (RD), tailgates and bonnets, left and right front doors for vehicles with three doors (produced separately), and left and right wings (produced separately). Additionally, a light tunnel exists in the main line where completed car bodies are inspected for imperfections.

Each work station, work group, or conveyor was modelled by integrating eniBRIC into elements from the VDA Automotive Toolkit [17]. The latter is a class library for Plant Simulation developed, maintained, and utilised by German automotive OEM. In addition to these components of production a variety of components of infrastructure was introduced. Specifically, suppliers for power (400 V and 690 V), pressured air (6 bar and 12 bar), laser light, cold water, cooling water, ventilation, smoulder suction, and lighting were instantiated in different quantities.

Convenient parameterisation was possible through use of the inherit functionality of Plant Simulation. Additionally, some features from the eniMES concept (see [18][19][20][21]) – an approach for the development of energy-efficient manufacturing execution system (MES) software – were implemented in order to control the operation states of all eniBRIC instances. In particular, an algorithm for shutting down and restarting individual subsystems has been conceived and implemented in an iterative process during which both the transition functionality of eniBRIC and the algorithm itself were verified. Figure 6 depicts an exemplary transition cascade for subsystem ‘FD 3 le’ and its interacting components that results from the execution of operation state switch commands generated as part of an examined production control approach. It should be noted that workgroup ‘FD 3 le B’ does not require pressured air at 12 bar, hence, it may start as soon as sufficient lighting is provided.

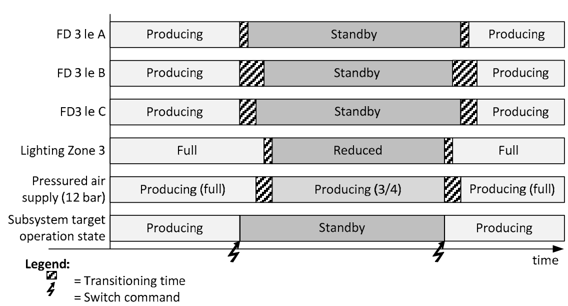

Figure 6: Transition cascade induced by eniMES algorithm.

Different approaches to energy-sensitive production control have also been implemented and examined in this model. Preliminary findings of this on-going research are discussed in [19] [20]. More recent findings did not just support the usefulness of eniBRIC for this kind of studies but also demonstrated that an energy-sensitive production control paired with advanced equipment control can save up to 18% electric energy usage while retaining high productivity in this exemplary production system [21].

4.2 Validating Energy Aware Software Tools

Novel approaches toward energy-efficient production control usually suggest to shutdown idle equipment in the shop floor. For this purpose, the eniMES framework developed by Fraunhofer IWU includes the eniCONTROL module, which provides corresponding algorithms (e.g. the one presented in the previous subsection). Validating these is an important part of the development process. However, recreating a multitude of scenarios with real equipment is usually too expensive and time consuming for which reason new development procedures, such as software-in-the-loop, are being employed. Quite similarly, virtual commissioning is being utilised to improve the quality of the realisation of planned production systems.

eniBRIC can be utilised for such studies and tasks. The hereafter discussed example is based on the simulation model from the previous subsection. Instead of employing emulations of eniCONTROL algorithms, the developed software is meant to determine the order of switch commands externally and execute them within the simulation model via an interface as well as a defined protocol (OPC DA).

A prerequisite for accomplishing these tasks is that a descriptive model of the production system as well as a certain set of parameters of the individual components is available to eniCONTROL. In order to allow for convenient parameter variation and to maintain a single data basis, this information is exported from the Plant Simulation model and imported into the eniMES framework prior to experiments. The resulting information flow for the validation of eniCONTROL employing eniBRIC is depicted in Figure 7.

Data exported from the simulation model using an XML interface is stored within eniLINK, which acts as eniMES’ data basis and integration platform. It is retrieved by eniCONTROL via an existing interface within eniMES. After determining new switch commands, the expected operation state changes of individual components are stored in eniLINK. They are further relayed to the model at the exact time, utilising the OPC DA interface available in Plant Simulation and an additional OPC DA server. Each instance of eniBRIC is represented by two OPC items, one for relaying the current target operation state to the model and one for providing status information on the currently active operation state. The latter can be stored in eniLINK for later reference. Whenever an OPC item changes, a method will be called within Plant Simulation which identifies the instance of eniBRIC that should switch to another operation state and starts the appropriate transition. The time synchronisation between the simulation and eniCONTROL is performed by means of additional OPC items signalling certain events, e.g. the beginning of a pause.

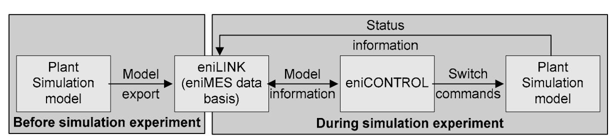

Figure 7: Information flow for eniCONTROL validation.

This experimental setup demonstrates how – in the context of virtual commissioning – novel energy aware software tools can be verified using eniBRIC. Erroneous transitioning cascades can be identified and the positive effects of utilising such new software (i.e. energy savings) can be measured.

4.3 Examining Equipment with Non-linear Consumption

For some studies it may be necessary to investigate the consumption of specific equipment in more detail. Furnace processes, for instance, generally have a high energy demand and occasionally consist of multiple phases with varying temperatures and thus multiple levels of consumption. This subsection discusses two approaches for modelling such equipment using the eniBRIC module.

The first example that has been investigated is the production of foam metal. An exemplary description of this process has been published in [22], where samples were first heated up to 120 °C and then up to 400°C. After being held at that temperature for some time the samples were finally heated to 1200 °C where they were then held again for some time. This process can be performed in a continuous furnace with three segments, one for each temperature level. Once all segments have been heated to their specific operation point, the power demand to maintain it is stable and depends on equipment losses and the necessary heat input of the samples. Accordingly, the furnace has been modelled in three individual segments, each consisting of a material handling station (i.e. SingleProc) enhanced with an instance of eniBRIC. Operation states are defined for each eniBRIC instance independently. It should be noted that the base load (i.e. the power demand when the furnace is in standby) should either be distributed evenly or assigned exclusively to one segment. Material enters the furnace ('ProdSystem') and is then routed through the individual segments where they remain for a predefined time. Figure 7 depicts this model in Plant Simulation.

Bars below the segments indicate the power demand scaled to the maximum demand of the three. Due to the fact that all eniBRIC instances operate individually, they cannot be controlled as one unit, i.e. operation state transitions have to be signalled to each segment. However, additional wrapper functions can be utilised to coordinate switch commands targeted at the furnace. Equipment failures have not been investigated in this example; however, the breakdown of a segment likely should affect all other segments.

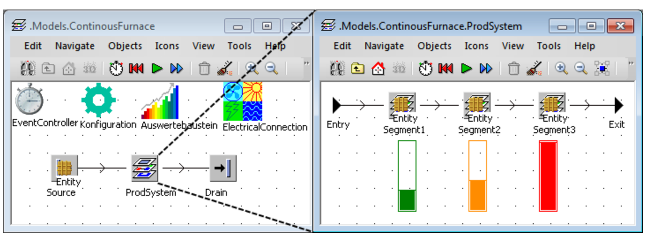

Figure 7: Model of a continuous furnace.

A second example investigates how processes with multiple operation levels can be modelled with only one instance of eniBRIC. For this purpose, a stationary furnace performing heat treatment for different variant parts has been simulated. The furnace consists of a single eniBRIC-enhanced material handling station, as depicted in Figure 9. All necessary operation states have to be defined prior to the simulation. The demand in each operation state can be determined by inspecting the targeted temperature profile. In general, three basic profiles can be differentiated:

- Heat up: energy input > energy loss
- Holding: energy input = energy loss
- Cool down: energy input < energy loss

The corresponding demands depend on the targeted temperature and – in case of heat up or cool down – the speed of the temperature change. Accordingly, all relevant profiles have to be identified and parameterised within the eniBRIC instance, quite similar to the EnergyBlocks described by Weinert et al. [9]. Furthermore, an order of states including the length, that each one of these shall be active, has to be defined for each variant part.

Figure 8 depicts the schematic temperature profiles of the heat treatment for the two hereafter regarded variants. In particular, 'Variant 1' has to be heated up, held at high temperature, cooled down to medium temperature, held again, and then cooled down. The heat treatment process for 'Variant 2' is less complex, i.e. the parts are only heated up, held at this high temperature and then cooled down again.

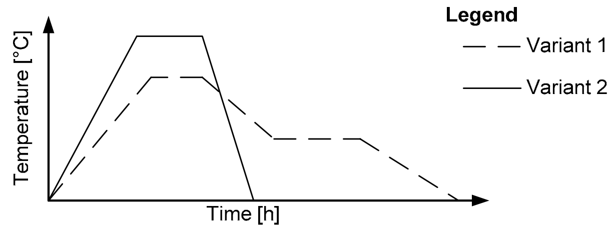

Figure 8: Schematic temperature profiles for two regarded variants.

When parts enter the material handling station they are inspected for their variant and the order of operation states along with the overall process time is determined. After work has commenced, eniBRIC receives switch commands every time a state transition is due, similar to the approach described by Thiede [14]. The cycle ends as soon as the overall process time is over, at which point the part leaves the station. These tasks are realised through additional custom methods. The resulting profile of consumption for two complete cycles for different variant parts as well as another ongoing cycle is also depicted in Figure 9. It should be noted that the absolute values shown are just exemplary.

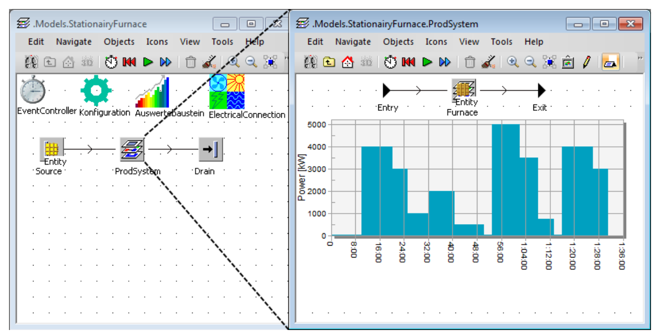

Figure 9: Model of a stationary furnace.

Equipment failures are not yet handled because it is difficult to determine the correct actions to be taken in heat treatment processes. While it may be sufficient to ensure that the overall time in each operation state has been reached, a part might just as well need to be scrapped or at least be subjected to another full cycle. Hence, this has to be investigated when conducting a study on a real existing furnace.

5 SUMMARY AND OUTLOOK

Manufacturing companies aim for environmentally benign production processes which can only be realised if holistic approaches to production (system) planning are utilised. For this purpose, a generic energy-enhancement module – eniBRIC – has been developed with respect to preliminary approaches of other researchers and user requirements, which have not been addressed sufficiently in previous work. It serves as a flexible enabler for energy-related studies in the material flow simulation software Siemens Tecnomatix Plant Simulation that can easily be integrated into existing models and work flows. The various use cases presented in this paper illustrate the extensive capabilities inherent to eniBRIC.

While the generic energy-enhancement module is fully functional for its intended purposes, data acquisition and configuration is still a major concern. In particular, a concept for metering the necessary energy data will have to be investigated. Furthermore, enhancing an existing model is a time consuming task, especially if no inheritance structures can be used for configuring the individual instances of eniBRIC. For this reason, possibilities for a simplified configuration concept will be explored.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] Gutowski, T.; Murphy, C.; Allen, D.; Bauer, D.; Bras, B.; Piwonka, T.; Scheng, P.; Sutherland, J.; Thurston, D.; Wolf, E. (2005): Environmentally benign manufacturing: Observations from Japan, Europe and the United States, in: Journal of Cleaner Production, Vol. 13, No. 1, pp. 1-17.

[2] Duflou, J. R.; Sutherland, J. W.; Dornfeld, D.; Herrmann, C.; Jeswiet, J.; Kara, S.; Hauschild, M.; Kellens, K. (2012): Towards energy and resource efficient manufacturing: A processes and systems approach, in: CIRP Annals – Manufacturing Technology, Vol. 61, No. 2, pp. 587-609.

[3] Thiede, S.; Herrmann, C. (2010): Energy Flow Simulation for Manufacturing Systems, in: Proceedings of the 8th Global Conference on Sustainable Manufacturing, pp. 273-278, Abu Dhabi, UAE.

[4] Löfgren, B.; Tillmann, A.-M. (2009): Relating manufacturing system configuration to life-cycle environmental performance: discrete-event simulation supplemented with LCA, in: Journal of Cleaner Production, Vol. 19, No. 17-18, pp. 2015-2024.

[5] Solding, P.; Petku, D. (2005): Applying Energy Aspects on Simulation of Energy Intensive Production Systems, in: Proceedings of the 2005 Winter Simulation Conference, pp. 1428-1432, Orlando, USA.

[6] Rager, M. (2006): Energieorientierte Energieplanung, Diss., Wiesbaden, University Augsburg.

[7] Lorenz, S.; Hesse, M.; Fischer, A. (2012): Simulation and Optimization of Robot Driven Production Systems for Peak-Load Reduction, in Proceedings of the 2012 Winter Simulation Conference, Berlin, Germany

[8] Junge, M. (2007): Simulationsgestützte Entwicklung und Optimierung einer energieeffizienten Produktionssteuerung, Diss., Kassel, University Kassel.

[9] Weinert, N.; Chiotellis, S.; Seliger, G. (2011): Methodology for planning and operating energy-efficient production systems, in: CIRP Annals – Manufacturing Technology, Vol. 60, No. 1, pp. 41-44.

[10] Skoogh, A.; Johansson, B.; Hanson, L. (2011): Data Requirements and Representation for Simulation of Energy Consumption in Production Systems, in: Proceedings of the 44th CIRP Conference on Manufacturing Systems, Madison, USA.

[11] Thiede, S.; Bogdanski, G.; Herrmann, C. (2012): A systematic method for increasing the energy and resource efficiency in manufacturing companies, in: Proceedings of the 1st CIRP Global Web Conference, pp. 28-33.

[12] Rahimifard, S.; Seow, Y.; Childs, T. (2010): Minimising Embodied Product Energy to support energy efficient manufacturing, in CIRP Annals – Manufacturing Technology, Vol. 59, No. 1, pp. 25-28.

[13] Wenzel, K.; Riegel, J.; Schlegel, A.; Putz, M. (2011): Semantic Web Based Dynamic Energy Analysis and Forecasts in Manufacturing Engineering, in: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, pp. 507-512, Braunschweig, Germany.

[14] Thiede, S. (2012): Energy Efficiency in Manufacturing Systems, Springer-Verlag, Berlin/Heidelberg.

[15] Wohlgemut, V.; Page, B.; Kreutzer, W. (2006): Combining Discrete Event Simulation and Material Flow Analysis based on a Component-Oriented Approach to Industrial Environmental Protection, in: Environmental Modelling and Software, Vol. 21, No. 11, pp. 1607-1617.

[16] Chiotellis, S.; Grismajer. M. (2012): Analysis of Electrical Power Data Streams in Manufacturing, in: Proceedings of the 19th CIRP International Conference on Life Cycle Engineering, pp. 533-538, Berkley, USA.

[17] Mayer, G.; Pöge, C. (2010): The Road to Standardization: From the Idea to Realization of the VDA Automotive Toolkit, in: Zülch, G. (Ed.): Integration Aspects of Simulation: Equipment, Organization and Personnel, pp. 29-36, Karlsruhe: KIT Scientific Publishing.

[18] Neugebauer, R.; Putz, M.; Schlegel, A.; Langer, T.; Franz, E.; Lorenz, S. (2012): Energy-Sensitive Production Control in Mixed Model Manufacturing Processes, in Proceedings of the 19th CIRP International Conference on Life Cycle Engineering, pp. 399-404, Berkley, USA.

[19] Putz, M.; Schlegel, A.; Stoldt, J.; Franz, E.; Langer, T. (2012): A Framework for Energy-Sensitive Production Control in MES, in Proceedings of the 14th International Conference on Modern IT in the Innovation Processes of Industrial Enterprises, Budapest, Hungary.

[20] Putz, M.; Schlegel, A.; Franz, E.; Langer, T.; Stoldt, J. (2012): Energy-sensitive control strategies for discrete part manufacturing, in: Proceedings of the 10th Global Conference on Sustainable Manufacturing, Istanbul, Turkey.

[21] Putz, M.; Schlegel, A.; Stoldt, J.; Franz, E.; Langer, T. (2012): Methodik und Framework zur energiesensitiven Fertigungssteuerung in der Variantenfließfertigung, in: Tagungsband Intelligente vernetzte Arbeits- und Fabriksysteme (VPP2012), pp. 131-140, Chemnitz, Germany.

[22] Jee, C. S. Y.; Özgüven, N.; Guo, Z. X.; Evans, J. R. G. (2000): Preparation of high porosity metal foams, in: Metallurgical and Materials Transactions B, Vol. 31, No. 6, pp. 1345-1352.

Manufacturing Automation for Environmentally Sustainable Foundries

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Abstract

Manufacturing automation can enable the foundry SMEs (Small-to-Medium manufacturing Enterprises) to be economically and environmentally sustainable. Foundry industry has significant challenges in the current regulatory and political environment with developing an economical and environmentally sustainable business model. Today, because of metal recycling, most foundries consider themselves as green. In reality, the foundry industry has yet to achieve the higher level of sustainability that the future will demand. Flexible manufacturing has already proven itself as a model for economic sustainability. While this strategy has been examined for general manufacturing, it has not been investigated in detail for the foundry industry. This paper proposes an approach on how flexible manufacturing automation can support the initiative for greener foundries.

Keywords:

Foundry Sustainability; Manufacturing Automation; Norway

1 INTRODUCTION

Manufacturing activity in Europe represents approximately 21% of the EU GDP and provides about 20% of all jobs (more than 30 mi) in 25 different industrial sectors, largely dominated by SMEs. The metal casting industry is a major manufacturing sector in US as well, that employed 143,986 people during 2008 with more than half or 81,056 employed in iron foundries. In recent years, roughly 14 million tons of metal castings are poured into molds each year in 2600 foundries, creating thousands of products. [1] Ninety percent of all manufactured products contain metal castings.

Foundry customers such as marine, automotive etc. are placing demands on founder's responsibilities towards environment, and these demands are increasing every day. High level of automation in foundries helps substantially boost product quality while upgrading older facilities and boost manufacturing competitiveness. In the Nordic region, this has led to heavy investment in improving the internal environments at foundries. Many innovative solutions aimed at sustaining the foundry industry have included use of flexible automation equipment [2], measuring energy consumption by automation and handling equipment [3] etc.

The foundry industry is primarily made of SME businesses with unique product and process combinations limiting their ability to develop and implement automation technologies. It is for this reason that the Norwegian Research Council initiated the Autocast project to bring together the national foundries to help them develop manufacturing automation solutions in an industry-academia collaborative environment. This paper lays the foundation for development of closed loop PLM solution for foundries, in which the number of papers is limited. Foundry SMEs in particular are in need help from automation technology, and some of the reasons are listed below

1. Foundries are intensive in manual labour
2. Sand cast parts have high variation in parts, due to multiple environmental variables such as temperature of molten metal, metal solidification defects etc. which is a huge detriment to automation
3. The extreme environmental working conditions of foundries necessitates the need for automation
4. HSE issues in foundries are an important driver for automation in the foundry as well.

From above it is easy to notice that the first, third and fourth drivers are the main reasons supporting automation of foundries. The second diver is a deterrent to flexible automation from a foundry perspective. The true potential of flexible automation is now being better realized to help the foundries stay competitive in global competition.

The rest of the paper is organized as follows: Section 2 presents the importance of robots in foundry automation and sustainability. Section 3 describes the methodology and the development of an automated solution used at the cast foundry described in section 4. Section 5 presents a brief overview the automation solutions at aluminum foundry and section 6 presents the summary.

2 FOUNDRY AUTOMATION AND SUSTAINANBILITY

Foundry operations have important environmental impacts, both within and beyond the manufacturing facility. The foundries depend on a range of natural resources which are consumed wholly or partly during production. These include sand, minerals, fuels and energy, water, quite apart the metal that is used to manufacture the product. Environmental effects from foundry can be identified from ISO 14001 as emissions to air (products of binders, vapors and gases, molten metal treatment, combustion products), releases to water (acids, solvents, heavy metals for treatment and disposal), waste management (disposal of waste sand, slag, flux residues), contamination of land (use of landfill for dumping waste), use of raw material (molding materials, fuel, energy) and other community issues. The implications of health and safety work act requirements in the foundry industry were examined by Hartmann et al. [4]

In today's foundry the working conditions, product quality, changeover times and manufacturing costs are significantly impacted by robots. Costs involved in implementing flexible robot automation to meet customer demand are more important in labor intensive foundries, when located in a high cost country, such as Norway. An additional factor of equal importance is that the industrial robot is cheaper as compared to manual labor as time goes on. While this particular type in 1976 to perform operations corresponding to 8-years to paid back within a year, it was in 1986 that the work performed, corresponding to 4 years of work. This type is no longer on the market. But similar types will now be able to perform operations corresponding to one man-year to be paid back within a year. In line with the development of new, more productive equipment, machinery more efficient than humans in terms of workload per NOK production cost. [5] This factor that the industrial robot is cheaper as compared to manual labor as time goes on matters in the strategic considerations for many businesses.

The use of robots in foundries is certainly not a recent development. The anticipated benefits of application of flexible automation, namely, improved worker safety, and higher quality castings dates back to the first such recorded application in die casting in 1961 at Ford Motor Company in the US. The use of robots in die casting have been in pouring metal (a hazardous operations requiring precise control to aviod spilling) ; parts integrity checking (the robot greatly simplifies the task by its ability to position the part in three dimensional space) ; cooling of parts (this next step in die casting process is greatly simplified by the robots which are capable of dipping parts in a coolant tank, placing it on a conveyor belt for air cooling and then picking it up) ; trimming (robotic deburring replaces press trimming) ; storage (robot flexibility enables part stacking to meet requirements) ; die insertion and die lubrication operations.

Much of the automotive industry is switching to aluminum parts because of their light weight and energy efficiency requirements. The aluminum foundries are used to cast automotive parts like chassis components, wheels and other complex thinner profile parts. Robots play a crucial role in aluminum foundries as well enabling part quality and consistency.

Few robot applications have been reported for sand casting foundries. The robots in such foundries can be used for handling sand cores, part insertion in casting dies, part deburring and part handling. A sand casting facility has been used as an application (Section 4) for the PLM methodology in the following section.

3 DEVELOPMENT OF AN AUTOMATED SOLUTION

In this section the main elements of modeling, selection, data flow and middleware are described.

PLM has specific objectives at each phase of the life cycle: beginning of life (BOL), middle of life (MOL) or end of life (EOL). Figure 1 shows the usage requirements that helps identify the main life cycle actors and activities of a MOL solution for an iron foundry. The foundry company should be able to record machine status. The operator working on the part should be able to record (depending on the downstream and final customer requirements) the manufacturing processes and parameters used in the system. Depending on the machine it may include heat lot number, metal batch number, holding time etc. The system actors should be able to retrieve data to show that the manufacturing processes comply with the customer regulations. The foundry should be able to gather, transmit, store and analyze data relating ,for example, to the raw material batch, metal composition, the manufacturing process of the part including automated machining and the handling processes used by them internally in the facility.

The foundry life cycle actors need product information data additional to the product itself during the MOL of a foundry operation. Depending on the data requirements and applications; one may need to processing to filter the data gathered. Depending on the data storage requirements dictated by the customer, the foundry may need to store static as well as dynamic type of data. RFID tags having different functions (data storage capabilities, processing, power management), specification (memory type, reading distance, frequency of operation) and application level can be used accordingly for such a purpose.

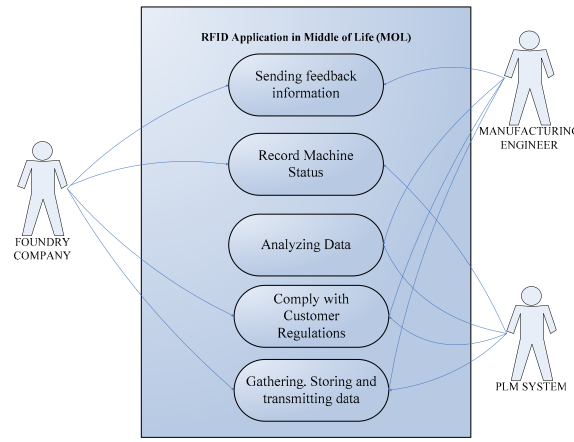

Figure 1: Usage requirements for MOL in cast foundry.

The data and information flow that could occur from BOL to EOL could be cast part information (production batch, date and shift of production, foundry facility etc.). Information from MOL to EOL could be part status information (casting defect on the parts), machine status (parts being casted, maintenance, critical part information etc.) A database software is required to store processed data (for example at an automated robot finishing cell) and manage it efficiently. The configuration of the database is determined by the foundry automation engineers based on cost and efficiency. Finally, the back end software can be defined as a part of a software system that processes the input data, and helps the user provide meaningful information such as OEE (Overall equipment effectiveness). This usually involves the use of legacy systems such as ERP (Enterprise Resource Planning), customer relationship management etc.

Methodology

The methodology starts with investigating the manufacturing system in concern. A variety of methods can be used for this purpose, such as: interviews with stakeholders, a walk-through the system, use of company's operating manuals etc. The primary task is to identify the operating rules. The resulting functional model forms the basis for identifying the data requirements. The main objective of this step is to develop a complete functional model of the system under investigation.

In the next step, a reference data model is developed with the intention to describe the integration among various components such as parts, resources, and the manufacturing logic into a single system to describe the flexible automation cell database implementation conceptually. The reference data model shows the major entities with their attributes and relationships. For this purpose, a series of IDEF modules can be assembled in hierarchical fashion so more details can be shown at lower levels.

In order to collect and store data as the next step, a relational database consisting of multiple data tables, makes it is possible to link data tables directly to the data sources, such the robots, the vision system, etc. via standard protocols. For a relational DBMS (database management system), each entity in the reference model becomes a table and each attribute becomes a column. The internal database to this finishing cell is required to maintain information about the operations performed on the part, the operation & movement date and time, the operator, machining status, outcome of the machining process, and the time of movement out from the automated storage. By utilizing the relational database design, the developed model can store, manage, and retrieve cast part processing data and make it available to the plant-wide ERP system. As long as all the relevant information is recorded in the local database of the cell the retrieval of all necessary information in the production process becomes easier.

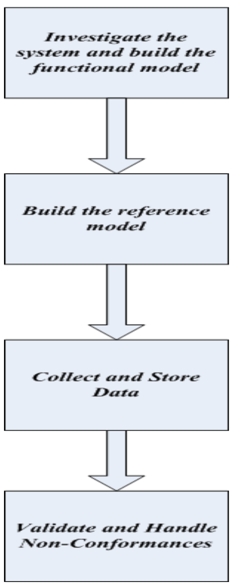

Figure 2: Methodology Overview.

A quality assurance plan is suggested to be developed as a final step, which ensures the data quality and personnel assigned who validate the system and establish a process to maintain the quality of data stored and the equipment. Any non-conformance should be submitted to the appropriate non-conformance authority for part disposition.

4 CAST IRON FOUNDRY AUTOMATION

After analysing the requirements of the sand cast finishing cell, a comprehensive data model and a series of functional models were developed with different levels of details.

The finishing cell installed at the foundry consisted of an ABB foundry robot, CNC milling machine, vision system for part orientation identification, RFID tags for part fixtures, and an automated storage rack. The part fixtures stored in the automated storage had passive RFID tags. The robot identified the orientation of the part/fixture supplied by the automated storage with the help of the signals from the vision system and the gripper on the robot oriented itself accordingly to handle the part/fixture. The RFID tags on the fixtures were read by the reader installed in the CNC milling machine bed and the appropriate G code to machine the cast part was loaded. Figure 3 shows the RFID tag on the bottom of the fixture (top arrow) and the RFID reader on the bed of the CNC machine.

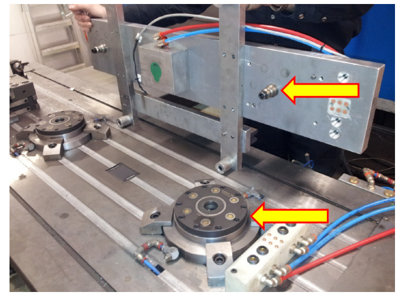

Figure 3: Passive RFID tag on the fixture and the reader on installed on the CNC milling machine bed.

The decisions to recycle/re-melt or repair the cast parts were taken according to the data read from the tags once the finishing operation is complete.

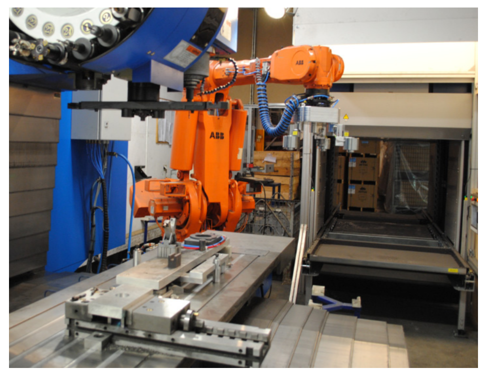

Figure 4: Foundry installed finishing cell.

The finishing cell data was stored in a database, which was directly linked to the company's ERP system through a HMI (Human Machine Interface).

5 ALUMINUM FOUNDRY AUTOMATION

The participating aluminium foundry has an advanced computer system to identify their OEE figures. All workstations in the enterprise are connected to computers that record cycle time, downtime, maintenance, etc. When a workstation powered by an operator takes longer than a cycle intended and expected the operator must enter a reason code for this. The computer system logs all activities and prepare a list of workstations and calculates OEE numbers automatically. All this enables the company at all times have full control over all workstations. They have chosen to divide the OEE figure for availability in two categories, one for maintenance and one for the adjustment of the workstation, the difference between these two is who is responsible for this downtime.

6 SUMMARY

There is a new mood for robot automation in foundry industry. Robots are being used today for their obvious benefits of improving safety, productivity and quality in many foundry SMEs. Global competition and increasing customer requirements are the two main factors in stimulating this trend. Flexible manufacturing automation is a key to the future development in foundries with more operations being carried out by robots. However, the following list of issues still need to be resolved for implementing a closed-loop PLM concept particularly for cast iron foundries:

- Only a partial implementation of closed loop PLM may be cost effective for SME foundries. This of course depends on a trade-off analysis of cost and effect.
- Regarding cast part marking, suitable part identification methods are generally dictated by the customers. A major bottleneck here is the cost of implementation of the methods.
- In terms of middle-of-life part traceability within the foundry, methods for filtering huge amounts of data to transform them into meaningful information, need to be developed.

The presented case studies from the Autocast project show the proposed concept can provide benefits to the life cycle optimization efforts.

7 REFERENCES

[1] CAEF (2009) The European Foundry Industry Report.

[2] Wadhwa, R.S.,(2012): Flexibility in manufacturing automation: A living lab case study of Norwegian metalcasting SMEs., Journal of Manufacturing Systems.

[3] Ystgaard, P.; Gjerstad, T.B..; Lien, T.K.; Herrmann, C.; Nyen, P.A.,(2010): Mapping energy consumption for industrial robots, Proceedings of the 19th CIRP International Conference on Life Cycle Engineering.

[4] Hartmann, EF, Johnson P (1995) Investment Casting, Institute of materials, London.

[5] Lien,TK,(1993) *Industri Robot Teknikk,* Tapir Forlag.

Bearing Condition Prediction Using Enhanced Online Learning Fuzzy Neural Networks

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Abstract

Machine health condition (MHC) prediction is useful for preventing unexpected failures and minimizing overall maintenance costs since it provides decision-making information for condition-based maintenance (CBM). This paper presents a novel bearing health condition prediction approach based on enhanced online sequential learning fuzzy neural networks (EOSL-FNNs). Based on extreme learning machine (ELM) theory, an online sequential learning strategy is developed to train the FNN. Taking advantage of the proposed learning strategy, a multi-step time-series direct prediction scheme is presented to forecast bearing health condition online. The proposed approach not only keeps all salient features of the ELM, including extremely fast learning speed, good generalization ability and elimination of tedious parameter design, but also solves the singular and ill-posed problems caused by the situation that the number of training data is smaller than the number of hidden nodes. Simulation studies using real-world data from the accelerated bearing life have demonstrated the effectiveness and superiority of the proposed approach.

Keywords:

Machine health condition (MHC); Fuzzy neural network (FNN); Time-series forecast; Prognosis; Online learning

1 INTRODUCTION

Machine health condition (MHC) prediction is useful for preventing unexpected failures and minimizing overall maintenance costs since it provides decision-making information for condition-based maintenance (CBM) [1]. Typically, MHC prediction methods can be divided into two categories, namely model-based data-driven methods [2]. Due to the difficulty of deriving an accurate fault propagation model [3], [4], researches have focused more on the data-driven method in recent years [5]. The neural network (NN)-based approach, which falls under the category of the data-driven method, have been considered to be very promising for MHC prediction due to the adaptability, nonlinearity, and universal function approximation capability of NNs [6]. Batch learning and sequential learning are two major training schemes of NNs. MHC prediction is essentially an online time-series forecasting problem which should perform real-time prediction while updating the NN. Thus, to save updating time and to maintain consistency of the NN, the sequential learning should be employed in such a problem.

The most popular NNs applied to MHC prediction are recurrent NNs (RNNs) and fuzzy NNs (FNNs). In [6], an extended RNN which contains both Elman and Jordan context layers was developed for gearbox health condition prediction. In [7], a FNN in [8] was applied to predict bearing health condition. In [9], an enhanced FNN was dev-eloped to forecast MHC. Next, in [10] and [11], a recurrent counterpart of the approach in [9] and a multi-step counterpart of the approach in [10] were presented to predict MHC, respectively. An inte-rval type-2 FNN was also proposed to predict bearing health condition under noisy uncertainties in [12]. Note that the batch learning was employed in [6], [7], [12]. Common conclusions from [6], [7], [9]-[12] are that the RNN usually outperforms the feedforward NN, and the FNN usually outperforms the feedforward perceptron NN, feedforward radial-basis-function (RBF) NN, and RNN. Recently, to improve prediction performance under measurement noise, an inte-grated FNN and Bayesian estimation approach was proposed for predicting MHC in [13], where a FNN is employed to model fault propagation dynamics offline, and a first-order particle filter is utilized to update the confidence values of the MHC estimations online. In [14], a high-order particle filter was applied to the same framework of [13]. A question in the approaches of [13], [14] is that the FNNs should be trained by the system state data (rather than the output data) which are assumed to be immeasurable.

Extreme learning machine (ELM) is an emergent technique for training feedforward NNs with almost any type of nonlinear piecewise continuous hidden nodes [15]. The salient features of ELM are as follows [15]: *i)* All hidden node parameters of NNs are randomly generated without the knowledge of the training data; *ii)* it can be learned without iterative tuning, which implies that the hidden node parameters are fixed after generation and only output weight parameters need to be turned; *iii)* both training errors and weight parameters need to be minimized so that the generalization ability of NNs can be improved; *iv)* its learning speed is extremely fast for all types of learning schemes. ELM demonstrates great potential for MHC prediction due to these salient features. Nonetheless, the original ELM proposed in [15] is not appropriate for predicting MHC since it belongs to the batch learning scheme. To enhance the efficiency of ELM, online sequential ELM (OS-ELM) was developed in [16], and was further applied to train the FNN in [17]. Due to its extremely high learning speed, the OS-ELM-based FNN in [17] seems to be suitable for MHC prediction. Yet, there are two drawbacks in [17] as follows: *i)* It is not good to yield generalization models since only tracking errors are minimized; *ii)* it may encounter singular and ill-posed problems while the number of training data is smaller than the number of hidden notes.

To further improve the efficiency of MHC prediction, a novel FNN with an enhanced sequential learning strategy is proposed in this paper. The design procedure of the proposed approach is as follows: First, a ellipsoidal basic functions (EBFs) FNN is proposed; secondly, the FNN approximation problem is transformed into the bi-objective optimization problem; thirdly, an enhanced online sequential learning strategy based on the ELM is developed to train the FNN; finally, a multi-step direct prediction scheme based on the proposed learning strategy is presented for MHC prediction. The developed enhanced online sequential learning FNN (EOSL-FNN) is applied to predict bearing health condition by the use of real-world data from accelerated bearing life. Comparisons with other NN-based methods are carried out to show the effectiveness and superiority of the proposed approach.

The structures of the rest paper are as follows. The architecture of the FNN is described in Section 2. The enhanced online sequential learning strategy based on the ELM is developed in Section 3. The multi-step direct prediction scheme is given in Section 4. Simulation results based on real-world bearing data are provided in Section 5. Conclusions are given in Section 6.

2 ARCHITECTURE OF FUZZY NEURAL NETWORK

For MHC prediction, we consider the *n*-input single-output system. Yet, the following results can be directly extended to the multi-input multi-output (MIMO) system. The FNN is built based on an EBF NN. It is functionally equivalent to a Takagi-Sugeno-Kang (TSK) fuzzy model that is described by the following fuzzy rules [18]:

$$\text{Rule } R^j: \text{IF } x_1 \text{ is } A_{1j} \text{ and} \cdots \text{and } x_n \text{ is } A_{nj} \text{ THEN } \hat{y} \text{ is } w_j \tag{1}$$

where $x_i \in \mathbb{R}$ and $\hat{y} \in \mathbb{R}$ are the input variable and output variable, respectively, A_{ij} is the antecedent (linguistic variable) of the *i*th input variable in the *j*th fuzzy rule, w_j is the consequent (numerical variable) of the *j*th fuzzy rule, *i* = 1, 2, …, *n*, *j* = 1, 2, …, *L*, and *L* is the number of fuzzy rules.

As illustrated in Figure 1, there are in total four layers in the FNN. In Layer 1, each node is an input variable x_i and directly transmits its value to the next layer. In Layer 2, each node represents a Gaussian membership function (MF) of the corresponding A_{ij} as follows:

$$\mu_{A_{ij}}(x_i \mid c_{ij}, \sigma_{ij}) = \exp\left[-(x_i - c_{ij})^2 / 2\sigma_{ij}^2\right] \tag{2}$$

where $c_{ij} \in \mathbb{R}$ and $\sigma_{ij} \in \mathbb{R}^+$ are the center and width of the ith MF in the *j*th fuzzy rule, respectively. Note that the MF in (2) is an EBF since all its widths σ_{ij} are different [18]. In Layer 3, each node is an EBF unit that denotes a possible IF-part of the fuzzy rule. The output of the *j*th node is as follows:

$$\phi_j(\mathrm{x} \mid \mathrm{c}_j, \sigma_j) = \exp\left[-\sum_{i=1}^{n}(x_i - c_{ij})^2 / \sigma_{ij}^2\right] \tag{3}$$

where $\mathrm{x} = [x_1, x_2, \cdots, x_n]^T \in \mathbb{R}^n$, $\mathrm{c}_j = [c_{1j}, c_{2j}, \cdots, c_{nj}] \in \mathbb{R}^n$, and $\sigma_j = [\sigma_{1j}, \sigma_{2j}, \cdots, \sigma_{nj}] \in \mathbb{R}^n$. In the last layer, the output $\hat{y}$ is obtained by the weighted summation of ϕ_j as follows:

$$\hat{y} = \hat{f}(\mathrm{x} \mid W, \mathrm{c}, \sigma) = \Phi(\mathrm{x} \mid \mathrm{c}, \sigma)W \tag{4}$$

where $\hat{f}(\cdot): \mathbb{R}^{n+L(1+2n)} \mapsto \mathbb{R}$, $\Phi = [\phi_1, \phi_2, \cdots, \phi_L] \in \mathbb{R}^L$, $\mathrm{c} = [\mathrm{c}_1, \mathrm{c}_2, \cdots, \mathrm{c}_L]^T \in \mathbb{R}^{L \cdot n}$, $\sigma = [\sigma_1, \sigma_2, \cdots, \sigma_L]^T \in \mathbb{R}^{L \cdot n}$, and $W = [w_1, w_2, \cdots, w_L]^T \in \mathbb{R}^L$.

For the TSK model, the THEN-part w_j is a polynomial of x_i which can be expressed as follows:

$$w_j = \alpha_{0j} + \alpha_{1j}x_1 + \cdots + \alpha_{nj}x_n \tag{5}$$

where $\alpha_{0j}, \alpha_{1j}, \cdots, \alpha_{nj} \in \mathbb{R}$ are weights of input variables in the *j*th fuzzy rule. The following lemma shows the universal function approximation property of the proposed FNN.

Lemma 1 [19]: For any given continuous function $f(\mathbf{x}): \mathcal{D} \mapsto \mathbb{R}$ and arbitrary small constant $\varepsilon \in \mathbb{R}^+$, there exists a FNN in (4) with proper parameters W, c and σ such that

$$\sup_{\mathbf{x} \in \mathcal{D}} \mid f(\mathbf{x}) - \hat{f}(\mathbf{x} \mid W, \mathrm{c}, \sigma) \mid < \varepsilon \tag{6}$$

where $\mathcal{D} \subset \mathbb{R}^n$ is an approximation region.

3 ONLINE SEQUENTIAL LEARNING STRATEGY

For training FNNs, consider a data set with *N* arbitrary distinct training samples: $\mathcal{N}_N = \{(\mathrm{x}_l, y_l)\}_{l=1}^N$, where $\mathbf{x}_l = [x_{l1}, x_{l2}, \cdots, x_{ln}]^T \in \mathbb{R}^n$, $y_l \in \mathbb{R}$, and *l* is the number of the sampling point. If a FNN with *L* hidden nodes can approximate these *N* samples with zero error, then there exist proper parameters W, c and σ such that

$$\Phi(\mathrm{x}_l \mid \mathrm{c}, \sigma)W = y_l \tag{7}$$

for all *l* = 1, 2, …, *N*. Since w_j in (5) can be rewritten into $w_j = \mathrm{x}_{le}^T\alpha_j$ with $\mathrm{x}_{le} = [1, \mathrm{x}_l^T]^T \in \mathbb{R}^{n+1}$ and $\alpha_j = [\alpha_{0j}, \alpha_{1j}, \cdots, \alpha_{nj}]^T \in \mathbb{R}^{n+1}$, one gets

$$W = [\mathrm{x}_{le}^T\alpha_1, \mathrm{x}_{le}^T\alpha_2, \cdots, \mathrm{x}_{le}^T\alpha_L]^T. \tag{8}$$

Substituting (8) into (7) for all *l* = 1, 2, …, *N*, applying the definition of Φ and making some manipulations, one gets

$$\begin{bmatrix} \mathrm{x}_{1e}^T(\phi_1\alpha_1 + \phi_2\alpha_2 + \cdots + \phi_L\alpha_L) \\ \mathrm{x}_{2e}^T(\phi_1\alpha_1 + \phi_2\alpha_2 + \cdots + \phi_L\alpha_L) \\ \vdots \\ \mathrm{x}_{Ne}^T(\phi_1\alpha_1 + \phi_2\alpha_2 + \cdots + \phi_L\alpha_L) \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix}.$$

From the above expression, it is easy to show that

$$\begin{bmatrix} \mathrm{x}_{1e}^T\phi_1, \mathrm{x}_{1e}^T\phi_2, \cdots, \mathrm{x}_{1e}^T\phi_L \\ \mathrm{x}_{2e}^T\phi_1, \mathrm{x}_{2e}^T\phi_2, \cdots, \mathrm{x}_{2e}^T\phi_L \\ \vdots \\ \mathrm{x}_{Ne}^T\phi_1, \mathrm{x}_{Ne}^T\phi_2, \cdots, \mathrm{x}_{Ne}^T\phi_L \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_L \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix}$$

which can be written into the following compact form:

$$H(\mathrm{X}, \mathrm{c}, \sigma)Q = Y \tag{9}$$

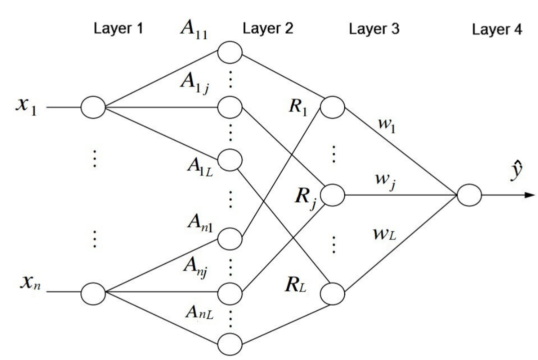


Figure 1: Architecture of fuzzy neural network.

where $X=[x_1,x_2,\cdots,x_N]^T\in\mathbb{R}^{N\times n}$, $Y=[y_1,y_2,\cdots,y_N]^T\in\mathbb{R}^{N\times 1}$, $Q=[\alpha_1^T,\alpha_2^T,\cdots,\alpha_L^T]^T\in\mathbb{R}^{(n+1)L\times 1}$ is the consequent parameter matrix, and $H\in\mathbb{R}^{N\times(n+1)L}$ is the hidden matrix weighted by the fired strength of fuzzy rules given by

$$H(X,c,\sigma)=\begin{bmatrix} x_{1e}^T\phi_1(x_1,c_1,\sigma_1),\cdots,x_{1e}^T\phi_L(x_1,c_L,\sigma_L) \\ x_{2e}^T\phi_1(x_2,c_1,\sigma_1),\cdots,x_{2e}^T\phi_L(x_2,c_L,\sigma_L) \\ \vdots \\ x_{Ne}^T\phi_1(x_N,c_1,\sigma_1),\cdots,x_{Ne}^T\phi_L(x_N,c_L,\sigma_L)\end{bmatrix}. \tag{10}$$

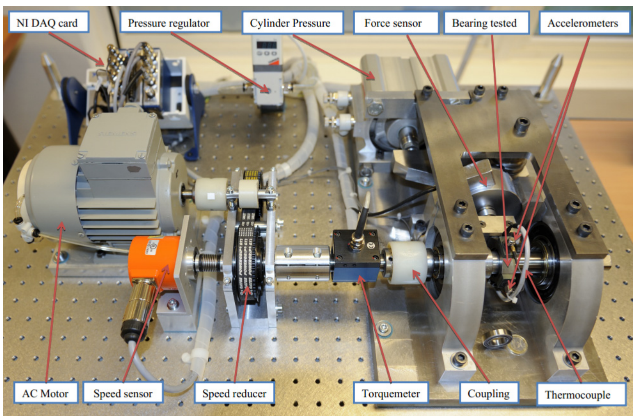


Figure 2: Experimental platform PRONOSTIA.

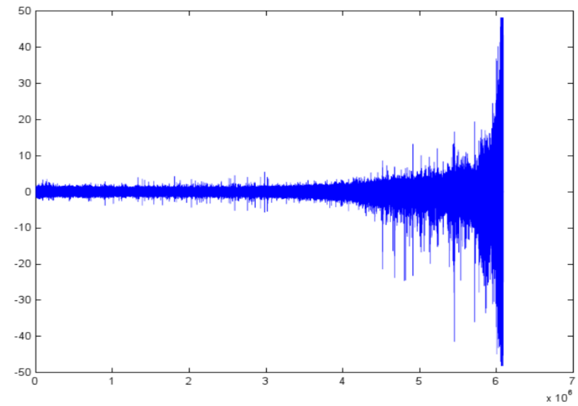


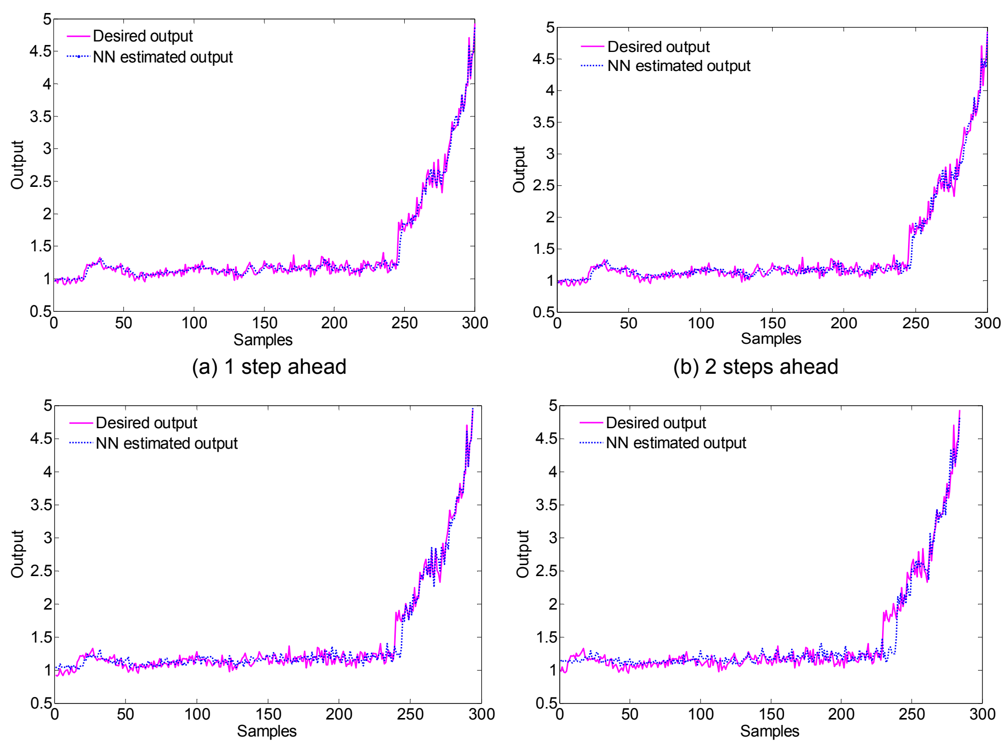
Figure 3: An example of the vibration raw signal.

From ELM theory, the parameters c and σ in (10) can be randomly generated and fixed after generation, i.e. the updating of antecedent parameters is not necessary. Usually, the equality in (9) cannot be obtained due to the limitation of FNN scale. Consider the following minimizing problem:

$$\min_{Q}\left(\|HQ-Y\|^2+\lambda\|Q\|^2\right) \tag{11}$$

where $\|\cdot\|$ denotes the Euclidean norm, and λ is a real positive constant. The least-squares solution of Q in (11) is as follows:

$$\hat{Q}=(H^TH+\lambda I)^{-1}H^TY. \tag{12}$$



(a) 1 step ahead (b) 2 steps ahead

(c) 5 steps ahead (d) 10 steps ahead

Figure 4: Initial training response of the proposed approach.

Now, give an initial data set: $\mathcal{N}_0 = \{(\mathrm{x}_l, y_l)\}_{l=1}^{N_0}$. From (12), one immediately gets

$$\hat{Q}_0 = K_0^{-1} H_0^T Y_0 \tag{13}$$

$$K_0 = H_0^T H_0 + \lambda I \tag{14}$$

where $Y_0 = [y_1, y_2, \cdots, y_{N_0}]^T$, $H_0 = H(\mathrm{X}_0, \mathrm{c}, \sigma)$ and $\mathrm{X}_0 = [\mathrm{x}_1, \mathrm{x}_2, \cdots, \mathrm{x}_{N_0}]^T$. Let $\hat{y}_l$ be the estimation of y_l with $l = 1, 2, \cdots$. The FNN output at the initial phase is as follows:

$$\hat{Y}_0 = H_0 \hat{Q}_0 \tag{15}$$

where $\hat{Y}_0 = [\hat{y}_1, \hat{y}_2, \cdots, \hat{y}_{N_0}]^T$.

Then, present the (k+1)th chuck of new observations: $\mathcal{N}_{k+1} = \{(\mathbf{x}_l, y_l)\}$ with $l = \sum_{j=0}^{k} N_j + 1, \sum_{j=0}^{k} N_j + 2, \cdots, \sum_{j=0}^{k+1} N_j$, where N_j denotes the number of observations in the (k+1)th chunk. From [16], one obtains the RLS solution for Q in (11) as follows:

$$K_{k+1} = K_k + H_{k+1}^T H_{k+1} \tag{16}$$

$$\hat{Q}_{k+1} = \hat{Q}_k + K_{k+1}^{-1} H_{k+1}^T (Y_{k+1} - H_{k+1} \hat{Q}_k) \tag{17}$$

where $H_{k+1} = H(\mathrm{X}_{k+1}, \mathrm{c}, \sigma)$, $\mathrm{X}_{k+1} = [\mathrm{x}_{\sum_{j=0}^{k} N_j + 1}, \cdots, \mathrm{x}_{\sum_{j=0}^{k+1} N_j}]^T$ and $Y_{k+1} = [y_{\sum_{j=0}^{k} N_j + 1}, y_{\sum_{j=0}^{k} N_j + 2}, \cdots, y_{\sum_{j=0}^{k+1} N_j}]^T$. The FNN output at the learning phase is as follows:

$$\hat{Y}_{k+1} = H_{k+1} \hat{Q}_{k+1} \tag{18}$$

where $\hat{Y}_{k+1} = [\hat{y}_{\sum_{j=0}^{k} N_j + 1}, \hat{y}_{\sum_{j=0}^{k} N_j + 2}, \cdots, \hat{y}_{\sum_{j=0}^{k+1} N_j}]^T$.

To avoid the singular problem for the matrix inversion of K_{k+1} in (17) while $N_0 < L$, one makes $P_0 = K_0^{-1}$ and applies the Woodbury identity to calculate P_0 as follows [20]:

$$P_0 = I / \lambda - H_0^T (\lambda I + H_0 H_0^T)^{-1} H_0 / \lambda. \tag{19}$$

Similarly, to avoid the ill-posed problem so that the computational cost for the matrix inversion of K_{k+1} in (17) while $N_i \ll L$ can be reduced, one makes $P_k = K_k^{-1}$ and $P_{k+1} = K_{k+1}^{-1}$, and applies the updating law of $\hat{Q}_{k+1}$ as follows:

$$P_{k+1} = P_k - P_k H_{k+1}^T (I + H_{k+1} P_k H_{k+1}^T)^{-1} H_{k+1} P_k, \tag{20}$$

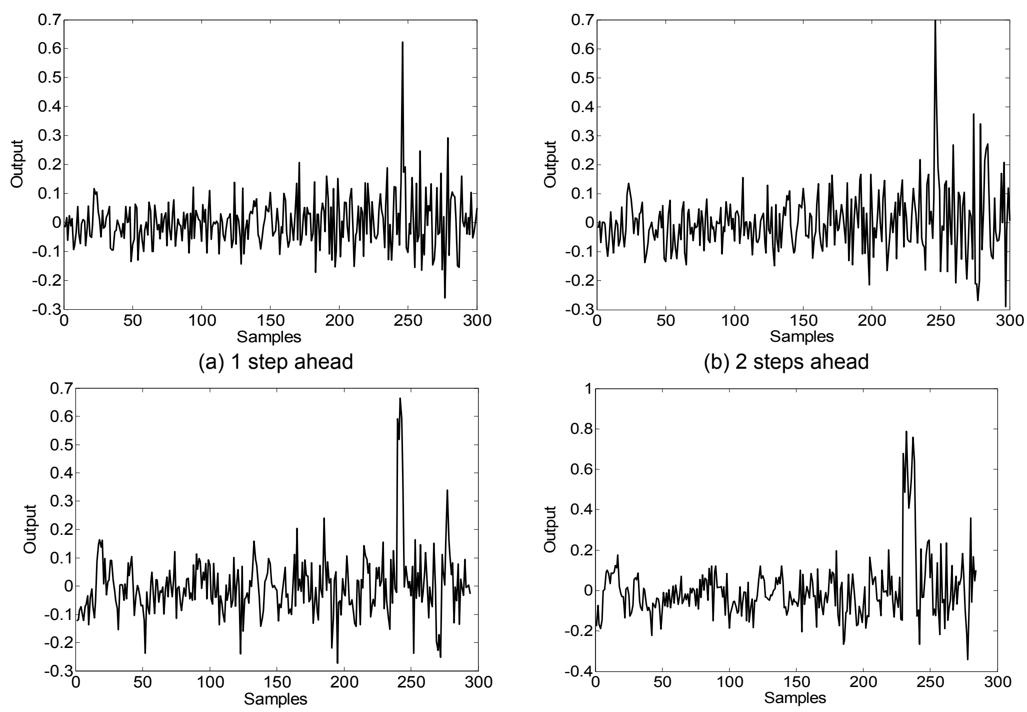
$$\hat{Q}_{k+1} = \hat{Q}_k + P_{k+1} H_{k+1}^T (Y_{k+1} - H_{k+1} \hat{Q}_k). \tag{21}$$

4 MULTI-STEP PREDICTION SCHEME

MHC prediction is essentially an online time-series prediction problem which should carry out updating and prediction concurrently. To carry out multi-step direct prediction, consider the nonlinear autoregressive with exogenous input (NARX) model as follows:

$$\begin{aligned} y_s(k+r) = f(&y_s(k), y_s(k-r), y_s(k-2r), \cdots, y_s(k-nr), \\ &x_s(k), x_t(k-r), y_s(k-2r), \cdots, x_s(k-nr)) \end{aligned} \tag{22}$$

where x_s and y_s are the input and target feature variables, respectively, r is the prediction step, n+1 is the maximum lag, i.e., the order of the system. Then, give a time-series data set: $\mathcal{T} = \{(x_s(i),$



(a) 1 step ahead (b) 2 steps ahead

(c) 5 steps ahead (d) 10 steps ahead

Figure 5: Initial training errors of the proposed approach.

$y_s(i))\}_{i=1}^{\infty}$, its initial set: $\mathcal{T}_0 = \{(x_s(i), y_s(i))\}_{i=1}^{n_0}$ with $n_0 > (n+1)r$, and choose the root-mean-square error (RMSE) as the performance index. Based on the proposed learning strategy, the multi-step direct prediction scheme of time-series is presented as follows.

Step 1) **Offline Initialization**: Obtain the initial training data set: $\mathcal{N}_0 = \{(\mathrm{x}_l, y_l)\}_{l=1}^{N_0}$, where $N_0 = n_0 - (n+1)r$, and

$$\mathrm{x}_l = [x_s(l), x_s(l+r), \cdots, x_s(l+nr), \\ y_s(l), y_s(l+r), \cdots, y_s(l+nr)]^T, \tag{23}$$

$$y_l = y_s(l + (1+n)r). \tag{24}$$

a) Randomly generate parameters: c and σ;

b) Calculate $H_0 = H(\mathrm{X}_0, \mathrm{c}, \sigma)$ by (10), where $\mathrm{X}_0 = [\mathbf{x}_1, \mathbf{x}_2, \cdots, \mathbf{x}_{N_0}]^T$;

c) Calculate $\hat{Q}_0$ using (13) with (14) (if $N_0 \geq L$) or with (19) (if $N_0 < L$);

d) Calculate the initial training performance: $\mathrm{RMSE}_{\mathrm{train}}(\hat{Y}_0, Y_0)$ with $\hat{Y}_0 = H_0\hat{Q}_0$ and $Y_0 = [y_1, y_2, \cdots, y_{N_0}]^T$;

e) Predict the next *r* step's time-series:

$$\hat{y}_{N_0+r} = H(\mathbf{x}_{N_0+r}^T, \mathrm{c}, \sigma)\hat{Q}_0;$$

f) Let $Y_{10} = y_{N_0+1}$ and $\hat{Y}_{10} = \hat{y}_{N_0+1} = H(\mathbf{x}_{N_0+1}^T, \mathrm{c}, \sigma)\hat{Q}_0$;

g) Set the training step: *k* = 0.

Step 2) Online Sequential Prediction: Present the (*k*+1)th training data set: $\mathcal{N}_{k+1} = (\mathrm{x}_{N_0+k+1}, y_{N_0+k+1})$, where x_{N_0+k+1} and y_{N_0+k+1} are given by (23) and (24), respectively.

a) Calculate $H_{k+1} = H(\mathbf{x}_{N_0+k+1}^T, \mathrm{c}, \sigma)$ by (10);

b) Update the prediction performance: $\mathrm{RMSE}_{\mathrm{Pred}}(\hat{Y}_{(k+1)k}, Y_{(k+1)k}) = [Y_{k(k-1)}^T, y_{N_0+k+1}]^T$, $\hat{Y}_{(k+1)k} = [\hat{Y}_{k(k-1)}^T, \hat{y}_{N_0+k+1}]^T$ and $\hat{y}_{N_0+k+1} = H_{k+1}\hat{Q}_k$;

c) Update $\hat{Q}_{k+1}$ using (17) with (16) (if $N_{k+1} \geq L$) or by (21) with (20) (if $N_{k+1} < L$);

d) Update the training performance: $\mathrm{RMSE}_{\mathrm{train}}(\hat{Y}_{k+1}, Y_{k+1})$, $Y_{k+1} = [Y_k^T, y_{N_0+k+1}]^T$, $\hat{Y}_{k+1} = H(\mathrm{X}_{k+1}, \mathrm{c}, \sigma)\hat{Q}_{k+1}$, and $\mathrm{X}_{k+1} = [\mathrm{X}_k^T, \mathbf{x}_{N_0+k+1}]^T$;

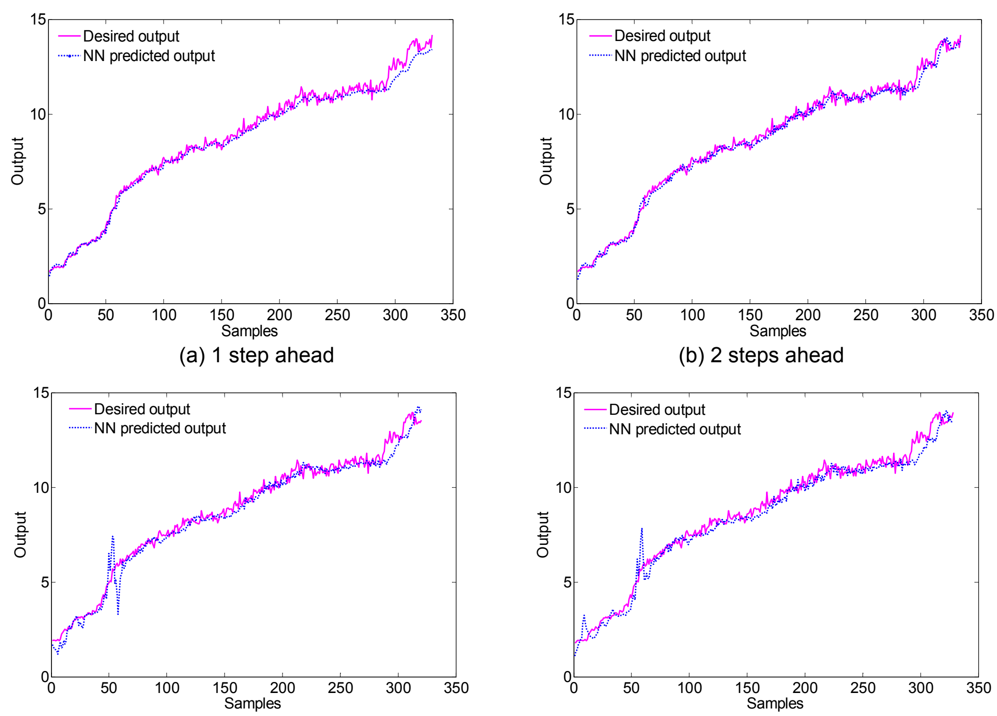
e) Predict the next *r* step's time-series:

$$\hat{y}_{(N_0+k+1)+r} = H(\mathbf{x}_{(N_0+k+1)+r}^T, \mathrm{c}, \sigma)\hat{Q}_{k+1};$$

f) Set the training step: *k* = *k* + 1 and go to Step 2.

5 SIMULATION STUDIES

The applied MHC monitoring data were collected from PRONOSTIA, an experimental platform dedicated to test and validate bearings fault detection, diagnostic and prognostic approaches [21]. As shown in Figure 2, the PRONOSTIA is composed of three main parts: a rotating part, a degradation generation part and a measurement part. The main objective of PRONOSTIA is to provide real



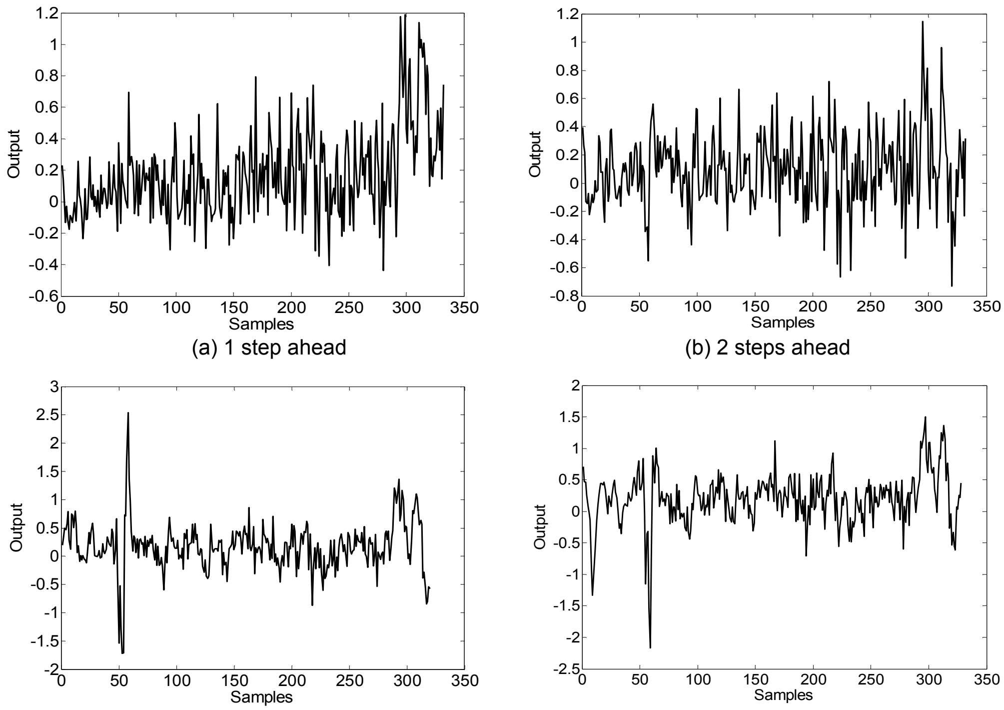
(a) 1 step ahead

(b) 2 steps ahead

(c) 5 steps ahead

(d) 10 steps ahead

Figure 6: Online prediction response of the proposed approach.



(a) 1 step ahead (b) 2 steps ahead

(c) 5 steps ahead (d) 10 steps ahead

Figure 7: Online prediction errors of the proposed approach.

experimental data that characterize the degradation of ball bearings along their whole operational life. This platform allows accelerating bearing degradation in only few hours. An example of the vibration raw signal gathered during a whole experiment is shown in Figure 3. The non-trendable and non-periodical statistical properties of this type of signals increase the difficulty of MHC prediction [22].

In this study, we choose two bearing data sets under the operating conditions: 1800 rpm speed and 4000 N load to carry out simulation. For the NARX model in (22), set n = 1, and r = 1, 2, 5 or 10, select x_s as the standard deviation (STD) of each vibration data set which consists of 2560 vibration signals, and y_s as the 5% trimmed mean of the vibration signal. The prediction procedure is as follows: First,

Step	NN Type	Training				Prediction			
		Time (s)	RMSE	STD	Accuracy (%)	Time (s)	RMSE	STD	Accuracy (%)
r = 1	ESL-FNN	0.0352	**0.0832**	54.010e-4	**97.197**	2.1145	**0.2343**	0.0354	**98.565**
	OS-ELM	**0.0312**	0.0865	34.100e-4	95.195	**2.0159**	0.2641	**0.0254**	97.548
	NARX-NN	1.5506	0.1153	**25.200e-4**	94.631	4.1824	0.3345	0.0191	96.744
r = 2	ESL-FNN	0.0334	**0.0987**	**5.6765e-4**	**97.120**	2.2387	**0.2645**	**0.0083**	**98.018**
	OS-ELM	**0.0250**	0.1056	6.9462e-4	94.585	**2.1141**	0.2837	0.0232	97.453
	NARX-NN	1.535	0.1220	197.00e-4	94.363	4.2151	0.4744	0.2707	95.970
r = 5	ESL-FNN	0.0388	**0.1054**	4.7654e-4	**95.078**	2.2416	**0.3879**	**0.0141**	**97.365**
	OS-ELM	**0.0324**	0.1181	**3.7799e-4**	94.044	**2.1541**	0.4562	0.0342	95.343
	NARX-NN	1.6427	0.1644	1474.0e-4	94.326	4.1434	0.4683	0.1815	95.832
r = 10	ESL-FNN	0.0295	**0.1250**	9.3490e-4	**94.418**	2.3015	**0.4561**	0.0355	**95.096**
	OS-ELM	**0.0264**	0.1441	**5.6543e-4**	93.317	**2.2784**	0.5441	**0.0341**	93.992
	NARX-NN	1.5085	0.1255	101.00e-4	94.285	4.0014	0.6344	0.1684	94.630

Table 1: Performance comparisons of all methods.

the offline initialization is carried out based on one data set to obtain an intimal FNN model; second, the online prediction is carried out based on another data set to forecast time-series of *r* steps ahead. To demonstrate the superiority of the proposed EOSL-FNN, the OS-ELM in [16] and the NARX-NN are selected as the compared methods, where 10 notes is applied to the NARX-NN, and 100 notes with $\lambda = 0.001$ are applied to the EOSL-FNN and OS-ELM. Two performance indexes, namely the RMSE and the mean absolute percentage error (MAPE), are defined as follows:

$$\mathrm{RMSE}(\hat{Y}, Y) = [E((\hat{Y} - Y)^2)]^{1/2}, \tag{25}$$

$$\mathrm{MAPE} = \frac{1}{n}\left(\sum\nolimits_{t=1}^{n} |(y_t - \hat{y}_t)/y_t|\right) \times 100\%. \tag{26}$$

The Accuracy index is defined as $(100\% - \mathrm{MAPE})$.

The initial training and online prediction performance of the proposed EOSL-FNN are depicted in Figure 4 - 7. One observes that high training and predicting accuracy is obtained under small ahead step, and satisfied training and predicting accuracy is still obtained under large ahead step. The performance comparisons of all prediction methods in term of the time, RMSE, STD and accuracy are shown in Table I. Note that the results are obtained from averaging 10 times' simulation results. One observes that both the EOSL-FNN and the OS-ELM are extremely faster (with small training and predicting time) and more stable (with small STD) than the NARX-NN, the EOSL-FNN performs similar or better (with small RMSE and Accuracy) than the NARX-NN and OS-ELM, and the EOSL-FNN performs a little slower (with larger training and predicting time) than the OS-ELM since it contains more adjusting parameters.

6 CONCLUSIONS

In this paper, a novel EOSL-FNN has been developed and successfully applied to predict MHC. An online sequential learning strategy based on the ELM is developed to train the FNN. A multi-step time-series direct prediction scheme is presented to forecast bearing health condition online. The proposed approach not only keeps all salient features of the ELM, including extremely fast learning speed, good generalization ability and elimination of tedious parameter design, but also solves the singular and ill-posed problems caused by the situation that the number of training data is smaller than the number of hidden nodes. Simulation studies using real-world data from the accelerated bearing life have demonstrated the effectiveness and superiority of the proposed approach. Further work would focus on bearing long-term condition and remaining useful life prediction using online dynamic FNNs.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] G. J. Vachtsevanos, F. L. Lewis, M. Roemer, el al (2006) : Intelligent Fault Diagnosis and Prognosis for Engineering Systems. Hoboken, NJ: John Wiley & Sons.

[2] A. K. S. Jardine, D. M. Lin, and D. Banjevic (2006): A review on machinery diagnostics and prognostics implementing condition-based maintenance, Mech. Syst. Signal Proc., vol. 20, no. 7, pp. 1483-1510.

[3] M. Yu, D. Wang, M. Luo and Q. Chen (2012) : Fault detection, isolation and identification for hybrid systems with unknown mode changes and fault patterns, Expert Syst. Appl., vol.39, no.11, pp: 9955-9965.

[4] M. Yu, D. Wang, M. Luo and L. Huang (2011). Prognosis of hybrid systems with multiple incipient faults: augmented global analytical redundancy relations approach, IEEE Trans. Syst. Man Cybern. Part A, vol. 41, no. 3, pp. 540-551.

[5] X. S. Si, W. Wang, C. H. Hu, et al (2011): Remaining useful life estimation - A review on the statistical data driven approaches, Eur. J. Oper. Res., vol. 213, no. 1, pp. 1-14.

[6] Z. G. Tian and M. J. Zuo (2010) : Health condition prediction of gears using a recurrent neural network approach, IEEE Trans. Reliab., vol. 59, no. 4, pp. 700-705.

[7] F. G. Zhao, J. Chen, L. Guo, el al (2009): Neuro-fuzzy based condition prediction of bearing health, J. Vib. Control, vol. 15, no. 7, pp. 1079-1091.

[8] M. Brown and C. Harris (1994): Neuro-Fuzzy Adaptive Modeling and Control. Upper Saddle River, NJ: Prentice Hall.

[9] W. Wang, M. F. Golnaraghi, and F. Ismail (2004): Prognosis of machine health condition using neuro-fuzzy systems," Mech. Syst. Signal Proc., vol. 18, no. 4, pp. 813-831.

[10] W. Wang (2007): An adaptive predictor for dynamic system forecasting, Mech. Syst. Signal Proc., vol. 21, pp. 809-823.

[11] J. Liu, W. S. Wang, and F. Golnaraghi (2009): A multi-step predictor with a variable input pattern for system state forecasting, Mech. Syst. Signal Proc., vol. 23, no. 5, pp. 1586-1599.

[12] C. C. Chen and G. Vachtsevanos (2012) : Bearing condition prediction considering uncertainty: An interval type-2 fuzzy neural network approach, Robot. Comput.-Integr. Manuf., vol. 28, no. 4, pp. 509-516.

[13] C. C. Chen, B. Zhang, and G. Vachtsevanos (2012): Prediction of machine health condition using neuro-fuzzy and Bayesian algorithms, IEEE Trans. Instrum. Meas., vol. 61, no. 2, pp. 297-306.

[14] C. C. Chen, B. Zhang, G. Vachtsevanos, el al (2011) : Machine condition prediction based on adaptive neuro-fuzzy and high-order particle filtering, IEEE Trans. Ind. Electron., vol. 58, no. 9, pp. 4353-4364.

[15] G. B. Huang, Q. Y. Zhu, and C. K. Siew (2006) : Extreme learning machine: Theory and applications," Neurocomputing, vol. 70, no. 1-3, pp. 489-501.

[16] N. Y. Liang, G. B. Huang, P. Saratchandran, et al (2006) : A fast and accurate online sequential learning algorithm for feed-forward networks," IEEE Trans Neural Netw, vol. 17, no. 6, pp. 1411-1423.

[17] H. J. Rong, G. B. Huang, N. Sundararajan, et al (2009) : Online sequential fuzzy extreme learning ma-chine for function approximation and classification problems," IEEE Trans Syst Man Cybern B Cybern, vol. 39, no. 4, pp. 1067-1072.

[18] S. Q. Wu, M. J. Er, and Y. Gao (2001) : A fast approach for automatic generation of fuzzy rules by generalized dynamic fuzzy neural networks, IEEE Trans. Fuzzy Syst., vol. 9, no. 4, pp. 578-594.

[19] Y. Lin and G. A. Cunningham III (1995) : A new approach to fuzzy-neural system modeling," IEEE Trans. Fuzzy Syst., vol. 3, no. 2, pp. 190-198.

[20] H. T. Huynh and Y. Won (2011) : Regularized online sequential learning algorithm for single-hidden layer feedforward neural networks," Pattern Recognit. Lett., vol. 32, no. 14, pp. 1930-1935.

[21] P. Nectoux, R. Gouriveau, K. Medjaher, et al (2012): PRONOSTIA: An experimental platform for bearings accelerated degradation tests, IEEE Int. Conf. Prognostics Health Management, Denver, Co, pp. 1-8.

[22] S. Porotsky (2012): Remaining useful life estimation for systems with non-trendability behaviour, IEEE Int. Conf. Prognostics Health Management , Denver, Co, pp. 1-6.

Manufacturing Scheduling for Reduced Energy Cost in a Smart Grid Scenario

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Abstract

This paper explores the feasibility of including manufacturing facilities in smart grid. A microgrid in a suburban region in Indiana serving 150 single-family homes, 4 medium-sized office buildings, and 1 flow shop is simulated using GridLAB-D. For residential and commercial buildings, passive controllers are implemented on thermostatically controlled devices. For the factory, Drum-Buffer-Rope (DBR) methodology is used to schedule processes to minimize impact on productivity while reducing power consumption during peak hours. Results suggest that it is possible for an industrial facility to become an integrated part of a smart grid. Future research opportunities related to smart factories are discussed.

Keywords:

Lifecycle Engineering; Smart Grid; Manufacturing Scheduling; Simulation

1 INTRODUCTION

Worldwide, the industrial sector is the largest energy consumer, responsible for about 50% of the total energy demand. Industrial energy consumption has almost doubled in the past 60 years and is expected to increase 40% by 2030 [1]. In the United States, about one-third of all the end-use energy consumption is associated with industrial activities and the total energy cost in 2006 was about $100 billion. Face with increasing energy costs and concerns regarding fossil fuel depletion and global warming, manufacturing enterprises are increasingly moving toward energy-efficient manufacturing.

Most previous research efforts directed at improving manufacturing energy efficiency have focused on upgrading existing or developing new machines and processes [2]. In addition to process/machine level changes, opportunities exist at system level, e.g., process planning and shop floor scheduling. Compared with machine or process upgrades, implementation of system-level changes will require far less intensive capital investment. Although research along this direction has been rare, recently there has been increased interest in this area. For instance, Subai et al. [3] considered energy consumption and waste generation in hoist scheduling for surface treatment processes. Wang et al. [4] developed an optimal scheduling algorithm for an automotive paint shop in order to reduce energy consumption. Particularly, Fang et al. [5] presented a new formulation that considers peak power load and energy consumption (and associated carbon footprint) in addition to cycle time for a flow shop scheduling problem.

An interesting point brought up by Fang et al. [5] is that industrial facilities are charged for both their actual energy consumption and the peak demand over the billing period. For many industrial facilities, the contributions from the two parts are comparable. Therefore, scheduling manufacturing operations for reduced peak load represents an additional opportunity for reducing energy cost. In addition, managing the peak demand of a manufacturing facility suggests that further energy cost reductions can be achieved if the rate of electricity changes over time. For instance, manufacturing schedules can be changed to have high power operations running when load charges are lower and vice versa. Moreover, a collection of manufacturing facilities can act together and contribute to balancing the demand with the supply of power grid, i.e., a smart grid scenario. To date, research on how users respond to and participate in a smart grid has been largely focused on residential and commercial buildings [6] [7]. This paper explores the feasibility of including manufacturing facilities in a smart grid and the potential benefits to both manufacturing enterprises and the power grid.

2 BACKGROUND ON SMART GRID

Traditionally, electricity is produced at power plants, and the power lines “carry” the power to homes, factories, and businesses. The power grid responds to changing demand by adjusting outputs of power plants in operation and/or by starting up/shutting down plants. The grid operator may also request load reduction from large energy users (called demand response). But largely the flow of electricity and information is in one direction. The traditional mode of operation has several issues. Peak demands are usually met by an array of 'peaking generators', which are only turned on for short periods. In some areas, supply of electricity at peak times may not be able to keep up with demand, resulting in blackouts, power cuts, and brownouts. To avoid these, more redundancy is needed. The relatively low utilization of peaking generators and the needed redundant capacity in the electricity grid results in low efficiency and high costs.

A smart gird has emerged as a solution to issues faced by a traditional power grid, which integrates the information and power grid technologies to provide an effective way of generate, transmit and distribute power. A key feature of a smart grid is two-way communication between the grid operator and the end users. With a smart grid, companies, homes, and factories will communicate with the grid for supply-demand balance and time-varying electricity price information as an input to operation decisions that generally seek to minimize energy cost. The grid operator collects user feedback and updates users on grid status.

The U.S. DOE divides electric power users into four sectors: commercial sector, industrial sector, residential sector, and direct use (i.e. commercial and industrial facility use of onsite net electricity generation). About fifty percent of the electric power is used for heating homes or commercial buildings in the winter and for cooling in the summer. In the past there have been significant efforts on investigating how residential and commercial buildings operate in a smart grid scenario. For instance, pre-cooling or pre-heating during off-peak hours has been identified as an effective strategy to reduce peak demand on the power grid and decrease energy costs.

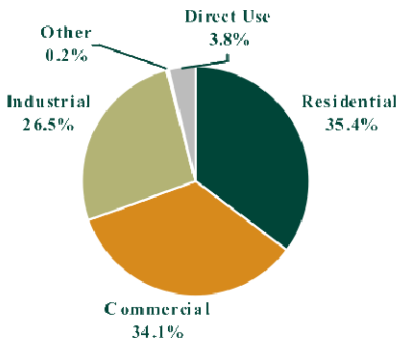

Figure 1: U.S. Electricity consumption by sector in 2009 [8].

As seen in Figure 1, the industrial sector accounts for approximately 25% of the total U.S. electricity consumption [8]. Compared with residential and commercial buildings, it is much more challenging for manufacturing facilities to participate in, and reap the benefits from a smart grid. For residential and commercial buildings, each energy-related operation can be seen as independent and usually has a high degree of flexibility. However, this is not the case for manufacturing facilities where operations are generally interdependent and any change in an operation schedule is subject to throughput/productivity constraint. As a result, research on energy-efficient manufacturing scheduling in a smart grid scenario has been extremely limited. In this paper we will model a microgrid consisting of residential, commercial, and industrial end users and investigate how manufacturing activities can be scheduled to take advantages of a smart grid.

3 INTEGRATED MODEL FOR A MICROGRID

For smart grid research, simulation using an integrated model is the most common approach. As shown in Figure 2, after being generated in the power plants, electricity is transmitted along the lines and delivered to customers. To better understand the behavior of the power system, an integrated model which describes the whole process is desirable.

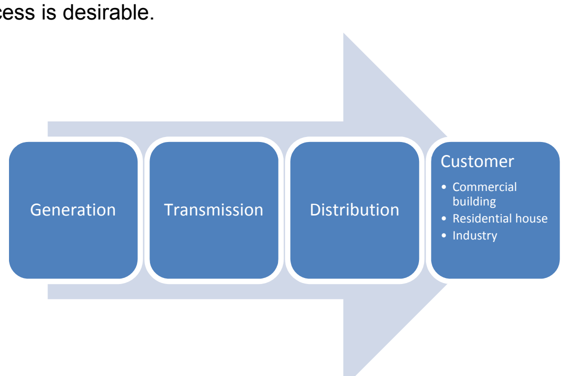

Figure 2: Flow of electricity in a power grid.

An integrated model combines commercial buildings, homes, and industrial facilities with control systems and marketing functions into an agent-based framework. Results from the simulation are used to evaluate the impact of various smart grid technologies and develop new strategies of the market. Many software tools have been developed for this purpose. The simulation model employed in this paper is based on GridLAB-D, an open-source platform developed by the U.S. Department of Energy [9].

GridLAB-D is a power system simulation tool which helps users to build, test, and develop a power transmission and distribution system. GridLAB-D has modules developed for homes and commercial buildings with detailed control and operation logic specified for energy-consuming devices (e.g., water heater, air conditioner, lights, and space heater). In addition, GridLAB-D can simulate an auction-retail process between the supplier and the customer. Here we will add industrial modules to GridLAB-D and build an integrated network that includes a power substation, transmission, distribution, residential modules, commercial modules, and industry modules.

3.1 Model Structure

A microgrid is considered that serves a hypothetical small suburban area in the state of Indiana. We consider a typical summer day with temperature profile shown in Figure 3.

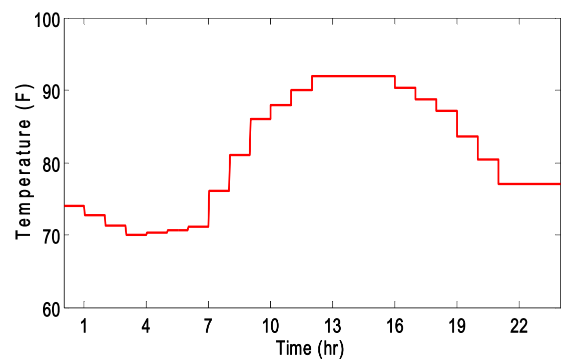

Figure 3: Temperature profile of a typical summer day in Indiana.

The integrated model developed in this study includes following components:

- Feeders. Feeders are used to describe the power flow from the generation station to the end user, i.e., power transmission and distribution. GridLAB-D has 24 built-in prototypical feeder modules, which represent different transmission/distribution designs used in various regions in the U.S. for home, commercial, and industrial applications. For the hypothetical area considered, one feeder is sufficient to meet the demands of all users.
- Residential modules. The microgrid of this paper considers 150 single-family houses with a variety of power consumption devices, e.g., lighting, appliances, and air conditioners. Each house has different characteristics, e.g., area, water demand, capacity of devices.
- Commercial modules. This study includes 4 middle-sized commercial buildings with lighting and HVAC being the major power consumption devices. Each of the four buildings hosts 12 offices with different power demands.
- Industry modules. Here one factory is considered and the facility runs a flow shop with eight processing steps.

3.2 Feeder Module

The GridLAB-D feeder module R5-12.47-4 [10], which serves a moderately populated suburban area, is used. The feeder module is connected to all the residential modules, commercial modules, and the industrial module. Figure 4 shows a small portion of the network represented by the feeder module. The major technical specification of the feeder is given in Table 1.

Nodes	1,075
Voltage (kV)	12.47
Load Capacity (kW)	3,700
Residential Transformers	150
Commercial Transformers	4
Industrial Transformers	1

Table1: Feeder parameters.

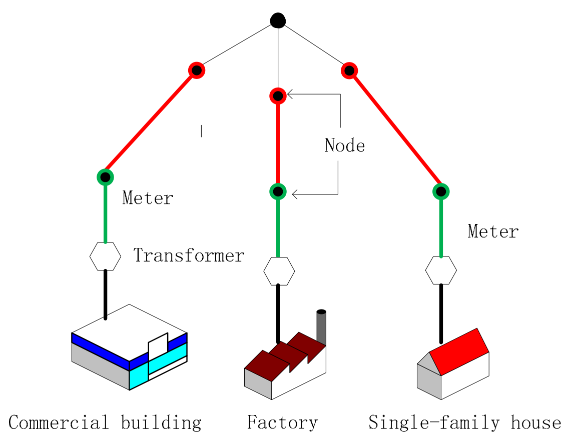

Figure 4: Part of R5-12.47-4 feeder.

3.3 Residential Modules

Residential modules consider water heaters, lights, wall outlets, and HVAC. Heat gains or losses from water heaters, lights, equipment, exterior walls, and air infiltration are also considered. For each of the 150 houses considered, these devices have different power ratings. In addition, each house has different floor areas and thermal insulation (R values). Table 2 lists the average parameter values for house characteristics that are considered.

Floor Area (sq ft)	2,500
Ceiling Height (ft)	8.0
Number of External Doors	4
Roof R-value	30.0
Wall R-value	19.0
Floor R-value	22.0
Door R-value	5.0
Light Capacity (W)	400 W
Light Fraction	0.98
Light Heat Gain Fraction	0.9
Water Heater Capacity	4.4 KW

Table 2: Residential building characteristics (average).

3.4 Commercial Building Modules

Office Floor Area (sq ft)	1,000
Office Floor Height (ft)	11
Light capacity (W)	2,000
Light Fraction	0.98
Lights Heat Gain Fraction	0.9
Plugs Capacity (W)	1,000
Plugs Fraction	0.9
Plugs Heat Gain Fraction	0.98

Table 3: Commercial building characteristics (average).

Within the simulation model, a commercial building is represented by a two-story, twelve zone model. The orientation and structure of each zone affects the HVAC load. For instance, the zones facing east receive more sunlight than other zones. In addition, heat flow through the window and door need to be considered. The location and orientation of each window and door are shown in Figure 5. Zone 1, Zone 3, Zone 4 and Zone 6 have two windows and one door, while the other two zones have one window and one door. Each zone has its own parameter values, such as lighting load, plug load, office area, window area, and wall area. Table 3 lists the average parameter values for various characteristics of the office zones. It is assumed that the commercial buildings are occupied from 8 am to 5 pm (EST) on Monday to Friday, and from 1 pm to 5 pm (EST) on Saturday and Sunday.

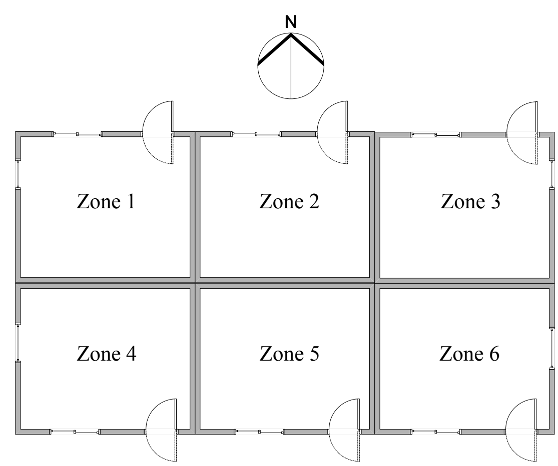

Figure 5: Floor plan of office building (1st and 2nd floor are identical).

3.5 Industry Module

This paper creates a new factory module that interfaces with the other established modules in GridLAB-D, e.g., power module, climate module, and distribution module. The factory module includes objects “Plant”, “HVAC”, “FactoryLights”, and “Machines”. The first three objects are similar to the case of commercial buildings and key parameters associated with them are provided in Table 4.

Floor Area (sq ft)	8,000
Floor Height (ft)	11
Light capacity (W)	2,000
Light Fraction	1.00
Lights Heat Gain Fraction	0.1

Table 4: Parameters of the factory.

The factory employs flow shop production with eight processing steps utilized to produce a part. That is, every part has to go through all the steps and the sequence of the steps is the same for all the parts produced. For simplicity, here it is assumed that one machine is needed for each process step. Table 5 lists the power demand for each machine and the processing time for each step. The throughput of this factory is assumed to be 162 parts/day. These settings are similar to the smart factory reported in [11].

	Power Demand (kW)	Processing Time (min/hour)
Machine 1	160	9 (1am to 8am); 6 (8 am to 1 am next day)
Machine 2	168	7.2
Machine 3	168	10.8
Machine 4	168	6
Machine 5	184	8.4
Machine 6	176	9
Machine 7	192	7.2
Machine 8	200	9.6

Table 5: Processing time for each step.

4 OPERATION STRATEGIES

4.1 Passive Controller for Commercial Building and Residence

In a smart grid scenario, the interactions between the grid operator and the power consuming devices at the customers determine the amount of electricity delivered and the electricity costs. Generally, a thermostatically controlled device measures the indoor temperature, determine a bidding price based on current market clearing price and load required for next time interval following some specified logic/algorithm, and provide the bidding price to the operator. The operator evaluates the status of power plants, demand requests, and all the bidding prices collected and determines a new market clearing price. After receiving the new clearing price, the device at the customer resets the set point accordingly and determines a new bidding price. This two-way communication will continue. To simplify, in this paper we consider the buyer only model. That it, the market clearing price is not affected by the decisions made by the devices at customers and the devices respond to a pre-defined time-varying market clearing price in order to minimize energy cost. This is reasonable for the microgrid considered here since the microgrid is only a small part of a large network and its contribution to total demand is minimal.

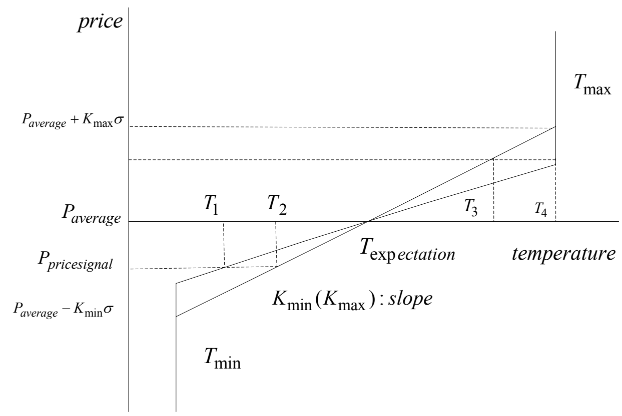

Figure 6: Control logic for determining adjusted cooling set point for residential and commercial buildings [12].

Figure 6 and Equation 1 show the operation strategy for a typical thermostatically controlled device (for instance, air conditioner). If the current market clearing price is lower than the average price of the previous 24 hour, the device will set parameter $T_{limit}=T_{min}$ and $K=K_{max}$, and choose T_2 as the new set point to save energy. Similarly, if the price is larger than the average price, then the device uses $K=K_{min}$ and $T_{limit}=T_{max}$, and choose T_4 as the new set point [13].

$$T_{reset} = T_{set} + (P_{pricesignal} - P_{average})\frac{|T_{limit} - T_{expectation}|}{K\sigma} \quad (1)$$

where $P_{average}$ is the mean price of electricity for the last 24-hour period, σ is the standard deviation of the electricity price for the same period, K_{min}, K_{max} are the slope, equal to price per degree of temperature change, T_{min}, T_{max} are the range of the temperature which customer can accept, K_{min}, K_{max} and T_{min}, T_{max} are comfort-setting parameters. K and T are chosen from K_{min}, K_{max} and T_{min}, T_{max}, depending on where $T_{current}$ presently resides on the lines.

4.2 Drum-Buffer-Rope Scheduling for Factory Operation

Drum-Buffer-Rope (DBR) is a scheduling algorithm derived from the Theory of Constraints (TOC)[11]. In our case, the power consumption during peak hours is a constraint as it is desired to minimize the energy cost. In other words, during peak hours it is desired to constrain the power demand to a relatively low level. With the DBR approach, the weakest link of the work-in-process is called "drum", which controls the whole output of a factory. The goal of DBR is to use the "buffer" to protect the weakest link by adding constant flow of work into the buffer. The amount of buffer is determined by the production constraint and the power constraint. The rope checks the status of the drum and buffers and determines whether or not to introduce a new part into processing.

Figure 7 illustrates the DBR approach from a simple production line with four steps, i.e., Processes A, B, C, and D. The production line operates from 9am to 6pm with 1pm to 3pm as the peak hours (with higher market clearing price). The factory sets the power constraint as 15 kW during the peak hours. As a result, only one process can continue operating while the other three have to stop. Since the production is constrained by Process C (the slowest among the four, i.e., the drum), to minimize impact on throughput we want to have Process C running during the peak hours and have Processes A, B and D stopped. In order to do this, we need to set up buffers before and after Process C. The size of buffer needs to be at least 8 (4 parts/hour for Process C times 2 hours, i.e., 1pm-3pm). At 3pm, the production line goes back to normal operation and all processes will start operating. Within the next 3 hours time period (before the shop closes at 6pm), due to parts stored in Buffer 2 Process D will suffer less degree of starving. The production line will be able to deliver 19 parts total instead of 11 (the normal). This actually catches up the productivity lost while Processes A, B, and D were shut down during peak hours. Please note this is an illustrative example only. In reality the production line is likely much better balanced and using DBR to minimize the impact on productivity involves significant computational challenges.

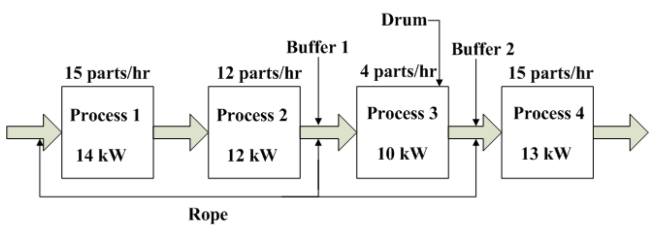

Figure 7: An illustrative example of Drum-Buffer-Rope methodology.

5 RESULTS

5.1 Pre-defined Market Clearing Prices

The time-depending market clearing price for the specific day considered is given in Figure 8. This price is used as a signal to the passive controller in the residential modules or commercial building modules. In the cooling model, the adjusted cooling set point will be higher than the initial cooling set point during the peak hours, while the adjusted set point will be lower than the set point during the off peak hours.

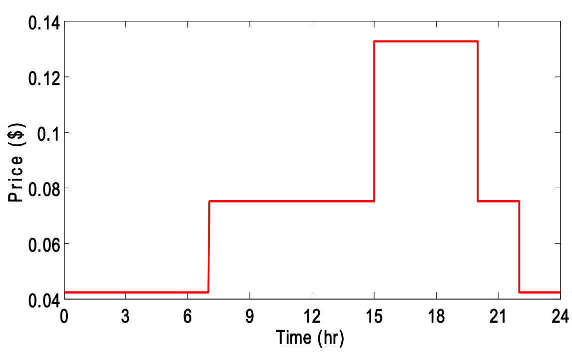

Figure 8: Market clearing price over a 24 hour time period.

5.2 Power Consumption Benchmark

To set a benchmark, we calculate the power consumption profile of homes, commercial buildings, and factory when the factory is operating without considering time-varying electricity price. For the residential and commercial buildings, four important parameters (maximum temperature T_{max}, minimum temperature T_{min}, and rate at which they will respond K_{min}/K_{max}) are set by the customers to be 3.8 °F, -3.1 °F, 2.06/1.25 \$/°F, respectively.

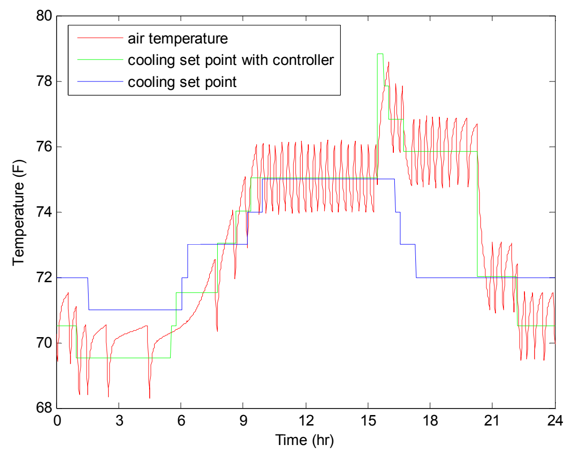

Figure 9: Room temperature and cooling set point for a typical residential building.

As an example, Figure 9 shows the temperature profile of a residential building. During peak hours, the controller adjusts cooling set point to be higher than the pre-defined value. On the contrary, overnight the controller keeps the adjusted cooling set point below pre-defined value i.e. pre-cooling. Figure 10 shows power consumption profile of all the 150 residential and 4 commercial buildings over a 24 hour period. Here the power consumption of the factory is not included since with considering time-varying electricity price the power demand of the factory will stay relatively constant over time. The inset of Figure 10 compares the power consumption from 3pm to 5pm with and without passive controller. It can be seen that electricity consumption can be reduced quite significantly during the 1st hour i.e. 3pm to 4pm. This can largely be attributed to pre-cooling effect and elevated adjusted cooling set point. During the 2nd hour i.e. 4pm to 5pm some reduction on electricity consumption is achieved but the magnitude smaller since the “stored” pre-cooling has been used up. It should be noted that the four important parameters (maximum temperature T_{max}, minimum temperature T_{min}, and rate at which they will respond K_{min}/K_{max}) are manually selected such that saving on electricity cost can be achieved. Larger savings are expected if the four parameters are to be optimized using software tools.

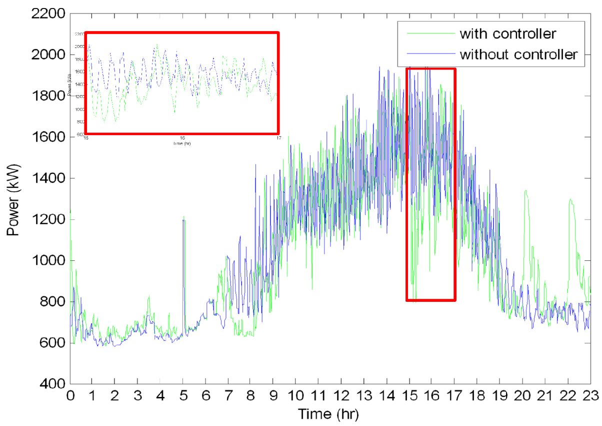

Figure 10: Total power consumption of residential and commercial buildings.

5.3 Power Consumption of the Factory

Based on DBR methodology, we use Excel spreadsheet to manually determine a new schedule which involves shutdown of several machines during the mid-park and on-peak hours. To simplify we assume each machine has unlimited buffer. As shown in Figure 11, it is possible to stop Processes 5, 6, 7 and 8 during the time period of 2pm to 4pm without affecting the productivity. That is, at the end of the day we can still deliver 162 parts. Since Process 4 is the slowest step or the drum which only produces 10 parts per hour, over the entire 24 hours time period it keeping running with the largest buffer size i.e. 45. The saving on electricity cost through adjusting the schedule is about 5%. Again, although the manually derived new schedule is able to achieve energy cost saving, likely it is far from the optimal. In fact, it has been pointed out that DBR methodology, although being simple and effective, cannot find the optimal result [14]. Fang et al. [5] has pointed out that the flow shop scheduling problem can become computationally very difficult when considering peak load even for a two-machine shop processing 36 jobs. Adding time-variant electricity price will only make the problem even more challenging. It is very likely that from practical point finding the true optimum is not feasible and instead efforts should be put on seeking heuristics that could deliver acceptable schedule in a timely manner.

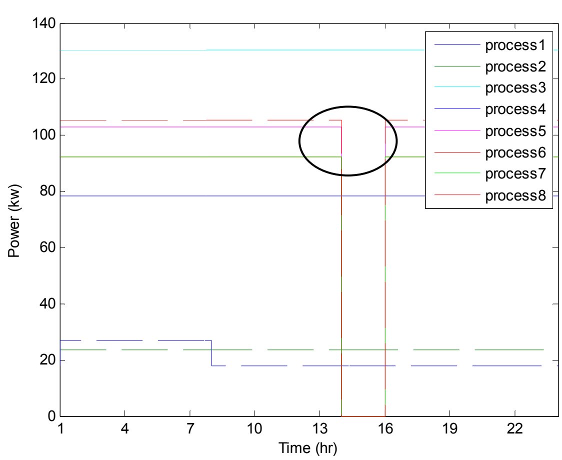

Figure 11. Power consumption of each process step.

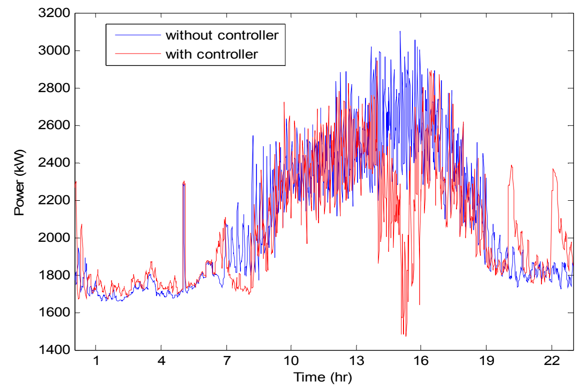

Figure 12: Power demand of the microgrid.

Figure 12 shows the overall power demand profile of the microgrid simulated over 24 hours time period. When comparing with Figure 10, one can see that including industry facilities can further reduce demand over peak hours. With many similar microgrids working together, we can expect significantly reduced stress on the overall power network. In ideal case one can expect with the participation of homes, commercial buildings, and factories in the smart grid the degree of demand fluctuation at grid level be greatly reduced.

6 SUMMARY

An integrated model of a microgrid serving 150 homes, 4 commercial buildings, and one flow shop factory is developed in this paper using open-source platform GridLAB-D. Passive controllers are implemented for residential and commercial buildings to minimize energy cost by adjusting demands from thermostatically controlled devices according to a pre-defined time-varying market clearing price. For the factory, drum-buffer-rope methodology is applied to develop new schedule that reduce energy consumption during peak hours while maintain daily throughput. Simulation results suggest that it is possible to have industrial facilities participate in smart grid and further reduce power grid stress during peak hours. In should be noted that in this paper a pre-defined profile of market clearing price is given. In the future bidding mechanisms need to be included so end users (including industrial facilities) can actively participate in grid demand-supply balancing. To maximize the potential benefits to both industrial facilities and the power grid, new scheduling algorithms are needed to generate energy/power efficient schedules under these dynamic conditions.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] IEA (2012), World Energy Outlook 2012.

[2] NAM, (2005): Efficiency and Innovation in US Manufacturing Energy Use, National Association of Manufacturers, Washington D.C.

[3] Subai, C., Baptiste, N. E., (2006): Scheduling Issues for Environmentally Responsible Manufacturing: The Case of Hoist Scheduling in An Electroplating Line, in: Int. J. production Engineering, Vol.99, No.1, pp.74-87.

[4] Wang, J., Li, J., Huang, N., (2009): Optimal Scheduling to Achieve Energy Reduction in Automotive Paint Shops, in: Proceedings of 2009 ASME Manufacturing Science and Engineering Conferences, October 4-7, 2009, West Lafayette, IN, USA.

[5] Fang, K., Uhan, N., Zhao, F., Sutherland, J.W. (2011), A New Shop Scheduling Approach in Support of Sustainable Manufacturing, Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Technische Universität Braunschweig, Braunschweig, Germany, May 2nd - 4th, 2011.

[6] Chao, H.P. (2010), Price-Responsive Demand Management for a Smart Grid World, The Electricity Journal, Volume 23, Issue 1, Pages 7–20.

[7] Thomas, A.G., i Cai, C., Aliprantis, D.C. (2012), Effects of Price-Responsive Residential Demand on Retail and Wholesale Power Market Operations, Proceedings of the IEEE Power and Energy Society General Meeting, San Diego, CA, July 22-26, 2012 (electronic).

[8] EIA, (2011) Electric Power Annual 2010, US DOE, Washington DC.

[9] GridLAB-D: http://www.gridlabd.org/

[10] Schneider, K.P., Chen, Y., Chassin, D.P., Pratt, R., Engel, D., and Thompson, S., (2008) Modern Grid Initiative Distribution Taxonomy Final Report, US DOE, Washington DC.

[11] Park, J., (2010), A Smart Factory Operation Method for a Smart Grid, 40th International Conference on Computers and Industrial Engineering, Awaji Island, Japan, July 25-28 2010.

[12] Pacific Northwest National Laboratory (2007), Pacific Northwest GridWise™ Testbed Demonstration Projects, Richland, Washington.

[13] Fuller, J.C., Kumar, N.P., Bonebrake, C.A. (2012), PNNL Report: Evaluation of Representative Smart Grid Investment Grant Project Technologies: Demand Response, Richland, Washington.

[14] Linhares, A. (2009). Theory of constraints and the combinatorial complexity of the product-mix decision, International Journal of Production Economics, 121 (1): 121–129.

Energy Efficient Solutions for Hydraulic Units of Machine Tools

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Abstract

Hydraulic units of machine tools are one of the main consumers of energy. Hydraulic functionalities of machine tools are e.g. the tool change, the work piece clamping, the palette change, the weight compensation of vertical axes or the supply of hydrostatic guidings. This paper describes possibilities to reduce the power consumption of hydraulic units. The power consumption of different hydraulic units is analysed and compared for an exemplary machining centre with regard to its different hydraulic functionalities.

The paper observes three hydraulic units, from the perspective of power consumption, in detail. One unit represents state of the art technology and the other two units are prototypic hydraulic units whose power consumption has been optimised. The first prototype includes a booster. The second prototype combines a frequency controlled variable-displacement axial piston pump with different accumulators for different pressure levels.

Besides power, pressure, flow rate and temperature are monitored for the different hydraulic units. In addition to that, further interdependencies of the hydraulic units and other ancillary components of the machining centre, e.g. heat transfer to the cooling system are analysed.

Keywords:

Machine tools; energy efficiency; hydraulics

1 INTRODUCTION

The results presented in this paper are based on the co-operative research project EWOTeK – enhancing the efficiency of machine tools by optimising the technologies for operating components – that was sponsored by the German Federal Ministry of Education and Research (BMBF). EWOTeK aims at optimising the energy efficiency of machine tools. The partners of this project were two machine tool manufacturers Gebr. HELLER Maschinenfabrik GmbH and INDEX-Werke GmbH, the component manufacturers KNOLL Maschinenbau GmbH, BKW Kälte-Wärme-Versorgungstechnik GmbH, Bosch Rexroth AG and Siemens AG and the Laboratory for Machine Tools and Production Engineering (WZL) at the RWTH Aachen. EWOTeK was scheduled to last three years from July 2009 to June 2012.

A demonstration machine tool was initially used to examine the power consumption associated with processing. On the basis of this, concepts were drawn up for the more efficient use of the entire machine, e.g. possibilities for a learning-based determination of the load of the machine tool and graded standby-concepts. At the same time, individual components of the machine were optimised. This involved requirement-oriented cooling and hydraulic concepts, requirement-based use of cooling lubricants, enhanced control in asynchronous drives for spindles and a lubrication of the spindle ball bearings that is adjusted to the needs. This paper describes the results to design energy efficient hydraulic units.

2 STATE OF THE ART OF THE ENERGY EFFICIENCY OF HYDRAULIC UNITS

Figure 1 describes the power consumption of different machine tools for various operating conditions. As the results do not reflect standardised operating conditions and not all references in detail describe which components run in which operating condition and what is exactly produced the different machine tools can not be compared with regard to energy efficiency. Furthermore these machine tools vary in type, size, equipment, functionality and design. Yet it can be stated that there is still improvement potential to more adjust the power consumption of machine tools to its actual operating condition; i.e. ready to produce and productive operation.

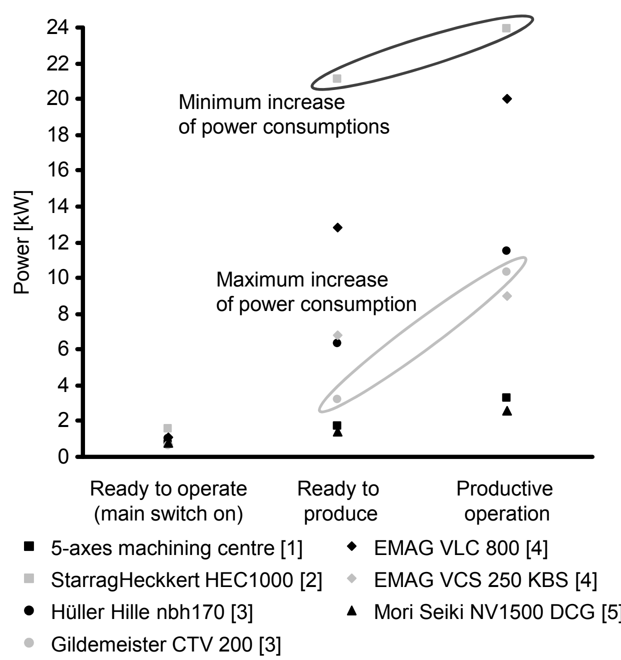


Figure 1: Power consumption of machine tools in various operating conditions.

To achieve this one has to focus on ancillary components of machine tools, i.e. cooling, hydraulics and coolant, as they are the main power consumers. [2, - 4, 6 - 10] analyse the power consumption of different machine tools. In average ancillary components have a share of 60% of the whole energy consumption of machine tools. Hydraulic units have an average share of 10%. Thus the optimization and the adjustment to the needs of ancillary components and also hydraulic units have a big impact on reducing the energy consumption of machine tools.

Hydraulic units fulfil different tasks in machine tools such as hydraulic weight compensation, work piece clamping and tracking, releasing and clamping of tools in the spindle, changing tools, opening and clamping the chuck, operating the revolver head clamping system, operating protective doors, changing and transporting pallets, supplying power to hydrostatic guidance systems and traversing hydraulic axes [11 - 13].

There is a variety of measures to more energy efficient hydraulic units. These measures can be summarised as follows [14]:

- energy efficient pumps
  - high degree of efficiency
  - controlled pump drives, e.g. variable speed pump drives controlled by means of frequency converter
- accumulator
- directional seat valves
- optimised hydraulic consumers with minimal leakage

[15] compares the degree of efficiency for a:

- variable displacement pump with constant drive,
- variable speed controlled pump drive with constant pump and
- variable speed controlled pump drive with variable displacement pump.

Variable speed pump drives can adapt the turning speed of the pump to the required volume flow. This leads to a decrease of power consumption. The accumulator helps to reduce the speed and pressure of the pump during holding pressure, i.e. when there is no hydraulic function performed. The pump is only activated when the pressure in the accumulator falls below a defined value. The accumulator compensates for leakages and serves to ensure rapid reaction to fluctuating volume flow rate requirements. Further information can be found in [16].

3 ANALYSIS OF THE ENERGY CONSUMPTION OF DIFFERENT HYDRAULIC UNITS

3.1 Description of the Machine Tool

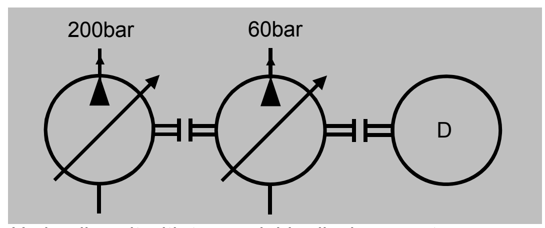
The energy efficiency analysis of the three different hydraulic units is performed on a Heller H2000 machining centre. This machining centre is suitable for both job-shop operations and series production. The hydraulic unit of this machining centre serves to fulfil the change of the pallets, the clamping and releasing of work pieces and the change of tools. Changing tools encompasses the hydraulic functions clamping and releasing the tool in the spindle and actuating the tool carrier system that transfers the tool from the tool magazine to the tool changer and back. To accomplish the pallet and tool change a pressure of 60bar with a maximum volume flow of 25l/min is required. To clamp work pieces needs a pressure of 200bar with a maximum volume flow of 14l/min.

3.2 Description of the Different Hydraulic units

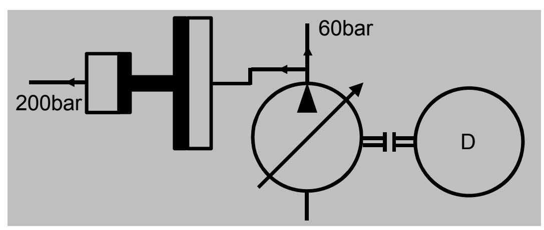
For the purpose of these studies three different hydraulic units are compared:

- hydraulic unit with two variable displacement pumps and a constant drive (state-of-the-art unit)
- hydraulic unit with one variable displacement pump, a constant drive and a booster (optimisation 1)
- hydraulic unit with one variable displacement pump with variable speed controlled pump drive and two accumulator, DvP-unit (optimisation 2)

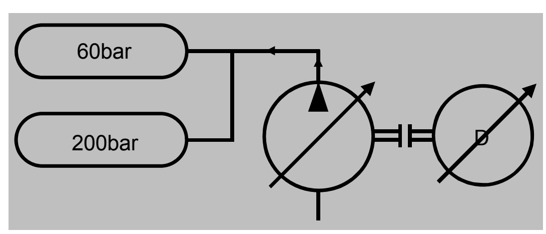
On the one hand a unit is analysed that from the point of view of energy efficiency represents state-of-the-art technology. On the other hand two units are examined whose energy consumption has been optimised. The unit corresponding to state-of-the-art technology has two variable-displacement axial piston pumps. The two pumps are mounted on a shaft and are driven by an induction motor with a connected load of 4kW. The first pump, in the following described as low-pressure pump, delivers a pressure of 60bar. The second pump, in the following referred to as high-pressure pump, delivers a pressure of 200bar.



Hydraulic unit with two variable displacement pumps and a constant drive



Hydraulic unit with one variable displacement pump, a constant drive and a booster (optimisation 1)



Hydraulic unit with one variable displacement pump with variable speed controlled pump drive and two accumulator; DvP-unit (optimisation 2)

Figure 2: Scheme of the different hydraulic units.

The first hydraulic unit whose energy consumption has been optimised (optimisation 1) replaces the high-pressure pump with a pressure intensifier called booster. This booster is fed via the low-pressure pump and generates the high-pressure with a fixed compression ratio.

The second hydraulic unit whose energy consumption has been optimised (optimisation 2) only has the high-pressure variable-displacement axial piston pump. It is again driven by an induction motor with a connected load of 4kW. This motor is equipped with a pressure controlled frequency converter. The high-pressure pump loads two accumulators; one low-pressure accumulator with 60bar and one high-pressure accumulator with 200bar. Further information on the DvP-unit can be found in [17]. The scheme of the three hydraulic units is depicted in Figure 2.

3.3 Measuring Setup

To compare the three hydraulic units the:

- power consumption of the hydraulic drive,
- pressure behind each pump and accumulator,
- leak and steering oil of each pump, volume flow of each pump outlet, volume flow of the tank outlet of each pump and
- temperature in the tank

are measured. Figure 3 depicts the exemplary measuring setup for the hydraulic unit representing state-of-the-art.

A Norma 5000 high precision power analyser from Fluke is used to measure the power. All measured signals are triggered, measured and recorded via a common dSpace system.

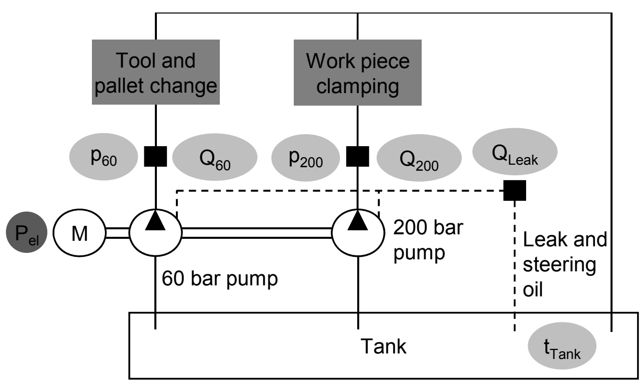


Figure 3: Description of the measuring setup of the hydraulic unit with two pumps, according to [18].

3.4 Experimental Procedure

To analyse the hydraulic units the three hydraulic functions of the machine tool:

- tool change,
- pallet change and
- work piece clamping

are taken into consideration. As there is no hydraulic function at all during most of the processing time, the behaviour of the hydraulic units during holding pressure is also analysed. Thus all possible conditions of the hydraulic units are covered for the machining centre under study. With the aid of the data obtained it is possible to calculate the energy consumption of any work piece or any defined scenario for the purpose of comparing the different hydraulic units and for calculating pay-back periods.

3.5 Test Results

Optimisation of the DvP-unit operating on a test bench

As a first step the DvP-unit is tested with a test bench. Therefore two simulation cylinders are used to represent the high- and low-pressure cycle of the machine tool. Before the optimisation these cylinders are used with 4/3 way valves. As you can see in Figure 4 the accumulators of the DvP-unit are reloaded every 125s during times where no hydraulic function is fulfilled. During these times the DvP-unit consumes 0.4kW.

To optimise the power consumption of the DvP-unit the following measures were taken:

- replace way valves with seat valves
- movement speed optimisation of the cylinders through the change of the settings of the choke valve as well as the pressure and flow compensator of the pump
- parameter optimisation of the frequency controller of the drive

As a result time between reloading the accumulator was extended to 400s. The power consumption during times where there is no hydraulic function fulfilled was reduced to 0.2kW and the power peak while reloading the accumulators was reduced from 3.4 to 2.3kW. With the help of the optimisations mentioned idle frequency of the hydraulic drive is reduced to 4Hz. Further advantages are the noise reduction of the DvP-unit through a very low turning speed and the reduction of thermal losses.

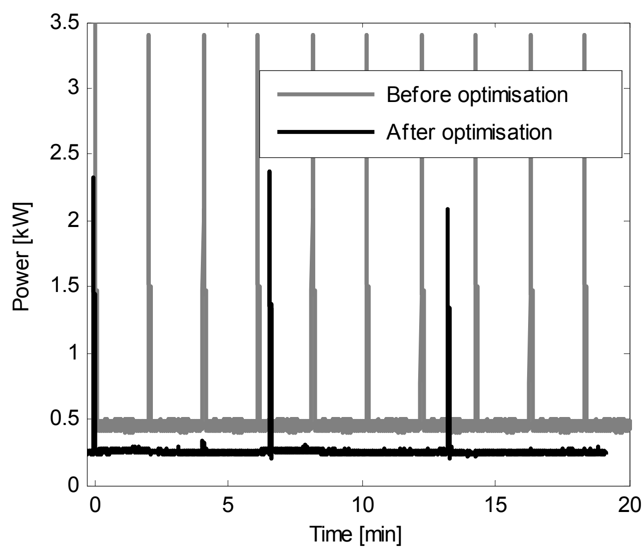


Figure 4: Optimisation of the power consumption of the DvP unit on the test bench.

Comparison of the three different hydraulic units operating on a machining centre

After the DvP-unit is optimised on a test bench the operation of the three hydraulic units is analysed on an exemplary machine tool. As a first step the power consumption of the state-of-the-art unit with two pumps and the unit with booster are compared for all hydraulic functions and during holding pressure, Figure 5.With the use of the booster the power consumption of the hydraulic unit can be reduced from 2.3 to 0.9kW. Also the volume flow of the leak and steering oil is reduced with the booster in the high pressure cycle by 3.1l/min. With a pressure of 200bar this already results in a reduction of the hydraulic power of more than 1kW.

As you can see, the releasing and clamping of the work piece takes a little bit longer with booster. Yet these functions are fulfilled parallel to the productive machine time. Thus it will not result in an extension of the productive time. The extended time of clamping and releasing work piece is due to a reduced volume flow in the high pressure cycle with booster. With the hydraulic unit with two pumps the high pressure pump delivers 13 l/min while the work piece is clamped or released, see also Figure 6. With the booster the volume flow in the high pressure cycle decreases to 4 l/min due to the fixed compression ratio between low pressure pump and booster.

Time for the tool and pallet change remains the same for both hydraulic units as the low pressure cycle is not changed. Changing pallets between two axis movements takes 8.6s with both hydraulic units.

Further results on the comparison of the hydraulic unit with two pumps and with booster can be found in [16]. The use of the booster offers the following additional advantages:

- reduction of the tank volume and needed hydraulic oil:
  As this machine tool is also sold to car manufacturers the tank of the hydraulic unit has to have four times the size of the volume flow of all pumps. This is a requirement of automotive industry. As the two pumps have a volume flow of 40l/min the tank has to have a size of 160l. With the booster the volume flow is cut to 25l/min which also cuts the volume of the tank to 100l.
- reduction of variety:
  The machine tool builder also sells this machine tool with a hydraulic unit only with a low pressure pump. Consequently the same tank can be used for the hydraulic unit only with low pressure pump and the hydraulic unit with low pressure pump and booster. This reduces variety as the tank with 160l is no longer needed.
- reduction of thermal heat:
  Compared to the hydraulic unit with two pumps the hydraulic unit with booster needs no external cooling. This reduces the power consumption of the machine tool's cooling system basing on a hotgas bypass by 0.2kW. A higher saving potential is possible with a cooling system working with digital-scroll compressor. This cooling unit is optimised from the point of view of energy efficiency and cuts the power consumption by 0.4kW. Further details on this energy efficient cooling system can be found in [19]. Additional power and cost savings can be achieved by using a smaller cooling system as the hydraulic unit with booster no longer needs to be cooled.
- noise reduction

Figure 6 compares the volume flow of the low and high pressure pump of the initial hydraulic unit with the volume flow of the pump of the DvP-unit. Each hydraulic unit fulfils the same hydraulic functions of the machine tool. The pump of the DvP-unit directly delivers the required volume flow for low and high pressure cycle. According to Figure 6 the pump of the DvP-unit provides a sufficient volume flow for releasing and clamping of the work piece. The volume that the pump of the DvP-unit provides for changing tools and pallets is not sufficient yet. A volume flow of up to 25l/min is required. The pump of the DvP-unit only delivers approximately 15l/min. Thus the pallet change takes 12.3s with DvP-unit compared to 8.6s with the initial hydraulic unit. This extra time for the pallet change is not acceptable.

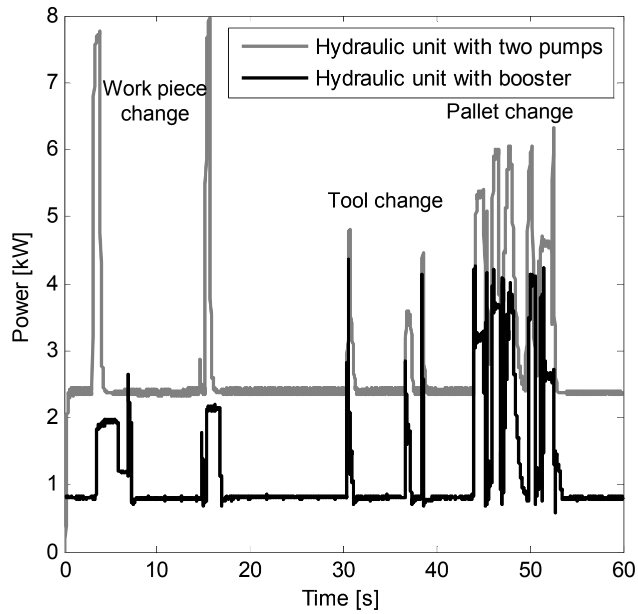


Figure 5: Comparison of the power consumption.

As a consequence the DvP-unit still has to be optimised operating with the machining centre. To achieve this, the following steps have to be considered:

- settings change of the pressure and flow compensator of the pump
- pivoting angle change of the pump and consequently change of the maximum volume flow
- parameter optimisation of the frequency controller of the drive
- settings change and optimisation of the Programmable Logic Controller (PLC)

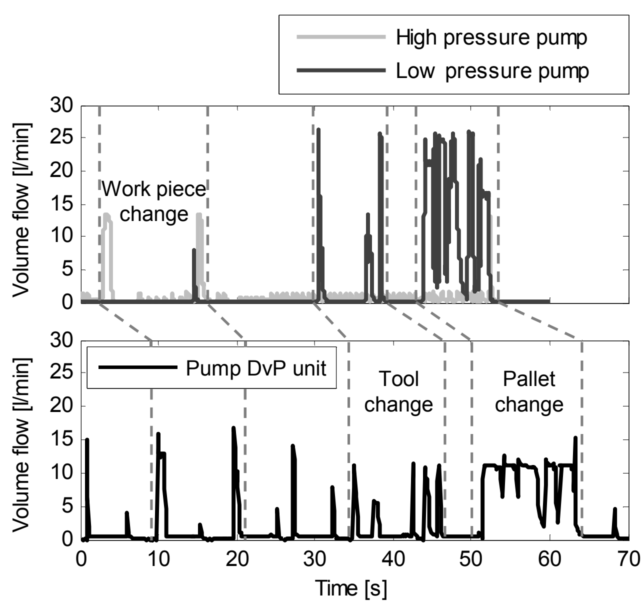


Figure 6: Volume flow.

Figure 7 shows the comparison of the three different hydraulic units. It must be stated that the measures of the DvP unit only derive from the test bench operation. In Figure 7 the three hydraulic units are compared with regard to the measures of:

- power consumption,
- pressure,
- leak- and steering oil and
- hydraulic power

during holding pressure.

An additional aspect is the leakage of the valves in the hydraulic cycle of the machine tool. The leakage of all valves was measured. All valves of the machine tool have a leakage sum of almost 0.1l/min. About 2/3 of this leakage is due to the valves in the high pressure cycle. Operating the machine tool with the hydraulic unit with two pumps or the hydraulic unit with booster the reduction of the leakage of the valves is not important. The leak- and steering oil of the pumps of the hydraulic unit that represents state-of-the-art is 40 times higher. The leak and steering oil of the hydraulic unit with booster is still nine times higher.

		Measures			
		Power consumption [kW]	Pressure [p]	Leak- and steering oil [l/min]	Hydraulic power [kW]
Hydraulic units	Hydraulic unit with two pumps	2.3	Low pressure pump: 60 High pressure pump: 200	Low pressure pump: 0.7 High pressure pump: 3.3	1.17
	Hydraulic unit with booster	0.9	Low pressure pump: 60 Booster: 200	Low pressure pump: 0.7 Booster: 0.2	0.14
	DvP-unit (test bench)	0.2 (with 4Hz)	14	2	0.05
Savings [%]	Booster to two pumps	61	0	0 (60bar) 94 (200bar)	90
	DvP-unit to two pumps	91	77 (60bar) 93 (200bar)	47	96

Figure 7: Comparison of the three hydraulic units during holding pressure.

Yet the leakage of the way valves has an influence on the operation of the DvP-unit. As the high pressure accumulator of the DvP-unit only has a useable volume of 0.02l the accumulator has to be reloaded every 16s. These many run-ups also lead to higher thermal losses. To reduce the number of restarts of the pump of the DvP-unit during pressure fluctuation with short time intervals the minimum operation time of the pump is set to 5s. Thus the ratio between pump running with full load and pump running with idle only is 5/16 during holding pressure. Operating the DvP-unit on the test bench with minimal leakage of the valves and cylinders this ratio was 5/400.

Consequently, all way valves of the machine tool, or at least the way valves in the high pressure hydraulic cycle, have to be replaced with seat valves to achieve a minimal power consumption of the DvP-unit.

4 COMPARISON OF LIFE CYCLE COSTING (LCC) OF HYDRAULIC UNITS

The use of the hydraulic unit with booster instead of the hydraulic unit with two pumps has an impact on the LCC. With regard to investment costs the hydraulic unit with booster saves costs of a plate heat exchanger, a proportional valve as well as some pipes, hoses and fittings as the hydraulic unit with booster has no longer to be cooled. Furthermore the dimensions of the tank can be reduced from 160l to 100l which also reduces investment costs. The second pump is replaced with the booster. To conclude, there should be some potential to reduce investment costs of the hydraulic unit with booster compared to the one with two pumps.

With regard to operating costs energy costs and costs of oil can be reduced by using hydraulic unit with booster. The power consumption of the hydraulic unit with booster is cut by 1.4kW compared to the hydraulic unit with two pumps. Additionally, cooling unit saves at least 0.2kW. Assuming an annual operating time of 4.000h the power consumption of the machine tool can be reduced by 6.400kWh. With energy costs of 10€cent/kWh this leads to a reduction of 640€ per year. As the tank volume is reduced by 60l also costs of hydraulic oil are reduced. Based on costs of hydraulic oil of 3€/l, 180€ can be saved every time the hydraulic fluid of the hydraulic unit is replaced.

As the DvP-unit is only analysed on a test bench yet, LCC is still unclear. Most probably the final unit will be changed for machine operation. Thus investment costs can not be calculated yet. In addition, power consumption and demand for cooling of the DvP-unit during machine operation will differ from test bench operation. Consequently comparison of LCC of the DvP-unit with the two other hydraulic units is still too uncertain.

5 SUMMARY AND OUTLOOK

This article compares three different hydraulic units:

- hydraulic unit with two variable displacement pumps and a constant drive (state-of-the-art unit)
- hydraulic unit with one variable displacement pump, a constant drive and a booster (optimisation 1)
- hydraulic unit with one variable displacement pump with variable speed controlled pump drive and two accumulator; DvP-unit (optimisation 2)

The first hydraulic unit represents state-of-the-art technology from energy efficiency point of view. The energy efficiency of the two other hydraulic units is optimised. The hydraulic unit with two pumps and the one with booster were both analysed on the same representative machining centre. This machining centre has two hydraulic cycles with different hydraulic functions; a high pressure cycle (200bar) and a low pressure cycle (60bar). The state-of-the-art hydraulic unit therefore has a low and a high pressure pump. For the hydraulic unit of optimisation 1 the high pressure pump is replaced with a booster. Thus the power consumption of the hydraulic unit can be reduced by 61% during holding pressure. Furthermore the leak and steering oil is cut by 3.1l/min.

The second optimisation, the DvP-unit, is analysed on a test bench to show the maximal possible reduction of power consumption. Compared to the hydraulic unit with two pumps the power consumption can be cut by 91%. Analysing the DvP-unit operating on the described machining centre still leads to an extension of the time to fulfill hydraulic functions. Consequently the the DvP-unit still has be optimised operating with the machining centre. The following steps will be considered:

- settings change of the pressure and flow compensator of the pump
- pivoting angle change of the pump and consequently change of the maximum volume flow
- parameterisation optimisation of the frequency controller of the drive
- settings change and optimisation of the Programmable Logic Controller (PLC)
- replace way valves of the machine tool with seat valves to extend the time between reloading the accumulators during holding pressure

After operating DvP-unit with the machining centre LCC of the DvP-unit can be calculated ad compared with the two other hydraulic units. In general it is possible to transfer all the results described in this paper on other machine tools.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] Devoldere, T., Dewulf, W., Deprez, W., Willems, B., Duflou, J. R. (2007): Improvement Potential for Energy Consumption in Discrete Part Production Machines, in: Proceedings of the 14th CIRP International Conference on Life Cycle Engineering. London, England, pp. 311 – 316

[2] Kircher, C., Geisler, R., Börsch, W. (2010): Maßnahmen zur Gestaltung energieeffizienter spanender Werkzeugmaschinen, in: Heisel, U.; Gadow, R.; Liewald, M.; Verl, A.; Spath, D.; Westkämper, E.: Fertigungstechnisches Kolloquium. Stuttgart, pp. 245 – 279.

[3] Mussa, S., Tilch, D. (2010): Energieeffiziente Werkzeugmaschine – Systematik und praktische Umsetzung, Symposium „Energieeffiziente Werkzeugmaschinen“, Metav, Düsseldorf, 24.02.2010.

[4] Rummel, W. (2010): Energieeffiziente Werkzeugmaschine. Möglichkeiten in der Produktkonfiguration, Brinkmann Symposium, 28.-29.6.2010.

[5] Vijayaraghavan, A., Dornfeld, D. (2010): Automated Energy Monitoring of Machine Tools, in: CIRP Annals - Manufacturing Technology 59, pp. 21 – 24

[6] Abele, E., Sielaff, T., Beck, M. (2012): Konfiguration energieeffizienter Werkzeugmaschinen, wt werkstattstechnik online, Vol. 102, No. 5, pp. 292 – 298.

[7] Augenstein, E., J. Nelles, A. Wurm (2011): Effiziente Werkzeugmaschine – Mehr Effizienz und weniger Abwärme in der Maschinenhalle, KKA Kälte Klima Aktuell, Sonderausgabe Großkältetechnik.

[8] Bäumler, S., Bode, H., Brecher, C., Breitbach, T., Hansch, S., Hennes, N., Prust, D., Tannert, M., Thoma, C., Wagner, P., Witt, S., Würz, T. (2011): Ressourceneffizienz im Werkzeugmaschinenbau, in: Brecher, C., Klocke, F., Schmitt, R., Schuh, G.: Wettbewerbsfaktor Produktionstechnik: Aachener Perspektiven, Proceedings of Aachener Werkzeugmaschinenkolloquium (AWK).

[9] Gontarz, A., Weiss, L., Wegener, K. (2010): Energy consumption measurement with a multichannel measurement system on a machine tool, ETH Zürich.

[10] Kuhrke, B. (2010): Ansätze zur Optimierung und Bewertung des Energieverbrauchs von Werkzeugmaschinen, Symposium „Energieeffiziente Werkzeugmaschinen“, Metav, Düsseldorf, 24.02.2010.

[11] Weck, M., Brecher, C., (2006): Werkzeugmaschinen 1, Maschinenarten, Bauformen und Anwendungsbereiche, 6. neu überarbeitete Auflage, Berlin Heidelberg: Springer-Verlag.

[12] Weck, M., Brecher, C., (2006): Werkzeugmaschinen 2, Konstruktion und Berechnung, 8. neu überarbeitete Auflage, Berlin Heidelberg: Springer-Verlag.

[13] Weck, M., Brecher, C., (2006): Werkzeugmaschinen 3, Mechatronische Systeme, Vorschubantriebe und Prozessdiagnose, 6. neu überarbeitete Auflage, Berlin Heidelberg: Springer-Verlag.

[14] Abele, E., Kuhrke, B., Rothenbücher, S., (2010): Entwicklungstrends zur Erhöhung und Bewertung der Energieeffizienz spanender Werkzeugmaschinen, in: Proceedings of the 1st International Kolloquium des Spitzentechnologieclusters eniPROD, Energieeffiziente Produkt- und Prozessinnovationen in der Produktionstechnik, Chemnitz, pp. 99 – 105.

[15] Helduser, S. (2009): Kompakt und dynamisch, O+P Ölhydraulik und Pneumatik, Volume 4, pp. 110 – 121

[16] Will, D., Gebhardt, N., (2008): Hydraulik: Grundlagen, Komponenten, Schaltungen, 4., neu bearbeitete Auflage, Berlin Heidelberg: Springer Verlag, pp. 253 – 254.

[17] Brecher, C., Bäumler, S., Triebs, J. (2012): Energieeffizienz von Werkzeugmaschinen, Messtechnik und Optimierungsmöglichkeiten der Hydraulik, in: Brecher, C.; Krüger, K.; Uhlmann, E.; Uhlmann, E.; Verl, A.; Klemm, P. (Hrsg.): Ressourceneffiziente Produktion, VDI Fort-schritt-Berichte, Reihe 2 684, VDI-Verlag, Düsseldorf, pp. 108 – 119.

[18] Brecher, C., Bäumler, S., Triebs, J. (2011): Design of Energy Efficient Hydraulic Units for Machine Tools, in: Seliger, G. (Hrsg.): Sustainable Manufacturing – Shaping Global Value Creation, CIRP 9th Global Conference on Sustainable Manufacturing, St. Petersburg, Russia, 28th – 30th September, pp. 190 – 195.

[19] Brecher, C., Bäumler, S., Jasper, D., Triebs, J. (2012): Energy Efficient Cooling Systems for Machine Tools, in: Dornfeld, D. Linke, B. (Hrsg.): Leveraging Technology for a Sustainable World, CIRP 19th Conference on Lifecycle Engineering, Berkeley, USA, 23th – 25th May, pp. 239 – 244.

Impact of Machine Tools on the Direct Energy and Associated Carbon Emissions for a Standardized NC Toolpath

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Abstract

In mechanical machining, significant energy use can be linked to carbon emissions and an increase in manufacturing cost. When machining a given component, the basic energy state dominates the total energy footprint as compared to tool-tip energy. Thus, the choice of machine tool is an important consideration in reducing the energy demand per product machined. In this work, a standardized NC toolpath was milled on machine tools in Singapore and the UK. The work significantly contributes to the knowledge on energy intensity in machining and the associated carbon dioxide emissions by presenting the impact of machine tools and geographical location.

Keywords:

Cutting; Energy footprint; Carbon dioxide footprint; Global manufacturing

1 INTRODUCTION

There is a growing need to quantify the energy footprint in manufacturing processes in order to develop: strategies for reducing energy intensity of products, manage the sensitivity of products due to increase in electricity prices and reduce carbon dioxide footprints. It is now well established that the total direct energy demand during a machining operation is dominated by the electrical energy requirements of the machine tool features [1-8]. This is referred to as the ‘fixed’ energy [2, 3] or the ‘basic’ state of a manufacturing resource or machine. The basic energy consumption is influenced by the design of the machine tool [9], and represents the energy demanded by the machine tool when operated at zero cutting load. In recent work, Branker and Jeswiet [10, 11], analyzed the environmental burden involved in the manufacturing of a sprocket on a Bridgeport GX480 VMC. They reported that the auxiliary units of the machine tool system dominated the energy budget.

To reduce the environmental burden (global warming potential) due to energy consumption in mechanical machining processes, energy demand must be reduced in any of the four LCA stages: manufacturing, transportation, use and end of life [12]. Narita et al. investigated the environmental burden for NC machine tools and reported that electricity consumption of the machine tool is the main critical factor from the viewpoint of global warming [13]. For a given component the link between the energy footprint and the carbon dioxide apportioned to the component due to energy use, can be established through the carbon emission signature (CES) [14]. The carbon emission signature is significantly affected by the proportion of carbon rich fuels used in power generation, compared to the percentage of low and carbon neutral power generation sources. The 2010, carbon emission signature, CES for France, Canada, United Kingdom, Germany, Singapore, USA, China and Australia was 0.079, 0.186, 0.457, 0.461, 0.499, 0.522, 0.766, 0.841 kgCO_2/kWhr respectively [15].

For 2011, the source of electricity for the UK and Singapore (SG) was as shown in Table 1. From Table 1, it is clear that in Singapore in 2011, the use of natural gas was dominant for power generation stations. Based on the data in Table 1 and Table 2, the CES for the UK and Singapore in 2011 was calculated to be 0.443 kg/kWhr and 0.601 kg/kWhr respectively.

Energy source	**UK (%)** [16]	**SG (%)** [17]
Coal	29.2	-
Natural Gas	40.7	75.8
Nuclear	19.1	-
Renewable	9.2	2.3
Fuel oil	-	21.6
Diesel oil	-	0.3
Other	1.8	-

Table 1: UK and Singapore fuel mix (for comparison).

		1 GJ of heat produced releases	
Type of fuel		**Δ*H* (kJ)**	**CO_2 (kg)**
Coal	$C + O_2 \Rightarrow CO_2$	- 394	112
Heavy oil	$C_{20}H_{42} + 30O_2 \Rightarrow 20CO_2 + 21H_2O$	-13300	66
Natural gas	$CH_4 + 2O_2 \Rightarrow CO_2 + 2H_2O$	-890	49
Biomass	$CH_2O + O_2 \Rightarrow CO_2 + H_2O$	-440	100
ΔH = Enthalpy: heat content; thermodynamic potential			

Table 2: Energy production fuels, the heat and CO_2 released [14].

1.1 Energy Modelling in Machining

Gutowski et al. [2], based on the analysis of an automobile machining line, proposed a mathematical model for the electrical energy requirement for manufacturing processes as shown in Equation 1.

$$E = (P_0 + k\dot{v})t \tag{1}$$

Where, E is the direct electrical energy in (J or Ws) required in machining processes, P_0 is the power consumption in (W), k is the specific energy requirement of the workpiece material in (Ws/mm^3), $\dot{v}$ is the material removal rate in (mm^3/s), while t is the cutting time in (s).

The need for an appropriate and generic energy estimation model motivated researchers into further work and subsequent models were developed by Diaz et al. [5], Mori et al. [18] and He et al. [19].

A unified and consolidated process planning centric model for machining processes was developed by Balogun and Mativenga [20] as shown in Equation 2. This model considers the effect of machine modules, auxiliary functions, axis movement and spindle speed characteristics for the total electrical energy estimation in mechanical machining processes.

$$E_{total} = E_b + E_r + P_{tc}t_{tc}\left[INT\left(\frac{t_2}{T}\right)+1\right]+ P_{air}t_{air} + \left(mN + C + P_{cool} + k\dot{v}\right)t_c \quad (2)$$

Where E_b, E_r, are the basic and ready state energy demand of the machine tool in (W), P_{tc}, P_{air}, P_{cool} represent tool change, air cutting and coolant power demand respectively and t_{tc}, t_c, T represents tool change time (s), cutting time (s) and Tool life (s) respectively, $mN + C$ is the spindle speed characteristics model. Other parameters retain their initial meanings.

The generic recommendations from Equation 2 are that the process planning centric direct energy model for machining should take into account

- The Basic and Cutting States, explicitly.
- Modelling the energy required to take a machine tool from the Basic State to a state where the axis and tool is ready for action and about to cut (Ready State).
- Direct energy requirements for spindles based, spindle design, spindle speed and machine tool power-RPM characteristics.
- The energy for tool change and the number of tool changes required.
- A distinction between energy demand for air cutting moves and the energy during toolpath execution when the tool is engaged in cutting.
- Modelling explicitly the influence of cutting speeds, feed and depth of cut to support process planning.
- Modelling machine tool specific accessories/modules.

1.2 Research Motivation

It is clear from energy monitoring of machining processes that the basic or zero load cutting state dominates the energy requirements in machining. Considering this fact, it is important to understand how choice of machine tool can alter the energy demanded for machining a given component and quantify the impact of making such decisions. Moreover, the carbon emission signature is an additional variable that affects the carbon footprint of a machined product. These combined factors have to be evaluated in assessing future costs of CO_2 footprints generated by manufacturing facilities. Such decisions can be vitally relevant and have to be taken now and in the future, accounting for the global mobility of capital and businesses and the increasing presence of companies in different geographical zones. This was the motivation for this work. The study was addressed in a round robin energy evaluation on machine tools undertaken by The University of Manchester, UK and Singapore Institute of Manufacturing Technology (SIMTech), SG.

2 ROUND ROBIN ENERGY ASSESSMENT ON MACHINE TOOLS

Two workpiece materials (AISI 316L stainless steel and AISI 1045 steel of dimensions 100 mm long by 50 mm wide and 20 mm height) were used in the end milling tests. The machine toolpath was standardized and evaluated for two cases covering: (i) conventional and (ii) high speed milling machining. The machine tools used were: a conventional speed Takisawa CNC centre and a high speed milling centre the Mikron HSM 400, both located in Manchester, UK. In Singapore, the cutting tests were done on a Hitachi Seiki VG-45 and Roeder RFM 700 for conventional and high speed milling respectively. The toolpath generated was a surface cleaning operation. The selected toolpath was kept simple in order to minimize the impact of the machine controller in modifying toolpath.

The cutting parameters and environment were kept constant as practically as possible for the two test locations. Table 3 shows details of the cutting tests. Electricity consumption was recorded with the Fluke 435 power meter and ELITEpro SP power meter. The vital energy data for the machine tools is provided in Tables 4 and 5 for the conventional and high speed milling tests respectively. This data is the critical energy demand indicators that should be optimized in order to develop energy efficient machining facilities. From Table 4 it is clear that the basic power required for the Takisawa machine is higher than that for the Hitachi machine, being values of 2.79 and 2.22 kW respectively. For the HSM tests, the basic power required for the Mikron HSM machine was 2.92 kW compared to 2.29 kW for the Roeder machine as shown in Table 5. The basic energy demand was 140, 185, 190 and 210 Whr on the Hitachi, Takisawa, Mikron and Roeder respectively. Comparing this to total energy demand in Tables 4 and 5, the basic energy demand was 75.7%, 78.7%, 69.04% and 71.8% on the Hitachi, Takisawa, Mikron and Roeder respectively. This result further confirms the impact of machine tool design and features on energy demand. Thus the design of next generation low energy demand machines could have a profound impact on reducing the energy footprint in machining.

Machine tool	**Takisawa & Hitachi Seiki VG-45**	**Mikron HSM 400 & Roeder RFM 700**
Tool diameter (mm)	50	8
Workpiece material	AISI 316L stainless steel	AISI 1045 steel
Inserts on tool holder	3	4
Spindle Speed (rpm)	650	32000
Depth of cut (mm)	0.5	0.2
Width of cut (mm)	50	0.2
Feed per tooth (mm/tooth)	0.038	0.1
Table feed in cutting (mm/min)	75	12800
Cutting fluid	Flood	MQL 15 ml/hr

Table 3: Machine tools and cutting parameters.

	Takisawa	Hitachi
Spindle Model	A06B-0652-B	Hitachi Spindle 45/4500rpm Main Motor: 15 hp
Spindle maximum power (kW)	11	11
Controller Model	MDSI	SEICOS MKIII controller
P_{basic} (kW)	2.79	2.22
Energy air cutting from area under graph (Whr)	198.1	159.9
Energy during machining with flood, area under graph (Whr)	234.4	185.4

Table 4: Basic Power Data of Machine Tools in Conventional Machining.

	Mikron	Roeder
Spindle Model	HVC140-SB-10-15/42-3F-HSK-E40	Fisher MFW-1230/42, max. 42,000 rpm
Spindle maximum power (kW)	10	14
Controller Model	Heidenhain TNC 410	PC-based customized controller by Roeders
P_{basic} (kW)	2.92	2.29
Energy air cutting from area under graph (Whr)	265.8	279.1
Energy during machining with MQL, area under graph (Whr)	274.8	292.7

Table 5: Basic Power Data of Machine Tools in High Speed Machining.

Detailed power-time domain profile during the air cutting and machining cycle and hence the direct energy requirements are shown in Figure 1, 2, 3 and 4.

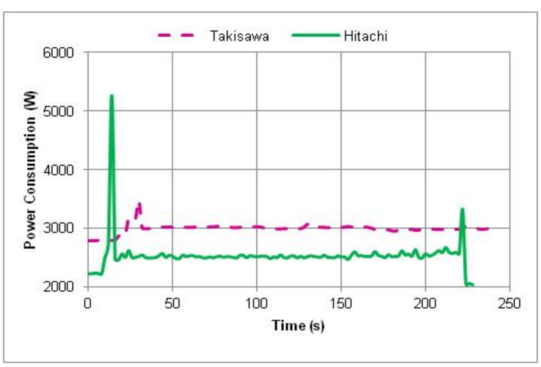

Figure 1: Power profile of Takisawa and Hitachi executing an NC toolpath at 650 rpm and air cutting.

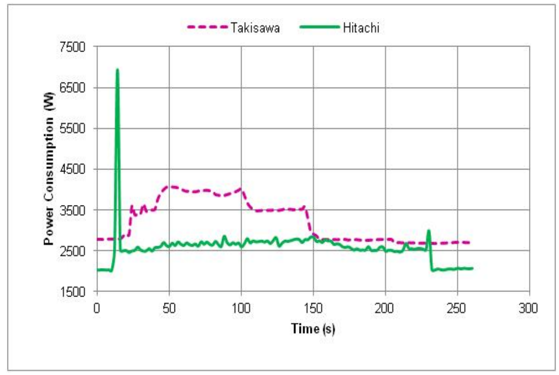

Figure 2: Power profile of Takisawa and Hitachi executing a standardized toolpath at 650 rpm under flood cutting environment machining AISI 316L stainless steel.

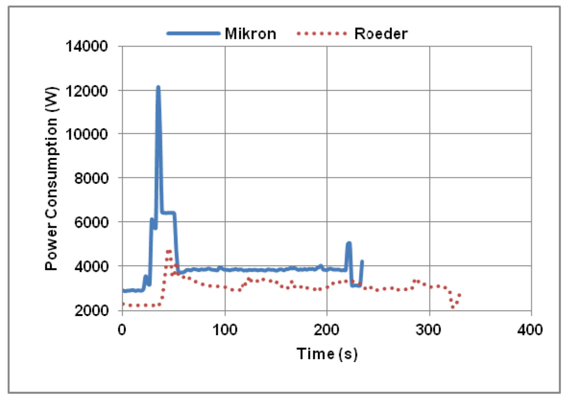

Figure 3: Power profile of Mikron and Roeder operating at zero cutting executing an NC toolpath at 32000 rpm.

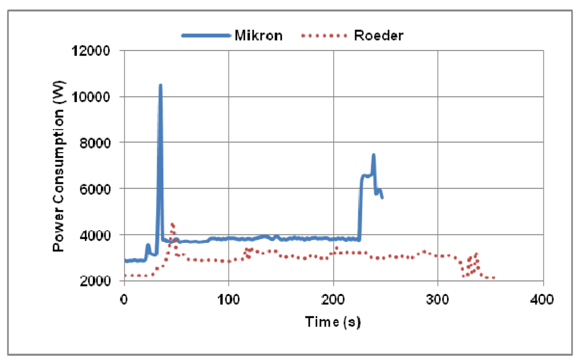

Figure 4: Power profile of Mikron and Roeder executing a standardized toolpath at 32000 rpm under MQL.

As shown in Figures 1, 2, 3 and 4, the power demand of the machine tool spindle causes a high surge in electricity consumption when the spindle is switched on. This is the characteristic peak seen in all the four figures. Comparing Figure 1 to 2, and Figure 3 to 4, it can be seen that the energy demand increases when going from an air cutting pass to actual cutting. Quantitative comparison of the energy state in air cutting compared to that in actual cutting shows that the machine tool energy consumption, which is the energy demand at the 'Basic state' and Ready State [18, 20] (steps that consume energy in preparing the machine for cutting), is 86.7%, 86.3%, 72.6% and 78.1% for Takisawa, Hitachi, Mikron and Roeder milling machines respectively. Testing machining toolpaths in air cutting can have significant contribution to increasing the energy footprint of a machine product or workshop.

3 ENERGY REQUIREMENTS AND CARBON FOOTPRINT IN INTERNATIONAL CONTEXT

Jeswiet and Kara [14], presented a model to evaluate carbon emissions derived from electricity generation as shown in Equation 3. In this equation, the "Carbon Emission Signature" (CES^{TM}) is used to specify CO_2 intensity or emission per unit of energy generated:

$$\textit{Carbon emission } [kgCO_2] = EC_{part}\,[GJ] \times CES^{TM}\,[kgCO_2/GJ] \qquad (3)$$

Where EC_{part} is the energy consumed to produce a component or manufactured product and CES^{TM} is the carbon emission signature as calculated for the energy mix. An average carbon intensity factor as specified in Section 1 is used for different geographical locations and countries. In this paper, the electrical energy required for machining each pass was calculated from the area under the power-time domain characteristic graph for the cycle time that the machine was operated.

The energy demand at spindle speed of 650 rpm for machining AISI 316L stainless steel on the Takisawa milling machine, was 20.9% more than machining the same NC toolpath on the Hitachi as shown in Figure 5. These machines were located in the UK and Singapore. However, due to the lower carbon emission signature of 0.443 kg/kWhr for UK, compared with 0.601 kg/kWhr for Singapore, the carbon footprint from direct electrical energy usage when executing the same NC toolpath in Singapore is higher by 7.3% at low speed machining, compared with the UK as shown in Figure 6. Thus the more energy efficient machine can have its environmental impact offset by its geographical location, if it is in a jurisdiction that has a higher carbon emission signature for its electrical energy as delivered from the national grid.

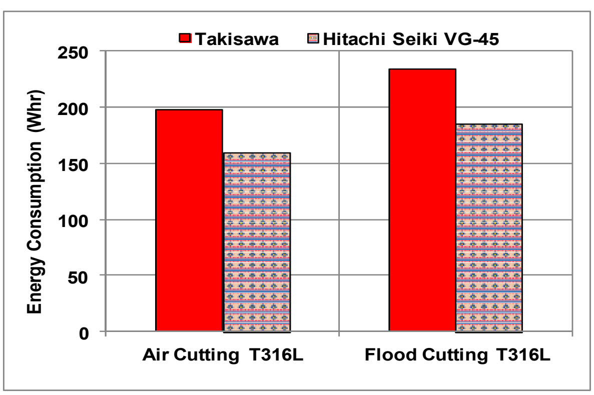

Figure 5: Energy consumption at 650 rpm on T316L.

However, with high speed machining of AISI 1045 steel at spindle speed of 32000 rpm shown in Figure 7, the carbon emission is 44.5% more in Singapore as shown in Figure 8. It can therefore be argued that the machine tool located in Singapore would need to be significantly more energy efficient than that in the UK so that it is not associated with a higher carbon footprint and global warming environmental potential. It appears from the analysis here that the typical differences in the energy demand by different machine tools can be less significant compared to the impact of moving a machine from a region of higher electricity carbon emission signature (CES^{TM}) to a region of lower CES^{TM}.

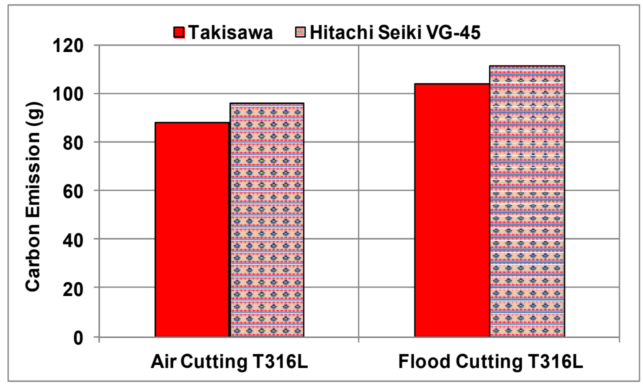

Figure 6: Carbon emission at low cutting speed of 650 rpm.

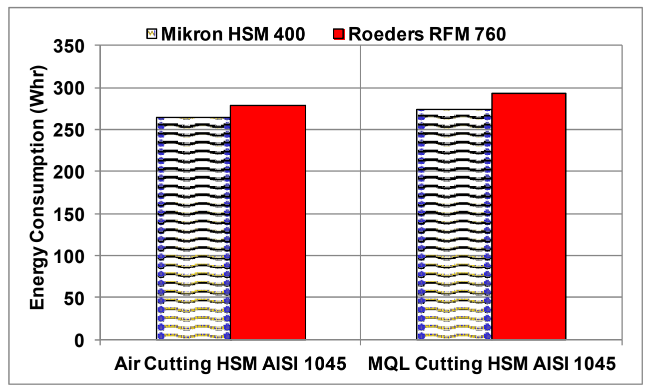

Figure 7: Energy consumption at 32000 rpm on AISI1045.

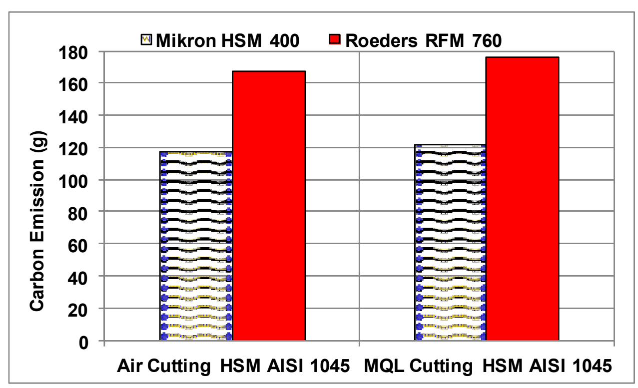

Figure 8: Carbon emission at high cutting speed of 32000 rpm.

The comparison for energy footprints for a similar machine located in different countries and executing a similar job is as shown in Figure 9, 10, 11 and 12. Singapore and the USA ranked proportionately to each other while the UK and Germany ranked proportionately in terms of carbon emitted.

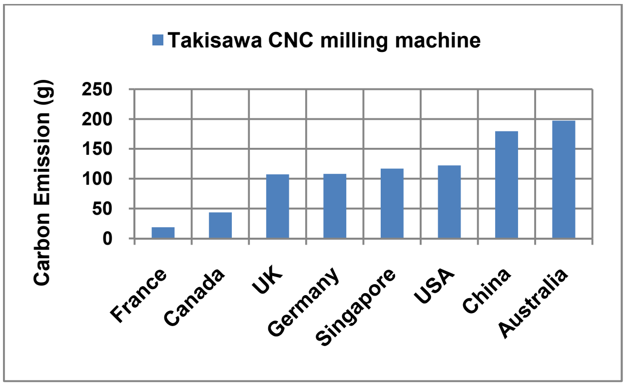

Figure 9: Direct energy derived carbon emission executing the same NC toolpath on Takisawa CNC milling machine in selected countries around the World based on 2010 CES™ data [15].

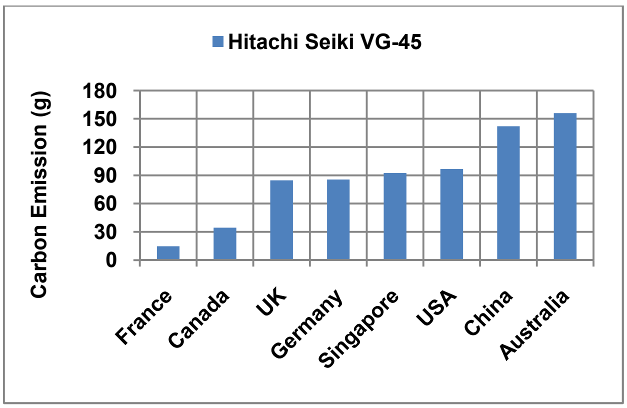

Figure 10: Direct energy derived carbon emission executing the same NC toolpath on Hitachi Seiki VG-45 in various countries around the World based on 2010 CES™ data [15].

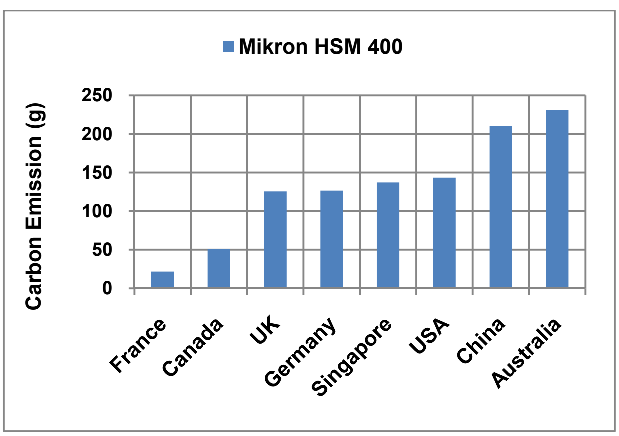

Figure 11: Direct energy derived carbon emission executing the same NC toolpath on Mikron HSM 400 in various Countries around the World based on 2010 CES™ data [15].

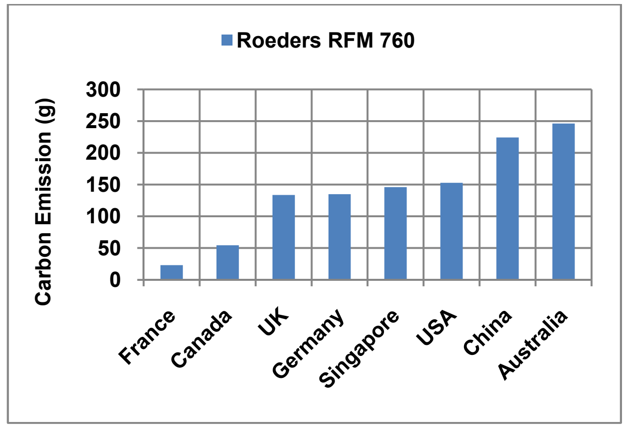

Figure 12: Direct energy derived carbon emission executing the same NC toolpath on Roeders RFM 760 in various Countries around the World based on 2010 CES™ data [15].

Executing the same NC toolpath in other countries, assuming the same machine tool system has was used in those countries, shows that under a low spindle speed of 650 rpm, a machine located in France will be associated with the lowest direct energy derived carbon dioxide footprint. On this environmental burden argument, it would appear that Australia and China are the worst locations for a setting up a machine shop (unless machine tools that are significantly more energy efficient are made for these locations).

4 CONCLUSION REMARKS

The research work investigated the impact of machine tools and country carbon emission signature (CES™) on the energy demand and associated carbon dioxide footprint when executing a standardized NC toolpath. The following points were drawn from the study:

1. In mechanical machining energy demand by the machine tool dominates the total energy compared to the energy required at the tool-tip (actual) cutting. Thus the choice of machine tool, or the design of more energy efficient machine tools, can be a significant strategy for reducing the energy and CO_2 footprint of machined components.
2. The assessment of energy requirements for standardized tool paths showed 20.9% reduction when comparing the Takisawa to the Hitachi machine in conventional machining; and 6 % reduction when comparing the Roeder RFM 760 to the Mikron HSM 400 machines in high speed machining.
3. Although the energy demand when executing the standardized NC tool path was lower or moderately higher for machines located in Singapore the direct energy derived carbon footprint was higher for Singapore in both conventional and high speed machining due to the relatively higher carbon emission signature for Singapore as compared to the UK.
4. When more energy efficient machines are used with a typical 20% lower energy demand, their carbon emission signature can be significantly increased by moving the machine from one geographical location to another due to differences in carbon emission signature between nation states. This may increasingly

become a relevant consideration due to international mobility of capital and manufacturing businesses. Introduction of carbon emission penalties or quotas will make this even more critical.

5. If an identical machine tool is located in France, assuming all conditions are the same, the direct energy derived carbon footprint for machines located in Canada, the UK, Germany, Singapore, USA, China and Australia will be worse. This implies that France due to its high dependence on nuclear power has a competitive advantage as a greener manufacturing environment in the context of location of machine shops.
6. In optimizing the energy intensity of manufacturing operations, the designers of the machine tools to be used in higher carbon intensity geographical locations, have to make a greater impact in reducing the energy demand for each machine tool, if they are to match the carbon footprint for nation states that have higher percentage of carbon neutral electricity generation methods.
7. **Note:**

- The investigation reported here is based on carbon footprints derived from direct electrical energy requirements and does not take into account the embodied energy of inputs to the machining process or other stages in the product life cycle.
- The carbon emission signature varies for nation states depending on their energy split in a particular year.
- Within one country different geographical locations or facilities can have electricity that is generated from different sources and hence different carbon emission signature.
- The machine tools reported in this study are a selected range of machine tools that were available from the participating laboratories and do not represent the best technology available on the market or from the designers of the machine tools.

5 REFERENCES

[1] Kordonowy, D.N. (2002): A Power Assessment of Machining Tools, BSc Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA.

[2] Gutowski, T., Dahmus, J., Thiriez, A. (2006): Electrical Energy Requirements for Manufacturing Processes, in: Proceedings of the 13th CIRP International Conference on Life Cycle Engineering, Leuven, Belgium.

[3] Dahmus, J., Gutowski, T. (2004): An Environmental Analysis of Machining, in: Proceedings of the ASME International Mechanical Engineering Congress and RD&D Exposition, pp. 1-10, Anaheim, California, USA.

[4] Devoldere, T., Dewulf, W., Deprez, W., Willems, B., Duflou, J. (2007): Improvement Potential for Energy Consumption in Discrete Part Production Machines, in: Proceedings of the 14th CIRP International Conference on Life Cycle Engineering, pp. 311-316, Waseda University, Tokyo, Japan.

[5] Diaz, N., Redelsheimer, E., Dornfeld, D. (2011): Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Use, Glocalized Solutions for Sustainability in Manufacturing, in: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, pp. 263-267, Technische Universität Braunschweig, Braunschweig, Germany.

[6] Vijayaraghavan, A., Dornfeld, D. (2010): Automated Energy Monitoring of Machine Tools, in: CIRP Annals - Manufacturing Technology, Vol. 59, No. 1, pp. 21-24.

[7] Rajemi, M.F., Mativenga, P.T., Aramcharoen, A. (2010): Sustainable Machining: Selection of Optimum Turning Conditions Based on Minimum Energy Considerations, in: Journal of Cleaner Production, Vol. 18, No. 10–11, pp. 1059-1065.

[8] Anderberg, S.E., Kara, S., Beno, T. (2010): Impact of Energy Efficiency on Computer Numerically Controlled Machining, in: Proceedings of the IMechE, Part B-Journal of Engineering Manufacture, Vol. 224, No. B4, pp. 531-541.

[9] Li, W., Zein, A., Kara, S., Herrmann, C. (2011): An Investigation into Fixed Energy Consumption of Machine Tools, in: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, pp. 268-273, Technische Universität Braunschweig, Braunschweig, Germany.

[10] Cao, H., Li, H., Cheng, H., Luo, Y., Yin, R., Chen, Y. (2012): A Carbon Efficiency Approach for Life-Cycle Carbon Emission Characteristics of Machine Tools, in: Journal of Cleaner Production, Vol. 37, pp. 19-28.

[11] Branker, K., Jeswiet, J., Kim, I.Y. (2011): Greenhouse Gases Emitted in Manufacturing a Product - A New Economic Model, in: CIRP Annals - Manufacturing Technology, Vol. 60, No. 1, pp. 53-56.

[12] Diaz, N., Choi, S., Helu, M., Chen, Y., Jayanathan, S., Yasui, Y., Kong, D., Pavanaskar, S., Dornfeld, D. (2010): Machine Tool Design and Operation Strategies for Green Manufacturing, in: Proceedings of the 4th CIRP International Conference on High Performance Cutting, pp. 271-276.

[13] Narita, H., Desmira, N., Fujimoto, H. (2008): Environmental Burden Analysis for Machining Operation Using LCA Method, in: Proceedings of the 41st CIRP Conference on Manufacturing Systems pp. 65-68, Tokyo, Japan.

[14] Jeswiet, J., Kara, S. (2008): Carbon emissions and CES™ in manufacturing, in: CIRP Annals - Manufacturing Technology, Vol. 57, No. 1, pp. 17-20.

[15] OECD/IEA CO_2 Emissions from Fuel Combustion 2012 - Highlights (Pre-Release) Available from: www.iea.org/publications/freepublications/publication/name,4010,en.html (accessed: November 2012).

[16] Department of Energy and Climate Change, Energy Digest of United Kingdom Energy Statistics (DUKES), Fuel mix disclosure data table, Available from: http://www.decc.gov.uk/en/content/cms/statistics/energy_stats/fuel_mix/fuel_mix.aspx (accessed: October 2012).

[17] Tan, R.B.H., Wijaya, D., Khoo, H.H. (2010): LCI (Life cycle inventory) Analysis of Fuels and Electricity Generation in Singapore, in: Energy, Vol. 35, No. 12, pp. 4910-4916.

[18] Mori, M., Fujishima, M., Inamasu, Y., Oda, Y. (2011): A Study on Energy Efficiency Improvement for Machine Tools, in: CIRP Annals - Manufacturing Technology, Vol. 60, No. 1, pp. 145-148.

[19] He, Y., Liu, F., Wu, T., Zhong, F.P., Peng, B. (2012): Analysis and Estimation of Energy Consumption for Numerical Control Machining, in: Proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture, Vol. 226, No. B2, pp. 255-266.

[20] Balogun, V.A., Mativenga, P.T. (2013): Modelling of Direct Energy Requirements in Mechanical Machining Processes, in: Journal of Cleaner Production, Vol. 41, pp. 179-186.

Modeling Energy States in Machine Tools: An Automata Based Approach

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Abstract

The growing amount of knowledge on machine energy consumption underlines the increasing interest in the sustainable aspect of manufacturing. The heterogeneity of production equipment and processes makes the machine hard to modeling. A method able to build an energy state-based model of a complex machine is presented. First the machine is divided into functional modules, afterword each module is modeled in terms of states and events with automata theory. A specific logic automaton represents the relationships existing among modules. Then, the machine state model is automatically obtained using a synchronization algorithm. The method has been validated on real machining centers.

Keywords:

Machine Tools; Energy Efficiency; Energy Modeling; Automata Theory

1 INTRODUCTION

1.1 Motivation

The amount of energy adsorbed by the industrial sector accounts more than 50% of the world energy consumption. Particularly, among the most energy-intensive sectors, metal industry reached in 2008 the 21.2% of the total industrial consumption [1].

A recent Directive of the European Parliament on Energy using Products [2] establishes a framework for the sustainable design of energy-consumers products, machine tools and production systems. The research projects and initiatives led by Cecimo [3] developed best practice guides and measures to improve environmental performances of machine tools. It is thus highly probable that important economic barriers and energy efficiency regulation can be defined in the years to come [4].

Since the influence of energy on machine tool life cycle cost depends on the automation level [5], preliminary environmental studies for machine tools indicate then up to 98% of the environmental impacts are due to the use phase machine consumption of electrical energy [3]. Consequently, in order to improve energy efficiency of machine tool usage, technical and organizational measures have been developed considering the single components and the whole machine. The most relevant measures are the eco-design of components aiming at minimizing power demands, the kinetic energy recovery systems (KERS) to reuse and recovery energy, and the implementation of control strategies for the efficient usage of components by minimizing processing time and non-value tasks [6]. All these measures have to use reliable models and methods for the estimation of the energy adsorbed by a machine or production system to process a workpiece. The development of machine models for energy saving purposes is the subject of this paper.

1.2 Previous Research

A common instrument to estimate energy consumption of machine tools is the use of databases or coarse models that provide averaged values for machining processes. These models can be used for rough and rapid evaluations but not in the detailed design phase of the machine tool structure and control strategy. The reason is that the level of detail of these instruments is not sufficient to evaluate properly machine energy profiles once applied on specific cases. In fact, these models are not able to discriminate the specificities of the power profiles signed by the analyzed manufacturing process, workpiece material and used equipment.

These methods and models are based on experimental data [7][8][9][10][11][12] and [4], implying that the machine must be physically available for power measures [13]. These methods are not conceived to be applied to the design phase, and their applications are limited in the machine tool use phase, because measurements within industrial environments are in several cases unsuitable owing to the high related times and costs.

Most of the models do not often consider auxiliary systems, while they focus on cutting process, and only few cases deal with secondary systems [14]. Therefore, neither optimization nor control can be grounded in these solutions [15]. Indeed, a suitable modeling approach has to rely on data easily available, while taking into account complexity and diversity of machine tools, and it has to include parameters that can be influenced by control. Furthermore, a machine model has to be both scalable according to the context of use and flexible to allow extensions and dynamic changes.

According to Dietmair [4], machine tools can be characterized as assemblies of components, or components, ensuring specific functions and requiring a portion of the total energy consumed. In the last years, various approaches to represent and determine energy consumption behavior of machine tool have exploited the machine modular structure.

Verl et al. [15] presented a modular modeling approach for machine tool energy consumption prediction. Detailed models have been developed for simulating the energy demand of a single component, in order to allow the easily substitution of each model with alternative ones. As examples, a coolant pump model and a centralized cooling supply system model are provided.

In [13] and [16] all components of the machines' individual function modules are analyzed with regard to their relevance to the overall energy consumption. The energetic behavior is modeled using Simscape modeling language in Simulink. Models allow parameterization, which provides a good reusability of them. The coolant system model is provided in [17] as an example.

Dietmar et al. [18] provided a framework for accurate modeling energy consumption in manufacturing systems using Petri Nets. The machine energy consumption is composed by the sum of machine components consumption, depending on machine states. Then, the model of a production system is built out of simple elementary models representing machines and supply systems. These sub-system models are coupled through connections between events, according to functional dependencies or control commands, thus creating linked states.

Despite the fact that all of the models presented in the recent years provide quite complete machine decompositions and energy modeling of the single components and functional modules, the complexity faced during the building of such machine models has never been tackled. As the number of components increases, also the building of the machine model makes more difficult. Further, the replacement or addition of a component might invalidate the work previously developed because the relationships existing among the functional modules are not linear and simple to formalize and modify.

1.3 Contribution

This paper presents a methodology for building energy state-based models of complex machine tools using the automata formalism. The starting point is the machine decomposition. Then, by synchronizing individual functional module models it is possible to create a unique model for the machine. More specifically, an automaton is independently defined to represent each functional module and the relationships existing among the modules can be implemented in a specific automaton, which represents the machine logic. Instead of analyzing the whole machine, that may be complex, the present approach allows to analyze each functional module independently and with minor efforts. Moreover, the logic of the machine is modeled with a dedicated automaton and the final model of the controlled machine represents only the feasible states of the machine according with a selected control strategy.

The machine can be decomposed at several detail levels, indeed each functional module can be decomposed in components, functionally dependent each other. Therefore, the method can be used for different purposes during the design phase (e.g., selection of energy saving components) or the production phase (e.g., machine control). Furthermore, coupling each state with an energy consumption parametric function can allow the simulation and the prediction of machine energy consumption in specific conditions.

1.4 Organization

The structure of the paper is briefly described. In section 2, a description of the energy states in machine tools and related transitions among them is given, whereas the detailed modeling methodology is explained in section 3. The method has been validated on real CNC machining centers, and a real case is presented in section 4 in order to give an example.

2 AN ENERGY STATE MODEL

A state can be defined as a physical-logic temporary representation of the system, seen as a group of subsystems. In the specific case of mechanical systems, an energy state represents the condition such that the system requires certain amount of energy in order to properly execute a task. Thus, each state can be associated to an energy consumption function, depending on the power required to maintain the state and the time spent in it.

2.1 The Machine Tool as System

In this paper the machine tool represents the **system**. Indeed, as explained previously, a machine tool can be decomposed in several machine functional modules in turn constituted by components. Thus, a machine functional module behavior can be represented by a set of states, whose energy profiles are created by the composition of the specific energy consumption profile of its components. The feasible combinations of functional module states compose the machine tool set of states where the machine can operate. Then, the energy consumption of each machine state will be given by the composition of the modules energy consumption, depending on the module state.

2.2 Events and Transitions

In discrete event systems the set of events used to model the occurrence to pass from one state to another has to be properly modeled. The events that govern the behavior of a machine tool refer to different levels: production system level, machine level and process level. Production system level events occur according to the external behavior of the machine, depending on the environment in which the machine operates. The machine level contains events related with machine characteristics, or with the achievement of certain conditions. The process events are those associated with the programing phase of the machine process, including the instructions given by the "G-Code". A list of the modeled events is provided as example in section 4.

3 MODELING METHODOLOGY

In order to describe the proposed approach, the methodology is explained in the following paragraphs while providing a technical survey on the formalism. In particular, section 3.1 contains the basic definition of **automaton**, section 3.2 details the creation of a single automaton for a machine tool functional module, and section 3.3 explains how the whole machine model can be built. For a detailed explanation of automata theory refer to [19].

3.1 Definition of Automaton

A finite automaton is a transition system described as a four-tuple $G \coloneqq (X, E, f, x_0)$, where G is a finite set of states in a discrete space, E is a finite set of events associated with G, $x_0 \in X$ is the initial state, and $f: X \times E \to X$ is the transition function such that $f(x_i, e) = x_j$ is defined, meaning that there is a transition labeled by event e from state x_i to state x_j with $x_i, x_j \in X$. A finite state automaton can be represented graphically by a directed graph or with a matrix expression that represents the transition function.

3.2 Single Functional Module Modeling

Since machine tool components mostly belong to mechanical, electrical, hydraulic or pneumatic systems, similar behaviors can be identified. Therefore, the related automata are similar one to the other, and an abstraction can simplify automata creation. The most common behaviors within functional module automata are the

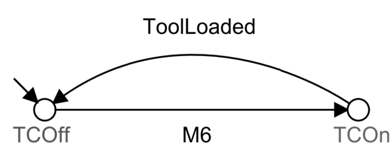


Figure 1: Example of switch automaton: the tool changer functional module.

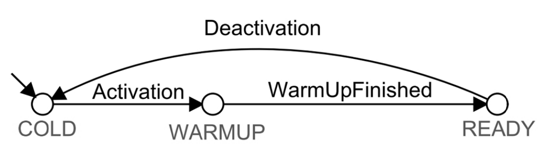
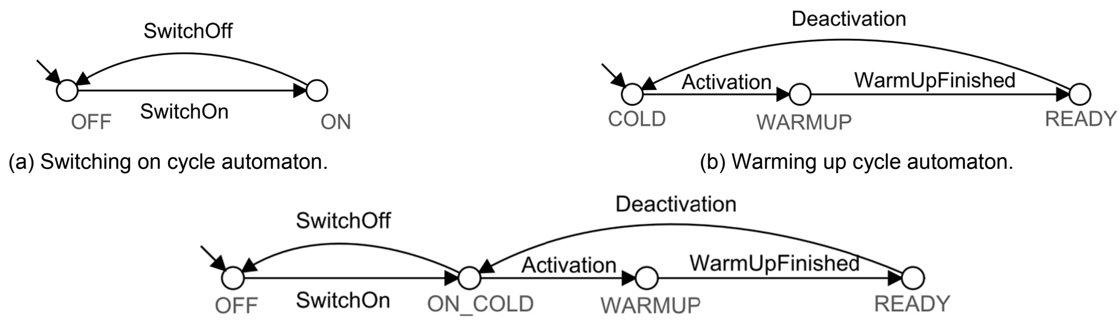


Figure 2: Example of compulsory passage automaton: a warm up.

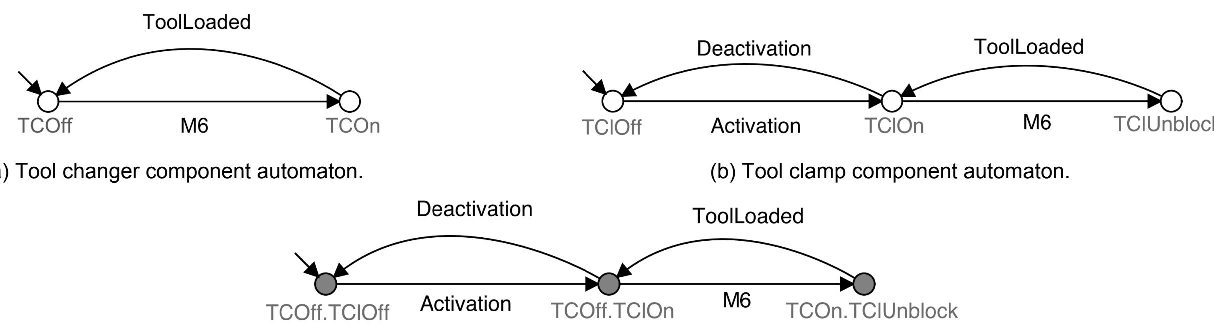


(a) Switching on cycle automaton.

(b) Warming up cycle automaton.

(c) Merged automaton.

Figure 3: Example of merged automaton (c): the module needs to be switched on (a) and then to be warmed up (b). The ON state after a switching on represents the COLD state that needs a warm up cycle.



(a) Tool changer component automaton.

(b) Tool clamp component automaton.

(c) Tool change functional module automaton.

Figure 4: Example of Synchronized Automaton: the tool changer and the tool clamp components are synchronized in order to create the Change Tool functional module automaton, whose states are represented by a vector composed by individual component states.

switch (Figure 1) and the **compulsory passage** (Figure 2). A switch occurs when the system passes from a state x_i to a state x_j (in Figure 1, with the G-code command M6) and vice-versa (in Figure 1, when the tool is loaded), whereas the compulsory passage entails the serial passage in one or more states between x_i and x_j or vice-versa.

The automaton of a machine object (i.e., a functional module or a component depending on the detail level) can be created using simple automata that already exist. Indeed, it is possible to merge an automaton with one or more automata, both from the basic set (e.g. switch, compulsory passage) and from the customized library of the company. Given two automata G_1 and G_2, such that $X_1 \cap X_2 \neq \emptyset$, let us define a new automaton $G_3 \coloneqq (X_1 \cup X_2, E_1 \cup E_2, f, x_0)$ where the initial state $x_0 = x_{0i}$ with $i = \{1\ or\ 2\}$, i.e., the initial state of one between the original automaton G_1 and G_2, and

$$f(x,e) \coloneqq \begin{cases} f_1(x,e) & \text{if } x \in X_1 \cap X_2 \wedge e \in E_1 \\ f_2(x,e) & \text{if } x \in X_1 \cap X_2 \wedge e \in E_2 \\ f_1(x,e) & \text{if } x \in X_1 \setminus X_1 \cap X_2 \\ f_2(x,e) & \text{if } x \in X_2 \setminus X_1 \cap X_2 \end{cases} \qquad (1)$$

By using the proposed operator, the user can create an automaton starting from few basic ones, and thus he can customize his component and functional module automata library. Figure 3 shows a general example for a switch on cycle followed by a warm up cycle, that is a typical behavior of machine functional modules, e.g., spindle, axis, chiller modules. The library can be easily extended with new automata, and it can provide the proper automata set to build out the model for a certain machine, or for a wide range of machines.

3.3 Whole Machine Modeling

In order to properly model the whole machine tool, it is mandatory to consider interactions between the functional modules. Indeed, the event set of each module includes private events that pertain to its own internal behavior and common events that are shared with other automata. The standard way of building models of entire systems from sub-systems is by parallel composition. Given two automata G_1 and G_2, let us denote $G_{||} = G_1 || G_2$ the parallel composition (often called synchronous composition) between G_1 and G_2 such that $G_{||} := (X_1 \times X_2, E_1 \cup E_2, f, (x_{01}, x_{02}))$, where

$$f\left((x_i, x_j), e\right) \coloneqq \begin{cases} f(f_1(x_i,e), f_2(x_j,e)) & \text{if } e \in E_1 \cap E_2 \\ f(f_1(x_i,e), x_j) & \text{if } e \in E_1 \setminus E_2 \\ f(x_i, f_2(x_j,e)) & \text{if } e \in E_2 \setminus E_1 \end{cases} \qquad (2)$$

with $x_i \in X_1 \wedge x_j \in X_2$. Therefore, in the parallel composition, a common event $e \in E_1 \cap E_2$, can only be executed if the two automata both execute it simultaneously, thus, the two automata are synchronized on the common events. Whereas a private event, that belongs to $(E_1 \setminus E_2) \cup (E_2 \setminus E_1)$, is not subject to such a constraint and it can be executed whenever possible. With this kind of interconnection, a subsystem can execute its private events without the participation of the other subsystems; however, a common event can only occur if both subsystems can execute it. If $E_1 \cap E_2 = \emptyset$, then there are no synchronized transitions and $G_1 || G_2$ represents the concurrent behavior of G_1 and G_2.

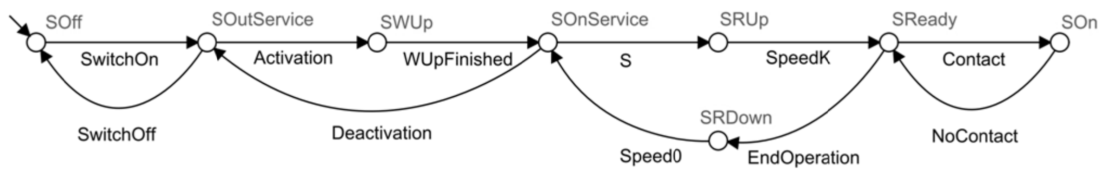


Figure 5: Spindle functional module.

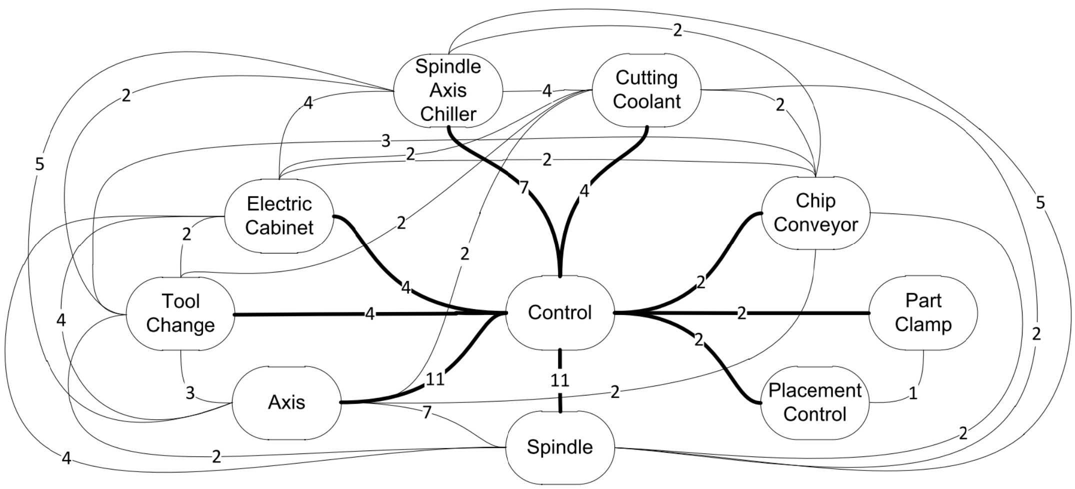


Figure 6: Relationships between automata that compose the controlled machine automaton.

Given the proper precedencies between events, an automaton, i.e., the logic automaton, can represent the relationships existing among modules. Thus, the synchronized model contains only the feasible combinations of functional modules states where the machine can operate. Moreover, it is controllable, because additional controllable events can be added to the model without the need to rebuild the automata from the beginning.

Thanks to its modular structure, the machine model allows extensions and changes, by adding or substituting a functional module automaton. When a new module is inserted in the machine, or an old one is replaced with a new version, it is possible to build a new automaton that represents it.

4 CONCEPT APPLICATION

The method has been validated on real machining centers. In order to provide an application example, the ComauSmartDrive 700L B AXIS© has been modeled. The machine working center is mainly composed by nine functional modules: the control cabinet, the axes, the spindle, the chiller (for the motors of the spindle and the axes), the tool change system, the cutting coolant system, the chip conveyor, the part clamp, and the placement control system. In this case the machine tool is modeled as a stand-alone machine, thus only events that belong to process and machine levels have been identified. The list of events is provided in Table 1.

Referring to Figure 5, the spindle functional module is detailed in the following. Firstly the spindle can pass from the Off state to the Out of Service state with the switch on, and vice-versa with the switch off. With the activation, the spindle module reaches the On Service state, after the warm up procedure (i.e., passing through the Warm Up state). In the On Service state the spindle is ready to move, or to be deactivated (i.e., to return in the Out of Service state). Following the command to start the movement, the spindle accelerates (i.e., Ramp Up state) until the desired constant velocity (i.e., Ready state), and it reaches the processing state (i.e., On state) depending if there is material removal or not. Given the condition that the operation is finished, the spindle decelerates (i.e., it passes in Ramp Down state) until it is completely stopped (i.e., it reaches the On Service state).

The method allows to define nine automata, one for each functional module, which have been implemented using the software Supremica©. The combined product between these automata is characterized by 60480 potential states. However, since the automata share several events, the states have been reduced to 432 with 2636 transitions using the synchronization algorithm.

The logic automaton that represents the dependencies between functional module automata is implemented, and the controlled machine automaton that result by synchronizing the logic automaton and the functional module automata has 49 states and 151 transitions. Regarding the detail level of interest of the energy consumption modeling, some states can be grouped and the machine automaton can be further simplified. The relationship between functional module and logic automata can be represented by a graph where the nodes represent automata and arcs represent the events shared. Figure 6 shows the structure of the relationships inside the controlled machine model.

In Figure 7 a portion of the controlled machine automaton is presented, and Table 2 reports the detail for each machine state. This portion of the machine automaton shows how the functional modules react to events from the initial state, i.e., the Off state. The machine logic avoids the occurrence of an event when its precedencies are not satisfied, e.g., it avoids that a part is loaded if an arrival is never occurred. Therefore, starting from the Off state, the whole machine tool can be switched on reaching the Out of Service state. Then, the machine can be activated and, through a Warm Up cycle, it reaches the On Service state. While the machine is out of service, in warm up or on service, an arrival can occur and the placement control system will be turned on, that means a change in the machine state. When the arrival occurs, if the machine is out of service, the activation would be requested, whereas, if the machine is already on service, the system would reach the Load Requested state and the part would be loaded in order to start the process.

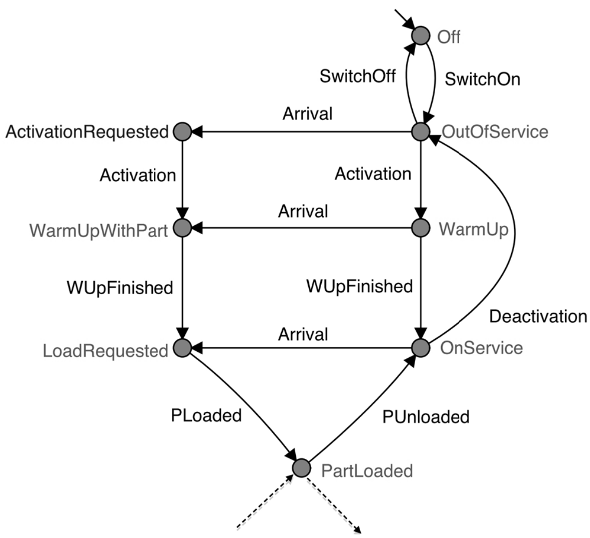


Figure 7: Portion of the controlled machine automaton.

5 CONCLUSIONS

A method to build energy state-based models of complex machine tools has been presented in this paper. The method is based on the automata formalism that fits well with the modular structure of machine tools. The complexity of machine tools is therefore managed by starting from automata models of simple components that are merged and synchronized until the whole machine (with its logic) is modeled.

The range of applicability of the presented approach is wide and concerns several users in different phases of the manufacturing process. In order to give some examples, the achieved model can be used to select energy efficient functional modules or to evaluate impacts of different design alternatives at machine level. Furthermore, the model can be used to simulate the energy consumption during the production of a specific new product, or to evaluate energy efficiency improvements achieved through a control strategies or other energy efficiency measures, within a certain production environment.

Future developments will be devoted to characterize each functional module state with an energy consumption parametric function. Therefore, energy-aware state control strategies can be developed and validated using the automata based machine model. Algorithms to reduce the machine automata in a simplified model to be used in large discrete event simulation models will also be investigated.

6 ACKNOWLEDGMENTS

The authors extend their sincere thanks to Paolo Beltramo and Daniele Borotto della Vecchia of Comau S.p.A. for their contribution to automata validation activity. The research has been partially funded by the European Community under the EU FP7-FoF.NMP (Grant agreement 285363) EMC2-FACTORY: Eco Manufactured transportation means from Clean and Competitive Factory.

Machine Level Events	**Description**
Activation	The module passes in On Service conditions.
Arrival	A part enters in the machine.
Contact	The material removal starts.
Deactivation	The module passes in Out of Service conditions.
Maximum Temperature	The maximum temperature allowed for the cooling fluid is reached. The glycol cycle starts.
Minimum Temperature	The minimum cooling fluid temperature is reached. The glycol cycle stops.
No Contact	The material removal finishes.
Pallet Loaded	The part is loaded and blocked on the machine.
Pallet Unloaded	The part is unblocked and unloaded.
Spindle steady state	The spindle finishes the rump up and reaches the steady state at the proper speed.
Spindle stop	The spindle finishes the rump down and stops.
Switch off	The main switch of the module is set on Off.
Switch on	The main switch of the module is set on On.
Tool loaded	Tool change cycle is executed. The requested tool is loaded on the spindle and blocked.
Warm Up cycle completed	The warm up cycle finishes, the module reaches the proper physical configuration to work.
Process Level Events	**Description**
Automatic Tool Change *M6*	Tool change cycle starts.
Cutting coolant starts *M7*	The cutting coolant system starts flow.
Cutting coolant stops *M9*	The cutting coolant system stops flow.
Feed *G01*	The axis starts feed movements.
Operation ends *M05*	The single operation is finished.
Part Program Finished *M30*	All the operations on the part are finished.
Rapid *G00*	The axis moves in rapid mode.
Spindle starts	The spindle starts accelerate in order to reach the target speed.

Table 1: Event list.

Machine State	Functional modules								
	Control Cabinet	Axis	Spindle	Axis-Spindle Chiller	Tool Change	Cutting Coolant	Chip Conveyor	Part Clamp	Placement Control
Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
Out of service	Out of service	Out of service	Out of service	Out of service	Off	Off	Off	Off	Off
Warm up	On	Warm up	Warm up	Warm up	Off	Off	On	Off	Off
On service	On	On service	On Service	On service	Off	Off	On	Off	Off
Activation required	Out of service	Out of service	Out of service	Out of service	Off	Off	Off	Off	On
Warm up with part	On	Warm up	Warm up	Warm up	Off	Off	On	Off	On
Load requested	On	On service	On Service	On service	Off	Off	On	Off	On
Part loaded	On	On service	On Service	On service	Off	Off	On	On	Off

Table 2: Controlled machine states with respective module states partial list (refers to Figure 7).

7 REFERENCES

[1] U.S. Energy Information Administration (2012): International Energy Outlook 2011, U.S. Energy Information Administration Technical Report, September 2012.

[2] Directive 2009/125/EC (2009), Directive of the European Parliament and of the Council, available at: http://www.cecimo.eu/.

[3] CECIMO - European Association of the Machine Tool Industries, http://www.cecimo.eu/.

[4] Dietmair, A., Verl, A., (2008): Energy Consumption Modeling and Optimization for Production Machines, in: IEEE International Conference on Sustainable Energy Technologies, ICSET 2008, pp. 574–579.

[5] Anderberg, S., Kara, S., (2009): Energy and Cost Efficiency in CNC Machining, in: the 7th CIRP Conference on Sustainable Manufacturing, Chennai, India.

[6] Zein, A., Li, W., Herrmann, C., Kara, S., (2011): Energy Efficiency Measures for the Design and Operation of Machine Tools: An Axiomatic Approach, in: Glocalized solutions for sustainability in manufacturing - Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Braunschweig, Germany, pp. 274–279.

[7] Dahmus, J.B., Gutowski, T.G., (2004): An Environmental Analysis of Machining, in: Manufacturing Engineering and Materials Handling Engineering ASME, pp. 643–652.

[8] Gutowski, T.G., Dahmus, J.B., Thiriez, A., (2006): Electrical Energy Requirements for Manufacturing Processes, in: 13th CIRP International Conference on Life Cycle Engineering, (LCE2010), Leuven.

[9] Gutowski, T., Dahmus, J., Thiriez, A., Branham, M., Jones, A., (2007): A Thermodynamic Characterization of Manufacturing Processes, in: Electronics & the Environment, Proceedings of the 2007 IEEE International Symposium, pp. 137–142.

[10] Gutowski, T.G., Branham, M.S., Dahmus, J.B., Jones, A.J., Thiriez, A., Sekulic, D.P., (2009): Thermodynamic Analysis of Resources Used in Manufacturing Processes. Environ. Sci. Technol., 43 (5), pp. 1584–1590.

[11] Devoldere, T., Dewulf, W., Deprez, W., Willems, B., Duflou, J.R., (2007): Improvement Potential for Energy Consumption in Discrete Part Production Machines, in: Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses, pp. 311-316.

[12] Dietmair, A., Verl, A., (2009): Energy Consumption Forecasting and Optimisation For Tool Machines, MM Science Journal, pp. 63-67.

[13] Abele, E., Eisele, C., Schrems, S., (2012): Simulation of the Energy Consumption of Machine Tools for a Specific Production Task, in: Leveraging technology for a sustainable world, Proceedings of the 19th CIRP Conference on Life Cycle Engineering, University of California at Berkeley, Berkeley, USA.

[14] Albertelli, P., Bianchi, G., Bigliani, A., Borgia, S., Matta, A., Zanotti, E., (2011): Evaluation of the Energy Consumption in Machine Tool: a Combined Analytical-Experimental Approach, in: 13th International MITIP Conference, Trondheim, Norway.

[15] Verl, A., Abele, E., Heisel, U., Dietmair, A., Eberspächer, P., Rahäuser, R., Schrems, S., Braun, S. (2011): Modular Modeling of Energy Consumption for Monitoring and Control, in: Glocalized Solutions for Sustainability in Manufacturing - 18th CIRP International Conference on Life Cycle Engineering (LCE2011), pp.341-346.

[16] Abele, E., Schrems, S., Eisele, C., Schraml, P., (2012): Simulation-Based Assessment of the Energy Consumption of Manufacturing Processes, in: Leveraging technology for a sustainable world, proceedings of the 19th CIRP Conference on Life Cycle Engineering, University of California at Berkeley, Berkeley, USA.

[17] Eisele, C., Schrems, S., Abele, E., (2011): Energy-Efficient Machine Tools through Simulation in the Design Process, in: Glocalized Solutions for Sustainability in Manufacturing - 18th CIRP International Conference on Life Cycle Engineering (LCE2011), pp.258-262.

[18] Dietmair, A., Eberspaecher, P., Verl, A. (2010): Predictive Simulation for Model Based Energy Consumption Optimization in Manufacturing System and Machine Control, in: Flexible Automation and Intelligent Manufacturing, FAIM2009, Teesside, UK.

[19] Cassandras, C.G., Lafortune, S., (2008): Introduction to Discrete Event Systems, 2nd ed., Springer Science Business Media, New York.

Combining Machine Tool Builder and Operator Perspective towards Energy and Resource Efficiency in Manufacturing

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Abstract

Various technical and organizational measures to improve energy and resource efficiency have been developed but studies still identify an efficiency gap when it comes to implementation. Thereby, two main perspectives need to be considered: the machine tool builder has a major role as the energy demand in operation is mainly determined in the design phase. On the other hand, the machine tool user focuses on the individual reduction of energy and resource demand and connected costs as well as environmental impact. Against this background, this paper presents a framework which brings together both machine tool builder and operator perspective which is underlined by two case studies.

Keywords:

Energy and Resource Efficiency; Continuous Improvement; Machine Tools

1 INTRODUCTION

As industrial observations as well as current research work clearly underline, considering the energy and resource consumption has strongly gained importance for manufacturing companies [1]. While favorably influencing the ratio of input and the useful product output, improving the energy and resource efficiency is a common approach towards environmental improvement of e.g. production machines. Studies show that basically many measures for improving energy and resource efficiency are available. However, the question is how to implement those measures within manufacturing companies [2]. In this context two important but quite different perspectives have to be taken into account: the machine tool builder as supplier of production equipment that requires energy for utilization, and the operator as the actual user of those machines. Figure 1 shows the relation of those perspectives on the energy consumption over the operation time of a production machine.

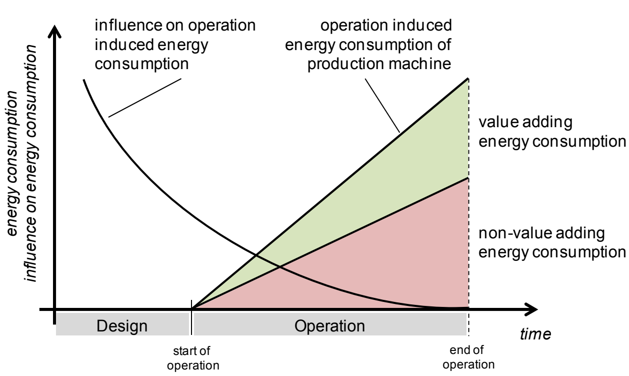

Figure 1: Influence on and occurrence of operation related energy consumption of production machines.

Quite clearly the machine tool builder basically has a major influence on the overall energy consumption of a machine. Through design (e.g. selection and dimensioning of components) and control of the machine the potential energy demand is basically determined. Additionally, decisions of the machine tool builder have a high leverage from a global perspective since an improvement of a machine type may have a positive effect on all his customers.

However, the energy consumption itself is caused by the operation over several years. Thereby, it can be distinguished between value adding energy consumption which is directly used for products or non-value adding shares which are e.g. caused by idling machines in stand-by mode [3]. Whereas the general boundaries are given by machine tool design (also from the customer's technical performance specifications) and control, the highly specific circumstances (e.g. production planning and control, shutdown regimes) and operation conditions (e.g. process parameters) determined by the operator, directly influence the energy related outcome. In the end, for the energy optimal performance over the whole lifetime of an individual machine, the energy efficient design and control is just a necessary but not sufficient requirement. Even the most efficiently designed machine can be operated quite inefficiently when applied for unfavorable operations or kept in stand-by mode without valuable outcome.

2 TECHNICAL BACKGROUND

2.1 Energy Flows in Machine Tools

Energy and resource flows at the input side of machine tools can be divided into two types: primary and auxiliary flows. The former include electricity and heat, while compressed air and process gases are examples of auxiliary flows. Within the machine tools, the energy input is transformed into mechanical and/or thermal forms of energy. On the output side, a major fraction of energy flows as waste heat and/or acoustic emission, while the other fraction is induced in the workpiece material.

The energy use of a machine tool depends on its states and operating parameters. In general, the states of a machine tool are *off, stand-by, production ready* and *production-mode*. Each state has its own energy utilization characteristics which correspond to the active sub-units in that specific state. In some cases, the non-productive modes have higher contribution to the total energy use relative to the production mode [3, 4].

2.2 Energy Efficiency of Machine Tools

Unlike energy conversion devices, the main objective of machine tools is not to transform energy, but to manufacture products. Thus, the useful input energy, such as fuel and electricity, is lost as low-grade heat in exchange for final services of manufacturing products. For this type of system, the energy efficiency can be quantified with the physical-thermodynamic definition of efficiency [5]. Also known as energy intensity, it is defined as the amount of energy used to produce one unit of physical useful output, e.g. GJ/ton or MJ/product.

$$\eta = \frac{Input\ energy}{Physical\ useful\ output} \quad (1)$$

Determining the denominator of Eq. (1) is relatively straightforward for machine tools users, e.g. the company's product. However, this is not the case for machine tool builders since a wide range of products can be produced by a machine tool. Furthermore, similar machines from different builders may have significantly different sub-units with various capabilities. At present, reference methods to overcome this issue are currently being developed as a part of the ISO 14955 standard – Environmental evaluation of machine tools [6]. Nevertheless, the energy intensity metric (Eq. (1)) has been widely used in the industry, illustrating its applicability in assisting manufacturers to improve their energy utilization performance.

3 COMBINED FRAMEWORK DEVELOPMENT

3.1 Framework Structure

Figure 2 shows the combined framework which brings together machine tool builder and operator perspective towards energy and resource efficiency in manufacturing.

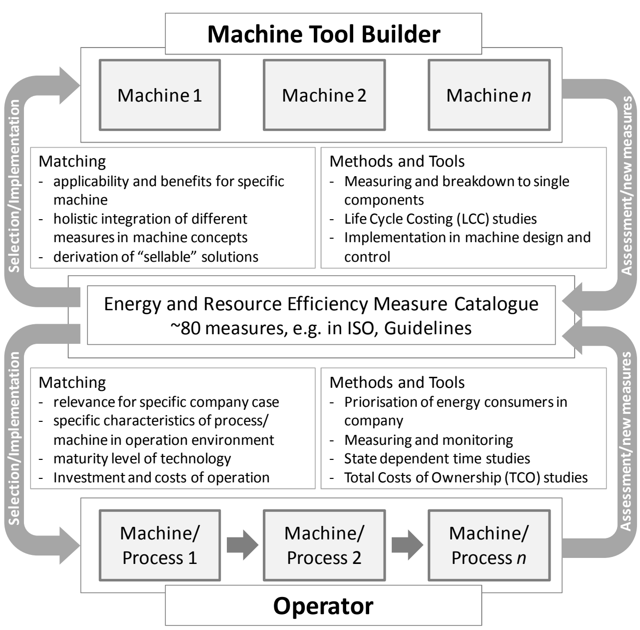

Figure 2: Framework for combined perspective on energy and resource efficient machine tools.

As mentioned earlier and further explained in Section 3.2, a diversity of energy and resource efficiency measures is available in research and industrial practice and can be found in guidelines and even in international standards already - both, from machine tool builder and operator perspective. The main question is which measures are favorable to select and implement respectively to buy or upgrade. Therefore, a matching of available measures with the individual situation has to take place which is supported by different methods and tools.

From machine tool builder perspective, the applicability and possible benefits need to be assessed based on detailed knowledge/ measurements of the machine with its components and control characteristics. Besides that, an economic evaluation has to be done to identify the financial efforts for development and integration of innovative measures as well as possible revenues due to the higher selling price. Technically and economically beneficial, as well as "sellable" solutions are merged into innovative machine tool concepts or modular add-ons. According to Figure 1, an ideal strategy is to provide standard machines which minimize the influence of the later operator through e.g. intelligent automatic shutdown routines and highly efficient processing with a variety of process parameters. This is certainly very difficult to achieve from an engineering point of view and also the individually necessary process parameter range and production circumstances are hard to predict beforehand. Alternatively the machine could be adapted and optimized towards a specific process. However, those individual solutions conflict with economies of scale and may lead to unfavorable machine tool prices.

The purchase price is still an extremely important argument for machine operating companies although studies underline that maintenance and energy can sum up to significant shares on total cost of ownership (TCO). With those TCO analyses an operator can take into account his individual circumstances and calculate whether a possibly higher investment sells off over the time of ownership due to e.g. energy savings. This requires knowledge on the machine state related energy demand as well as time studies to identify the composition of consumption with relation to the different states [7]. Additionally, an operator is typically interested to improve energy costs and environmental impact from company perspective as well. Therefore, appropriate methods and tools need to be applied which allow an easy identification and analysis of the most relevant consumption drivers with highest impact [2].

The single building blocks of the framework: energy and resource efficiency catalogue; machine tool builder perspective; and operator perspective are described in more detail in the following sections.

3.2 Overview and Classification of Available Energy and Resource Efficiency Measures

During the last decades, various energy and resource efficiency measures for industrial systems have been proposed and implemented. Until recently, these measures are focused on the energy intensive sector of industrial systems, such as iron and steel, pulp and paper, cement, and petrochemical industries. In the case of machine tools, several efforts have been made in order to compile energy and resource efficiency measures. Such catalogue of measures will on the one hand help machine tool builders to design improved machines and machine tool users to better utilize their machines.

In general, energy and resource efficiency improvements on machine tools can be performed by reducing, reusing and recovering energy. The decomposition of these three types of measures into machine tool design parameters has shown that the first type has higher availability than the others [8].

The currently developed ISO 14955 standard on the environmental evaluation of machine tools includes lists of energy efficiency improvement measures for metal cutting and forming machine tools [6]. The measures are organized based on the components which are focused on. Furthermore, a quantitative grading of estimated energy efficiency is given for each measure. Table 1 shows exemplary energy efficiency measures for metal cutting machine tools [7]. Among others, also [9, 10] provide overviews of potential improvement measures.

1. Overall machine concept	
1.1	Minimization of moved masses
1.2	Reduction of friction
1.3	Optimization of the electrical design
2. Drive units	
2.1	Regenerative feedback of inverter system
2.2	Use of energy efficient motors
2.3	Use of high quality reducers
3. Hydraulic systems	
3.1	Selection of optimal drive subsystem
3.2	Reduce hydraulic losses/leakage
3.3	Match the pressure level to the load cycle
4. Pneumatic systems	
4.1	Selection of optimal drive subsystem
4.2	Optimized compressed air system
4.3	Directed switch off
5. Electric systems	
5.1	Minimize energy losses in power supplies
5.2	Converter with power factor correction
5.3	Thermal management reg. control cabinet
6. Cooling lubrication system	
6.1	Discontinuous operating pumps
6.2	Minimal quantity lubrication
7. Cooling system	
7.1	Thermal management of machine tool
7.2	Cooling at the source
7.3	Demand depended cooling
8. Peripheral devices	
8.1	Demand depended controlled peripherals
9. Guidance for energy efficient use	
9.1	Optimization of work piece processing
9.2	Minimize non-productive time
10. Control systems	
10.1	Default setting for operating conditions
10.2	Automatic operating state switching
10.3	Monitoring of current energy consumption

Table 1: Exemplary list of energy efficiency measures for metal cutting machine tools [7].

Besides the technical measures, energy efficiency in machine tool utilization can also be improved by organizational measures. Organizational measures are mainly focused in reducing the energy demand by optimizing the time factor of processes. Examples include using optimal material removal rate in a machining process [12] and implementing energy-conscience process and production planning [13]. Measures in category nine in Table 1 can also be considered as organizational measures. Furthermore, in contrast with technical measures which are more focused on machine tool design, organizational measures are to be applied by machine tool users in their manufacturing operations.

Duflou et al. [1] divided the energy and resource efficiency measures in three main categories: optimized machine tool design, optimized process control, and process and machine tool selection. Sections 3.3 and 3.4 will discuss the implementation of these measures from machine tool builder as well as operator perspective respectively.

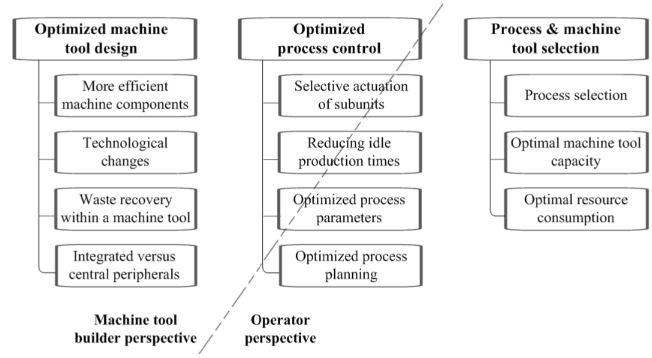

Figure 3: Energy and resource efficiency measures, based on [1].

3.3 Efficiency Measures from Machine Tool Builder Perspective

As original equipment manufacturers (OEM), machine tool builders typically have a big influence on the machine tool design and related energy and resource consumption patterns. The most important requirement for eco-design at machine tool level is the knowledge about the energy and resource flows throughout the intended machine tools. Detailed information on the contribution of various subunits (e.g. drives, coolant system, hydraulic system …) to the total energy and resource consumption during the different production modes (e.g. standby, production ready, production …) facilitates an efficient optimization procedure [7].

As shown in Figure 3, eco-design activities at machine tool level can be divided in four categories. While integration of best available technologies (BAT) of sub-components such as more efficient drives, linear axes or pumps contributes to reduce the machine tool consumption up to a few percentages, more drastic gains can be achieved by technological changes. For instance, a movement from CO_2 laser applications towards fiber or diode laser systems will reduce the related energy consumption with more than 50%. Examples of internal waste recovery can be found in more efficient waste recycling procedures as well as kinetic energy recovery systems (KERS). Finally, optimized scaling and supply methods of peripherals such as compressed air, lubrication and cooling systems have a relevant potential for ecological impact reduction. Life cycle costing (LCC) techniques can be applied to check the economic feasibility (e.g. pay back periods) of the identified measures.

Besides machine tool design, an OEM can also facilitate energy and resource efficient process control by implementing smart (ecological) machine tool control. While on the one hand, non-required subunits can be switched off during certain production modes, an automatic shift towards less energy consuming production modes can further reduce the total environmental impact on the other hand. For the latter one, a trade-off should be made with the machine tool availability (e.g. time needed to switch back to the production mode).

3.4 Efficiency Measures from Machine Tool Operator Perspective

From machine tool operator perspective two major steps of action can be distinguished:

Identification and Prioritization of Major Consumers

From a company's point of view it is important to identify the major drivers of consumption while they bear the highest leverage on total energy costs or environmental impact. Therefore, an energy portfolio can be used which classifies consumers according to (nominal) power and operating hours and provides distinctive decision support for further application [2], as depicted in Figure 4.

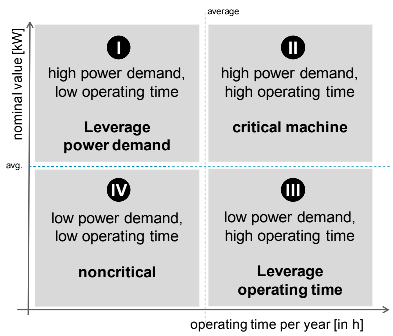

Figure 4: Energy portfolio for classification of energy consumers in manufacturing companies [2].

This systematic classification facilitates the identification of major consumers which require a detailed analysis regarding their individual energy and resource consumption. While updating the underlying data based on measurements, the energy portfolio can also be used as continuous method for improving efficiency.

Detailed Analysis of Consumers and Improvement Measures

For major consumers (or in case of specific investment decisions) a detailed measurement of energy and resource flows is necessary. As indicated before, e.g. the energy consumption is not static but rather dynamic, depending on the operation mode of the machine. Through appropriate metering and monitoring strategies it is possible to identify component specific power demands and also – with combined conduction of time studies – the time and energy demand during different operation modes [3]. In case of assessed and known specific energy demands of existing production machines, energetic performance specifications can be addressed within strategic machine purchasing processes [14]. With relation to the catalogue of available efficiency measures (see section 3.2), this directly triggers possible fields for improvement. However, from individual operator perspective it is crucial to calculate, whether certain technically applicable measures are really worthwhile to be implemented. Therefore, the now available detailed knowledge on machine tool consumption behavior needs to be connected to company specific operation data, e.g. the utilization rate of a machine. On this base, a case specific total cost of ownership (TCO) study can be conducted which reveals whether new investments or retrofit measures pay off over time under the individual circumstances.

4 APPLICATION

4.1 Case Study on Welding

Machine tool and manufacturing equipment users commonly face the situation that new equipment with higher performance indicators is promoted to have less resource and energy demands with better throughput over time. In order to implement the alternative equipment, a certain invest (purchasing costs of new device subtracted by the proceeds of the asset) has to be made. The arising question is, whether the new equipment is going to have an expedient pay-off period through energy and resource savings. In the selected case study scenario two welding installations are investigated by a quick TCO as recommended in Section 3.4.

The existing model A is an asset welding installation with comparatively lower technical performance indicators. As derived from the reference welding run in Figure 5, the specific output is 21.7 m/h of welding line on standard steel with an average electrical power demand of 7.37 kW during welding operation and 0.64 kW during standby. Additionally, the shield gas demand is 17 L/min. The welding installation alternative to be compared with is model B with an 36% higher output of 29.5 m/h of welding line with a 24% lower shielding gas demand of 13 L/min and an electric process power demand of 6.62 kW (-10%) and 0.25 kW (-61%) during standby.

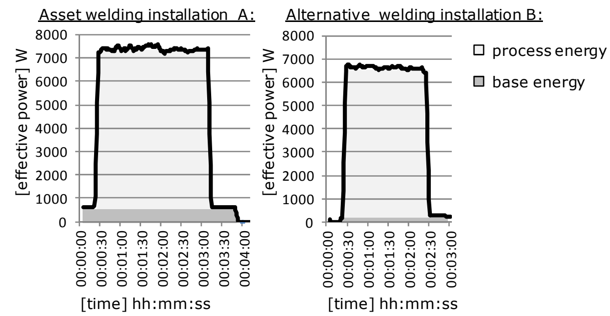

Figure 5: Energetic assessment of two alternative welding installations with one meter welding line reference.

The alternative welding installation B obviously provides better performance indicators. These need to be weight within a simplified total cost of ownership evaluation in order to state, whether the specific utilization and cost factor conditions allow an expedient return of invest through energy and resource cost savings. The specific factors that need to be considered are the specific utilization rates (hours of operation and idle to processing time ratio) as well as the specific material and energy cost factors. Figure 6 shows the break even analysis based on the functional unit of meters welding line produced.

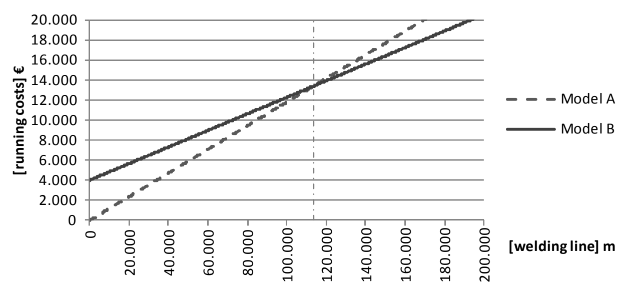

Figure 6: Break even analysis based on TCO calculation of two alternative welding installations.

As shown in Figure 6 the required investment of 4000 € has to be recovered by the savings on energy (0.17 €/kWh) and shielding gas (0.39 €/L, at 200 bar) in order to pay off after 113500 meters of welded line. Based on the scenario of 250 working days per year and a two shift model on the welding installation with a utilization rate of 80% (20% idle) an amortization would take place after 15 month. A usage scenario of only 3 hours of operation during a one shift model would on the other hand result in a pay off period of more than 6 years with fixed energy and resource prices.

The case study has shown the necessity for a life cycle oriented assessment of investments based on their energy and resource costs especially in small and medium sized production companies applying job shop manufacturing with lower utilization rates of their manufacturing equipment.

4.2 Case Study on Air Bending Processes

Using statistical time studies, Devoldere et al. [3] concluded that the actual bending operation represents less than 10% of the total production time of air bending processes. Consequently, the energy consumption of hydraulic press brakes during standby mode (e.g. program loading, sheet positioning…) is substantial. In order to reduce the required standby power, the involved machine tool builder redesigned the hydraulic system. First, the used gear pump was replaced by an adjustable (step-less) flow pump to increase the process flexibility. Afterwards, a reduction of the pump dimensions was realized by the use of a frequency convertor.

Figure 7 shows the power profile of a similar air bending operation (load of 40 ton, bending speed of 1 mm/s) on four machine tools representing three machine tool architectures and two capacities:

- Machine tool A: Conventional hydraulic press brake with a maximum capacity of 80 tons.
- Machine tool B: Hydraulic press brake equipped with an adjustable flow pump and a maximum capacity of 135 tons.
- Machine tools C and D: Hydraulic press brakes equipped with an adjustable flow pump and frequency convertor. Maximum capacities of 135 tons and 80 tons respectively.

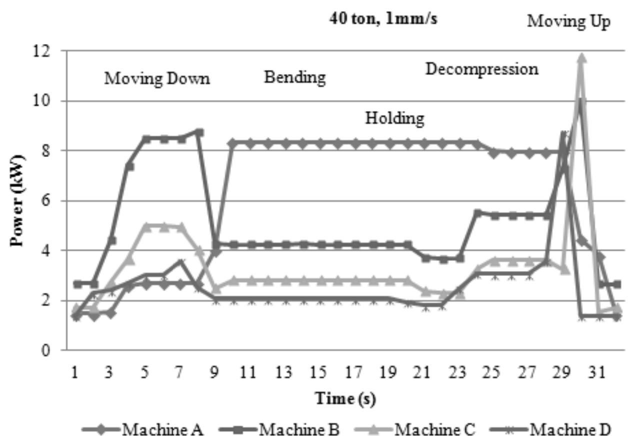

Figure 7: Comparison of the power consumed during the same task (load of 40 tons, slow approach: 1 mm/s) on four machine tools.

From energy point of view we can observe reductions up to 60% in consumed energy during the actual bending operation and returning of the ram. Taking into account also the non-productive modes (e.g. standby modes), the energy savings correspond to approximately 25% of the total consumed energy.

Furthermore, comparison of the energy requirements of machine tools C and D indicates that, due to the higher required fixed power levels for machine tools with increasing maximum capacities, proper machine tool selection (e.g. using machine tools as near as possible to their maximum capacity) will lead to energy consumption savings of more than 20%.

Besides machine tool selection, the operator can also select optimal process parameter settings. In this respect, an increase of the bending speed leads to a significant reduction of the bend energy. The higher power requirements are compensated by the lower production time.

A more comprehensive description of these energy improvement measures for air bending processes is provided by Kellens et al. [8].

5 SUMMARY

Without question, the topic of energy and resource efficiency has gained significant importance in manufacturing within the last decade. This development has triggered the development of many technical and organizational measures for improvement of manufacturing machine tools and related equipment. Still, many studies identify a predominant gap between the postulated energy and resource efficiency and the presently assessed one in manufacturing companies. As shown in this paper, two combined approaches are necessary to enable the best possible degree of efficiency of manufacturing processes. It was said that the machine tool builder has the highest impact on the possible reachable degree of energy and resource efficiency during operation of a machine tool when designing it. Therefore, a set of tools for gaining energy and material flow transparency in machine tools as well as tools to gain life cycle cost transparency is provided to create “sellable” machine tools with the best spectrum of energy and resource saving components specifically tailored to the demands of the usage scenario of the utilizing company. On the other hand, an operator oriented tool set is developed to identify and prioritize the most energy and resource demanding processes in order to utilize their present machine and equipment park as energy and resource efficient as possible to produce goods with the demanded quality and throughput. Complementary economic evaluation tools have been recommended to evaluate the best possible strategic investment on process substitutions or manufacturing equipment with TCO tools. Two case studies are additionally presented to underline the practical applicability of the developed framework and the integrated tools. The case studies have shown the importance of life cycle oriented tools and the need for specific use case scenarios to truly design effective machine tools and to define the most efficient utilization.

This paper presents a framework which brings together both machine tool builder and operator perspective. Both individual leverages on energy and resource efficient manufacturing have been targeted and integrated methods and tools have been presented and evaluated in two case studies.

Further work focuses on the integration of energy and resource flow metering and monitoring directly in machine tools to enable a quicker improvement process during the design of next generation machine tools as well as in the integration of machine tools in energy management and monitoring systems to easily evaluate the best operating behavior and quicker organizational improvement processes within existing manufacturing environments.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] Duflou, J.R., Sutherland, J.W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, K., Hauschild, M., Kellens, K. (2012): Towards energy and resource efficient manufacturing: A Processes and systems approach, CIRP Annals – Manufacturing Technology, Vol.61, No.2, pp. 587-609.

[2] Thiede, S.; Bogdanski, G.; Herrmann, C. (2012): A Systematic Method for Increasing the Energy and Resource Efficiency in Manufacturing Companies, In: Procedia CIRP - 1st CIRP Global Web Conference: Interdisciplinary Research in Production Engineering (CIRPE2012), Elsevier, 2012, Volume 2, pp. 28-33, ISSN 2212-8271.

[3] Devoldere, T., Dewulf, W., Deprez, W., Willems, B., Duflou, J. (2007): Improvement Potential for Energy Consumption in Discrete Part Production Machines, in: Advances in Life Cycle Engineering for Sustainable Manufacturing Business, Springer, pp. 311_316.

[4] Dahmus, J.B., Gutowski, T.G. (2004): An environmental analysis of machining, in: Proceedings of IMRCEE 2004, November 13-19, Anaheim, California, USA.

[5] Patterson, MG (1996): What is energy efficiency? Concepts, indicators and methodological issues. Energy Policy, Vol. 24, No. 5, pp. 377-390.

[6] ISO 14955 - Environmental evaluation of machine tools – Part 1: Design methodology for energy-efficient machine tools (Draft).

[7] Kellens, K., Dewulf, W., Overcash, M., Hauschild, M., Duflou, J.R. (2012): Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) Part 1: Methodology Description, Int. J. of Life Cycle Assessment, Vol.17, No.1, pp. 69-78.

[8] Zein, A., Li, W., Herrmann, C., Kara, S. (2011): Energy Efficiency Measures for the Design and Operation of Machine Tools: An Axiomatic Approach, in: Glocalized Solutions for Sustainability in Manufacturing, Springer.

[9] Kellens, K., Dewulf, W., Duflou, J.R. (2011): Environmental Analysis of the Air Bending Process, 14th ESAFORM Conference on Material Forming, AIP Conference Proceedings, Vol. 1353, pp. 1650-1655.

[10] Cecimo (2012), Self-Regulatory Initiative (SRI), online, http://www.cecimo.eu/ecodesign-eup/selfregulation.html, last accessed 31/10/2012.

[11] Eco Machine Tools (2012): Task 6 Report – Improvement Potential, online, http://www.ecomachinetools.eu/typo/reports.html, last accessed 31/10/12.

[12] Diaz, N., Redelsheimer, E., Dornfeld, D. (2011): Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Use, in: Glocalized Solutions for Sustainability in Manufacturing, Springer.

[13] Weinert, N., Chiotellis, S., Seliger, G. (2011): Methodology for planning and operating energy-efficient production systems. CIRP Annals – Manufacturing Technology, Vol. 60, No. 1, pp. 41-44.

[14] Zein, A. (2012): Transition towards Energy Efficient Machine Tools, pending for publication in Springer Verlag, Berlin Heidelberg, ISBN 978-3-642-32246-4

Method and Calculation Tool for Carbon Footprint Assessment of Machine Tool

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Abstract

This paper describes the method and calculation tool for carbon footprint assessment of machine tool. This method can get greenhouse gas (GHG) emission of the manufacturing stage of standard parts from bill of material directly. Furthermore, this paper provides the calculation method of the finishing allowance of the machined parts. The proposed method may not only accelerate engineers' estimation of carbon footprints for machined parts, but also obtain GHG emission of machined parts from the engineering drawing. A carbon footprint assessment tool of machine tool is developed by using Access software. A machine tool case is presented to demonstrate the capability of the proposed method and calculation tool.

Keywords:

Machine tools' ErP; Carbon footprint; Life Cycle Inventory

1 INTRODUCTION

Global warming has become a topical issue in recent years. Main source of carbon dioxide emissions that affects global warming is from electricity generation, transportation, and industry demand. Therefore, for solving global warming problem and reducing CO2 emissions, the international society begin a joint effort to seek for the low carbon products. Recently, it has growing needs for product carbon footprint assessment. According to the PAS2050 carbon footprint standard [1], direct emission must be measured. However, because that measurement is often unavailable, the life cycle inventory and impact assessment software/databases were introduced. On the other hand, the great amount of data in those software/databases and the lack of specific system boundary have made the assessment more and more difficult for the designer to conduct.

To evaluation the environmental burden caused by products is the responsibility of green design. Currently, life cycle assessment (LCA) method [2] is used to analysis the degrees of environmental burden caused by products. The results of traditional LCA are accurate and acceptable. However, it takes much time, high cost and needs clear information of the product. It is a trend that develops simple LCA [3] instead of complex quantification and evaluation. Narita et al. [4] presented an equation for calculating carbon footprint of machine tool in different cutting conditions. Azkarate et al. [5] developed an environmental burden assessment method for machine tool. Morbidon et al. [6] pointed out the problems in integrating CAD software tool with LCA software tool and proposed a method for calculating environmental impact of manufacturing process of component by inputting the process parameter values. Azevedo et al. [7] show the results of a comparison between a simple LCA and a detailed LCA of a machine tool. Schischke et. al. [8] have reported a study of machine tool for the EUP/ErP regulation. They used VHK LCA tool to perform the LCA assessment of five different machine tools and found over 90% carbon footprint of machine tool is in use stage. Chen and Wen [9] proposed a criteria for selection inventory data for carbon footprint of products from five LCA software and databases.

There are a lot of small and medium sized enterprises (SMEs) in Taiwan. When they attempt to utilize the LCA tools for product eco-design tasks, they can't afford to have environmental specialists working full-time with LCA tools in their technical group. Furthermore, many SMEs have small and short product series. The tools available today are in general too complicated and time-consuming to be used on these short product series.

This paper presents the method and calculation tool for carbon footprint assessment of machine tool. This method can get greenhouse gas (GHG) emission of the manufacturing stage of standard parts from bill of material directly. Furthermore, this paper provides the calculation method of the finishing allowance of the machined components from engineering drawing. A customized carbon footprint assessment tool of machine tool is developed by using Access software. A machine tool case is presented to demonstrate the capability of the proposed method and calculation tool.

2 CARBON FOOTPRINT AND LCA

Carbon footprint is a measure of carbon dioxide emissions that affects global warming in a product. The calculation of carbon footprint in product is based on LCA and global warming potential. PAS2050 and ISO14067 are the standard for guiding the calculation processes of carbon footprint. On March 2010, the EPA of Taiwan built "Taiwan Carbon Label" program. Therefore, there is a need to develop a simple carbon footprint calculation tool for new products of SMEs in Taiwan.

The life cycle of a product including material, manufacture, assembly, transportation, use and end-of-life treatments. Comprehensively consider all life cycle stages of product and quantify its impact on the environment is called life cycle assessment (LCA). The reliability of LCA value is very important in product evaluation of environmental impact. Most of studies focus on the uncertainty of data in LCA tool's database. However, the accuracy and quality of inventory process in LCA analysis is also very important for the results of computing LCA. Furthermore, different software has the same data name and the impact assessment results of data are not the same. Therefore, there is a need to develop a selection process for choosing best suitable data for LCA calculation.

3 DIFFICULTIES OF DATA SELECTION IN LCA TOOLS

Usually, the designer uses the bill of material (BOM) of product to perform LCA or carbon footprint calculation. The problems of data inventory analysis by using software for machine tools are in the following:

(1) It can not find the data in all software.

(2) It is ignored because the software has data but with different names.

(3) It can find the data with the matching name in the software, but the data quality is poor.

(4) There is a variety of similar name information in the software and the designer does not know how to choose.

(5) Different software has the same data name. However, the impact assessment results of data are not the same. Therefore, the designer does not know how to select.

(6) The proportion of composite components is unknown.

(7) Inventory of materials used different units.

(8) The name of components in the bill of material (BOM) of product can not find in the LCA software.

Table 1 shows the solutions of above 8 difficulties of data selection in LCA analysis. The problem (1) to (4) is the problem of miscarriage of justice of name and quality of data. The problem (5) can be solved by criteria for selections of life cycle inventory data in Reference 8. The problem (6) is a usual problem and can be solved by checking the proportion of components in detail or deciding the distribution by average. The problem (7) can be solved by finding suitable unit transformation information. The problem (8) is the problem of different name level between the name of components and the name of material in the LCA software. Therefore, the carbon footprint tool should provide the high level data with the name of components in the BOM of product.

Problems	Method of solution
1. No data	Find substitute data.
2. Name of misunderstanding	Check the name again.
3. Data quality	Compare the data quality.
4. Many names	Ask supply chain to check again or make a subjective judgments.
5. Different value in different software	Propose criteria of inventory data selection.
6.Unknown proportion	Check the proportion in detail or find distribution by average.
7. Different unit	Find unit transformation information.
8 No data for different level name	Provide the high level data with the name of components in the BOM of product.

Table 1: Solutions for difficulties in LCA data selection.

4 METHOD FOR CARBON FOOTPRINT ASSESSMENT OF MACHINE TOOL

This section proposes the techniques to provide the designer some useful concept for getting greenhouse gas (GHG) emission of the manufacturing stage of standard parts from bill of material directly. Furthermore, this section provides the calculation method of the finishing allowance of the machined parts. The proposed method may not only accelerate engineers' estimation of carbon footprints for machined parts, but also obtain GHG emission of machined parts from the engineering drawing.

4.1 Standard Component

It is difficulty for designer to find suitable GHG emission data of standard component from current LCA database. In this study, we build a GHG emission database of standard component and embedded into a customized carbon footprint assessment software tool for machine tool. The coefficient of carbon footprint of manufacturing process for each standard component can be obtained from supplier directly or calculated from the information of bill of material and the engineering drawing of this standard component.

Some carbon footprint of manufacturing process of simple standard components is listed in Table 2. The designer can find greenhouse gas (GHG) emission of the manufacturing stage of standard parts by using the information of bill of material from the customized carbon footprint assessment software tool directly.

Name of component	Carbon footprint of manufacturing process (Equiv. Kg CO2/kg)
Bolt	0.98261
Nut	1.88264
Spring	0.8804
O-ring	1.3428

Table 2: Partial list of the carbon footprint of standard component.

4.2 Machined Component

As for the machined component, it needs to develop the calculation method of the finishing allowance of the machined parts. For cutting and milling processes, one can calculate the surface area of the machined component from the engineering drawing file of SolidWorks CAD software, as shown in Figure 1. Then, based on the manufacture precision requirement information in the engineering drawing file (as shown in Figure 2), one can select the suitable finishing allowance of the machined component to obtain the removable volume by multiplying the finishing allowance with surface area. Finally, weight of removable material of machined component can be calculated by multiplying the removable volume with density. Therefore, the carbon footprint of manufacturing process of this machined component can be obtained by multiplying the weight of removable material with coefficient of carbon footprint of manufacturing process.

For drilling process, the designer needs to calculate the removable volume of drilling through hole. Then, one can use the same procedure to obtain the carbon footprint of drilling process of this machined component. However, for drilling non-through hole, one needs to multiply the adjusting weight (1.057) to correct the error.

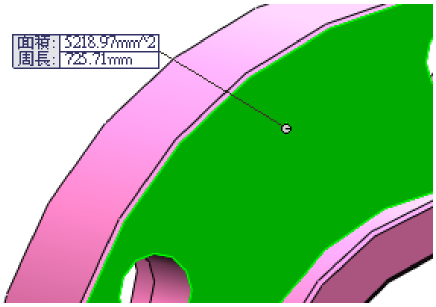

Figure 1: Surface area calculation by SolidWorks CAD software.

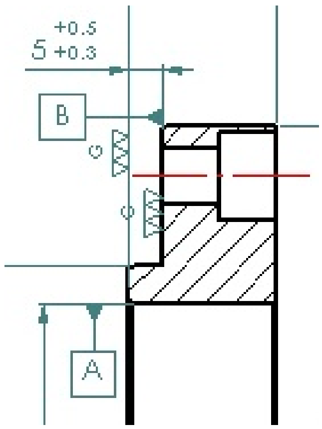

Figure 2: The manufacture precision requirement information in the engineering drawing file of the SolidWorks CAD software.

4.3 Use, Transportation and End-of-Life Stages

The major carbon footprint source been considered in use stage is the consumption of electricity and lubrication oil. The calculation of carbon footprint for transportation and end-of-life stages are the same as other type products.

5 CARBON FOOTPRINT CALCULATION TOOL OF MACHINE TOOL

Based on the proposed criteria for selection of life cycle inventory data in Reference 9, one can select the best suitable data from five LCA database/ software for carbon footprint calculation of a specified product. Customized assessment software tool was also built to help the designer assessing carbon footprint for each company. In this study, a Chinese language based simple software – Global Warming Potential Calculator for machine tool is developed. The purpose is to assist automation in using the method in carbon footprint calculation of machine tool for SMEs in Taiwan. This carbon footprint assessment software tool of machine tool is developed by using Access software. The welcome page, interface page and carbon footprint value page of this tool are illustrated in Figure 3, Figure 4, and Figure 5, respectively. The designer can calculate carbon footprint of product by using the information in BOM table of this product. The customized carbon footprint software tool with the Chinese language interface and the high level coefficient of greenhouse gas (GHG) emission data for standard parts in database are the two characteristics of this software tool.

Figure 3: The welcome page of “Global Warming Potential Calculator” tool.

After entering the welcome page, the first step is to input the assembly component (subsystem) from the “standard component” or “machined component” list, as shown in Figure 4. The second step is to enter the “machine tool” item to add new machine tool in list, as shown in Figure 5. The electricity and cutting cooling oil used in use stage, truck type and traveling distance in transportation stage and information of end-of-life stage should also input their value simultaneously. This software will update the carbon footprint value as the new item is input in this tool.

Furthermore, the maintenance interface page in Global Warming Potential Calculator of machine tool is illustrated in Figure 6. The function of this maintenance interface page is designed for the user to maintain the database of this tool.

6 EXAMPLE

6.1 Problem Description

The EMVC machine tool designed by ITRI is selected as design example to demonstrate the capabilities of proposed method and developing carbon footprint software tool. The specification of EMVC machine tool is shown in Table 3. This machine tool can be divided into six subsystems, such as tool magazine, working table, column, base, saddle, and headstock.

Figure 4: The interface page of “Global Warming Potential Calculator” tool.

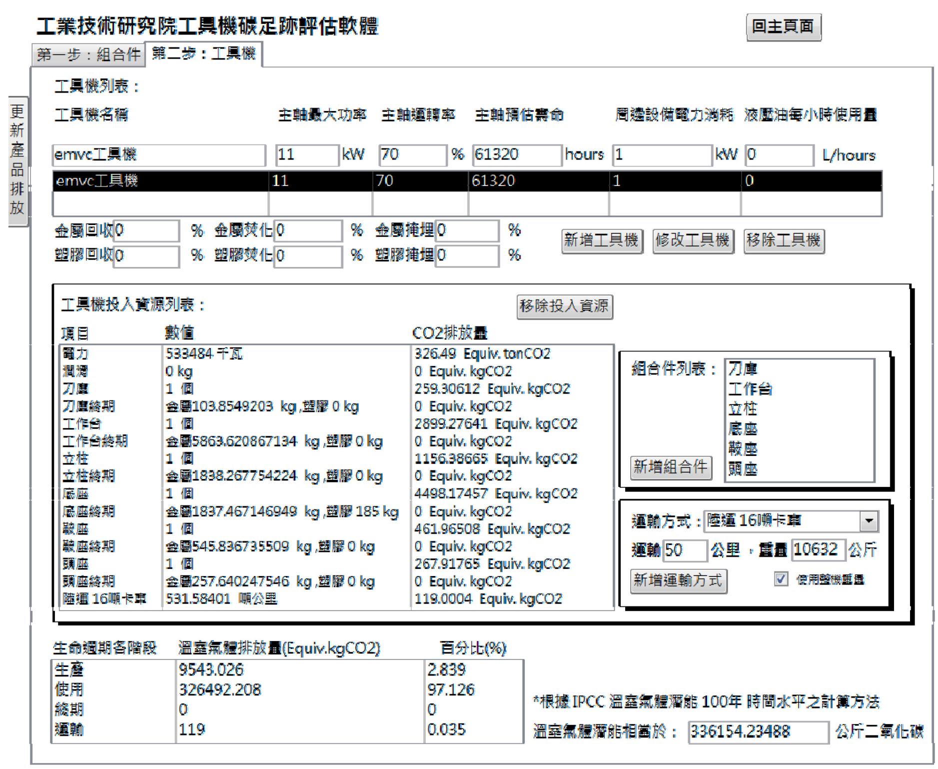

Figure 5: The value of carbon footprint page in Global Warming Potential Calculator.

Figure 6: The maintenance interface page in Global Warming Potential Calculator.

EMVC Machine Tool	Specifications
Weighjt	10184 kg
Maximum Speed	11 kW
Operation Rate of Spindle	70 %
Life of Spindle	7 years
Electricity Consumption of Peripheral Equipments	1 kW
Transportation	50 km

Table 3: Specification of EMVC machine tool.

6.2 Carbon Footprint Calculation Process

The processes of carbon footprint calculation of EMVC machine tool can be divided into four stages, such as production, use, transportation and end-of-life stages. This machine tool is transported 50 km by using the 16 tons truck. The interface page of carbon footprint calculation in each life cycle stages of the EMVC machine tool is shown in Figure 7.

6.3 Numerical Results

The value and percentage of carbon footprint of EMVC machine tool is shown in Table 4. It is obvious that the carbon footprint of machine tool is dominated by the use stage.

Life Cycle Stages	Carbon footprint (Equiv. Kg CO2)	Percentage %
Production	9543.026	2.839
Use	326492.2	97.126
End-of-Life	0	0
Transportation	119	0.035
Total	336154.2	100

Table 4: The carbon footprint of EMVC machine tool.

The percentage of carbon footprint in production stage of EMVC machine tool is only 2.839%. However, it is the second large stage in life cycle of EMVC machine tool. The value of carbon footprint of each component in production stage of EMVC machine tool is shown in Table 5.

Name of components	Carbon footprint (Equiv. Kg CO2)	Percentage %
Tool Magazine	168.98152	2.90
Working Table	2895.49922	49.71
Column	1153.36124	19.80
Base	929.07093	15.95
Saddle	410.41089	7.04
Headstock	267.91765	4.60

Table 5: The value of carbon footprint of each component in production stage of EMVC machine tool.

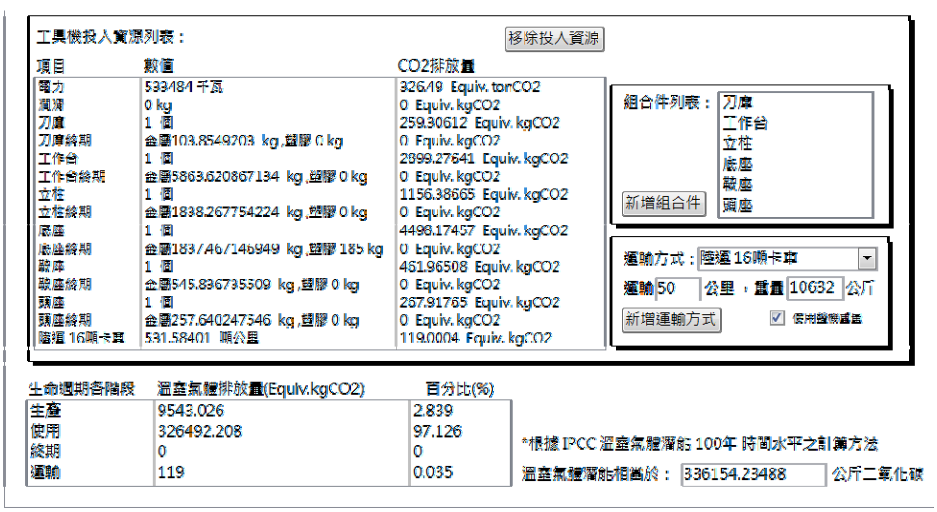

Figure 7: The value of carbon footprint in each life cycle stages of the EMVC machine tool.

7 CONCLUSIONS

This paper presented the method and calculation tool for carbon footprint assessment of machine tool. The customized carbon footprint software tool with the Chinese language interface and the high level coefficient of greenhouse gas (GHG) emission data for standard parts in database are the characteristics of proposed method and tool. This method can help the designer to get carbon footprint of the manufacturing stage of standard parts from bill of material directly. Furthermore, The proposed method may not only accelerate engineers' estimation of carbon footprints for machined parts, but also obtain GHG emission of machined parts from the engineering drawing. The EMVC machine tool case demonstrated the capability of the proposed method and calculation tool. Currently, the number of high level coefficient of greenhouse gas (GHG) emission data for standard parts in database is still required to expand. It hopes that this kind of greenhouse gas (GHG) emission data will available in most LCA or carbon footprint tools in the near future.

8 ACKNOWLEDGMENTS

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9 REFERENCES

[1] BSI (British Standards Institution). (2008): PAS 2050: 2008 Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services. UK, BSI.

[2] Wenzel, H., Hauschild, M., Alting, L. (1997): Environmental Assessment of Product-Methodology, Tools and Case Studies in Product Development, Vol. 1, Chapman & Hall, London.

[3] Graedel, T. E. (1998): Streamlined Life-Cycle Assessment, Prentice Hall .

[4] Narita, H., Kawamura, H., Norihisa, T., Chen, L. Y., Fujimoto, H., Hasebe, T. (2006). Development of Prediction System for Environmental Burden for Machine Tool Operation. JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing, *49*(4), pp. 1188-1195.

[5] Azkarate, A., Ricondo, I., Pérez, A., Martínez, P. (2009). An Assessment Method and Design Support System for Designing Sustainable Machine Tools. Journal of Engineering Design, *22*(3), pp. 165-179.

[6] Morbidoni, A., Favi, C., Germani, M. (2011). CAD-Integrated LCA Tool: Comparison with Dedicated LCA Software and Guidelines for the Improvement. In J. Hesselbach & C. Herrmann (Eds.), *Glocalized Solutions for Sustainability in Manufacturing* (pp. 569-574): Springer Berlin Heidelberg.

[7] Azevedo, M., Oliveira, M., Pereira, J. P., Reis, A. (2011): Comparison of Two LCA Methodologies in the Machine-Tools Environmental Performance Improvement Process. In: proceedings of the 18th CIRP International Conference on Life Cycle Engineering (LCE2011), pp. 575-580, Braunschweig, Germany, May 2-4.

[8]. Schischke, K., Hohwieler, E. , Feitscher, R. König, J. Wilpert, P., Nissen, N. F. (2011). Energy-Using Product Group Analysis Lot 5: Machine tools and related machinery Draft Task 4 Report, Fraunhofer Institute for Reliability and Microintegration, IZM, Berlin, February 28, 2011.

[9]. Chen, J.L., Wen, Y.-H. (2012): Developing a Simple Carbon Footprint Calculation Tool with the Criteria of Inventory Data Selection, Proceedings of the 19th CIRP International Conference on Life Cycle Engineering, Berkeley, USA, May 22-24,

Manufacturing of Optimized Venturi Nozzles Based on Technical-Economic Analysis

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Abstract

Due to limitations relating to the current manufacturing process of Venturi nozzles, high potentials for increasing the efficiency of the nozzles cannot be used. Initially, CFD-simulations are used to determine the potential for optimization. The simulation also provides details about the requirements in terms of production accuracy and surface roughness of the optimized nozzle. Furthermore, different manufacturing processes, with focus on additive manufacturing, are analyzed with regard to their applicability of manufacturing the nozzles. An economic investigation of the different manufacturing processes is done by using a self-developed calculation tool, which calculates the average production costs per unit and thereby allows a conclusion about the profitability of the different processes.

Keywords:

Venturi nozzle; additive manufacturing process; cost evaluation tool

1 INTRODUCTION

Within this paper different manufacturing processes for producing vacuum generators for vacuum handling systems are analyzed and assessed.

Definitions of important terms, the classification of the topic and the determination of goals for this investigation are given in this chapter.

1.1 Vacuum Handling Technology

For vacuum handling negative pressure is generated in a closed system in order to hold an object with a gripper. Usually a suction cup is used to build the closed system on the interface between the gripper and the object to be handled [1]. First the suction cup is placed on the object and then the air from the inner of the cup is extracted. Thus the static pressure declines and a pressure difference between the closed volume of the suction cup and the surrounding is generated. This causes a force which pushes the object against the suction cup. The higher the negative pressure within the suction cup, the higher the force [2].

In practice a negative pressure is generated for airtight materials (e.g. metal sheet, plane plastics etc.). According to this, the effective area and thus the number of suction cups can be determined with the mass of the object and the amount of acceleration.

A vacuum handling system usually consists of the following components [3]:

- Vacuum generator (pump, blower, ejector)
- Contact element (e.g. suction cup)
- Peripheral equipment (hose, mounting parts etc.)
- Kinematics (e.g. industrial robot)

The classification of vacuum generators results from the kind of used energy [4] [5]. Generally they are divided into electrical and pneumatic vacuum generators. Electrical vacuum generators are all kinds of electrical pumps, like the frequently used rotary vane pump. Furthermore, side channel blowers are often used for applications where only little negative pressure but high volume flow is required.

Most of the pneumatic vacuum generators are based on the Venturi effect [6]. The so called ejectors have a convergent-divergent nozzle in their inner side. If the air in the inner of the nozzle reaches sonic speed, this is called a “de Laval” nozzle. It is also possible that the air after the narrowest flow cross-section accelerates to supersonic. Industrial pneumatic vacuum generators are able to generate a vacuum up to -850 mbar, depending on the inlet pressure [7].

1.2 Scope of Investigation

Ejectors for vacuum generation exist with different range of functions. Starting with the so called basic ejectors, which are used for vacuum generation only, up to intelligent ejectors with integrated sensors and valves a wide range of different ejectors exist [7].

In every type series there are different power stages available. The power stage is mostly influenced by the nozzle size.

Object of this investigation is a special basic ejector series, where the housing is already made of plastics, but the nozzle itself is made of aluminum.

1.3 Goal of Investigation

There are certain constraints in designing the nozzle contour when producing it with CNC turning. Especially the Venturi nozzle is concerned of these constraints, because there are very small dimensions (<0.5 mm) in the inner. This requires a precise and more complex inner contour than the receiver nozzle.

The subordinate goals of this paper are:

- Determination of the potential for optimization through a flow optimized design of the Venturi nozzle with CFD simulation.
- Investigation of alternative manufacturing processes for their applicability to generate a complex inner contour of a Venturi nozzle.
- Economic comparison and evaluation of different manufacturing processes with respect to profitability.

Purpose of this paper is a quantity-dependent statement about the economic efficiency of nozzle production with different manufacturing processes as well as a determination of technical benefits of these processes.

2 EVALUATION OF THE EJECTOR OPTIMIZATION POTENTIAL BY USING FLOW SIMULATION

According to the first intermediate objective of this work CFD-simulations (Computational Fluid Dynamics) will help towards optimizing today's ejectors. Therefore the commercial software code Fluent from ANSYS is used. The simulation results will give a first idea in regard to the applicability of additive manufacturing technologies within this process. Those first results will be required for a further feasibility study.

2.1 Simulation Model

The modeling of fluid systems requires an abstraction and simplification of the real geometry. In this case the flow domain should be large enough to capture the basic flow effects (e.g. vortex, delamination, shock waves, etc.) regarding to the output quantities (e.g. pressure drop). Thus, the ejector geometry is reduced to the Venturi nozzle because of its relevant impact on the important output parameters.

2.2 Optimization Measures for the Venturi Nozzle Geometry

The issue of this investigation is an optimization of the Venturi nozzle geometry with regard to the pressure drop in between inlet and outlet of the Venturi nozzle. Although, the manifold possibilities for designing the nozzle inner contour should be tapped.

The new nozzle shape was adopted from existing designs that have already been proved in other industrial nozzle applications. A tangential changeover of the inner contour is observed in many cases. This shape is preferred regarding to the flow characteristics. The previous manufacturing process - turning - limits the inner nozzle contour to discontinuous changes. This leads for example to additional eddies and tear-off edges that will reduce the efficiency of the entire ejector system. The modification of the nozzle is shown in figure 1.

A comparison of the simulation results of the optimized nozzle with the standard nozzle design shows 35% less pressure drop in between the inlet and outlet of the Venturi nozzle. This result demonstrates clearly a possible increase in efficiency for the ejector. An additive manufacturing process can be used to realize this optimized nozzle shape.

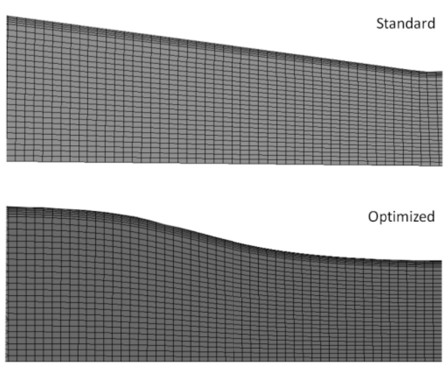

Figure 1: Detail of the Venturi nozzle contour - Standard vs. Optimized.

3 ADDITIVE MANUFACTURING

Different to conventional manufacturing techniques the manufacturing process and the technical boundaries of additive manufacturing approaches are not common knowledge. Therefore, the end of this chapter is dedicated to the description of the rapid prototyping process that is considered to be the most suiting for the fabrication of the nozzle. Prior to that, the reasons that lead to this choice will be introduced. Part of the selection process was the investigation about the influence of the part's surface roughness on the performance of the nozzle, since a relatively large surface roughness is inherent to parts built using additive manufacturing systems. For this purpose further CFD simulations were conducted. Following, the simulation results will be shown.

3.1 Impact of the Surface Roughness on the Efficiency of Venturi Nozzles

An investigation on the impact of the surface roughness should point out the technical limits regarding several manufacturing processes. Furthermore this investigation should help to select the ones with the best performance. Therefore, the inner surface of the Venturi nozzle is modified virtually and CFD simulations are carried out. The result of this step is the determination of the impact of the surface roughness for the inner contour of the nozzle. In this case the standard nozzle will be the reference for a comparison. The standard nozzle is manufactured from aluminum with a surface roughness of Ra=1.6µm. On the other hand the additive manufacturing process generally comes up with a much higher surface roughness. This can be 10 times or more. Hence, the surface roughness of the standard turning process can be nearly neglected (Ra~0µm).

Figure 2 shows the impact of the surface roughness with regard to the pressure drop across the Venturi nozzle.

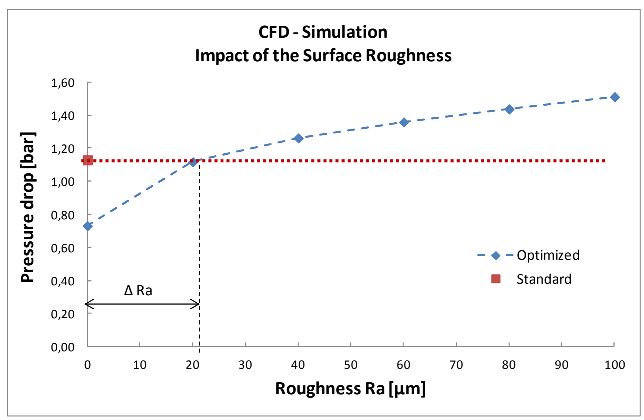

Figure 2: Impact of the surface roughness.

The trend points out that an optimized nozzle contour with a surface roughness of Ra~0µm would decrease the pressure drop up to 35%. However, an increase of the surface roughness Ra up to 30µm would minimize the advantage of an optimized nozzle shape. On the other hand, this means that an additive manufacturing process should not lead to a roughness higher than Ra 20-30µm. Otherwise it would not be competitive according to the technical point of view. This intermediate result clarifies the importance of a high surface quality for the manufacturing process.

3.2 Selection of the Appropriate System

As outlined above, the achievable surface roughness of the different fabrication processes is critical for the performance of the Venturi nozzle. Additionally the system has to be capable to fabricate the part in a sufficient geometric accuracy. The higher the precision the more perfect the optimized nozzle contours can be fabricated. The tolerance of parts built by using conventional manufacturing techniques is generally ± 0.1mm, whereas the tolerance for the narrowest central part of the nozzle is ± 0.02mm. To get an overview of the available rapid prototyping systems scientific papers were evaluated [8, 9]. Subsequently, leading suppliers, like for instance 3D Systems and Stratasys, were interviewed to get more information about the performance, the acquisition and the operating costs of their systems. Eventually, the Projet HD 3500 PLUS from 3D Systems was considered to be the most appropriate system for the fabrication of the Venturi nozzles. With a vertical resolution of 34µm and a lateral resolution of 16µm it has the highest precision of all systems taken into consideration. Furthermore, already the preceding model attained a good surface quality [9], which has been further improved for the current model according to the manufacturer. Moreover, the acquisition costs of 96.775€ and the material costs for the support (0.179€/cm³) and the build material (0.296€/cm³) are relatively low for an additive manufacturing system. A further advantage compared to other systems is the possibility to get rid of the support material by melting it. In other systems it is often necessary to break out the support material. First of all, this could be a problem within the narrow nozzle and furthermore there might stay residual parts that prohibit a good air flow and thus decrease the efficiency of the device. To build up the object the Projet HD 3500 PLUS employs the so called Multi-Jet Modeling method developed by 3D Systems (see Figure 3). This technique will be introduced shortly in the following to gain a basic idea of its technical aspects.

3.3 Multi-Jet Modeling

The technique is quite similar to the common 2D printing process. The print head consists of hundreds of nozzle pairs. The first nozzle prints the support material which is a fusible wax. The wax is hardened at the desired position directly via the low temperature of the environment. The second nozzle prints the build material at the positions required for the device. Like for many other additive manufacturing methods the material is a photopolymer. Directly after the application it is hardened by the succeeding UV lamp. After the deposition of a complete layer, the platform is lowered and the next layer can be printed.

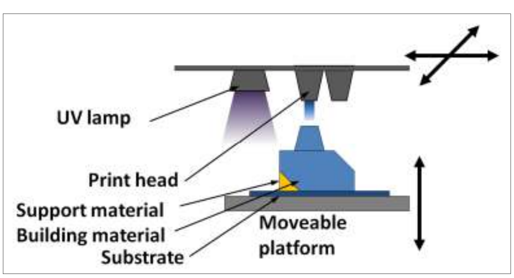

Figure 3: Schematic setup of the Multi-Jet Modeling method.

4 ECONOMICAL EVALUATION OF THE INVESTMENTS

4.1 Cost-Comparison Method

Beside the technical feasibility, the profitability of an innovation is of high importance for the sustainable success of products and processes. There are two main approaches which support the management in order to evaluate machine or process investments: Static and dynamic investment appraisals. Dynamic approaches, unlike static ones, consider the point of time, when cash-in and out-flows during the considered machine life happen. By not considering the time of cash-flows, the calculation is being simplified, while it still provides users with a comprehensive overview about the economic benefits of competing investment options. Thus, the method became very popular within the industry. Within the static investment appraisal, the cost comparison method tells decision makers in a fast and well-arranged way, which of the competing options is the most profitable within a considered machine life time. This method requires that the revenues of the competing investment objects are equal. The cost comparison method considers the total expenses of an investment. Those costs consist of fixed and variable costs. Fixed costs consist of calculatory depreciations of the purchase price, its calculatory interest rate, maintenance costs of the machine and occupancy costs. These factors are all independent of the capacity utilization level. Hence, these factors are quite stable and cannot be modified in a short period of time. Due to this characteristic, labor costs can also be specified as fixed costs [10]. This applies especially within countries with strong labor rights. Variable costs are being put together by material costs per unit and costs for the energy during the usage of the machine. Figure 4 below outlines the single components of the cost comparison method.

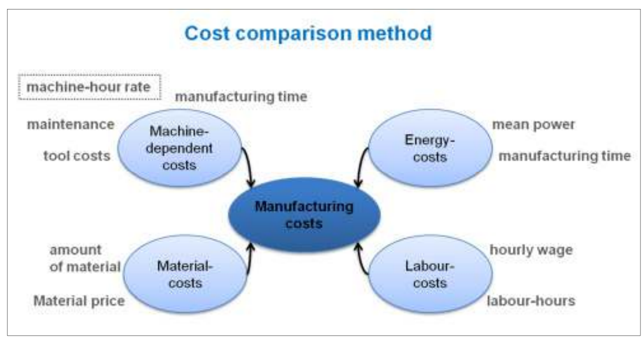

Figure 4: Content of the cost comparison method.

4.2 Cost Comparison of Three Different Manufacturing Options

By using the above described cost comparison method the following three manufacturing options for manufacturing a Venturi nozzle are being compared:

- **Option 1:** Application of conventional manufacturing technologies (CNC-turning)
- **Option 2:** Application of the generative manufacturing option MJM.
- **Option 3:** Application of the plastic injection molding

Those three manufacturing options are described in the following:

Option 1: Conventional manufacturing (turning)

During the manufacturing process of the whole ejector, the process steps shown in figure 5 are required. The Venturi nozzle is located inside of the ejector and consists of the Venturi nozzle and the receiver nozzle. Each of them is produced from a semi finished aluminum part and then gets equipped with an O-ring. In the next step, they are put together and eventually assembled inside of the ejector. The O-rings prevent that air is being streamed out. The body of the ejector is made of plastic and hence is made by using an injection molding machine. To complete the process the connection pipes and the sound absorbers are assembled.

Option 2: Rapid Manufacturing

This option is being manufactured by using the rapid manufacturing technologies described in chapter 3.3. The production and assembling process is very similar to the one described in option 1. The main difference is that the nozzle can be produced as one part. Therefore, no other subsequent assembling steps are required.

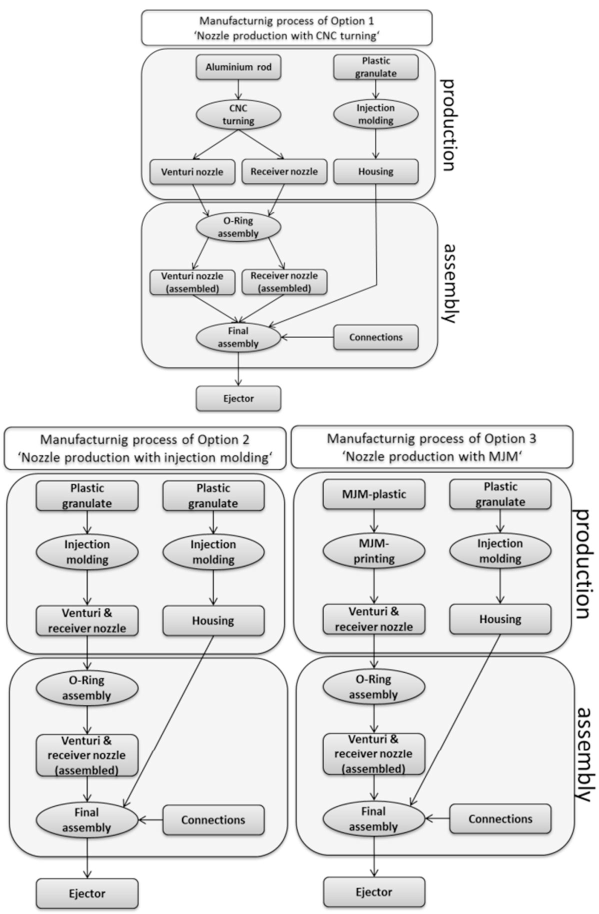

Figure 5: Comparison of the required process steps of the three competing manufacturing options.

Option 3: Injection Molding

This option has great advantages when it comes to material price costs and the surface quality. On the other hand, each dimensional variation at the parts requires the construction of a completely new tool. Due to the small dimensions of the considered parts, it is required to make usage of special micro-injection molding machines. The inner diameter of the smallest nozzle measures only 0,5mm. These small dimensions tell that there is not much room for deviations from the original form. Due to the rotational-symmetric design of the nozzle, strains during the cool-down phase should not be expected. The potentials of this manufacturing process become quite obvious considering figure 5. The sub-figures show the three described manufacturing options, which process steps are required to get from the raw material to a finished product.

In order to realize the different manufacturing options, three different machines were required. A conventional CNC-turning machine was taken for option 1. For option 2, the machine Project HD3500 Plus was used, while option 3 was realized by using a micro-injection molding machine. A great amount of data for the following economical investigation could be obtained from machine manufacturers and only very few assumptions had to be done to complete the calculation inputs.

4.3 The Calculation Tool and Possibilities of Investment Evaluations

In order to realize an automatic and user-friendly cost comparison, a calculation and evaluation tool has been developed. It offers the opportunity to be filled with all relevant data, like machine purchase prices, material costs etc. Furthermore, the tool allows adding the planned production volume for a year. It automatically generates a graph, which shows the manufacturing costs for each of the three competing options according to the production volume.

By using this tool, decision makers are equipped with an easy-to-use tool that almost instantly tells them which manufacturing options is the most economical according to cost inputs and the planned production volume. Regarding the results of shown the graph, the impact of fixed and variable costs become quite obvious.High fixed costs usually require high production volume in order to be profitable at costs per unit. On the other hand, lower fixed costs are normally advantageous within low production volumes.

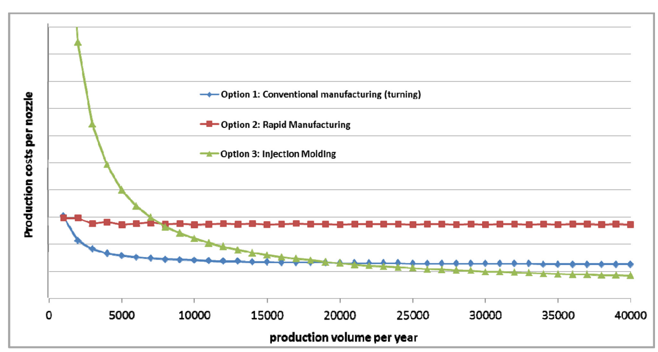

Figure 6: Manufacturing costs as function of parts/year.

Figure 6 above shows that the manufacturing options 1 and 2 have comparable low fixed costs. This makes those manufacturing options favorably during low production volumes. Having a closer look at option 2 it turns out that this option has comparable high variable costs. These costs can be explained by high material prices (variable costs). Option 1 has low variable costs, as can be seen on the significant drop in costs per unit, as the production volume rises. Option 3 is not very economical during low production volumes. However, it picks up with option 1 and 2 due to its very low variable costs. Eventually, by reaching 20.000 parts per year, it even becomes the most economical option. As can be seen, it is great importance to investigate the dependency of fixed and variable costs to the production volumes. This tool considers both factors and generates the manager with a user-friendly, ad-hoc and comprehensive analysis tool.

5 SUMMARY

The origin of this paper was a nozzle contour limited by the subtractive nozzle manufacturing process with CNC-turning machines.

In the first part of this analysis, a simulation-based estimation of the technical potential of an enhanced nozzle contour was done. It showed a potential for optimization of 35% less pressure drop along the Venturi nozzle. However, this more complex contour is not producible with the current turning machines. For this reason a technical analysis was conducted to investigate possible manufacturing processes. Due to the possibility to realize complex geometries simply, additive manufacturing processes were focused in this investigation. Because of their poor surface roughness further simulations were done to identify the influence of surface roughness to the efficiency of the Venturi nozzle. Another considered production process for the nozzle production is injection molding. The different processes were analyzed for their economic competitiveness. For this purpose an excel-based tool was developed which calculates the production costs per nozzle dependent on the yearly production volume. It showed that the additive manufacturing process could not compete economically with the other manufacturing processes. Furthermore, the technical advantages of the optimized nozzle contour could not fully be exploited because of the poor surface roughness.

Injection molding, however, can reach the simulated results due to the good surface roughness and the possibility to produce a flow optimized nozzle. It became apparent that this process is economically beneficial from 20,000 nozzles per year.

6 OUTLOOK

With specific regard to manufacturing option 2 and 3 the entire ejector could also be manufactured by using Rapid Manufacturing as well with Injection Molding, due to less process steps. Though it is impossible to manufacture the ejector within one process step because of an undercut, it can be imagined to manufacture two half shells. Those shells could be then joined in a further step, e.g. by ultrasonic welding. Anyway, this process would need a further technical feasibility study, e.g. concerning the leak tightness of the weld.

7 REFERENCES

[1] Hesse, S. (2011): Greifertechnik: Effektoren für Roboter und Automaten, Carl Hanser Verlag, München.

[2] Herwig, H. (2008): „Strömungsmechanik A-Z“, Vieweg+Teubner Verlag, Wiesbaden.

[3] Hesse, S. (2010): Grundlagen der Handhabungstechnik, Carl Hanser Verlag, München.

[4] Seegräber, L. (1993): Greifsysteme für Montage, Handhabung und Industrieroboter, Expert-Verlag, Böblingen.

[5] Hesse, S. (2005): Robotergreifer: Funktion, Gestaltung und Anwendung industrieller Greiftechnik, Carl Hanser Verlag, München.

[6] Spurk, J. H., Aksel, N. (2010): Strömungslehre: Einführung in Die Theorie Der Strömungen, Band 1, Springer-Verlag, Berlin-Heidelberg.

[7] J. Schmalz GmbH (2012): Vakuum-Komponenten Katalog 2012/2013“, Glatten.

[8] Kim, G. D., Oh, Y. T. (2007): A benchmark study on rapid prototyping processes and machines: quantitative comparisons of mechanical properties, accuracy, roughness, speed, and material cost, in: Proc. IMechE, Vol. 222, pp. 201-215.

[9] T.A. Grimm & Associates Inc. (2010): 3D Printer Benchmark: European Edition

[10] Milberg, J. (2002): Erfolg in Netzwerken, Springer-Verlag, Berlin-Heidelberg.

Analysis of Energy Consumption in CNC Machining Centers and Determination of Optimal Cutting Conditions

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Abstract

This paper deals with the minimization of machine tool (CNC milling centre) energy consumption during the usage phase. This study shows that the selection of the main process parameters can entail energy savings in manufacturing metal components. The analysis exploits a developed and experimentally updated energy consumption analytical model. The main analyzed machine functional modules (spindle, axis, chillers, tool change system, auxiliaries and the cutting process) are described in terms of power adsorption and energy usage. The global energy consumption function, as the summation of the energetic consumption of the listed machine tool components, is expressed in a closed analytical form and then it is numerically optimized to find out the cutting conditions (basically cutting speed and feed rate) that satisfy the minimum energy criteria. The optimization procedure takes into account the wear of the tool and the energy required to produce the tools itself. The numerical results reported in this work refer to the face milling of an aluminum prismatic workpiece. In the analyzed case, the identified optimal conditions are compared to those obtained following the production time minimization criteria.

Keywords:

Machine Tool; Energy Consumption; Cutting Optimization; Tool Wear

1 INTRODUCTION

Manufacturing is accountable for about 33% of total final energy consumption [1] and it is estimated that energy demand, within few years, will be 45% higher than today levels. It is therefore of paramount relevance to reduce the production system energy demand. Machining represents one of the main energy-consuming activities in manufacturing industries and energy consumption determines 20% of machine tool operating cost. Furthermore, at least 60-90% of the overall equivalent CO_2 is emitted during the machine working phase[2] [2]. In this scenario, the machine tool energy consumption reduction is becoming a binding goal.

Focusing on machining, we can say that the power related to the manufacturing process is a function of the machined material, the specific technology used for machining, the desired accuracy and the process rate [3] [4] [5]. A simple equation expressing the machining power consumption is [3]:

$$P = P_0 + K_c \cdot MRR \quad (1)$$

where P_0 is the power [W] consumed by all the machine functional modules at zero load (i.e., the machine is not cutting), K_c is the cutting pressure or specific energy [N/mm^2] and *MRR* is the material removal rate [mm^3/s]. The constant term P_0 is the tare power of the machine. As auxiliary systems increase so this term enhances [6].

The energy adsorbed by the machining process is simply the integral of the power in time:

$$E = \int_0^t (P_0 + K_c \cdot MRR)\, dt \qquad \frac{E}{V} = \frac{P_0}{MRR} + K_c \quad (2)$$

where *t* is the process time duration and V is the volume of material to be removed. In general, cutting parameters (i.e., cutting velocity, feed rate and depth of cut) affect *MRR*, *t*, and K_c. Also, it is well-known that process time and material removal rate are related (t=V/MRR), as the last increases the time to complete the process decreases.

The cutting tool and the workpiece material (e.g., material, geometry, etc) affect both the cutting pressure and the maximum achievable material removal rate [5]. Materials that are difficult to cut are typically characterized by high values of K_c and low values of *MRR*. For instance, titanium alloys machining needs high energy values basically due to the quite high material resistance, the low cutting speed that has to be used for machining and the large tare (due to the high machine performance needed for the cutting process). On the contrary, aluminum alloys require small energy consumption because they are characterized by small K_c and large *MRR* values.

In order to make the previous analysis more realistic, tool life and cost should not be overlooked, especially when particular materials are machined like titanium alloys, for which tool wear is particularly crucial. For instance, the increase of the cutting speed leads to the increment of both the *MRR* and the tool changing rate. This relationship has to be considered if minimization of energy consumption is pursued [7]. Rajemi et al. [8] dealt with the minimization of energy consumption in turning. They considered the cutting speed as the main process parameter to be optimized. The proposed approach takes into account also the energy consumed by the process and the energy footprint of each cutting edge. They also analyze how the tool footprint affects the optimal value of the cutting velocity. However, their approach does not consider the feed axis velocity as a process parameter and the associated power consumption. This last term could be significant in value and furthermore the axis power losses affect the power consumption of the axis chiller system. Therefore, the inclusion of the axis power consumption seems to be relevant for energy saving purposes and it is the subject of this work.

The paper deals with energy consumption in milling. The contribution is twofold. First, an analytical model for the estimation of energy consumption of Computer Numerically Controlled (CNC) milling machines is proposed. The model includes the energy consumption contributions of the following machine tool functional modules: Numerical Control (NC), drives, machine tool axis, axis chiller, spindle chiller, spindle system, tool changer and chip conveyor. A first but not complete version of the model was developed in [9].

Second, the energy minimization of a milling operation is tackled to find the optimal cutting parameters. The optimization considers the different phases of the process time: set-up, machining, tool change and axis motions (considering both feed and rapid motions). The tool wear was also considered in the optimization procedure by using the Taylor's law. The energy optimization was performed considering either a single parameter (cutting speed – *base case*) or two parameters (cutting speed and feed rate – *multi-parameter case*) to be optimized. This represents a novelty in respect to other previous works together with the inclusion in the analysis of the axis power consumption that affects the optimal values of cutting velocity and feed rate.

The paper is organized as follows. Section 2 presents the analytical model that allows to compute the power and energy consumed by a milling machine. The optimization model is formulated in section 3. The application of the proposed models to a real machine is shown in section 4. Section 5 concludes this paper describing the research activities the authors are currently working on this subject.

2 ANALYTICAL MODEL FOR ENERGY CALCULATION

This section proposes an analytical approach to estimate the amount of energy required by a machine tool that processes a mechanical component.

2.1 Main Assumptions and Methodology

In order to be able to compute the overall energy consumption, it is necessary to estimate the energy consumption of each considered machine tool functional module (auxiliaries, axis, spindle, chillers, chip conveyor, etc) during different production phases (i.e. workpiece set-up, machining, tool changes, workpiece approach and rapid axis movements).

Face milling of a prismatic workpiece was selected as a simplified technological reference case. The material volume to be removed is characterized by the following dimensions: L, d, W. This assumption does not limit the validity of the adopted approach and of the presented results.

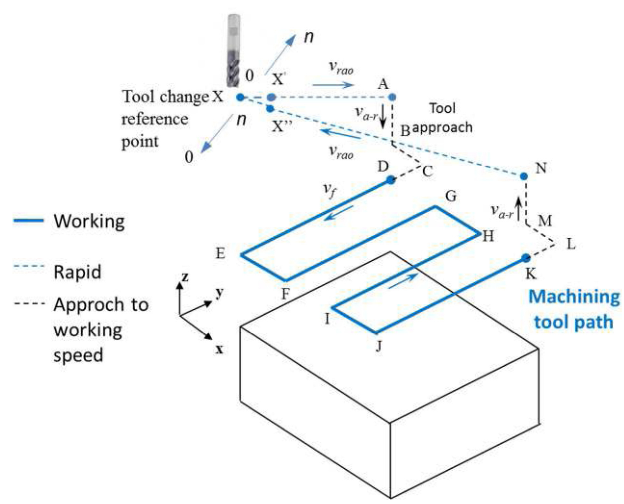

Figure 1: Tool path for a face milling operation (adapted from [10]).

Production phases are simplified as shown in Figure 1: workpiece setup, rapid axis motions, workpiece approach at feed velocity, machining and tool changes. The following machine tool functional modules were considered in the overall energy model: axes, spindle, axis chillers, spindle chiller, tool changer, pallet clamping, unloading system and other minor components that exhibit constant power consumption.

The total energy required to machine the workpiece is computed summing up the contribution of each machine tool functional module in different production phases:

$$E = E_{fixed} + E_{axes} + E_{axis\ chillers} + E_{spindle} + E_{spindle\ chiller} + \\ + E_{chip\ conveyor} + E_{tool\ changer} + E_{pallet\ clamp} \quad (3)$$

Since energy is the integral of power over time, it is necessary to define power consumption models of each considered machine functional module. Some of the adopted assumptions are derived from [10]. Additional assumptions are now briefly reported. The axis friction is modeled considering a static and a viscous contribution. The axis chiller exhibits a power consumption that depends on the power losses of the axis. The approach and retract of the tool from the path are considered in the calculation for all the times they are repeated during the process.

The overall production time t can be computed considering the following contributions:

$$t = t_1 + t_2 + t_3 \quad (4)$$

where t_1 represents the time required to execute the workpiece setup, t_2 the machining time and t_3 is the overall "chip to chip" time that includes rapid axis motions time, tool workpiece approach time and the overall time to perform the tool changes. Tool life affects t_3 and consequently the entire production time. Taylor's law was used to model the tool life as a function of the cutting velocity. The axes power consumption is calculated considering both the mechanical power and the Joule losses [11]. With regard to spindle, its losses are considered through a generic efficiency μ.

The instantaneous power required to move axes depends on the axis kinematics (considering both friction and inertial contributions) and on the load due to the cutting process.

With regard to the axis chiller, its power consumption is composed of a constant part (linked to the pump power consumption) and a variable one (linked to the compressor and the fan) that linearly depends on the power dissipated by the motor.

A detailed description of the behavior of these components becomes relevant in combination to the entire work cycle.

2.2 Axis Power

In this paragraph, the adopted energy model of each considered machine tool component will be described. Refer to Albertelli et al. [9] [11] for more details on the adopted models.

The calculation of the power adsorbed by a machine axis takes into account the mechanical power $P_m(t)$ as well as the losses $P_r(t)$:

$$P(t) = P_m(t) + P_r(t) \quad (5)$$

with $P_m(t) = F_m(t) \cdot v(t)$.

In order to estimate the mechanical power required to move the axis, both inertial and friction contributions were considered:

$$F_m(t) = c_s \cdot sign\big(v(t)\big) + c_d \cdot v(t) + M \cdot a = K_t \cdot i_{q\ rms}(t) \quad (6)$$

where F_m is the force motor [N], c_s is the equivalent static friction coefficient [N], c_d is the equivalent dynamic friction coefficient [N·s/m], M is the equivalent axis inertia [kg], a is the axis acceleration [m/s^2], K_t is the force constant of the motor [N/A$_{rms}$] in case of a linear electrical motor, i_{q_rms}(t) is the quadrature current (rms value) [A_{rms}] and $v(t)$ is the axis velocity [m/s]. The same model can be adopted also for rotative motors.

The dissipated power is $P_r = R \cdot i_q^2(t)$, where i_q(t) is the quadrature current [A] (with $i_{q\,rms} = i_q^2(t)/\sqrt{2}$) and R is the phase resistance [Ω]. For sake of simplicity only the Joule losses were considered in the model. It is therefore possible to rewrite equation (5) as follows:

$$P(t) = F_m(t) \cdot v(t) + R \cdot 2 \cdot \left(\frac{F_m(t)}{K_t}\right)^2 \quad (7)$$

2.3 Chiller Power

The power consumption of the axes chiller is described through a linear relationship [9]:

$$P_{axes\ coolant} = P_{sby} + \theta \cdot P_r(t) \quad (8)$$

where the parameters θ and P_{sby} (the standby power linked, basically, to the recirculating pump) can be identified with a regression analysis. This model assumes that the chiller has a basal power consumption and an additional contribution that depends on the tasks the machine is executing. Basically the power adsorbed by the axis depends on the linked axis load.

2.4 Calculation of Overall Energy

Axis:

According to axes task, and looking at Figure 1, the following contributions need to be computed for estimating the axis energy consumption:

$$E_{axes} = E_{rm} + E_{aws} + E_w \quad (9)$$

E_{rm} is the energy required to perform rapid movements (Figure 1, path X-A and N-X), E_{aws} is the energy required to approach the workpiece at working speed (path A-D and K-N) and E_w is the energy required by axis during machining. These three components are detailed below.

The axis energy depends on the number of rapid movements n_r that is directly linked to the number of tool changes n_t:

$$n_r = 2 \cdot n_t + 2 \quad (10)$$

and therefore:

$$E_{rm} = n_r \cdot \sum_{i=x,y,z} \int_{\bar{t_0}}^{\bar{t_1}} \mathrm{P_{rm}}_i(t)\, dt \quad (11)$$

$\mathrm{P_{rm}}_i(t)$ represents the power required by the generic *i axis* and it is computed using expression (7).

A trapezoidal speed profile was assumed for each axis movement. It is assumed that the energy linked to the axis braking phase can be partially (φ) recovered by the axis drive:

$$\int_{\bar{t_0}}^{\bar{t_1}} \mathrm{P_{rm}}_i(t)\, dt = \int_{\bar{t_1}}^{\bar{t_2}} \mathrm{P_{acc}}_i(t)\, dt + \varphi \cdot \int_{\bar{t_2}}^{\bar{t_3}} \mathrm{P_{rc}}_i(t)\, dt - \int_{\bar{t_3}}^{\bar{t_1}} \mathrm{P_{dec}}_i(t)\, dt \quad (12)$$

Where $\bar{t_2}$- $\bar{t_1}$ is linked to the time interval in which the axis accelerates, $\bar{t_3}$- $\bar{t_2}$ the time interval in which the axis moves with feed velocity and $\bar{t_1}$- $\bar{t_3}$ the time interval in which the axis decelerates.

The energy required by the axis during the workpiece approach phase (E_{aws}) can be computed using the same relationship and knowing the feed velocity and the distance that needs to be covered. The tool path can be break into different parts (Figure 1): $\overline{AB}$ along axes z, $\overline{BC}$ along x and $\overline{CD}$ along y. In order to calculate the total energy for this movement, it is necessary to define the number of approaches (γ) for each direction that depends on the dimensions of the material volume to be removed (L, w, d) from the workpiece, the tool (diameter *D* and axial engagement a_p):

$$\gamma_x = \frac{\mathrm{w}}{D} \quad \gamma_y = \frac{\mathrm{w}}{D} \quad \gamma_z = \frac{\mathrm{d}}{a_p} \quad (13)$$

Thus:

$$E_{aws} = \sum_{i=x,y,s} \gamma_i \cdot \int_{t_1}^{t_2} P_{aws_i}(t)dt \quad (14)$$

where P_{aws} depends on the feed velocity v_f.

As far as the term E_w, even during processing, the power required by the axes is given by the sum of two contributions: mechanical power and electric power lost due to Joule effect *P*, during t_2. An additional mechanical power term linked to the need to overcome the force on the axis due to the process was also considered. The cutting force along the feed direction is approximately considered to be one third of the main cutting force:

$$F_{cutting} = \frac{K_c \cdot a_p \cdot a_e \cdot f_z \cdot z}{\pi \cdot D \cdot 60} \quad (15)$$

where K_c is defined as:

$$K_c = K_{cs} \cdot h_m^{-w} = K_{cs} \cdot \left(a_z \cdot sin(\chi)\right)^{-w} \left[\frac{N}{mm^2}\right] \quad (16)$$

where K_{cs} is the specific cutting pressure [N/mm^2], h_m is the average chip thickness [mm], w is a constant, depending on material, is the insert lead angle [rad], a_p is the axial engagement [mm], a_e radial engagement [mm], f_z is feed per tooth [mm/tooth]. Therefore, E_w can be written as:

$$E_w = \frac{1}{3} \cdot F_{cutting} \cdot v_f \cdot t_2 \quad (17)$$

Axes chiller

For sake of simplicity the power consumption proportional to the axis load is computed only when each axis moves at constant velocity. The short intervals in which the axes speed up and decelerate are neglected

Fixed power

Fixed power is absorbed whenever the machine is switched on. P_0 is the constant power given by the sum of all components included in this group

$$E_{fixed} = P_0 \cdot t_p \quad (18)$$

Tool changer

It is assumed that the power to execute the tool changing is required only for the time needed to replace (i.e., t_{tc}). The energy required to move the tool towards the change position location is taken into account in the axis model. Thus $E_{tool\ changer}$ is computed as follows:

$$E_{tool\ changer} = P_{tc} \cdot t_{tc} \cdot n_t \quad (19)$$

Clamp pallet

It is assumed that this component is enabled for the entire processing cycle:

$$E_{cp} = P_{cp} \cdot t_p \quad (20)$$

The components described below are considered to be active only during machining phase.

Spindle

The energy required by this component is approximated considered the sum of both the cutting power and the spindle losses computed by means of the spindle efficiency:

$$E_{cutting} = \frac{P_{cutting} \cdot t_2}{\eta} \quad (21)$$

Spindle chiller

As the Spindle model approximation, for spindle chiller the power is considered constant:

$$E_{spindle\ chiller} = P_{spindle\ chiller} \cdot t_2 \quad (22)$$

<u>Chip conveyor</u>

This component is active when chip is removed, so during machining (i.e., t_2):

$$E_{chip\ conveyor} = P_{chip\ conveyor} \cdot t_2 \quad (23)$$

Table 1 summarizes each component model proposed above.

Component	Model
Axis	Equation (9)
Axis chiller	Equation (8)
Spindle	Equation (21)
Spindle Chiller	Equation (22)
Chip Conveyor	Equation (23)
Fixed Power	Equation (18)
Pallet Clamp	Equation (20)
Tool Changer	Equation (19)

Table 1: Components model proposed.

3 ENERGY OPTIMIZATION

Knowing the analytically behavior of the analyzed machine functional modules during the modeled milling operation, it is possible to optimize the cycle trying to reduce the required energy to process a generic mechanical component.

Assuming to follow the approach of the machine's user, all the equipment (e.g., machine tool and cutting tool) is considered given and not changeable. The parameters considered as the decision variables of the energy optimization problem are the cutting velocity and the feed per tooth as these are the main factors to determine power and energy of the process that are the main process parameters to be set to perform a milling operation[12]. The optimization model is formulated as follows:

$$min \quad E(v_c, f_z) \quad (24)$$

$$v_{c\,min} \le v_c \le v_{c\,max} \quad (25)$$

$$f_{z\ min} \le f_z \le f_{z\ max} \quad (26)$$

$$f_z^2 \le R_a^* \frac{8 \cdot R_\varepsilon}{1000} \quad (27)$$

where v_c is the cutting velocity and, f_z is the feed rate per tooth. Inequalities (25) and (26) constrain the cutting speed and feed per tooth within the range recommended by the tool manufacturer. The last constraint concerns the respect of surface finish (R_a^*) where R_ε is the nose radius; in case of roughing operations constraint (27) is not imposed.

4 TEST CASE

It was considered a face milling of an aluminum alloy as the reference case to show the potentialities of an energy minimization strategy. It was supposed to use a Jotech (technical data are listed on Table 2) as the reference machine centre.

Table 3 shows the parameters adopted to machine aluminum alloy with fracture toughness of 350 N/mm^3. The Tool selected is a Sandvik Coromant 390 Mill, and Taylor parameters were suggested by Sandvik Coromant itself. The selected axial depth of cut was equal to 4 mm.

Parameter	units	Value		
Machine Axes		x	y	z
Rapid rate v_{rapid}	m/min	40	40	40
a_{max}	m/s^2	8	8	8
Phase resistance R	Ω	1.9	1.7	0.8
Equivalent axis inertia M	kg	524.6	134.4	333.0
Equivalent static friction coefficient	N	76.8	81.6	690.3
Equivalent dynamic friction coefficient	Ns/m	755.3	267.5	4012
$v_{spindle\ max/nom}$	rpm	32000/24000		
$P_{spindle\ max/nom}$	kW	3.7-3.0		
Tool change time t_{tc}	s	3		
Force constant of the motor k_t	Vs/m	1.5		
Slope of Axis Cooler model θ		0.346		
Fixed Power (P_0)	W	1200		
$P_{spindle\ cooler}$	W	800		
Axes cooler standby power P_{sby}	W	556.28		
Chip conveyor power $P_{chip\ conveyor}$	W	100		
Tool changer power P_{tc}	W	80		

Table 2: Jotech machine tool parameters.

Parameters	uom	Value
Cutting Velocity v_c (min-max)	m/min	300-2000
Feed per tooth f_z (min-max)	mm/tooth	0.01-0.3
Taylor equation constant C	m/min	2100
Taylor equation coefficient α	-	0.35
K_{cs}	N/mm^2	680
w	-	0.2

Table 3: Tool-Material properties and Cutting parameters ranges.

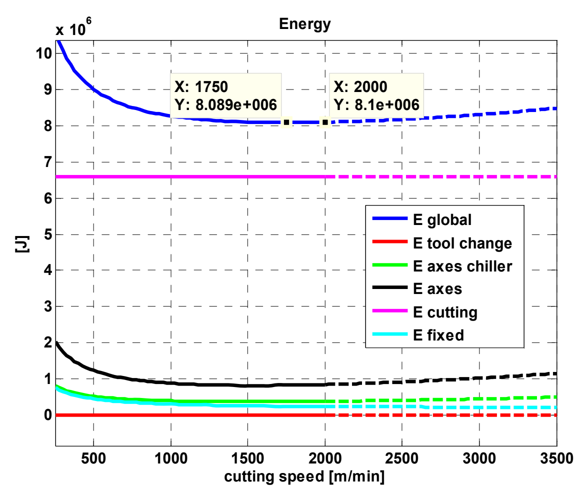

Figure 2: Energy contributes.

4.1 Single Parameter: Cutting Speed

The analysis was performed first considering the cutting speed as the only parameter to be optimized (*basic case*). Figure 2 shows both the energy consumed by some of the analyzed functional machine tool modules and the global energy consumption as a function of the cutting speed.

The global energy consumption curve exhibits a minimum when the cutting speed is close to 1775 m/min while the global production time (Figure 3) has a minimum close to 2000 m/min. Moreover, Figure 4 shows how both the global energy consumption and the production time change in respect to the cutting speed. Increasing the cutting speed both the average global energy consumption and the production time (due to t_3) increase, (left branch of the curve). The same effect can be also observed adopting very low cutting speeds (right branch of the curve). In this case the production time increment is basically due to increment of the machining time (t_2).

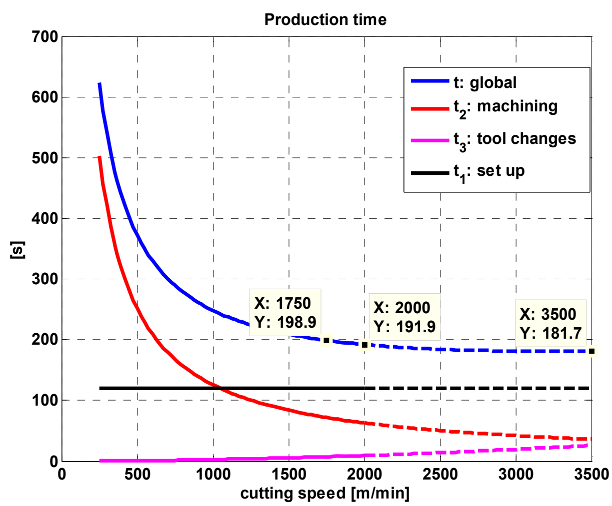

Figure 3: Time as cutting speed function.

Parametri	uom	Optimum Energy criterion	Optimum Time criterion	Optimum Energy criterion(*)	Optimum Time criterion(*)
Energy (E)	*kJ*	8089.1	8100	9156.8	12200
Optimum velocity (v_c)	*m/min*	1750	2000	700	2000
Time (t)	*s*	198.9	191.9	300.8	191.9

Table 4: Comparison between different criteria (feed rate=0.3mm/tooth rev - *base case*).

As it can be observed in Figure 4, the two remarkable points, as also reported in Table 4 are marked on the curve: they are linked to the optimum cutting conditions considering respectively the production time and the energy consumption minimization criteria. In general, a different production paradigm selection can affect the global energy consumption: in the analyzed case only 0.13% of the energy could be saved switching to an energy oriented cutting parameter selection. The cutting speed values that minimize the associated function are quite different but in this region the energy curve is very smooth and the energy saving is irrelevant. This is mainly due to the high contribution of the energy needed to remove the material compared to the other contributions. The modelling approach proposed in this paper considers the energy consumption linked to axes (both axes and chiller axes) that generally can affect the minimum energy point location: this contribution could lead to select lower cutting speeds compared to the traditional production time paradigm. In this case the effect is not so evident because the production time minimum is located above the upper cutting speed limit for aluminum processing.

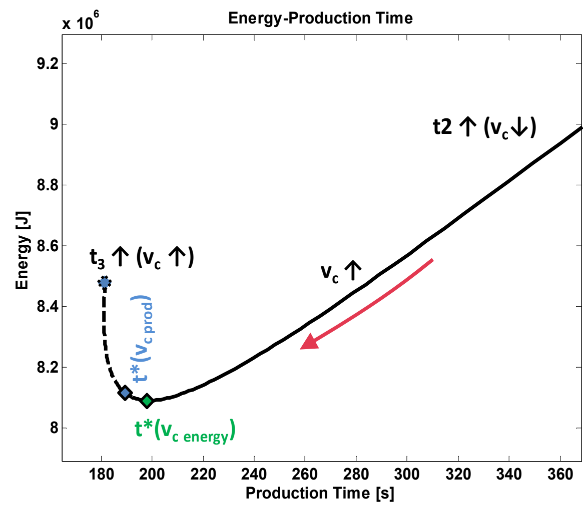

Figure 4: Energy as a time function.

A similar analysis can be also performed considering an additional energy consumption contribute: the amount of energy used to produce the cutting tool inserts, Table 4. This interesting results were achieved basically due to the adopted machine tool energy modeling that considers machine tool components whose power consumption depends on the main cutting parameters (i.e. axis and chillers). This aspect indeed penalizes the use of higher cutting speed more than the tool wear does. On the other hand, too low cutting speeds negatively affect the global energy consumption basically due to the increment of the production time through the constant power contributes. Previous approaches (i.e. [8]) showed that energy consumption reduction oriented criterion basically leads, if the energy required to produce the tool is not considered, to the same result of that obtained with the production time minimization criterion.

4.2 Two Parameters: Cutting Speed and Feed Rate

Considering both the cutting speed and the feed rate as the main milling parameters (*multi-parameters case*), Figure 5 shows the response surface that describes the global energy consumption. Moreover, it exhibits how the energy consumption minimum depends both on the considered cutting parameters: the optimal cutting speed significantly differs if different feed rates are chosen. Deepening the analysis, it can be observed that the higher the feed rate, the more the cutting speed that guarantees the energy consumption minimization differs from the cutting speed that minimizes the production time. In this case, the minimum energy consumption is linked to the maximal feasible feed rate.

In the optimization process it is also possible to consider the energy required to produce cutting edges (total energy per insert is 5.3 MJ considering both material and manufacturing [6] [8]). Considering this additional contribute in the *base case* the optimal cutting conditions tends to diverge more from the cutting parameters that minimize the production time (refer to the two last columns of Table 4, (*)). The added contribute penalizes further the tool wear if it is compared to the production time optimization as already presented in [8].

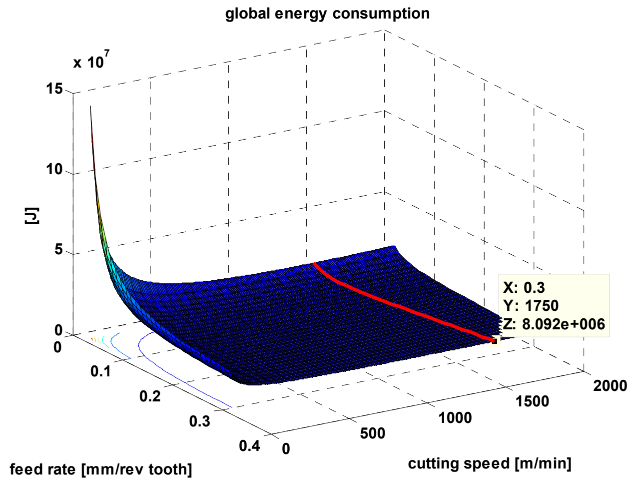

Figure 5: Energy function varying both cutting speed and feed per tooth.

5 CONCLUSIONS

An analytical model for the estimation of the energy consumed by a machine tool in a milling process has been proposed. The model is based on the definition of simple energy models representing the energy consumption of the main functional modules of a CNC machine tool.

The optimization of the cutting conditions to minimize energy consumption minimization in milling has also been proposed. Different machine tool functional modules and productions phases were considered. The analysis showed that, even if a more complex energy consumption model has been proposed, the additional contributions do not allow to save a relevant quantity of energy compared to the typical cutting speed selection paradigm. Indeed, the inclusion or not of the tool footprint can significantly change the selection of the cutting parameters. In the analyzed numerical case, the energy usage of the milling process can be globally minimized only if the energy for tool production is considered and the machine modules are properly modeled. Thus, a careful selection of what objects to model together with the adequate modeling of their interactions seems to be fundamental when developing energy assessment models for complex systems.

Future work will be dedicated to enlarge the analysis for considering the energy utilized to fully understanding how the characteristics of the machine and of the workpiece affect the optimal cutting conditions.

6 REFERNCES

[1] IEA, "Worldwide trends in energy use and efficieny," 2008.

[2] N. Diaz, M. Helu, S. Jayanathan , Y. Chen, A. Horvath and D. Dornfeld , "Environmental analysis of milling machine tool use in various manufacturing environments," in *Sustainable Systems and Technology (ISSST), 2010 IEEE International Symposium on*, 17-19 May 2010.

[3] T. Gutowski, J. Dahmus and A. Thiriez, "Electrical Energy Requirements for Manufacturing Processes," *13th CIRP International Conference on Life Cycle Engineering, Leuven, May 31st – June 2nd,* 2006.

[4] T. Gutowski, J. Dahmus, A. Thiriez and M. Branham, "A Thermodynamic Characterization of Manufacturing Processes," *Proceedings of the 2007 IEEE International Symposium on Electronics & the Environment,* pp. 137-142, 2007.

[5] T. Gutowski, M. Branham, J. Dahmus, A. Jones, A. Thiriez and D. Sekulic, "Thermodynamic Analysis of Resources Used in Manufacturing Processes," *Environmental Science & Technology,* vol. 43, no. 5, pp. 1584-1590, 2009.

[6] J. Dahmus and T. Gutowski, "An Environmental Analysis of Machining," in *Proceedings of IMECE2004*, Anaheim, California, 2004.

[7] N. Diaz, M. Helu, A. Jarvis, S. Tönissen, D. Dornfeld and R. Schlosser, "Stategies fot minimum energy peration precision machining," in *Laboratory for Manufacturing and Sustainability.* , UC Berkeley, 2009.

[8] M. Rajemi, . P. Mativenga and A. Aramcharoen, "Sustainable machining: selection of optimum turning conditions based on," *Journal of Cleaner Production,* p. 1059–1065, 2010.

[9] P. Albertelli, G. Bianchi, A. Bigliani, S. Borgia, A. Matta and E. Zanotti, "Evaluation of the energy consumption in machine tool: a combined analytical-experimental approach," in *13th International MITIP Conference - The Modern Information Technology in the Innovation Processes of the Industrial Enterprises*, Trondheim, Norway, 2011.

[10] O. Avram and P. Xirouchakis, "Evaluating the use phase energy requirements of a machine tool system," *Journal of Cleaner Production,* p. 699–711, 2011.

[11] P. Albertelli, G. Biachi, A. Bigliani, A. Borgia and A. Matta, "Evaluation of energy consumption in machine tools: an analytic approach," in *APMS 2010 International Conference on Competitive and Sustainable Manufacturing, Products and Services*, Cernobbio (CO), Italia, 2010.

[12] A. Bhattacharya, S. Das and A. Batish, "Estimating the effect of cutting parameters on surface finish and power consumption during high speed machining of AISI 1045 steel using Taguchi design and ANOVA," *Production Engineering,* vol. 3, no. 1, pp. 31-40, 2009.

[13] N. Diaz, E. Redelsheimer and D. Dornfeld, "Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Use," in *Glocalized Solutions for Sustainability in Manufacturing*, 2011.

[14] N. Diaz, S. Choi, Y. Chen, S. Jayanathan, Y. Yasui, D. Kong, S. Pavanaskar and D. Dornfeld, "Machine Tool Design and Operation Strategies for Green Manufacturing," in *Proceedings of 4th CIRP International Conference on High Performance Cutting, 2010*, Berkeley, 2010.

[15] S. Kara and W. Li, "Unit process energy consumption models for material removal processes," *CIRP Annals - Manufacturing Technology,* vol. 60, no. 1, pp. 37-40, 2011.

[16] M. Mori, M. Fujishika , Y. Inamasu and Y. Oda, "A study on energy efficiency improvement for machine tools," *CIRP Annals - Manufacturing Technology,* vol. Volume 60, no. 1, p. 145–148, 2011.

Increasing the Energy Efficiency in Metal Cutting Manufacturing through a Demand Based Coolant Filtration

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Abstract

The coolant supply uses in typical applications of metal cutting manufacturing on average 50 % of the electrical energy. A main optimization option is the retrofit of demand-based control strategies in the supply system. Previous studies showed that a high saving potential remains in pressure filter plants for coolant cleaning. The plants are operated constantly on an excessive power level, independent on the coolant demand. A concept of a demand-based control is introduced and evaluated in simulations using the example of precoat filters. The analysis at an existing plant shows an energy saving potential of up to 73 %.

Keywords:

Energy Efficiency; Coolant; Filtration; Precoat filter; Control

1 INTRODUCTION

Due to rising energy costs and increasing importance of climate protection, energy efficiency in industry becomes more and more relevant. Studies of the Robert Bosch GmbH showed that in typical applications of metal cutting, the coolant uses on average 50 % of the electrical energy [1]. Therefore, the energy reduction of the coolant supply system is the focus of this research.

Coolant is used in the metal cutting processes to increase the rate of metal removal, extend the service life of the tools and improve the surface quality of the work pieces. The primary tasks of the coolant include cooling, lubricating, flushing and transporting. The coolant is used and treated in a circulatory system. This circuit can basically be divided into the functional units: supply, return, cleaning and cooling (Figure 1). The contaminated coolant is transported back to the cleaning unit after the use in the machine tool. There, the contamination is separated from the coolant in a filter system to reach again the required fluid cleanness rating. In addition, the coolant temperature is stabilized in a cooling unit, via heat exchangers. A distinction is made between centralized and decentralized circulation systems. Centralized systems are generally preferred, as they are usually more advantageous in terms of cost than decentralized ones and are therefore the focus in this paper [1,2,3].

Various measures have been developed in recent years to increase the energy efficiency in the coolant supply system. The goal of a prior study, carried out at the Robert Bosch GmbH, was to identify further energy saving potentials in state of the art coolant facilities. Therefore the energy efficiency of several centralized coolant supply systems has been evaluated. The pumps account for the biggest part of the energy needs in the coolant system. So far the main emphasis in the planning and operation of the facilities was placed on low acquisition costs and high plant availability, and the energy efficiency was not sufficiently considered. Therefore the pumps have often been designed with simple pump solutions, such as pumps with bypass-control. These simple solutions have one thing in common: the pumps are operated with constant speed and cannot adapt properly to varying demand. This results in poor energy efficiency, as the coolant demand varies in centralized supply system due to the supply of various machine tools and ongoing production modifications. Therefore a demand based pump control, such as variable speed or level control, is reasonable in the entire supply system and is now state of the art in most of the functional units. The analysis showed that in most types of filter systems with pressure filters, there still remains a high energy saving potential. The filter pumps are constant speed driven and the filter system works continuously on an excessive power level, independent of the need for cleaning. A pump control cannot be implemented readily due to the operating mechanism of the filters. The evaluation of the energy saving potential and a concept for a demand based control is presented in this paper using the example of precoat filter systems. Precoat filters are commonly used for coolant cleaning in fine machining processes [4].

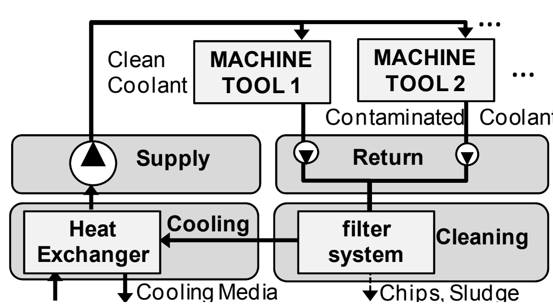

Figure 1: Functional units of a coolant supply system.

2 STATE OF THE ART

2.1 Precoat Filter System

A precoat filter system is illustrated in Figure 2. The filter pump delivers coolant from the dirt tank through the filter to the clean tank. The filter system works in a separate cleaning loop and the surplus cleaned coolant flows back into the dirt tank via the overflow pipe. Typically it is specified to carry 10% more coolant in the cleaning loop than the volume needed in the production [4,5].

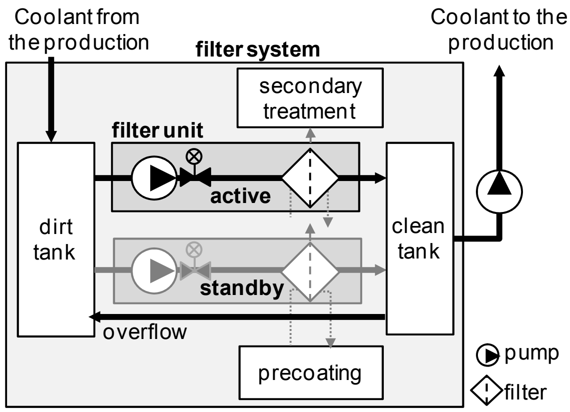

Figure 2: Scheme of a filter system with precoat filters.

In the case of precoat filters, a filter aid is dispersed on a filter element prior to the filtration. The filter elements are often vertically mounted filter cartridges. An example of a precoat filter is illustrated in Figure 3. The filter elements are used as a carrier on which the filter aid forms a filter cake which is retained due to the differential pressure resulting from the flow. The filter cake takes over the task of filtration by which even very fine particles are retained. Therefore, precoat filters serve, in particular, for fine cleaning [2,5].

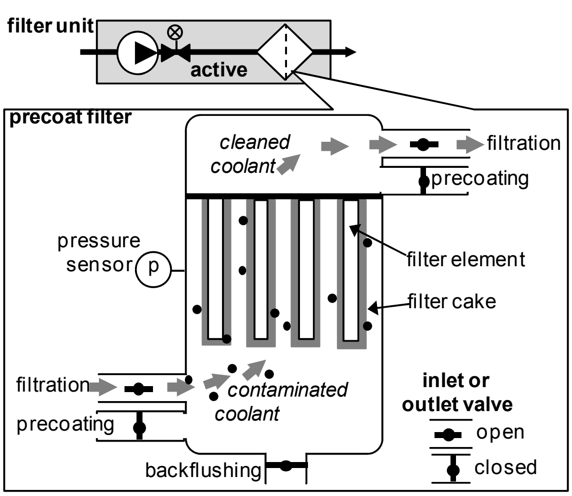

Figure 3: Precoat filter with vertical mounted filter elements.

The filter resistance and consequently the differential pressure rise during filter operation due to the increasing contamination. The filter cleaning is induced when a specified pressure is reached. In centralized systems the filter cleaning is done automatically by backwashing the filter content to the secondary treatment. The change from precoating to filtration, to backwashing and again to standby is done by a coordinate switching of the valves and the pumps [5]. In order to achieve a continuous supply of cleaned coolant despite the filter cleaning, filters units are operated in alternate service. As soon as a filter in operation reaches the specified cleaning pressure, a filter in standby is first precoated in a separate precoating loop and takes over the filter operation before the contaminated filter is backflushed (Figure 4). The filter overtakes the standby task after backflushing until another filter reaches the cleaning pressure. Large centralized filter systems consist of several operating filter units and one filter unit in standby [4,5]. Instead of alternate filter operation, another possibility is to supply the production with coolant out of a buffer tank during filter regeneration. But precoating takes around ten to twenty minutes. Therefore this option is in most cases disadvantageous due to the necessary space and the costs for coolant in the buffer tank.

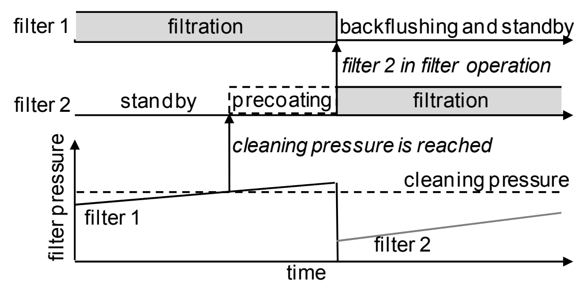

Figure 4: Filtration sequence with alternated filter.

2.2 Filter Pump Operation in a Filter Unit

The filter pump needs to deliver the necessary flow rate through the filter. Therefore the pump needs to generate a certain differential pressure in order to overcome the geodetic head and the flow-dependent pressure drops resulting from the flow resistance of the pipe and the filter.

The filter pumps are operated nowadays with constant speed. In general, centrifugal pumps are used as they are advantageous for this application. To achieve a constant filter performance, the required flow rate should be constant independent on the rising filter resistance. This is a problem, since the flow rate of a constant speed driven centrifugal pump depends strongly on the flow resistance. The solution to achieve a mostly constant flow rate is to increase the entire flow resistance with a throttle which is placed between the pump and the filter (see Figure 5). With the additional flow resistance of the throttle, the impact of the varying filter resistance is reduced and consequently the flow variations too. But the result of the increased resistance is a greater need for pump pressure and thus a higher pump power.

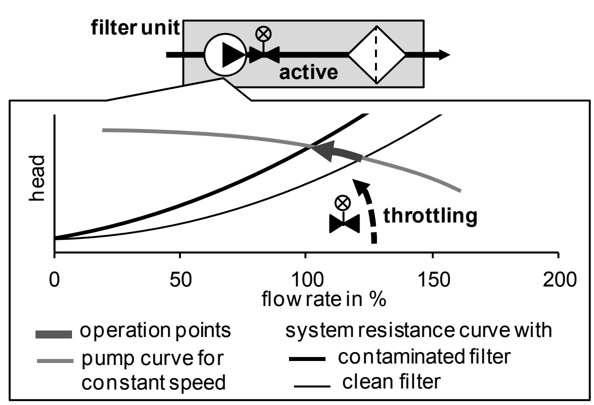

Figure 5: Pump operation with constant speed.

2.3 Evaluation of the Energy Efficiency

Due to the simple operating mode and the relatively low plant complexity, the requirements placed on high plant availability and low acquisition costs have been met. However, in regards to energy efficiency, the plants are operated inefficiently. The filter system operates continuously with all filters independent on the actual need of coolant. The filter pump of each filter is operated with constant speed. Therefore the minimum flow rate has to be determined based on the maximum coolant demand needed in the production. But the average demand on coolant in the production is in general much lower than the maximum demand. The pump is adjusted with the throttle in such way that the minimum flow rate is maintained, even with maximum filter contamination (see Figure 5). A lower filter contamination results even in a higher flow rate than required, due to the pump characteristic. In addition the pressure loss of the throttle increases quadratically with the flow rate. The excessive flow rate results therefore also in an excessive need of pump pressure. Both, the excessive flow rate and excessive pump pressure result in an inefficient operation. In addition, up to 80 % of the pump performance is dissipated as heat into the coolant [6]. Consequently, more cooling power is needed to stabilize the coolant temperature due the excessive heat input through the inefficient pump operation.

An extensive research and numerous interviews of experts have been undertaken. The authors do not know any work so far in which a control strategy for a demand based operation of a precoat filter system is implemented.

3 CONCEPT OF A DEMAND-BASED OPERATION

The basic approach is to adapt the cleaning performance based on the coolant demand in the production with a follow-up control. The approach is illustrated in Figure 6. It consists of basically two units: the follow-up control and the procedure of the filter resistance determination.

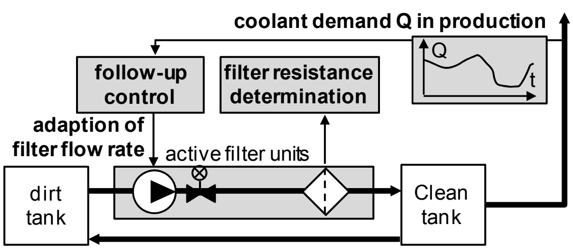

Figure 6: Approach for a demand-based operation.

Follow-up control

The flow rate in the cleaning loop of the filter system is adapted continuously with a follow-up control based on the actual coolant demand in the production. The throughput of each filter is adjusted with speed-controlled filter pumps via a frequency converter. With this, the pump speed, and consequently the pump performance is constantly adapted to the necessary flow rate and pump pressure required (Figure 7).

It should be noted that in filter systems with more than one active filter, a possibility is also to take filter out of operation during reduced coolant demand. But the filter cake is retained on the filter elements by the flow so that the filter can only be taken out by backflushing. Therefore the cost for the filter aid for a new precoating needs to be considered. The continuous adaption of the flow through each filter is therefore the main opportunity to reach an energy and resource efficient operation.

Filter resistance determination

With the adaption of the filter flow rate, a new procedure of the filter resistance determination is needed to trigger the cleaning processes. As illustrated in chapter 2.2., the filter cleaning in existing facilities takes place after reaching a defined cleaning pressure. This is possible since with constant pump speed, exists a direct relationship between the filter pressure and the filter resistance (operation point curve in Figure 5). Through the variation of the pump speed the flow rate, and consequently the flow-dependent filter pressure, changes with same filter resistance (operation field in Figure 7). The filter pressure sinks with a reduction of the flow rate and the cleaning procedure would not be triggered at the right time. Therefore the filter pressure can no longer be used as a filter cleaning criterion.

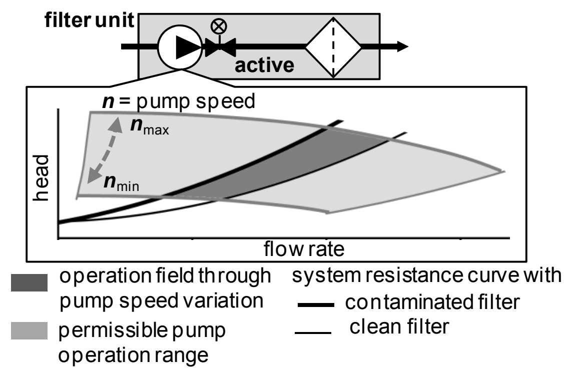

Figure 7: pump operation with variable speed control.

It needs to be considered that modernizations of existing filter systems are more common than building up new facilities, as the centralized filter systems are part of the service area and are operated over more than 20 years [4]. Therefore a retrofit solution of the given approach for existing filter systems is important. The energy savings need to be analyzed in order to determine the payback period of a retrofit. So first, the modeling of the filter unit is introduced in the following section, as simulations are necessary to evaluate the energy saving potential of different options as well to assess the control behavior. Afterwards the detailed design of the follow-up control is introduced and evaluated in a simulation scenario. The design of the procedure of the filter resistance determination is the topic of further research.

4 MODELLING OF A FILTER UNIT

It is sufficient to evaluate the electrical energy intake of the pump of one filter unit in the filter system as the hydraulic designs of the filter units are mostly identical. The energy saving potential can be evaluated with sufficient accuracy by calculating the electrical energy at the average operation point of the pump. Therefore stationary models are used.

The model of the hydraulic pump system is given in more detail as it is used also for the evaluation of the follow-up control later on. The head loss of the system h_{sys} is a function of the flow rate Q and depends of the geodetic head h_{geo}, the actual filter resistance r_F and the flow resistance of the pipe and fittings ∂. The head losses of the pipe and fittings, such as the throttle, increase quadratic with the flow rate [7]. The filter area is sized in general such that a flow through the filter cake between 1 m/h and 9 m/h results [5]. Due to this small flow and other factors, the head loss over the filter is proportional to the flow rate [8]. Various materials such as cellulose products or diatomaceous earth are used as filter aids. Cellulose products lead to a compressible filter cake so that the filter resistance is a function of filter pressure [8]. At present the authors do not know any published work about the compressibility behavior of the filter cake using cellulose in the application field of coolant cleaning. On the basis of opinions of experts and comparable analysis in other application fields, it is assumed so far that the filter resistance with cellulose product also behaves as incompressible [9]. The resulting equation is:

$$h_{sys}(r,Q) = r_F Q + \delta Q^2 + h_{geo} \quad (1)$$

The pump characteristic curve given for nominal speed n_n by the manufacturer can be approximated with a polynomial of two degrees. The curve can be converted to other pump speeds n by the affinity laws [10]. The resulting equation of the pump head h_p is:

$$h_p(Q,n) = a_2 Q^2 + a_1 Q(n/n_n) + a_o (n/n_n)^2 \quad (2)$$

The operation point is the point of intersection of the system curve and the pump characteristic curve. The equation for the flow rate results therefore by equating both equations. The varying parameters in controlled operation are the pump speed and the filter resistance. Figure 8 shows the measured and the calculated filter flow rate for different filter contaminations and pump speeds in an existing precoat filter system in which diatomaceous earth is used as filter aid. The flow rate was reduced by decreasing manually the pump speed of the filter pump with a frequency converter. The slip of the asynchronous motor is neglected in the simulation. The calculation agrees well with the measurement.

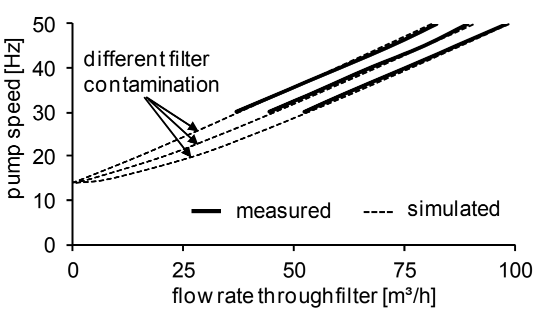

Figure 8: Measured and simulated filter flow rate curve.

The calculation of the electrical energy intake needed for the delivered flow rate and head is presented briefly in the following, the detailed description is given in [4]. The mechanical pump power is calculated by the flow rate, the head and the pump efficiency. The pump efficiency curve is given by the manufacturer and is approximated with a polynomial of degree four and converted to different pump speeds by the affinity laws. The motors are almost exclusively asynchronous machines. The electrical energy intake of the motor is calculated based on the mechanical pump power and pump speed with an electrical equivalent circuit model of the motor. The motor frequency of the asynchronous machine depends on the slip and can be calculated by numerical determination of the roots of the model equation. The manufacturer state that the frequency converter efficiency is almost constant over the considered operation range and is therefore accounted with a constant parameter.

5 EVALUATION OF THE ENERGY SAVING POTENTIAL

The energy saving potential of two possible retrofit scenarios has been evaluated at an existing precoat filter system: the retrofit of the control using the existing pumps and the retrofit of the control with an additional pump exchange which offers less throttling. A certain throttling is always needed as the operation points need to be in the permissible operation range of the pump (see figure 6). Figure 9 shows the measured and calculated electrical pump power depending on the flow rate with average filter resistance. The simulation agrees well with the measurement.

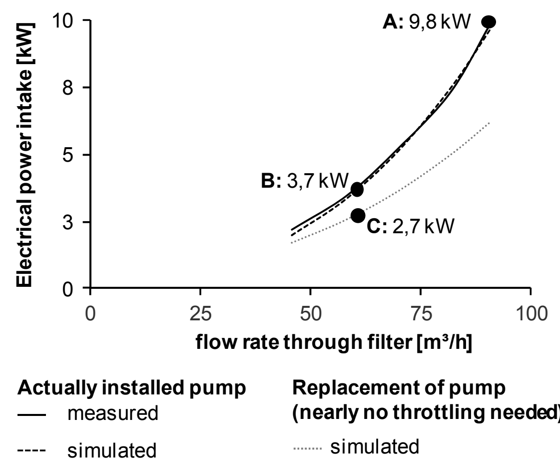

Figure 9: Evaluation of the electrical power intake.

Point A shows the average operation point of the existing pump with constant speed and Point B the average operation point of the same pump and throttle settings, but with speed control where only the required flow is delivered. The calculated energy saving is 62 % and it is calculated that the control can cost-efficiently be retrofitted. Point C shows the calculated average operation point of the retrofit of the control with a new selected pump which offers less throttling. With the pump exchange, an energy saving of 73 % is calculated. But an analysis showed that a pump exchange is not suitable for a retrofit, as the cost of a pump exchange exceeds the additional energy savings.

It should be noted that the throttle of the existing pump could be opened in controlled operation a bit further to reduce the pressure losses, but only in such way that the pump is still operated in the permissible range. An additional throttle control to reduce the throttling with increasing filter resistance was not taken into consideration due to the additional costs and relatively low additional energy saving potential.

6 CONCEPT OF THE FOLLOW-UP CONTROL

6.1 Requirements of the Control Design

Several conflicting requirements have been derived by expert interviews which need to be considered for the control design. The main requirements are:

- Adjustable surplus volume in the cleaning loop from 0 % up to the currently demanded 10 %.
- Limitation of the minimum flow rate and the rate of change of the flow rate to avoid a damage of the filter cake
- Maintenance of a certain level in the clean tank to ensure the security of supply

A minimum filter flow rate is necessary so that the filter cake is held on the vertical filter elements and particles still settle on the filter cake. In addition the rate of change of the flow through the filter may also not exceed a certain limit to avoid damaging of the filter cake.

The limitation of the maximum rate of change of the flow through the filter results in a temporary undersupply and consequently to a drop of the clean tank level, in the case of an abrupt rise of the coolant demand in the production. The supply pumps are switched off automatically after a minimum level is reached to protect them from running dry. This results in a supply shortfall and needs to be avoided at all time! Due to reasons of space and costs, the clean tank volume is such small that an undersupply can lead to a short fall normally within a few minutes. Therefore, the clean tank level must not fall under a certain level in controlled operation to ensure the security of supply.

6.2 Control Design

The required surplus volume affects the entire scope of the control designs. In order to keep the costs and complexity low the aim is to use as few sensors as possible. The flow rate through each of the active filters is the input into the clean tank and the supplied flow rate to the production is the output from the clean tank. With no surplus volume the control could be realized already with a single level control of the clean tank, where only a single level sensor would be necessary. But this is not possible as a surplus volume up to 10 % and with this a certain amount of overflowing of the clean tank is required. Another possibility to control the filter flow rate would be to keep up a certain amount of coolant through the overflow pipe. But a retrofit of a sensor device to measure the overflow is very cost intensive as it is a part filled pipe. Therefore the flow rate through each filter needs to be measured and regulated based on the measured flow rate into the production. Modern facilities are often already provided with the necessary flow rate sensors for process monitoring purposes. Own experiments have also shown that ultrasonic flow meters lead to sufficient accuracy which can be retrofitted cost-efficiently by mounting onto the pipe. Figure 10 shows the revised control design. The control design consists of three units: The flow control (one for each filter), the set point calculation and the level control. The three units are explained in more detail in the following.

Flow control

The set pump speed is calculated in the flow control based on the derivation between the required and the actual flow rate through the filter. The simulation showed that a single integral control is most suitable to realize the flow control. As a very low dynamic behavior is required, an additional proportional or a differential component gains no advantage. As shown in Figure 8, the flow rate changes in the relevant area nearly proportional with the pump speed, independent of the filter resistance. Therefore the limitation of the rate of change of the flow rate is realized by the limitations of the rate of change of the pump speed. As a single integrator control is used the integrator output equals directly the set pump speed. All pump speed limitations are therefore realized with the limitation of the integrator. Thereby a wind-up of the integrator is avoided at the same time. The derivations of the flow signals are often relatively high in particularly with existing flow sensors as they were chosen only for process monitoring. One possibility to compensate measuring deviations is signal smoothing. But the simulation showed that the dynamic of the flow control should only be adjusted by the integrator without signal smoothing as the resulting time lag due to the smoothing leads relatively fast to oscillatory behavior.

Set point calculation

In the set point calculation, the required flow rate for each filter is calculated based on the measured flow rate into the production. The specified surplus volume is added to the measured flow rate into the production and split up equally over all active filters. The derivation of the measured supply flow rate can be reduced through signal smoothing as the value is not a controlled value. The resulting time lag only delays the set point value.

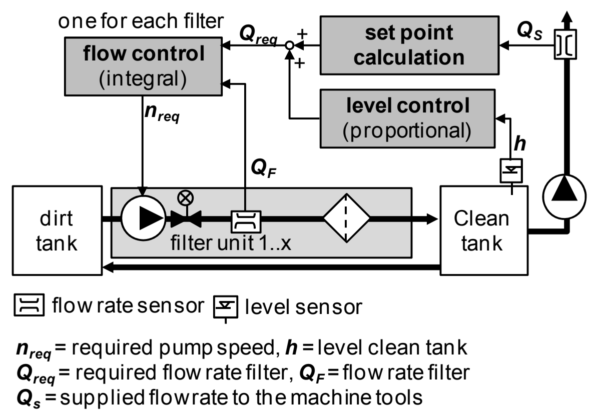

Figure 10: Design of the follow-up control.

Level control

The resulting time lag of the set point value through signal smoothing as well as the strong limitations of the rate of change of the pump speed, results in a temporary undersupply of the clean tank in case of a rising coolant demand in the production. If the plant operator specifies a surplus cleaning volume of 0 %, the clean tank would stay at the reduced level after a temporary undersupply as soon the filter flow rate again reaches the set point. Therefore a level control of the clean tank is necessary to refill the tank volume up to the set level. An adequate level sensor is often installed already or can be retrofitted easily. A proportional level control is sufficient as the filling of the clean tank volume has integral behavior. The control output is added to the set point value of the filter flow rate. A measurement error of the tank level leads to fluctuation of the set point value of the flow control. But the level is in general calculated by the measured pressure at the bottom of the tank which measurement error is relatively low. In addition, a relatively high level of smoothing is possible in the simulation without oscillation behavior.

6.3 Simulation Scenario

A simulation scenario of the follow-up control is given in the following for a filter unit in the considered existing filter system. Tests at the filter pump with a rate of change of the pump speed below 1 Hz/s showed a system response without delay. Therefore the introduced model equation from section 4 is used to calculate the flow rate. In addition, the actual measured errors of the flow rate sensors are added to the calculated flow rate.

Based on the requirements, the task is to keep the dynamic of the control as low as possible to avoid a damage of the filter cake, but at the same time not having a too excessive level drop of the clean tank in case of a sudden rise of coolant demand in the production.

A surplus cleaning volume of 0 %, a minimum flow rate of 50 m³/h and a limit of rate of change for the pump speed of 0.5 Hz/s were specified for the simulation scenario. Figure 11 shows the result of the simulation. In the beginning the control is deactivated since the switching from precoating to filter operation is set up for nominal pump speed. The control is activated at point 1. The control adapts the filter flow rate in the specified permissible limits until the set point value is reached. Despite the measurement error of the flow rate, a relatively constant flow is reached with an accordingly high reset time of the integrator. At point 2 the maximum jump of coolant demand is simulated. The set point value reaction is delayed due to the signal smoothing. The filter flow again is delayed due to the limitations and the high reset time of the integrator. The delay results in an undersupply and thus a drop of the clean tank level. The set point value is increased by the level control output to again reach the required level. The maximum level drop is about 3 % of the tank volume which is not critical. As a result, it can be noted that all requirements can be met.

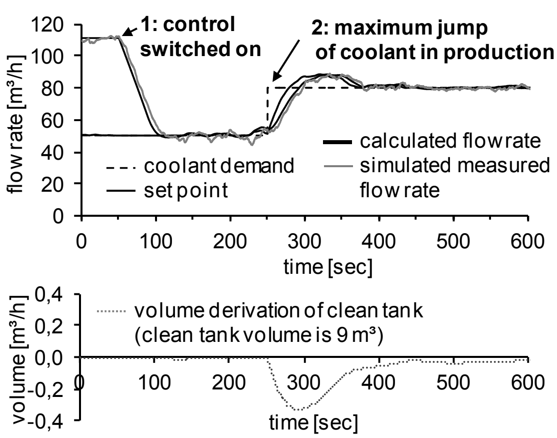

Figure 11: Simulated scenario of the follow-up control.

7 CONCLUSION

The coolant supply has the highest use of electrical energy in metal cutting. A previous study showed that there exist no demand-based control strategies for most types of filter systems with pressure filters, in which the coolant is cleaned for reuse. So far, the filter pumps are constant speed driven to reach high plant availability with low acquisition costs. Therefore, the cleaning performance needs to be set based on the maximum coolant demand in the production. In addition, pump throttling, which leads to high pressure losses, is required to reduce the flow rate drop resulting from the rising filter contamination. All in all, this results in a continuously operation of the filter system on an excessive power level, independent of the actual need for cleaning.

The introduced control concept is presented using the example of centralized precoat filter systems. The cleaning performance is regulated with speed controlled pumps, based on the coolant demand in the production. One outstanding issue was whether the conflicting requirements given for the filtration and the security of supply can be met. Due to the filter mechanism, it is only permissible to change the filter throughput in very small intervals. Despite this requirement, an abrupt rise of the demand of coolant in the production must not lead to a critical under supply. Through the use of a validated simulation model, it could be shown that both requirements can be met. Another question was the possible energy savings to evaluate the cost-benefit of the control. Tests at an existing plant showed that a retrofit of the control using the existing pumps and throttle settings, leads to an energy saving of 62 %. Due to this high saving potential, it is calculated that the control can cost-efficiently be retrofitted. The simulation with a pump selection which offers reduced throttling shows an energy saving potential of up to 73 %. But an analysis showed that this pump selection is more suitable for new filter plants and not for a retrofit as the cost of a pump exchange exceeds the additional energy savings.

The filters need to be regenerated due to the rising filter contamination. So far, the filter regeneration is triggered when a specified filter pressure is reached since the pressure is equivalent to the filter contamination due to the constant pump speed. With the implementation of the control, an adaption of the filter regeneration mechanism gets necessary. The development of the filter regeneration mechanism is the topic of the further research in the project.

8 ACKNOWLEDGMENTS

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9 REFERENCES

[1] Westphal, F., Behnke, S., Rahäuser, R. (2011): Energieeffizienz in der Produktion, Lecture presented at GSaME Annual Meeting 2011, Stuttgart

[2] N.N. (2007): Kühlschmierstoffe für spanende und umformende Fertigungsverfahren, VDI 3997-1, Beuth Verlag GmbH, Berlin

[3] N.N. (2005): Pflege von Kühlschmierstoffen für die Metallbe- und –verarbeitung, VDI 3997-2, Beuth Verlag GmbH, Berlin

[4] Rahäuser, R., Meier, M., Klemm, P. (2012): Offene Potentiale im Kühlschmierstoffkreislauf, wt werkstatttechnik online, pp. 299-305

[5] Triesch, J. (2010): Reinigung von Kühlschmierstoffen, ISBN 978-3-8169-2955-0, Expert Verlag, Renningen

[6] Tornau , D. (1999): Kühlschmierstoffe und Anlagen, ISBN 978-3816911609, Expert Verlag, Renningen

[7] N.N. (2009): Auslegung von Kreiselpumpen, ISBN 3-00-004734-4, KSB AG, Frankenthal

[8] Stieß, M. (1993): Mechanische Verfahrenstechnik 2, ISBN 3-540-55852-7, Springer Verlag, Berlin

[9] Zeller, A. (2011): Substitution der Kieselgur durch regenerierbare Zellulosefasern auf einem neuartigen Filtrationssystem für Brauereien, Dissertation, Fakultät für Mechanische Verfahrenstechnik, technische Universität Bergakademie Freiberg

[10] Walter, W. (2009): Kreiselpumpen und Kreiselpumpenanlagen, ISBN: 978-3-8343-3168-7, Vogel Buch Verlag, Würzburg

Improved Product Quality and Resource Efficiency in Porous Tungsten Machining for Dispenser Cathode Application by Elimination of the Infiltration Process

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Abstract

Porous tungsten is a difficult-to-machine material commonly used in the manufacture of high-performance dispenser cathodes [1]. The functional performance of such cathodes is directly linked to the surface porosity of the machined porous tungsten workpiece. Conventional machining leads to smearing of surface pores [1]. Current industry practice involves the use of a plastic infiltrant that stabilizes the pores during machining [2]. In order to increase the sustainability of the dispenser cathode manufacturing process, we propose a materials-science driven approach to machining porous tungsten. Heated and cryogenic machining are compared to determine an effective method to increase surface porosity. The ductile/brittle transition of the body-centered-cubic (BCC) refractory metal tungsten is exploited to alter the cutting mode between shear cutting (heated machining) and controlled brittle fracture (cryogenic machining). We conclude that cryogenic machining via controlled brittle fracture using a fine-grained PCD tool is the most effective approach to infiltrant-free machining of porous tungsten for dispenser cathode applications.

Keywords:

porous tungsten; dispenser cathode; fracture machining

1 INTRODUCTION

Porous tungsten is a difficult-to-machine material that is used in various applications which require high strength and high temperature (refractory) properties. Porous tungsten is produced when pure tungsten is sintered under specific conditions, leaving a sponge-like polycrystalline tungsten matrix. The average pore sizes for the approximately 81% dense material used in this study ranged from 3-10 microns. Porous tungsten is used primarily in the manufacture of dispenser cathodes. The porosity of the tungsten workpiece is essential to the functional performance of these cathodes, since the mechanism by which electrons are emitted from the cathode relies on a proprietary coating that each cathode is impregnated with [1]. A lack of porosity does not allow the impregnated material to penetrate the cathode's surface and thus functionality is impaired. In order to ensure maximum porosity, several processes have been developed [2]. First, the use of copper as an infiltrant allowed retaining porosity by avoiding smearing of pores during machining, which is a result of collapsed tungsten ligaments. Because it is nearly impossible to remove the entirety of the infiltrant after machining, copper was replaced by a polymer material. Nevertheless, residual infiltrant remains a cause of reduced cathode life and lower than ideal electron emission. In order to avoid the use of infiltrant entirely, several approaches have been proposed and tested. Machining porous tungsten at room temperature has proven to not be a successful approach, since smearing cannot be avoided [3]. Cryogenic machining, which involves the use of liquid nitrogen as a coolant, has shown considerable promise during previous studies [1]. The selection of proper machining parameters as well as the use of an appropriate cutting tool whose material grade and geometry as suitable for machining tungsten is critical. Optimization of the aforementioned criteria led to the suggestion that a combination of PCD tooling with very low edge radii (5-10 microns) and very low cutting speed (44.6 m/min) and feed (0.06 mm) at low depth of cut (0.05 mm) [2]. It is worth mentioning that these parameters are based entirely on mathematical optimization of empirical data. Up to this point, the mechanism and material properties of porous tungsten have not been sufficiently considered. We propose and approach that starts with the unique properties of porous tungsten and have selected two reasonable approaches for machining this material with maximum as-machined porosity as the central consideration. More specifically, the physical properties of tungsten, a refectory metal of body-centered-cubic (BCC) lattice structure show a significant dependence on temperature. At low temperatures, the metal behaves in a brittle fashion [4]. Fracture occurs very easily, yet yield strength is increased [5]. Conversely, at high temperatures plastic deformation of tungsten is possible and the material is essentially ductile [6]. The temperature range during which these two behaviors overlap is commonly referred to as the ductile/brittle transition temperature. It is nearly impossible to give a precise number for this transition, since many variables such as processing history, impurities, etc. play a large role in determining the exact value of the transition temperature [4]. For the material obtained for this study, the ductile/brittle transition temperature occurred around approximately 150℃.

In order to efficiently machine porous tungsten, two approaches were considered. The first approach consists of machining the metal in its low-temperature embrittled state by controlled fracture.

To achieve this condition, negative rake tooling was used to maximize compressive stresses and fracture individual ligaments. The second approach was to machine the porous tungsten workpiece at high temperatures via ductile shear using sharp, positive tooling. This work is concerned with comparing these two approaches and evaluating their effectiveness in achieving maximum as-machined porosity for optimum functional performance while eliminating the environmentally harmful infiltration process.

2 EXPERIMENTAL

The results of this study were obtained on a HAAS TL2 CNC lathe. An SCMCN123 tool holder with CCGW 32.51 PCD inserts was used to machine the samples. Four different diamond grades of various grain sizes (1200:1.7µm, 1300:6 µm, 1500:25 µm, 1800:25+4 µm) were compared. Cryogenic cooling was achieved via Air Products' ICEFLY system with a liquid nitrogen pressure of 1.5 MPa and a flow rate of approximately 0.5 kg/min. Heated machining was performed using a MAPP torch to heat the sample. Pre-heated and pre-cooling were carried out for 90 seconds while the sample rotated at 100rpm. Facing cuts were taken following a single cleaning pass on a 1.5cm diameter bar of 81% dense sintered porous tungsten. Samples of 2mm thickness were parted off using an abrasive wheel. SEM analysis was performed using a Hitachi S4300 scanning electron microscope. Image analysis for porosity and surface smearing measurements was performed using the software program ImagePro [2].

Figure 1: Overview of Experimental Setup.

In order to compare the effectiveness of both heated and cryogenic machining, a range of machining parameters was chosen. The depth of cut was fixed at 0.127mm to limit the amount of parameters for this finish machining operation. Three cutting speeds, 10, 18 and 36 m/min as well as three feed values, 0.025, 0.051 and 0.076 mm/rev were selected based on previous optimization studies [2, 7]. The number of samples collected for heated machining was limited once it had been determined that heating the workpiece led to immediate destructive tool wear for the PCD grades used in this study. Table 1 summarized the machining parameters for all of the samples created for this study.

Tool Grade, Sample	v_{cut} (m/min)	f (mm/rev)	acceptable facing cuts
1200.1	18	0.025	4 (cryogenic)
1200.2	18	0.076	3 (cryogenic)
1200.3	36	0.025	1 (cryogenic)
1200.4	36	0.076	1 (cryogenic)
1200.5	36	0.051	1 (heated)
1300.1	18	0.025	1 (cryogenic)
1300.2	18	0.013	1 (cryogenic)
1300.3	36	0.0254	1 (cryogenic)
1300.4	36	0.013	1 (cryogenic)
1300.5	36	0.051	1 (heated)
1500.1	18	0.025	1 (cryogenic)
1500.2	18	0.013	1 (cryogenic)
1500.3	10	0.025	1 (cryogenic)
1500.4	10	0.013	1 (cryogenic)
1500.5	18	0.051	1 (heated)
1800.1	18	0.025	1 (cryogenic)
1800.2	18	0.013	1 (cryogenic)
1800.3	36	0.025	1 (cryogenic)
1800.4	36	0.013	1 (cryogenic)
1800.5	36	0.051	1 (heated)

Table 1: Experimental matrix for PCD grades 1200, 1300, 1500 and 1800 (a_p=0.127mm).

3 RESULTS AND DISCUSSION

3.1 Cryogenic Machining

Comparing the four different diamond tool grades in this preliminary study showed that only grade 1200 is capable of producing more than one acceptable porous surface. While grade 1500 did yield a porous surface during the first cut, the cutting edge of this grade failed catastrophically via chipping during the second cut in samples 1500.1 and 1500.2. Grade 1200 produced by far the best results and provided proof for the concept of machining by controlled micro-fracture. To illustrate this concept, the following figure shows a comparison of a perfect fracture surface (a) and properly cryogenically machined porous tungsten (b):

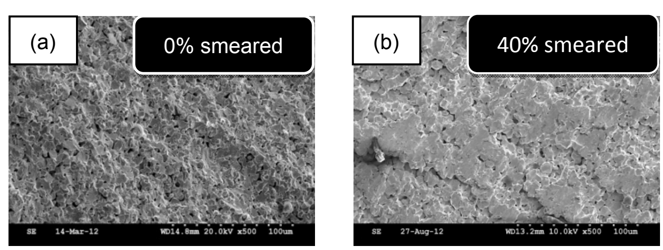

Figure 2: Comparison between SEM micrographs of a brittle fracture surface (a) and a cryogenically machined surface (b) of porous tungsten.

The following figure shows the correlation between tool wear and surface quality for sample 1200.1:

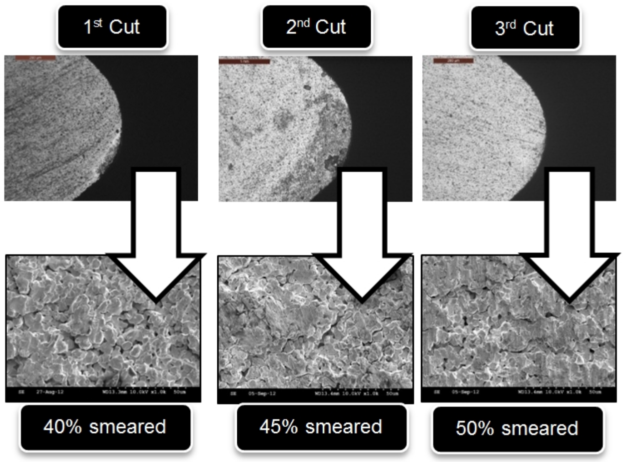

Figure 3: SEM micrographs of cryogenically machined porous tungsten, illustrating the correlation between surface quality and tool wear during successive facing cuts (v=60sfm, a=0.005”, f=0.001”, PCD grade 1200).

While cryogenic machining did not produce a perfect brittle fracture surface, sample 1200.1 had a surface that consisted of 60% fracture surface and only 40% smearing. The inherent porosity of 81% dense porous tungsten is approximately 180 pores per 100 µm x 100 µm area. With an industry standard of 30 pores in that same area, 40% smearing still yields 108 pores, which is a 260% improvement over the industry standard. Successive facing cuts did reduce the effective surface porosity slightly, yet the acceptability cutoff does not occur until 83% smearing. Because perfect brittle fracture was not achieved, the as-machined surface is a combination of uniformly distributed smeared islands and areas of perfect brittle fracture that reveal the inherent porosity of the workpiece. Careful examination of the SEM micrographs revealed a thickness of approximately 5-10µm for the smeared layer. In the dispenser cathode manufacturing process, chemical etching may be able to remove this relatively thin layer, resulting in the maximum obtainable porosity. The surface morphology of the cryogenically machined samples can be seen in the following figure.

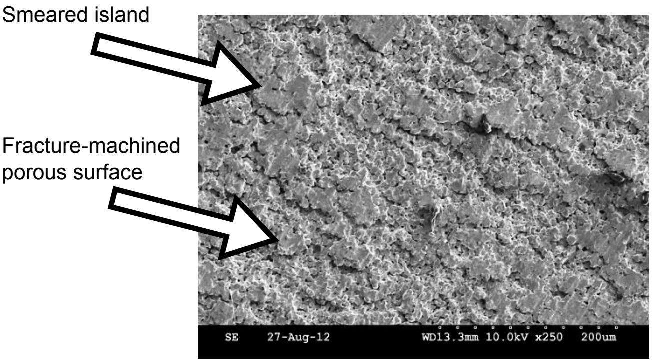

Figure 4: SEM micrograph of cryogenically machined porous tungsten surface illustrating surface morphology.

3.2 Heated Machining

Heated machining did not yield an acceptable surface. Tool wear appears to be a major concern when machining porous tungsten at elevated temperatures. Elongated surface cracks and excessive smearing, which is evidence of severe plastic deformation dominated the surfaces. Figure 5 shows a typical example for the kind of catastrophic tool wear that occurred for all four different PCD grades during heat machining. The cutting edge chipped off almost entirely which in turn did not allow a functional surface to be produced.

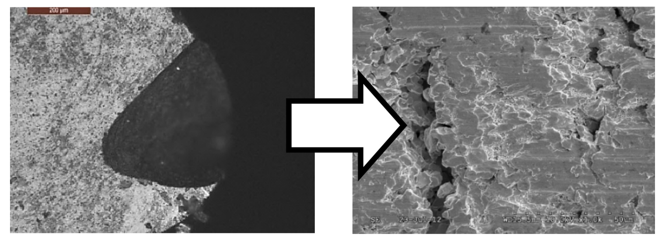

Figure 5: Optical tool wear image (plan view of flank) of PCD grade 1200 insert and SEM micrograph of corresponding porous tungsten surface produced via heated machining, showing evidence of both severe plastic deformation (smearing) and elongated surface cracks.

As a whole, heated machining of porous tungsten with PCD tools did show that tungsten machines very differently at elevated temperatures. With surface porosity as the chief objective, cryogenic machining by brittle fracture was far more effective that heated machining via shear in the ductile regimen. Because of the apparent limitations of PCD tools for heated machining, this approach was not carried out beyond the initial investigative experiments.

4 CONCLUSION

Using cryogenic machining, we have illustrated an infiltrant-free method for machining porous tungsten. While previous studies have shown the potential applicability of cryogenic machining to this particular issue, this study proposes the novel approach of machining via controlled brittle micro-fracture. Rather than producing a smeared surface with some residual pores, this method creates a surface whose morphology is characterized by both regions of perfect brittle fractures as well as evenly distributed smeared islands. The surface porosity obtainable by this method exceeds the current standard of the dispenser cathode manufacturing industry by 260%. Future work will have to be done on optimizing the machining parameters for PCD grade 1200, which was the only cutting tool material capable of performing multiple acceptable facings cuts. Moreover, the ability of other tool geometries and grades to achieve controlled micro-fracture machining will have to be determined. Eventually, a FEM-analytical hybrid model may be able to accurately predict to cutting mode (ductile shear vs. brittle fracture) and the surface porosity of porous tungsten based on a suitable material model.

5 REFERENCES

[1] J.O. Tarter, M.E., F. Pusavec, and I.S. Jawahir, *Cryogenic Machining of Porous Tungsten for Dispenser Cathode Applications*, in *IVEC 2008*.

[2] F. Pusavec, A.D., J. Tarter, M. Effgen, O.W. Dillon Jr., J. Kopac, I.S. Jawahir, *Optimization of Machining Performance in Finish Turning of Porous Tungsten under Cryogenic Conditions*, in *2nd Intl. Conference "Innovative Cutting Processes & Smart Machining"*2008: Cluny.

[3] S. Chen, D.H., M. Effgen, and I.S. Jawahi, *An Investigation of Sustained Machining Performance for Controlled Surface Quality Requirements in Porous Tungsten.* IEEE Transactions on Electron Devices, 2005. **52**(5): p. 903-908.

[4] A. Wronszku, A.F., *The Ductile-Brittle Transition in Polycrystalline Tungsten.* Journal of the Less-Common Metals, 1964. **6**: p. 413-429.

[5] A. P. Valentine, D.H., *Effect of Temperature on the Brittle Fracture of Polycrystalline Tungsten.* Journal of the Less-Common Metals, 1969. **17**: p. 353-361.

[6] Giannattasio, A., et al., *Brittle-ductile transitions in polycrystalline tungsten.* Philosophical Magazine, 2010. **90**(30): p. 3947-3959.

[7] Pusavec, F., *Porous tungsten machining under cryogenic conditions.* International Journal of Refractory Metals and Hard Materials, 2012. **35**: p. 84-89.

Green Key Performance Indicator Based on Embedded Lifecycle Energy for Selection of Cutting Tools

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Abstract

Many companies face increasing demands from markets to have environmentally friendly manufacturing processes. This paper proposes a Green Key Performance Indicator for selection of cutting tools, based on embedded lifecycle energy of the insert. This facilitates decision making to achieve green machining. Two insert materials were investigated; one solid carbide and one ceramic insert. The main work piece material was gray cast iron. The results show that the embedded lifecycle energy of a ceramic insert is considerably higher than for cemented carbide but, due to higher material removal capacity, the ceramic insert has a better Green Performance Indicator.

Keywords:

Embedded energy; metal cutting; performance indicator

1 INTRODUCTION AND BACKGROUND

Today, an increasing awareness of the need for reducing green house gas emissions, together with demands for energy efficiency and government legislations put more pressure on companies to investigate their manufacturing processes on these issues. The energy efficiency of the machine tool and related machining processes has been addressed by several researchers. In an overarching paper concerning machine and process energy efficiency, substantial work has been carried out by Duflou et al. [1]. They distinguish different system scale levels of manufacturing. Kara and Li [2] investigated the relationship between energy consumption and process variables for material removal processes, such as milling and turning. Methodologies for energy consumption estimation in machining through resource modelling have been proposed by Newman et al. [3].

Kara and Jeswiet proposed a Carbon Emission Signature, CES so that a manufacturer can place a green house gas label on each product [4]. They developed a method to connect the electrical energy used in manufacturing directly to the carbon emissions that are created using electrical energy. For a certain electrical power grid, the end user can see the amount of green house gases emitted making the product.

However, there is a lack of useful decision tools regarding the selection of cutting inserts. On the market, there are tens of thousands of different inserts to choose from and new ones are added weekly from different manufacturers. Thus, a performance indicator for selecting cutting tools from an environmental perspective would be useful. Alongside considerations on economy and quality, this can serve as a guide for decision makers in different machining operations to choose an insert. Studies have been presented on the relationship between energy efficiency and machining cost e.g. Anderberg, et al. [5] Helu et al. [6-7]. Anderberg et al. [8] developed the machining energy consumption model employed in [5] to include not only the use phase of the machining process, but also the embodied energy of the cutting tool. The embodied energy used herein was based on Dahmus and Gutowsky [9], which were rough estimations. To be able to more accurately assess the actual environmental impact of machining operations, it was concluded that better values of the embodied energy of different cutting tools was needed.

The aim of this paper is to propose a Green Performance Indicator, GPI and to provide a methodology to calculate the GPI based on the embedded lifecycle energy in cutting tools explained below. The purpose is to rate different types of insert materials for turning operations of different materials in order to achieve green machining [10]. The proposed performance indicator as intended as an improvement over merely considering the embedded energy of the tool insert or even considering the lifecycle energy of the tool as a criterion.

The indicator is based on the embedded lifecycle energy of the insert, the embodied energy of the insert for processes such as ore extraction, crushing, sintering, coating and transportations between different manufacturing stages until it reaches the end user, as well as tool use and disposal phase. This is subsequently related to its capability to remove material. This methodology is demonstrated in two cases of selection between a carbide and ceramic insert for turning of grey cast iron and Inconel 718.

The authors are well aware of the difficulty to obtain reliable values on which the indicator is based. The model presented in this paper is highly transparent in order to facilitate improvements. Furthermore, the GPI does not yet take into consideration the spindle efficiency of the machine tool at different spindle speeds, nor does it regard non-linear behaviour of the work piece material that affects the specific cutting energy and material separation as function of feed and cutting velocity, which was discussed previously by Beno et al. [10].

2 GREEN PERFORMANCE INDICATOR

The proposed Green Performance Indicator, GPI is defined as follows (eq. 1):

$$GPI = \frac{\text{Material Removal per Insert}}{\text{Embedded Lifecycle Energy}} \tag{1}$$

The premise is recommended starting values from the manufacturer´s tool selection system from which to obtain cutting speed feed, maximal depth of cut and service life. Thus, providing the material removal data for the selected insert and selected work-piece material.

Obviously, the accuracy is reliant on the quality of acquired data and, naturally, these values vary for different manufacturers of cutting tools. The depend, for instance, on the location where the tungsten carbide, cobalt and silicon nitride is mined in relation to the insert manufacturing and where the tool is to be used in world. This affects the amount of transport work required in different stages of the insert life-cycle and carbon emissions of local energy sources. Another important parameter is the amount of recycled material that is used in the production of new inserts. Carbide has a high degree of recycled material compared to ceramic that has none.

3 SELECTION OF CUTTING TOOLS AND WORK-PIECE MATERIAL

3.1 Selection of Work-Piece Material

The selected work-piece material was SS0727-02, a grey cast iron widely used in heavy trucks and earth moving construction equipment. This material exhibits negligible changes in the specific cutting force, k_c in range used in this study. Thereby, any non-linear behaviour is removed from the cutting data used in the comparison of the GPI.

3.2 Selection of Cutting Tools

To demonstrate how a GPI can be used, two inserts manufactured from totally different materials were chosen for conducting longitudinal turning. One coated tungsten carbide insert and one silicon nitride (ceramic). The tools were selected so that they both were recommended for turning of the same work-piece material by the tool manufacturer. All cutting data presented here can be obtained from open sources from the manufacturer, see Table 1. The cutting velocity used in this paper has been adapted so the tool life of each cutting edge will be 15 min.

4 LIFE-CYCLE INVENTORY

A Life cycle inventory (LCI) was performed for both cutting tools. The functional unit (f.u.) was one cutting tool insert (thus omitting the environmental aspects of the tool holder, which is negligible since it poses a work life of several years). This, in turn, was translated into the weight for each insert. The comparison between the two types of inserts is hence based on the embedded energy in kJ per insert weight. The results from the conducted LCI including four lifecycle phases (material production, tool manufacture, tool use and material recycling) for both inserts are shown in Table 2. All materials data are taken from the well known database of CES EduPack 2012 [11].

4.1 Embedded Lifecycle Energy

Material Production

Here, the constituents of the solid carbide manufacturing energy are presented separately, since different carbides will have different composition along with transport energy. These values can also vary as a function of grain size. The ceramic insert consists of one substance so only one value of energy is required.

	Insert	Comment	Solid Carbide	Ceramic
	Product name		TNMG 16 04 08-KM 3205	
	Manufacturer		Sandvik Coromant	Sandvik Coromant
	Material Composition			
	Tungsten Carbide		62%	N/a
	Recycled Tungsten Carbide		30%	N/a
	Cobolt		8%	N/a
	Silicon Nitride		N/a	100%
	Coating		CVD-coating with titanium carbide (TiC), aluminium oxide (Al2O3) och titanium nitride (TiN)	
1	Insert Weight [g]		7	5
2	Number of Cutting Edges		6	6
3	Service Life per Edge [min]		15	15
	Work Piece Material		Grey Cast Iron SS0727-02	Grey Cast Iron SS0727-02
4	Specific Cutting Force, kc [N/mm2]		900	900
	Application Area		Medium Rough Machining	Medium Rough Machining
	Cutting Data			
5	Cutting Depth, ap [mm]		3	3
6	Feed, f [mm/rev]		0,35	0,5
7	Cutting Velocity, Vc [m/min]		325	490
8	Material Removal Rate, MRR [cm3/min]	R5*R6*R7=	341,25	735

Table 1: Summary of properties of the two inserts of the comparison.

Tool Manufacture

The embedded energy is calculated using either the weight of the insert or from the mantle surface of the insert, case for the coating. Here, an optional adhesive layer included. Edge treatment is based on grinding and is estimated. The manufacture of an insert is similar for the two types, where powder metallurgy principles are used (pressing and sintering) followed by grinding to net shape and for the solid carbide inserts PVC coating processes.

Tool Use

The number of cutting edges is based on the design of the insert, i.e., practical limitations depending on tool wear is neglected. This entails that the number of edges is an integer. The energy consumption derived in this paper is based on closed form equations regarding power consumption integrated over service life time to obtain the manufacturing energy. The overall efficiency of the machine tool is set to 80 pct.

The principal cutting force is calculated according to (eq. 2):

$$F_c = f * a_p * k_c \qquad (2)$$

where f is the feed per revolution, a_p is the depth of cut and k_c is the specific cutting force

However, one must remember that ceramic inserts are normally used with negative rake angle which makes the principle cutting force increase with 1-1.5 pct. per degree. This will contribute to overall higher energy consumption but has been neglected in this paper.

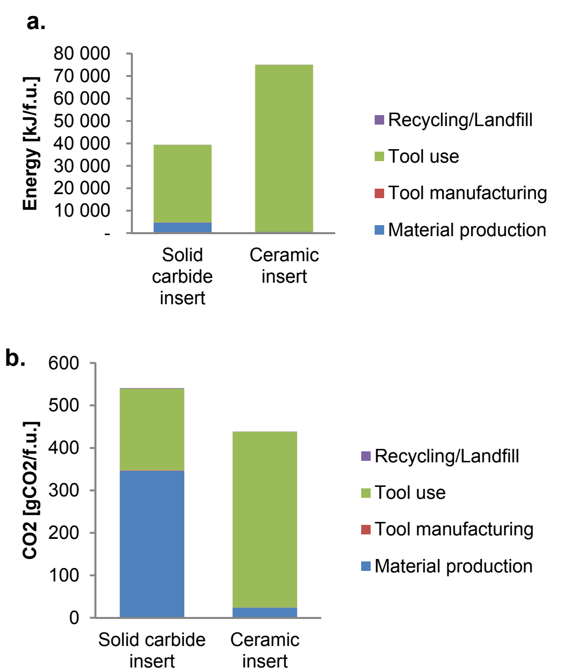

Figure 1: **a**. Energy consumption per functional unit, i.e. insert. **b**. Carbon emissions per functional unit. for tool use in Sweden.

Material Recycling

Recycling of carbide is very common but requires vast amounts of energy in order to separate the tungsten carbide from the binder, cobalt. The amount of recycled carbide that is mixed with virgin carbide will vary significantly with different grades. Ceramic inserts will mostly be transported to landfill instead of recycling.

5 RESULTS

The results from the LCI, see table 2, show that the total energy consumption over the service life of a solid carbide insert is considerably less than for a ceramic insert. They also show, as expected, that the tool use phase, is by far the largest contributor to the embedded lifecycle energy of both inserts. For the solid carbide insert, though, the material production phase does have a significant contribution of around 12 pct. of the embedded lifecycle energy. This can be seen in Figure 1a, above. Figure 1b shows the corresponding CO_2 emissions, to be discussed later.

It is not sufficient, however, to just compare the LCI results of the energy consumption or the CO_2 emissions of the two cutting tools to determine which insert has lower environmental impact. The energy consumption, for example, must be considered in relation to cutting performance. The outcome is not obvious, since high material removal rate, also give high energy consumption.

5.1 Energy Based Performance Indicator

As an improvement, a key indicator, based on the ratio between the estimated material removal of an insert and its embedded lifecycle energy was formulated and used: the green performance indicator. The GPI for the two tool materials in the comparison is shown in Table 3. For cast iron, the GPI values are 779.0 cm^3/MJ for the carbide insert and 881.6 cm^3/MJ for the ceramic. For Inconel 718 as work piece material, the same trend is observed. Higher value of the GPI indicates better environmental performance, which shows that the ceramic insert is a better alternative in order to lower the environmental impact in terms of energy use in the considered cases.

Comparing figure 1a and 1b, there is an apparent contradiction. The ceramic insert has higher life cycle energy but lower carbon footprint. Since most energy in the world is produced from fossil fuels, it is easily presumed that the CO_2-emissions reflect the embedded energy of the inserts. In the present examples, however, a significant part of the energy mix of the electricity in the use phase is renewable, since Swedish conditions have been applied. An emission value of 5.56 g CO_2/MJ useful electricity has been used for Swedish electricity. According to ref [11], however, fossil fuels may emit 200 g CO_2/useful MJ of electric energy, which would increase the emissions dramatically and make ceramic inserts a greater CO_2 emitter than the solid carbide in countries with fossil-dominated energy mix.

It should be noted that although the ceramic insert appears to be the more environmentally friendly alternative of the two, the difference is very small and varies between 5 pct (Inconel 718) and 13 pct (cast iron). Therefore, the accuracy of underlying data must be taken into account, which means that the selection of insert materials based on these environmental considerations is still uncertain. The machining parameters which in turn dictates the MRR used for the specific application, significantly influences the environmental impact in the user phase. On an industrial basis, these are not necessarily the recommended or optimal parameters.

5.2 Emission Based Performance Indicator

The energy used for each phase of the life-cycle, and the associated CO_2-emissions for the present cases (Sweden) are compiled in Table 4. The CO_2-emissions from the life-cycle of the solid carbide insert is dominated, not by the tool use, but by the material production. The CO_2-emissions from phase (i) is nearly twice of that from phase (iii) and make up 64 pct. of the total emissions. For the ceramic insert, though, the tool use phase is the dominant one, responsible for nearly 95 pct. of the total CO_2-emissions. Tool use in Sweden, and other countries with a high degree of renewable or nuclear energy in the energy mix, can result in very low CO_2-emissions for the tool use phase, which is electric use, mainly.

	(i) Material Production			
9	Powder Production Energy (primary)		4578,4	580
10	Transport Energy (primary)	Source-Austria	20,5	12,5
11	Powder Production Energy (secondary)		26,2	0
12	Transport Energy (secondary)	India-Austria	5,3	0
13	Transport Energy (secondary)	Austria-Sweden	5,9	
14		Within Sweden	1,3	
A	Material Production Energy per insert (i) [kJ]	sum (R9-R14)	4 637,6	592,5
	(ii) Tool Manufacturing			
	Process Energy			
15	Powder Compacting		5	3,5
16	Sintering		15	11
17	Edge Treatment		9	6,6
18	CVD-Coating		106	0
19	Al-Coating		0,5	0
20	Ti-Coating		4,3	0
21	Transport Energy	Within Sweden	1,3	0,9
B	Tool Manufacturing Energy per Insert (ii) [kJ]	sum (R15-R21)	141,1	22,0
	(iii) Tool Use (Turning) per Cutting Edge			
22	Cutting Power [W]	R4*R5*R6*R7/60=	5118,75	11025
23	Machine Efficiency [%]		80	80
24	Process Power [W]	R22/R21=	6398,4375	13781,25
25	Process Energy [J]	R22*R3*60=	5758593,75	12403125
C	Tool Use Energy per Insert (iii) [kJ]	R25*6 edges=	34 551,6	74 418,8
	(iv) Material Recycling			
	Process Energy			
26	Zink Based Carbide Extraction Process [kJ/kg]		10800	0
27	Per Insert [kJ]	R26*R1/1000=	75,6	0
28	Crushing [kJ/kg]		208	0
29	Per Insert [kJ]	R28*R1/1000=	1,456	0
30	Transport Energy	Sweden-India	15,8	0
31	Transport to landfill			0,9
D	Material Recycling Energy (iv) [kJ]		92,9	0,9
	Embedded Lifecycle Energy [kJ]		**39 423,1**	**75 034,2**

Table 2: Contributions to the embedded lifecycle energy of the two inserts of the comparison.

Insert material	**solid carbide**		**ceramic**	
Work piece material	Cast iron SS0727-02	Inconel 718	Cast iron SS0727-02	Inconel 718
Material Removal Rate, MRR [cm³/min]	341	50	735	100
Material removal per insert for a tool life of 15 min [cm³] **(Material Removal=MRR*t*n)**	341x15x6 = 30713	50x15x6 = 4500	735x15x6 = 66150	100x15x6 = 9000
Green Performance Indicator, GPI [cm^3/MJ]	30713/39.4 = **779.1**	4500/39.4 = **114.1**	66150/75.0 = **881.6**	9000/75.0 = **119.9**

Table 3: Material removal, MR, for different combinations of insert and work piece materials.

Since the CO_2-emissions are the primary cause of climate change concerns, another performance indicator may better represent the true environmental impact of a chosen tool than GPI, in particular for countries with high proportion of renewable energy in the energy mix. This more pertinent indicator (Material Removal Footprint) could be based on the amount of CO_2 emitted during the lifetime of a cutting tool, divided by the associated material removal. This value will vary with the work piece material and in the comparison based on Table 4, this ratio will be: 540.8/30713=17.6 mg/cm^3 for the solid carbide insert and 483.3/66150=7.3 mg/cm^3 for the ceramic. This means less than half the emissions per removed volume of material for the ceramic tool, compared to the solid carbide one, which emphasizes the picture from the GPI values.

		Solid carbide insert		**Ceramic insert**	
Life-cycle phase	Process + Transport	Energy [kJ/f.e]	CO_2 [gCO_2/f.e]	Energy [kJ/f.e]	CO_2 [gCO_2/f.e]
(i)	Material production	4 654.1	346.2	592.5	24.0
(ii)	Tool manufacturing	141.1	1.1	22	0.2
(iii)	Tool use	34 551.6	192	74 418.8	414
(iv)	Recycling/Landfill	92.9	1.5	0.9	0.1
Total		39 439.7	540.8	75 034.2	438.3

Table 4: Summary of embedded energy and emissions of the two inserts of the comparison.

6 DISCUSSION

The necessary data for the implementation of a GPI already exist, since many companies conduct inventory work regarding their energy consumption. The different cutting tool manufacturers could easily facilitate this just by disclosing embedded energy in their products, in a similar way as one does with feed and cutting velocity recommendations for end users today. Several of the large tool manufacturers have recently presented substantial improvements of their web based tool selection services that could contain this additional information. Together with the proposed methodology, it should be possible for the tool manufacturers to aid the user in selecting more environmentally friendly inserts. These would have a high material removal capacity as well as low embedded energy and carbon footprint. It is necessary in such a system that the country of use should be included and the country's energy mix for the machining operations and their associated CO_2 emissions considered.

Further studies are needed to elucidate the actual energy/CO_2 reduction potential in selecting a tool with a higher GPI, i.e. better environmental performance. Factors influencing this are fixed vs. variable energy consumption of the machines, machine idle (as a consequence of inefficient CNC program structure, loading/ unloading, in-process inspections etc.) and standby.

From a lifecycle perspective, Uede [12] states that the environmental burden of the machine tool during use accounts for 95 pct.. This shows similarities to the situation presented in this paper regarding the tool lifecycle. Li and Kara [13] and Diaz et al. [14] presented empirical models of actual energy use during machining, with similar results. Such models may also be useful for estimating the actual energy during use phase for different tools. There are still a few problems with a model based approach compared to measuring energy use directly on the machine. This primarily concerns the possibility to generalize the models to different machines, materials and tools.

7 CONCLUSIONS

This paper proposes a green key performance indicator based on the relationship between the material removal capacity and the embedded life-cycle energy of the cutting tools. The GPI methodology is presented in full transparency with the intention of improvements. A life cycle inventory for solid carbide vs. ceramic inserts in a turning operation for grey cast iron reveals that, in the present example, the ceramic insert has a GPI that is 13 pct. higher (better) than the carbide. The trend is similar for Inconel 718 as work material. The environmental impact in terms of CO_2 emissions depends crucially on the energy mix of the country of tool use.

The use of such an indicator can aid the process planner in selecting more environmentally friendly tools. However, the quality of data upon which such an indicator is based can be difficult to extract. Here, tool manufacturers have a responsibility and a marketing possibility in presenting such information to the customer, preferably in an easy-to-interpret format.

8 REFERENCES

[1] Duflou, J. R., Sutherland, J. W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M., Kellens, K. (2012): Towards energy and resource efficient manufacturing, in: Annals of the CIRP, Vol. 61, pp. 587-609.

[2] Kara, S., Li, W. (2011): Unit process energy consumption models for material removal processes, in: Annals of the CIRP, Vol. 60, pp. 37-40.

[3] Newman, S. T., Nassehi, A., Imani-Asrai, R., Dhokia, V. (2012): Energy efficient process planning for CNC machining, CIRP Journal of Manufacturing Science and Technology 5, pp. 127–136.

[4] Kara, S., Jeswiet, J., (2008): Carbon emissions and CES™ in manufacturing, in Annals of the CIRP, Vol 57 - Manufacturing Technology 57, pp. 17–20

[5] Anderberg, S., Kara, S. and Beno, T. (2010) Impact of energy efficiency on computer numerically controlled machining, Journal of Engineering Manufacture (Part B), 224(B4): p. 531-541

[6] Helu, M. Rühl, J. Werner, P. Dornfeld, D. Lanza, G. (2011) Evaluating trade-offs between sustainability, performance, and cost of green machining technologies, Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Braunschweig, Germany, pp. 195-200.

[7] Helu, M. Behmann, B. Meier, M. Dornfeld, D. Lanza, G. Schulze, V. (2012) Total cost analysis of process time reduction as a green machining strategy, Proceedings of the 19th CIRP International Conference on Life Cycle Engineering, Berkeley, CA, USA, pp. 299-304.

[8] Anderberg, S., Beno, T., Pejryd, L. (2012): Energy and Cost Efficiency in CNC Machining from a Process Planning Perspective, Sustainable Manufacturing Shaping Global Value Creation , pp 393-398

[9] Dahmus, J. B. and Gutowski, T. G. An environmental analysis of machining. In ASME International Mechanical Engineering Congress and RD&D Expo, Anaheim, California, 2004, pp. 1–10.

[10] Beno, T.; Anderberg, S., Pejryd, L., (2010): Green machining – improving the bottom line, in: Proceedings of the 16th CIRP International Conference on Life Cycle Engineering (LCE2009), Cairo, Egypt.

[11] See, e.g. Ashby, M. F. (2009), Materials and the Environment, Butterworth-Heinemann/Elsevier.

[12] Uede, K. (2004) *Latest Technical Trends of Machine Tools,* Koyo Engineering Journal English Edition, (165E): p. 14-19

[13] Li, W. and Kara, S. (2011) *An empirical model for predicting energy consumption of manufacturing processes: a case of turning process,* Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 225: p. 1636-1646

[14] Diaz, N., Redelsheimer, E. and Dornfeld, D. (2011) *Energy consumption characterization and reduction strategies for milling machine tool use*, Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Braunschweig, Germany

A Universal Hybrid Energy Consumption Model for CNC Machining Systems

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Abstract

To estimate and optimise energy usage of CNC machines, a comprehensive energy model is required. In this paper, a universal hybrid energy consumption model is proposed, which is comprised of component energy model at the lower level and operational state transition model at the higher level. It is scalable to suit the users' needs, and the detailed energy profile can be readily obtained. Component-Mode-State matrix is firstly defined. Together with the state transition graph and chain matrix, energy information becomes available to a CNC controller. A prototype CNC machining system has been developed to demonstrate the feasibility of the model. Potential energy savings by adopting this energy model in industrial exercises are discussed.

Keywords:

Energy Consumption Model; State Transition Model; CNC Machining; Energy Efficiency

1 INTRODUCTION

In the new era of global competition in manufacturing industry, improving energy efficiency has attracted a great deal of attention. As a matter of fact, energy intensity persists in an industrialised country with production being responsible for 1/3 of the primary energy consumption [1]. In addition to increasing energy prices, manufacturers are expected to pay extra cost in the future, e.g. carbon tax. It has become a high-priority target to optimise energy efficiency in order to stay competitive. Computer Numerical Control (CNC) machine tools are the key players in machining systems. The trend towards increased automation will accordingly enlarge the energy cost portion of the total cost [2]. The main environmental impact of CNC machines is attributed to electrical energy consumption during the use stage, which accounts for more than 95% of the life cycle energy usage [3]. Measures to analyse the energy efficiency of machine tools in the use phase have been developed and deployed. As one of the most widely accepted measures in industry, specific energy consumption has been studied. Two different types of its definitions are presented in Section 2 and the most effective one is selected to comprehensively describe the whole machining process. It is found that to calculate the accurate value for such measure, a truthful energy consumption model is highly required. Unlike a typical cutting energy model, the proposed hybrid energy consumption model considers not only the major energy users (e.g. cutting energy), but also that of the entire machining system. Therefore, it is more suitable to tackle the problem in the sophisticated machine tools. A two-level model is presented in Section 3, comprising of component energy model at lower-level and operational state model at upper-level. Therefore, energy model is scalable for the users' interests, and the detailed energy profile can be portrayed. Compliant with ISO 14955, Component-Mode-State matrix (CoMoS) is defined, and the machining events, e.g. spindle on, coolant off, are used to trigger the transition between different states. Moreover, with state transition diagram and process chain matrix proposed in this research, estimation of energy consumption can be exercised easily. Employing the proposed model, energy efficiency analysis can be automatically performed by a CNC controller, and online optimisation becomes possible. In Section 4, a modelling procedure is outlined to develop a hybrid energy consumption model for a 3-axis milling machine. The results show that total energy usage of a machining process can be accurately predicted. Energy efficiency improvements are suggested based on the proposed model in Section 5. Discussions and conclusions are given in the end.

2 ENERGY EFFICIENCY MEASURES

Before we introduce measures to improve energy efficiency of machine tools, it is important to first clarify the meaning of energy efficiency. In general, energy efficiency (η_{energy}) is defined as relationship between the output achieved and the resources used, where resources mean total energy input in this research work,

$$\eta_{energy} = \frac{Output_{production}}{Input_{energy}} \tag{1}$$

It can be further specified using a variety of indicators or measures based on physical or economic parameters.

2.1 Specific Energy Consumption

Specific energy consumption (μ) is one of the energy efficiency measures that commonly accepted in manufacturing industry. There are principally two types of specific energy consumption [4]. One is the direct specific energy for material removal, which can be called specific energy of material μ_1. It can be calculated using Eq. 2. This value describes the energy per volume unit required to physically form a chip and thus remove the material.

$$\mu_1 = \frac{F_{cutting}}{a_p \cdot h} \tag{2}$$

where $F_{cutting}$ – cutting force (N),

a_p – depth of cut (mm),

h – non-deformed chip thickness (function of feed-rate and the angle that a cutter enters a workpiece).

The other type describes the energy that is required by a machining system to remove material. There are three existing approaches to evaluate it (see Eq. 3, 5 and 6). As shown in Eq. 3, the cutting power, $P_{cutting}$ is used to calculate μ_2, divided by *MRR* for the current operation. One limitation of this value is that only the cutting activities are considered. Non-removing actions (i.e. *MRR*=0), such as rapid traverse, are not included, which makes this measure most suitable for assessing different machining settings,

$$\mu_2 = \frac{P_{cutting}}{MRR} \tag{3}$$

where $P_{cutting}$ – cutting power (W),

MRR – Material Removal Rate (mm^3/min).

$$MRR = \frac{a_p \cdot a_e \cdot V_f}{1000} \tag{4}$$

where a_e – width of cut (mm),

V_f – feed-rate (mm/min).

Alternatively, total energy required is considered to comprehensively describe the whole machining process. It is related to the total volume of the removed material as expressed in Eq. 5. This value (μ_3) includes all non-value adding activities necessary to machine the component (e.g. rapid traverse). However, in production, all parts machined often consist of qualified (fine) parts, defect parts, and scrap parts. The scrap part or defects may require further processing, re-work or disposal. This often means additional energy is required. Therefore, to effectively calculate specific energy consumption, only the qualified part should be considered (see Eq. 6).

$$\mu_3 = \frac{E_{total}}{MRV} = \frac{E_{total}}{MRV_{part} \cdot No_{part}} \tag{5}$$

where E_{total} – total energy consumed of a machining process (kWh),

MRV – volume of removed material (mm^3),

MRV_{part} – volume of removed material per part (mm^3),

No_{part} – total number of parts produced in a machining process.

$$\mu_4 = \frac{E_{total}}{MRV_{part} \cdot No_{fine}} \tag{6}$$

where No_{fine} – the number of fine parts produced.

In this paper, μ_4 is selected as the measure for specific energy consumption. This represents a true value of specific energy usage in energy-efficient machining, considering energy usage, productivity and quality achieved.

2.2 Energy Consumption Model

Over the years, researchers in this area endeavour to find out how to model energy consumption during machining. It was started with examining the cutter-workpiece interaction [5]. Numerous energy models were proposed to estimate the cutting energy consumption [6, 7].The deriving process of theoretical models is time consuming due to the nature of complexity of the processes. Later, statistic modelling based on massive data became more popular, e.g. response surface methodology [8]. These so-called empirical models utilise the production data to establish the relationship between the main variables and the energy usage [9, 10]. More factors that indicate an impact on energy consumption are considered in the experimental tests, e.g. machining condition [11]. Both approaches above concentrate on actual cutting energy. However, researchers dealing with sophisticated CNC machine tool systems nowadays realise that the actual cutting energy only accounts for 15%-25% of the total energy consumed by a machine tool [12]. A comprehensive review on energy consumption model can be found in [13]. Figure 1 depicts an example of energy consumption profile of a machining process. The cutting energy is like “the tip of the iceberg”. Therefore, discrete state modelling was introduced to model systematic energy usage [1]. More components of a machine are being considered in this approach. Hence, a complete energy profile can be obtained. In this paper, a universal hybrid energy consumption model has been developed to combine the strengths of different techniques. It considers detailed theoretical or empirical energy models at the component level, so that specific energy usage, e.g. cutting energy, can be estimated. Furthermore, state transition model is adopted to facilitate the low-level models in order to portray the total energy profile of a machining process.

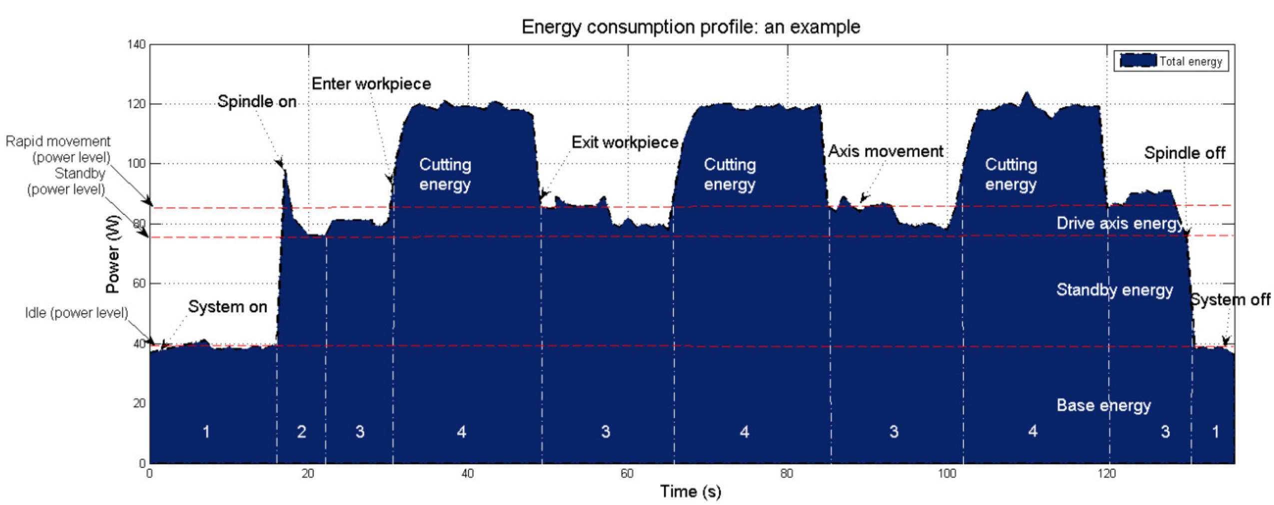

Figure 1: An example of entire energy consumption profile of a machining process.

3 HYBRID ENERGY CONSUMPTION MODEL

Hybrid modelling approach is firstly mentioned in Dietmair and Verl's [14] work. The intention there is not to develop a single model to explain the behaviour of all machines, but to provide a modelling tool framework for optimising machines, control and usage. In this paper, the authors proposed a hybrid energy model, which combines more than one approach to predict energy consumption of a machining process to achieve improved estimation in terms of accuracy, scalability and effectiveness. Before introducing the proposed model, it is necessary to clearly define the terms in use. Here, we follow the definitions in ISO 14955-1 [3].

Machine tool components are defined as mechanical, electrical, hydraulic, or pneumatic device of a machine tool, or a combination thereof, e.g. Spindle, Drive axis, and Machine cooling.

Component operating modes mean different designed modes in which a component can stay or operate, i.e. ON, OFF and HOLD.

Operational states mean defined combinations of ON, OFF, and HOLD states of components or units, e.g. Stand by and Processing.

Machining events are the incidents or changes of component operating mode that result in the shift of operational state, e.g. Spindle on and Cutter enters workpiece.

Two stages are taken to construct the hybrid model. In the first stage, the total energy usage is divided by operational states, shown as number 1-4 in Figure 1 (e.g. 4 is processing). In the second stage, the energy usage of each operational state is decomposed by a number of components in use. Every component works only in one of its operating modes, thus consistent power behaviour is expected. This can be expressed in Eq. 7. The power value $P_{state\ i,component\ j}$ can be obtained in three ways, i.e. power model, actual measurement or rated power. For instance, the spindle power during cutting can be calculated from cutting energy model [5], or measured using wattmeter. This information can be summarised in a reference table (see Table 1 as an example).

$$E_{total} = \sum_{i=1}^{n} E_{state_i} = \sum_{i=1}^{n}\sum_{j=1}^{m} E_{state_i,component_j} = \sum_{i=1}^{n}\sum_{j=1}^{m} P_{state_i,component_j} \cdot t_i \quad (7)$$

where t_i – time period of individual operational state, which can be measured or estimated by *MRV*/*MRR* (s).

Three modelling tools are used in developing a hybrid energy model.

	ON/Cutting (W)	OFF (W)	HOLD/Traverse (W)
Spindle power	$33-0.02\times n+0.4\times V_f+16\times a_p-0.56\times V_c-0.03\times MRR-2\times D-0.0002\times n\times V_f-0.1\times n\times a_p+0.0005\times n\times V_c+0.00005\times n\times MRR-0.2\times V_f\times a_p+0.00004\times V_f\times V_c+0.0002\times V_f\times MRR+5.2\times a_p\times V_c+0.02\times a_p\times MRR-0.002\times V_c\times MRR$	0	$0.015\times n-2$
Motor power	$-11+0.006\times n+0.14\times V_f-42.5\times a_p-0.7\times V_c-0.015\times MRR+2.9\times D-0.00007\times n\times V_f+0.02\times n\times a_p+0.00004\times n\times V_c-0.00001\times n\times MRR+0.02\times V_f\times a_p+0.002\times V_f\times V_c+0.00007\times V_f\times MRR+0.4\times a_p\times V_c+0.008\times a_p\times MRR-0.00006\times V_c\times MRR$	0	11
Controller	39	0	39

Table 1: Reference table for the experimental system, where *n* is spindle speed (rpm) and *D* is the diameter of the cutter in milling and drilling or workpiece in turning (mm).

A. Component-Mode-State matrix (CoMoS)

The matrix is designed to contain the status of component modes related to all the operational states of a machine tool. In the rows, machine tool components are listed, while the columns present the operational states. The element of the matrix is a particular mode of a machine tool component. Numbers can be used to represent the modes, e.g. 0 (OFF), 1 (HOLD) and 2 (ON). In such way, the matrix can be easily interpreted by a machine controller.

B. State transition diagram

State transition diagram is employed to give an abstract description of the behaviour of a machining system. This behaviour is represented in series of machining events that could occur in one or more possible operational states. A machining process is composed of a number of operational states, which are modelled as vertices/states with energy consumption data from the reference table. The transitions between different states are modelled as edges. Each edge can be labelled with time and/or energy required for transition. It is noted that a limitation of this diagram is that you need to define all the possible states of a system.

C. Process chain matrix

This matrix gives an instance of a specific machining process based on the CoMoS matrix and state transition diagram. It chains the sequenced columns of CoMoS matrix to describe a particular machining procedure. This enables energy estimation and comparison of alternative processes by an intelligent controller. Due to the page limits, examples of the designed tools are given together in Section 4.

4 MODELLING PROCEDURE

Based on the modelling procedure outlined below, a hybrid energy model is developed for the Sherline 2010 3-axis milling machine in the Manufacturing System Laboratory, The University of Auckland. The components and sensors of the machine tool are depicted in Figure 2.

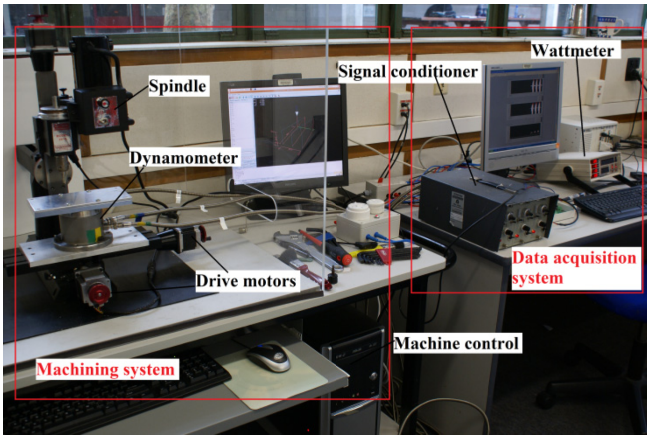

Figure 2: Experiment platform for development of a hybrid energy consumption model.

Step 1: Develop the reference table

For Sherline 2010, spindle, drive motors and machine controller are the main energy consumers. Wattmeter is used to record the actual power value of each component respectively. A series of experiments are conducted to derive the component power consumption models. Identical slots are machined on aluminium blocks using HSS milling cutters. A 4-factor, mix-level Taguchi orthogonal array is designed, considering 3 level of spindle speed, depth of cut and feed-rate and 2 level of cutter diameter. The cutting forces along X and Y axis are measured using Kistler dynamometer to compare actual cutting power and spindle power intake. Detailed experimental data is omitted due to page limit. Using multiple regression method, we derived the second-order empirical models of the spindle and motor power during cutting and the motor power during rapid traverse. The R-square values of the statistic model are approximately 1, and P-values are less than 0.03. A reference table of the prototype machining system is given in Table 1.

Step 2: Construct the CoMoS matrix

There are 5 distinct operational states of this system, i.e. idle, stand by, rapid traverse, processing and off, whose energy behaviour differs from each other. The events that incur power overshoot, such as spindle on (Figure 1), contribute no significant energy share because of its short lasting time. The CoMoS matrix of Sherline machine is presented in Table 2.

Step 3: Draw the state transition diagram of the system

A state transition diagram of the system is given in Figure 3. Four active operational states are considered (exclude non-consuming OFF state) and the machining events that trigger the transitions are represented by arrow lines.

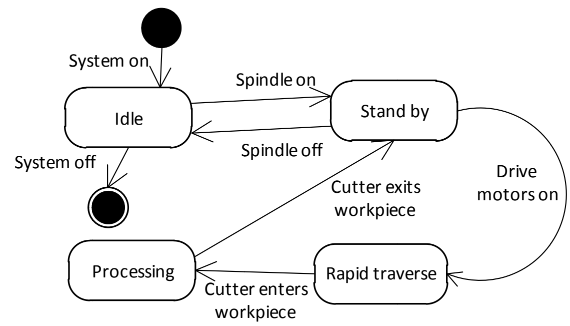

Figure 3: State transition diagram of the Sherline milling system.

Step 4: Generate process chain matrix for a specific process

Now, for a specific machining process, process chain matrix can be generated based on CoMoS and state transition diagram. Table 3 shows the process chain matrix for 3-slot milling process as illustrated in Figure 1.

Therefore, the hybrid energy consumption model of the milling process using Sherline 2010 can be expressed as follows,

$$
\begin{aligned}
E_{total} &= \sum_{i=1}^{n} E_{state_i} = \sum_{i=1}^{n}\sum_{j=1}^{m} P_{state_i,component_j} \cdot t_i = P_{control} \cdot t_{idle} \\
&+ (P_{spindle\_1} + P_{control}) \cdot t_{standby} + (P_{spindle\_1} + P_{motor\_1} \\
&+ P_{control}) \cdot t_{traverse} + (P_{spindle\_2} + P_{motor\_2} + P_{control}) \cdot t_{cutting}
\end{aligned} \quad (8)
$$

The actual energy consumption of the process (the area of the power signal measured by wattmeter in Figure 1) is 0.00339 kWh, while the value of the model-based estimation is 0.00341 kWh. Further, the hybrid model can also be tailored to estimate segmented energy, e.g. spindle energy. In this case, the estimation is 0.00178 kWh compared to 0.00176 kWh measured.

Following the procedure outlines in this section, a hybrid energy consumption model can be obtained for a certain machining system.

	Idle (S1)	Stand by (S2)	Rapid traverse (S3)	Processing (S4)	Off (S5)
Main spindle	0 (OFF)	1	1 (HOLD)	2 (ON)	0
Drive motors	0	0	1	2	0
PC Controller	2	2	2	2	0

Table 2: CoMoS matrix of the Sherline milling machine.

	S5	S1	S2	S3	S4	S3	S4	S3	S4	S1	S5
Spindle	0	0	1	1	2	1	2	1	2	0	0
Motors	0	0	0	1	2	1	2	1	2	0	0
Controller	0	2	2	2	2	2	2	2	2	2	0

Table 3: Process chain matrix for a specific milling process.

5 DISCUSSIONS AND CONCLUSIONS

To perform trustworthy and comprehensive energy efficiency analysis, an energy consumption model for machining systems is in demand. In this paper, a universal hybrid energy consumption model is proposed. It is flexible, scalable and complete, considering not only the major energy consumers, but also the entire machining system. Employment of the universal hybrid model, insights on energy efficiency improvements are provided.

Develop energy-efficient components

As expressed in Eq. 8, spindle is the main energy consumer of a machine tool. It contributes a significant share of the total energy; therefore, contributes much to increasing the energy efficiency. The selection of the spindle can have a significant effect. A spindle drive operating below its rated power leads to energy loss. If the spindle limits the maximum metal removal rate of a process, the process inevitably takes longer. In this case, energy efficiency decreases due to the longer base load consumption. There is a potential for more efficient design of milling processes in the consideration of the efficiency of spindle motors. Potential savings may also be sought from the use of energy-efficient pumps in the coolant/lubricant circuit.

Reduce the base load

The base load of a machine tool means energy consumption required during non-productive phases. It is dictated substantially by auxiliary components such as NC controller or cooling fans. Besides the use of energy efficient components, many possibilities for reducing the base load can be achieved by proper energy management. With energy management, consumers are specifically switched off by the machine control in non-productive phases. Scraps equally consume the base energy and inevitably increase energy consumption per part. Manufacturing with accuracy can therefore become a decisive factor for the energy efficiency of a machine tool.

Deactivate auxiliary components

The hybrid model suggests energy consumption can be significantly reduced by selective deactivation of some auxiliary components, particularly with machining centres for smaller production batches. However, consistent switch-off of auxiliary components (e.g. spindle cooling or compressed air supply) may have the opposite effect. Careful planning of energy saving effects is a fine balance to strike right. Therefore, a smart CNC controller, employs the hybrid energy model, can be used for energy management of a machine tool and its associated peripheries. This is envisaged as a future research direction.

Reduce machine idle time

Reduction of machine idle time, e.g. setup or job waiting, is also suggested by the hybrid model. Because of the relatively high base load of a machine tool, non-cutting time has a critical effect. To reduce the energy consumed per part, non-cutting periods should be kept as small as possible. One feasible way is using reliable sensor for faster setup, e.g. workpiece touch probe. Additionally, an intelligent energy-efficient process planning or production scheduling system is preferred.

The universal hybrid energy consumption model proposed in this paper can be adopted in various applications. Energy-efficient process planning, for example, can use the hybrid model to predict the energy usage of alternative machining plans, and optimise the parameters eventually. Smart machine control is another area that can benefit from the model. Enabled by the modelling tools introduced above, a machine controller can evaluate the energy usage dynamically and automatically during production and take proper actions to save energy. Future work will focus on model-based energy optimisation.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] Dietmair, A. and A. Verl, A generic energy consumption model for decision making and energy efficiency optimisation in manufacturing. International Journal of Sustainable Engineering, 2009. 2(2): p. 123-133.

[2] Anderberg, S. and S. Kara. Energy and cost efficiency in CNC machining. in Proceedings of the 7th CIRP Conference on Sustainable Manufacturing. 2009. Chennai, India.

[3] ISO/DIS, 14955-1, Machine tools -- Environmental evaluation of machine tools -- Part 1: Design methodology for energy-efficient machine tools, 2012, International Organisation for Standardisation (ISO): Geneva, Switzerland.

[4] Anderberg, S., T. Beno, and L. Pejryd. Energy and cost efficiency in CNC machining from a process planning perspective. in Proceedings of the 9th Global Conference on Sustainable Manufacturing. 2011. St Petersburg, Russia.

[5] Munoz, A.A. and P. Sheng, An analytical approach for determining the environmental impact of machining processes. Journal of Materials Processing Tech., 1995. 53(3-4): p. 736-758.

[6] Shao, H., H.L. Wang, and X.M. Zhao, A cutting power model for tool wear monitoring in milling. International Journal of Machine Tools and Manufacture, 2004. 44(14): p. 1503-1509.

[7] Bayoumi, A.E., G. Yücesan, and D.V. Hutton, On the closed form mechanistic modeling of milling: Specific cutting energy, torque, and power. Journal of Materials Engineering and Performance, 1994. 3(1): p. 151-158.

[8] Draganescu, F., M. Gheorghe, and C.V. Doicin, Models of machine tool efficiency and specific consumed energy. Journal of Materials Processing Technology, 2003. 141(1): p. 9-15.

[9] Radhakrishnan, T. and U. Nandan, Milling force prediction using regression and neural networks. Journal of Intelligent Manufacturing, 2005. 16(1): p. 93-102.

[10] Kadirgama, K. and K.A. Abou-El-Hossein, Torque, power and cutting force prediction model by using response surface method and factorial design. European Journal of Scientific Research, 2007. 18(1): p. 20-44.

[11] Aggarwal, A., et al., Optimizing power consumption for CNC turned parts using response surface methodology and Taguchi's technique-A comparative analysis. Journal of Materials Processing Technology, 2008. 200(1-3): p. 373-384.

[12] Gutowski, T., et al., Environmentally benign manufacturing: Observations from Japan, Europe and the United States. Journal of Cleaner Production, 2005. 13(1): p. 1-17.

[13] Peng, T. and X. Xu, Energy-efficient machining systems: a critical review. The International Journal of Advanced Manufacturing Technology, 2012. (submitted).

[14] Dietmair, A. and A. Verl. Energy consumption assessment and optimisation in the design and use phase of machine tools. in 17th CIRP International Conference on Life Cycle Engineering. 2010. Hefei, China.

Ecological Assessment of Coated Cemented Carbide Tools and Their Behavior during Machining

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Abstract

In the last years and even decades the research on ecological evaluation models has grown. Both procedures for entire companies or plants as well as methods for describing single processes have been developed. Therefore the demand for process oriented approaches which can be aggregated into considerations of higher levels is prevailing.

In machining the use of coated cutting tools is widely known and accepted. Up to now the additional expenses for coating the tool with PVD or CVD procedures are evaluated from an economic point of view. Although several approaches have been introduced in order to ecologically evaluate coated cutting tools and their behavior during machining, there is still a demand for further specification.

This paper concentrates on the ecological evaluation of PVD coatings and their respective effect in machining, e.g. longer cutting times or increased material removal rates. The presented procedure provides an intuitive evaluation scheme for determining the advantage of coated cutting tools. Furthermore an approach for assessing the ecological impact of coated cemented carbide tools will be demonstrated and used within the evaluation. In this context the connection to the manufactured product has to be established. This is achieved by attributing the expenses for the coated tools to the number of produced parts, which is changing due to the different tool life regarding the usage of coatings. The presented approaches can be used for ecological and economic evaluation procedures and contribute to ecological process models.

Keywords:

Manufacturing; Coated Cutting Tools; Ecological Evaluation

1 INTRODUCTION

The ecological impact of manufacturing processes increasingly attracts notice as public discussions, governmental purposes and also increasing costs for energy and materials urge industries to make a contribution to a sustainable development. Especially machine tools and their auxiliary equipment have been in the center of interest as they were identified as inefficient by the energy using products directive of the EU [1]. However, besides the improvement of machine tool components, their efficient control and the peripheral units, the processes also offer an effective lever to reduce the ecological impact of a product [2].

In metal cutting, the process parameters determine surface quality, chip formation, tool wear but also energy demand for the machine tool and material removal rate and thus productivity. The efficiency of a cutting process increases with higher process parameters, as the productivity rises more than the energy demand. Therefore the specific energy demand decreases [3]. Increased process parameters make high demands on the cutting tools as they influence the thermomechanical load spectrum. Hence, it is important to take the tool life and the ecological impact of the tool production into account in order to assess the life cycle of products including machining processes correctly.

State-of-the-art carbide tools are made of powder-metallurgically produced cemented carbide. The material consists of a cobalt binder phase with tungsten carbide which provides the wear resistance and hardness of the cutting tool. Complex shaped indexable cutting inserts and shaft mounted tools are subsequently grinded for the desired geometry. A large percentage of indexable inserts does not require shaping processes after the sintering as they are directly pressed and sintered to final geometry. [4] Afterwards the cemented carbide tools can be coated in order to improve certain properties during the cutting application.

The coatings are either applied by a Chemical Vapour Deposition (CVD) or by a Physical Vapour Deposition (PVD) process. Whereas the coating is refined on the tool by a chemical reaction under high temperatures (up to 1100° C) using the CVD-process, the coating is applied physically on the substrate in a PVD-process. Some coatings are applied via CVD (e.g. TiC), others are exclusively generated via PVD (e.g. TiAlN). [4] The main advantages of PVD-coatings are internal compressive stresses in the coating which inhibit crack extension and a broad applicability as a result of low temperatures during the process. A drawback of PVD-coatings compared to CVD-coatings are shadowing effects due to the physical deposition and thus limitations with regard to complex geometries.

The coating of cutting tools adds additional expenses in the manufacturing phase of the tool. On the other hand coatings usually allow to increase cutting parameters or increase the tool life. This is caused by the coating itself which increases the ability to withstand high temperatures and decreases the friction between work piece and cutting material. Also the coating itself, depending on the process it is applied to the tool substrate, inserts residual compressive or tension stresses within the tool. This can increase the ability to resist certain spontaneous loads which are commonly observed in many cutting processes. Depending on the substrate material residual stresses may also lead to shorter tool life times [4].

As there are two opposing trends of coating a tool, it is not clear if the coating leads to a improvement or worsening of the overall ecological impact of a cutting process. The exact consumptions of materials such as titanium, process gases and electrical energy are not quantifiable up to now. Also within the PVD coating processes there are many different factors that may influence the total amount of necessary materials and energies, such as the number and size of work pieces to be coated. Also analogous processes used for coatings other than cutting tools cannot be transferred directly for the application within machining due to specialized solutions for these tools.

2 APPROACH

Within this paper an approach for estimating the ecological advantage of physical-vapour-deposition (PVD) coatings in cutting processes will be presented. Due to the lack of exact and quantifiable data for the cutting tools and their coating process itself, a composition of information gathered from the literature, own experiments and the results of a BMBF (German Ministry of education and research) public funded project (BEAT) have been used for this approach. Since the impact of the coating process caused by direct consumptions such as electrical energy, use of argon and krypton as well as the coating material (e.g. titanium) cannot be determined in detail within this paper, a threshold will be given up to which the coating process is advantageous.

The approach targets the determination of the ecological impact of two cutting tools, one indexable insert with and one without PVD coating. Because of higher cutting parameters such as cutting speed, feed per tooth or depth of cut, which are possible due to the coating, the ecological impact is expected to decrease. The foundation of this assumption relies on reduced cycle times and therefore reduced standby power consumptions of the machine tool. Although this assumption can only be kept up if the machine is shut down directly after production, it represents a good indicator for the productivity. Nevertheless, techniques for putting machine tools in automated standby modes are gaining importance and the given assumption will be applied for the ecological evaluation. Furthermore higher tool life times lead to less impact caused by cutting tools and their manufacturing.

Within the project BEAT indexable inserts as well as high speed steel milling tools have been addressed. In order to determine the impact of these tools, an estimation on the substrate material of cemented carbide tools, a cobalt binder phase with tungsten carbide, as well as the high speed steel for the full milling tools had to be performed. For this task PE International (PE) conducted research how the impact of tungsten carbide and high speed steel can be estimated. In this procedure PE followed typical methodologies which included the estimation of the scarcity of the material, the necessary effort for acquiring usable amounts of the material as well as the required gathering and production processes. In addition, the efforts for metal powder preparation and sintering of the tool substrate material of the carbide inserts were included based on previous works of *Karpuschewski et. al. [5]*. With expertise from the laboratory for machine tools and production engineering (WZL) of RWTH Aachen and PE International the grinding process for achieving the final geometry has been estimated. The grinding process has been measured and the electrical power has been determined. The consumption for grinding of indexable inserts naturally is less significant than the consumption for grinding the final shape of full high speed steel milling tools due to smaller cutting volumes and therefore processing times.

From this expertise a new dataset has been included into the developed software BEA*T*ool [6] and the GaBi 5 database. This dataset supports three different sizes of indexable inserts as well as three high speed steel milling tools, which represent usual sizes which are commonly used in the industrial application. Within this paper the indexable inserts and their usage have been investigated in detail. The final ecological impact per tool, represented by primary energy demand (PED) and the product carbon footprint (global warming potential), as well as the insert sizes are shown in Table 1. The GWP has been calculated by using the CML2001 (upd. 2009) conversion factors.

	Size	PED / MJ	GWP / kg CO_{2e}
Small	*08*	*4,47*	*0,257*
Medium	18	16,16	0,921
Big	25	39,9	2,22

Table 1: Size, primary energy demand and global warming potential of the indexable insert data sets per tool.

As described before, the datasets include the necessary energy for gathering, metal powder preparation and sintering as well as electrical energy for grinding the final shape of the tools.

3 EXPERIMENTAL PROCEDURE

For the experimental procedure the previously mentioned small cemented carbide tools were used PVD-coated as well as uncoated in a step milling process with a four cutting edges tool in ADI 900 (austempered ductile iron) with a width of cut of 8 mm, a depth of cut of 3 mm and a step length of 300 mm. The process parameters were selected according to the recommendations of the tool manufacturers as illustrated in Figure 1.

In order to investigate the isolated effect of coatings, the experiments were conducted without cooling. Furthermore also CVD coated tools have been used. However, these tools were not able to resist the thermomechanical load during the cutting process. A common reason for this fact is the presence of residual stresses in the cutting tool which lead to spontaneous chipping of the tool.

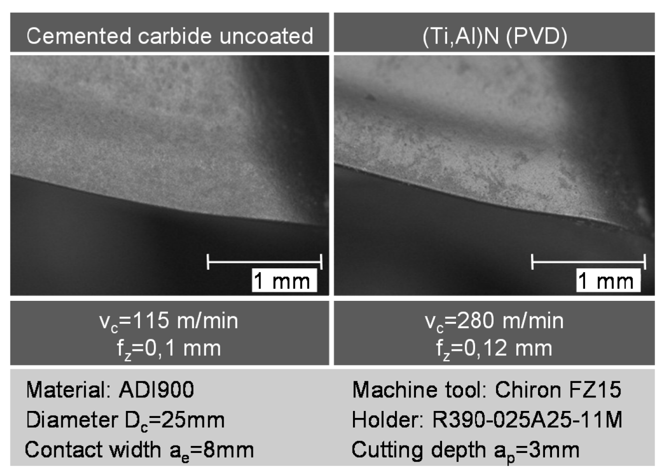

Figure 1: Experimental Setup.

The material ADI 900 with its austenitic-ferritic microstructure and its exceptional strain hardening makes great demands on the cutting tools [8]. The poor machinability of ADI 900 predestines it as a good material for the investigation of the ecological effects of coating, because of the highly expected advantages of the coating in tool life time and process stability.

In order to evaluate the ecological benefit of coated tools, the progress of the flank wear width as well as the consumption of electrical energy was observed and compared. In this investigation the flank wear has been documented from the first usage of a tool to the total tool life.

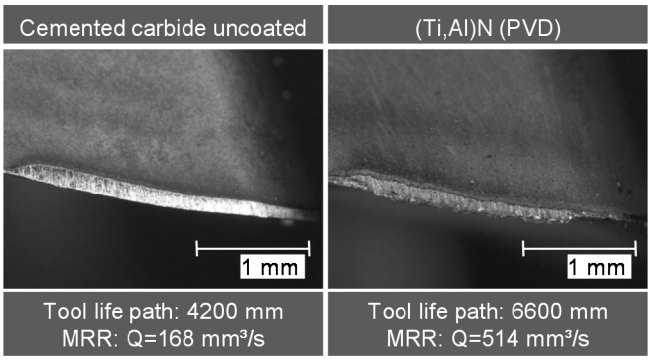

Figure 2: State of the tools at the end of service life.

As it can be seen in Figure 2, both the coated and the uncoated tool reach the end of tool life due to the excess of the tool life criterion of 200 µm flank wear land width. Whereas the uncoated tool was used in 4200 mm feed stroke, the coated tool reached end of tool life after traveling 6600 mm of feed stroke, see Figure 3. This behavior could be observed in three repetitions and is illustrated as mean values of these experiments. Thus, the ecological impacts of the tool manufacturing can be distributed on more parts as more work pieces can be machining with one tool. Furthermore, the coated tool was used with a much higher cutting speed and a higher feed resulting in a higher material removal rate and thus productivity advantages. In this case the maximum feed stroke which can be achieved using one tool to the flank wear width maximum of 200 µm increased by more than 30 % when using coated vs. uncoated tools.

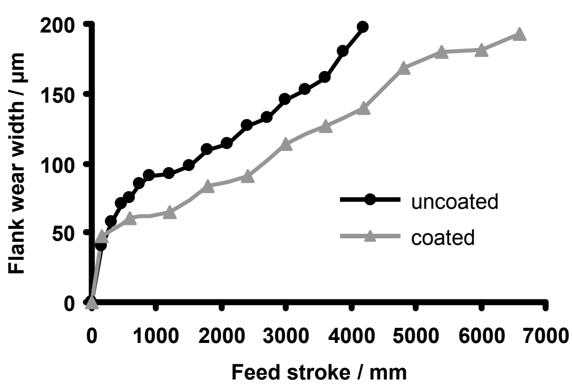

Figure 3: Flank wear width development of coated and uncoated tools.

Besides the effect of the cutting speed on the higher productivity of the cutting process, the cutting speed affects the electrical power consumption of the machine tool. These effects are shown in Figure 4. Whereas the machining time can be reduced to around one third, the level of energy consumption is raised by 18 % by the higher revolution speed and cutting cross section. Previous results indicate that the correct choice of the cutting parameters can influence the energy consumption of cutting processes significantly [3].

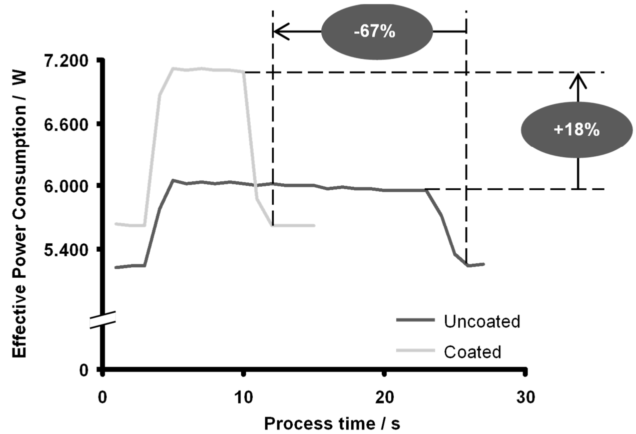

Figure 4: Effects on process time and electrical power consumption.

The use of the coated tool has a multiple positive effect on the ecological evaluation of the cutting process. The following effects can be separately addressed:

- Higher cutting parameters lead to a reduced specific cutting energy, which makes the cutting process more efficient
- Less energy due to machine tool base load is consumed as the primary processing time is reduced
- A higher tool life leads to fewer tool changes and thus a further reduction of energy required due to base load.

Provided that there are no negative effects on the quality and the scrap rate, the only negative effect besides the additional expenses for the coating itself is the increased power consumption during the process. This increase is overcompensated by the reduced cutting process time as will be shown in the ecological process evaluation [3].

The results indicate that the gained advantage in tool life time can either be used for longer tool life and therefore less tool changes or even higher process parameters can be used in order to increase the productivity significantly. The last approach leads to a similar tool life time. Which of the approaches leads to favorable results, has to be determined by the industrial application and the producing company. Whenever the cutting process is a bottleneck in the production chain, higher productivity may lead to essential benefits. Otherwise an extensively high number of tool changes and the corresponding primary energy demand as well as costs for the tools may not be tolerable by the company. For the industrial application, clear calculation recommendations such as the following are necessary.

4 ECOLOGICAL PROCESS EVALUATION

The advantages previously discussed can be ecologically evaluated. Therefore all the consumptions of electrical energy and cutting tools have been calculated and assessed regarding the primary energy demand as well as the global warming potential for a product. For this matter the required cutting process of the sample workpiece as used in the experimental procedure has been chosen (notch geometry: length: 300 mm, width: 8 mm, depth: 3 mm).

For this goal, the non-productive times used for tool changes as well as auxiliary times such as set-up times and work piece changes had to be included into the considerations. This approach is in line with typical cost calculations of the literature [4]. During non-productive times the machine power load P_{Stdby} has been measured for the used machine tool and is assumed to be present during tool changes and other auxiliary times. In this special case the tool change time $t_{ToolChange}$ is estimated to be 120 s due to the four inserts, another 40 s are assumed for the total auxiliary times t_{aux} per part.

The total energy consumption of the process per part has been calculated as follows, consisting of the process energy $E_{process}$ including energy for tool movements E_{jog}, the tool change energy $E_{ToolChange}$, the auxiliary time energy E_{Aux} and the energy necessary for the tools E_{Tools}.

$$E_{total}=E_{process}+E_{ToolChange}+E_{Aux}+E_{Tools}\text{, with}$$

$$E_{process}=P_c \cdot t_c+E_{jog}$$

$$E_{ToolChange}=P_{Stdby} \cdot t_{ToolChange}$$

$$E_{aux}=P_{Stdby} \cdot t_{aux}$$

$$E_{tools}=n_{tools} \cdot E_{tool}=\frac{t_c}{4 \cdot T} \cdot E_{tool}$$

In this case the number of tools per part can be calculated with the tool life time T, the cutting time t_c and the number of indexable inserts per tool (4) as used in the above equations.

Based on these equations the conversion to primary energy has to be performed. For the conversion of electrical energy to primary energy as well as the global warming potential the typical German conversion factor of the Gabi 5 Software has been used in order to assure consistent data [7].

The results of the ecological evaluation are illustrated in Figure 5. The shares of the different energy types of the primary energy for manufacturing one sample work piece are shown. It can be observed that the primary energy demand when using coated tools shifts to the production energy whereas the efforts for tool change and tool manufacturing are decreasing significantly. This can be explained by the longer tool life time and faster production times. It has to be stated that in this case the higher power load during production is overcompensated by the shorter production time (Figure 4).

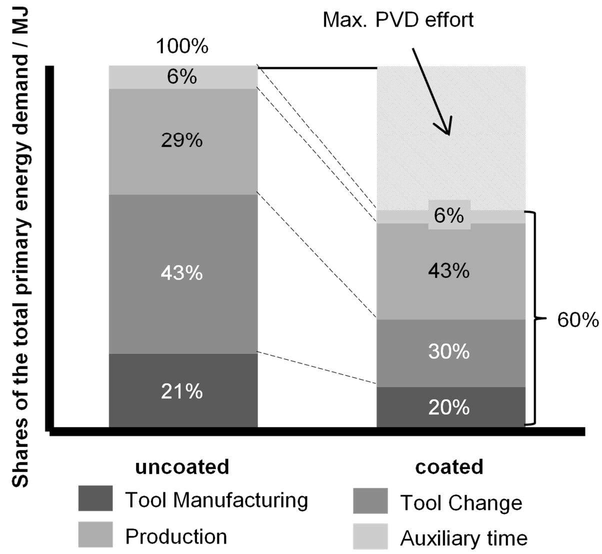

Figure 5: Shares of the total primary energy demand of the coated and uncoated tool application case.

The most interesting result is the total savings regarding the primary energy demand. When using coated cemented carbide tools vs. non-coated tools the total primary energy demand decreases to 60 % per work piece. Therefore the maximum primary energy demand might be invested into the PVD coating of the tools which is about 40 % of the total primary energy demand per work piece. This leads to an amount needed which is almost doubled the tool substrate manufacturing primary energy demand. Again, the manufacturing of a cutting tool used in this experiment consumes 4.47 MJ of primary energy and 0,257 kg of CO_{2e}. Still, the maximum PVD effort as illustrated in the figure above has to be distributed on all the tools used for one work piece.

Typical PVD-sputter coatings consist of titanium which is transported and deposed on the tools. Under a specific environment the intended coatings can be achieved. When taking into account the tool surface as well as the necessary amount of titanium due to the surface thickness, it can be said that the impact of the titanium itself will be significantly lower than the tool substrate itself. This is caused by the significantly lower mass of titanium in comparison to the substrate. Typical coating thicknesses are about 3-8 µm. In the PVD-coating process kryptonite and argon are used to create the needed gas environment. Also heat and a vacuum, usually created by electrical energy, have to be applied in order to achieve the coating. These consumptions and the time needed to apply the PVD-coating have to be assessed in order to estimate the advantage of coated tools.

One very important fact has not been addressed yet. During the PVD coating process many tools can be coated at the same time. Depending on the machine used and the size of the tools themselves, the number of simultaneously processed number can be between several parts as well as thousands of small indexable inserts. It is therefore highly likely that the coating process will not outweigh the process gains for many difficult to cut materials such as ADI 900 in this case.

It has to be stated, that in this special case a difficult to cut material has been the basis of the experiments. There are several applications where the use of coatings may not lead to significantly advantageous results and therefore is environmentally not favorable.

In order to determine the advantageousness of using coated cemented carbide tools, a straightforward approach may be used. The gained productivity needs to exceed the additional necessary primary energy demand of the coating process. The productivity, as shown before, can be derived by the necessary consumptions during production. The savings during the production process reflect the productivity gain. This leads to the following approach based on consumptions per work piece.

$$PED_{tool,coated}-PED_{tool,uncoated}=\Delta PED_{tool}<\Delta PED_{process}=PED_{process,uncoated}-PED_{process,coated}$$

In this equation all efforts as illustrated in Figure 5 except the tool manufacturing are included in the process consumptions (index: process). The tool manufacturing and coating consumptions are subsumed in the tool values (index: tool). Also this approach can either be used for the primary energy demand or the global warming potential, respectively the product carbon footprint. In the presented case all values, except $PED_{tool,coated}$, ΔPED_{tool} respectively can be calculated. Therefore the maximum effort for applying a PVD coating can be estimated.

5 CONCLUSION

In this paper an approach for assessing the advantageousness of PVD coatings has been presented. Based on created datasets for the substrate materials of cemented carbide as well as high speed steel tools the total required amount of primary energy can be determined within the cutting process. This leads to a clear understanding how much effort needs to be included into tools and their application within the machining. Due to higher cutting parameters and subsequently decrease production times, PVD coated tools may lead to the reduction of the total necessary primary energy demand. In the usage phase of the cutting tools higher cutting parameters may also lead to significantly higher power loads which have to be measured against the production time reduction. In the presented case the higher parameters lead to higher power loads that are outweighed by the resulting shorter cutting time.

Nevertheless, the surface quality has to be kept in mind. In finishing processes, where the dilemma between productivity and surface quality is imminent, this methodology needs to be adapted and extended. The presented case experimental results have been performed by using rough milling. Therefore the surface quality is not one of the key performance indicators. Consequently, in the future more and more methodologies for assessing the mentioned dilemma of productivity and environmental impact can be expected.

A clear methodology in line to the common calculation of manufacturing costs has been presented in order to determine the consumptions and ecological impacts during machining. This has to include the consumption of cutting tools as well as electrical energy of the machine tool. Another forthcoming feature will be to include lubricoolant costs for those processes which are performed under the help of this auxiliary material, including the necessary consumptions of additionally pumps and filtrations.

It is of utmost importance to determine the efforts necessary for PVD coatings in order to verify the assumptions made in this paper. Therefore measurements of materials and electrical energy for PVD coating processes have been started in close cooperation with a coating partner and will lead to useful results which will then be published in the future.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] N.N. (2009): Richtlinie 2009/125/EG des europäischen Parlamentes und des Rates zur Schaffung eines Rahmens für die Festlegung von Anforderungen an die umweltgerechte Gestaltung energieverbrauchsrelevanter Produkte

[2] Klocke, F.; Schuh, G.; Döbbeler, B.; Pitsch, M.; Schlosser, R.; Lung, D.; Assmann, D.; Hein, C.; Malek, R.: Simplified Life Cycle Analysis of a Forming Tool in the Automotive Industry. In: Dornfeld, D.; Linke, B. S. (Hrsg.): Leveraging Technology for a Sustainable World. Proceedings of the 19th Cirp Conference on Life Cycle Engineering, University of California at Berkeley, Berkeley, USA, May 23 - 25, 2012: Springer Verlag, 2012, S. 79–84.

[3] Schlosser, R.; Klocke, F.; Lung, D. (2010): Energy and Resource Consumption of Cutting Processes. How Process Parameter Variations can Optimise the Total Process Efficiency. In: CIRP (Hrsg.): 17th CIRP International Conference on Life Cycle Engineering (LCE 2010). 19.05-21.05, Anhui, China, 19.05-21.05.

[4] Klocke, F. (2008): Fertigungsverfahren 1. Drehen, Fräsen, Bohren. (Reihe: VDI-Buch). 8 Aufl. Berlin, Heidelberg: Springer-Verlag

[5] Karpuschewski, B.; Kalhöfer, E.; Joswig, D.; Rief, M. (2011): Energiebedarf bei der Herstellung von Hartmetall-Wendeschneidplatten. In: ZWF. Jg. 106, Nr. 09, S. 602–605.

[6] Klocke, F.; Lung, D.; Döbbeler, B.; Binder, M. (2013): Produktbezogener Carbon Footprint erfordert neue Vorgehensweisen der Bewertung – Von der Technologiekette zum produktspezifischen CO_2-Fußabdruck. In: WT-Online Jahrgang 103 (2013) H. ½

[7] GaBi 4 / GaBi 5: Software und Datenbank zur Ganzheitlichen Bilanzierung. IKP, Universität Stuttgart und PE International AG, Leinfelden-Echterdingen, 1999-2011. www.gabi-software.com.

[8] Klocke, F.; Arft, M.; Lung, D. (2010): Material-related aspects of the machinability of Austempered Ductile Iron. In: Production Engineering – Research and Development 4 (2010), No. 5, p. 433-441.

A Study on an Evaluation Method of Eco-efficiency of a Diamond Coating Process

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Abstract
Since one of the most important goals of sustainable manufacturing is to obtain high eco-efficiency. One of the authors has proposed a new eco-efficiency type index called "total performance indicator (TPI)." In order to evaluate TPI of manufacturing processes, an evaluation method of manufacturing quality is indispensable. Diamond coatings to substrates are important manufacturing processes having wide varieties of applications. The developed coating process can be carried out by using compact and low cost set-up. In the paper, the authors use the new diamond coating process for a case study. Throughout the evaluation of the quality characteristics, costs and environmental impacts of the process, the paper tries to say that the new diamond coating process can be an eco-efficient method.

Keywords:
Eco-efficiency; total performance indicator; diamond coating

1 INTRODUCTION

Since one of the most important goals of sustainable manufacturing is to obtain high quality manufacturing by low environmental impact, eco-efficiency [1] of manufacturing processes can be the key indicator. However, since the cost is also an important factor in industrial processes, one of the authors has proposed an eco-efficiency type index called total performance indicator (TPI). In order to evaluate manufacturing processes by using TPI, an evaluation method of manufacturing quality is indispensable, since the numerator of TPI is value as well as the original eco-efficiency.

Diamond coatings to substrates are important manufacturing processes that have wide varieties of applications. One of the authors has developed a diamond coating process by using combustion flame. The developed coating process can be carried out by using compact and low cost set-up. It means that the environmental impact and the cost of the new process can be relatively low if the calculation considers the environmental impact and the cost of the facility. In the paper, the authors use the new diamond coating process for a case study. Throughout the evaluation of the quality characteristics and environmental impacts of the process, the paper tries to say it will be possible to quantify the eco-efficiency of the new diamond coating process. The result of the case study also suggests that the new process is more eco-efficient than the other coating processes require large facilities.

2 TOTAL PERFORMANCE ANALYSIS

2.1 Definition of Total Performance of Manufacturing Process

In the former research [2], one of the authors proposed an index to evaluate a kind of an eco-efficiency of products and an evaluation procedure using the index. The index was named as Total Performance Indicator (TPI) and the evaluation procedure using the index was named Total Performance Analysis (TPA). In order to evaluate real eco-efficiency of products, product's utility value, cost and environmental impact are considered simultaneously. The proposed index was the simplest combination of environmental and economical efficiencies. The difference of the TPA from normal eco-efficiency is that the method considers not only environmental impact but also economical aspects. TPA can also divide the products to components and can evaluate value creation efficiency of each component separately. Thus, it is possible to suggest which components are the bottlenecks in creating the value of the product efficiently. The next step of the study was to apply the same idea to evaluate the eco-efficiency of manufacturing processes [3, 4]. Since the environmental, economical and quality aspects are the keys in manufacturing processes, the point is how to quantify qualities of manufacturing processes. Usually manufacturing processes are combinations of many segment processes. In addition, there are many ways to combine processes and boundary conditions. Therefore, it is very important to evaluate which manufacturing process is really eco-efficient comparing to alternative options. We define the total performance of the manufacturing process by (1). The equation expresses the balance of the product value created by the process, versus the cost and environmental impact necessary to fabricate the product. Then, (2) shows the simplified TPI of each segment process. The numerator 'Vi' of the equation may vary due to process quality. Manufacturing quality also has a strong relationship between cost and environmental impact of the process. We can quantify how efficient the target manufacturing process is, by calculating (2). After analyzing the manufacturing process and calculating the TPI of each segment process, it is possible to draw a TPI view graph. Segment processes with shallow slopes are suggested to be the primary targets of improvement. The image of analysis of segment processes and improvement are shown in Figure 1.

$$TPI_{process} = \frac{V}{\sum_{i=1}^{i=n} \sqrt{MCE_i \cdot MCC_i}} \qquad (1)$$

$TPI_{process}$: Total performance indicator
MCCi: Cost of *i*th segment process,
n: Number of segment processes
MCEi: Environmental impact of *i*th segment process

$$TPI_{segment} = \frac{V_i}{\sqrt{MCE_i \cdot MCC_i}} \quad (2)$$

$TPI_{segment}$: Total performance indicator of the segment process
Vi: Value of the product added by *i*th segment process

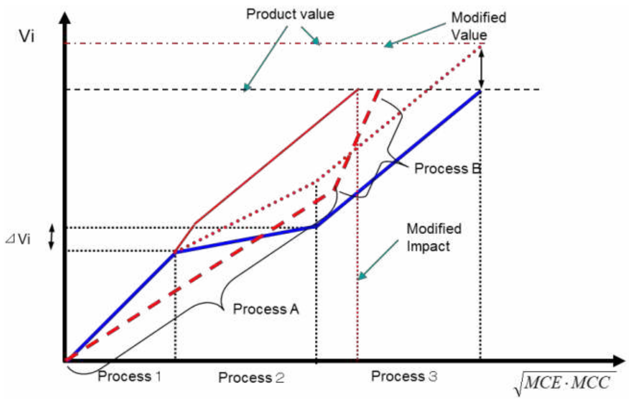

Figure1: Schematic image of segment process evaluation.

2.2 Generalized Procedure of Process TPA

Firstly, a general procedure to evaluate manufacturing processes by TPA should be discussed. The outcome of the manufacturing process is the product. Therefore, sum of values of segment manufacturing processes is equal to the value of the product. Usually, products have several functions. In the method, it is defined that the product value can be allocated values of different functions, based on the relative importance of the functions. Functions with importance are called Functional Requirements (FR) in the method. Applying QFD [5, 6], it is possible to clarify importance of each functional requirement of the product by using discrete score such as 9, 3, 1. Next (3) shows the calculation of the values of functional requirements.

$$V_k = V \cdot (u_k / T) \quad (3)$$

FRV_k: value of kth functional requirement
V: value of the product
U_k: importance of kth FR based of QFD type scoring
T: sum of importance of all functional requirements

The second step of the analysis is to determine the contribution of each quality characteristic to the values of functional requirements. By identifying the relationship between functional requirements and quality characteristics using QFD again, value of each quality characteristic can be calculated by using (4). Table 1 shows the general idea to allocate values of functional requirements to quality characteristics, and (4) shows the general relations between values of FRs with values of quality characteristics

$$QV_k = \sum_{i=1}^{n} V_i \cdot (w_{i,k} / T_i) \quad (4)$$

QV_k: Value of kth quality characteristic
V_i: Value of ith FR
$w_{i,k}$: importance of kth quality characteristic on ith FR
T_i: sum of importance of all the related quality characteristics

		Functional requirements					
		Functional requirement 1	.	Functional requirement i	.	Functional requirement n	Value of quality characteristics (kJPY)
Value of FR (kJPY)		V_1		V_i		V_n	V
Quality characteristics	Quality characteristic 1	w_{11}		w_{i1}		w_{n1}	QV_1
	···	··	·	··	·	··	
	Quality characteristic *k*	w_{1k}		w_{ik}		w_{nk}	QV_k
	···	··	·	··	·	··	
	Quality characteristic *m*	w_{im}	·	w_{im}	·	w_{nm}	QV_m
	Sum	T_1	·	T_i	·	T_n	

Table 1: Calculation of values of quality characteristics.

The third step of the analysis is to know the contribution of each segment process on the value. By identifying the relation between each segment process composing the total manufacturing process and quality characteristics, it is possible to calculate value of segment processes. This calculation is shown in (5). Table 2 shows the value allocation based on (5). Again, the relational strengths between quality characteristics and segment processes will be determined, using the QFD type scoring based on engineers' technological knowledge.

$$PV_j = \sum_{k=1}^{m} QV_k \cdot (x_{j,k} / S_k) \quad (5)$$

PV_j: Value of jth segment process
QV_k: Value of kth quality characteristic
$x_{j,k}$: relation strength between *k*th quality characteristic and *j*th segment process
S_k: sum of importance of related segment processes.

		Value of quality characteristics	Segment process 1	·	Segment process j	·	Segment process l
Quality characteristics	Quality characteristic 1	QV_1	x_{11}	·	x_{j1}	·	x_{l1}
	· · ·	· ·	· ·	·	· ·	·	· ·
	Quality characteristic k	QV_k	x_{k1}	·	x_{jk}	·	x_{lk}
	· · ·	· ·	· ·	·	· ·	·	· ·
	Quality characteristic m	QV_m	X_{1m}	·	x_{jm}	·	x_{lm}
	Value of the segment process (kJPY)		PV_1	·	PV_j	·	PV_l

Table 2: Value allocation to segment processes.

2.3 Eco-efficiency of Manufacturing Processes

Through the procedure mentioned in the former section, values of quality characteristics are calculated in the second step of the analysis and values of segment processes are calculated in the third step of the analysis. Using these data, eco-efficiency of each segment process can be defined. Usually, eco-efficiencies of products or industrial sections are defined as (6).On the other hand, our eco-efficiency type index; TPI of segment processes can be defined by (7).

$$Eco - efficency = \frac{Added\ Value}{Environmen tal\ impact} \quad (6)$$

$$TPIp_j = \frac{PV_j}{\sqrt{E_j \times C_j}} \quad (7)$$

$TPIp_j$: total performance indicator of the *j*th segment process

E_j: environmental impact of *j*th process

However, environmental impacts of manufacturing processes should not be considered separately, since environmental impacts caused by productions of manufacturing set-ups may occupy large parts of total environmental impacts. It is usual that improvements of manufacturing processes are realized along with improvements in manufacturing set-ups. In the analysis, environmental impacts of segment processes are evaluated through (8) taking environmental impacts of productions of manufacturing set-ups into account. In the equation, first 3 terms are those which can be considered as life cycle inventories in normal LCA procedures. The last term is what we are proposing in our method. As well as the environmental impact, costs of the process should be considered including all the costs caused by the manufacturing process. (9) shows the calculation of the cost term of TPI.

$$E_j = (Ee_j + Ec_j + Ew_j) + Ep \times \frac{tp_j}{T \times L} \quad (8)$$

Ee_j: environmental impact caused by energy consumption

Ec_j: environmental impact caused by consumables

Ew_j: environmental impact caused by waste treatment

Ep: environmental impact caused by the production of the total manufacturing set-up

tp_j: process time of *j*th process (hour)

T: total hour of operation per year (hour)

L: average lifetime of the production line (year)

$$C_j = (Ce_j + Cc_j + Cw_j) + Cp \times \frac{tp_j}{T \times L} \quad (9)$$

Ce_j: cost of energy consumption

Cc_j: cost of consumables

Cw_j: cost of waste treatment

Cp: cost of the total production line

2.4 Quantification of Process Improvement

In evaluating manufacturing processes with eco-efficiency, absolute values of eco-efficiency have no significant meaning. Since usually, manufacturing processes are intermediate steps of production, value of the segment process may change due to business-to-business relations. Much more important thing is whether the process improvement has been carried out and whether the efficiency of manufacturing process has been enhanced. As it was mentioned in the beginning, the purpose of the procedure to evaluate quality characteristics is to find the target of improvement. Once the process is improved, it is also necessary to quantify the improvement and compare conventional processes with improved processes. Equation shown below expresses how the process improvement can be quantified. Plus, (11) shows the quantification of the improvement of the segment process.

$$QV_k' = QV_k \times \frac{P_k'}{P_k} \quad (10)$$

QV_k': Value of improved *k*th quality characteristic

P_k: original performance index of *k*th quality characteristic

P_k': performance index of improved *k*th quality characteristic

$$PV_j' = \sum_{k=1}^{m} QV_k \cdot (x_{j,k} / S_k) \cdot \frac{P_k'}{P_k} \quad (11)$$

PV_j': value of improved *j*th segment process

3 CASE STUDY

3.1 Diamond Coating Using Combustion Flame

Diamond is a material which has distinguished material properties such as high durability, hardness, etc. It has become more and more popular and industrially significant to use diamond as an engineering material. Recently, it is said that diamond coating [7, 8] to some cutting tool materials such as tungsten carbide may improve performances of cutting tools greatly. However, problems of current processes for diamond coating are slow process speed and necessity of large manufacturing set-ups. As an alternative process of diamond coating, one of the authors has proposed a new process using combustion flame [9, 10]. Diamond films are synthesized by combustion flame using commercial acetylene-oxygen mixture gas. Figure 2 is the schematic view of the experimental set-up of the new diamond coating method. The proposed method has various advantages over other methods, such as high synthesis speed, safety, stability, low cost of equipment and no electricity usage. These advantages may reduce the environmental impact of the manufacturing process greatly.

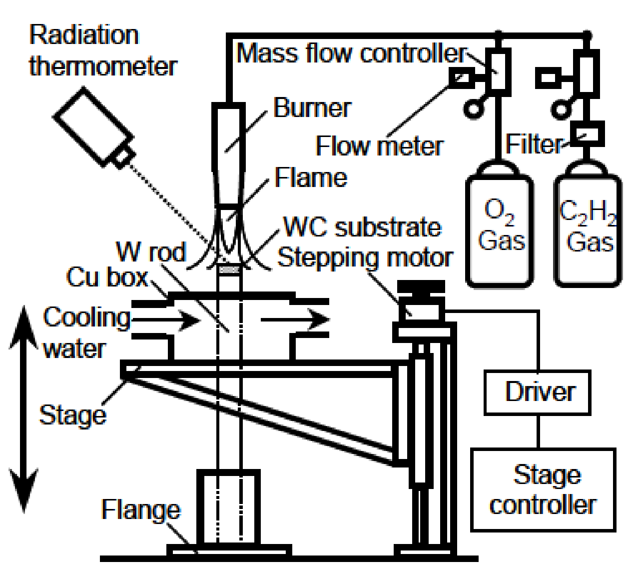

Figure 2: Experimental set-up for synthesizing diamond by combustion flame.

3.2 Inventories of the New Diamond Coating Process

To calculate the environmental impact of the manufacturing process, functional unit should be defined first. Plus, input and output inventories of the process should be also listed. Since in this experimental process, diamond is synthesized on 10mm diameter substrate shown in Figure 3, the area of the diamond film is 314mm^2. Thus, unit area of synthesized diamond can be defined as the functional unit and the total inventories should be divided by 314.

Functional unit: 1mm^2 of the synthesized diamond film

Input:

C_2H_2 gas: 70.9*10^{3}mm^3/s

O_2 gas: 63.8*10^{3}mm ^{3}/s

Etching liquid: $K_2[Fe(CN)_6]$ 0.01kg, KOH 0.01kg, water 100ml

Chemical treatment liquid: H_2SO_4(96%) 3ml, H_2O_2(30%) 88ml

WC substrate: 10mm diameter, 3mm thickness

Cooling water: unknown

Output

Coated WC substrate: 10mm diameter, 3mm thickness

Waste liquid: about 200ml

Combusted gas (CO_2): 140*10^{3}mm^3/s

Warmed water: unknown

Process time: 60 minutes (combustion time, 40 minutes)

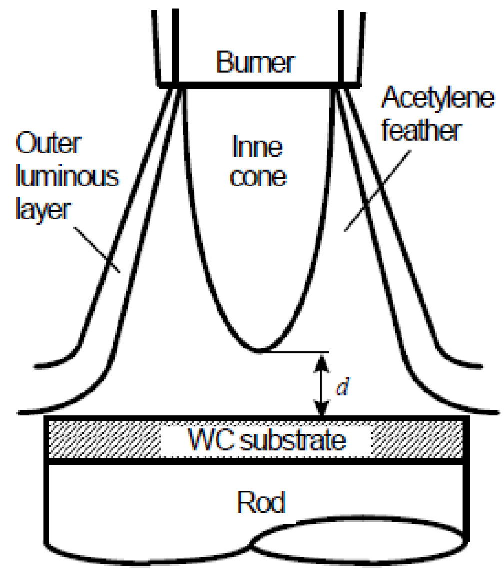

Figure 3: Outline of the flame combustion.

3.3 Rough Estimation of Environmental Impact

Based on existing surveys or databases, a rough estimation of environmental impact of the above-mentioned process was carried out. Table 3 and 4 indicate the CO_2 emission data of major inventories. The other environmental impact such as environmental impact caused by production of manufacturing set-up, can be neglected in this method. Environmental impact of electricity usage and other consumables are also negligible. Table 6 shows the cost of energy, consumable, waste treatment and manufacturing set-up. In calculating the environmental impact and cost of manufacturing set-up, we assumed that the set-up can be operated 1600 hours per year and can be used 5 years. Totally, to make 1mm^2 of diamond film, environmental impact is about 0.0044kg-CO_2eq and the cost is about 5 JPY.

C_2H_2 gas	Chemicals
0.00217	0.00005

Table 3: Input inventories (kg-CO2/mm^2).

Liquid waste treatment	CO_2
0.00005	0.0021

Table 4: output inventories (kg-CO2/mm^2).

Cost of energy consumption	Cost of consumables	Cost of waste treatment	Cost of manufacturing set-up
0	4	0.3	0.4

Table 5: Cost of the process(JPY/mm^2).

3.4 Quality Characteristics of Diamond Coating

Basically, purpose of coating diamond crystalline on the surface substrate is to make the surface more durable. Thus the functional requirements of the diamond coating process can be expressed as Table 6. By normalizing the total value as 1, value of each functional requirement can be calculated. On the other hand, the existing studies [9, 10] indicate that quality characteristics of diamond coating except area are "thickness of the film," "grain size of the crystal," "delamination strength." So, these characteristics are defined as quality characteristics and the values of the characteristics can be calculated using QFD like scoring shown in Table 2. The allocation of values of the functional requirements to values of quality characteristics is shown in Table 7.

Functional requirements	Relative importance	Value
Durable	3	0.25
Good cutting performance	9	0.75

Table 6: Functional requirements of the diamond coating.

Functional requirement		Quality characteristics		
	Value	Thickness of the film	Grain size	Delamination strength
Durable	0.25	9	3	9
Good cutting performance	0.75	1	9	3
Value of quality characteristics		0.2	0.5	0.3

Table 7: Allocation of value to quality characteristics.

3.5 Estimation of Environmental Impacts and Costs

As we mentioned in the former section, this method is only significant, when a conventional process and improved manufacturing process are compared by TPI. Thus, a rough estimation of TPI of usual diamond coating process was carried out. Usually, diamond coating is done by Chemical Vapor Deposition (CVD). The method requires large manufacturing set-up, since it is necessary to vacuum the deposition chambers. Although there are many types CVD machines, Table 8 shows a set of typical specifications. Based on the data shown in the table, environmental impact (Table 9) and cost (Table 10 of the CVD process was estimated. In calculating the environmental impact and cost, we assumed that the thickness of the film is 5 micron. In the table, '-'shows that the factor is negligible. Again, we assumed that the manufacturing set-up can be operated 1600 hours per year, for 5 years.

Power consumption	20kVA
Dimension	1.8m×1m×1m
Weight	1,000kg
Target diameter	100mm
Deposition speed	0.3μm/hour

Table 8: Typical specifications of plasma CVD machine.

Environmental impact caused by energy consumptions	Environment-al impact consumables	Environment-al impact of waste treatment	Environment-al impact of production of manufacturing set-up
0.0325	0.0002	-	0.017

Table 9: Environmental impact of diamond coating using CVD (kg-CO_2/mm^2).

Cost of energy consumptions	Cost of consumables	Environment-al impact of waste treatment	Environment-al impact of production of manufacturing set-up
1.9	-	-	6

Table 10: Cost of diamond coating using CVD (JPY/mm^2).

3.6 TPI Evaluation of the Processes

Using the diamond synthesis method by the combustion flame, almost same grain size and thickness of the film can be obtained. However, this method still has an uncertainty in delamination strength. Thus, as the first step we assume that the delamination strength of the new process is half of the normal process. The other 2 characteristics are the same. Thus, from (10), (11) and Table 9, values of the CVD diamond coating and the combustion flame coating can be calculated as below, correspondingly.

$$PV_{combustion} = 0.85\ ,\ PV_{CVD} = 1.0 \qquad (11)$$

Costs and environmental impacts of the combustion flame method can be calculated by Table 3 to 5. Costs and environmental impact of CVD method can be calculated from Table 8 to 10. Based on these data and (10), TPI of both processes can be calculated using (7). Figure 4 shows the comparison of TPI.

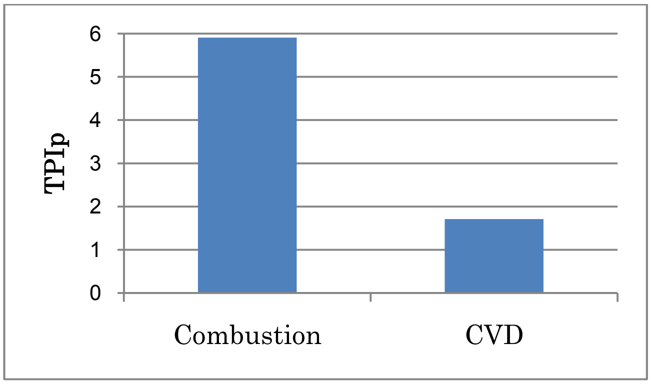

Figure4: Comparison of TPI of both processes.

4 CONCLUSIONS

In this paper, a new method to evaluate eco-efficiency of manufacturing processes was proposed. The method which was named Total Performance Analysis (TPA) was first developed to evaluate efficiencies of products, in the aspect of value creation efficiency and applied to evaluate manufacturing processes for establishing sustainable production. The feature of the evaluation is to take the value of the manufacturing process as the numerator, and square root of the environmental impact and cost as the denominator. The evaluation method was applied to an example which is a manufacturing process of diamond films. One of the authors proposed a new diamond coating method using combustion flame. Since the new method doesn't need a large facility, vacuum pumping, clean room etc., it was expected that the new process is environmentally benign. Results of the case study shows that the proposed manufacturing process by using combustion flame for diamond coating to substrates is much more eco-efficient, since the environmental impact and the cost are both lower than those of usual CVD method. At the same time, the evaluation method; TPA seems to be a useful method in analyzing efficiencies of manufacturing processes.

As for the future work, it is necessary to examine whether the quantification procedure of the values of manufacturing processes based on the values of quality characteristics is reasonable enough. In addition, more precise evaluation of quality characteristics in this or another case study is necessary to insist the effectiveness of the evaluation method.

5 REFERENCES

[1] Association for Electric Home Appliances, (2012): Annual Report of Home Appliances Re-cycle –FY2011, pp.19-21. (In Japanese).

[2] Kondoh S., Masui K., Hattori M.; Mishima N. and Matsumoto M. (2008): Total Performance Analysis of Product Life-cycle Considering the Deterioration and Obsolescence of Product Value: International Journal of Product Development, Vol.6, Nos.3/4, pp334-352.

[3] Kondoh S., Mishima N., Hotta Y., Watari K. and Masui K. (2009): Total Performance Analysis of Manufacturing Processes:, International Journal of Automation Technology, Vol.3 No.1, . pp.56-62.

[4] Kondoh S., Hyuga H., Zhou Y., Mishima N. and Hirao K. (2010): Analysis of Eco-efficiency of Ceramics Manufacturing Processes for Silicon Nitride: Proceedings of 17th CIRP/LCE.

[5] Akao K. (1990): Quality Function Deployment, Productivity Process:, MIT press, Cambrige, M.A.

[6] Kondoh S., Umeda Y. and Togawa Y. (2007): Development of redesign method of production system based on QFD: Journal of Advanced Mechanical Design, Systems, and Manufacturing, Vol. 1, No. 1, pp.181-192.

[7] Polini, R., Allegri, A., Guarino, S., Quandrini, F., Sein, H., and Ahmed, W. (2004): Cutting Force and Wear Evaluation in Peripheral Milling by CVD Diamond Dental Tools: Thin Solid Films, Vols. 469-470, pp.161-166.

[8] Narayan, R. J., et.al. (2006): Microstructural and Biological Properties of Nanocrystalline Diamond Coatings: Diamond and Related Matrials, Vol. 15, Nos. 11-12, pp.1935-1940.

[9] Takahashi M., Kamiya O. and Ohyoshi T. (2005): Synthesis of Diamond Film on Molybdenum Substrate Surface by Combustion Flame Considering the Delamination of the Interface: Transactions of JSME, Series A, Vol.71, No.703, pp.578-583. (In Japanese)

[10] Takahashi M., Kamiya O. and Ohyoshi T. (2011): Step Synthesis Method for Diamond Films on Tungsten Carbide Substrate Surface by Combustion Flame: International Journal of Materials Engineering for Resources, Vol.18, No.1, pp.18-23.

Injection Mould Design: Impact on Energy Efficiency in Manufacturing

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Abstract

The paper presents a systematic approach for energy efficient engineering of injection mould design. It supports engineers with analysing design outcomes for an energy efficient operation of injection moulds, while the approach needs to guarantee the appropriate final products' quality and assure production process performance over several years of usage. An ICT supported systematic approach is presented that enables engineers to monitor manufacturing processes, learn from past designs and elicit knowledge for designing new injection moulds that can be operated with less energy usage. Gained experience and key results are presented that were collected in automotive plastic part production.

Keywords:

Design for Energy Efficient Manufacturing; Manufacturing Systems Energy Monitoring; Knowledge based Injection Mould Design

1 INTRODUCTION

Producers of plastic parts are facing hard global competition. Besides high quality and reasonable costs, environmental impact has become an important factor, which is closely linked with energy consumption. A key element for the life-cycle of plastic parts in the stage of manufacturing is the design of the injection mould. Mould design represents a challenging and costly task seeking to fulfil and match requirements of the product designer and the production site. A huge amount of factors must be taken into consideration for mould design. Some main factors are mould size, number of cavities, cavity layout, runner and gating systems, shrinkage of the material and ejection systems [1].

Industry and specifically the automotive domain are at the forefront of searching for new ways to reduce environmental impact of production processes. Besides the EU proposals for reducing CO_2 emissions, automotive companies are targeting at ECO-Innovations that are opening a wider field beyond engine and powertrain technology. This includes the production of parts for a car [2].

Injection moulding as the most important and most widespread procedure of polymer processing for finished plastic parts [3], can address several challenging demands on competitiveness: Plastic parts are typically lightweight and offer a great freedom of design for the product designer at low cost.

The injection moulding process still offers opportunities for improvement considering energy efficiency. Potential energy savings for sub-systems are within a range of 10% to 80% [4]. Our own work as well as previous other research specifically identify the importance of effective collaborative teams [5] and that good solutions for innovation problems strongly depend upon the designers. Creative designers using powerful design tools will be able to solve technical problems rather fast [6].

As Bogdanski, Spiering et. al. point out, a key enabler to facilitate energy efficiency in production environments is to monitor energy flows and feedback this information addressee oriented [7]. Main motivation of our work was to elaborate a systematic approach that supports the analysis of injection mould design outcomes considering energy efficient mould operation. The key idea was to feedback this information to the mould designers so they can exploit knowledge on cause-effect type relations, especially facilitating to learn from similar problems addressed or solved before.

In this paper we are presenting the underlying idea for energy efficient injection mould design. We will highlight the key factors in mould design which have high impact upon energy demand in production process and describe the related approach for evaluating energy efficiency of moulds in an automotive manufacturing environment.

2 METHODOLOGY

2.1 Energy Consumption in Injection Moulding Processes

Core element of the injection moulding process is the injection mould itself that is operated on the injection moulding machine while requiring a pump and cooling water as well as additional equipment for drying granulate and handling / transportation of produced parts. These appliances consume electrical energy, which is the key energy source in injection moulding. As presented in [8], shares of energy consumption for hydraulic injection moulding systems split up as follows: Mould temperature regulation (36,1%), the machine drive, screw and control (47,2%), the plasticising unit heating (16,7%).

The machine, as the main consumer of energy seems to be the first lever towards a more energy efficient production. In fact, a 30% to 60% cut of energy costs can be achieved by investing in new machinery, changing from old hydraulic to all-electric machines [9]. This measure is regularly taken into account while planning infrastructure investments. This principle is also applicable for the other equipment such as dryers, pumps, etc..

Targeting only at the appliances directly consuming electrical energy, leaves out the injection mould. Our key idea was to analyse the combination of mould, machine, material and auxiliaries. The required energy per part is considered as being quite stable when combining a part specific mould with a specific machine. There are two categories of sub-processes in the injection moulding processes:

- Energy consumption is partially determined by granulate plasticising, closing and opening the machine. Those parameters are directly influenced by the shot weight, part geometry and mould size. These are considered as stable determinants (focus part – machine – combination).
- In contrary, the mould temperature regulation and the plasticising unit heating are mainly characterised by

consuming energy over time. Especially in machine-idle-situations in the injection moulding process. E.g. residual cooling time can be considered as machine idle time.

The definition of residual cooling time is: Minimum theoretical cooling time that is required for solidifying under optimal cooling conditions, due to material and volume, plus additional cooling time, due to inefficiencies of the mould's cooling system minus processes in the injection moulding cycle overlapping cooling time.

The logical assumption was to aim at a reduction of such inefficiencies (i.e. improving the cooling system) for being able to reduce specifically the energy required for temperature regulation and plasticising unit heating (focus mould – machine combination).

2.2 Challenge Addressed

The mould's cooling system is an integral part of the injection mould and determines its cooling efficiency. Cooling channels are usually manufactured by drilling. The holes are joined (intersecting holes or by hoses) or separated by plugs to create a directed flow of cooling liquid inside the mould. It is not easy to make substantial changes to the cooling system once it is manufactured. Therefore, the design of the injection mould is the ideal stage in the life cycle for having an impact on cooling inefficiencies. As also [10] identifies, it is extremely challenging to forecast future energy consumption of a mould precisely at the design stage.

The assessment whether an injection mould's cooling system is optimally designed can't be solely connected to the minimisation of cooling inefficiencies. To determine the degree of optimality of the injection mould's cooling system and its impact on the energy efficiency in manufacturing, key performance indicators (KPI) are needed. The most important KPI in injection moulding is and will be 'cost per part' [11]. It is the main goal of a mould designer to minimize this figure. When energy efficiency is introduced as a new sub-goal, related KPI's might include:

- Energy required for producing a plastic part,
- Overall number of parts to be produced with the mould,
- Wasted energy, due to residual cooling time, per part
- Effort and time required for designing the mould,
- Effort, energy and resources for mould manufacturing,
- Expected life-time of the mould, and
- Effort and energy required for mould change.

The estimated number of parts to be produced with the mould can be considered as key constraint when carrying out a cost benefit analysis. The impact of costs as well as energy related consequences, having in mind an overall optimum, are conflicting with the discrete optimum of a single mould. The mould designer must not forget about the basic constraints with respect to part quality and required productivity.

The research work had to take into account that most injection moulds are designed individually as these are unique or produced in very small number of units. There are general similarities, but due to the complex engineering of cooling systems inside a mould, one cannot easily reuse existing design solutions for similar products. In automotive industry for example, the OEM is accumulating thousands of different CAD-based mould designs for different types, variants as well as prototype parts. It is a challenge to reuse this knowledge. Regarding energy efficiency in injection moulding, only little knowledge is available so far. Peças et al. for example assessed the difference in environmental impact between different manufacturing methods for moulds with low production volumes [12]. For larger production volumes they discovered the environmental impact of the mould manufacturing phase becoming insignificant in comparison to the use stage of the mould [13].

Our work is accompanied by a case study in the automotive industry, where injection moulds are designed, built and used in production for medium to large quantities. Hence, main challenge addressed was to elaborate an approach to capitalise the available engineering knowledge and gather new knowledge about energy flows as well as energy efficiency in the use phase of injection moulds. This is e.g. identification of correlations between design alternatives and their impact on energy efficiency in production. This paper presents feedback from the use phase of moulds that can be exploited for design of new moulds.

2.3 Analysis of Injection Mould Design Impact

For being able to assess an impact on energy efficiency, there is the need to analyse the existing mould design with respect to the required quality, effort, energy and costs. These requirements have to be put in relation to the necessary energy to produce a part. The existing design knowledge base had to be analysed to find out what relevant information could be useful for the mould designers and / or process engineers considering aspects of energy efficiency in production phase. The idea was to set-up a knowledge repository to continuously collect information and provide a possibility for evaluation accordingly. Thiede, Spiering and Kohlitz showed that structuring energy information of injection moulding processes in sub-phases is beneficial to analyse the influence of energy efficiency measures due to the dynamic behaviour of electricity demand [14]. This approach is pursued in this paper. The work was structured in the following main phases:

1. Structure the injection mould design procedure in main tasks,
2. Identify those tasks related to the design of the cooling system which could be improved by providing additional information,
3. Analyse production and maintenance procedures to elaborate an approach for analysis that does not disturb the production,
4. Elaborate a structured data model that combines relevant information in context of the produced parts,
5. Develop a measurement approach and related equipment,
6. Carry out energy measurements for a representative sample of injection moulds,
7. Expert-analysis of measurement data to identify key consequences of design decisions in relation to energy efficiency.

3 ENGINEERING OF INJECTION MOULDS

Analysing the moulding cycle, the following elements are strongly influenced by the mould design:

a) Residual cooling time
b) Mould movement (open, close)

While the time for mould movement depends a lot upon the injection moulding machine and its environment such as robot for taking out parts, minimum residual cooling time is directly linked to the design of the mould and its cooling system. Taking a close look at the cooling system can help improving mould performance a lot. Our studies have shown that residual cooling time is the key factor driven by mould design towards highly productive and energy efficient moulds.

As an example, when building a new two-cavity mould for a housing of a filter, it was possible to reduce cycle time from 58 seconds down to 34.7 seconds only by improving the cooling system of the mould. This was achieved by using regular water cooling and regular drilled holes in the mould steel. Only by means of an optimized mould design the new mould was able to run approximately 1.67 times more quickly compared to the old, slow running mould.

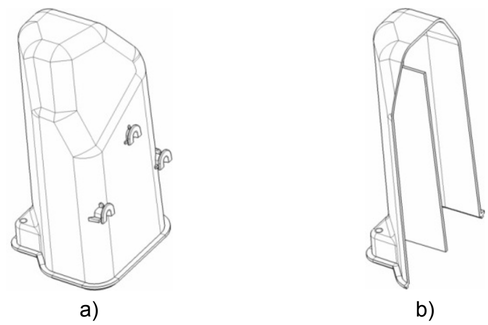

Figure 1: Filter housing made of Polypropylene.
a) Isometric view, outer undercuts.
b) Isometric section cut, inner undercut.

Depending upon the number of parts needed, the designer might consider reducing the number of cavities. This would save investment for the mould and make it possible to use a smaller injection moulding machine.

The amount of cavities in a mould is mainly a cost-driven decision [11], depending upon production volume and mould cost. Furthermore, the mould complexity and injection moulding machines available in the production plant have influence upon the reasonable amount of cavities in a mould. Ideally the total cost of ownership shall be analysed as described in [14]. For the filter housing case study mould, the number of cavities was kept to two.

This example shows that good mould performance does not necessarily mean having to use high-end cooling technology like mould inserts with conformal cooling lines made by laser, using special mould materials or special cooling technology such as CO_2-cooling or similar (all these principles are having reasonable applications, but in many cases it is possible to achieve good solutions with regular technology).

3.1 Limiting Factors During Tool Design

Especially in automotive industry timing schedules are very narrow and the budget for mould and mould design is limited. Despite modern CAD-Systems, mould design is still a bottleneck-activity when manufacturing a new mould.

For big moulds it is common practice to start mould manufacturing long before mould design is fully finished. This creates quite a time pressure for the mould designer, as he has to keep finishing bit by bit of his design in a way that mould manufacturing can continue without disruption. Furthermore, this can limit the design alternatives for the designer to create an optimum mould design, as he is no longer free to change the mould design at a late stage.

FEM-simulation of cooling system layouts is feasible from the technical point of view, but most CAD-systems lack full integration into the FEM software. This requires additional work, which usually needs to be done by an FEM-expert. Furthermore, time for FEM calculation still takes a long time (hours to days). The main issue about FEM is that it does not design a good cooling system; it is only showing the weak points. Depending upon the mould designer's knowledge and creativity, several loops are necessary to get a result close to the optimum. For these reasons, FEM analysis is only used for a small percentage of mould designs.

3.2 Cooling System Design

Many designs of cooling systems are still done experience based due to various limiting factors as described above. Such cooling systems are not necessarily bad, but rarely optimal. Either the mould designer "over-engineers" the cooling systems resulting in high costs for mould manufacturing, or the system is having weak points, which will result in slow mould operation due to long residual cooling time.

Figure 2 shows the importance of correct positioning of the cooling lines (symbolized by a big circle). The small dots (2 x left / right, 1 x centre) symbolize a control point on the mould surface. The centre dot marks the "weak point" of the system. The mould surface at the centre dot will always be warmer compared to the mould surface at the outer dots. This is due to size and position of the cooling lines. As the mould needs to be stable, it is unfortunately not possible to have cooling liquid underneath the whole moulded surface.

Efficient cooling system design is about reducing residual cooling time. It is important to notice that performance of a cooling system is driven by the weakest point. It is not always possible to reduce residual cooling time to zero. Depending upon the type of plastic processed a small residual cooling time may be required in order not to spoil mechanical properties or surface appearance of the moulded part.

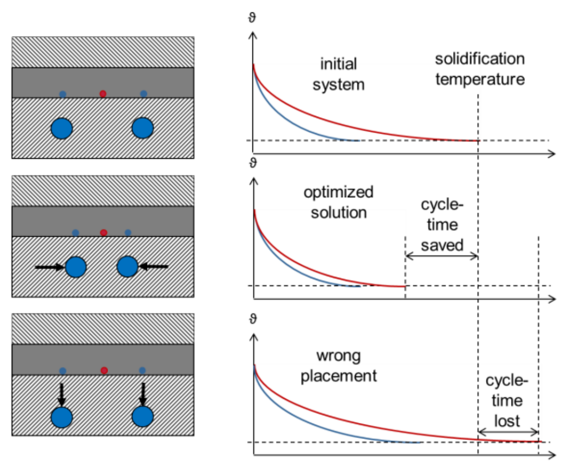

Figure 2: Importance of correct position of the cooling lines.

Designing a cooling system for a 3D-shaped part is a much more complex task. The mould designer does not only have to pay attention to geometric restrictions resulting from the shape of the part, he has furthermore to keep space for functional elements such as plastic injection (e.g. hot-runner system) and elements for demoulding of the part (e.g. ejector pins, sliders, segments). The shape and position of the sliders, segments and ejectors can be designed in different ways. Often sliders and segments need to have a cooling system themselves. This means, the cooling system is influenced by the functional elements and at the same time the cooling system has influence upon their shape.

Figure 3 shows a flow chart of the cooling system design process; this process often requires an iterative approach.

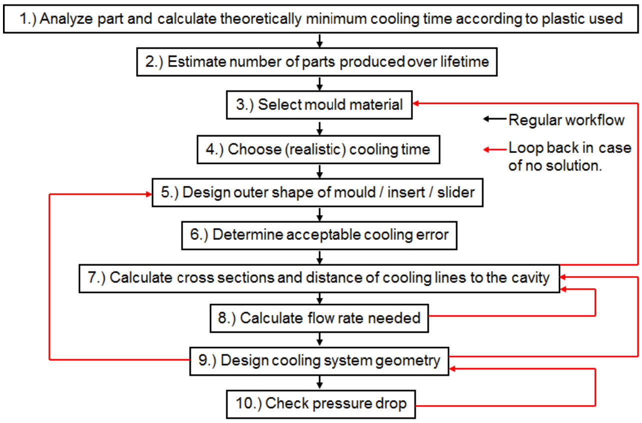

Figure 3: Cooling system design process.

3.3 Rules for Energy Efficient Mould Design

As a rule, improving energy efficiency can be achieved by improving the performance figure "energy used per kg plastic material in injection-moulding process", respectively "energy intensity". This performance figure usually improves (gets smaller) as the amount of material processed is increased. Therefore, multi-cavity tools are more efficient than single cavity tools.

For energy efficient part design it is of course important to minimize part weight before. Cold runners in the mould should be minimized in order to have a good performance figure "energy used per part".

Measurements show, that energy consumption will be reduced if a mould runs more quickly (see chapter 5 for details). This effect is of special interest for design of energy efficient injection moulds, because a reduced cycle time is of highest interest from the economical point of view as well. This helps to justify additional mould design work in order to find better design solutions for crucial characteristics of a mould which are – besides quick movement of the mould – mainly related to the mould's thermal state:

a) Minimize residual cooling time by creating an efficient cooling system for the mould according to Figure 5.

b) Insulate mould (at least clamping plates) if materials are processed which require a mould temperature higher than 50°C.

c) If possible, use inserts for the moulded part. This gives the mould a quicker thermal response due to reduced mass and better thermal insulation. Ramp-up times can be reduced. Sophisticated cooling systems are easier to manufacture when using inserts.

It is important for the mould designer to look at absolute energy consumption and possible savings as described in chapter 5.

In [15], Hein describes an advanced mould design for a small mould, reducing power consumption during ramp up more than 95%. This is great from the technological point of view, but when looking at absolute power reduction (saving 2 kW during ramp-up) it becomes clear that it will be hard to justify the additional design work and costs for such a small saving in absolute numbers.

Doing the right mould design requires the designer to have additional knowledge about the injection moulding process, especially knowledge about the different stages of the cycle, their duration and the related energy consumption in each stage.

4 APPROACH APPLIED

Transparency about energy consumption in concrete injection moulding sub-processes and figures about possible savings are a vital basis for making improvements. In the analysed production of automotive injection moulding products, there was not sufficient data available to quantify potentials regarding possible energy savings for the vast variety of products.

In our case, energy measurements had to be conducted on a large quantity of running processes in a manufacturing environment with very limited resources that can be employed for activities beyond the daily production.

We therefore decided to design a systematic approach to analyse energy efficiency of processes and possible savings which is highly standardized while being adaptable to most kinds of different technologies in injection moulding as presented in Figure 4. The analysis approach described in [7] served as a basis for a new data model here called "energy monitoring setup" and standardized database to be able to constantly increase the knowledge about energy flows in injection moulding processes by measurements in production. To achieve comparability, we decided not to store the measurement results in the database, but instead the even more standardized results of the analysis of the measurements, focussing on KPI's which are valuable for a comparison between processes. The database application is supposed to be used as a tool for fast and easy comparison of different processes by means of KPIs. A detailed analysis of a process is still possible by studying the internally linked detail measurement file raw data and adjacent created analysis files.

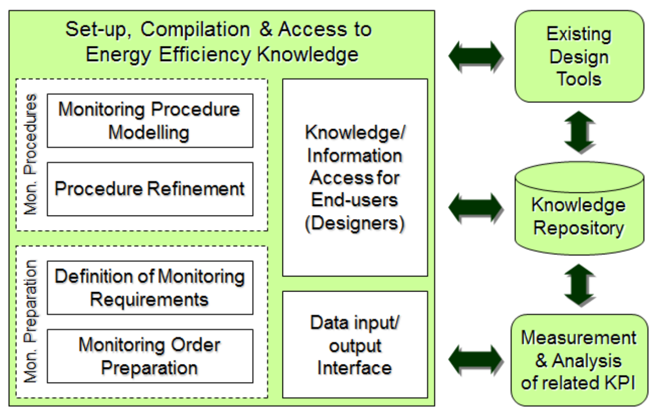

Figure 4: Approach for knowledge acquisition and provision.

Since a single injection moulding process is discontinuous and normally several thousand times equally repeated, we performed temporal measurements. Our data model was designed accordingly, yet adaptable to also be used for continuous measurements which are expected in new machine generations. Our idea is to create a self-enhancing data base which is applicable to a technological and towards year of construction diverse machine park, which was the case for our use case described in chapter 5. Since temporal measurements need to be carefully planned and protocolled, our data model features several functions to ease the task of planning like standardized protocols and algorithms for selecting measurement objects.

In order to minimize disruption of production when measuring, we diverted every procedure which does not necessarily have to be performed directly in production to a later evaluation phase. Doing so significantly increased the acceptance of our activities in production.

5 GAINED EXPERIENCE AND RESULTS MEASURED IN AUTOMOTIVE PRODUCTION

5.1 Considered Use-Case

The developed approach was applied to two large injection moulding facilities, running over 400 moulds in very large quantities for the automotive industry. The portfolio ranges from small (<5g product weight) functional parts to very large (>3,500g product weight) parts for visible areas like bumpers. Consequently, our standardized approach had to be capable to evaluate small machines with only 300kN clamping force up to big machines with 40,000kN clamping force. Furthermore the machines significantly differ in year of manufacture, their technological capabilities and energy efficiency measures. The used moulds were ranging from simple designs with mechanically actuated ejector pins and only 2 cooling channels up to moulds with very complex slide feed ejection combined with an automated removal via robots and cooling via a comprehensive cooling system of up to 48 separate channels.

In this production environment we so far conducted over 120 energy measurements, mainly on machines and devices in production states, but also idle and stand-by states. We focused on measuring all direct energy consumers (machine, tempering and removal devices) at an injection moulding production cell simultaneously and enhanced our measurement results with single measurements of machine components and auxiliaries. With an automated analysis, energy measurement data is combined with available production data like cycle time, times for sub-phases of the cycle and also process parameters like material temperature. For all measurements on active processes the KPIs "energy intensity per part" and "energy consumption in different phases of the production cycle" is obtained consistent statistically validated over several cycles. The number of included cycles for validation was thereby increased in case of significant non cycle based energy consumption behaviour. The analysis results are exported to a standardized file, which can be directly imported to the result database described in chapter 4.

The effect of decreasing the residual cooling time is sketched in Figure 5. During the residual cooling time basically only the tempering device needs to provide fluid to the mould's cooling system. Usually the machine and other auxiliaries are in an idle state to be ready to eject the product as soon as it reaches the ejection temperature. This idle-state can significantly contribute to the entire energy consumption. In three exemplary measurements on hydraulic machines the average power consumption of the idling machine was 50%, 134% and 167% of the consumption of the tempering device during residual cooling time. For measurements on standard hydraulic machines we found out that the power demand during residual cooling time was 49.7% of the average power demand during the entire process. This highlights the potential for energy savings by an enhanced mould cooling design.

From the perspective of a mould designer, larger moulds usually have more cooling channels and incorporate much more complex cooling systems. It seems a feasible approach to firstly look at larger moulds, running on larger machines with a comparatively high average power demand (in our measurements the average power consumption ranges from 5.2 kW for a process with 18g total shot weight to 234.4kW for a process with 5,308g total shot weight). However, for products above 1,300g shot weight we observed that the residual cooling time is not a bottleneck in these processes, as actually no residual cooling time was necessary. The reason for this is that with increasing shot weight the plasticisation period of the material is usually prolonged. Consequently, since cooling and plasticisation are parallel processes, there is no residual cooling time in such cases. Furthermore, with rising shot weight the removal process normally gets more complex. Above 1,300g shot weight, removal processes are almost always assisted by robots. In consequence, longer opening strokes of the mould become necessary; cumulating in longer removal times, which also reduce residual cooling time. The interesting finding is that more comprehensively designed cooling systems for very large parts will probably not result in high energy savings. This is at least true as long as the residual cooling time is not the bottleneck of those processes (it should be noted that still a small reduction in energy consumption might be achieved by increasing quality rates or by decreasing flow resistances in cooling channels and therewith lower energy demand of the tempering device pump).

A contrary approach would be to first look at very small products. The specific energy demand (energy per amount of produced material) of processes for very small products is generally much higher compared to processes with high product weight. This coherence was stated by our measurements as well as in literature [16], [17]. In order to maximize the total energy savings, this approach is not very effective since the absolute energy consumption in those processes is significantly lower. The small amount of material processed per time when producing small parts leads to high values for specific energy consumption on a "per weight basis". Saving residual cooling time in these processes might considerably decrease the specific energy intensity on a "per weight basis", but this will not result in high savings in absolute values.

So our approach is to empirically identify a product class with highest possible savings for our efficiency measure. We therefore assumed a possible reduction of residual cooling time by 20% for all our measured processes, a conservative assumption compared to the example shown in chapter 3. Subsequently, we calculated the total possible energy savings per minute of production time. We therewith could identify those products in our measurement portfolio, which are most suitable for further investigation and group them according to their characteristics. Concerning the efficiency measure "efficient cooling systems" we identified the following characteristics to describe a product class with highest possible savings:

- Medium to high maximum wall thickness, this in general is the main determinant for the total cooling time [18].
- Parts for visible areas or complex functional parts
- Shot weight between 60 g and 1,300 g

Of course, this result must be seen as a starting point for a further detailed analysis. Whether the cooling time and therewith also residual cooling can be reduced is always dependent on a variety of factors, mainly related to material characteristics and visual requirements of the product. Each process therefore still has to be evaluated solely. However, due to the developed instruments and methods, it was possible to focus our activities and optimize efforts to save energy by significantly lowering the number of products to be analysed in detail.

The approach can also be used to investigate the effectiveness of other efficiency measures and furthermore also the interaction between different improvement measures.

New injection moulding machines often feature already implemented energy efficiency measures like for example actively controlled hydraulic drives. In contrast to old machines the energy consumption of the machine during especially residual cooling time and removal processes is significantly reduced, as shown on the lower half of Figure 5.

A reduction of energy consumption per part is achieved by lowering the load curve in the last five phases of a cycle, including a significant reduction of 55% during residual cooling time. For the shown process, total energy savings are higher, if using active hydraulic drives instead of speeding up the cooling process. This result can be outweighed if a better cooling system can additionally increase the quality rate of the process and therewith significantly reduce the use of material and energy consumption in pre-processes.

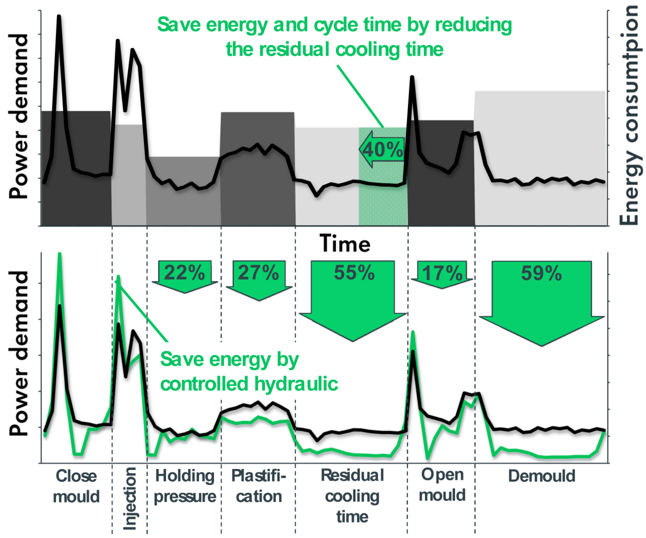

Figure 5: Comparison between the effects of reducing the energy consumption by less residual cooling time in contrast to using controlled hydraulic drives on an exemplary process.

Another important fact however becomes obvious looking at Figure 5. If both measures are applied simultaneously, their effect will not be additive. The total energy savings of both measures are lower in comparison to the sum of savings by each measure solely applied.

With this knowledge we can support production planning to consider energy efficiency and maximize the effect of already applied efficiency measures. As an example, products with long demoulding processes and residual cooling time should be preferably produced on new machines with actively controlled drives. Furthermore, we can focus on enhancing the cooling system of those moulds for products of our identified product class which will be operated on older machines without actively controlled drives.

6 CONCLUSIONS

We described an approach to foster a more energy efficient production of plastic parts. Based on this we focused on how designers of injection moulds can influence the energy efficiency of injection moulding processes and verified the potentials in an extensive case study. In this study we analysed over 120 injection moulding processes in plastic part production plants for automotive industry. We also empirically determined a product class which is most promising to focus on energy savings by an optimization of injection mould design. Furthermore it was pointed out how energy efficiency measures might interact with each other.

Our future work will further extend the process database and detail our optimization strategy by including more efficiency measures in the analysis.

7 ACKNOWLEDGEMENT

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8 REFERENCES

[1] Tang, S.H. et al.; Design and thermal analysis of plastic injection mould. Journal of Materials Processing Technology 171 (2006); pp. 259-267.

[2] Eco-Innovations – More ideas for climate protection; Verband der Automobilindustrie. Website last accessed on 16.09.2012 http://www.vda.de/en/arbeitsgebiete/eco-innovations/

[3] Schwarz, O.; Ebeling, F.; Furth, B; Kunststoffverarbeitung. Würzburg: Vogel Verlag 2009.

[4] Godec, D.; Rujnić-Sokele, M.; Šercer, M. (2012): Energy Efficient Injection Moulding of Polymers, in: Acta Tecnica Corviniensis, Bulletin of Engineering, Tome V, Fascicule Jan.-Mar. 2012, pp. 103-108.

[5] Germani, M.; Mengoni, M.; Collaborative Network for Mould Design. Proceedings of the ICPR 2007, 19th Int. Conference on Production Research. Aug. 2007, Valparaiso, Chile.

[6] Eltzer, T.; Cavalucci, D.; Caillaud, E. (2005): Improvement of mold design: a new method based on contradictions, in: Proceedings of ANTEC 2005, pp. 899-903, Boston, Massachusetts, USA.

[7] Bogdanski, G.; Spiering, T.; Li, W.; Herrmann, C.; Kara, S. (2012): Energy Monitoring in Manufacturing Companies – Generating Energy Awareness through Feedback, in Proceedings of the 19th CIRP LCE , Berkeley, USA.

[8] Wortberg, J., Kamps, T., Schiffers, R.(2003): Welche Energie kostet ein Antrieb, Kunststoffe 03, pp. 64-70.

[9] Tangram Technology Practical worksheets for industry. Energy worksheets1-12; http://www.tangram.co.uk/TI-Energy Worksheets (Plastics) - Tangram.PDF

[10] Weissmann, A.; Ananthanarayanan, A.; Gupta, S. K.; Sriram, R.D. (2010): a systemtatic methodology for accurate design-stage estimation of energy consumption for injection moulded parts, in: Proceedings of the ASME 2010 IDETC/ CIE 2010 Conference, Montreal, Quebec, Canada.

[11] Rees, H.; Catoen, B. (2006): Selecting Injection Molds – Weighing Cost vs. Productivity, Hanser Verlag, Germany.

[12] Peças, P.; Ribeiro, I.; Folgado, R.; Henriques, E. (2009): A Life Cycle Engineering Model for Technology Selection: a Case Study on Plastic Injection Moulds for Low Production Volumes, in: Journal of Cleaner Production, Vol. 17, No. 9, pp. 846-856.

[13] Ribeiro, I.; Peças, P.; Henriques, E. (2008): Environmental Impact of Plastic Injection Moulds, in: Proceedings of the 3rd International Conference PMI2008, Ghent, Belgium.

[14] Thiede, S.; Spiering, T.; Kohlitz, S.; Herrmann, C.; Kara, S. (2012): Dynamic Total Cost of Ownership (TCO) Calculation of Injection Moulding Machines, in Proceedings of the 19th CIRP LCE, Berkeley, USA.

[15] Hein, R. (2010): Energieeffizientes Werkzeugkonzept, Kunststoffe 2/2010, pp. 28-32., Hanser Verlag, München, Germany

[16] Thierez, A.; Gutowski, T. (2006): An environmental analysis of injection molding, Electronics and the Environment, in: 2006 IEEE Symposium on Electronics & Environment, pp. 195-200.

[17] Gehring, A./Stübs, O./Bastian, M. (2010): Der Energieverbrauch auf dem Weg vom Granulat zum Artikel, in: VDI-Wissensforum (Hg.): Spritzgießen 2010 – Fachtagung Spritzgießen 2010, S. 29-40, Düsseldorf.

[18] Menges, G.; Michaeli, W.; Mohren, P. (2007): Spritzgießwerkzeuge, Carl Hanser Verlag, München, Germany.

Simulation of Ultrasonic Cleaning and Experimental Study of the Liquid Level Adjusting Method

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Abstract

In this paper the three-dimensional models of ultrasonic cleaning were established in COMSOL Multiphysics and corresponding cleaning effect under different frequencies and liquid levels were simulated. Then the frequencies suitable for remanufactured components were studied and the cleaning effect under different liquid levels were tested by experiment. The experimental results were processed by Matlab and contrasted with simulation results. It shows that the disadvantages caused by the standing wave can be eliminated by adjusting the liquid level.

Keywords:

Ultrasonic Cleaning; Sound Field Simulation; Liquid Level Adjusting Method

1 INTRODUCTION

As one of the main methods of physical cleaning, Ultrasonic Cleaning is more and more popular in industry owing to the advantages of rapid, satisfactory cleaning and low cost [1-6]. Ultrasonic Cleaning is also free from restrictions to sophisticated shapes and surfaces and easy to realize automation. Any positions that cleaning liquid can reach, there will be the cavitation effect, and there will be the cleaning effect [7]. However, due to lack of theoretical researches and experimental evidences on the cleaning effect, most companies only rely on traditional experience to design cleaning equipments. Thus the low technological content of products and low degree of standardization are resulted from the absence of unified and objective evaluation methods.

At present, some numerical methods such as Computer Flow Dynamic Method, Finite Element Method and Finite-Difference Time-Domain Method are applied to the analysis on ultrasonic field. The two methods, Two-phase Fluid Model Simulation based on Computer Flow Dynamic Method and Two-step Calculation Method based on Finite Element Analysis Method, demand researchers to solve too many linear equations to get obvious sound field distribution. Here we applied COMSOL Multiphysics software to solve partial differential equations based on equivalent integral weak form and quickly get accurate results [8].

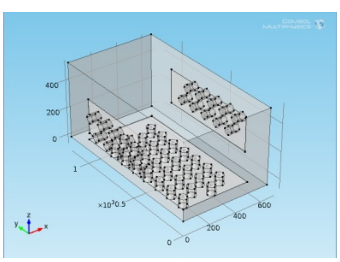


Figure 1: The model of the cleaning vessel.

Currently, almost all parameters are kept the same in practical ultrasonic cleaning process. But the cleaning result is not always satisfactory, because some positions on the surface of workpieces can't get cleaned thoroughly. To solve this problem, the liquid level adjusting method was put forward [9]. To measure the cleaning effect, foil erosion assessments were carried out in this paper, but it is only suitable for qualitative measurements. To solve this problem, we provided a new idea for the quantitative assessment of cleaning effect by post-processing the experimental results.

2 SIMULATION OF ULTRASONIC SOUND FIELD

2.1 Model Definition

The BK-4800B ultrasonic cleaning machine was used in this study. Its dimensions were 1200 mm × 650 mm × 545 mm (depth).

Three vibrating plates made of stainless-steel are implanted. The three-dimensional model in COMSOL is shown in Figure 1. When the power is supplied, the electric energy will be transferred into ultrasonic mechanical energy by ultrasonic transducers [10]. The ultrasonic waves are transmitted in the cleaning vessel, and the vibrating plate, cleaning liquid and ultrasonic are motivated to generate multi-physical coupling effects.

To simulate the interior sound field of the cleaning vessel in two-dimensional condition, internal vibrators are arranged equidistantly. This paper takes ABCDEFGH eight cross-sections successively, and definitions of the eight cross-sections are shown in Figure 2.

Ultrasonic transducers attached to the interior of the vibrating plates use PZT-5H as the fundamental material. The vibrating plates are set to linear elastic body. In sound-solid coupling model, assume using reference pressure to water, temperature is set to 293.15 K. Select attenuation type of linear elastic as the fluid. Total absorption coefficient α for the sound waves in water is 5.684×10^{-7} (Np/cm).

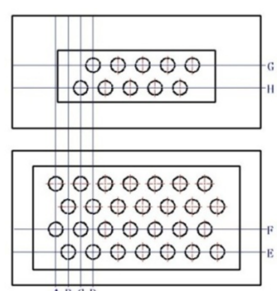
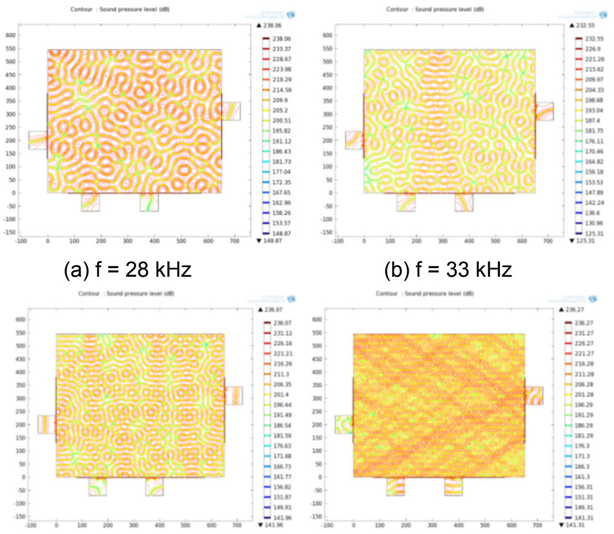


Figure 2: The A~H cross-sections.



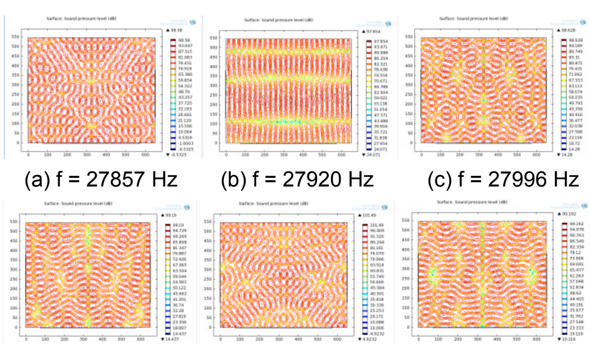
(a) f = 28 kHz (b) f = 33 kHz

(c) f = 40 kHz (d) f = 80 kHz

Figure 3: The photographs of cleaning effect at different frequencies in C cross-section.

2.2 Characteristic Frequency Analysis

Normally ultrasonic frequencies for cleaning are located between 25kHz and 130 kHz. 28 kHz, 33 kHz, 40 kHz, 80 kHz, 100 kHz and 120 kHz are commonly used. This paper calculates sound field distribution on C cross-section when the vessel is set to be full of water and corresponding frequencies are 28 kHz, 33 kHz, 40 kHz and 80 kHz. The frequency domain analysis is selected in acsl module. In sound-solid coupling module, the transducer is replaced by point source. Transducer power is set to 100 W/m. The simulation results of C cross-section are shown in Figure 3.

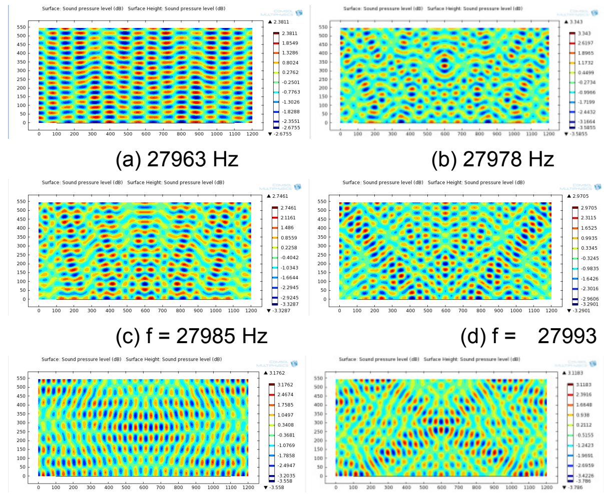


(a) f = 27857 Hz (b) f = 27920 Hz (c) f = 27996 Hz

(d) f = 28075 Hz (e) f = 28078 Hz (f) f = 28085 Hz

Figure 4: Characteristic frequency analysis of C cross-section.

As can be seen through the simulation, the higher the frequency is, the denser the contours distribute. It means that if the cleaning intensity is higher, the parts will get higher degree of cleaning. It can also be seen in Figure 3 that if the frequency is lower, the size of the vesicular outline produced by contour will be larger. The higher the value of the contour edges is, the higher the relative pressure of the cavitation bubble collapse will be. Thus, high frequency can be used for cleaning precision parts. Relatively low frequency can be used for cleaning non-precision, heavy dirt parts.



(a) 27963 Hz (b) 27978 Hz

(c) f = 27985 Hz (d) f = 27993 Hz

(e) f = 28032 Hz (f) f = 28083 Hz

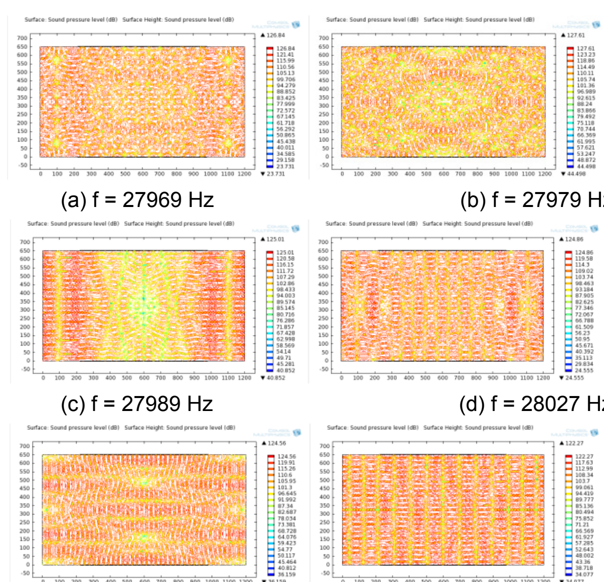
Figure 5: Characteristic frequency analysis of E cross-section.

2.3 The Effects of Characteristic Frequency on the Acoustic Field Distribution

This paper takes 28 kHz as the target frequency and analyzes the characteristic frequency of the cleaning vessel. During the simulation, the number of frequencies to be solved is taken as 6.

For C cross-section, the simulation results of characteristic frequency analysis are shown in Figure 4.

As can be seen in the C cross-section, at different characteristic frequencies, the photographs of sound field are different.



(a) f = 27969 Hz (b) f = 27979 Hz

(c) f = 27989 Hz (d) f = 28027 Hz

(e) f = 28063 Hz (f) f = 28088 Hz

Figure 6: Characteristic frequency analysis of G cross-section.

However, in C cross-section there is an obvious central symmetry along the direction x=325.

For E cross-section, the simulation results of characteristic frequency analysis are shown in Figure 5.

For G cross-section, the simulation results of characteristic frequency analysis are shown in Figure 6.

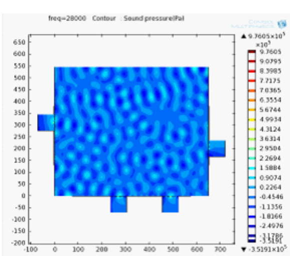
According to the characteristic frequency analysis and combination of the sound field distribution in G cross-sections, it can be derived that: At different frequencies, the sound field is symmetric along y=600. According to the analysis of E cross-sections, due to the coupling effect of the underside of the vibration plate and the side of the vibration plate, the sound field is centrosymmetric along the direction z=255 instead of z direction.

2.4 Simulation of Ultrasonic Sound field with Different Liquid Levels

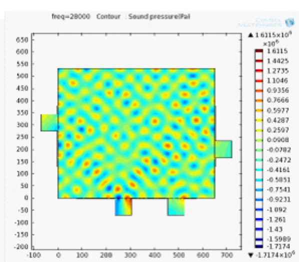
To study the relationship between the cleaning effect and the liquid level, D cross-section was taken as an example. The variations of sound field distribution in X-Z direction under different liquid levels are simulated. From the vessel being full of water, the height of the liquid level being 545 mm, we had the simulations every after lowering the height of the liquid level by λ/4 (λ equals 53.6 mm when the temperature is set to 293.15 K, the frequency of the ultrasonic wave is set to 28 kHz) until the height of the liquid level reached (545-3λ) mm. The typical simulation results of the D cross-section are shown in Figure 7.

From the simulation results, the following conclusions can be referred: The distribution of ultrasonic waves is inhomogeneous in the cleaning vessel. There exists standing wave in the sound field. The ultrasonic intensities are higher in the positions where the ultrasonic waves overlap and lower in the positions where the waves are offset by each other. So adjusting the height of the liquid level can change the sound field distribution and the position of the standing wave.

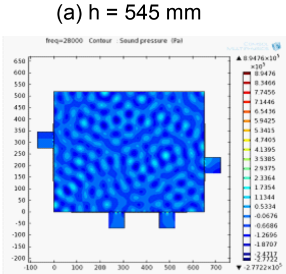
3 THE LIQUID LEVEL ADJUSTING EXPERIMENT IN ULTRA-SONIC CLEANING



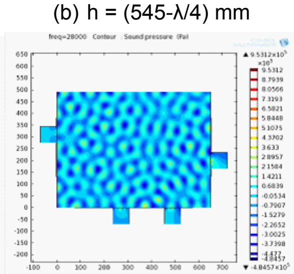
(a) h = 545 mm



(b) h = (545-λ/4) mm



(c) h = (545-λ/2) mm



(d) h = (545–λ) mm

Figure 7: The sound field distribution of D cross-section under different liquid levels.

Figure 8: Cleaning result of D cross-section.

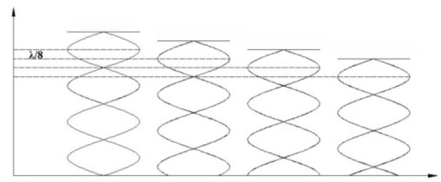


Figure 9: Schematic diagram of liquid level adjusting.

Figure 10: The cleaning result of D cross-section by liquid level adjusting method.

3.1 Experimental Scheme

The foil erosion assessment is based on the erosion effect of the ultrasonic cavitation on the aluminum foil. The 20~30 mm thick aluminum foil was supported by a stainless steel stent and positioned within the cleaning vessel. After being eroded by the ultrasonic for 40 seconds, the aluminum foil was taken out. The ultrasonic intensity can be qualitatively tested by measuring the area lost in the cleaning process. The photograph of the erosion patterns produced by the cleaning vessel is shown in Figure 8.

From Figure 8, standing wave exists in the ultrasonic cleaning process and it causes the inhomogeneous cleaning effect in the cleaning vessel. This phenomenon affects the cleaning result severely. The liquid level adjusting method is adopted to change the positions of the standing wave, and the schematic diagram of the liquid level adjusting method is shown in Figure 9. By changing the cleaning parameters in the cleaning process, we can realize the homogeneous cleaning effect to the workpieces. The following sections are detailed experiment process.

Firstly, when the cleaning vessel was full of water (the height of the liquid level was 545 mm), the aluminum foil was put on the D cross-section and we switched on the cleaning machine. 10 seconds later, the cleaning machine was switched off and we got the aluminum foil numbered D1.

Secondly, the aluminum foil was kept in the same position and the drain valve was opened, the drain valve was closed when the height of the liquid level reached 538.3 mm, switched on the cleaning machine. 10 seconds later, we got the aluminum foil D2.

Thirdly, the process above was repeated and got the aluminum foil numbered D3 (the height of the liquid level was 531.6 mm) and aluminum foil numbered D4 (the height of the liquid level was 524.9 mm).

	1	2	3	4	5
D4-1	1	3	45	43	8
D4-2	0	4	55	36	5

Table 1: Grayscale percentages of D4-1 and D4-2 (%).

The next step we scanned the aluminum foil and cut the image under the height of liquid level 524.9 mm and got image numbered D4-1, which is shown in Figure 10. Last, one piece of aluminum foil was put in the vessel and corroded by the normal cleaning method for 40 seconds. Using the same processing method above, we got image D4-2, which is shown in Figure 8.

3.2 The Analysis of Experimental Results

In this section we adopted the statistical method to measure the sound field distribution of D4-1 and D4-2. After the experiment, we processed the image grayness by Matlab. The principle of the grayscale percentage is that the grayscale is divided into 255 color values. Taking 1~50, 51~100, 100~150, 150~200, 200~255 as 5 grayscale groups. The points falling in each grayscale group were counted respectively. The percentages are given in Table 1. The curves of the percentages are shown in Figure 11.

From Figure 11 we can see, when the workpieces are cleaned without adjusting the liquid level, the percentage of the points falling in the color threshold 100~150 is much higher than the other points. The distribution of sound field is inhomogeneous. By adjusting the liquid level, the percentage of the points falling in the color threshold 100~150 is lower than before but the percentage of the points falling in the color threshold 150~200 is higher. This means that the sound field distribution is improved by the liquid level adjusting method, the ultrasonic energy is redistributed and the cleaning blind zones are eliminated.

4 SUMMARY

- In the process of the sound field simulation, COMSOL Multiphysics can overcome the contradiction between accuracy and the amount of computation. Through modeling and simulation computation, ultrasonic frequency and power of the vibrators can be determined for different cleaning objects. Under higher frequencies, the contours are denser. That means, with higher cleaning intensity, the higher cleanliness the parts will get. If the frequencies are lower, there will be the larger the size of the vesicular outline produced by contour, and there will be higher values of the contour edges, also there will be higher relative intensity caused by the cavitation bubble collapse. So high frequency can be used for cleaning precision parts. Relatively low frequency can be used for cleaning non-precision, heavy pollution parts.
- Because of the reflection and overlapping of the ultrasonic waves in the cleaning vessel, standing wave exists in the cleaning process.
- The standing wave has an influence on the sound field distribution and leads to the inhomogeneous cleaning effect. The positions where the ultrasonic intensities are higher, the cleaning effect is better; the positions where the ultrasonic intensities are lower, the cleaning effect is not satisfactory.
- The sound field distribution in the cleaning process is much homogeneous by adjusting the liquid level. The liquid level adjusting method can weaken the influence of the standing wave and eliminate the cleaning blind zones and finally reach the requirement of thorough cleaning.

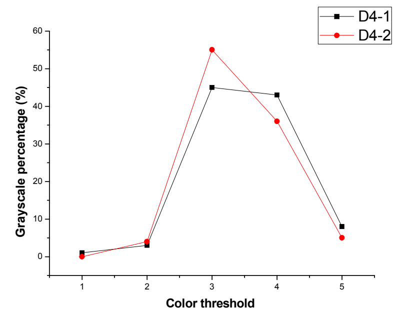


Figure 11: The grayscale percentage curves.

5 ACKNOWLEDGMENTS

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6 REFERENCES

[1] Bao, S. H.; Chen, L. (2004):The Principle and New Development of Ultrasonic Cleaning, in: Journal of Further Education of Shaanxi Normal University, Vol. 21, No. 2, pp. 107-109.

[2] Hu, X. J.; Yang, Y. (2004): Ultrasonic Cleaning, a Technology Focused Attention upon, in: Cleaning Technology, Vol. 2, No. 1, pp. 47-51.

[3] Chen, S. Z. (2004): Ultrasonic Cleaning Technology and It's Development, in: Cleaning Technology, Vol. 2, No. 2, pp. 7-12.

[4] Zhang, M. D. (2002): Specific action of ultrasonic cleaning for replacing ODS cleaning technology, in: Technical Acoustics, Vol. 21, No. 4, pp. 195-199.

[5] Chen, Y. M.; Lei, J. X. (2007): Ultrasonic cleaning technology and design of automatic cleaning line for valve parts, in: Cleaning World, Vol. 23, No. 3, pp. 33-36.

[6] Deng, X. M.; Cui, M. (2000): The Design and Control of the Rinsing System of the Automatic Ultrasonic-Cleaning Line, in: Journal of Wuyi University, Vol. 14, No. 4, pp. 65-68.

[7] Fang, Q. P.; Lin, Z. M. (1998): Megasonic cleaning—a new technology of ultrasonic cleaning, in: Chemical Cleaning, Vol. 14, No. 2, pp. 31-32.

[8] CnTech Co., Ltd. (2009): Design of Post Combustion Furnace Based on COMSOL Multiphysics, in: Aeronautical Manufacturing Technology, No. 11, pp. 93-94.

[9] Kiyak, M.; Altan, M.; Altan, E. Prediction of chip flow angle in orthogonal turning of mild steel by neural network approach, in: The International Journal of Advanced Manufacturing Technology, No. 3, pp. 251-259.

[10] Song, Z. W.; Zhou, D. L. Application of cleaning technology of supersonic wave in mechanical manufacturing Industry, in: Cleaning World, Vol. 22, No. 8, pp. 14-17.

Software Support for Environmentally Benign Mold Making Process and Operations

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Abstract

To face increasing concerns about energy and environmental impact in product manufacturing, effective estimation of the processes' impact is necessary as a way of improvement. In this paper, software support is suggested for the mold making process. We analyzed energy consumption in two major operations in mold making, computer numerically controlled (CNC) milling and electric discharge machining (EDM). Software tools were developed to evaluate possible energy consumption and environmental impact among different process plans. Estimation based on nominal conditions can lead to underestimation due to changing conditions of machining. By the software support, more reliable estimation was achieved with considering various operational parameters and conditions.

Keywords:

Mold Making; CNC Milling; EDM; Energy Consumption; Simulation

1 INTRODUCTION

Molds and dies (molds) are popular mass production tools. With the reversely machined shape of molds, design products can be repetitively produced with high efficiency. For many products including consumer electronics, automobiles, and kitchen tools, molds are main production methods. As design gets more important in market competition, molds of higher precision and quality became a key component in manufacturing design products. As a result, a large market exists in global scale for molds, which are manufactured and consumed with amount of €65B in 2008 [1] and many products are influenced by molds in various aspects of manufacturing technology.

Inflating cost of raw material and increasing concern about environmental impact raised environmental sustainability to one of important criteria for product developers. Resource efficient and environmentally benign manufacturing technology is getting more attention from the product manufacturers. Due to the molds' position in product manufacturing, the environmental impact of mold-making is an important issue both for molds makers and product developers. According to an industrial report, molds are responsible for about 5% of the related products' cost [2]. For a manufacturing method, this is not a small number. On the contrary, this is another fact representing the important position of molds.

Molds are produced by various precision machining processes and actually the biggest buying sector of some precision machine tools: more than 80% of EDM tools are used for molds [3]. Generally, mold making requires various and complex information for processing and many software in industry support molds in various ways, Shape design (CAD), operation planning (CAM), and various analyses (CAE) are supported. Environmental analysis of manufacturing process is also such a complicated work that software support is indispensible for effective measure. However, environmental impact is a new topic for the software developers and their support is not sufficient yet. On the other hand, because molds are manufacturing intensive products, to evaluate the energy consumption and environmental impact of mold making, related process consideration is indispensible.

Life cycle assessment (LCA) is generally accepted as an effective mean to measure environmental impact. However its requirement of the large amount of time, data, and resources are pointed out as a barrier to practical usage [4]. In case of mold making, more emphasis on process analyses is required and various operation conditions need to be considered. While many LCA tools generally use statistic estimation of manufacturing operations, there is a large gap between nominal- and actual process performance in terms of material removal rate and the cycle time. As a result, analysis with existing LCA tools does not provide useful information yet. In this paper, we present a software-based approach to supplement general LCA tools by handling more details of mold making processes on environmental impacts

2 LITERATURE REVIEW

Machine tools consume significant amount of electric power during their use phase, which CECIMO claimed to be the biggest source of environmental impact [5]. Enparantza et al. showed that energy consumption cost takes about 80% of purchase price of a grinding machine according to the life cycle cost (LCC) analysis [6]. Diaz et al. found that about 70% of the total emissions of machine tools result from the use phase [7]. For these, energy consumption analysis attracted many researchers in concern of environmental impact. Munoz et al. analyzed the mechanism of a material removal process and designed an integrated energy consumption model that includes process energy consumption, process rate, and waste-stream flow [8]. Dahmus et al. investigated the energy demand of individual function parts of a machine tool and found that rather than cutting energy, peripheral functions, which include computer, fans and tool change, take considerable part in energy consumption of machine tools [9].

To analyze the energy consumption of machine tools, various manufacturing processes have been analyzed and related models have been suggested. Models for injection molding [10] and casting [11, 12] have been suggested. These models can be applied to the practice with similar statistic analyses thanks to their mass production characteristics. Cutting processes like milling and turning processes also have been analyzed by many researchers. However, these processes are more dynamic in practice and statistic approaches cannot have similar efficacy to mass production technologies, Dietmair et al. introduced a model to predict energy consumption during a machining operation [13].

Software-based simulation tools have also been suggested as an effective ways of estimating energy consumption and resultant green house gas (GHG) emissions. Narita et al. developed an "environmental burden analyzer" with numerical data and showed how each component of CNC machining comprises environmental burden [14]. Heilala et al. focused on the analysis of the environmental impact, automation level and ergonomics of the manufacturing system [15]. They proposed a hybrid method using discrete event simulation and analytic calculation. Shao et al. summarized the procedure of developing virtual simulation tools of machining [16].

3 MOLD MAKING PROCESS

Molds are manufacturing intensive products. According to the research about a progressive die, 37% of its life cycle cost is due to manufacturing and 45% due to maintenance [17]. Because such maintenance is generally carried out by additional machining, it is possible to assume manufacturing activity covers more than 80%. Among various unit processes, CNC milling and EDM play an important role in mold making. According to Peças' work about mold manufacturing time analysis, two processes were found to take almost 80% of total production time as displayed in Figure 1 [18].

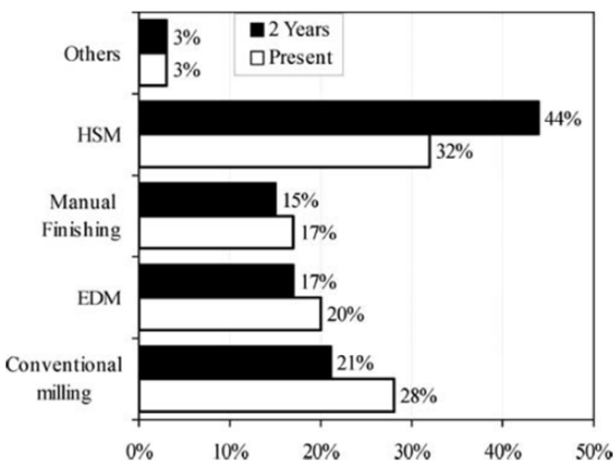

Figure 1: Distribution of production time in mold manufacturing [18].

For its capacity, CNC milling is preferred in machining complex design surfaces with high accuracy. Its computational support for handling huge amount of data makes it possible to address the geometric complexity of fabricated products. Simulation software that utilizes computer graphics and numerical analysis has been successfully used to improve the productivity and quality of milling operations. Early work at Berkeley included Cybercut [19] and this was extended to include basic environmental tradeoffs in follow on work [20].

Electric discharge machining (EDM) is the most popular non-conventional machining technology. EDM removes material from work-piece irrespective of the shape and hardness by the thermal energy caused by the spark between the electrode and work-piece immersed in dielectric fluid. Because there is no physical contact in machining, difficult shapes like a deep slender hole can be fabricated by EDM even with hard material like Titanium alloy. However, MRR for EDM is generally so low that the resultant long cycle time makes the process a bottle neck in process planning. Due to relatively simple motions in EDM, software support for EDM is limited in modelling electrodes and verifying positional error in machining rather than analysis of operation performance.

These two processes are especially popular in manufacturing plastic mold products, where complex design shapes and slender ribs and holes are generally required. While there is the case where the other processes play an important role such as the case of CNC grinding in glossy surface machining, processes with milling and EDM can explain much about mold making process without losing generality. Hence we focused on these two processes in this work.

4 MOLD MAKING EVALUATION

Computer based simulation is generally used in manufacturing processes to manage huge amount of manufacturing information and various computation. From cutting quality confirmation to tool collision detection, many issues are tested and fixed with software tools to avoid the problems before execution. The environmental sustainability and energy efficiency are new issues in conventional manufacturing. The intangibility and complexity of the environmental impact make it hard for engineers to take new criteria in the manufacturing planning. However such difficulty explains why software support is important regarding the issues. Incorporating environmental impact or sustainability concerns into existing simulation coverage is required to improving related manufacturing processes and addressing the increasing demand for sustainable product development.

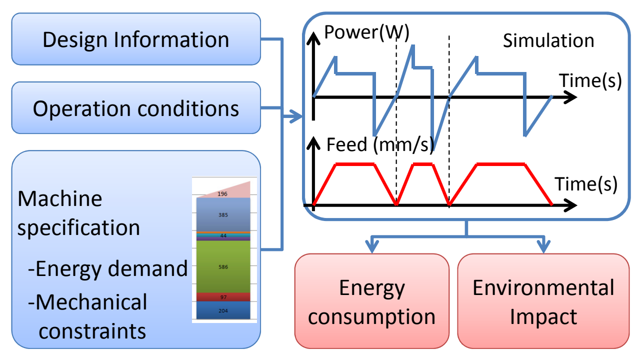

Figure 2: Information flow for process sustainability analysis.

Figure 2 shows the information flow for the process simulation in this work. Design information, operating conditions, and machine tool specifications are three input data and energy consumption and environmental impact are output. Based on the related machine characteristics, different contents and logics will be put to the corresponding data segments: in case of milling, tool paths and the cutting tool geometry would be the part of design information. With this information, the process is simulated and analyzed to estimate resultant energy consumption and environmental impact. Overall impact of mold making process can be evaluated by gathering analyzed results of all the sub-processes.

A software tool was implemented on the basis of Esprit CAM™ and its API. Table 1 shows such information available within Esprit CAM. Because Esprit CAM™ supports the milling process from tool path design to verification, many functions are available for the process analysis. Hence, more integrated analysis can be implemented with the information flow in Figure 2. On the other hand, Esprit CAM™ doesn't support EDM. (This paper handles die-sinking EDM. This is the different type from wire-EDM which is supported by Esprit CAM™.) Considering this, we used the pocket feature for the milling process instead. Because EDM is generally used for machining deep cavities and the pocket feature can provide useful geometric information for the cavities, this can be a good alternative.

	Process information
Milling	cutting tool geometry, feed rate, spindle RPM, width of cut, depth of cut, tool path points
EDM	section area, top/bottom depth, periphery length, volume, draft angle

Table 1: Process information supported by Esprit CAM.

4.1 Evaluation Methods

Among various works, two methods are popular in concern of energy consumption in machine tools. One uses power demand structure of machine tool components. The other uses the process specific energy.

Every component of machine tools has specific functions to serve and various operations are performed by combined work of components. Dahmus investigated the power demand of each functional part of a machine tool and analyzed power demand variation across different operation conditions. He found that most of the total energy is consumed for supportive functions and peripheral devices and claimed that almost 76% of the total energy is constantly wasted regardless of the machining status [9]. Despite some advances in the machine tool design, such inefficiency has not been overcome yet [21].

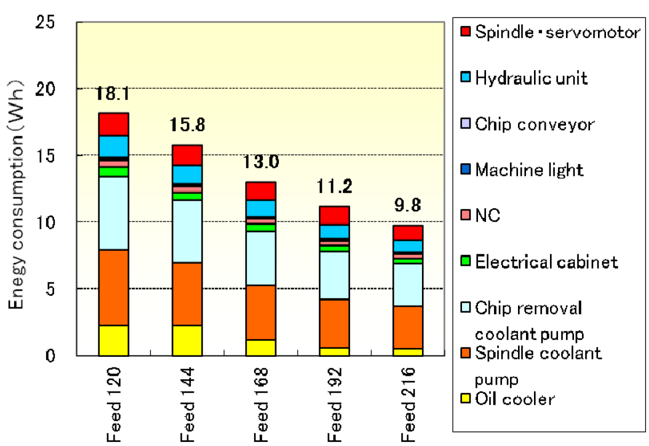

Figure 3: Energy consumption of Moriseiki milling operations [22].

Considering power demand components and operating status of machine tools, it is possible to estimate required power for specific operations as like the example of Figure 3, where different feed speeds affect running time of each component and the resultant energy consumption. Hence, various machine tools were analysed and various relations were identified between operation conditions and components. Generally, three different categories are used for different components: constant (energy consumed by the functions that are not directly related to the machining), run-time (energy consumed for machining functions with fixed value regardless of the varied cutting conditions), and cutting energy portion (energy consumed by the material removal action of a machine tool, which is dependent on the load applied to the machine tool). Based on these works, more efficient machine tool designs and operation strategies were suggested. Because the peripheral devices still accounts for larger portion of the total energy consumption than the material removing behaviour, appropriate information of power demanding structure of machine tools is necessary for energy estimation and analyses of machine tools.

Specific energy is defined as the energy consumed for machining unit volume of material. Different from the power demand components' case, a simple equation shown below is used as reference and the specific energy is calculated with corresponding material removal rate. Coefficients C1 and C2 were empirically defined in many research.

$$E_{spec} = \frac{C_1}{MRR} + C_2 \tag{1}$$

Energy consumption can be estimated with simple multiplication of target removal volume and specific energy for the machine tool. Because this is generally applicable to any process, specific energy is useful in comparison of different operations. However, when the variance of material removal rate is large, reliability of this method is limited. About this limitation, Diaz et al. used sub-divided intervals for changing material removal rate in milling [23]. On the other hand, when the machine is idle or standby status, this method cannot provide relevant information for users because no material is removed in such case. Hence, using another method to cover non-machining time would be more effective in mold making analysis.

Regarding the variety of mold making, we used the power demand structure as a basis for this work and compensate its weakness with additional consideration of the machining process.

4.2 Breakdown of Energy Consumption

Compared to machining devices, operating status of peripheral devices is very simple. Many peripheral devices like lightning have only two different modes of on and off. Hence the variance of power demand in peripheral devices is very small and the demand can be considered as constant.

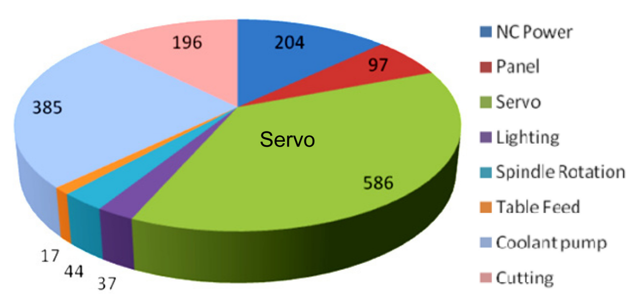

Figure 4: Power demands of Moriseiki NVD1500 [24].

Taniguchi et al. analyzed and broke down the power demand of Moriseiki NVD 1500 CNC machine and the result is displayed in Figure 4. In their work, NC power, panel, servo, and lighting are peripheral devices and others are machining devices. We tested the same kind of machine tool and measured power demand in various milling operations with Yokogawa 240W power meter. Power demand in idle status was measured about 940W, which matches the sum of power demands of peripheral devices in Figure 4. Based on this, it would be possible to handle the power demand of a peripheral device as an inventory data. With this inventory data, energy consumption of the device can be calculated by multiplying the inventory data and the corresponding operation time. In case of machining devices, power demand cannot be treated with one simple value and operation status and load conditions are needed to be considered for estimating energy consumption.

Kellens et al. investigated power demands of EDM in different operation modes as shown in Figure 5. In their work, power demand of the pump ranged from 50 up to 72% of the total power demand and was found to be the biggest portion and the current generation for machining contributes only about 10%. They also compared time shares of three different modes and found that 66% of time is consumed for operation [25]. Agie-Charmilles, a major EDM manufacturer, developed ECO software to improve their products by considering the power demand structure and avoiding non-necessary power waste in idle mode. They claimed that they reduced 90% of electricity consumption. In this paper, we will consider only deep cavity machining with jump and side flushing. This strategy is very popular in small consumer electronics mold making and the difficulty of process planning is well known in this case.

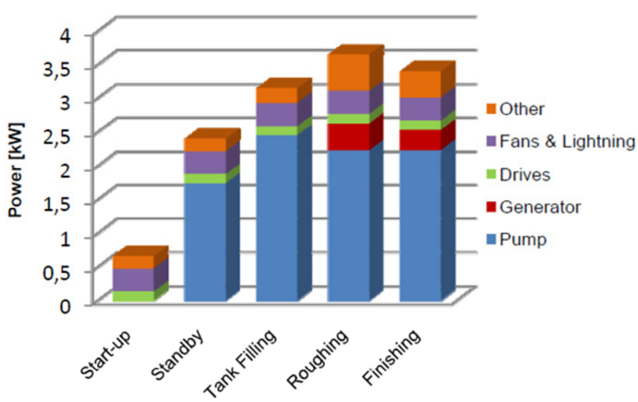

Figure 5: EDM power consumption [25].

4.3 Material Removal Rate (MRR)

Because CNC milling and EDM are both subtractive processes which remove material from a workpiece, MRR represents the capacity and performance. Therefore, MRR plays an important role in the estimation of energy consumption. Generally, as explained in the specific energy method, higher MRR can reduce the cycle time and energy consumption.

MRR in CNC milling is geometrically defined as follows. Because depth of cut and width of cut are defined with tool paths and cutting tool geometry, if feed speed can be controlled and monitored, MRR can be easily calculated with this equation. This assumption is effective in case of simple tool path shape with long segments. However, as will be explained in the next section, actual feed speed is not easy to control.

$$\text{MRR}_{\text{mill}} = \frac{\text{depth}}{\text{of cut}} \times \frac{\text{width}}{\text{of cut}} \times \text{feed}/\text{min} \tag{2}$$

In case of EDM, many different factors influence MRR in EDM: the peak current size, gap voltage, spark gap, material property of work-piece and electrode and dielectric fluid are included in these factors. Hence MRR in EDM cannot be simply defined. While discharge energy, which is defined by the gap voltage, the current size and discharge duration time, is known to be proportional to MRR [26], Okada et al. pointed out that only 10~13% of the energy transferred to work-piece and used for material removal and that more than half of energy is wasted [27]. Hence efficiency factor is needed in MRR definition. On the other hand, the discharged current and voltage in EDM have pulsed waveform. This pulse cycle is comprised of pulse on and pulse off time. Discharge current flows and material is removed only in pulse on time. Considering these two efficiency factors, material removal rate in EDM operation can be described as follows.

$$\text{MRR}_{\text{edm}} = \alpha \times \left(\frac{\text{discharge}}{\text{current}} \times \frac{\text{discharge}}{\text{voltage}} \times \frac{\text{pulse on time}}{\text{total time}} \right) \tag{3}$$

Because melting or evaporation by thermal energy is the main reason for material removal in EDM, the following empirical relationships were established [26]. In this equation, M_w represents melting point of the workpiece material. This equation enables the users to compare EDM performance in different workpiece materials..

$$\text{MRR} = \frac{\text{discharge}}{\text{current}} \times \left(6.64 \times 10^{-7} \times M_W^{-1.23}\right) \tag{4}$$

With nominal feed speed in milling and pulse information in EDM, material removal rate can be evaluated and compared with target removal volume to extract the operation cycle time and related energy consumption.

4.4 Performance Variance

In the general procedure, the cycle time is estimated with the average MRR defined in specific process conditions. The removal volume can be calculated with CAD tools in concern of stock and target geometries. By dividing this volume with the average MRR, the required cycle time of the process can be estimated. This procedure is simple and effective when the average MRR can represent the process performance. However, if this condition is not satisfied, e.g. if the feed speed in milling operation and associated MRR vary too much during machining, this method cannot provide reliable estimation quality.

While the definition of MRR looks simple, CNC milling is a very dynamic process. Many different strategies can be planned for the target shape and the cycle time, surface quality and accuracy can be affected by the strategy. Tool paths are composed of many different lengths of line segments. Due to the mechanical constraints of servo motors, table feed speed to each direction and spindle rotation cannot move ideally. Because feed speed is an important factor of MRR, this limitation is directly related to MRR. Because tool path segment length limits maximum possible feed in milling machine tools [28], distribution of tool path segment lengths make it difficult to estimate the actual feed speed and MRR of the process. Because acceleration and deceleration rates are defined as machine tool constant, the rates are independent of tool path lengths [29]. Hence, when the tool paths are composed of many short length segments, more time is wasted for acceleration or deceleration and low feed movements. This explains why cycle time estimation and energy consumption analysis based on nominal feed speed cannot provide reliable results in complex tool paths.

The cycle time estimation is also a difficult problem in EDM. While material removal capacity is determined by discharge condition, discharge cycle varies and MRR changes. Dielectric fluid contamination is known to be main reason for this change. During the EDM operation, removed material from work-piece or electrodes is accumulated as particles in dielectric fluid. This contamination increases the probability of arc discharge which defects work-piece. To avoid this defect, actual machining rate is decreased. In Figure 6, flushing conditions with different electrode jump height (H_j) were compared with regard to machining rate and it was found that removal performance is dramatically weakened with the contamination density over a threshold [30]. According to this analysis, poorly designed flushing condition decreases actual performance and increases the cycle time much more than designed value.

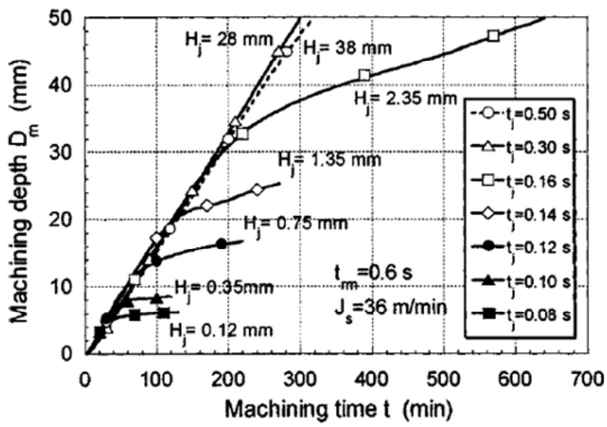

Figure 6: Jump height and depth relation in EDM [30].

4.5 Process Evaluation

Kong et al. explained how different tool path strategies can affect the cycle time and energy consumption [31]. Five different tool path strategies for a rectangular pocket were compared with a software tool. Figure 7 shows the estimated processing time and energy consumption for the milling process. While the same values were used in feed speed, width of cut and depth of cut, the chart shows the difference in each case. The tool path pattern affects the number of segments and distribution in segment lengths. As shown in the graph, in the worst case, different tool path strategies can make 25% difference in the cycle time or 100% in energy consumption for the same pocket milling.

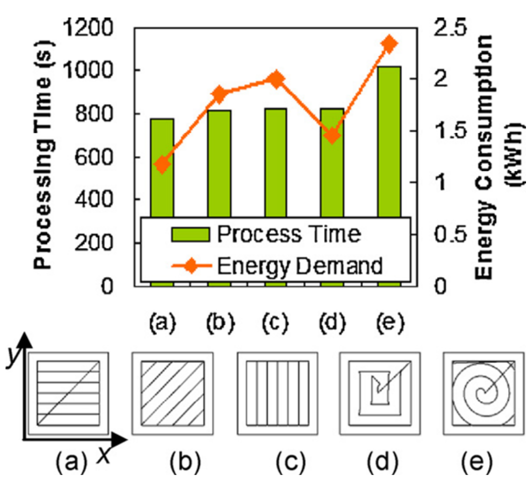

Figure 7: Processing time and energy consumption of various tool-paths [31].

In terms of EDM, two different depths of cavities were compared with different flushing conditions based on Kellens' and Cetin's works. Table 2 shows the estimated cycle time and energy consumption for each case. While other conditions like the peak current size, voltage, and pulse cycle were set to the same condition, different jump heights affect flushing conditions and resultant machining performance of EDM operations. This result shows why appropriate estimation is needed for EDM operations in concern of the cycle time and energy consumption.

Jump Height		0.35	0.75	1.35	2.35
Depth 30mm	Time (min)	-	830	410	180
	Ratio (%)	-	461%	228%	100%
	Energy (kWh)	-	21.1	10.7	4.8
Depth 20mm	Time (min)	1300	360	120	120
	Ratio (%)	1090%	300%	100%	100%
	Energy (kWh)	32.4	9.2	3.1	3.2

Table 2: Inventory of products assessed.

5 CONCLUSION

Estimation method for energy consumption in the mold making process was suggested and implemented with a software tool. For this, two important processes of CNC milling and EDM were analyzed. Most energy is consumed for peripheral devices regardless of machining status and variance of the power demand for the devices is trivial. These characteristics are useful for building life cycle inventory for the process analysis and software tools. On the other hand, variance in machining performance leads to poor process analysis in both cases. Because many different factors affect the performance, software support is necessary in handling the process information and estimating the cycle time and energy consumption effectively. Furthermore, CAD/CAM integrated software tools can be an effective way of adopting energy consumption and environmental sustainability as new manufacturing criteria into mold making practice.

While CNC milling and EDM cover many cases of the mold making process, there are more factors to consider for better estimation. More experimental work is required to support the model. Regarding the popular high speed milling, the analysis of smoothly connected tool paths is required. Due to the tendency of using less number of electrodes, more complex shape of electrodes need to be considered in EDM analysis. Besides, other processes like grinding and utilities like HVAC, lighting and water are also important factors.

6 ACKNOWLEDGEMENT

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7 REFERENCES

[1] Camacho, J. (2010): Worldwide tooling trends and production, in: 13TH International Special Tooling & Machining Association World Conference

[2] BizHospital (2012): Korea mold industry roadmap, from http://www.bizhospital.co.kr

[3] Agie-Charmilles (2006): EDM Applications. Corporate Publications

[4] Lindahl, M. (2006): Engineering designers' experience of design for environment methods and tools - Requirement definitions from an interview study, in: Journal of Cleaner Production, Vol. 14, Issue 5, pp. 487-496.

[5] CECIMO (2009): Concept Description for CECIMO's Self-Regulatory Initiative (SRI) for the Sector Specific Implementation of the Directive 2005/32/EC (EuP Directive)

[6] Enparantza, R., Revilla, O., Azkarate, A., Zendoia, J. (2006): A Life Cycle Cost Calculation and Management System for Machine Tools, in: 13th CIRP International Conference on Life Cycle Engineering, pp. 711-716.

[7] Diaz, N., Helu, M., Jayanathan, S., Chen, Y., Horvath, A., Dornfeld, D. (2010): Environmental Analysis of Milling Machine Tool Use in Various Manufacturing Environments, in: IEEE International Symposium on Sustainable Systems and Technology.

[8] Munoz, A., Sheng, P. (1995): An analytical approach for determining the environmental impact of machining processes, in: Journal of Materials Processing Technology, Vol. 53, Issue 3-4, pp. 736-758.

[9] Dahmus, J. (2007): Applications of Industrial Ecology: Manufacturing, Recycling, and Efficiency, in: PhD Thesis, Dept. Mech. Eng., Massachusetts Institute of Technology, Cambridge, MA.

[10] Thiriez, A., Gotowski, T. (2006): An Environmental Analysis of Injection Molding, in: Proc. of the 2006 IEEE International Symposium on Electronics and the Environment, pp. 195 – 200.

[11] Neto, B., Kroeze, C., Hordijk, L., Costa, C. (2008): Modelling the Environmental Impact of an Aluminium Pressure Die Casting Plant and Options for Control, in: Environmental Modeling & Software, Vol. 23, Issue 2, pp. 147-168.

[12] Dalquist, S., Gutowski, T. (2004): Life Cycle Analysis of Conventional Manufacturing Techniques: Sand Casting, in: Proc. Of the ASME International Mechanical Engineering Congress and RD&D Exposition.

[13] Dietmair, A., Verl, A. (2006): Energy Consumption Modeling and Optimization for Production Machines, in: IEEE International Conference on Sustainable Energy Technology, pp. 574 - 579.

[14] Narita, H., Kawamura, H., Norihisa, T., Chen, L., Fujimoto, H., Hasebe, T. (2005): Development of Prediction System of Environmental Burden for Machine Tool Operation (1st Report), in: Transactions of the Japan Society of Mechanical Engineers. C, Vol. 71, No. 704, pp. 1392-1399.

[15] Heilala, J., Vatanen, S., Tonteri, H., Montonen, J., Lind S., Johansson B., Stahre J. (2008): Simulation-based sustainable manufacturing system design, in: Proc. of the 2008 Winter Simulation Conference, pp. 1922 - 1930.

[16] Shao, G., Kibira, D., Lyons, K. (2010): A Virtual Machining Model For Sustainability Analysis, in: Proc. of the ASME 2010 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference.

[17] Tönshoff, H., Oelschlager, H., Petzold, J. (2001): Life cycle cost orientation in the die and mold making industry, in: Proc. of 2nd international conference and exhibition on design and production of dies and molds, Kusadasi.

[18] Peças, P., Henriques, E. (2009): Intrinsic innovations of die sinking electrical discharge machining technology: estimation of its impact, in: Int. J. of Advanced Manufacturing Technology, Vol. 44, pp.880–889.

[19] Wright, P., Dornfeld, D. (1998): Cybercut; A Networked Machining Service, in: Trans. North American Manufacturing Research Institute, SME, Vol. 26, pp. 281-286.

[20] Dornfeld, D., Wright, P., Wang, F., Sheng, P., Stori, J., Sundarajaran, V., Krishnan, N., Chu, C. (1999): Multi-agent Process Planning for a Networked Machining Service, in: Trans. North American Manufacturing Research Institute, pp. 191-196.

[21] Devoidere, T., Dewulf, W., Deprez, W., Willems, B., Duflou, J. (2007): Improvement Potential for Energy Consumption in Discrete Part Production Machines, in: Proc. of 14th CIRP International Conference on Life Cycle Engineering, pp. 311-316.

[22] Mori, M. (2010): Power consumption reduction of machine tools, in: 2010 CIRP General Assembly

[23] Kara, S., Li, W. (2011): Unit process energy consumption models for material removal processes, in: CIRP Annals - Manufacturing Technology, Vol. 60, pp. 37–40.

[24] Taniguchi, M., Kakinuma, Y., Aoyama, T. Inasaki, I. (2006): Influences of downsized design for machine tools on the environmental impact, in: Proc. of MTTRF 2006 Annual Meeting, pp. 1-4.

[25] Kellens, K., Dewulf, R., Duflou, J. (2011): Preliminary Environmental Assessment of Electrical Discharge Machining, in: Proc. of the 18th CIRP International Conference on Life Cycle Engineering, pp. 377-382.

[26] Yeo, S., Tan, H., New, A. (1998): Assessment of waste streams in electric-discharge machining for environmental impact analysis, in: Proc. of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 212, No. B5, pp. 393-401.

[27] Okada, A., Uno, Y., Okajima, I. (2000): Energy Distrihution in Electrical Discharge Machining with Graphite Electrode, in: Memoirs of the Faculty of Engineering, Okayama University, Vol. 34, No. 1, pp.19-26.

[28] Coelho, R., Souza, A., Roger, A., Rigatti, A., Ribeiro, A. (2010): Mechanistic approach to predict real machining time for milling free-form geometries applying high feed rate, in: Int Journal of Advanced Manufacturing Technology, Vol. 46, pp. 1103–1111.

[29] Suh, S., Kang, S., Chung, D., Stroud, I. (2008): Theory and design of CNC systems, Springer-Verlag, London.

[30] Cetin, S., Okada, A., Uno, Y. (2003): Electrode jump motion in linear motor equipped die-sinking EDM, in: Journal of Manufacturing Science and Engineering, Vol. 125, Issue 4, pp. 809-815.

[31] Kong, D., Choi, S., Yasui, Y., Pavanaskar, S., Dornfeld, D., Wright, P. (2011): Software-based tool path evaluation for environmental sustainability, in: Journal of manufacturing systems, Vol. 30, Issue 4, pp. 241–247.

Exergy Analysis of Atomic Layer Deposition for Al_2O_3 Nano-film Preparation

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Abstract

In this paper exergy analysis is applied on Atomic Layer Deposition (ALD) of Al_2O_3 thin film to analyze the utilization and losses of exergy in ALD system. The exergies associated with material flow, heat flow, and work flow are calculated. Based on the exergy balance equation, exergy loss is calculated for the ALD Al_2O_3 process and then exergy efficiency is calculated with a value of 2.72×10^{-5}. According to the result it can be concluded that the utilization of exergy is extremely low in ALD Al_2O_3 process. This research can be useful for future energy consumption and optimization of ALD system.

Keywords:

Atomic layer deposition; exergy loss; exergy efficiency

1 INTRODUCTION

With the development of nanotechnology, nano-films have been applied in many fields, such as semiconductor industry, computers, cosmetics and medical devices. In recent years Al_2O_3 thin films have been widely used in microelectronic devices as a possible high-k gate dielectric material to replace SiO_2 [1]. The miniaturization of semiconductor industry has placed ever increasing demands on thin film deposition techniques and has led to the requirement for atomic level control of thin film deposition, which drives the continuous development and advancement of the Atomic Layer Deposition (ALD) nanotechnology [2].

ALD is a bottom-up nano-scale manufacturing technology for depositing highly uniform and conformal thin films by alternating exposures of a surface to vapors of two or more chemical reactants [3]. ALD technology is a widely used nanotechnology to deposit nano-films and has been increasingly studied as a typical process to deposit Al_2O_3 thin films.

However, there are still many sustainability issues associated with this nanotechnology. ALD operations are both material- and energy-intensive, and have a large proportion of waste/emissions generated from precursor chemical use and energy consumptions [4]. So, studying and improving energy efficiency of ALD technology is an important problem, which is in need of research.

One of the most useful concepts to describe the utilization efficiency of energy is exergy. The definition of exergy is: the maximum useful work that can be obtained from a system at a given state in a given environment. As a thermodynamic approach exergy analysis is used to analyze and improve the efficiency of chemical and thermal processes and it has been widely applied in order to find the most rational use of energy [5].

Atomic Layer Deposition (ALD) for Al_2O_3 thin film has been chosen as the research object in this paper. Exergy analysis method is applied to analyze the utilization of exergy in ALD system. Based on the exergy balance equation exergy loss is obtained and then exergy efficiency is calculated. Through exergy analysis, energy consumption distribution can be obtained and the processes consuming more energy can be clearly identified. This demonstrates the direction we should focus our efforts to improve ALD system energy efficiency. The research can be treated as a foundation for future optimization research work.

2 METHODS AND RESULTS

This section presents the methods employed in this research for analyzing the exergy efficiency of ALD of Al_2O_3 system. Firstly, the principle of ALD of Al_2O_3 nano-film is provided and then, the ALD reaction system and the process conditions are described. In the following, exergy analysis methods are introduced which include the calculation method for both exergy efficiency and exergy loss. In this section, exergy loss of ALD of Al_2O_3 system is quantitatively determined by calculating the exergies associated with material flow, heat flow, and work flow in the ALD of Al_2O_3 nano-film process. Finally, exergy efficiency of the ALD of Al_2O_3 system is calculated and presented.

2.1 The Principle of ALD of Al_2O_3 Nano-film

In a typical ALD process two gas phase molecules are alternatively exposed to a substrate in an ABAB…sequence. Typical ALD of Al_2O_3 nano-film uses tri-methyl-aluminum $Al(CH_3)_3$ (TMA), as metal source, and water H_2O, as oxidant. Deposition mechanism of Al_2O_3 by ALD is based on the following reaction:

$$2Al(CH_3)_3 + 3H_2O \rightarrow Al_2O_3 + 6CH_4$$

In the ALD process, this reaction is split into the following two half reactions:

$$Al - OH + Al(CH_3)_3 \rightarrow Al - O - Al(CH_3)_2 + CH_4 \quad (1)$$

$$Al - CH_3 + H_2O \rightarrow Al - OH + CH_4 \quad (2)$$

The Al_2O_3 ALD growth occurs during alternating exposures to TMA and H_2O and the thin film growth is very linear with the number of reaction cycles. After each reactant exposure, there is a purging period using N_2 to remove unreacted gases.

2.2 The Reaction Equipment and Conditions

The ALD system studied is a Cambridge NanoTech Savannah 100 system. The reaction conditions and parameters are listed in table 1 below.

Parameters	Values	Units
Diameter of reactor	149.76	mm
Depth of reactor	6.22	mm
Inlet temperature	423	K
Outlet temperature	423	K
Reaction temperature	473	K
Reaction pressure	0.5	Torr
Process pressure (N_2)	0.19	Torr
Flow rate of N_2	20	sccm
Pulsing pressure of TMA	0.23	Torr
Pulsing pressure of H_2O	0.36	Torr
Pulsing time of TMA	0.015	s
Pulsing time of H_2O	0.015	s
Purging time	5	s
Silicon wafer diameter	4	inch
System power	900	W
Pump power	0.45	KW
Reaction time	1	h

Table 1: Equipment sizes and reaction parameters.

2.3 Exergy Analysis Method

Exergy analysis method is based on exergy balance equation to determine exergy loss and exergy efficiency. Exergy loss (ΔE) is the transfer of exergy from the overall system to its surroundings. This exergy transfer is associated with either the transfer of mass or the transfer of energy to the surroundings [6]. Exergy efficiency is usually defined as utilized exergy divided by used exergy. It is a number between 0 and 1, since all real processes involve exergy loss. A simple definition of exergy efficiency expresses all exergy input as used exergy, and all exergy output as utilized exergy. So the exergy efficiency η_{ex} becomes [7]:

$$\eta_{ex} = \frac{E_{out}}{E_{in}} = 1 - \frac{\Delta E}{E_{in}} \tag{3}$$

For a steady flow open system the exergy balance equation can be obtained according to Figure 1.

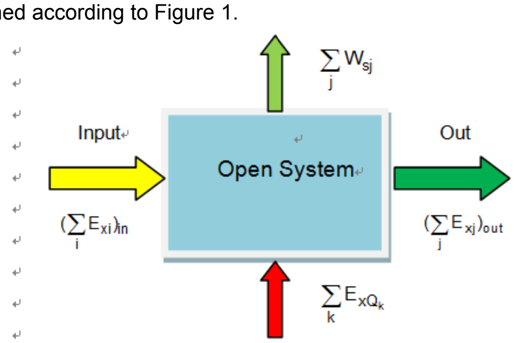

Figure 1: Steady flow open system exergy balance diagram.

Exergy balance equation is [8]:

$$\sum_i (E_{xi})_{in} + \sum_k E_{xQ_k} = \sum_j (E_{xj})_{out} + \sum_j W_{sj} + \sum_i W_{Li} \tag{4}$$

Where, $\sum_i (E_{xi})_{in}$ is the exergy entering the system associated with material flow;

$\sum_k E_{xQ_k}$ is the exergy entering the system associated with heat flow;

$\sum_j (E_{xj})_{out}$ is the exergy leaving the system associated with material flow;

$\sum_j W_{sj}$ is the work leaving the system;

$\sum_i W_{Li}$ is the work loss due to internal exergy loss of the system.

From equation (4), work loss (W_L) due to internal exergy loss of the system can be obtained [8].

$$\sum_i W_{Li} = \sum_k E_{xQ_k} + \sum_i (E_{xi})_{in} - \sum_j (E_{xj})_{out} - \sum_j W_{sj} \tag{5}$$

However, it should be noticed that the equation (5) can be only applicable to processes without chemical reaction. If there is chemical reaction in the process, the chemical exergy should be added into the equation.

2.4 Determination of Exergy Loss of the ALD of Al_2O_3 System

ALD is operated at a relatively high temperature for supplying the energy input to enable the surface reactions of precursors happen in their vapor phases. Since the precursor vapors are carried into the ALD reactor through an inert carrier gas, N_2, here we employ ideal gas laws and conditions to model the gas states and reactions within the ALD reaction system.

Calculation of Exergy Associated with Heat Flow

The reactor is heated to 200℃ (473K) and the temperature is maintained during the whole reaction process. The material of the reactor is stainless steel. The reference temperature is 298K.

From the first law of thermodynamics [8], the energy consumption, Q, of the ALD system can be calculated by:

$$Q = U + W$$

Where, *U* is the internal energy gain of ALD system;

W is the dissipated energy.

The internal energy gain, U, can be calculated by:

$$U = m \times C_g \times \Delta T$$

Where, *m* is mass of the heated component;

C_g is specific heat capacity of the material, for stainless steel C_g is 470J/(kg·K);

ΔT is temperature difference.

The dissipated energy, W, can be calculated through [9]:

$$W = q_{convection} \times t + q_{radition} \times t$$
$$= h \times A \times \Delta T \times t + \varepsilon \times \sigma \times A \times T^4 \times t$$

Where, $q_{convection}$ is the rate of heat dissipation on a surface by convection;

$q_{radition}$ is the rate of heat dissipation on a surface by radiation;

t is the heat dissipation time;

h is convection coefficient, here its value is 60W/m²·K;

ε is emissivity of material, ε is 0.8;

σ is Stefan-Boltzmann constant;

A is surface area of heat dissipation;

T is absolute temperature.

As a result, we get:

$$Q = (m \times C_g + h \times A \times t) \times \Delta T + \varepsilon \times \sigma \times A \times T^4 \times t \quad (6)$$

By substituting the known parameters into formula (6), Q can be obtained.

$$Q = 856.91KJ$$

Exergy caused by heat flow can be calculated by the equation [8]:

$$E_{xQ} = Q(1 - \frac{T_0}{T}) \quad (7)$$

Where, T_0 is the temperature of surroundings;

T is the temperature of the heat source.

Thus the exergy caused by heat flow, E_{xQ}, can be obtained.

$$E_{xQ} = 317.04KJ$$

Calculation of the Exergy Entering the System Associated with Material Flow

Usually, exergy is divided into physical exergy (E_{xph}) and chemical exergy (E_{xch}). Physical exergy is present when a system is at temperature T, and pressure p, which are not the same with the environmental state (T_0, p_0). The maximum work can be extracted by returning the system to the environmental state. Chemical exergy is present when a substance is in a different chemical formulation with the reference state (T_0, p_0). The maximum work can be extracted through the chemical reaction that will return it to its natural concentration [10].

The calculation method of physical exergy is [8]:

$$E_{xph} = (H - H_0) - T_0(S - S_0) \quad (8)$$

Where, *H* is the enthalpy at state (T, p);

S is the entropy at state (T, p);

H_0 is the enthalpy at reference state (T_0, p_0);

S_0 is the entropy at reference state (T_0, p_0);

T_0 is the temperature at reference state.

The thermodynamics parameters of reactants and resultants are listed in tables 2 and 3.

	$Al(CH_3)_3$(g)	H_2O(g)	Al_2O_3(s)	CH_4(g)
$\Delta_f H_m^\Theta$ (kJ/mol)	-74.1	-241.826	-1675.7	-74.6
S_m^Θ (J/(mol·K))	103.68	188.835	50.92	186.3
$\Delta_f G_m^\Theta$ (kJ/mol)	-10.0	-228.61	-1582.3	-50.5

Table 2: The standard molar formation enthalpy and molar entropy of reactants and resultants [11].

	T(K)	$Al(CH_3)_3$(g)	H_2O(g)	Al_2O_3(s)	CH_4(g)
C_p (J/(mol·K))	298	80.4	33.60	79.15	35.7
	600	112	36.4	112.5	52.2
	800	125	38.8	120.1	62.9

Table 3: The values of molar heat capacity at constant pressure of reactants and resultants at different temperatures [11].

The relationship between the molar heat capacity and temperature can be described by the following formula.

$$C_p = a + bT + cT^2 \tag{9}$$

Where, a, b and c are empirical constants. They can be determined by choosing three different groups of data: (T_1, C_{p1}), (T_2, C_{p2}) and (T_3, C_{p3}) and substituting these data into the following formula [11].

$$\frac{C_{p,1}}{(T_1-T_2)(T_1-T_3)} + \frac{C_{p,2}}{(T_2-T_1)(T_2-T_3)} + \frac{C_{p,3}}{(T_3-T_2)(T_3-T_1)} = c$$
$$\left(\frac{C_{p,1}-C_{p,2}}{T_1-T_2}\right) - \left[(T_1+T_2)c\right] = b$$
$$(C_{p,1} - bT_1) - cT_1^2 = a \tag{10}$$

Name	C_p(J/(mol · K))
$Al(CH_3)_3(g)$	$C_p = 33.78 + 0.18T - 7.9\times10^{-5}T^2$
$H_2O(g)$	$C_p = 31.81 + 4.39\times10^{-3}T + 5.44\times10^{-6}T^2$
$Al_2O_3(s)$	$C_p = 20.42 + 0.24T - 1.44\times10^{-4}T^2$
$CH_4(g)$	$C_p = 19.00 + 5.67\times10^{-2}T - 2.26\times10^{-6}T^2$
$N_2(g)$[12]	$C_p = 28.99 + 1.85\times10^{-3}T - 9.65\times10^{-6}T^2$

Table 4: The molar heat capacity of reactants and resultants at constant pressure as the function of temperature. The masses of precursors and carrier gas N_2 entering the reactor in 1 hour are listed in table 5.

According to the values shown in table 3, the molar heat capacity of reactants and resultants depending on temperature can be obtained and the results are listed in table 4.

Precursors	Molar weight (mol)	Mass (g)
$Al(CH_3)_3$	4.02×10^{-4}	2.90×10^{-2}
H_2O	8.29×10^{-4}	1.49×10^{-2}
N_2	0.05	1.392

Table 5: The masses of precursors and N_2.

The physical exergy entering the system can be calculated according to a method detailed in [10]. The result is shown in table 6.

Name	Enthalpy change (KJ)	Exergy (KJ)
$Al(CH_3)_3$	1.98×10^{-3}	4.46×10^{-4}
H_2O	1.45×10^{-3}	-8.54×10^{-4}
N_2	6.95×10^{-2}	0.023
Total value	72.93×10^{-3}	2.26×10^{-2}

Table 6: Physical exergy entering the system.

In other words, the exergy entering the system associated with material flow is:

$$\sum_i (E_{xi})_{in} = 2.26\times10^{-2}\,KJ$$

Calculation of the Chemical Exergy during the Reaction

The values of standard exergy of reactants and resultants are shown in table 7 [13].

Name	Standard Exergy (KJ/mol)
Al	788.186
C	410.515
H	117.575
O	1.977
$Al(CH_3)_3$	3067.906
H_2O	8.517
Al_2O_3	0.003
CH_4	830.315

Table 7: Standard exergy of reactants and resultants.

The exergy value of a substance at state (T, p) can be obtained from the formula available in [13]. For gases the calculation formula is as following.

$$E_x(T,p) = E_x^{\Theta} + \int_{T_0}^{T}(1-\frac{T_0}{T})C_p dT + RT_0 \ln(\frac{p}{p_0}) \tag{11}$$

Where, $E_x(T,p)$ is the exergy of a substance at state (T, p);

E_x^{Θ} is the standard exergy of the substance;

C_p is molar heat capacity;

R is molar gas constant.

For solids, pressure has no impact on exergy values, the formula can be changed as following.

$$E_x(T,p) = E_x^{\Theta} + \int_{T_0}^{T}(1-\frac{T_0}{T})C_p dT \tag{12}$$

The exergy values of reactants and resultants at reaction state are listed in table 8.

Reactants and Resultants	Exergy (KJ/mol)
$Al(CH_3)_3$	3069.15
H_2O	8.54
Al_2O_3	3.53
CH_4	831.88

Table 8: Exergy values of reactants and resultants at reaction state.

The masses of reactants and resultants in 1 hour reaction process are listed in table 9.

Reactants and Resultants	Molar weight (mol)	Mass (g)
$Al(CH_3)_3$	5.60×10^{-5}	4.04×10^{-3}
H_2O	8.40×10^{-5}	1.51×10^{-3}
Al_2O_3	2.80×10^{-5}	2.85×10^{-3}
CH_4	1.68×10^{-4}	2.69×10^{-3}

Table 9: The masses of reactants and resultants.

For a chemical reaction the chemical exergy change is:

$$\Delta E_{xch} = \sum \gamma_i E_{xi} \tag{13}$$

Where, γ_i is the stoichiometric coefficient of entity i. For reactants, γ_i is negative and for resultants, γ_i is positive;

E_{xi} is the exergy of entity i.

Thus the chemical exergy of the reaction can be calculated:

$$\Delta E_{xch} = -3.27\times10^{-2} KJ$$

Calculation of the Exergy Leaving the System Associated with Material Flow

The calculation method of the exergy leaving the system associated with material flow is similar to the method of calculating the exergy entering the system.

The masses of the substances leaving the system are listed in table 10.

Name	Molar weight (mol)	Mass (g)
Unreacted $Al(CH_3)_3$	3.46×10^{-4}	24.96×10^{-3}
Unreacted H_2O	7.45×10^{-4}	13.39×10^{-3}
CH_4	1.68×10^{-4}	2.69×10^{-3}
N_2	0.05	1.392

Table 10: The masses of the substances leaving the system.

The physical exergy leaving the system is listed in table 11.

Name	Enthalpy change (KJ)	Exergy (KJ)
Unreacted $Al(CH_3)_3$	-1.70×10^{-3}	-5.68×10^{-4}
Unreacted H_2O	-1.30×10^{-3}	-4.40×10^{-4}
CH_4	-3.70×10^{-4}	-3.31×10^{-4}
N_2	-6.95×10^{-2}	-0.023
Total value	-72.87×10^{-3}	-2.43×10^{-2}

Table 11: Physical exergy leaving the system

In other words, the exergy leaving the system associated with material flow is:

$$\sum_j (E_{xj})_{out} = -2.43\times10^{-2} KJ$$

Calculation of the work entering the system

According to the given parameters the work entering the system comes from a vacuum pump. The power of the pump is 0.45 KW, so the work done by the pump is:

$$W_{in} = P_p t = 0.45\times1 = 0.45KW\cdot h = 1620KJ \tag{14}$$

Calculation of the work leaving the system

According to the feature of ALD of Al_2O_3 preparation process, the exergy leaving the system caused by work is zero.

Calculation of Exergy Loss

Exergy loss of ALD of Al_2O_3 process can be obtained based on the above mentioned exergy balance equation (5).

$$\Delta E = W_L = 1937.01KJ \tag{15}$$

2.5 Exergy Efficiency of the ALD of Al_2O_3 System

By substituting the known values into the exergy efficiency formula (3), exergy efficiency can be obtained as follows:

$$\eta_{ex} = 1 - \frac{\Delta E}{E_{xQ} + E_{xin} + W_{in}} = 2.72\times10^{-5} \tag{16}$$

As a result the ALD of Al_2O_3 preparation process is very energy intensive and most of the energy input into the system is wasted. In other words, the energy utilization efficiency is extremely low.

3 CONCLUSIONS

Atomic Layer Deposition (ALD) is a promising nanotechnology for depositing Al_2O_3 nano-films. Although highly uniform Al_2O_3 nano-film can be obtained by ALD, it has serious sustainability problems which need to be addressed prior to the large-scale applications of the ALD technology in a broad array of industries. The utilization efficiency of materials and energy is very low in nano-films preparation process by ALD. In this paper ALD of Al_2O_3 is chosen as the research object to analyze the utilization of the available energy----exergy. Exergy analysis is chosen as the analysis method. The exergies associated with material flow, heat flow, and work flow are calculated. Based on the exergy balance equation exergy loss of the process is obtained and then exergy efficiency is calculated. According to the results it can be concluded that the utilization efficiency of exergy is extremely low in ALD of Al_2O_3 preparation. It also can be seen that large proportion of the energy is consumed by system heating. In a word, most of the energy input into the system is at last wasted. Therefore, it is necessary to take measures to reduce the energy consumption and improve the energy efficiency in ALD for nano-thin-film manufacturing.

4 ACKNOWLEDGMENTS

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5 REFERENCES

[1] Widjaja, Y., Musgrave, C.B. (2002): Quantum chemical study of the mechanism of aluminum oxide atomic layer deposition, in: Appl. Phys. Lett., Vol. 80, No. 18.

[2] George, S.M. (2010): Atomic Layer Deposition: An Overview, in: Chem. Rev., Vol. 110, pp.111-131.

[3] Lim, B.S., Rahtu, A., Gordon, R.G. (2003): Atomic Layer Deposition of transition metals, in: Nat. Mater., Vol. 2, pp.749-754.

[4] Yuan, C.Y., Dornfeld, D. (2010): "Integrated Sustainability Analysis of Atomic Layer Deposition for Microelectronics Manufacturing", Journal of Manufacturing Science and Engineering, 132(3), 2010, 030918.1-7.

[5] Torio, H., Angelotti, A., Schmidt, D. (2009): Exergy analysis of renewable energy-based climatisation systems for buildings: A critical view, in: Energ. Buildings, Vol. 41, pp. 248-271.

[6] Tsatsaronis, G., Cziesla, F. (2009): Exergy and Thermodynamic Analysis, in: Exergy, Energy System Analysis and Optimization, Reading, Vol.1.

[7] Wall, G., Gong, M. (2010): On Exergetics, Economics and Desalination, in: Thermal power plant and co-generation planning, Reading, Vol.3.

[8] Zhu, Z. Q., Wu, Y. T. (2005): Chemical Engineering Thermodynamics, Chemical Industry Press, Reading, Beijing.

[9] Yang, S. M., Tao, W. Q. (2006): Heat Transfer, Higher Education Press, Reading, Beijing.

[10] Ma, P. S. (2005): Chemical Engineering Thermodynamics, Chemical Industry Press, Reading, Beijing.

[11] Dean, J.A. (2003): Lange's Handbook of Chemistry, Wei, J. F. Trans, Science Press, Reading, Beijing.

[12] http://webbook.nist.gov/cgi/cbook.cgi?Formula=N2&NoIon=on&Units=SI&cTG=on#Thermo-Gas

[13] Zheng, D. X. (2010): Fluid and Process Thermodynamics, Chemical Industry Press, Reading, Beijing.

Investigation of Energy, Carbon Dioxide Emissions and Costs in Single Point Incremental Forming

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Abstract

The LCA of sheet metal forming processes is lacking in studies of sustainability issues and quantification of energy and carbon dioxide (CO_2) emissions. This paper summarizes an investigation of the relationship between technical parameters in single point incremental forming (SPIF) and energy use. Using a life cycle analysis (LCA) approach, the associated CO_2 emissions are estimated. Costs are calculated using an economic model presented in CIRP previously, and modified for SPIF. The relationships are used in an optimization example which entails producing a complex hat with reduced energy use and CO_2.

Keywords:

Economics; CO_2 emission; Life Cycle Analysis; Incremental Forming

1 INTRODUCTION

Of topical issues facing manufacturers is the pressure towards greater energy efficiency and greenhouse gas emission reduction in step with rising energy prices and environmental costs, such as carbon costs [1-6]. For example, apart from existing carbon markets and taxes, a recent 2011 report recommended that G20 countries should adopt a carbon price of $25/tonne CO2 [5]. Understanding that a carbon price represents a cost risk for contract competition, amongst other environmental burdens and socially acceptable practices, a recent CIRP paper suggested the use of a new economic model [7] to guide manufacturing strategy. Apart from its application to existing processes [8], the model can be applied to developing processes like Single point incremental forming (SPIF). Whilst there are several works on energy and CO2 emissions in material removal processes [7-16], there is lacking literature covering sustainability issues and environmental impact quantification in sheet metal forming [17]. As SPIF continues to develop as a forming technique [18-22], relevant studies need to be conducted to inform lifecycle analysis (LCA) and manufacturing strategy [23].

2 ECONOMIC MODEL MODIFIED FOR SPIF

A new economic model with explicit accounting for energy and CO_2 emissions was recently proposed in a past CIRP paper [7], with example sub-component equations described for milling. In order to use the model for SPIF, several modifications were made. Firstly, the machining cost term is replaced by the forming cost term, C_f, as shown in Eqn 1,

$$C_p = C_f + C_s + C_l + C_t + C_{MD} + C_{MID} + C_{ED} + C_{EA} + C_{env} \quad (1)$$

where C_p is the cost per part; C_f is the forming cost; C_s is the set up cost; C_t is the tool cost; C_{MD} is the direct material cost; C_{MID} is the indirect material cost; C_{ED} is the direct energy cost; C_{EA} is the ancillary energy cost and is C_{env} the environmental cost [7,23]. Since the model approaches full cost accounting, the impact of different optimization objectives can be discerned. This is considered powerful when considering a more holistic analysis as opposed to focussing on only one criterion, like energy efficiency [9, 15], without being able to fully appreciate the corresponding impact on other areas like tool life and part cost.

In addition, for the SPIF process used, there is no coolant system as in milling. Instead, lubricant is manually applied between the tool and sheet. Thus, the equation for indirect material cost must be modified to Eqn 2,

$$C_{MID} = \left(LOf \cdot K_{LOf}\right) + \left(LO \cdot K_{LO}\right) \quad (2)$$

where *LOf* (L) is the lubricant for forming, *LO* (L) is the machine lubricant and they are multiplied by their unit costs ($/L) respectively. This would also change the process CO_2, P_{CO2}, equation for determining the environmental (carbon) cost to Eqn 3,

$$P_{CO2} = E_{CO2} + LOf_{CO2} + LO_{CO2} + TL_{CO2} + ML_{CO2} \quad (3)$$

where LO_{CO2} is the CO_2 for the lubricant used in the machine itself as in milling and LOf_{CO2} is the CO_2 for the lubricant used in the SPIF process. Also shown is the CO_2 from the energy (E_{CO2}), tool (TL_{CO2}) and direct material (ML_{CO2}). These are all calculated knowing the amount of each used and their emission intensity (EI). This method for accounting for the CO2 beyond electricity [and] recognizes that the lifecycle of other inputs impacts that of the final product.

Generally, when this type of analysis is considered for material removal processes like milling, there are clear guidelines for tool life prediction and a process rate metric like the material removal rate (MRR). Furthermore, there is a standard comparative energy use metric for specific energy consumed in energy per volume removed [12, 14, 24]. However, comparable metrics are lacking for SPIF.

Whilst tool life prediction is not covered in the literature, it is suggested that in the presence of lubrication, negligible wear is observed [18]. However, the wear is observed to increase with spindle speed [21], with the dominant mechanism being adhesive wear for a tool-sheet combination like a softer workpiece material (aluminum) and harder tool material (steel) [18]. Thus, a simple Taylor tool life relationship is assumed with C =60.96 [m/min] and n = 0.11[24, 25] for the SPIF tool. Furthermore, the process speed factor, k_{PSF}, is proposed as a process rate metric and is given in Eqn 4,

$$k_{PSF} = \lambda \cdot FD \cdot ST \cdot D \quad (4)$$

where λ is a calibration constant (assumed 1 for this study), *FD* is the feed rate in mm/s, *ST* is the step size increment in mm and *D* is the tool size in mm. The resulting unit of mm^3/s is proportional to some volume through which the tool passes in a period of time, comparable to MRR. None-the-less, empirical calibration of Eqn 4 is left for future work to gain better relative and physical meaning.

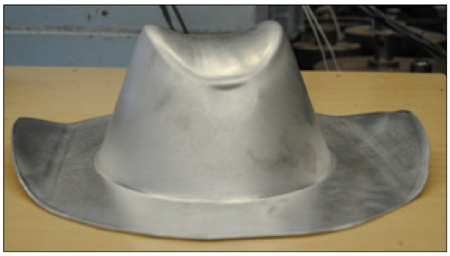

Figure 1: Aluminium Hat made with SPIF [26].

3 MODEL DATA ACQUISITION

The goal of the SPIF operation was to manufacture an aluminium hat as shown in Fig. 1. In order to gauge the impact of changing certain inputs or parameters on energy use, process time, CO2 emissions and finally cost, a series of simple bowls were produced at the settings shown in Table 1. The base scenario outlines the default settings previously used to make the hat. Of interest were changing the process parameters: feed rate (FD) and step down increment (ST); and inputs: lubricant (LOf) and tool size (TL). Energy use was determined using power-time profiles for each part [23,26]. An important breakdown in the energy use is direct energy (E_D) and ancillary energy (E_A) [7, 8, 23, 26]. The E_D is considered that required for the process while the E_A is for supporting systems such as the movement of unloaded servos and computer console[7,12,26]. The amount of material and lubricant were determined using a digital scale (kg) and measuring cylinder (L) respectively.

	Test	Specifications for Different Cases					
0	**Base Scenario**	Speed: 600 RPM, Feed Rate (FD): 2032mm/min [80 in./min], Lubricant (LOf): 75W140, Step Down (ST): 0.254 mm [0.01 in.], Tool Size (TL): 6.35mm [0.25 in.]					
1	**Lubrication (LOf)**	75W140	75W90	80W90	Mineral Based	Used Cooking Oil	Chassis Grease
2	**Feed Rate (FD) [mm/min]**	1524	2032	2540		3048	4064
3	**Tool Diameter (TL) [mm]**	4.7625	6.35	9.525		12.7	-
4	**Step Down (ST) [mm]**	0.254	0.381	0.508		0.635	-

Table 1: Summary of test parameters for the SPIF Bowls.

Using the data from the simple bowl series and other input data in Table 2, the economic model was used to assess the optimum process parameter (k_{PSF}) for the ultimate objective of minimum part cost (C_p). Other sub-objectives investigated were for minimum energy (E_p), minimum time (t_p), minimum process CO_2 (P_{CO2}), and maximum tool life (T).

Once the trend in the simple bowl series was observed and the method for achieving the given objectives outlined, the hat process was improved within the parameter space tested. More detailed experimental data for the hat study is available in [26]. Essentially, a doubling of the FD and ST was prescribed as discussed further in Section 4. Other adjustments included changing the lubricant type from 75W140 to used cooking oil based and increasing the tool size to 9.525 mm to accommodate the larger ST. In effect, using the simple bowl series to characterize the process allowed a reduction in the hat tests needed as it is the part that takes much longer to manufacture and uses more material etc.

Input [Units]	Value	Ref.
Electricity Price (Kingston, Canada) [$/kWh]	0.11	
Electricity Grid CO_2 EI/CES™ [kg CO_2/kWh]	0.17	[6]
Labour Rate [$/hr]	50.00	[27]
Burden Rate[$/hr]	8.00	[9]
SPIF tool cost [$/tool]	25.00	[28]
Weight of SPIF Tool (1/4”) [kg]	0.136	
Weight of SPIF Tool (3/8”) [kg]	0.109	
Weight of SPIF Tool (1/2”) [kg]	0.114	
Cost of Aluminium Sheet 3003O [$/kg]	9.18	[27]
Carbon Price [$/tonne CO_2]	25.00	[5]
Cost of Machine Grease, K_{LO} [$/L]	12.68	[27]
Cost of Forming lubricant, K_{LOf} (75W140) [$/L]	20.00	[28]
Cost of Forming lubricant, K_{LOf} (75W90) [$/L]	15.00	[28]
Cost of Forming lubricant, K_{LOf} (80W90) [$/L]	12.00	[28]
Cost of Forming lubricant, K_{LOf} (Mineral Oil) [$/L]	2.00	[29]
Cost of Forming lubricant, K_{LOf} (Used Cooking Oil Ester) [$/L]	2.80	[29]
Material Used (Bowl), ML [kg]	0.198	
Material Used (Hat), ML [kg]	0.346	
Machine grease use rate [L/s]	4.63E-08	
Emission Intensity of forming lubricant, EI_{LOf} (Synthetic/Mineral) [kg CO_2/L]	3.295	[29]
Emission Intensity of forming lubricant, EI_{LOf} (Used Cooking Oil) [kg CO_2/L]	0.512	[29]
Emission Intensity of machine lubricant EI_{LO} [kg CO_2/L]	0.472	[10]
Emission Intensity of tool, EI_{TL} [kg CO_2/kg]	6.4	[30]
Emission Intensity of material, EI_{ML} [kg CO_2/kg]	8.72	[31]

Table information. Cost in Canadian Dollars.

Table 2: Summary of Non Experimental Model Inputs.

4 RESULTS AND ANALYSIS

4.1 Simple SPIF Bowl

Fig. 2 illustrates the results for cost per part, C_p, against k_{PSF} for the bowls at various *FD*, *ST*, *LOf* and *TL*. It should be noted that the introduction of the k_{PSF} is effective in identifying testing scenarios that have the same result when comparing the FD and ST series. The same overall trend as in Fig. 2 was seen for t_p, E_p and P_{CO2} such that the higher the FD and ST, the better the operation, with the exception of tool life which decreased with increased process rate as dictated by the tool life equation. As such, the fastest FD and ST, and therefore k_{PSF}, is recommended for minimum C_p, t_p, E_p and P_{CO2} at constant spindle speed in the given parameter space.

The TL had a smaller effect than the FD and ST. However, the variability observed is due to the tool life and actual weight difference of the tools. The larger the tool diameter, the higher the surface speed, resulting in faster tool wear as described in the Taylor model [24, 25]. In addition, the amount of CO_2 due to the tool is directly related to the amount of material (weight).

It is obvious that the LOf would not affect the process rate, and so all values fall in the same spot. However, it was seen that simply changing the lubricant type to a more eco-benign lubricant could reduce the CO_2 burden without affecting the part finish.

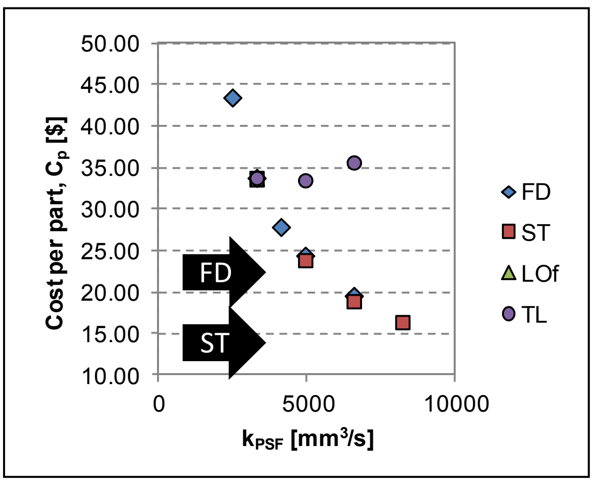

Figure 2: Economic model results for SPIF bowls showing cost per part.

4.2 Complex SPIF Hat

As indicated in section 3, the bowl results were used to inform the hat process improvements. It was demonstrated that increasing the FD and ST, therefore higher k_{PSF}, meant better performance for minimizing C_p, t_p, E_p and P_{CO2}. Table 3 summarizes the findings for the hat analysis after using the economic model with the acquired data. In Table 3, it is clear that there is a synonymous impact on the C_p, t_p and E_p looking at the percentage difference in the values. For the given circumstances, these are correlated, such that the optimization of one can be used as the proxy for the other. The small reduction in P_{CO2} can be attributed to the dominance of the material burden at 3.02 kg CO_2. Removing the material from the P_{CO2} shows a reduction from 0.27 kg CO_2 to 0.07 kg CO_2, or 74%. This is higher in the reduction for C_p, t_p and E_p which was roughly 66% due to the additional change arising from using less lubricant and more eco-benign lubricant. The tool life and process rate metric require future work, although the assumptions used showed the general trend expected.

Apart from the absolute cost per part, the cost breakdown was explored as shown in Fig. 3.

	Scenario 1 (S1)	Scenario 2 (S2)	Difference % (final-initial) / (initial)
C_p [$]	98.86	32.85	-67
t_p [s]	6264	2188	-65
E_p [kWh]	1.27	0.39	-69
P_{CO2} [kg CO_2]	3.29	3.09	-6
T [min]	2.74E+05	1.21E+04	-96
k_{PSF} [mm^3/s]	3277	19664	+500
FD [mm/min]	2032	4064	+100
ST [mm]	0.254	0.508	+100
TL [mm]	6.35	9.525	+50
LOf	75W140	Used Cooking Oil Ester	-

Table 3: Summary of hat data from the model.

As discussed in previous work [7,8], cost rates weigh the importance of specific cost terms. This in turn drives the sub-components that are minimized. In both cases, the cost due to forming dominates the overall cost of the hat. This is because the forming process is time intensive. Moreover the workpiece is a sheet rather than a block of material, such that its relative contribution is reduced, as compared to a material removal operation [17].

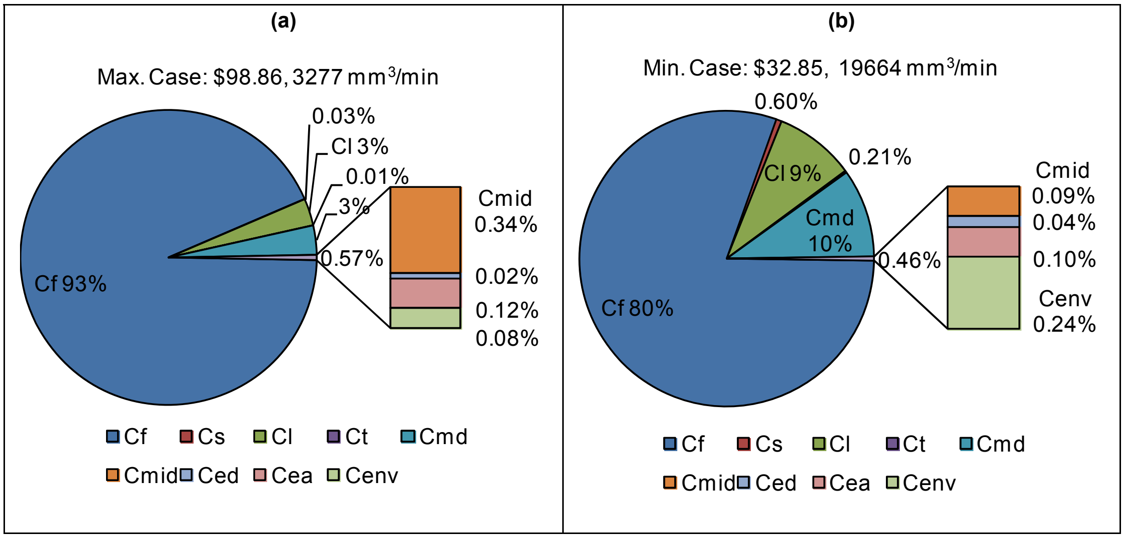

Figure 3: Cost breakdown of the hats for two scenarios: (a) base scenario; (b) modified. Note: the segments are labelled clockwise from C_f.

In Fig. 3(b), for the modified hat, C_f represents 80% of the cost compared to 93% for (a). The large reduction (2.8 times) in process time means that the contribution of the forming cost is reduced. The next highest costs are handling/idling (C_l) and material (C_{MD}) costs. In both cases, the set up (C_s), tool (C_t), indirect materials (C_{MD}), energy (C_{ED}, C_{EA}) and environmental (C_{env}) costs represent a minimal portion. Again, the large processing time dominates other costs. Interestingly, the proportion of energy costs remains the same in both cases, although the ratio of direct to ancillary energy changes, with E_D increasing in significance with more aggressive parameters. The E_A, like the forming cost is highly time dependant, reducing in significance as the process time is reduced. Finally, the proportion of C_{env}, C_l, C_{MD}, C_s, and C_t increase in the more optimum hat (b) as the forming contribution decreases. Again, C_{env} has a small measurable effect on the cost, but other environmental costs would need to be included to understand their true significance. Comparing Fig. 3(a) and (b), it is apparent that the increased proportion of C_{env}, even with the absolute reduction in the CO_2 emissions means that strategies should be employed to further reduce the portion of the cost and therefore profits that it represents. Finally, the savings in energy and carbon cost would be magnified for operations with more expensive energy or that function in locations with “dirtier” electrical grids.

5 DISCUSSION

The economic model was used in comparing the optimum parameters for different objectives of interest in SPIF. For the given circumstance, many of the prescribed settings were synonymous as shown in the bowl study. Then, process learning was demonstrated when extrapolating the findings of the bowl study to the hat, which was the target product.

Considering the embodied CO_2 emissions in the hat, the material of the workpiece dominated. Whilst process and indirect material improvements were able to reduce the non-workpiece CO_2 emissions to being nearly negligible, using workpiece material with comparable performance but lower environmental burden is recommended.

The tool life model, LCA data for CO_2 emissions and the process rate metric proposed are areas for improvement as they are lacking in the literature for SPIF. A challenge in the CO_2 footprint analysis is finding appropriate EI references for the inputs. However, the assumptions made were reasonable for benchmarking purposes.

6 CONCLUSION

In this paper, a new economic model was used to improve a process in SPIF to demonstrate its application. A simple bowl study was used to improve the process parameters for a more complex SPIF part, a Hat. The general relationships observed were used to show how faster rates mean lower time, energy, process CO_2 and therefore cost for constant spindle speed. However, it is understood that more aggressive rates would have a negative impact on tool life. In addition, the environmental costs showed a small measurable effect, but could increase in significance with burdens beyond CO_2.

7 REFERENCES

[1] Science academies of the G8 countries, plus Brazil, China, India, Mexico, and South Africa, (2009), G8+5 Academies' joint statement: Climate change and the transformation of energy technologies for a low carbon future, Climate Change at the National Academies, US National Academy of Sciences, Washington, D.C., 1 -2.

[2] International Energy Agency (IEA), (2011), Energy Prices and Taxes – Quarterly Statistics, OECD Publishing, Paris, France, Vol. 2011/2, pp 1 -546.

[3] Zhu, W., (2011), China raises power prices for business, farmers as summer shortage looms, May 31, 2011, Bloomberg News, http://www.bloomberg.com/news/2011-05-30/china-raises-industrial-power-prices-in-15-provinces-to-help-ease-shortage.html

[4] McKane, A., Desai, D., Matteini, M., Meffert, W., Williams, R., Risser, R., (2009), Think Globally: How ISO 50001 – Energy Management can make industrial energy efficiency standard practice, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, pp. 1-16.

[5] Max, A., (2011), "Paper on climate financing targets fuel subsidies", Sept. 21, 2011, The Guardian (UK), http://www.guardian.co.uk/world/feedarticle/9857669

[6] Jeswiet, J., Nava, P., (2009), Applying CES to assembly and comparing carbon footprints, International Journal of Sustainable Engineering, 2 (4), 232-240.

[7] Branker, K., Jeswiet, J., Kim, I.Y., (2011), Greenhouse gases emitted in manufacturing a product, A new economic model, Annals of CIRP, 60 (1), 53-56.

[8] Branker, K., Jeswiet, J., (2012), Using a New Economic Model with LCA-based carbon dioxide emission inputs for Process Parameter Selection in Machining,19th CIRP Intl Conf on Life Cycle Engineering (in progress)

[9] Anderberg, S. E., Kara, S., Beno, T., (2010), Impact of energy efficiency on computer numerically controlled machining, IMECHE, 224 (B), 531-541.

[10] Narita, H, Kawamura, H., Chen, L., Fujimoto, H., Norihisa, T., Hasebe, T., (2008), Development of Prediction System of Environmental Burden of Machine Tool Operation, Journal of Environment and Engineering, 3 (2), 307 -315.

[11] Gutowski, T., (2007), The Carbon and Energy Intensity of Manufacturing, 40th Seminar of CIRP, Keynote Address, Liverpool University, Liverpool, UK.

[12] Gutowski, T., Dahmus, J., Thiriez, A., (2006), Electrical Energy Requirements for Manufacturing Processes, 13th CIRP Intl. Conf. Life Cycle Eng., Leuven, 623 -627.

[13] Diaz, N., Redelsheimer, E., Dornfeld, D., (2011), Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Use, J. Hesselbach, C. Herrmann (eds.), Glocalized Solutions for Sustainability in Manufacturing, Springer-Verlag Berlin Heidelberg, 263 -267.

[14] Kara, S., Li, W., (2011), Unit process energy consumption models for material removal processes, Annals of CIRP, 60 (1), 37-40.

[15] Mativenga, P.T.,Rajemi, M.F., (2011), Calculation of optimum cutting parameters based on minimum energy footprint, Annals of CIRP, 60 (1), 149-152.

[16] Mori, M., Fujishima, M., Inamasu Y., Oda Y., (2011), A study on energy efficiency improvement for machine tools, Annals of CIRP, 60 (1), 145-148.

[17] Ingarao, G., Di Lorenzo, R., Micari, F., (2011), Sustainability issues in sheet metal forming processes: an overview, J. Clean. Prod., (19), 337-347.

[18] Duflou, J., Tunçkol, Y., Szekeres, A., Vanherck, P., (2007), Experimental study on force measurements for single point incremental forming, Journal of Materials Processing Technology, 189 (1-3), 65-72.

[19] Duflou, J. R., Verbert, J., Gu, J., Sol, H., Henrard, C., Habraken, A.M.,(2008), Process window enhancement for single point incremental forming through multi-step toolpaths, Annals of CIRP, 57, 253-256.

[20] Hamilton, K, Jeswiet, J., (2010), Single point incremental forming at high feed rates and rotational speeds: Surface and structural consequences, Annals of CIRP, 59 (1), 311-314.

[21] Jeswiet, J., Micari, F., Hirt, G., Bramley, A., Duflou, J., Allwood, J., (2005), Asymmetric Single Point Incremental Forming of Sheet Metal, Annals of CIRP, 54 (2), 88-114.

[22] Crina, R., (2010), New Configurations of the SPIF Process - A Review, Journal of Engineering Studies and Research, 16 (4), 33 -39.

[23] Branker, K., (2011), A Study of Energy, Carbon Dioxide Emissions and Economics in Machining: Milling and Single Point Incremental Forming, Master's thesis, Queen's University, Kingston, Ontario, Canada.

[24] Kalpakjian, S., Schmid, S.R., (2006), Manufacturing Engineering and Technology 4thEd. Prentice-Hall Inc. Upper Saddle River, New Jersey.

[25] Yan, J., Murakami, Y., Davim, J.P., (2009), Tool Design, Tool Wear and Tool Life, in K. Cheng (Ed.) Machining Dynamics, Springer-Verlag London Limited, 117-149.

[26] Branker, K., Adams, D.W., Jeswiet, J., (2011), Initial analysis of cost, energy and carbon dioxide emissions in single point incremental forming – producing an aluminium hat, Intl J of Sustainable Engineering, iFirst, 1-11.

[27] Personal Communication, (2011), Machine Shop at Queen's University, Kingston, Ontario, Canada.

[28] Personal Communication with D. Adams, (2011), McLaughlin Hall at Queen's University, Kingston, Ontario, Canada.

[29] Nava, P., Jeswiet, J., Kim, I.Y., (2010), Calculation of carbon emissions in metal forming manufacturing processes with eco-benign lubrication, Transactions of NAMRI/SME 2010, 38, 751-758.

[30] Kara, H., (2009), Carbon Impact of Remanufactured Products - End Mill Cutting Tools, Center for remanufacturing and reuse, UK, pp.1-21.

[31] Hammond, G., Jones, C., 2011, Inventory of Carbon and Energy (ICE V2.0), Department of Mechanical Engineering, University of Bath, UK.

Semi-empirical Modeling of the Energy Consumed during the Injection Molding Process

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Abstract

This paper presents a semi-empirical model for determining the energy consumption of an injection molding machine based on the energy profile of the injection molding process. The model utilizes empirical data to the idle or baseline energy consumption of the machine tool, which is non-negligible. A theoretical analysis is used to determine the processing energy, which can be a significant contribution because of the design and the rheological non-Newtonian nature of polymers. A thermo-mechanical analysis of the material plasticizing and injection process is incorporated into the model to accurate assess the theoretical processing energy. The errors in the model are considered and the model performance is validated with findings in literature.

Keywords:

Injection Molding; Semi-Empirical Modeling; Specific Energy Consumption

1 INTRODUCTION

Energy conscious manufacturing has become a reoccurring theme for designers and manufacturers to help lower the environmental footprint of their products by allocating efforts a product's life-cycle, wsignificant emphasis is put on the product's embedded energy. In the case of manufacturing, thorough understanding the energy profile and behavior of the machine tools can allow proper process and material based decisions to be made for reducing the embedded energy. This is crucial in large industries, such as plastics, which is the third largest in the U.S. with market value at over $300 billion [1]. Roughly a third of this value can be attributed to the injection molding market alone, which has a capacity of over 17,000 facilities [1] and install base of over 100,000 injection molding machines (IMMs) [2]. Therefore, improvements to the injection molding processes may have large energy saving implications on the entire plastics industry.

However, obtaining machine tool level energy consumption data can be very time consuming, expensive, and impractical, especially considering the scale of design-of-experiments (DOE) necessary for various materials and under different processing conditions. Therefore, the aim of this research is to create a low cost, comprehensive, and robust injection molding model for accurately predicting the energy consumption of a molded part.

2 BACKGROUND

Plastic IMMs have been used since the turn of the 20th century, with major technological developments occurring from within the last 50 years where parts over 50 pounds and clamp forces exceeding 8000 tons are possible [2].

IMMs can be classified into three categories: hydraulics, all-electrics, and hybrids [3][4]. Hydraulic IMMs are the most mature technological type and utilize pressurized hydraulic cylinders from one or two electric motors and hydraulic pumps to actuate the injection unit and mold clamping. All-electric IMMs represents a relatively new and upcoming technology where electric servo-motors actuate the injection and clamp actuation. All-electrics offer lower power consumption and faster cycle times, but are typically more expensive and limited in the clamp force size. Hybrid IMMs offer the best of both worlds by utilizing the enhancements of all-electric with the addition of hydraulic clamping for high clamp forces. Despite the relatively high new sales of all-electrics and hybrids, hydraulics still represent the largest installed base [2]. Thus, hydraulics will be the primary focus of this paper.

Modeling the energy consumed during injection molding requires detailed understanding of the cycle time behavior and power consumption profile. As shown in Figure 1 the process of injection molding involves many stages where the majority of which occur serially. Post-injection involves parallel stages of plasticizing and part cooling. Note that this type of cycle time behavior represents the majority of thermoplastic (TP) polymers where the material is pre-heated prior to injection and cooled before ejection. Thermoset (TS) polymers are heat treated after injection to cure the polymer in the mold [4]. Due to lack of data, thermoset polymers were not validated in this paper. The generalized IMM power consumption profile is shown in Figure 2; the magnitude of the power in each stage/component will differ depending on the IMM technology and material type.

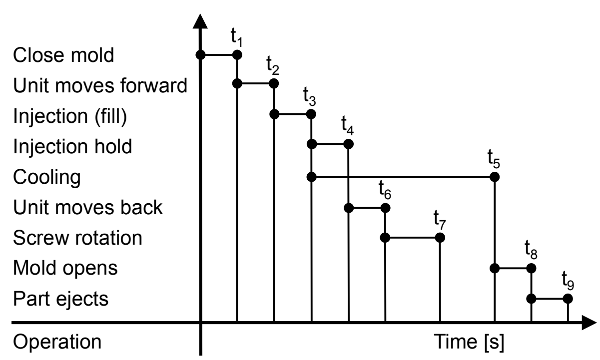

Figure 1: Gate-to-gate cycle time [5].

Power consumption profile can be split into two components: *fixed power*, which represents the idle or baseline power required for machine operation, and *variable power*, which represents machine operations that add direct (e.g. molding) or indirect (e.g. ejection) value to the part [6]. During the operation of a hydraulic IMM, the fixed power represents the baseline power (e.g. computer, controls), idling stage of the heaters for both the barrel and mold, and the idle running of the hydraulic motor(s), all of which can significantly contribute to the overall energy consumption.

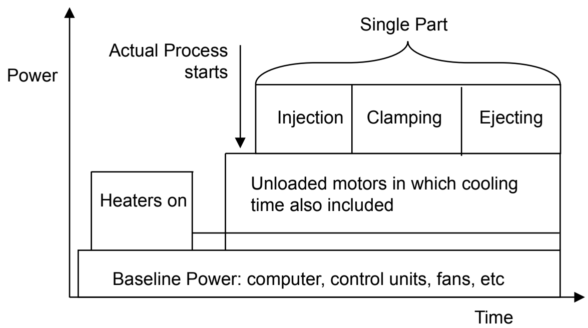

Figure 2: Power characteristics of the injection molding cycle [5].

Past attempts at modeling the energy consumption during injection molding have been well characterized. A common and popular metric is defining a material's *Specific Energy Consumption* (SEC) for a given process [6]. The SEC is essentially the energy required to add, remove, or shape a given mass.

In characterizing the SEC for injection molding, various works in literature have used a theoretical approach while others directly measure the power consumption during molding. Works that model the energy consumption using thermodynamic principles determine the melting energy required and approximate the injection energy as simply the product of the average injection pressure and injected volume [3][7][8][9]. Some have also calculated the power required for screw rotation based on the material's rheological properties [3][8]. The major drawback to the thermodynamic models is that they only encapsulate a small portion of the actual energy consumption. A recent study by Duflou et al. [10] shows that the discrepancy between the thermodynamic models to actual data can range from a factor of 2.4x to over 11.2x.

More representative values for the SEC have been obtained through empirical studies. Qureshi et al. [11] conducted a DOE for mapping out and modeling the SEC of polystyrene. Gutowski et al. [6] and Theriez [3] have collected numerous SEC values for various polymers and different machine sizes and process rates. Ribeiro et al. [7] investigated the influence of part design and calculated the efficacy of the thermodynamic model to the measured data (although the SEC was not directly determined). A more comprehensive study by Weissman et al. [12] took the average measured power consumption of each stage in the molding cycle and their respective theoretical cycle times (with the aid of professional molding software) to obtain an estimate of the total energy per part. While this model took into account tool setup energy and part design, the authors neglected to decouple plasticizing power from cooling power thereby potentially reducing the accuracy of the model.

All the empirical studies that had process parameter variations showed an inverse relationship with SEC to throughput. This trend is due to the higher utilization of the variable energy with respect to the total energy at higher throughputs (the fixed power is relatively constant). However, the trend is mitigated as the machine size (characterized by clamping force) is increased [6], which suggests that the fixed or baseline power does not directly scale proportionally to the size of the machine.

The findings of the empirical studies are useful, but they are often limited in terms of robustness. The reported SEC values apply only to a particular machine size, material, and part design. Mapping out the SEC for the entire family of polymers processed in differently sized machines under a set of throughputs and different geometries would simply be infeasible. Thus, a semi-empirical model that utilizes the strengths of both modeling techniques types may be successful.

3 MODELING

This paper presents a semi-empirical model that is based on theoretical principles and empirical relations. In the previous section, Figure 2 showed the complexity of the injection molding process where numerous stages occur when molding a part. However, since each stage can be considered discrete and virtually independent, superposition can be used to determine the total energy consumption. The SEC then can be constructed as the product sum of the power consumption and time from each stage:

$$SEC = \frac{E_i + E_h + E_r + E_m + E_{moc} + E_b}{TPT\ t_c}$$
$$= \frac{Pt|_i + Pt|_h + Pt|_r + E_m + Pt|_{moc} + (P_b + P_h)t_c}{m_{part}} \quad (1)$$

where E and P denotes the energy and power, respectively, and the subscripts i, h, r, m, moc, b, h, and c denotes the injection energy, hold/pack energy, screw rotation energy during plasticizing, polymer melting energy, mold open/close energy, idle or baseline energy, heater power loss, and cycle time, respectively; TPT is the throughput and m_{part} is the mass of the injected part.

The energy to inject and fill the mold (E_i) and the energy for melting (E_m) and plasticizing (E_r) is highly material dependent and can be explicitly modeled using thermo-mechanical principles. The remaining stages are difficult to explicitly model due to their high dependence on the machine size and manufacturer's design. Therefore, an empirical approach is used to generalize the actual power consumption during idling, holding, and mold opening/closing with respect to machine size. The following few sections will describe in detail each stage of model.

3.1 Thermo-Mechanical Model

The power required to inject the molten polymer is a function of the volumetric flow rate and the hydraulic pressure loss [13]. Taking account the efficiency of the motor and hydraulic pump, the power delivered to the electric motor can be written as:

$$P_i = Q\frac{dP_t}{\varepsilon_M \varepsilon_h} \quad (2)$$

where Q is the volumetric flow rate entering the mold, dP_t is the total pressure loss in the mold, ε_M is the electrical efficiency of the motor (which is dependent on the motor size), and ε_h is the hydraulic efficiency of the pump. The total pressure loss can be further calculated as the sum of the channel pressure losses:

$$dP_t = dP_s + dP_r + dP_{mo} \quad (3)$$

where dP_s, dP_r, dP_{mo} are the channel pressure losses of the sprue, runner, and mold, respectively. Due to the non-Newtonian viscoelastic behavior of the molten polymer the channel pressure loses are modified to yields the following equation (for the mold) [13]:

$$dP_{mo} = \frac{ML_{mo}}{H_{mo}} \left[\frac{2Q(1/n+2)}{W_{mo} H_{mo}^2} \right]^n \tag{4}$$

where L_{mo}, H_{mo}, and W_{mo} are the channel length, height, and width of the mold, respectively. The parameters M and n are coefficients derived from the non-Newtonian viscosity and shear rate model (see Section 3.4). Similar equations hold for the sprue and runner.

The power required for screw rotation and plasticizing is highly dependent on the screw design, size, rotational speed, and the shear temperature dependent viscosity. The equation for plasticizing power delivered by the electric motor is given by [13]:

$$P_r = \bar{\mu}(\dot{\gamma}, T) \frac{\pi^2 N^2 D_b^2 WL}{\sin \bar{\theta} H \varepsilon_M} \left(4 - 3\cos^2 \theta_b \frac{Q_{ex}}{Q_d} \right) \tag{5}$$

where $\bar{\mu}(\dot{\gamma}, T)$ is the average viscosity at shear rate, $\dot{\gamma}$, and temperature, T; N is the screw speed, D_b is the screw diameter, W is the screw channel width (distance between flights), H is the screw channel height, L is the screw length, $\bar{\theta}$ is the average screw helix angle, θ_b is the screw helix angle at the barrel surface, Q_{ex} is the volumetric rate exiting the screw, and Q_d is the volumetric flow rate that is dragged by the screw. Note that $0 \le Q_{ex} \le Q_d$ and when $Q_{ex} = 0$ (i.e. when the shot volume is full) the rotational power is at its maximum, and when $Q_{ex} = Q_d$ (i.e. open flow) the rotational power is at its minimum.

While the shearing during plasticizing may generate some heat, barrel heaters are needed to melt the polymer and to reach proper injection temperatures. The additional thermodynamic energy required depends on the polymer's crystalline structure and can be determined by the following equation [3]:

$$E_m = mc_p(T_i - T_{hop}) + \lambda m H_F^o \tag{6}$$

where m is mass of the shot, c_p is the average specific heat capacity, T_{inj} is the injection temperature, T_{hop} is the polymer temperature in the hopper, λ is the average degree of crystallinity (note crystallinity decreases with temperature), and H_F^o is the average heat of fusion at 100% crystallinity. For amorphous polymers, λ is set to zero.

Equation 6 describes the minimum energy required to melt the polymer. However, in reality there are conductive heat losses primarily through the barrel, screw, and mold. The heat losses are heavily dependent on the machine size and design, and while a proper heat transfer analysis is beyond the scope of this study, the analysis can be simplified by assuming natural or free convection as the primary means of heat dissipation. Therefore, the equation for the heat loss is given by:

$$P_h = (P_{heat,b} + P_{heat,p})/\eta_{heat} \tag{7}$$

where $P_{heat,b}$ and $P_{heat,p}$ are the convective heat loss (in Watts) for the barrel and mold platen, respectively. The η_{heat} term is designated to be the ratio of the convective heat loss to the total loss; hence $1 - \eta_{heat}$ represents the conductive and radiative heat losses. The convective heat loss of the barrel can be modeled as a cylinder where the outer diameter is the characteristic length, which is assumed to be 2.5 times that of the barrel diameter. The equation is expressed as [14]:

$$P_{heat,b} = \pi \, Nu_D \, k_{air} \, L_b \, (T_i - T_{amb}) \tag{8}$$

where k_{air} is the thermal conductivity of air at the average temperature, L_b is the length of the barrel and is assumed to be equal to the screw length, T_i is the injection temperature (in reality the barrel surface temperature is less than the injection temperature due to insulation of the barrel), T_{amb} is the ambient air temperature and is assumed to be 20°C. The term Nu_D is the Nusselt number, which is the ratio of the convective to conductive heat transfer across the barrel [14] and is approximated as:

$$\boldsymbol{Nu_D = 0.48\, Ra_D^{0.25} \qquad 10^4 \le Ra_D \le 10^7} \tag{9}$$

where Ra_D is the Rayleigh number, which describes the ratio of the free convective flow to the thermal diffusivity. The Rayleigh number is also defined as the product of the Grashof and Prandtl numbers and can be written as [14]:

$$\boldsymbol{Ra_D = \frac{g\, \beta\, (T_i - T_{amb})\, (2.5\, D_b)^3}{\nu_{air}\, \alpha_{air}}} \tag{10}$$

where g is the grativational accerlation (9.81m/s^2), β is the coefficient of volume expansion and is taken as the inverse mean temperature, $2.5D_b$ is the outer barrel diameter, ν_{air} and α_{air} is the kinematic viscosity and thermal diffusivity of air at the average temperature, respectively. The natural convective heat loss for the mold platen can be calculated in a similar manner where the characteristic length is the platen height and the heat transfer profile is assumed to be that of a vertical wall.

3.2 Empirical Model

A meta-analysis from various empirical studies of the injection molding power consumption profiles was conducted to construct the models for the idle or baseline (P_b), clamp hold (P_h), and mold open/close (P_{moc}) power consumptions. Various profiles involving different machine sizes were publically found in literature and analyzed. Figure 3 shows an example profile of polystyrene with a 15-ton injection molding machine [11]. Power consumptions of each stage in the profile were approximated as accurately as possible.

The results of the meta-analysis showed very high correlations between the idle, hold, and open/close power consumption to machine size. It was observed that the best fit for idle and holding power consumptions was linear while the mold opening and closing fit was exponential. Fitting other stages such as injection and plasticizing was also attempted, but no clear correlations could be made as expected.

From the empirical data, the models were formulated using linear regression (log-linear for exponential curves) and the coefficients of the slope, m, and y-intercept, b, are calculated using the equations:

$$m = \frac{N \sum_{j=1}^{N} (T_j P_j) - \sum_{j=1}^{N} T_j \sum_{j=1}^{N} P_j}{N \sum_{j=1}^{N} (T_j^2) - \left(\sum_{j=1}^{N} T_j \right)^2} \tag{11}$$

$$b = \frac{\sum_{j=1}^{N} P_j - m \sum_{j=1}^{N} T_j}{N} \tag{12}$$

where T_j is the *jth* data point for machine size (in tons), P_j is the corresponding power consumption, and N is the degrees-of-freedom (i.e. number of data points). A similar equation can be formulated using the natural logarithm to linearize the exponential fit. The results of the regression are tabulated in Table 1.

Idle Power	Hold Power	Mold O/C Power
$P = mT + b$	$P = mT + b$	$P = Ae^{BT}$
$m = 0.0269$	$m = 0.0328$	$A = 1.115$
$b = 0.782$	$b = 0$	$b = 0.0066$
$R^2 = 0.98$	$R^2 > 0.99$	$R^2 = 0.99$

Table 1: Regression coefficients for empirical model.

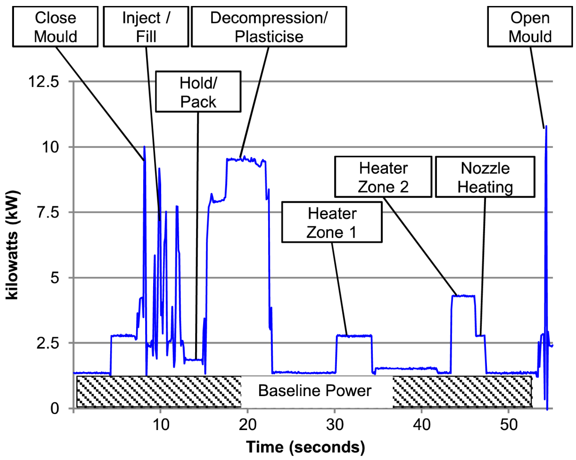

Figure 3: Example power consumption profile [11].

As shown in Table 1, the empirical models fit the data extremely well with the coefficient of determination, R^2, above 0.98 for each model. Despite the high fits, errors in the empirical model are taken into account and are reflected in the outcome. It should be noted that the regression models are valid between 15 to 550 tons due to lack of data at larger machine sizes.

3.3 Cycle Times

In order to calculate the SEC, the power components, detailed in Sections 3.1 and 3.2, are multiplied by their respective cycle times. Note the cycle times in each stage calculated herein are in units of seconds.

The time to inject and fill the sprue, runner, and mold can be approximated using the equation [15]:

$$t_i = 2V_t \frac{dP_t}{P_i} \tag{13}$$

where V_t is the total injected volume, dP_t is the total pressure loss from Equation 3, and P_i is the injection power from Equation 2.

The required time for plasticizing is approximated by the mean residence time, which is the time to plasticize a given shot volume, and can be theoretically determined using the equation [13]:

$$t_r = \frac{HWL_{meter}}{\sin\bar{\theta} Q_{ex}} \tag{14}$$

where H, W, $\bar{\theta}$, and Q_{ex} are the same parameters as in Equation 5, and L_{meter} is the length of the screw metering section where the large majority of the plasticizing occurs.

The time to pack and hold the molten polymer as well as the time to cool the mold follows the same fundamental conduction heat transfer principle. It is assumed that once the molten polymer in the sprue solidifies the injection unit can be retracted. Therefore, the approximated 1-D heat conduction solution for the hold time is given by [15]:

$$t_h = \frac{\kappa R_s^2}{\pi^2 \alpha} \ln\left[\frac{4(T_i - T_{mo})}{T_x - T_{mo}}\right] \tag{15}$$

where R_s is the sprue radius, α is the average thermal diffusivity of the polymer, T_i is the injection temperature, T_{mo} is the mold temperature, T_x is the polymer melting temperature, and the κ term is a geometric factor, which equals 2/3 for a cylindrical channel. The cooling time, t_{cool}, follows the same equation above with $\kappa = 1$, $T_x = T_{eject}$ (the recommended ejection temperature), and R_s is replaced with h_{max} (the maximum mold wall thickness).

The remaining cycle times involves the mold resetting, which includes movement of the injection unit, mold opening and closing, and part ejection. The resetting time can be approximated using the machine's specified dry cycle time, t_d. However, the reported dry cycle time is typically measured during an empty run with the mold opening and closing at full stroke. Therefore, the dry cycle time can be adjusted to account for actual part sizes, and is estimated using the equation [15]:

$$t_{moc} = 2 + 1.75 t_d \left[\frac{(2D_{mo} + 0.05)}{L_{mo}}\right]^{0.5} \tag{16}$$

where D_{mo} is the part depth and L_{mo} is the maximum clamp stroke. The above equation assumes a 40% opening speed, a part ejection time of 1s, an injection unit travel time of 1s, and a part clearance of 0.05 meters.

Combining Equations 13-16 yields the cycle time. However, as shown in Figure 1, several stages such as holding and plasticizing occur during part cooling. Therefore, to avoid double counting, the actual cycle time is computed as:

$$t_c = t_i + t_{moc} + t_{cool} \qquad \{t_{cool} > t_h + t_r\}$$
$$t_c = t_i + t_h + t_r + t_{moc} \qquad \{otherwise\} \tag{17}$$

3.4 Non-Newtonian Viscosity Model

A unique property of thermoplastic polymers is their viscoelastic behavior, particularly at temperatures above the glass-transition temperature and into the molten state. Unlike Newtonian fluids where the shear stress varies linearly with the shear rate and thus viscosity is constant, the rheological properties of polymer melts vary with shear rate and exhibit "shear thinning" behavior where the viscosity decreases with increasing shear rates [13]. To model the highly nonlinear non-Newtonian viscosity, the four-parameter Carreau Model is used:

$$\frac{\mu(\dot{\gamma}, T) - \eta_\infty}{\eta_o(T) - \eta_\infty} = \frac{1}{\{1 + [\tau(T)\dot{\gamma}]^2\}^{[1-n(T)]/2}} \tag{18}$$

where η_o is the zero shear (or Newtonian) viscosity, η_∞ is the viscosity at infinite shear (assumed to be zero), τ is the relaxation time, n is the Power Law index ($n < 1$ for shear-thinning), and $\dot{\gamma}$ is the shear rate [13]. Each of the parameters (with the exception of η_∞) is dependent on the temperature (and pressure, but assumed to be negligible), where an increase in temperature will decrease the viscosity. At low shear rates the polymer melt behaves more as a Newtonian fluid and is less shear rate dependent as temperature increases.

The for rotational shear done by the screw is used to determine the average shear rates during plasticizing (shear rates during injection are accounted for in Equation 4), and is given as [13]:

$$\dot{\gamma} = \frac{\pi D_b^2 N^2 W \cos\theta_b}{3 Q_{ex}} \tag{19}$$

where N, D_b, W, θ_b, and Q_{ex} are the same parameters as in Equation 5. Note that the shear rates during plasticizing are typically lower than that of during injection (same volume at longer processing times) and in some cases may approach that of Newtonian behavior.

4 MODEL PERFORMANCE

Several reported SEC values, publically found in literature, were used to validate the semi-empirical model. Three thermoplastic polymers, polystyrene (PS), Nylon (PA6), and high-density polyethylene (HDPE), were chosen due to the data availability of their process parameters, and are summarized in Table 2. The parameters for the model are also shown in Tables 3. The process parameters in Table 3 (excluding injection and mold temperature) were adjusted to match the cycle times and throughputs from Table 2. Reasonable dimensional approximations were made based on the description and volume of the part (e.g. a cup modeled as a cylinder with a base).

Material	PS [11]	PA6 [7]	HDPE [3]
Machine Size [tons]	15	75	550
Shot Size [g]	15.6*	880	930
Cycle Time [s]	53.6	30.7	17.7
Throughput [kg/hr]	1.05	10.31	188.66
SEC [MJ/kg]	**9.11**	**2.35**	**2.49**
Part Design	disk	cup	5 gal pail

Table 2: Summary of reported SEC values and respective parameters (*estimated part weight).

Material	PS	PA6	HDPE
Injection Rate [cm^3/s]	40	105	850
RPM	30	150	200
Average Injection Temp	160 [11]	280 [4]	250 [4]
Ejection Temp [C]	80	130	65
Average Mold Temp [C]	20 [11]	90 [4]	27 [4]
Crystallinity	*amorph.*	*semi c.*	*semi c.*

Table 3: Process parameters used in the model.

The process parameters in Tables 2 and 3 were inputted into the model and a Monte Carlo method was used to obtain the mean SEC and 95% confidence interval. The model results for the three polymers are tabulated in Table 4 and plotted in Figure 4. For each material, the reference SEC value from Table 2 is juxtaposed with the model as well as data from two professional material/LCA software databases: Gabi by PE International [16] and CES Selector by Granta Design [17]. For consistency, the same injection molding unit-process module in Gabi was used for all three polymers, while individual datasheets were read from the CES Selector.

As shown in Figure 4, the proposed model performs extremely well, with the reference values well within the 95% confidence interval. The range of the confidence interval, however, is drastically different for polystyrene where the maximum error at 95% confidence is over 23%. This can be attributed its relatively low throughput where the slope of the SEC versus throughput curve is steeper and hence has a higher sensitivity to the cycle time. The higher sensitivity to cycle time is prorogated during the Monte Carlo simulation and thus resulting in a larger relative standard deviation.

	PS	PA6	HDPE
Mean	8.80	2.42	2.39
Standard Deviation	1.057	0.163	0.147
95% Confidence Interval (±)	2.072	0.319	0.288
Relative Error	3.40%	2.98%	4.02%
Confidence Interval Range (±)	23.55%	13.18%	12.05%

Table 4: Model results and errors.

Even with a relatively larger confidence interval range, values from Gabi and CES are clearly seen to differ more significantly. This can be explained by noting the limitations and assumptions of the software. While the injection molding module in Gabi is parametric, the function is a generic linear relation of only to the mass. Hence there is no notion of factoring different machine sizes and throughputs thus giving a higher level of uncertainly. Note that the data given by the software may not necessarily be incorrect since at some particular machine size and throughput the values should be accurate.

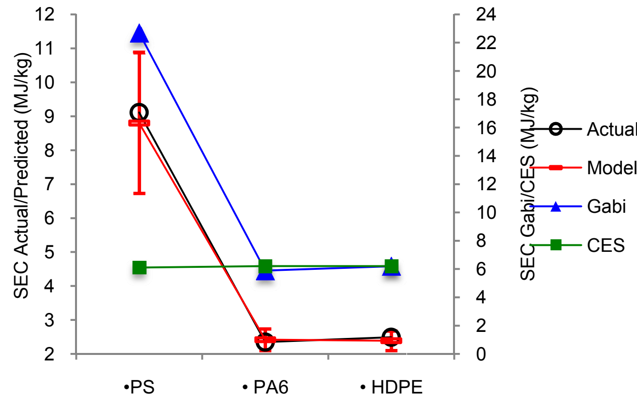

Figure 4: Comparison of model performance.

Figure 5 shows the relative energy breakdown by stage for each of the three polymers. Observe that the contribution of the idle energy decreases with decreasing cycle time (or equivalently increasing throughput). Higher throughput typically implies a shorter cool time since in most cases (depending on the material and part design) cooling is the bottleneck stage. With a shorter cooling time less (baseline) energy is being consumed from simply waiting for the part to cool. Another observation is that the ratio of plasticizing to injection energy is highest in the PA6 case (the injection energy is nearly indistinguishable), which suggests that the heat (temperature) was the dominant means of plasticizing (higher temperature lowers the viscosity). The contribution of the plasticizing and injection energy for the HDPE case is relatively large, which is partially attributed to the high viscosity even at high shear rates.

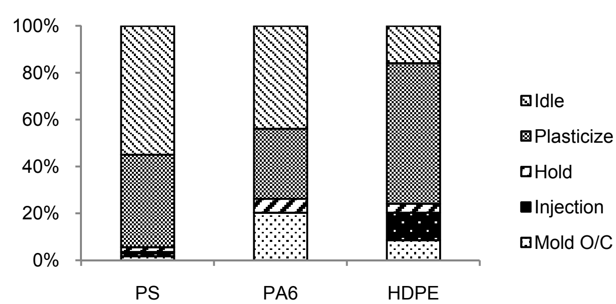

Figure 5: Relative distribution of energy consumption by stage.

5 DISCUSSION OF ERRORS

As with any modeling involving empirical data, especially by means of meta-analysis, errors associated with quality of the data were unavoidable. There were several types of errors involved in this model. The first arise from the extraction of the power consumption values based on images rather than the source data. Due to the limited resolution of the power profile images best estimates of the average power were determined. Additionally, for power consumption profiles where the idling clearly showed discernable cycling of the heaters (e.g. in Figure 3) the baseline power was used. This was to reduce double counting of the wasted heater power accounted for in Equation 7.

There were also errors due to uncertainty in replicating the processing parameters, machine model, and material (e.g. polymer grade) that were used in creating the original power profiles. Furthermore, approximations in the part dimensions were obviously subject to errors.

Uncertainty and errors in the data were handled using normally distributed probability density functions (PDFs). For data coming from a published source a 2.5% to 5% error was assigned as the standard deviation, while 10% to 15% error was assigned for non-verified data (e.g. part dimensions). Average relative errors were used to represent the standard error in the regression models. The mean values and respective 95% confidence intervals (±1.96 sigma) were determined by using a Monte Carlo technique with an adequate sample size of *N=10,000*.

The final error type was due to the quality of the modeling. Figure 6 below shows the contribution of the total energy calculated by the empirical model vs. the theoretical model. For an instance, the HDPE case shows more sensitivity to the theoretical modeling, which implies that errors from the thermo-mechanical model (i.e. injection and plasticizing) have a greater influence than the errors from the empirical model. In addition, more accurate representation of the material properties, such as having density, specific heat, and thermal conductivity vary as a function of temperature, can improve the accuracy. However, this ratio is highly dependent on the material, process parameters, throughput, etc. as shown when compared to the PA6 case.

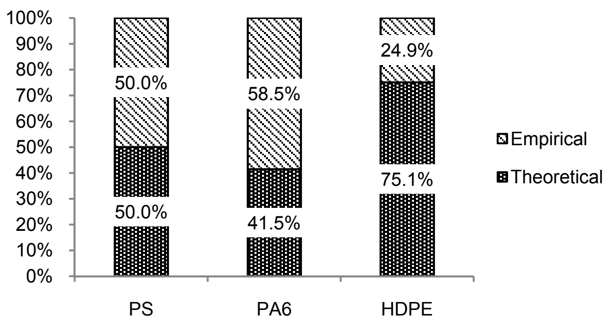

Figure 6: Ratio of empirical to theoretical energy consumption.

6 SUMMARY

This paper presented a detailed semi-empirical model for accurately predicting the electrical energy consumed during injection modeling. The model took into consideration the polymer's rheological non-Newtonian viscoelastic properties and part design while utilizing both thermo-mechanical fundamentals and empirical data. The incorporating the machine specific power characteristic empirical data greatly improved the accuracy of the model. When compared to professional software databases the model performed exceptionally well, particularly when factoring in processing throughput.

Further work is necessary improve the accuracy, particularly the confidence interval range, and robustness of the model. Expansion of the empirical data can included to model machine sizes greater than 550-tons as well as different machine types (e.g. all-electrics), while slight modifications can be made to include non-thermoplastic polymers, such as thermosets and elastomers. Addtional enhancements can be made by adding the power component of a hot runner (not all processes require a hot runner) and by including the energy consumption of any auxiliary equipment such a barrel chiller and dryer for the hopper.

7 REFERENCES

[1] SPI, Inc. (2009): Plastics Fact Sheet, in: www.plasticsdatasource.org, Accessed 11/27/2012.

[2] Barr, D. (2003): Injection Molding Hydraulics the Pressure is Rising, in: Machinery Lubrication { http://www.machinery lubrication.com}, Accessed 11/27/2012.

[3] Thiriez, A. (2006): An Environmental Analysis of Injection Molding, Master Thesis at MIT, Cambridge, MA.

[4] Rosato, D.V., Rosato, D.V., Rosato, M.G. (2000): Injection Molding Handbook, 3rd ed., Kluwer Academic Publishers, Norwell, MA.

[5] Kalla, D., Twomey, J., Overcash, M. (2009): MC2 Injection Molding Process Unit Process Life Cycle Inventory, pp. 1-14, {http://cratel.wichita.edu/uplci/injection-molding/}, Accessed 7/26/2012.

[6] Gutowski, T., Dahmus, J., Thiriez, A. (2006): Electrical Energy Requirements for Manufacturing Processes, in: Proc 13th CIRP Intl Conf LCE, pp. 623-628, Leuven, Belgium.

[7] Ribeiro, I., Peças, P., Henriques, E. (2012): Assessment of Energy Consumption in Injection Molding Process, in: Proc. 19th CIRP Intl Conf LCE, pp. 263-268, Berkeley, California.

[8] Mattis, J., Shen P., DiScipio, W., Leong K. (1996): A Framework for Analyzing Energy Efficient Injection-Molding Die Design, in: Proc 1996 IEEE Intl Symp Elec Env, pp. 207-212 Dallas, Texas.

[9] Gutowski, T., Branham, M.S., Dahmus, J.B., Jones, A.J., Thiriez, A. (2009): Thermodynamic Analysis of Resources Used in Manufacturing Processes, in: Env Sci Tech, Vol. 43, No. 5, pp. 1584-1590.

[10] Duflou, J.R., Kellens, K., Guo, Y., Dewulf, W. (2012): Critical Comparison of Methods to Determine the Energy Input for Discrete Manufacturing Processes, in: CIRP Annals – Mfg Tech, Vol. 61, No.1, pp.63-66.

[11] Qureshi, F., Li, W., Kara, S., Herrmann, C. (2012): Unit Process Energy Consumption Models for Material Addition Processes: A Case of the Injection Molding Process, in: Proc 19th CIRP Intl Conf LCE, pp. 269-274, Berkeley, California.

[12] Weissman, A., Ananthanarayanan, A., Gupta, S.K., Sriram, R.D. (2010): A Systematic Methodology for Accurate Design-Stage Estimation of Energy Consumption for Injection Molded Parts, in: Proc. ASME 2010 IDETC/CIE, pp. 1-13, Montreal, Quebec.

[13] Tadmor, Z., Gogos, C.G. (2006): Principles of Polymer Processing, 2nd ed., Wiley-Interscience, Hoboken, NJ.

[14] Incropera, F.P., DeWitt, D.P., Bergman, T.L., Lavine, A.S. (2007): Fundamentals of Heat and Mass Transfer, 6th ed., John Wiley & Sons, Hoboken, NJ.

[15] Boothroyd, G., Dewhurst, P., Knight, W.A. (2011): Product Design for Manufacture and Assembly, 3rd ed., CRC Press, Boca Raton, FL.

[16] Gabi (Version 5) [Computer Software], PE International, Stuttgart, Germany.

[17] CES Selector 2012 (Version 11.9.9) [Computer Software], Granta Design Limited, Cambridge, United Kingdom.

Evaluation of the Resource Efficiency of RFID-Controlled Supply Chains

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Abstract

The application of RFID to control production and logistic processes is an approach for managing the increasing complexity in the automotive supply chain. Besides economic aspects, the use of energy and materials as well as its environmental impact are gaining importance in investment decisions and process redesign. Therefore, a method for evaluating the resource efficiency of RFID-controlled supply chains is needed. This paper introduces a six-step method which enables companies to evaluate the environmental impact of the RFID-caused process changes in the planning process.

Keywords:

Supply chain management; Life cycle assessment; Auto-ID technologies

1 INTRODUCTION

Due to an increasing variety of products and the pressure to innovate, manufacturing companies often focus on their core competencies. This causes the development of complex supply chain networks with many associated partners [1]. Reduced throughput times and stock buffers additionally pose a challenge for the coordination of these networks. The application of RFID (Radio frequency identification) to control production and logistic processes is an approach to manage this increasing complexity in the automotive supply chain.

Besides economic aspects, the use of energy and materials and its environmental impact are getting more and more important in supply chain planning. Globalization, the industrialization of the populous emerging economies and the growing world population influence the availability of resources and render environmental conditions, e.g. in form of the climate change [2]. As a result, political regulations as well as increasing prices motivate companies to consider environmental aspects in their investment decisions.

A reduced consumption of resources in terms of energy and material can be realized through the implementation of RFID-based control architectures in production and logistic processes. This can be achieved within transportation processes through higher capacity utilization and less special transports. Other effects of the use of RFID with positive environmental impact are reduced stocks and paperless communication because of an electronic transmission of work orders.

Studies show that in ten years the application of information and communication technologies (ICT) can reduce Greenhouse gas emissions (GHG) five times the amount which is caused by ICT usage (Figure 1). According to the GeSi study intelligent production control, dematerialization and optimized logistics contribute over one third to the positive effects [3]. These results also illustrate the need for a differentiated evaluation of negative and positive effects on the environment caused by the use of ICT related technologies such as RFID. On the one hand there are numerous advantages associated with the supply chain process design which is enabled by RFID. On the other hand the use of a technology generally causes additional resource consumption. Especially production and use of ICT hardware as well as its disposal requires resource input.

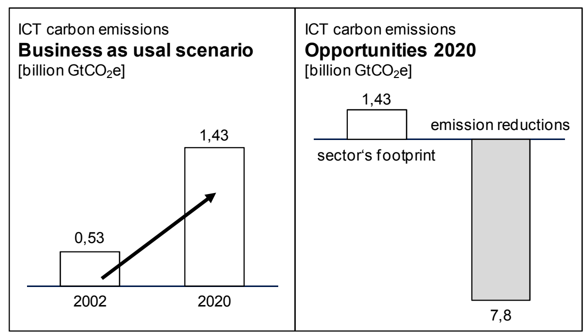

Figure 1: Potentials of ICT [3].

This paper therefore presents a method for evaluating the resource efficiency of RFID-controlled supply chains which is in line with the ISO 14040 on life cycle assessment (LCA). The general framework for environmental evaluation is discussed in section 3 as well as existing approaches for environmental evaluation in supply chains. Beforehand, the RFID technology is introduced (section 2). Section 4 then presents a six-step method for the evaluation of resource efficiency, which has been developed within the research project RAN (RFID-based Automotive Network). The method enables to assess positive as well as negative effects of the use of RFID throughout the supply network.

2 RFID

In recent years, the use of wireless-based RFID technology has become increasingly important. By means of electromagnetic fields, a contactless data exchange between the RFID tag and the receiver is enabled. The advantage of RFID systems compared to other auto-ID systems, such as the commonly used barcode, is that multiple objects can be detected automatically and simultaneously without visual contact. However, certain materials in the environment, such as metal, produce a shielding effect [4].

Apart from the increased efficiency by automated reading operations, companies applying RFID expect more opportunities for the improvement of the entire process chain. On the one hand the low-cost generation of additional data can increase transparency in the supply chain; on the other hand new process controls in the supply chain can be implemented.

In the corresponding literature numerous potentials resulting from the use of RFID technology are mentioned. Apart from cost savings through automation, an improved inventory management, less inventory shrinkage, reduced processing times or increased transport capacity utilization can be realized. Cost savings can arise from less error correction costs or by optimization of product recalls, for example [5, 6]. These potentials influence on the one hand the economic efficiency of processes, but on the other hand also have an impact on the resource efficiency (Figure 2). A reduced consumption of resources – in terms of material and energy – can be achieved through the use of RFID-based control architectures, for example in transport processes, through reduced stocks or paperless communication.

Whereas approaches for the economic evaluation of RFID are already intensively discussed in literature, methods for the evaluation of resource efficiency are far less mature [7]. Therefore it is necessary to adapt and clarify existing approaches, to make them fit to the technology specific requirements.

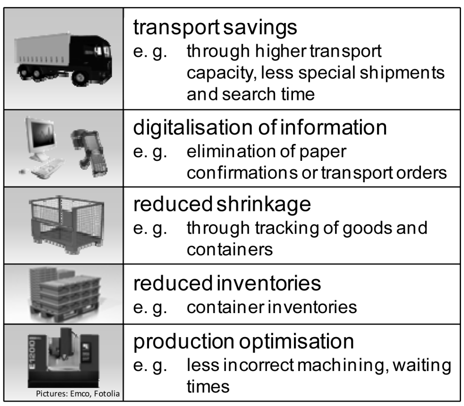

Figure 2: Potentials of the use of RFID.

3 RESSOURCE EFFICIENCY EVALUATION

3.1 LCA

There are various methods to evaluate the environmental impact of products, such as the PAS 2050 of the British Standards Institution or the Green House Gas Protocol (GHGP). However, life cycle assessment (LCA) according to ISO 14040 is the only standardized method [8].

Goal of a LCA is the accounting and evaluation of the environmental impacts throughout the life cycle, from raw material extraction, production and use phase to recycling and disposal. In opposite to other evaluation methods like the PAS or GHGP, LCA according to the ISO standard does not focus on a specific impact category, such as the climate change [9]. An overview of commonly used life cycle impact categories is given by the U.S. Environmental Protection Agency [10] and Guinnée et al. [11].

A complete life cycle assessment in line with the ISO 14040 consists of 4 main steps [9]:

1. The goal and scope of the study have to be defined.
2. Input/output data of the regarded product system has to be collected (life cycle inventory analysis – LCI).
3. To better understand the environmental significance, specific impact categories are associated with the inventory results (life cycle impact assessment - LCIA).
4. Consistent with the goal and scope defined, the results of the LCI and LCIA have to be interpreted.

Object of the study is a product, which can be any good or service. The evaluation of the RFID use in supply chains constitutes a special case as it analyzes rather process chain design than a single product. Therefore approaches have to be adapted.

3.2 Evaluating the Environmental Impact in Supply Chains

The evaluation of resource efficiency in supply chains poses a challenge for research as well as for practitioners, with regard to the wide system boundary and the general complexity in production networks.

An existing model overcoming this aspect is the Green SCOR model. This approach is built on the classical Supply Chain Operations Reference Model (SCOR) (Figure 3). It aims at collecting environmental data over the whole supply chain in order to calculate supply chain performance and to configure processes. Key metrics are carbon emissions, air pollutant emissions, liquid waste, solid waste and the percentage of recycled waste [12].

Another approach which concretizes the inventory phase of a LCA for supply chains is the one of Albino [13]. Here, an input-output model for the analysis of a local or global supply chain is presented (Figure 3). It focuses on revealing relationships among processes to finally improve supply chain design from the environmental perspective.

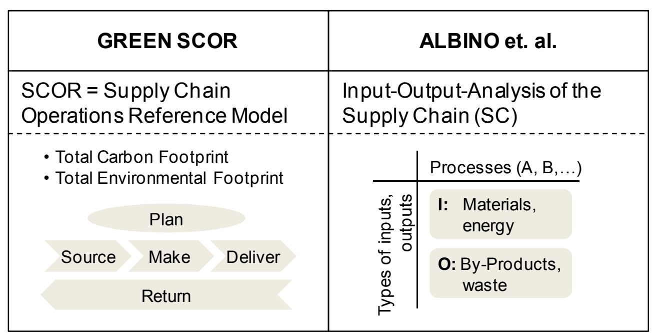

Figure 3: Resource efficiency evaluation in supply chains [12,13].

Regarding existing approaches to evaluate the resource efficiency of RFID in supply chains, four main challenges become apparent:

- Especially the definition of the system boundary as well as concrete valuation rules are not focus of the detailed discussion.
- As mentioned above, most LCA approaches are more product than process orientated.
- An absolute evaluation of the supply chain is normally conducted. This implicates – in contrast to a comparative analysis - a high effort for data collection.
- The mentioned approaches postulate the use of a specific impact category (e.g. climate change) or do not aggregate the outcome of the inventory analysis. Supporting the selection of appropriate indicators is a subordinated issue.

4 METHOD TO EVALUATE RESSOURCE EFFICIENCY IN RFID-CONTROLLED SUPPLY CHAINS

To evaluate the potential impact of RFID in production and logistic processes on the environment a six-step method is applied (Figure 4). First of all, the supply network has to be modeled. In addition, the system boundary of the evaluation needs to be specified. The evaluation as a whole is designed as comparative analysis between an initial process and an optimized network configuration which is enabled by the RFID technology. The following two steps comprise the identification of positive as well as negative effects of RFID on resource efficiency. The required RFID hardware, for example transponders and read/write devices, causes additional resource expenditure. After the quantification of all effects (step 4) the environmental impacts have to be determined through a life cycle impact assessment. To support the evaluation, life cycle data for the relevant hardware components were calculated and integrated in the method. The last step is the analysis and critical review of the evaluation.

The following sections present the developed method step by step.

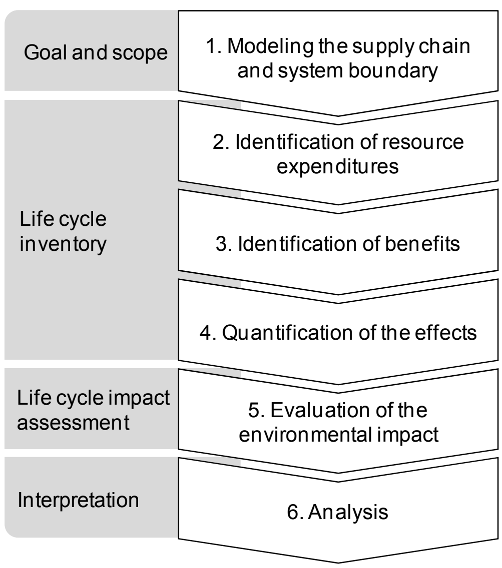

Figure 4: Method to evaluate resource efficiency of RFID.

4.1 Modeling the Supply Chain and System Boundaries

System Boundary

In the first step of the evaluation method the goal and the scope pursued by the assessment have to be defined. These determine significantly the level of detail and the amount of time required for the evaluation.

In particular the following aspects have to be discussed:

- Motivation
- Target group
- System boundary

The reason why the evaluation is carried out has to be stated clearly. One motivation can be the preparation of an investment decision or the review of an ongoing RFID project. The motivation determines particularly the requirements for data to be collected (e.g. detail level of collected data concerning the RFID benefits).

Closely linked to the reasons for conducting the evaluation is the addressed target group. It defines particular requirements on the form and content of the evaluation results as well as preparation of the analysis to be performed.

Probably the most complex issue in the first step of the evaluation method is the determination of the system boundary. RFID can be applied both intra-corporate or across companies. Depending on the goals defined, the evaluation may therefore only include the company's own benefits and expenditures through the use of RFID or also consider effects arising throughout the supply chain. There must be a definition of which effects can be really attributed to the RFID project. For example, if further process improvements – besides RFID – are implemented, which is often the case in RFID projects, they can be included in the assessment or not. A careful definition in advance ensures consistency throughout the evaluation process. This is particularly important when several people are involved in the data collection, e.g. in different segments of the supply chain.

As mentioned above a difference evaluation between an actual process (without RFID implementation) and a target process (RFID-supported) is adopted. During a lifecycle-orientated evaluation of resource efficiency of RIFD, two cases generally have to be considered. Firstly, for the implementation of the target process, resources, especially the RFID hardware, have to be purchased. Additionally the replacement of resources can become unnecessary. The latter occurs for example when container inventories can be reduced through a RFID-controlled container management. Secondly, there may be process changes which cause the disposal of resources, e.g. robots for handling processes or barcode scanners. These resources can optionally be reused elsewhere in the organization. For the consideration of these two cases in the evaluation, the following scheme is proposed (Figure 5):

Resources	Production	Use	End-of-Life
Newly purchased equipment, elimination of re-procurement	✓	✓	✓
Release/disposal, further use in other processes	–	✓	–

Figure 5: Evaluation scheme for resources.

For the implementation of the target process newly acquired resources must be included with their full life cycle in the evaluation. This is also applied to resources which are eliminated in the optimized RFID process. Second category is formed of already existing resources - such as equipment - which are subject to changes. The latter means additional installation or release of existing resources as well as further use in other processes. For these resources only the use phase is included in the evaluation if there is a change between the initial and the target process. Here resource expenditure arising by production and disposal process cannot be attributed to the regarded RFID implementation.

Process Modeling

Besides the definition of the system boundary the supply chain has to be modeled in an appropriate granularity. Firstly, the modeling method should illustrate the material flow as the goal of the modeling is primarily to allocate resource benefits and expenditures to the process. Secondly, indirect processes such as planning activities have to be considered.

In addition to that, the modeling of product systems (system flow chart) as described in the ISO 14040 [9] could become necessary.

This further specification is needed to evaluate the particular environmental impact of single identified effects of RFID in an extra life cycle assessment.

Figure 6 visualizes the two levels of resource efficiency evaluation.

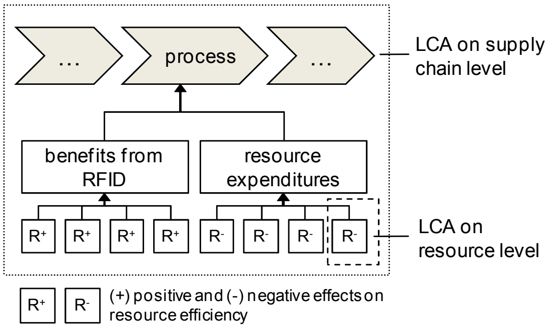

Figure 6: Evaluation levels.

4.2 Identification of Resource Expenditures

Comparing the initial process with the target process two different types of additional resource expenditures in the RFID-controlled process can occur:

- Resource expenditures caused by process changes
- Installing the RFID infrastructure

Process Changes

The implementation of a RFID control in production and logistics may change single processes [7]. This can result in increased energy consumption, if for example equipment is additionally installed or its operational mode is changed. If additional transports become necessary to realize the target process they have a negative effect on resource efficiency. Generally, during the process design phase attention should be paid to these kinds of process changes to avoid them whenever possible.

RFID Infrastructure

The RFID deployment is associated with the installation of a complex IT infrastructure which has to be taken into account in the resource efficiency evaluation. According to the required hardware, several hierarchical levels of RFID infrastructure can be distinguished. At the lowest level, there are the RFID transponders, which are tagged on objects such as containers or product components. RFID readers – on the second level – permit to store data on the transponder or read information from the transponder. To evaluate this data and thus make it usable for process control appropriate support systems are needed (third level of infrastructure). The central information broker at the top level regulates the cross-company data exchange and provides the necessary data in a standardized format to the different companies in the supply chain. The data is normally physically stored on different repositories being located at the individual companies.

4.3 Identification of Benefits

Identifying positive as well as negative effects of the use of RFID can be carried out simultaneously. This also reduces time and effort especially when the knowledge of process experts for the evaluation of different sections of the supply chain is required.

Potential benefits of RFID were already described in section 2. Generally two different categories of benefits can be distinguished. On the one hand there are direct effects which occur in a specific process. This can be for example less transportation between the incoming goods department and the warehouse. On the other hand there are effects which result from error avoidance. RFID can ensure the quality of a process. Errors normally cause additional resource expenditures, for example in form of return transports or reworking measures. Especially this last type of benefits is difficult to identify as they are connected with numerous effects. Furthermore, consequences of errors only occur with a certain probability as well as they are not always detected at the same point. These probabilities have to be determined to capture all effects of RFID on resource efficiency.

4.4 Quantification of the Effects

In this step the identified effects influencing resource efficiency have to be quantified to complete the life cycle inventory analysis.

Some of the resource expenditures or benefits identified in the previous steps have to be further specified, because they are linked to the consumption of several resources. For example, the RFID hardware is built out of many individual components, which can again consist of several materials. To determine the environmental impact in the next step savings or additional expenditure for each material have to be declared. It should be noted that these data are often not fully available for the companies. This can be avoided if published LCA data sets for components or the whole product already exist. For these LCA data sets consistency with the product to be evaluated has to be checked. Especially for production equipment the required life cycle data is often not available. For products which are also used by private end consumers such as IT hardware (e.g. computers, screens, printers) the data availability is higher. Though, the quality of available data can often not be assessed when detailed information about the calculation method is missing. Nonetheless it is better to use data which is considered to be an approximation then to exclude certain effects from the evaluation [14].

The determination of resources – in terms of individual materials or modules with predictable environmental impact – represents the first step of quantification (Figure 7). In the second step additional information necessary to determine the environmental impact has to be documented. Different life-cycle databases contain numerous resources and allow through the use of pre-calculated indicators, such as the carbon footprint, an assessment of the environmental impact. However, to attach proper characterization factors to the identified resource efficiency effects, additional descriptive information about the resources is often needed. This is particularly the case when resources have been passed through further processing or a particular process itself has to be quantified, for example, a transport process. Therefore for each resource – besides the exact quantity – information on the type, form or physical state has to be obtained. In the case of energy, for example, it is relevant in what country it was generated from what source it was won. Quantification of transports requires additional information on fuel type, the emission class of the vehicle or load.

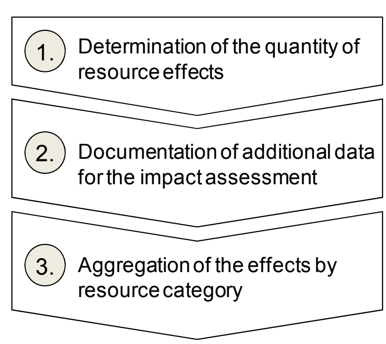

Figure 7: Procedure for the quantification of resource expenditure.

In the third step similar resources on the two sides - resource expenditures and benefits - can be aggregated. This simplifies the mapping of characterization factors for the calculation of the environmental impact, because potentially fewer factors have to be assigned. In addition, an overview of the nature and amount of different resources is provided.

4.5 Evaluating the Environmental Impact

In the penultimate step of the evaluation of the resource efficiency of RFID-controlled supply chains the impact assessment has to be carried out. Which impact categories are to be used should have been determined in the first step of the evaluation method. An impact category which is often used in industry, especially in the automotive industry, is the climate effect (product carbon footprint). To what degree this factor is suitable for the assessment of the resource efficiency of the RFID depends in particular on the type of occurring benefits. For example, if transports are saved, the climate impact is - due to the occurring emissions - a reasonable factor for the assessment of environmental impact. For other benefits, such as the saving of paper, another impact category could be more appropriate.

To calculate resource efficiency, any quantified resource expenditure or benefit has to be multiplied with the characterization factor of the selected impact category. The product of quantity and characterization factor is the respective indicator value. These values must be added subsequently from the process module level to supply chain level. Afterwards overall effects, such as the environmental impact of the implemented RFID hardware, which cannot be allocated to single process steps, have to set off against process related effects. The calculation can be done both for intra-company processes as well as on cross company perspective. It should be noted that in the summation of company-individual assessment results, no effects are double accounted – e.g., the elimination of transportation at the original equipment manufacturer (OEM, causation) and logistics service providers (impact).

To facilitate the evaluation process and provide the RFID users with the relevant life cycle data for RFID hardware two representative RFID transponders and a RFID reader were analyzed. Exemplarily the life cycle assessment of a RFID smart label is presented here.

A smart label is built up as self-adhesive label. The inlay of the label consists of a carrier foil, the chip and the antenna. Data on the material composition of the considered RFID tag were taken over from the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) who provide a material list including the mass fractions [15]. Apart from the outer layer made of polypropylene and paper as well as the acrylate adhesive, the carrier film of PET and the antenna reach the largest mass fraction. The mass of the chip is less than 1% of the mass of the entire inlay. Figure 8 shows the system flow chart of the manufacturing process investigated for the smart label.

The construction of bar tags varies in that way that the RFID inlay is surrounded by a solid plastic case. Therefore the manufacturing process implies that additionally the plastic case has to be manufactured – normally through injection molding – in which the inlay is then inserted. For the number of 1000 smart labels or bar tags a footprint of 14.7 kg and respectively 91.3 kg CO_2 equivalent (CO_2e) was calculated.

The disposal of transponders – according to the application in the supply chain – takes place after varying life time. This is especially determined by the object – e.g. containers or components of the automobile – which carries the transponder. It is relevant whether the object is circulated in a closed process or if it leaves the process after a single pass and comes with the product to the customer. Whereas smart labels usually remain on the carrier at the end of life, bar tags are usually separated for disposal. For the disposal in the municipal waste a credit of of 3.3 kg CO_2e for the 1000 smart labels or respectively 24.1 kg CO_2e for 1000 bar tags can be added to the overall balance. In this value the influence of waste collection, transport and the operation of the incinerator and credits for the provision of heat and recovery of ferrous and non-ferrous metals are taken into account [16].

An alternative method of disposal is the disposal of bar tags in plastic recycling, as the plastic housing accounts for a very high proportion by weight. In this case, a higher CO_2e credit may be

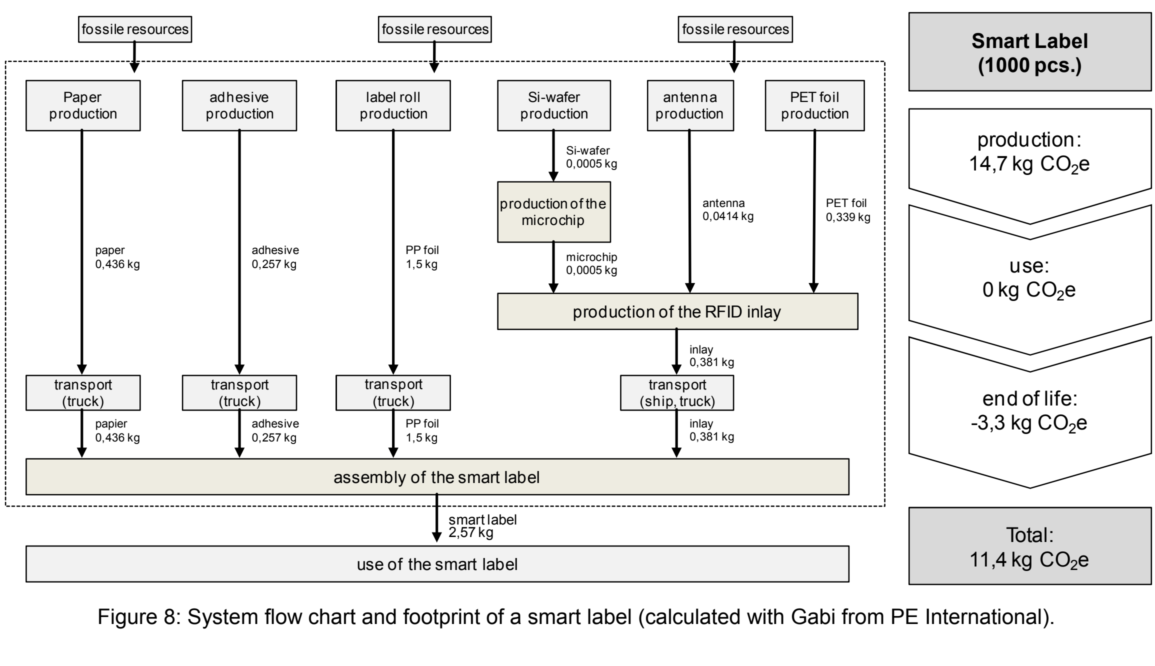

Figure 8: System flow chart and footprint of a smart label (calculated with Gabi from PE International).

assumed. But due to the introduction of the RFID inlay in the recycling process undesirable substances are fed, which may have in a larger quantity effects on the process performance and the quality of the recycled material. [16] This is also the case when transponders remain at the carrier – such as the smart labels – and are recycled together.

4.6 Analysis

The last step of the evaluation method is the analysis of the results. Besides the elements described in the ISO 14040 [7], the analysis of the evaluation of the resource efficiency of the use of RFID in supply chain management allows to identify drivers of environmental performance. Trough sensitivity analysis influences of a single RFID implementation on resource efficiency can be detected. Additionally an alignment with economic evaluation can become necessary in favor of enabling process reengineering.

5 SUMMARY

The paper presented a new approach to evaluate the resource efficiency of RFID-controlled supply chains in line with the ISO 14040 standard for life cycle assessment. To assess the resource efficiency of the RFID use holistically, it is necessary to determine the benefits that result from the use of technology on the one hand, and on the other hand also take all related additional resource expenditures into account. The latter are especially consequences of the production, operation and disposal of the used RFID hardware and the necessary IT infrastructure. Benefits may arise in a variety of ways through the use of RFID-based control architectures. Efficient transport processes, lower inventories and paperless communication lead to an increase in resource efficiency. Newly procured resources, which are necessary for the implementation of an optimized target process must be – in contrast to already existing resources within the company – subject to a life-cycle-oriented environmental assessment. This is case for RFID hardware. An exemplary life cycle assessment of RFID transponders was shown in the last section of the paper. When data is not publicly available – from life cycle data bases, the manufacturer or third parties such as environmental institutes – a similar assessment has to be carried out. Throughout the whole evaluation process, data availability and quality in the quantification as well as in the impact assessment pose the key challenges. As many different effects on resource efficiency occur – concerning for example different equipment – a method for the quick evaluation of these effects is needed. Additionally, to ensure solid evaluation results, methods to judge the data quality level have to be further developed.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] Bullinger, H.-J.; Kühner, M.; Van Hoof, A. (2002): Analyzing supply chain performance using a balanced measurement method. International Journal of Production Research, Vol. 40, No. 15, pp. 3533-3543.

[2] BMU (2011): Strategie Ressourceneffizienz Climate Protection and Growth – Germany's Path into the Renewable Energy Age. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (available online at http://www.bmu.de/files/english/pdf/application/pdf/broschuere_klima_wachstum_en_bf.pdf)

[3] GeSI (2008): SMART 2020: Enabling the low carbon economy in the information age. The Climate Group of the Global eSustainability Initiative (available online at http://gesi.org/portfolio/report/69).

[4] Finkenzeller, K. (2010): RFID Handbook: Fundamentals and Applications in Contactless Smart Cards, Radio Frequency Identification and Near-Field Communication. Wiley; 3rd edition, 2010. ISBN: 978-0470695067

[5] Fleisch, E.; Ringbeck, J.; Stroh, S.; Plenge, C.; Strassner, M. (2004): From Operations to Strategy: The Potential of RFID for the Automotive Industry. Universität St. Gallen / ETH Zürich: M-Lab Arbeitsbericht Nr. 23 2004.

[6] Vilkov, L.; Weiß, B.: Prozessorientierte Wirtschaftlichkeitsanalyse von RFID-Systemen anhand eines Referenz-Wirkungsmodells. In: Becker, J. et al. (Hrsg.): Wertschöpfungsnetzwerke. Konzepte für das Netzwerkmanagement und Potenziale aktueller Informationstechnologien. Heidelberg: Physica 2008. ISBN: 978-3-7908-2055-3.

[7] Reinhart, G.; Irrenhauser, T.; Reinhardt, S.; Reisen, K.; Schellmann, H. (2011): Wirtschaftlicher und ressourcen-effizienter durch RFID?. In: ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, Vol. 106, No. 4, pp. 225-230.

[8] Schulz, R.; Zadek, H.: Bewertung von Emissionen und Ressourcenverbrauch; in: Zadek, H.; Schulz, R. (Hrsg.): Sustainable Logistics – Nachhaltigkeit von Logistikzentren durch Emissionsbewertung, Ressourcenschonung und Energieeffizienz. Hamburg: Deutscher Verkehrs Verlag 2011. ISBN: 978-3-87154-450-7.

[9] DIN 14040 (2006): Life cycle assessment – Principles and framework, Beuth, Berlin.

[10] EPA (2006): Life cycle assessment – Principles and practices. U.S. Environmental Protection Agency, Cincinnati/Ohio (available online at http://www.epa.gov/nrmrl/std/lca/pdfs/chapter1_frontmatter_lca101.pdf)

[11] Guinée, J.B.; Gorrée, M.; Heijungs, R.; Huppes, G.; Kleijn, R.; Koning, A. de; Oers, L. van; Wegener Sleeswijk, A.; Suh, S.; Udo de Haes, H.A.; Bruijn, H. de; Duin, R. van; Huijbregts, M.A.J. (2002): Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer Academic Publishers, Dordrecht, 2002. ISBN 1-4020-0228-9.

[12] Supply Chain Council (2010): Supply Chain Operations Reference Model 10.0. Supply chain Council, Inc., 2010. ISBN: 978-0-615-20259-4

[13] Albino, V.; Izzo, C.; Kühtz, S. (2002): Input-output models for the analyses of a local/global supply chain. Int. J. Production Economics, Vol. 78, No. 2, pp. 119-131.

[14] Hunt, R. G.; Bogusi, T. K.; Weitz, K.; Sharma, A. (1998): Case Studies Examining LCA Streamlining Techniques. International Journal of Life Cycle Assessement, Vol. 3, No. 1, pp. 36-42

[15] ISO/IEC TR 24729 (2007), part 2: Recycling and RFID tags. Berlin: Beuth 2007.

[16] Erdmann, L.; Hilty, L.; Althaus, H.-J.; Behrendt, S.; Hischier, R.; Kamburow, C.; Oertel, B.; Wäger, P.; Welz, T.(2009): Einfluss von RFID-Tags auf die Abfallentsorgung - Prognose möglicher Auswirkungen eines massenhaften Einsatzes von RFID-Tags im Konsumgüterbereich auf die Umwelt und die Abfallentsorgung. Umweltbundesamt 2009.

Impact of Parameter Estimation Inaccuracies on a Repairable Item System

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Abstract

Inventory control for spare parts is an element of life cycle management for machines. For reliable spare part supply and low costs for part procurement and recycling, spares are provided by closed-loop supply chains. After removal from the machine broken parts are repaired and put back into stock. Estimations of demand level, repair time and replenishment time are difficult to make and can be inaccurate, incurring suboptimal stock levels. A simulation model was built to analyze the effects of varying input parameters and their impact on supply chain performance.

Keywords:

closed-loop supply chain; spare parts; multi-echelon; simulation

1 INTRODUCTION

In many industry branches life-cycle costing becomes increasingly important. Diminishing revenues and a growing number of competitors require companies to keep operating and life-cycle costs of their machines as low as possible. Spare parts need to be available when requested to keep machine downtimes to a minimum.

Environmental legislation, high costs of the spare parts, lack of raw materials or lack of spare parts by the OEM increase the importance of closed-loop supply chains. After removal from the machine, the part is sent to a repair shop and repaired. The repaired part is put back into stock and is available for future spare part requests.

Because of economic and environmental reasons the inventory levels in the entire supply chain should be as low as possible, but at the same time guarantee reliable spare part supply. Controlling inventories in different warehouses in the repairable item system is challenging, because of feedback in the loop. The lower the number of parts in the supply chain, the lower the impact on the environment and the use of natural resources. There is a tradeoff, however, between inventory level reduction and the service level of part supply. To set correct inventory levels for the warehouses, estimates of different parameters like the demand level or the repair time have to be made. If these estimates are inaccurate, the calculated inventory levels are not optimal.

A simulation model was built to analyze the effects of varying input parameters, assuming a triangular distribution for the replenishment and the repair time and Poisson distributed demand. Supply Chain performance is analyzed, comparing the part fill rates. In this paper a literature review will provide an overview of past and current research activities in closed-loop supply chains for repairable items. An introduction to the developed simulation model follows. Section 3 presents results when input parameters are varied and discusses their impact on the supply chain performance.

2 LITERATURE REVIEW

Life-cycle costing is the focus of different publications. Denkena et al. [1] conduct a life-cycle cost analysis for a helicopter engine. They develop a tool for forecasting spare part demand, taking spare part requirements into account. Finding that spare part demand is very intermittent in the aviation industry, Romeijnders et al. [2] present a two-step method for forecasting spare part demand, using the information of type of component repaired. Syntetos and Boylan [3] analyze the most-well cited intermittent demand estimation procedures. They find that both the accuracy of forecasts and their variability have great impact on service level achievements.

Kilpi and Vepsäläinen show that combined spare part pooling saves costs and is very popular in the aviation industry [4]. Presenting over 60 papers, Kenndedy et al. [5] provide an overview of research findings about managing spare parts inventories. Some models allow backordering, where requests that cannot be fulfilled because of a stock-out situation are queued and wait for the next part to arrive. The METRIC model presented by Sherbrooke [6] was the first mathematical model for multi-echelon closed-loop supply chains. Other authors that optimize spare part inventory are Xiancun and Hongfu [7] or Tracht et al. [8], [9]. Selcuk [10], Wong et al. [11] as well as Guide and Sirvastava [12] publish research findings on repairable item control in different industry branches.

Many papers investigate the effects of lateral transshipments, where spare parts can be shifted between warehouses of the same echelon. Paterson et al. [13] provide an overview of multi-echelon supply chains with lateral transshipments and sorts the papers by different criteria. They distinguish between continuous and periodic review, backordering and lost sales, proactive and reactive transshipping, etc. Kranenburg and van Houtum [14] model a partial pooling structure which consists of main local warehouses and regular local warehouses. Lateral transshipments are only allowed between main local warehouses. By varying the number of local warehouses, they find that a small number of local warehouses is sufficient to obtain most of the transshipment benefit. Tracht et al. [15] present a simulation model for customer-owned stock. Some of the spare parts in the system are property of a customer and to date have not been taken into account by the spare part provider. The publication shows that disregarding these parts, incurs overstocking at the central warehouse.

Methods for dealing with supply chain dynamics in a one-way supply chain are presented in [16]. It organizes publications by categories like the bullwhip effect, supply chain resilience, and supply chain stability.

This paper focuses effects of varying input parameters in a closed-loop supply chain. Parameters like the demand level or the repair time have to be estimated to set the right inventory levels. If these forecasts are inaccurate, the supply chain performance is not optimal, because of over or under stocking at the warehouses. In the following the simulation model used for the investigation is introduced.

3 SIMULATION MODEL

3.1 Multi-echelon Supply Chain for Repairable Items

The simulation model used to conduct the investigations already served for other experiments. The most important characteristics of the model that only vary in details from the original one are described here. For results of former experiments and a thorough description of the model please see Tracht et al. [15].

Model Description

Figure 1 shows the supply chain for repairable items. In case of part failure the part is taken from stock at the distribution warehouses (dw) and is sent to the location of the machine. The broken part is removed from the machine and is sent to the repair shop, where it is repaired. Then, the part is put back into stock to fulfill future requests.

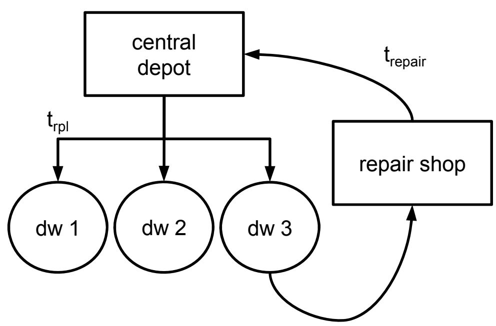

Figure 1: Two-echelon supply chain for repairable items [15].

When a spare is taken from the distribution warehouse, a replenishment is requested at the central depot. In case of a stock out at the distribution warehouse the request backorders and waits until the replenishment arrives. The broken part is removed from the machine and sent to the shop, when the spare is available for replacing the broken part. Thus the number spares in the entire supply chain remains constant.

When a replenishment is requested at the central depot and the central depot is out of stock, the replenishment request also backorders until a part that arrives from the repair shop becomes available. When different distribution warehouses await a replenishment delivery, the distribution warehouse with the greatest replenishment demand is served first. The replenishment demand is the sum of backordered request $n_{dw,backorder}$ and the minimum stock level at the distribution warehouse $n_{dw,msl}$ minus the number of parts that are on the replenishment transport $n_{dw,rpl}$ [15]:

$$n_{dw,d} = n_{dw,backorder} + n_{dw,msl} - n_{dw,rpl} \quad (1)$$

Parameters

The demand level λ is Poisson distributed and is varied during the investigation. The repair time t_{repair}, which also comprises transportation times to and from the repair shop, follows a triangular distribution with varying mean. The upper and lower bounds are 20% above or below the mean.

The time required for spare part to be transported from the central warehouse to the distribution warehouses is the replenishment time t_{rpl}. The mean of the replenishment time is also varied during the investigation and follows a triangular distribution. The upper and lower bounds are also 20% above and below the mean.

Each experiment with different parameter settings is repeated 50 times to calculate confidence intervals and mean values of the output parameters. The confidence coefficient equals 0.95. The simulation model generates 1,000 requests for each simulation run. Measurement of all output values begins after 100 simulated requests to allow the transient effects to settle.

The demand levels at the different distribution warehouses are equal to each other. Every distribution warehouse stocks two spare parts each ($n_{dw,msl} = 2$) and serves the same number of requests during the simulation run. Every distribution warehouse that is added to the system increases demand level on the entire supply chain.

3.2 Course of Investigation

In industrial applications estimations for t_{repair}, t_{rpl} and λ have to be made. The forecasts in many cases are not revised regularly so that inaccurate input values of one of the parameters causes a sub-optimal stock level. A sudden increase in demand is also probable and can cause wrong stock levels. Due to inclement weather or strike the repair time or the replenishment time can rise. To analyze the impact of parameters that are off the forecast, a parameter analysis is conducted.

The part fill rate is used to compare different input parameter sets. It equals the percentage of requests that can be fulfilled immediately from stock without backordering. Part fill rates and inventory levels of the warehouses and the depot are interrelated by feedback in the closed-loop supply chain. A part fill rate of 90% at the distribution warehouse is assumed to be optimal, i.e. giving a good tradeoff between inventory costs and costs that arise during waiting for a spare. Only the part fill rate of the distribution warehouse is relevant for reliable spare part supply to the machines.

First the number of distribution warehouses is set to 1. The stock level at the central depot is determined so that the distribution warehouse part fill rate is above 90 %, when $t_{repair} = 5$ days, $t_{rpl} = 5$ days and λ = 1/10 requests/day. The input parameters t_{repair}, t_{rpl} and the λ are varied in order to investigate the impact of the parameter changes.

Second the number of distribution warehouses is set to 10. For $t_{repair} = 5$, $t_{rpl} = 5$ days and λ= 1/10 requests/day the central depot stock level is determined to guarantee a distribution warehouse part fill rate above 90 %. Again t_{repair}, t_{rpl} and λ are varied.

4 SIMULATION RESULTS

In the following effects of inaccurate estimates for different parameters will be analyzed. The figures show results for the case with one distribution warehouse and ten distribution warehouses in the system. The confidence intervals are so narrow that they almost equal the mean value in most of the experiments.

4.1 One Distribution Warehouse

Figure 2 shows the part fill rates of the central warehouse and the one distribution warehouse when t_{repair} is varied. The central depot stock level equals 2 parts. The mean part fill rate of the central depot changes significantly from 99.5 % to 72.4 %, whereas the mean part fill rate of the distribution warehouse remains almost constant at around 90 %, when $t_{repair} < 5$ days and falls slightly to 87.1 % if $t_{repair} > 5$ days. If the forecast of the average repair time is inaccurate, the effect on the performance of the distribution warehouse is low.

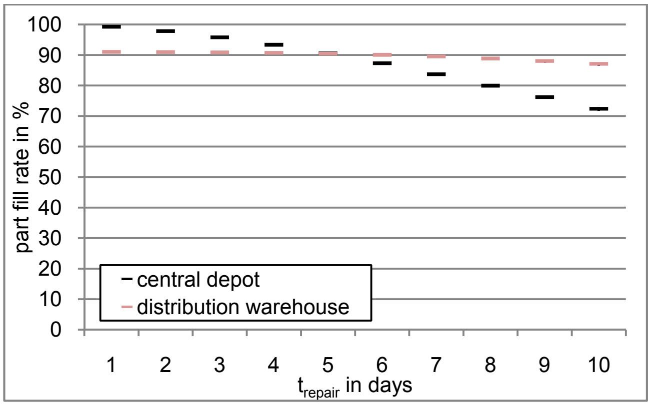

Figure 2: Part fill rates over t_{repair} with one distribution warehouse.

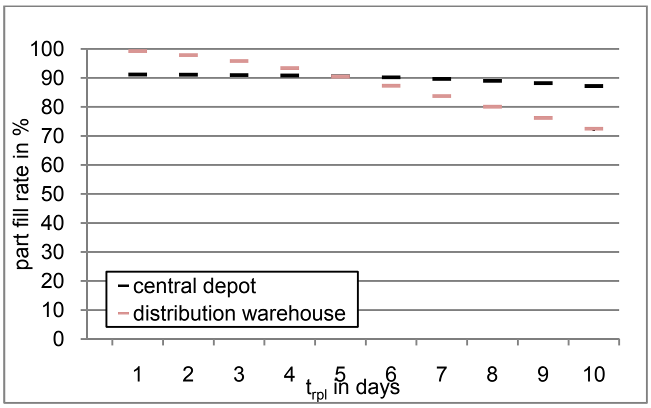

Figure 3: Part fill rates over t_{rpl} with one distribution warehouse.

Figure 3 shows the effects of varying replenishment time t_{rpl}. The part fill rate at the distribution warehouse is affected strongly, whereas the central depot rate remains almost constant. These effects are contrary to what happens, when t_{repair} changes. The distribution warehouse mean part fill rate falls from 99.3 % to 72.4 %, when t_{rpl} increases from 1 to 10 days.

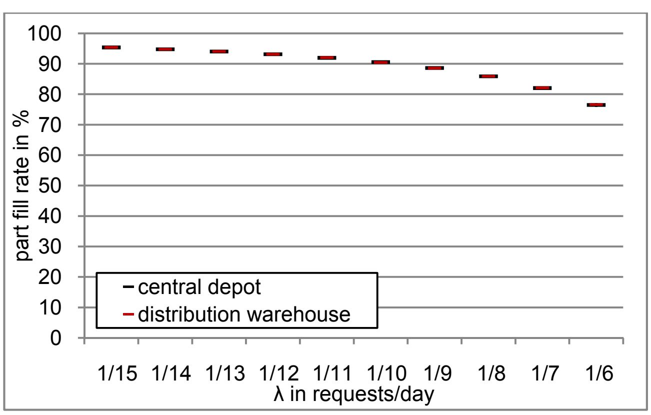

Figure 4: Part fill rates over λ with one distribution warehouse.

Figure 4 shows the mean part fill rates when the demand level λ varies. The part fill rates of the central warehouse and the distribution warehouse are identical, when demand increases or decreases. The mean part fill rates drop to 76.6 % when the demand level increases. The part fill rates at the central depot are more sensitive to a varying λ or varying t_{repair} than a varying replenishment time $t_{rpl.}$

4.2 Ten Distribution Warehouses

Figure 5 shows the part fill rate when t_{repair} varies for the case with ten distribution warehouses. The central depot holds 7 parts. The distribution warehouse part fill rate remains almost constant and approaches asymptotically the value 91 %, if t_{repair} is decreased from 5 days to 1 day. When t_{repair} > 5 days, the mean part fill rate of the distribution warehouse decreases. If t_{repair} =10 days, the mean part fill rate of the distribution warehouses equals 78.0 %.

The mean part fill rate of the central depot falls considerably to 9.5 %, if t_{repair} > 10 days. With ten distribution warehouses the part fill rates of both the central warehouse and the distribution warehouses are more sensitive to changes of t_{repair} than with one distribution warehouse (compare Figure 2).

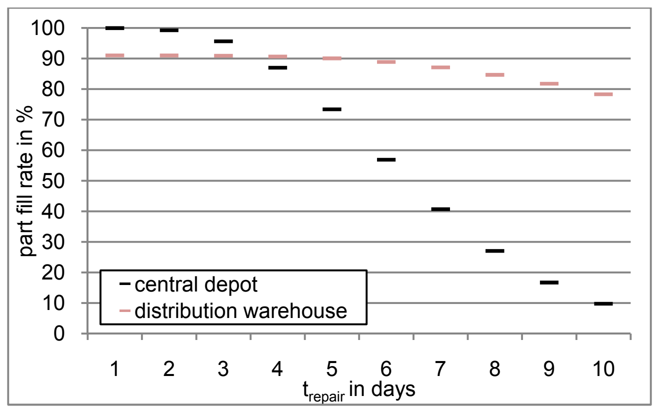

Figure 5: Part fill rate over t_{repair} for ten distribution warehouses.

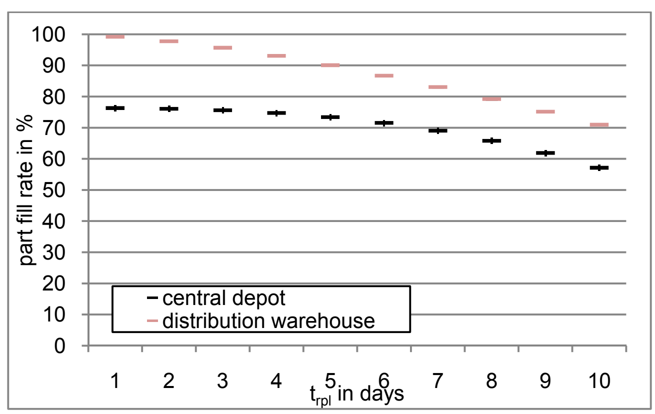

Figure 6: Part fill rates over t_{rpl} with ten distribution warehouses.

Figure 6 shows the part fill rates when t_{rpl} changes. Compared to Figure 5, the t_{rpl} has a bigger impact than the variation of t_{repair} on the part fill rate of the distribution warehouse.

As t_{rpl} varies, the part fill rate at the distributions warehouse changes considerably. It falls from 99.2 % to 71.0 % and is almost equal to the case with one distribution warehouse. The fall of the part fill rate does not depend on the number of distribution warehouses (compare Figure 3). To the contrary, the change of the central depot part fill rate is greater, when there are more distribution warehouses. It drops to 57.1 %, if t_{rpl} = 10 days. Decreasing t_{rpl} from 5 to 1 days, the central depot part fill rate approaches 86 %.

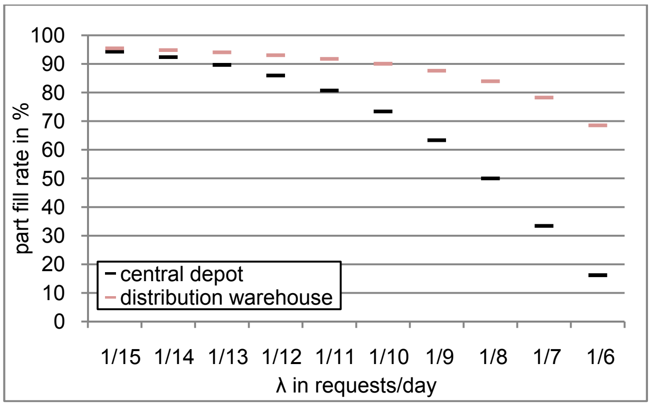

Figure 7: Part fill rate over λ for ten distribution warehouses.

Figure 7 displays the part fill rate over λ for ten distribution warehouses. The mean part fill rate at the distribution warehouses changes considerably and drops to 68.1 %. It does not fall as much as when varying the replenishment time t_{rpl}. The part fill rate at the central depot falls to 16.2 %, when the demand level λ increases. Compared to Figure 4, the part fill rate at the central depot and the distribution warehouse are affected more strongly, when there are ten warehouses in the system.

The influence on the part fill rates depends on the parameter that varies and the number of distribution warehouses in the supply chain. When t_{rpl} is varied the distribution warehouses are affected more strongly, when t_{repair} is changed the impact on the central depot is greater. Alterations of λ affect both part fill rates. But impact of the central depot part fill rate is greater, when there are ten distribution warehouses. When there are ten distributions warehouses, for example, the demand is the ten times higher than with only one distribution warehouse. Thus the change of λ has a bigger impact than with only one distribution warehouse.

5 CONCLUSION

Accurate estimation of demand levels, repair times, and replenishment times are of great importance for optimal spare part stocking in closed-loop supply chains for repairable items. Wrong forecasts cause sub-optimal stock levels and increase life-cycle costs for machines.

A simulation model was built to analyze the effects of varying input parameters on the supply chain for repairable items. The investigation shows that the variation of the parameters has different impacts on the part fill rates at the central depot and the distribution warehouses.

The replenishment time affects more strongly the distribution warehouse part fill rate than the central depot fill rate. For the case with ten distribution warehouses the central depot fill rate falls from 76.3 % to 57.1 % and with one distribution warehouse from 91.1 % to 87.2 %. The distribution warehouse part fill rate falls from 99.2 % to approximately 72 %, no matter how many distribution warehouses there are.

The repair time has a greater impact on the central depot than the distribution warehouse. The central depot fill rate falls from almost 100 % to 72.2 % (one distribution warehouse) or 16.2 % (ten distribution warehouse), whereas the distribution part fill rate varies between 91.1 % and 87.1 % (one distribution warehouse) or 78.3 % (ten distribution warehouses). The demand level λ affects both the central depot and the distribution warehouse part fill rate the same way when there is only one distribution warehouse in the system. When there are ten distribution warehouses in the system, the central depot fill rate is affected a lot more than the distribution warehouse fill rate and falls to as low as 16.2 %.

Because good distribution warehouse performance is required for reliable spare part supply for the machines, the replenishment time should be as short as possible and its variation as low as possible. Big variation of the replenishment time incurs unreliable spare part supply and reduced customer satisfaction.

As systems for repairable items become bigger, comprising more distribution warehouses, the accuracy of the estimation must increase to guarantee low life-cycle costs for the machines. The more distribution warehouses there are in the system the greater the impact of parameter changes is. Thus future research should be focused on improving forecasts of the demand level and replenishment time to realize economical life-cycles for the machines.

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7 REFERENCES

[1] Denkena, B., Eikötter, M., Blümel, P., Schneider, R., Khowwigkai, S. (2010): Life Cycle Cost Analysis and Prognosis Model in the Aviation Industry, in: Proceedings of the 5th International Conference on Innovative Production Machines and Systems, p. 260-265.

[2] Romeijnders, W., Teutner, R., Jaarsveld, W. (2012): A two-step method for forecasting spare parts demand using information on component repairs, European Journal of Operational Research, Vol. 220, No. 2, pp. 386-393.

[3] Syntetos, A., Boylan, J. (2010): On the Variance o Intermittent Demand Estimates, International Journal of Production Economics Vol. 128, No. 2, pp. 546-555.

[4] J. Kilpi, A. Vepsäläinen, (2004): Pooling of spare components between airlines, Journal of Air Transport Management, Vol. 10, Issue 2, 2004, p. 137 ff.

[5] Kennedy, W.J., Patterson, J.W., Fredenhall, L.D. (2002): An Overview of Recent Literature on Spare Parts Inventories, in: International Journal on Production Economics, No. 76, pp. 201-215.

[6] Sherbrooke, C. (1968): METRIC: A Multi-Echelon Technique for Recoverable Item Control, Operations Research, 16, pp. 122-141.

[7] Xiancun, N., Hongfu, Z., Ming, L. (2008): Research on Optimization Model of Civil Aircraft Spare Parts Inventory Allocation, in: Proceedings of the Control and Decision Conference, Yantai, China, pp. 1042-1045.

[8] Tracht, K., Mederer, M., Schneider, D. (2011): Effects of Lateral Transshipments in a Multi-Echelon Closed-Loop Supply chain, ed. Hesselbach, J. Hermann, C.: Glocalized Solutions for Sustainability in Manufacturing, Springer, pp. 443-447.

[9] Tracht, K., Mederer, M., Schneider, D. (2011): Source Selection in Spare Part Supply, in: Proceedings of the 44th International Conference on Manufacturing Systems, Madison, WI, USA.

[10] Selcuk, B. (2012): An Adaptive Base Stock Policy for Repairable Item Inventory Control, International Journal of Production Economics, in Press.

[11] Wong, H., Cattryse, D., van Oudheusden, D. (2005): Stocking Decisions for Repairable Spare Parts Pooling in a Multi-Hub System, International Journal of Production Economics, No 93-94, pp. 309-317.

[12] Guide Jr., V.D.R., Srivastava, R. (1997): Repairable Inventory Theory: Models and Applications, European Journal of Operational Research, No. 102, pp. 1-20.

[13] Paterson, C.; Kiesmüller G; Teunter, R.; Glazebrook, K. (2010): Inventory Models with Lateral Transshipments: A review, in: European Journal of Operational Research, in Press.

[14] Kranenburg, A.A., van Houtum, G.J. (2009): A New Partial Pooling Structure for Spare Parts Networks, European Journal of Operational Research, No.199, pp. 908-921.

[15] Tracht, K., Mederer, M., Schneider, D. (2011): Impact of Parameter Changes in a Service Provider Closed-Loop Supply Chain with Customer-Owned Stock. ed.: Dornfeld, D., Linke, B., Leveraging Technology for a Sustainable World, Springer, pp. 593-598.

[16] Stich, V., Quick, J., Hering, N. (2012): Coping with Supply Chain Dynamics - Review and Synthesis of Existing Contributions, ed.: Dornfeld, D., Linke, B., Leveraging Technology for a Sustainable World, Springer, pp. 599-603.

The Analysis of Sustainable Supply Chain Management

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Abstract

With sustainable supply chain management (SSCM), more companies have benefitted from trying to be sustainable or "green" in their practices. However, there are still many challenges associated with sustainable practices and many of these are raising more questions than answers. This paper focuses on both sustainability and supply chain management from both conceptual and practical perspectives, relating the definition of SSCM to the conceptual view of a sustainable supply chain management system. In addition, the frequency of SSCM practices in Taiwan and Vietnam are introduced and presented.

Keywords:

Supply Chain Management; sustainable supply chain management; Sustainable conceptual model

1 INTRODUCTION

Currently, the integration of sustainability with supply chain management (SCM) is emphasized both by industry and the academic community [1]. It has become an increasing concern for companies of all sizes and across a wide range of industries [2]. With sustainable supply chain management (SSCM), more and more companies have benefitted from trying to be sustainable or "green" in their practices. However, there are still many challenges associated with sustainable practices and many of these are raising more questions than answers [3]. The first challenge is the definition of sustainability itself while creating benefits to meet present needs conflicts sharply with the possible impact that sustainable practices will have on the lives of future generations [7]. Others Challenges associated with sustainability and SCM go beyond economic considerations and the way in which people understand and implement practices with only limited knowledge, experiences and tools [5, 7-8]. These challenges emerged so there is a urgent need for research in sustainable supply chain management so as to bridge the gaps in current practices. However, the literature on sustainable supply chain management is still very limited regarding current practice [9]. This study focuses on both sustainability and supply chain management (SSCM) from both conceptual and practical perspectives. Our goal is to tackle the questions below.

- What is the conceptual view of SSCM and how it relates to current practice?
- What factors are considered in theSSCM and how they interact?

To figure out the nature of the Sustainable Supply Chain Management, initiatives adopted from result of past companies, five factors, i.e., Strategy, Pressure, Internal Management, External Management and Risk Management. are addressed in the conceptual model. *Strategy* is the first step before running a business, it keeps important role along the period of products so that it has high impact on firms and companies from the beginning and during operating. *Pressure* is normally being considered in the regulations and policies from government and or stakeholders/ suppliers, but in this research I address Pressures in the Monitor of Performance perspectives with elements subsidized involved. *Internal Management* includes all managing sustainable stages inside supply chains to make sure all of them are working tightly with the goals of the company. *External Management* refers to relationships and communication to suppliers and or stakeholders in terms of defining them and improving them and next is to redesign. Just like a cycle activity to which considering closely to the three tripe bottom lines of sustainability. Finally, *Risk Management* is the most normal problems companies faced in operations management, it is also one of the most difficult tasks in practices. Risks can be defined as Uncertainty sometime and related to many activities and impact them either.

These five factors in the SSCM model strongly influence SSCM practices. To achieve business success, it is necessary to embed SSCM practices in both investment and training. Research in the field is quickly emerging to identify the trends in supply chain management (SCM) and incorporate these into business practices. By using the methodologies of literature review, this paper aims to present a picture of SSCM from theory to practice, collect data from the field, and analyse the SSCM model focusing on gaps of current practices.

2 LITERATURE REVIEW

2.1 Theories of SCM

SCM as a concept was introduced in the early 1980s but received most attention from 1990 onwards. A supply chain is a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flow of products, services, finances and/or information from a source to a customer' (with carbon footprint). Lu et al. [11] proposed a hybrid solution to collaborative decision-making in a decentralized supply-chain to increase the competiveness. Tan [12] discussed the purchasing and supply activities of manufacturers in SCM. The most comprehensive analysis of the multidisciplinary, wide-ranging research on SCM is illustrated by the study of Chen et al. [13] as shown in Fig 1.

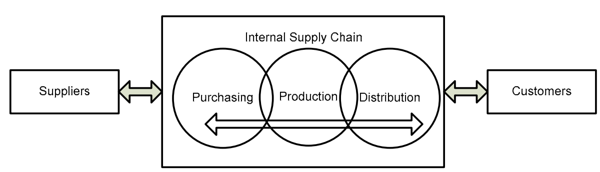

Figure 1: An illustration of a company's supply chain [13].

2.1.1 An Overview of SCM in Vietnam

In 2011, industrial parks (IPs) in Vietnam employed over 1.5 million people and industrial zones attracted more than 8,500 projects which worth a total of US$ 70 billion. 48% of the provinces in South Vietnam have industrial zones as opposed to 20% in the North. Currently, huge SCM investment on auto/motorcycle industry in Vietnam proposed new incentives from both foreign and domestic enterprises, which include Hyundai, Yamaha, Piaggio and Honda. Growth is not limited to high technology industry, Traditional insdutries such as leather and footwear are currently ranked as the 3rd largest industry cluster in terms of total goods produced. In addition, the export of bags, hats, wallets and umbrellas rose by 35.6% in 2011. There are three key drivers in the Vietnam industrial development: a low-cost labor market (cheapest in comparison to China and Thailand), market potential and political stability.

In spite of these influences, the economy generally faces internal weaknesses and challenges, reflected by low competitiveness in several industry sectors. Vietnam still lags behind many other countries in terms of infrastructure development, supply chain maturity and development of a national business policy framework. Secondly, cluster development and industrial policy still show limited strategic growth in private business sectors. The third weakness is road framework; although the investment in road infrastructure is presently recorded at more than 10% of GDP as compared to 7-8% in Thailand and China, many businesses remain locked to propel transport costs as oil prices escalate. The fourth internal weakness are seaport management and hindrances to coastal trade. Some international seaports (in Ho Chi Minh, Danang and Haiphong) that can handle large ships, still provide low quality service. For instance, port infrastructure development has not kept pace with export growth, high service costs, long customs delays (usually 3-7 days, in some cases up to one month, as compared to Singapore harbour only takes 10 minutes), the absence of an international container transhipment port, railways, and roads are disconnected to the seaport system. These factors hinder efficient domestic coastal trade and the air transport system, causing passenger capacity barriers, especially at international airports. Hence, there is a significant opportunity to develop export and domestic transhipment channels with more effective utilization of air cargo. The fifth challenge to economic development in Vietnam is the railway system where an outdated infrastructure attempts to support 2,600 kilometers of railway. For instance, although the North-South railway (linking with Beijing) is being upgraded, the fact that there is no alternative or full dual-track system in Vietnam. Even slight congestion at one location can halt the whole line. There is a lack of rail lines to economic and industrial zones, ports and to Laos and Cambodia; rail lines are of poor-quality with narrow-gauge lines limiting train speed and frequent accidents caused by having too many crossings at roads in residential areas.

These challenges are pushing Vietnamese enterprises toward a global economic collapse with many exporting industries temporarily decrease production, of which even the mostly heavily relied on exports that once represented 70% of GDP. Vietnam needs more long-term strategies with SCM played as one of the most important role in economic performance. Supply chain managers are thus raising their influence in the development of many companies, but labor in the field is limited and skilled job expertise is missing. In the future, Vietnam needs to establish occupation standards that guide the carriers and encourage labor utilization to directly fit the abilities and skills of the workers. In SCM for example, more highly educated managers with superior training skills should be involved. By involving more education and training in the field of SCM, the first step toward sustainable development in Vietnam's economy will be realized.

2.1.2 An Overview of SCM in Taiwan

Taiwan is one of the most developed countries in Asia, ranking only slightly below the US in terms of technology development. Much of Taiwan's technology has been transferred from the US, and is considered one of the largest players in global supply chain. The US is the world's biggest manufacturer of dozens of computer products, ranking third in computer manufacturing and fourth in the semiconductor industry. In 2007, Taiwan left the US behind in the running as it emerged as one of top countries in laptop manufacturing; Acer produced 3.72 million laptops, and production volume increases 54%.

Most export manufacturers are located in Hsinchu, the center of technology in Taiwan, where 400 high tech companies are established. There are hundreds of high tech companies in various sizes, mostly of them supply computer parts which can be delivered overnight to most of parts in the world. These companies include: TSMC, a leader in giant chip factories in addition to Acer [14] and Asus [15]; MediaTek, the most successful producer of chip mobiles "made in China". Hence, many researchers agree that Taiwan's small niche in the technology industry is not conducive to encourage investment in R&D and to develop strictly Taiwanese product brands. In addition, copyright is a problem emerging both in high tech companies and traditional industry. Moreover, due to heavy consumer pressure, many high tech companies have moved their production facilities to other areas that can offer cheaper costs, to China for example.

At the same time, some high tech companies are trying to make further improvements in their supply chain and enter into new application areas of the global market. Acer and HTC, for example, have recently known as two of the top Taiwan brands in the world. Many companies provide innovations based on previous technologies in order to release new products into the market; i.e., Asus has become the first runner in EPC production, and Acer in SC innovation.

2.2 Sustainable Supply Chain Management (SSCM)

The term "sustainable" has become something of a watchword for the 21st Century. Using the keywords sustainable or sustainability can explore more than 40,000 articles surrounding the concept [16]. The meaning of "sustainable" management is defined or paraphrased from several sources (Valiela et al., 2000), and reflects the need for humans to live on the income from nature's capital rather than on the capital itself. To achieve the standards of sustainability, companies have to ensure the manufacturing of products without creating environmental damage or disobeying social standards. Sustainability thus has a relationship between sustainable development and the use of resources including fuel, food, land and water is a very significant concern [17]. SSCM has its roots in both Sustainability and Supply Chain Management literature and involves a broadened approach to supply chain management [1]. Many researchers have given consideration to both sustainability and supply chain management [3, 18, 19]. However, consideration of SSCM in a review of related literature is still limited. Only parts of the literature are reviewed [20]. Carter and Roger [21] defined SSCM as:

"the strategic, transparent integration and achievement of an organization's social, environment and economic goals in the systemic coordination of key inter-organizational business processes for improving the long-term economic performance of the individual and its supply chain."

2.2.1 An Overview of SSCM in Vietnam

As a global trend, SSCM has recently been highlighted and considered for implementation within many industries in Vietnam. According to Aberdee's survey on 360 companies (2010), 76% of the industries tested agreed to include sustainable standards in the total process or some part of the process in their supply chains. GS1 [22] is an international barcode organization in Vietnam, which is active in issuing barcodes for manufacturers, providers, wholesalers, retailers and other interested players. GS1's standard systems can be divided into 5 categories: code standards, barcode standards, electronic pack standards, global networks standards and mobile commerce standards. GS1 is considered as one of the most influential companies in Vietnam supply chain activities. One of the biggest leaders in the chemical industry, BASF applied GS1's barcode system to distribute more sustainable products and to provide more sustainable supply chains.

Over the last ten years, Vietnam has been considered as one of the most rapidly developing countries in the world. In 2011, Vietnam was ranked 8th within the top 50 countries in terms of logistic services, ranking only below some of the best-known countries in the region in terms of supply chain management, such as Thailand, Indonesia, Malaysia, China and India. In July 2012, the Summit Supply Chain 2012 mentioned that more supply chain management investment such as retail sales, warehousing, logistics, motors, cars, electrics, building materials, leather, textiles, chemicals, food, beverages, energy, pharmaceuticals, wood, etc. in North Vietnam. The summit was especially interested in sustainability of supply chain management as an indicator of success factors for Vietnam and the competitive challenges Vietnam will face going forward. One of the solutions proposed by the summit is to connect the North to other regions for long-term development; in addition, one of the keys for development of a sustainable supply chain is internal management within each organization and firm.

2.2.2 An Overview of SSCM in Taiwan

Out of the most developed countries in Asia, Taiwan is one of the biggest suppliers of technological products to the US and Western countries. As mentioned above, some of production sites have been moved to other countries, mostly China, to solve consumer problems.

TSMC [23] is proud of its sustainable supply chain mostly in terms of the strategies implemented in risk management. Risk management concerns include business continuity plans, geographical risk, earthquake risk management, company training, climate change risk management, fire risk management, general environmental, safety and health, new influenza pandemic response and prevention, transportation risk, suppliers' supply chain risk management and interruption of information systems risk management. The Company accordingly attends to any risks to its supply chain partners. TSMC is committed to build a "green supply chain" so as to respond to global environmental issues and exert its influence to encourage supply chain partners to follow suit. In 2009, TSMC developed a Sustainability Evaluation Score metric to assess suppliers' supply chain risk and sustainability that covers delivery, quality, financial, operational and other risks, to form a supply chain risk map. In 2011, TSMC surveyed a total of 56 critical suppliers, including: silicon wafer, gas, chemicals, quartz parts, masks, parts cleaning and other raw materials suppliers, transport companies and logistics services, which covered more than 90% of the total purchase amount.

Acer's carbon disclosure project (CDP), through its supply chain program, is one of the most successful SSCM practices. In addition, Acer began participating in the EICC carbon reporting system in 2010 and several suppliers were invited to engage in carbon information response work on a small-scale in the same year. This system is similar in content to the CDP questionnaire, and the database is mutually accessible by all parties, making it easier for Acer to stay abreast of supplier greenhouse gas (GHG) management. Through the Keep Supply Chain GHG Working Group, Acer continued to request carbon data disclosure from first and second tier suppliers and set a 3% carbon reduction target for all supplier products in 2010. Acer claims two absolute GHG reduction targets by the EU: first, to cut emissions by 50% by 2050, and to achieve a 30% reduction in the emissions of industrialized nations by 2020. In 2010, Acer in Hsinchu replaced office lighting equipment with energy-saving lamps. The statistics show that 86,000 kilowatt hours of electricity were saved and emissions were thus reduced 54 tons of CO2. By the end of 2010, office equipment in all Taiwan offices were replaced with a total of 147 multifunction printers, and all newly selected equipment carry the Taiwan EPA Green Mark ecolabel which indicates the equipment does not use toxic materials, has reduced ozone and noise pollution, achieves a low-energy equipment design and uses only environmentally-friendly ink.

Ford (2012) Taiwan, the well-known manufacturing companies, has a science-based strategy to reduce GHG emissions from products and operations by focusing on stabilizing carbon dioxide (CO2) concentrations in the atmosphere. Ford has also set a goal to reduce facility CO2 emissions by 30% per vehicle by 2025 as compared to a 2010 baseline, building on a 31% reduction achieved between 2000 and 2010. Ford is also committed to reduce the overall environmental footprint of vehicles and operations across a range of environmental issues. For example, it plans to continue increasing the use of sustainable materials in vehicles, reduce the amount of waste going to the landfill by 20% per vehicle between 2010 and 2011 and plan to reduce it by a further 10% per vehicle in 2012. It is also continuing to reduce VOC emissions from operations through the use of innovative technologies.

3 FIVE DIMENSIONS OF SSCM

A number of experts are surveyed and analyzed in Vietnam and Taiwan. This paper defines SSCM 'as a management system in which parts: Strategy, Pressure, Internal Management, External Management and Risk Management co-work tightly to fulfill its goals'. These five dimensions are shown in Figure 2.

3.1 Strategy

Strategy might lead companies to large profits. A well-planned strategy may lead companies in a positive direction during periods of healthy product sales with few risks, or conversely lead the company the wrong way when there are problems. Some sub factors should be considered in a company where good SSCM strategy is addressed. These factors include: learning and transfer of knowledge, responsibility of supply chain managers, a dedicated organization for training and motivating people, R&D investment, teaming up the supply chain manager and stakeholder executives early on in the process, consideration of uncertainty, understanding cause-effect relations among trends, consideration of a KIP system, providing incentives and motivating people, generating awareness of the long-term benefits of change and implementing best practices.

3.2 Pressure

There are many elements involved: evaluating the impact of supply chain activities on the three primary considerations of sustainability (Economic, Environment and Ecological/Social aspects), defining product suppliers and beneficial measures/methods and pressure team management.

3.3 Internal Management

Elements raised during operation and monitor the works of the SSCM system include: managing the process in terms of continuous improvement, knowing customers, enhancing efficiency and minimizing environmental impact, managing products in terms of customization, estimating and managing product lifecycles, establishing the integral concept of “design for SSCM”, evaluating and controlling the impacts of a rising or decreasing variety in product parts, defining and developing relevant fields of knowledge, transforming tacit knowledge into explicit knowledge to enable information transparency by IT-Tolls, enhancing communication, establishing a culture for lifelong learning, mapping and improving a company’s location in the network, leveling capacities according to supply and demand, designing and maintaining infrastructure based on ecological standards, managing people and teams.

3.4 External Management

All outside elements that directly impact a company should be included. This can be achieved by defining stakeholder impacts, which involves in defining and assessing primary stakeholders, developing strong relationships with stakeholders, combining stakeholder communication with expertise and innovations, communication and stakeholder involvement in practices, addressing economic and social concerns without ignoring the commitment of top management, eliminating trade-offs or conflicts between regulations and effective supply chain performance, tracking and monitoring practices following regulatory developments, monitoring government policies and competitors’ initiatives, redesigning relationships with customers and stakeholders.

3.5 Uncertainty (Risk Consideration)

This research addresses some of the levels of uncertainty for companies considering the SSCM system by defining and relating the risks to a company in light of that company’s goals, by ensuring the simplicity of every plan and process so that each of these is likely to be adopted by company employees, by having sufficient knowledge of the entire supply chain, by reducing the chance of risk by analyzing the risk in context before undertaking a particular route, by demanding strong and consistent leadership from management, from the top down, to mitigate risk, and by trying to understand others’ points of view. Once a suitable framework has been determined to fit a particular enterprise, risk knowledge can be enhanced by cooperating with others outside of business and by dealing with risks resulting from social and environmental impacts while at the same time understanding that risks are constantly evolving.

4 DISCUSSION

All indicators observed in these results indicate that factors of SSCM should be strongly considered both in academia and industry. The factors adopted from the success of the bestLog research project and other researches in practice were collected in order to examine company practices in Vietnam and Taiwan. This was done through the survey method, the results of which indicated agreement with each of the five factors of the SSCM model. The hypotheses designed and tested attest that each of the five factors is strongly influential in the actual SSCM practices used by industry in both Taiwan and Vietnam. Through the process, we can conclude that both SSCM education and practical training should be involved early on in a company’s implementation of SSCM practices. The present definition of SSCM should also be applied in schools and in practice.

All indicators of the five factors were observed at high levels; Vietnam’s were almost always higher than Taiwan’s. For each factor, only some main success practice indicators were selected. Indicators addressed within pressure strongly impact on the SSCM model like the other factors. However, those indicators might differ among companies according to location, cultural differences, firm size, product field, facilities, ability, experiences, etc. Accordingly, indicators attached under Strategy strongly influence the SSCM model. Next, Internal Management indicators also strongly influence the model, but in reflecting the country’s characteristics, they might show different rates of impact on SSCM. External management indicators were shown to be at a higher level in Vietnam than in Taiwan, and the p value of all five factors included in the External Management section indicate a significant difference between the two countries. Moreover, the results show that there are differences between Vietnam and Taiwan at some levels; “Develop KPI (Key Performance Indicators) system taking into Account”, and “Managing people and teams in terms of doing right in the way of top management” that might cause differences in terms of the economy. Taiwanese companies are mostly independent manufacturers and outsourcing owners, conversely many companies in Vietnam are outsourced and are hired by Western countries. Recently, due to customer pressure and sustainable requirements in Taiwan, manufacturing of parts has tended to move from local areas to other areas such as China. Meanwhile Vietnam is considered as an attractive area in Asia with a bigger population than Taiwan’s, and it has recently received more consideration for investment by Western companies. In 2011, Vietnam ranked 8th in the top 50 countries in the 2011 GLSI (Global Logistic Service Index), after some of the most considered countries in supply chain region, such as Thailand, Indonesia, Malaysia, China, and India. Taiwan is not ranked in the index. Another factor that might be considered in interpreting the result findings are the interviews conducted with managers and researchers in SSCM; 66.7% of those interviewed in Vietnam (n=78) were researchers studying in schools, whereas 93.4% of Taiwanese respondents (n=32) were company managers.

5 CONCLUSIONS

This research has some limitations. The findings of this study are relevant to both researchers and managers in many fields concerned with a sustainable supply chain, but data were collected from a relatively small group of respondents. Furthermore, this research did not consider the relationship among some or all of the factors impacting SSCM; rather, it focused solely on discovering the influence each factor has on SSCM. In addition, these factors were tested only in Taiwan and Vietnam, so the results may possibly differ in other countries within the same region or in other areas of the world. T The results may also differed from different interviewed group. Disimilarity in the size of companies would also result in different strategies being used to achieve SSCM.

The findings are neither clear nor significant enough to establish a valid comparison between countries in terms of how SSCM practices might affect the overall economy of a country. In future research, an analysis of SSCM practices applied in different Asian countries might prove interesting.

6 REFERENCES

[1] Po'vova A.B., (2009), Sustainable supply chains: Key Challenges. Computer Aided Chemical Engineering, Vol 27, 127–132.

[2] Seuring J., Sarkis J., Muller M., Rao P., (2008. Sustainability and supply chain management – An introduction to the special issue, Journal of Cleaner Production, Vol 16, No15, pp 1545-1551

[3] Linton J. D, Klassen R., Jayaraman V., (2007). Sustainable supply chains: An introduction. Journal of Operation Management, Vol 25, No 6, pp 1075-1082.

[4] WCED, (1987). World Commission for Environment and Development, Our common Oxford. Oxford University Press

[6] Filho K.F., (2004. Supply chain approach to sustainable beef production from a Brazilian perspective, Livestock Production Science, 90, pp 53-61.

[7] Zhu, Q., Sarkis J., Cordeiro J. J., Lai K. H., (2008a). Firm-level correlates of emergent green supply chain management practices in the Chinese context, Omega, Vol 36, No 4, pp 577-591

[8] Zhu, Q., Sarkis J., Lai K.H., (2008b). Green supply chain management implications for 'closing the loop'. Transportation Research Part E, Vol 44, No 1, pp 1-18.

[9] Gold, S., Seuring S., Beske P., (2010V. Sustainable supply chain management and inter – Organizational Resource: A literature Review, Corporate Social Responsibility and Environmental Management, Vol 17, , No , pp 230–245.

[10] Mentzer, J. T., DeWitt, W., Kddbler, J. S., Min, S., Nix, N.W., Smith, C.D. and Zacharia, Z. G., (2001): Defining supply chain management, Journal of Business Logistics, 22 (2), pp 1-25.

[11] Lu, S. Y.P., Lau, H. Y. K., Yiu, C. K. F., (2012), A hybrid solution to collaborative decision-making in a decentralized supply-chainJournal of Engineering and Technology Management, Vol 29, No.1, January–March, pp. 95-111.

[12] Tan, K. C., (2001), A framework of supply chain management literature, European Journal of Purchasing and Supply Management, Vol 7, No 1, pp. 39-48.

[13] Chen I. J., Paulraj A., Lado A. A., (2004). Towards a theory of supply chain management: the constructs and measurements, Journal of Operations Management, Vol. 22, No. 2, pp 119-150.

[14] Acer, (2010), http://www.acer-group.com/public/Sustainability/

[15] Asus, 2010, http://csr.asus.com/english/index.aspx#114

[16] Larson D. L., Mao L. P., Quiram G., Sharpe L., Stark R., Sugita S., Weiler A., (2011). A framework for sustainable invasive species management: Environmental, social, and economic objectives, J Environ Manage. Vol 92, No 1, 14-22.

[17] Dincer, I., Rosen, M.A., (2002). Thermal Energy Storage System and Applications, Wisley: London.

[18] Gupta, S. and Palsule-Desai, O., (2011). Sustainable Supply Chain Management: Review and Research Opportunities, IIMB Management Review, Vol 23, pp 234 - 245.

[19] Ofori G., (2000. Greening the construction supply chain in Singapore. European Journal of purchasing and supply management, Vol 2000, No 6, pp; 195-206

[20] Gold, S., Seuring S., Beske P., (2010). Sustainable supply chain management and inter – Organizational Resource: A literature Review, Corporate Social Responsibility and Environmental Management, Vol 17, No. 4, pp230–245.

[21] Carter, C, R. and Rogers D. S., (2008). A Framework of Sustainable Supply Chain Management: Moving Toward New Theory, International Journal of Physical Distribution & Logistics Management, Vol 38, No. 5, pp. 360 – 387.

[22] TSMC, (2012), http://www.tsmc.com/english/csr/collaborates_with_suppliers.htm

[23] GSI. http://www.gs1vn.org.vn/default.aspx?portalid=5

Levers for Management of Resource Efficiency in the Tool and Die Making Industry

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Abstract

The tool and die making industry enables the series production of goods by manufacturing tools and dies in one- as well as small-batches. Vast differences in factor costs in conjunction with the development of know-how in low-wage countries have shaped a new competitive environment for the tool and die making industry in recent years. It demands the increase of efficiency in resource utilization while continuously being able to meet the requirements for reliable manufacturing of high quality tools and dies. Value creation design and life cycle optimization of tools and dies represent levers with which these demands can be addressed. The manufacturing process and tools and dies themselves are characterized by a high complexity. This key property is owed to the fact that specifications vary greatly between orders for tools and dies as they are manufactured in small- and one-batches. The complexity of the process has to be mastered by actively controlling the value creation depth, whereas the complexity of the tool or die has to be mastered by optimizing the tool according to the customers' requirement over its life cycle. Value creation design and life cycle optimization have yet to be successfully employed in the tool and die making industry. This paper elaborates the potential of these two levers that focus on the integration of the supply chain to sustainably enhance resource efficiency for the customer.

Keywords:

Energy; Resource Management and Efficiency; Manufacturing Systems Life Cycle; Life Cycle Costing (LCC); Life Cycle Engineering and Management

1 INTRODUCTION

The tool and die industry is one of the key industries in the manufacturing sector due to its role in the industrial supply chain between product development and series production of manufacturing goods. Excellent goods from high wage countries can only be manufactured at economical prices with the support of efficient and highly productive order fulfillment processes. The tool and die industry largely contributes to the economic performance of major economies [1, 2, 3, 4]. Nevertheless the tool and die industry in high wage countries faces margin losses as well as increasing competition from Eastern Europe and Asia [5, 6]. Facing this situation, the industry has to develop differentiators to preserve international competitiveness on the global market.

Customers demand and increasing level of quality and overall performance of a tool over its life cycle with regard to their specific requirements. At the same time the prices for tools and dies have to be reduced in order to answer the enlarging availability of tools and dies on the global market. Quality, performance, and price have significant influence on the resource efficiency of a tool. For the purpose of this paper, resource efficiency is defined as the ratio of all relevant resources that are required to produce a tool or die and its performance. Resources are the entirety of material and immaterial effort required to develop and manufacture a tool or die from the entry of a customer's order until the installation at the customer. A decrease in resources will result in higher resource efficiency if the performance of the tool stays constant. The performance thereby represents the capacity of a tool or die to meet the requirements of the customer. An increase in performance with constant resources will cause a rise in resource efficiency. In this context resource efficiency is a measure for the control of a tool or die making company between the aspects that are put in to realize the value creation and the result that is achieved for the customer. The management of resource efficiency therewith is an inevitable capability that has to be possessed by tool and die making companies to ensure the sustainable development in the described market environment.

In order to be able to successfully achieve the enhancement of resource efficiency levers that integrate further parties in the supply chain in the value creation process of tools and dies will be addressed in this paper. Those levers are the design of value creation and life cycle optimization. As basis for enhancing resource efficiency the tool and die making industry will be presented by its characteristic manufacturing process, its position in the industrial supply chain as well as by its success factors. In the third chapter the demands for the design of value creation depth and life cycle optimization will be discussed. Chapter four and five will introduce design of value creation depth and life cycle optimization as levers to realize the enhancement of resource efficiency. The conclusion will finalize this paper.

For the purposes of this paper the word tool will represent a tool as well as a die.

2 CURRENT DEMANDS FOR THE TOOL MAKING INDUSTRY

In this chapter the order fulfillment process of the tool making industry will be introduced. After the introduction the success factors for the industry will be presented to set up the framework for the detailing of levers for enhancing of resource efficiency in further chapters. In continuation the position of tool making companies in the industrial supply chain and the life cycle of tools will be discussed.

2.1 Order Fulfillment Process in the Tool Making Industry

The tool and die making industry is the enabler for series production of manufacturing goods. Typically tool making companies manufacture one batches as a tool or die does give a long term supply for the series manufacturing. The traditional process chain is shown in figure 1 [5, 7, 8].

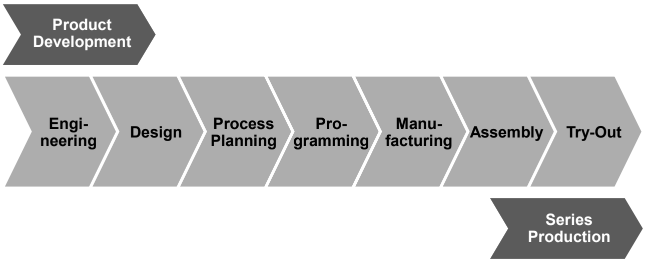

Figure 1: Tool making process chain.

The engineering starts with the development of the tool. In the next step the design department designs the tool. Process planning is responsible for the detail planning of the manufacturing process of the manufacturing of all components of a tool. The programming converts the data of the tool designs into programs for the manufacturing machinery to be able to manufacture the components with the resources intended to the required specifications. In the manufacturing department all tool components are manufactured. Those components are assembled to a tool in the assembly department. In the try-out it is checked whether series parts can be produced to the required specifications. If the requirements are not entirely met, the tool is disassembled and components will be reworked. Due to this characteristic of the tool and die industry there are planned and unplanned orders that need to be processed with the same resources [7, 8, 9. 10, 11]. Unplanned orders in this context are those which require changes in existing process plans. Furthermore maintenance orders for tools or dies which are coming from the series production add to the severity of that characteristic [7, 8, 10, 11]. The tool making process chain is embedded in the development and production of series products.

2.2 Success Factors for the Tool Making Industry

Tool making companies are measured by their customers with the key performance indicators due date reliability, lead time and quality first [12]. Regarding ressource efficiency the performance of tools has to be aligned with these indicators to be valued by the customer. Due date reliability and lead time refer to the capacity of the manufacturing process in tool making. On the other hand quality resembles a capacity of the tool as product for the customer itself at the point of sale. In the following the inherent demands of tool making companies derived from the key performance indicators will be discussed and value creation design and life cylce optimiszation will be introduced as measures to answer those demands.

Process-Oriented Success Factors

In order to be able to meet key performance indicators due date reliability and lead time the entire order fulfilment process needs to be efficient and productive. The target of an efficient and productive order fulfilment process is operative excellence [5]. While those demands by the customer have to be attended to operatively, a sound strategy and a business model is also required to reach sustained success [7]. Strategy and the stringent derivation of business models specifically for the tool making industry have been addressed in different works over recent years. FRICKER has proposed a model for stringent strategy in the tool and die making industry [13]. FRICK provided eight successful business models for tool and die making companies [7]. According to SCHUH ET AL. operative excellence can be mastered by successfully occupying six action fields in the tool making industry. These are [5]:

- Sales
- Knowledge Management
- Employee Development
- Synchronization
- Standardization
- Value Creation Design

The sales department is the interface towards the customer. The responsibility of the sales department is to aquire new customers by selling tools as well as services that are rapidly gaining importance as part of the portfolio of tool making companies [14]. As tools and dies are no consumer products and are rather considered manufacturing equipment by the series production, the sales department in the tool and die industry does require a specific approach.

Knowledge Management and Employee Development refer to the systematic use of employees and their knowledge to realise differentiation against competition.

Synchronization focuses on the planning and execution of all processes of order fulfilment. As mentioned the complexity of the process structure in the tool making industry is not only described by the multitude of different components which have to be made to be able to assemble a tool, but also by the different order types that enter a tool room form, the try-out department or the series production. The aspect of synchronization has to be addressed in order to be able to practically utilise the theoretic capacity of the machine park while still being reliable to the due date and being able to deliver tools and dies with competitive lead times [8].

The standardization of tools is an imperative for tool making companies in their attempt to repeat process steps and simplify procedures in all parts of the process chain. Standardization is an aspect that is already much exercised in series production and has been established in the industry in recent years [10, 15, 16, 17].

Value creation design requires the management of value creation depth as well as the aspect of cooperation with other companies. The value creation depth refers to the amount of processes that are required for the manufacturing of tools which are performed internally. In series production, especially in the automotive industry, the value creation depth reaches levels below 30% [18]. An increased demand for mastering relations with suppliers is linked to that development. In the tool making industry the value creation depth is at about 70% [5]. The systematic use of external suppliers for the order fulfilment process will be addressed in this paper with value creation design

The management of value creation depth offers a practical approach to mastering the action field of value creation design. Thereby a measure for tool making companies is supplied that supports the path towards operative excellence.

Product-Oriented Success Factors

The tool making industry is a core part of the industrial supply chain. A tool is developed and manufactured in a tool making company according to the established process chains. The tools then spend the majority of their respective life cycle in the series production. This situation is shown in figure 2.

However in practice the interaction is limited between series production and tool making companies representing the two parties that are responsible for a tool over its life cycle. The requirements of series production to the capacity at the point of sale focuses on the capability of the tool to manufacture series products to set specifications at that point of time. This requirement is represented by the success factor quality which has been established above in chapter 2.2 [12]. No success factor of the three most important ones to the customer refers to the product itself of the course of time it is used in series production. Much rather do the success factors represent the process quality of the tool making company only. Life cycle optimization addresses the phase a tool is manufactured as well as the entire extent of time it is used in series production. Life cycle optimization can only be resource efficient if the inherent efforts achieve amortization by compensation of the customer. In the following chapters of this paper it will be elaborated further how life cycle optimization can positively affect resource efficiency of tools although it is not yet established in the most relevant success factors in the tool making industry.

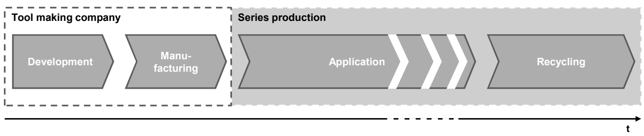

Figure 2: Life cycle of a tool.

3 VALUE CREATION DESIGN AS LEVER FOR MANAGEMENT OF RESOURCE EFFICIENCY IN THE MANUFACTURING PROCESS

Value Creation Design offers a lever to manage resource efficiency by target-orientedly cooperating with suppliers for the value creation process of tools. We have developed a methodology to support tool making companies in exploiting the benefits of value creation design. In this chapter the potential of value creation design will be introduced. The introduction is followed by an analysis of existing works on the subject. The core part is the presentation of the methodology and the status quo of its development and application in practice.

3.1 Target of Value Creation Design in the Tool Making Industry

Increased competition due to global availability of tools and services at premium quality result in the necessity to reduce prices for the customer. This development has experienced massive intensify-cation in recent years. It may be expected that this development will continue to affect the tool making industry in the foreseeable future [1].

The development of consumer products is performed in periodic cycles. This underlying circumstance leads to an aggregation of orders for tools when the development phase of consumer products has specified product dimensions. On the other hand there are periods of lack of demand for tools while the development cycle has not progressed to a stage where product specifications would allow the manufacturing of tools. The described situation is shown in figure 3.

The target is the development of a methodology for designing value creation depth in the tool making industry to explicitly address the described enhanced order fluctuation. Order fluctuation directly results into great volatility of capacity utilization. Internal capacity utilization is maximized in periods of high demands. In periods of little demand capacity utilization is low and negatively impacts the cost structure of tool making companies.

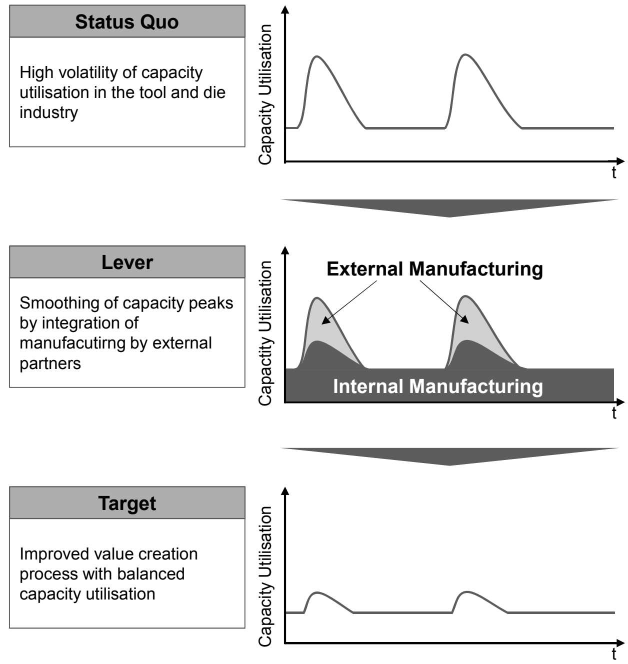

Figure 3: Target of value creation design.

The design of value creation depth directly refers to the subject by systematically supporting the use of internal and external resources to execute the order fulfillment process. Given the characteristic of different types of orders this task is especially demanding. The trend that can be observed in other industries to focus on certain competencies has reached low levels of value creation depth cannot be identified in the tool making industry [5]. The action fields of operative excellence require tool making companies to apply principles that have been well established in the series production. While that development has shown significant progress with regard to standardization and synchronization, value creation design has yet to be appropriately addressed. The identified potential and gap to series production underscore the demand for a measure to support value creation design to become more productive and efficient as operatively excellent tool making companies.

3.2 Analysis of Prior Works on Managing Value Creation Design

In order to design a methodology for design of the value creation depth, works with a comparable focus have to be assessed to identify existing knowledge and precisely define the deficiency that is existent for the tool making industry with regard to the topic. Therefore existing works on the subject of value creation design in small batch industries have to be analysed.

SMITH established in 1776 that everyone should focus on the occupation that he is best at [18, 19]. The concept of design of value creation depth can be traced back to COASE who posed the question of what motivates a company to execute one transaction more or less [20, 21]. In current practice the design of value creation depth is directly linked to the subjects of outsourcing and Make-or-Buy decision making. Outsourcing refers to the permanent use of external sources to complete defined processes [22, 23]. On the other hand Make-or-Buy is focused on short term decisions that have less strategic character than outsourcing.

Outsourcing literature describes the concept of focusing on core competencies. However a practical approach with regard to the execution in the tool or other small batch industries specifically could not be identified. Although the approach to make-or-buy is more practical, literature predominantly addresses in which scenarios sourcing is required [24, 25]. With regard to industry focus works on the manufacturing industry in general do exist [26]. Small batch industries are not specifically addressed.

This leaves the field of supplier management for analysis as supplier identification and selection are part of the operative design of value creation depth. However, supplier management is defined as a superior function in the industry which is continuously accompanying outsourcing or make-or-buy and does therefore not address the operative aspect of value creation design [27]. Hence it may be established that there is no measure available to the tool making industry for operatively design its value creation depth.

3.3 Proposed Solution for Value Creation Design

In the following the methodology for design of value creation depth in the tool industry is presented. Value creation design refers to the strategic use of internal and external sources to complete the order fulfillment process. With proper design of value creation depth the capacity utilization of tool making companies can be improved. The content of this paper approaches that field with a methodology for the operative design of value creation depth.

The methodology is set up for tool companies that possess a sound strategy and a business model as those requirements have to be met in order for operative excellence to show positive results for a company. It consists of four steps that have to be executed in the defined consecutive order (compare figure 4).

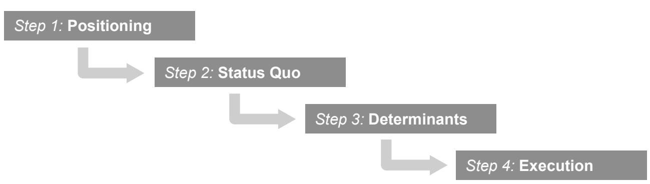

Figure 4: Overview of phases of the methodology for design of value creation depth.

In the first step it is checked whether the set-up of the order structure in the company is stable enough to successfully manage the internal value creation depth as an operative action. If the demand of the positioning of the tool making company for stability in the order structure is satisfied, the execution of the methodology continues with the second step.

The second step focuses on the gathering of data with regard to the status quo of product, process, and competencies of a company that are relevant input for managing value creation depth. The order fulfillment process is mapped and tools are broken down into configuration modules that represent parts of a tool that can be considered for manufacturing at different sources. Also core competencies are defined to be able to support existing strength with the methodology. It is specifically defined how the required information has to be gathered.

The established foundation of knowledge is employed in the third step to design an evaluation system according to individual requirements of a company. The target of the management of the internal value creation depth is defined and determinants for the sourcing decision are developed. The determinants are put together into an evaluation system. With the evaluation system different sources are assessed regarding their ability to execute a defined process. For different planning scenarios specific evaluation systems are set up to attend to the demands of the source for configuration modules based on the nature of a scenario.

In the fourth step the evaluated processes are combined to configuration modules. All configurations then are allocated to all resources which are required for their manufacturing. The execution of the sourcing decision can then be based on the availability of resources in different scenarios.

The junction of the four established steps is the methodology for the adaptive management of internal value creation depth. The methodology is also characterized by the flexibility of attending to different scenarios with regard to the planning horizon. Result of the methodology is a detailed set of information on where configuration modules should be sourced in different scenarios. With this methodology the tool making industry is supplied with a capable instrument to design value creation and increase the level of operative excellence in a company. This operative excellence will ultimately be required to create differentiation and manufacture competitively.

With the methodology tool making companies are able to define the configuration modules that have to be manufactured internally or those that have to be sourced externally. This is defined by the execution in step two. The detailing of step four allows the ranking of configuration modules with regard to preferred internal or external execution. Capacity utilisation defines the amount of configuration modules that are sourced. The capacity utilisation has to be evaluated for different types of resources separately as available capacities have to match the manufacturing requirements of the tool or die components. The separation of steps two and three allows the stringent customization of the determinants according to the actual need of a company that is stringently derived from the set of information required by the second step.

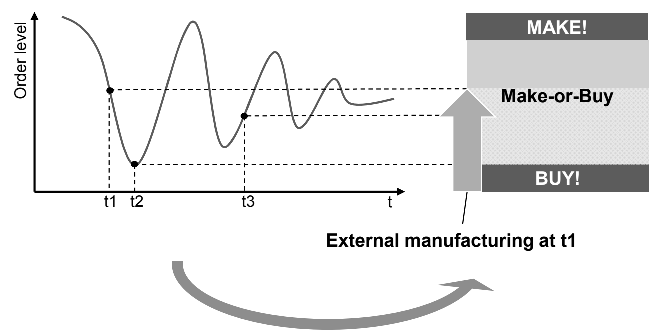

Figure 5: Example for application of the methodology at different points of time.

As shown in figure 5 the intensity of sourcing that is performed can be dictated by the order volume and inherent capacity utilization of the resources. The capacity utilization and order volume are the defining parameters for the management of the internal value creation depth. This is supported by the successful validation of the methodology with two companies of the tool making industry in Germany [28].

4 LIFE CYCLE OPTIMIZATION AS LEVER FOR MANAGEMENT OF TOTAL RESOURCE EFFICIENCY OF TOOLS

Life cycle optimization can be exploited as a lever to manage the total resource efficiency of a tool by improving its characteristics over the entire life cycle. In the following target and inherent potential of life cycle optimization for tools will be explained. In continuation existing approaches on the subject are introduced. Finally a proposed solution for life cycle optimization in the tool making industry will be presented.

4.1 Target of Life Cycle Optimization in the Tooling Industry

The optimization of the life cycle of a tool aims at target-orientedly improving the capabilities of a tool that are required over the life cycle. The life cycle is initiated by the development phase of a tool. The life cycle ends with the recycling or scrapping of a tool after it has been used for series production. The improvement of a tool's characteristic focuses especially of the phase in series production as the optimization should ultimately benefit the customers of tool making companies. The picture of the target is illustrated in figure 6. By thoroughly designing the tool in the developing phase accounting for specific requirements of the manufacturing process and further phases the overall resources required should be reduced. This demands more effort in the development phase to be able to accomplish the amortization of those extra efforts in all following phases of the life cycle of the tool (compare figure 6).

Life cycle optimization therewith offers benefits to the tool making companies as well as to the customer by enabling an increase in cost efficiency. Cost can be lowered and the performance of the tool can be enhanced to fit the specific requirements of a customer. Life cycle optimization offers a measure for differentiation against competition to tool making companies with advanced know-how capacities.

The continuous application of life cycle optimization will only be possible if extensive information regarding all phases of a tool can be gathered. The integration within the supply chain of tool making companies with companies from series production is a prerequisite for that.

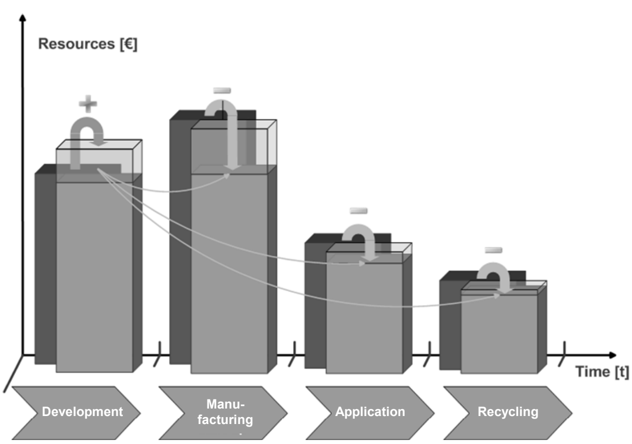

Figure 6: Target of life cycle optimization of tools.

The result of life cycle optimization will strengthen the strategic position of tool making companies for their customers. The measure supports a sustainable development of the tool making industry and offers a lever for increasing cost efficiency and differentiation against growing global competition.

4.2 Analysis of Prior Works on Life Cycle Optimization

There are some existing approaches concerning the tool's life cycle that mainly focus on calculation of life cycle costs. The key to life cycle optimization is the efficient use of resources of a tool over its life cycle. While the need for life cycle optimization by controlling resource consumption in the tooling industry has been acknowledged, no holistic solution has been proposed yet [29]. The research project LCC and its follow-up project QProLCC for instance developed a tool to prognosticate manufacturing costs, optimization costs, maintenance costs and costs of idleness depending on different tool parameters, but still cannot make a clear statement about consumption of resources like raw materials, energy and commodities during the tool's life cycle [11].

The recently finished government-funded research project EnHiPro focused mainly on optimizing energy and auxiliary use. EnHiPro's fundamental approach intended to integrate consumption measuring in existing ERP systems aiming to combine ecological and classical production-related goals. EnHiPro generated a certain degree of transparency regarding specific consumption and cost drivers. Furthermore interdependencies with manufacturing efficiency have been identified. EnHiPro's outcomes might be capable of continuously increasing energy and auxiliary efficiency [12].

The life cycle optimization proposed in this paper wants to take the next step forward and investigate not only energy efficiency but overall resource efficiency. Furthermore we want to consider the whole life cycle of a tool, not only parts of which.

4.3 Proposed Solution for Life Cycle Optimization

We are addressing life cycle optimization currently within the European research project "TEC – Total Efficiency Control". TEC is coordinated by the Laboratory for Machine Tools and Production Engineering (WZL) of the RWTH Aachen University (Germany) and the Institute for Production Technologies (IFT) of the Technical University Vienna (Austria). Fifteen companies of the tool making industry or its direct partners and suppliers are further members of the project consortium. Through this constellation the expertise of research institutions and companies of the industry are united to drive the subject of life cycle optimization forward. Overall the project consists of three consecutive periods. In the first period the life cycle of a tool is structured and analyzed. Based on the results of the first period, measures for the optimization of the efficiency of resource consumption of the tool over its life cycle are set up, tested, and finally validated. Within the third period of the project a program will be designed to gather the required data for sustainably executing the optimization. Furthermore a business model will be developed to support companies of the tool and die making industry in successfully selling life cycle optimization as added value to their customers.

In the first period the stages of a tools life cycle are defined as specifically as possible. The four phases established prior in this paper are then taken as basis for further detailing. For all phases the parameters influencing the use of resources during a certain stage are collected. The first period is executed in strong collaboration between all partners of the project consortium. For the definition and detailing of the life cycle the input of those partners that are tool making companies as well as their customers is relevant. A key aspect of the first period is the development of a unified understanding of all stages of a tool's life cycle. To this point the interaction between tool making companies and series production has not been extensively existent or was lacking transparency. The stages of the life cycles are validated by the practical experiences within the consortium as well as by a reference tool that will be specifically build for the TEC research project.

The second phase aims at the development and design to optimize the performance of a tool over its life cycle. Those measures address all phases of a tools life cycle. The second period bases on the first as it utilizes all the gathered results on the stages of the life cycle and also the parameters with regard to resource consumption that have been assigned to all stages. Possible examples for measures over the four phases:

- Development: Adjustment of tool design to isolate components that are subject to wear and require replacement during the production phase
- Manufacturing and start-up: Application of new hardening treatments to reduce wear on tool components
- Production phase: Establishment of routine maintenance procedures to eliminate tool breaks
- Recycling: Development of new recycling procedures to reduce unnecessary maintenance and bound capital

The measures will be tested and validated with all partners of the consortium. Additionally a second reference tool will be built to measure improvements over the life cycle performance in comparison to the first tool build in the first period.

In the final phase of TEC program will be set up to calculate the resource consumption over all phases of the life cycle. Thereby an instrument for the precise measurement of the status quo of a tool's performance is set up. It can also serve as basis to draw comparison between tools that were made or optimized differently. Those comparisons will assist enhancement through life cycle optimization. A business model that will be designed in the last period can serve as reference for tool making companies to practically exploit the potential of life cycle optimization by explicitly offering it to their customers. Therewith the last step to meet the goal of enhancing resource efficiency and differentiation of tool making companies with advanced know-how capacities we be completed.

TEC is to be completed with the end of the calendar year 2013. After the formation of the project consortium we are currently in the process of executing the first period of the research project.

5 CONCLUSION

In this paper two levers for increasing resource efficiency in the tool making industry have been presented. Both levers aim at advancing the integration of the tool and die making company in the industrial supply chain. The process of manufacturing tools can be improved by value creation design. With value creation designed partners of tool making companies are target-orientedly employed to improve the quality of the order fulfillment process and enhance resource efficiency. The second lever aims at the integration of the customer as the next entity of the supply chain. With the integration of the customer series production the performance of the tool over its entire life cycle can be improved. Therefore the consumption of resource of the life cycle has to be reduced. While the proposed methodology for value creation design is already being applied in practice in the tool and die industry, life cycle optimization has yet to be developed further for sustained practical application. This is also represented by the fact that existing works on life cycle optimization in the tool making industry are research project.

Future works should focus on the further development of the capacities and life cycle optimization in the tool making industry. The integration into the industrial supply chain will be a differentiating factor for tool making companies in the future.

6 REFERENCES

[1] Schuh, G., 2011, Wettbewerbsfaktor Produktionstechnik – Aachener Perspektiven, Aachen.

[2] IRN, Inc., 2002, A Competitive Assessment of the Die and Mold Building Sector – A West Michigan Perspective, Grand Rapids, MI.

[3] Holmes, J., Rutherford, T., Fitzgibbon, S., 2005, Innovation in the Automotive Tool, Die and Mould Industry, Network Structure of an Industrial Center, Queens University, Toronto.

[4] Menezes, J., 2004, European Mould Making: Towards a New Competitive Positioning, Proceedings of the 4th International Colloquium Tool and Die Making for the Future, Aachen.

[5] Schuh, G., Boos, W., Kuhlmann, K., Rittstieg, M., 2010, Operative Exzellenz im Werkzeug- und Formenbau, Aachen.

[6] Klocke, F., 2006, Werkzeugbau in China – Chance oder Bedrohung?, Aachen.

[7] Frick, L., 2006, Erfolgreiche Geschäftsmodelle im Werkzeugbau, Shaker, Aachen.

[8] Kuhlmann, K. K., 2011, Methodik zur Gestaltung von Geschäftsprozessen im Industriellen Werkzeugbau, Apprimus, Aachen.

[9] N.N. (unpublished), 2008-2011, Competition „Excellence in Production“, WZL and IPT, Aachen.

[10] Boos, W., 2008, Methodik zur Gestaltung und Bewertung von modularen Werkzeugen, Apprimus, Aachen.

[11] Gaus, F., 2010, Methodik zur Überprüfung der Logik eines Geschäftsmodells im Werkzeugbau, Apprimus, Aachen.

[12] Schuh, G., Boos, W., Gaus, F., Schittny, B., 2009, Toolmaking for the Future – A Global Study of Today's Situation and Future Trends in the Tooling Industry, WZL, Aachen.

[13] Schleyer, C., 2006, Erfolgreiches Kooperationsmanagement im Werkzeugbau, Shaker, Aachen.

[14] Schuh, G., Ziskoven, H., 2010, Intelligent Tools Enable New Services and Increase the Competitiveness of Toolmakers and Plastic Parts Producers, Conference Transcript 19th Annual Frontiers in Service Conference, Karlstad.

[15] Ericsson, A., Erixon, G., 1999, Controlling Design Variants (Modular Product Platform), Society of Manufacturing Engineers, Dearborn, MI.

[16] Rapp, T., 1999, Produktstrukturierung: Komplexitätsmanagement durch modulare Produktstrukturen und –plattformen, Deutscher Universiätsverlag, Wiesbaden.

[17] Li, Z. K., Li, X. R., Zhu, Z. C., 2011, Scalable Platform Robust Reconfiguration Method with Sensitivity Analysis and Fuzzy Clustering, AMM, 52-54, doi: 10.4028/www.scientific.net/AMM.52-54.1026.

[18] Schwarz, G., 2005, Outsourcing, In: Hermes, G., Outsourcing – Chancen und Risiken, Erfolgsfaktoren, Rechtssichere Umsetzung, 15-37, Haufe, Munich.

[19] Smith, A., 2008, An Inquiry into the Nature and Causes of the Wealth of Nations, ebooks, Adelaide.

[20] Coase, R. H., 1937, Nature of the Firm, Economica, 4/16, 386-405.

[21] Klein, P. G., 2005, The Make-or-Buy Decision: Lessons from Empirical Studies, In Ménard, C., Shirley, M., Handbook of New Institutional Economics, Springer, Dodrecht.

[22] Küchler, P. R., 1998, Outsourcing – Im Wandel von Kostenreduktion zu Wertschöpfung, In Köhler-Frost, W.: Outsourcing – Eine Strategische Allianz besonderen Typs, Erich Schmidt, Berlin.

[23] Hollekamp, M., 2005, Strategisches Outsourcing von Geschäftsprozessen. In Zerres, M.: Hamburger Schriften zur Marketingforschung, Dampp, München.

[24] Strasser, J. F., 1989, „Make or Buy“ in der Produktion, In Hess, W., Strasser, J.F., Junger, M., Ludwig, B. D., Stirnemann, K.E., Bruderer, H., Jeschko, A., Peter, K., Gartmann, S., Jäger, H., von Oetinger, B.,: Make or Buy – Eine Neue Dimension der Strategischen Führung, Industrielle Organisation, Zurich, 21-30.

[25] Mikus, B., 2001, Make-or-Buy-Entscheidungen, Unternehmensrechnung und Controlling, Chemnitz.

[26] Höhne, T., 2010, Einflüsse von Make or Buy-Entscheidungen auf die Termintreue, Apprimus, Aachen.

[27] Gienke, H., 2007, Produktionsorganisation, In Gienke, H., Kämpf, R.: Hanbduch Produktion, Hanser, Munich, 551-740.

[28] Schittny, B., 2011, Wertschöpfungsgestaltung, In Schuh, G., Boos, W., Werkzeugbau Akademie Forschungsbericht 2010/ 2011, Apprimus, Aachen.

[29] Kuhlmann, K., 2009, Total Efficiency Control – Ressourceneffiziente Werkzeuge stärken den Werkzeugbau, In Feifel, S., Walk, W., Wursthorn, S., Schebek, L., Ökobilanzierung 2009, KIT Scientific Publishing, Karlsruhe, 151-156.

[30] FQS, 2010, Qualitätsorientierte Prognose des Lebenszyklus von Werkzeugen und Formen.

[31] BMBF, 2012, EnHiPro - Energie- und Hilfsstoffoptimierte Produktion.

Identification and Promotion of Effective and Efficient Product and Material Cycles via Crowdsourcing

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Abstract

To increase use productivity of products and materials, promising combinations of process steps in recycling and manufacturing shall be identified and promoted. Crowdsourcing offers the chance where every member of a community is able to contribute with particular knowledge and innovative ideas about recycling and manufacturing in a collaborative way. The most effective and efficient single or combined processes have to be identified and promoted in order to substitute less good processes. For comparison and evaluation, contributions are structured as value creation modules, clustering product, process, equipment, organization and human related information. This paper describes how manufacturing and recycling process steps are structured, combined and evaluated. The approach is applied on manufacturing of bicycles as a labor intensive and manufacturing of photovoltaic as a capital intensive example.

Keywords:

Process Evaluation; Knowledge Pool; Crowdsourcing

1 INTRODUCTION

To increase use productivity of products and materials, recycling offers a promising opportunity. Transforming used products into newly desired products effectively and efficiently via recycling and manufacturing requires specific information such as included materials, necessary processes and equipment. However, numerous kinds of products with various material combinations make it difficult to gather all the required information for as many as possible transformations of used into new products. The internet gives chance for motivated people to form a community, where every member is able to participate with his particular knowledge and innovative ideas about recycling and manufacturing in a collaborative way. To initialize such community, the task of gathering is announced as an open call. Such open call, where a task is outsourced towards an undefined, generally large group of people is also known as crowdsourcing. Contributions to such crowdsourcing call – all sorts of information about recycling and manufacturing process steps – are collected as a common knowledge pool. Besides filling the pool, most effective and efficient single or combined process steps have to be identified and promoted in order to substitute less good processes. However, contributions to open calls usually vary in breadth and depth, making comparison and evaluation difficult or even impossible. Hence, contributions are structured in the sense of value creation modules, clustering product, process, equipment, organization and human related information. This paper describes how manufacturing and recycling process steps are structured and integrated in the common knowledge pool. It is shown, how these process steps are evaluated, based on economic, environmental, social and technological indicators. The approach is applied on bicycles in a labor intensive industry and manufacturing of photovoltaic in a capital intensive industry.

2 MATERIAL CYCLES

2.1 Reasons for Material Limits

Non-renewable raw materials are limited due to the fact that the earth can be understood as a closed system. Limitation becomes relevant, when material demand exceeds material supply. Detailed reasons on the supply side are limited **geological reserves** as actual natural deposits. Technological and economic difficulties can handicap **mining** of materials. Some materials which occur as **co-products,** cannot be mined exclusively and depend on mining of other materials**.** Local **socio-economic conditions** may influence mining activities in a negative way. Concentration of mining activities on few countries or companies may create shortfalls due to monopolization. In a global market, supply and demand can be restricted due to **ex- and import restrictions** of a supplying or demanding country. Material demand can occur or increase due to new technologies, an increased consumption or market speculations.

2.2 Strategies to Increase Material Availability

To increase availability, materials can be regained as so-called secondary raw materials out of used products by material and product recycling. In the case of aluminium, the production of secondary raw material requires 20 times less energy than primary production processes. Material recycling activities reduce products to the level of raw materials. In the European Union the recycling rates are e.g. for aluminium 32% and for copper 76%. Product recycling activities like reuse, remanufacturing or refurbishment sustain the integrity of parts, components or complete products [1]. Availability of used products, an adequate return rate and efficient treatment processes limit recycling activities.

2.3 Challenge of Material Cycles

In existing products bound materials can be utilized in product or material recycling as feedstock to create new products. To avoid negative effects like downcycling and increase material efficiency, manufacturing and recycling processes have to be selected based on the specific situation and boundary conditions [2]. To realize an intelligent process selection, numerous process combinations for all sorts of materials and products have to be taken into account. E.g. The Blue Economy describes an approach of how byproducts of one process may be resourceful assets for a second process [3]. Such catalogue of processes seems to be hard to realize by a single institution. In many cases, in-depth knowledge is required, e.g. regarding materials or assembly details for certain products.

3 SUSTAINABLE MANUFACTURING COMMUNITY

Product users represent a big and diverse group of people with knowledge from all sorts of domains and fields of application. Motivating as many as possible of these users to share their ideas, concepts, practices and inside knowledge about manufacturing and recycling processes represents a promising approach to establish and intensify material cycles in particular. As emergent synthesis, these users are intended to consolidate the so called sustainable manufacturing community [4]. To realize and coordinate a community for material cycles, the concepts of prosumer and crowdsourcing are utilized. Besides gainful employment for companies or organizations, individual working arises as an alternative model. Customers shift from passive recipients to active creators, so called prosumer [5]. The prosumer does not only provide demand requests but also contributes pro-active information regarding possible solutions into the value creation process [6]. The prosumer can be characterized as actively and productively involved in the process of creating value. They represent a source of economic value and shall be systematically integrated in the organization of value creation [7]. Within the sustainable manufacturing community, motivated people are addressed, who are not necessarily driven by monetary interests but rather by a joined or greater good or personal development. Projects like Wikipedia [8], an encyclopedia, or open street map [9], a global map, are able to create and motivate communities in order to gather information. For these projects, peoples are addressed via crowdsourcing calls to contribute.

3.1 Crowdsourcing

Crowdsourcing *"is the act of taking a job traditionally performed by a designated agent (usually an employee) and outsourcing it to an undefined, generally large group of people in the form of an open call.*" [10] It is used to open the innovation process of companies to get user ideas and solutions from the outside. However, a continuous flow of contributions is required to continuously increase the knowledge, e.g. for new products or processes.

3.2 Member Interaction and Incentives

In order to get contributions, members of the community have to be motivated or their effort compensated. According to the 1-9-90 rule, only 1% of the community is highly dedicated and continuously develops the initial idea. 9% contribute from time to time and 90% of all community members just consume without return. To increase the overall number of members for the sustainable manufacturing community, the following mechanisms shall be addressed:

- Altruism: letting others benefit from contributed knowledge without expected return;
- Qualification: learning about how materials and products are gained by recycling and products are manufactured;
- Realization: create new useful products, e.g. by using locally available materials and old products;
- Commercialization: identifying proper opportunities to create one's own business.

3.3 Legislative Framework

Sharing of ideas may result in legislative conflicts within the community. Patents are well known in industry to protect ideas and technologies and inhibit competitors from using such. However, such mechanism would cripple the idea of the sustainable manufacturing community by blocking the spread of promising recycling-manufacturing process combination. Therefore, the licensing model of Creative Commons (CC) is used [11]. CC consists of the modules 'Attribution' (BY),, allowing others to alter and distribute contributions, as long as origin is credited; 'share Alike' (SA), allowing altering contributions and publishing them under the same licence; 'Non-Commercial' (NC), requiring the contribution not to be used for commercial purposes; and 'No Derivative' (ND), not allowing any alteration. These modules can be combined into six different licenses.

3.4 Challenge

If many people contribute, technological depth, domain or complexity of that contribution is hardly predictable. Such contribution is intended to describe a transformation of input into output materials or products. Vertically integrated, combined process steps as value creation modules constitute technological processes chains for respective products. Different process chains shall be combined horizontally to form a value creation network (VCN). This allows the use of intermediate products, by-products or waste of one process chain as input for other chains in the sense of the mentioned approach by The Blue Economy. All possible combinations are evaluated and the most suitable selected. However, to enable such functionality, all contributions have to be comparable and combinable.

4 SUSTAINABLE MANUFACTURING PLATFORM

To cope with the outlined challenge, a method for storing, combining and evaluating manufacturing and recycling processes is described in the following. Figure 1 depicts the framework of the sustainable manufacturing platform (SMP). Goal is, to collect knowledge of a spread community, store it in a knowledge pool and make it usable for the community. Via an internet platform, ideas, concepts and approaches are contributed by community members.

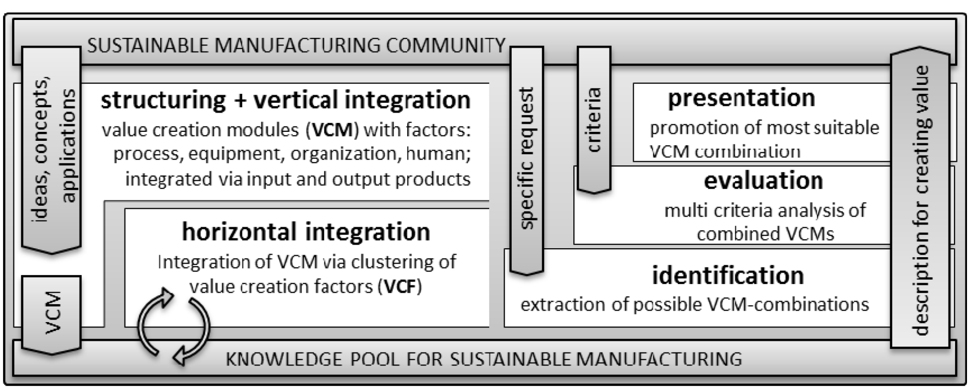

Figure 1: Framework – sustainable manufacturing platform.

These contributions are structured as so called value creation modules (VCM) and stored in the knowledge pool. The knowledge pool is continuously indexed, creating horizontal links between different contributions. Horizontal links are meant to introduce cooperation and competition between different contributions. Specific solutions can be requested by the community. Requests can be related to manufacturing details of a product or suggestions about realizable products out of a given waste material. Horizontally and vertically integrated value creation modules are identified in the knowledge pool and extracted. If possible, different solutions are created and evaluated. Evaluation criteria can be attached to the request in order to fit individual preferences. The knowledge pool uses a share-reuse-and-improve approach, where the community is empowered with the possibility to exchange ideas, utilize them for manufacturing purposes and reposte experience and improvments. The advantage of this approach is that the development procedure is shared and parallelly processed in various locations around the globe. This may reduced the time required to specify the required VCM including their factors.

4.1 Structuring into Value Creation Modules

Community members are able to formulate their ideas, concepts and or applications as long as they fulfill the structural requirements of a value creation module (VCM). The value creation factors VCF are process (how?), equipment (by what?), organization (when? where?) and human (who?) [12]. The VCF 'product' is related to links between different VCMs and addressed as input or output material. Vertical links are set by member input. VCMs are characterized via VCFs, which are specified via attributes like

- Product (What?): size, weight, color, used materials or number;
- Process: time, type or VDI 8580 category;
- Equipment: energy use, capacity or size;
- Organization: organization form or logistic integration;
- Human: ergonomic situation or required qualification.

Continuous innovation for each VCF makes it difficult to predict, which attributes are used by community members to describe their contributions. Therefore, the SMP provides the possibility to define new attributes on the fly. The relation between VCN, VCMs and VCFs is depicted as a UML (universal modeling language) class diagram in figure 2.

4.2 VCM Integration

With an increasing number of VCMs and products, chances increase that similar processes are contributed and stored. Such VCMs may substitute each other and the appropriate VCM has to be identified. In other cases, VCMs complement each other by input and output products. To identify horizontal links, attributes which describe the VCFs product, process, equipment, organization and human are compared between different VCMs. The links between two VCMs are always based on one or more similar attributes of one or more VCFs. Members are able to indicate preferred attributes in their request to filter links between VCMs.

The horizontal linkage of the VCMs is intended to enable the identification of:

- Customer VCMs, which have specific products as input;
- Supplier VCMs, which have specific products as output;
- Competitors and collaborators, which have similar input or output products or which have similar VCM characteristics in processes or equipment;
- Similar processes, which may substitute processes chains partly or completely

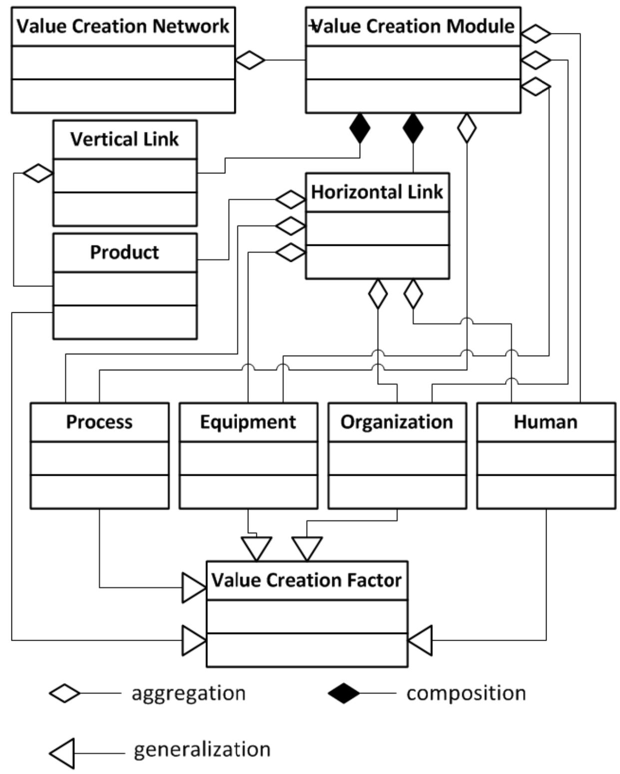

Figure 2: Class structure of Sustainable Manufacturing Platform.

The contributed, vertically and horizontally integrated VCMs constitute the knowledge pool for sustainable manufacturing.

4.3 VCM Identification

In order to utilize the knowledge pool, requests can be formulated by specifying input and output products, VCF characteristics or choosing a specific VCM.

If not provided, the request data is used to identify, initial VCMs. All vertical linked VCMs and for all these VCMs all horizontally linked VCMs are extracted from the knowledge pool. Number of extracted VCM may vary, depending on level of integration of the initial VCMs within the VCN.

4.4 Evaluation of VCM Combinations

Even if all contributions are structured as VCMs, the level of detail varies. An increased number of attributes make it more easy, to identify similar VCMs and therefore increase the level of integration. In generall, the evaluation is realized as comparison of VCFs, based on specific attributes and comparing for clusters of VCMs as summary of attributes. However, it cannot be assumed that data for all attributes of a VCF is contributed. This can affect the VCM evaluation in a negative way. Both methods are limited in information value, compared to detailed assessment methods like Life-Cycle-Assessment. In the future, the evaluation process will be combined with a sustainability analysis, clustering the criteria regarding economic, environmental and social dimensions.

4.5 Result Presentation

For each evaluation criteria and for combined criteria, the most suitable process chains with their VCMs are presented to the user.

Global input and output products as well as all processes steps, required equipment and qualifications are summarized, to provide a overview of the solution. A step by step description of the whole process chain is enriched by multimedia data like figures or movies with the intention to increase the level of quality for the user. The user is able to accept a first result or to request further solutions by specifying more criteria.

The sustainable manufacturing platform is implemented as a web platform which enables access for users and third party software application via internet as well as with mobile devices like smart phones.

5 EXAMPLES

The presented framework and its intended usefulness are applied onto the field of manual assembly of bicycles and primarily automated manufacturing of photovoltaic modules. In both examples the number of VCMs were over 100. To indicate the framework mechanics, figure 3 depicts a simple example. ABS plastics granulate is used to manufacture a cup via a) injection moulding and b) 3D printing. 3D printing still requires filament, produced out of granulate. Manufacturing process chains for a cup were requested

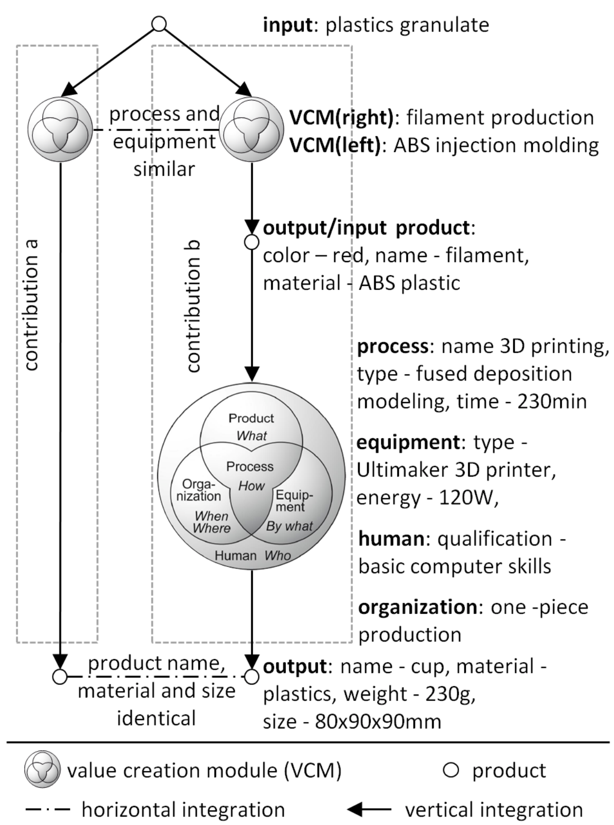

Figure 3: horizontally integrated contribution – example for plastic cup production.

5.1 Manual Processes - Bicycles

In general, a bicycle can be seen as consisting from a frame, a fork set, saddle area, pedal and crank set, front wheel, rear wheel, brake sets, cables, cable insulations and various smaller components, furthermore, gears and gear shifter sets, when applicable, e.g. in the case of mountain bikes and race bikes. Most of these components and their subcomponents can be manufactured with different process types. An example of such is the wheel hub that can be manufactured by different process types, e.g. by casting the rough outer and inner periphery, then drilling the necessary holes into the flanges and turning the outer and inner periphery into more exact dimensions. Another example is to cast the flanges onto a high wall thickness tube, which is again drilled for the necessary hole-arrangement and turned to the exact outer and inner periphery. A third variation of manufacturing the wheel hub is to take a block of the specific alloy and machine it down to the exact hole array, and the required inner and outer periphery [13].

Manufacturing of a bicycle is currently carried out in various types of manufacturing systems, such as through mass manufacturing, mass customization and through fine art craft manufacturing. The mass manufacturing has many different segments such as capital intensive manufacturing, where the degree of automation is very high and robots and special purpose machines handle most of the manufacturing. Another different type of bicycle mass manufacturing is a labour intensive type, where manual workers carry out the work [14] [15].

For the analysis, VCMs for the following processes were considered:

- Manufacturing process chains for a stainless steel bike frame, an aluminium bike frame and a steel bike frame;
- Process chains for the standard components shared with the different frame types, as mentioned before;
- Typical recycling procedures for the different types of frames and the standard components.

Disassembly of most bicycle frames and components is manual. Based on the remaining value of the components the remanufacturing strategy is decided. Bicycle frames, forks and handle sets are often reconditioned, spent parts replaced and the bicycle equipped with a set of new tires, sprockets, chain, breaks/brake pads and cables, depending on what is required to be replaced. Repair shops gather the spent parts according to either materials or component group at their end-of-life (EOL) stage. The most common recycling strategy is to ship the bicycle components, including the metal frames to collection centres, which then sort and send the materials to recycling. Many parts of bicycles are made from highly alloyed parts, with a relatively high value but they are not kept apart from the low valued parts. The reason for this is the low functionality of the parts, the variety of parts and the little knowledge or the difficulty in identifying the high value parts. Low costs for waste disposal and available channels for the high value parts compared to the low value parts obstruct the horizontal integration of the recycled materials into other industry sectors [16].

5.2 Automated Processes - Photovoltaic Modules

Goal of this analysis was, to identify potentials for integrating different kinds of recycled photovoltaic modules into the manufacturing process of new modules and other industry sectors. For the analysis, VCMs for the following processes were considered:

- Manufacturing process chains for CdTe / CdS, CIGS, amorphous silicon, mono-crystalline and polycrystalline silicon modules;

- Processes chains for thick film modules, chemical, mechanical and thermal recycling;
- Common industrial applications for PV manufacturing and recycling byproducts like cement industry for recycled glass.

Current recycling processes are more or less in an experimental stage or realized as pilot factories. Main activities can be found regarding chemical recycling. But also the conversion of silicon tetrachloride to trichlorosilane via converters is already implemented on an industrial scale. However, cleaned target materials are contaminated with sand blasting agents. Only disposal could be found as (EOL) a solution. For aluminum chloride, no EOL application could be identified but should be evaluated as input material for the pharmaceuticals and cosmetics industries. The reasons for not realized horizontal integration into other industry sectors are cost intensive implementation of appropriate equipment, low costs for waste disposal and volume of waste material and end-of-life modules. The number of integrations is still very low and hinder the economical operation of recycling and reprocessing facilities for PV modules of all kinds.

6 SUMMARY

The overlaying research question of this paper is how the dynamics of competition and cooperation in globalized markets can be utilized by innovative technology to cope with the challenge of rationally required mankind`s sustainable development on earth. The paper describes the sustainable manufacturing platform as a framework to increase sustainability in manufacturing. How manufacturing and recycling process steps are structured, vertically and horizontally integrated, combined and evaluated is explained. How the evaluation is based on economic, environmental, social and technological indicators, is shown. The approach was applied on bicycles and photovoltaic manufacturing.

7 OUTLOOK

The success of the proposed platform depends highly on contributions. A critical number of processes are required to enable solutions for request of users with and without background in manufacturing. In order to realize the mentioned sustainability analysis, external tool and third party programs are analized for their applicability and possibility to integrate. Therefore the sustainable manufacturing platform provides an XML interface for machine based data exchange. Another application is a real-time support for product designers.

8 ACKNOWLEDGMENTS

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9 REFERENCES

[1] Allwood, J.M., Ashby, M.F., Gutowski, T.G, Worrell, E. (2011) Material Efficiency: a White Paper, Resources Conservation and Recycling, in press

[2] Heyer, S.; Seliger, G. (2011): Demand driven Recycling in Value Creation Cycles. In: Proceedings of the 44th CIRP International Conference on Manufacturing Systems, Madison, USA.

[3] Pauli, G.(2010): Blue Economy-10 Years, 100 Innovations, 100 Million Jobs. Paradigm Pubns.

[4] Ueda, K.; Takenaka, T.; Vancza, J.; Monostori, L., (2009): Value creation and decision-making in sustainable society. In: CIRP Annals - Manufacturing Technology, Nr. 58, Volume 2, pp. 681-700.

[5] Toeffel, A. (1980): The Third Wave, Zukunftschance. Perspektiven für die Gesellschaft des 21. Jahrhunderts, ISBN 3-442-11350-4.

[6] Redlich, T. (2010): Open Production Gestaltungsmodell für die Wertschöpfung in der Bottom-up-Ökonomie. PhD thesis, Helmut-Schmidt-Universität.

[7] Kleemann, M.; Voß, G.; Rieder, K.: Crowdsourcing und der Arbeitende Konsument. In: Arbeits- und Industriesoziologische Studien, Jahrgang: 1, pp. 29-44, 2008.

[8] Wikipedia (2012), www.wikipedia.org, last visit Dec. 2012.

[9] Open Street Map (2012): www.openstreetmap.org/, last visited Dec. 2012.

[10] Hopkins, R. (2011): What is Crowdsourcing?. In: Sloane, P. (eds.): A guide to open innovation and crowdsourcing, Kogan Page.

[11] Creative Commons (2012): creativecommons.org/, last visit Dec. 2012.

[12] Seliger, G. (2007): Sustainability in Manufacturing, Springer Verlag Berlin Heidelberg.

[13] Den, S., Personal communication about bicycle manufacturing (2012): J.G. Steingrímsson, Editor, TU-Berlin: Berlin.

[14] Kotha, S., (1996): From mass production to mass customization: The case of the National Industrial Bicycle Company of Japan. In: European Management Journal, Volume 14, Issue 5, pp. 442-450

[15] Chen, Y.-S., Lin, M.-J. J., Chang, C.-H., Liu, F.-M. (2009): Technological innovations and industry clustering in the bicycle industry in Taiwan. In: Technology in Society, Volume 31, Issue 3, pp. 207-217.

[16] Schauer, E. and Eggert, N., Personal communication about bicycle recycling in Europe (2012): J.G. Steingrímsson, Editor, TU-Berlin: Berlin.

Part Agent Advice for Promoting Reuse of the Part Based on Life Cycle Information

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Abstract

In order to promote reuse of parts for achieving sustainable society, we are developing part agent system. A part agent that consists of a network agent and radio frequency identification technologies manages information of the corresponding part throughout its life cycle and provides users with advices on maintenance of the part. In this paper, a framework is proposed to create appropriate advices based on life cycle information of the part. To be used in the framework, a method was developed to estimate reusability of a part against operations of a user based on causal network on failures.

Keywords:

Part agent; Life cycle; Bayesian network

1 INTRODUCTION

The effective reuse of mechanical parts is important for developing a sustainable society [1]. To realize effective part reuse, it is essential to manage individual parts over their entire life cycle because each individual part has a different reuse history.

For reuse-based production, manufacturers need to capture the quantity and quality of the parts returned for reuse. However, with the exception of leased products such as photocopiers [2], most products, once sold, are not under manufacturer's control, which makes it difficult for manufacturers to predict the quantity and quality of returned parts. They may be reused through markets that are beyond the manufacturer's control. Uncontrollable and unpredictable diversity of user behavior, hinder the management of parts by manufacturers.

On the other hand, it is difficult for product users to manage and carry out appropriate maintenance on the large number of a variety of parts of manufactured products owned by them. Difficulties in managing all these parts—not to mention inaccessibility to appropriate maintenance information—impede management by users, in spite of the fact that more environmentally friendly actions are required from users if they are to reuse parts effectively.

On the basis of these considerations, we propose a scheme whereby a part "manages" itself and supports user maintenance activities. For this purpose, the authors propose a management system that includes network agents and radio-frequency identification (RFID) tags [4] [5]. The network agent is assigned to an individual part of a product to which an RFID tag is attached. It is programmed to follow its real counter part throughout its life cycle. We named this network agent as "part agent" [6] [7] [8] [9] [10] [11] [15].

The part agent provides users with appropriate advice on the reuse of parts and promotes the circulation of reused parts. Using this mechanism, consumers can also be advised about environmentally friendly ways of product use and predicted product failures. Such advice helps users to manage the product during the use phase of its life cycle.

Researchers propose methods to design life cycle of products where designers select appropriate life cycle options for a product by evaluating various values throughout its life cycle [34]. Importance of life cycle scenario and aspects of product-service systems have been recognized [35]. Evaluation of life cycle options is made using life cycle simulation [33]. Most of them are based on calculation of product flow among life cycle stages. Agent based approach is employed when individual part is focused [30].

However, life cycle expected in design phase may not be achieved particularly in case of parts or products with long life cycle. Changes in economic circumstances, development of new products and technologies and other factors may undermine the life cycle option chosen in design phase. We consider robustness and adaptive nature is important in life cycle design and execution. We consider part agent of our proposal can be used for that purpose.

In this paper, we propose a framework for part agent to generate advices in order to support reuse of parts based on life cycle information. To select a life cycle path appropriate for the situation, part agent compares possible paths by estimating their values considering predicted behavior within a near future. This framework will be applied to various estimation of life cycle on which part agent generates advices for user. As one of such estimation, we have developed a method to evaluate a reused part appropriate for operations of a user. Part agent evaluates the user's operations on the part by using a causal network called Bayesian network that is created based on state of the part and information of life cycle model. The agent advises the user on an appropriate reused part based on the results of evaluation. Preliminary results of implementation are shown.

The concept of the part agent system is described in section 2. In section 3, the proposed framework for part agent to generate advices based on life cycle information is described. A method for the estimation of reused part based on causal network of failures is described in section 4. Discussions and remaining issues are shown in section 5. The paper is summarized in section 6.

2 PART AGENT FOR SUPPORTING THE PRODUCT LIFE CYCLE

2.1 Conceptual Scheme of Part Agent

The proposed part agent system is based on the following usage scenario. The system uses the part agent to manage all information about an individual part throughout its life cycle. The proposal assumes the spread of networks and high-precision RFID technology.

The part agent is generated at the manufacture phase of the main parts, when an RFID tag is attached to its corresponding part. The part agent identifies the ID of the RFID tag during the part's life cycle, and tracks the part through the entire network. We chose RFID tag for the identification because RFID has higher endurance against environmental stress than printed codes such as bar code that may deteriorate or be covered by dirt in a long period of part's life cycle.

In contrast to Product Embedded Identifier or PEID technology [17] that involves a small computing chip, an RFID tag, and sensors to support the middle and end of life of the products, our goal is to promote multiple reuses of individual parts that may not necessarily be managed by manufacturers, which require a "lightweight" system.

Figure 1 shows the conceptual scheme of the part agent. The part agent collects information needed to manage its corresponding part, by communicating with the various functions within the network. These functions may involve a product database that provides product design information, an application that predicts deterioration of parts, one that provides logistics information, or one that provides market information. Further, the part agent communicates with the functions in the local site, such as sensory functions that detect the state of the part, storage functions for individual part data, and management and control functions of the product. Communication is established using information agents that are subordinate network agents generated by the part agents.

On the basis of the collected information, the part agent provides users with appropriate advice on managing the corresponding part. When the user makes a decision concerning product usage, the part agent provides necessary directions with regard to product management and control functions. The agent also contacts a part manufacturer regarding the repair of the part, when it foresees part failure.

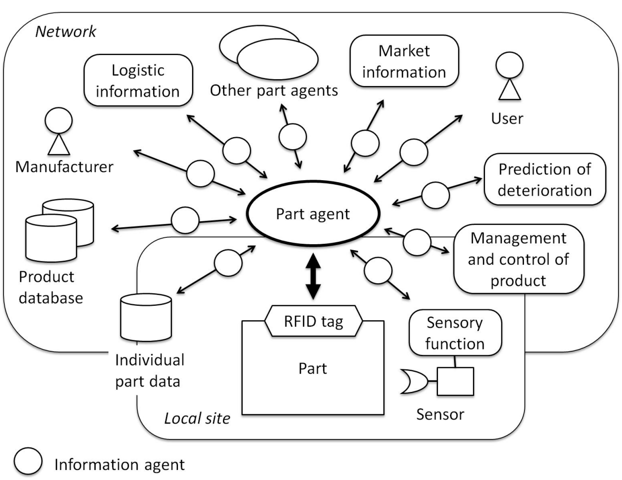

Figure 1: Conceptual scheme of part agent.

2.2 Development of Functions of Part Agent

Functions of part agents have been developed to promote the reuse of parts. Part agent can advise its user replacement of the corresponding part based on its deterioration level and market information [6-8, 14]. Nakada [13] developed a function to notify users the cumulative environment burden a product imposes and to warn them about use of the product with excessive environment burden. He also developed a function to advise users replacement of computer hard disk drive (HDD) based on failure prediction using S.M.A.R.T. (Self-Monitoring, Analysis and Reporting Technology [18]).

In addition to implementation of these functions for part agents, life cycle simulations of parts, part agents and users are conducted to investigate the effective strategy for reuse of parts. The importance of user's preference in promoting the reuse is recognized [10, 11]. Further, it is revealed from the simulation that diversity of user's preference is effective both for reuse of parts and for user's satisfaction [14]. Shigeji developed a method to capture user preference through questionnaire as a simple function for each preference cluster [16]. Although the concept of part agent is not introduced, Kondoh [19] also proposes a method for assembly of reused parts using multi-agent simulation.

3 AGENT ADVICE BASED ON LIFE CYCLE INFORMATION

It is difficult to determine life cycle of a product in detail because you cannot foresee what will happen in future. To overcome this problem, we think life cycle should be designed to allow possible changes. As design of robust life cycle is not a topic in this paper, we simply assume that a life cycle stage in the model has multiple life cycle paths connecting to its next stages in order for part agent to be able to select an appropriate path at the time of execution. For example, 'use' stage may have three paths; one leads to 'maintenance' stage, another to 'disposal' stage and the third one back to 'use' stage.

Figure 2 illustrates our life cycle model. Life cycle path represents a transfer from a life cycle stage to another stage. Stage and path has concerned values required or generated there, such as cost, environmental load and benefit. Multiple paths may exist starting from a stage as described above. Part agent decides at every time step which path to be followed. For that purpose, as will be described below, part agent estimate future possible actions. Probability assigned to each life cycle path represents an estimated probability that part agent takes the path.

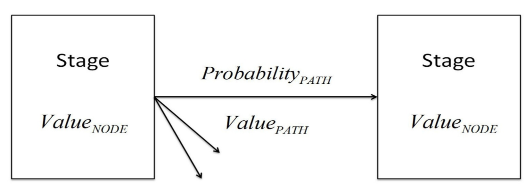

Figure 2: Life cycle model.

We propose, as shown in Figure 3, a basic framework for part agent to make an appropriate advice to the user based on the life cycle model and other related information. In each time step, part agent takes a following procedure. First, part agent picks up all the candidate paths from current life cycle stage and then checks each path if it is 'active' or not. For example, if the part has a failure and does not work, then the path back to 'use' stage (which means that the part will continue to be used) cannot be followed and should be marked as 'inactive'.

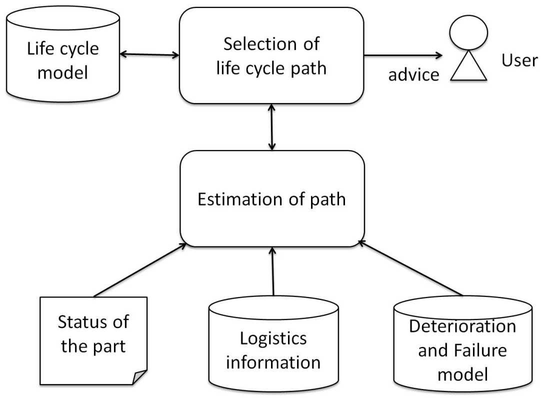

Figure 3: Framework for part agent to generate advice.

```
accumulated_value ( node, depth ) {
  expected_value = 0;
  if ( depth>0 ) {
    for each ( path connected to node ) {
      next_node = the other node of path;
      value = value_of_path ( path ) +
        value_of_node( node ) +
        accumulated_value(next_node, depth-1);
      expected_value = expected_value +
              value * probability(node, path);
    }
  }
  return expected_value;
}

select_path ( node, depth ) {
  max_value = 0; max_path = null;
  for each ( path connected to node ) {
    if ( path is active ) {
      next_node = the other node of path;
      value = value_of_path ( path ) +
        value_of_node( node ) +
        accumulated_value(next_node, depth-1);
      if ( value > max_value ) {
        max_path = path; max_value = value;
      }
    }
  }
  return max_path;
}
```

Figure 4: Selection of life cycle path.

Next, part agent evaluates each active path. The evaluation is based on estimation of the path using information including current status of the part, logistics information and information on deterioration and failure. The evaluation is made based on not only the current state but also the predicted state of near future.

Figure 4 explains the algorithm described in a C-like expression. Function *accumulated_value* evaluates the argument stage *node* considering the states within *depth* time steps in future. For each life cycle path starting from the node, the function adds the value assigned to the path, the value contained in the node at the other end of the path and all the value from paths and nodes connected to the node within *depth* steps that are collected recursively. Functions *value_of_path* and *value_of_node* estimates specific values corresponding to the path and the node. As the value is an expected value based on future activity of the part, probability of the path is applied. Function *probability* estimates the probability of the path based on deterioration and logistics information, though it is not elaborated in this paper.

Path for recommendation is selected using function *select_path* to select a path with maximum value from all the active paths starting from the current node. Note that, for the current node and paths starting from it, value is an actual value though, for the next nodes and further nodes, their value is expectation.

Part agent creates advice to the user according to this algorithm. The recommended path differs depending on the estimation, i.e., what kind of value is interested and how to estimate it.

4 EVALUATION OF REUSED PART

4.1 Reusability Depending on Usage

As an example for the estimation, we have developed a function of part agent that evaluates the reusability of parts. Even if a reused part includes a small defect, a user may use it depending on his usage. For example, when a reused part has a short residual life, a user rejects it because he needs a part with longer life, but another user may pick it up because he will use it just for a limited period.

In order to promote reuse of part, it is necessary to capture the needs of individual user and to decide if a reused part satisfies the needs. A problem is that, in most cases, no clear relation has been established between the usage of a part and possibility of its defects. Hence, we take a probabilistic approach.

4.2 Causal Network on Failures

Figure 5 shows a scheme we propose to evaluate reused parts. Part agent collects all the information about the corresponding part such as sensory information on the part, information on other parts acquired from other part agents and information on its user from his/her input.

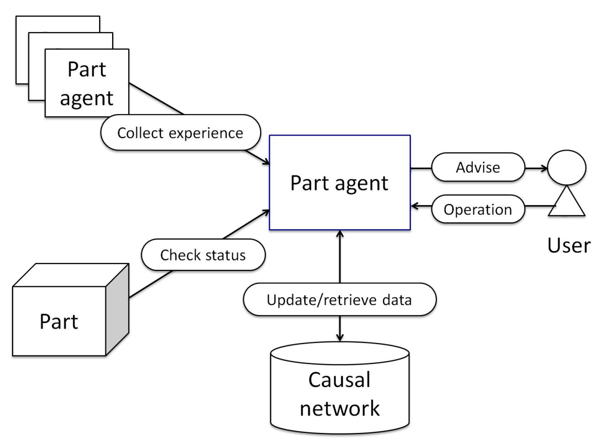

Figure 5: Evaluation of reusability.

The part agent creates and maintains causal network for failures based on this collected information. Causal network or Bayesian network represents causal relationship among related events with conditional probability [36]. Part agent calculates probability of failure using this network and proposes appropriate advices to the user.

Figure 6 shows an example of causal network representing causal relation between user's operations and failures of a product. Nodes with rounded box represent inputs to the network that are, in this case, operations by the user. Nodes with square box represent events related by causal relations. Events with shaded box cannot be observed directly, which means that we have to suppose their occurrence based on other observable events. This example model contains 3 operations for user's choice and 2 observable states that can be measured via sensory data. It represents the following causal relations; *Operation A* and *B* cause *Defect 1* that in turn affects *Observed state 1*. *Defect 1* and *Operation C* cause *Defect 2*. If *Defect 2* occurs, it not only affects *Observed state 2* but also requires maintenance.

Conditional probability is assigned to each node in Bayesian network. It describes how much the occurrence of the event is affected by the prior events in its causal relation. For example, in Figure 5, conditional probability for node *Defect 1* is shown in the table at the top left. It shows the probability of *Defect 1* for the combination of *Operation A* and *Operation B*, i.e., *P(D1|OpA, OpB)*.[1] It reads that, the probability of *Defect 1* is 0.1 if both operations do not occur, 0.4 if only *Operation B* occurs, and so on.

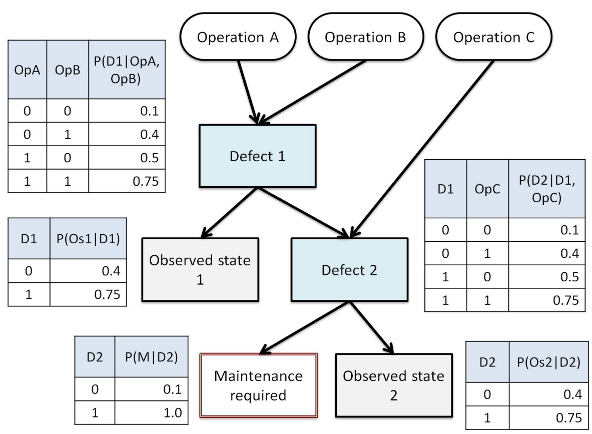

Figure 6: Representation of causal relations with conditinal probability tables.

4.3 Evaluating Reused Parts

Here we assume that we have two reused parts, *Part 1* and Part *2*. *Part 1* has a poor value in *Observed state 1* and a good value in *Observed state 2*. On the contrary, *Part 2* has a good value in *Observed state 1* and a poor value in *Observed state 2*. We also have two users, *User 1* and *User 2*. Their prior probability for *Operation A*, *B*, *C*, that represents how the two users use the product, is shown as in Table 1.

Based on this information on parts and users with the information of causal network shown in Figure 6, the probability for the requirement of maintenance is calculated as shown in Table 2. Note that, for *User 1*, its probability of maintenance with *Part 2* is higher than that with *Part1*. And for *User 2* it is higher with *Part 1* than with *Part 2*. Thus, part agent recommends *Part 1* for *User 1* and *Part 2* for *User 2*.

	Operation A	Operation B	Operation C
User 1	0.25	0.25	0.25
User 2	0.75	0.75	0.25

Table 1: Prior probability of user operation.

	Use Part 1 P(M|Os1)	Use Part 2 P(M|Os2)
User 1	0.370	0.428
User 2	0.66	0.611

Table 2: Probability for the requirement of maintenance.

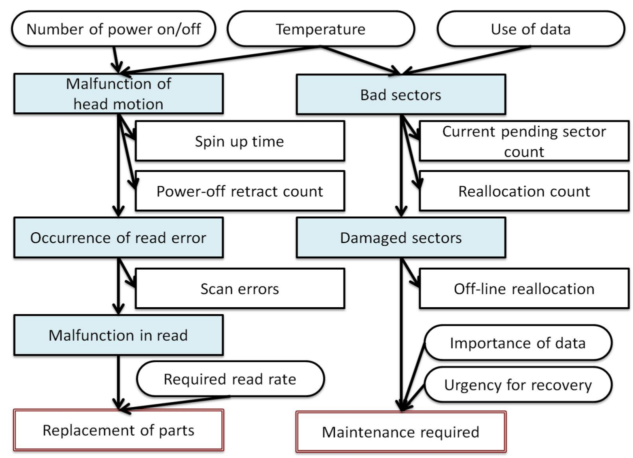

Figure 7: Causal network on HDD failure.

Part agent recommends a reused part appropriate for the user by stochastic analysis of the relation between user operation and failure based on causal network.

Using this method, we have implemented a function of part agent that supports replacement of HDD. We used S.M.A.R.T [18] for observation of HDD failure and the causal network on HDD failure shown in Figure 7 for estimation. Simulation is performed with 4 users with different usage patterns and 6 HDDs with different S.M.A.R.T errors. Part agent recommends appropriate HDD for each user.

In order to use Bayesian network for evaluating reused part we need to create an appropriate causal network and to estimate its conditional probabilities. Generally, events and relations in causal network are extracted by analyzing correlations among possible occurrences based on experienced data. This means accumulation of a good amount of experience is required on the target part or product. We consider the diagram of failure mode and effect analysis (FMEA) generated in design phase of the product could be applied as its causal network. Estimation of conditional probabilities also requires experienced data. Additionally, as occurrences of events such as failures affect the probability, we need to continually

[1] In the expression of probability, event names are shortened such as *D1* for *Defect 1*, *OpA* for *Operation A* and *OpB* for *Operation B*.

update the data in conditional probability tables. We need to develop a function of part agents to gather the related event data from the same type of products in a similar situation and to update the data in conditional probability tables. If an appropriate causal network with conditional probability tables is available for the target part, we consider the proposed method using part agents is applicable and effective to estimate reusability of the part.

5 DISCUSSION

A framework is proposed for part agents to accommodate to various estimations based on life cycle information. As an example of estimations, a method to estimate the usability of reused parts based on causal network is developed though it has not been fully integrated in the framework. We think that the following estimations are major candidates to be integrated in the framework;

Deterioration and Failure

To clarify and predict deteriorations and failures of parts is one of the most important issues. As described in section 3, estimation of values in near future would be an effective tool for generating advices. Degradation of performance, probability of failure and related cost required for maintenance should be predicted. However, they are very difficult issues. Google reports that some S.M.A.R.T errors would lead to HDD failures within limited days but they also emphasize probabilistic nature of the phenomena [24]. Considering reused parts, it might also be necessary to consider further effects such as a correlated progress of dynamics and deterioration of mechanical devices [26][27]. That is why we expect that an approach based on probability such as described in section 4 would be helpful.

Logistics

Locations and cost of transportation would also be one of the important and required estimation. In addition to the delivery of parts, transportation for take-back of parts should be considered for reused parts [31]. Some method should be developed to collect required volume and quality of reused parts timely from widespread locations of users.

User's Preference

User's preference on replacement of parts is considered as a key tool to promote the reuse of parts [16][32]. Not only estimation of user's preference on a part but also estimation of user's preference itself is issues to be solved.

Reusability Based on Causal Network

We consider estimation of reusability of a part against user's operation described in section 4 has two major issues that are the update of conditional probability table and the creation of causal network, as depicted previously. As for the former issue, conditional probability is based on the accumulated data of user's operations and resulting occurrences on products or parts. Method should be developed to capture such information and to reflect it to conditional probability in causal network. The latter issue, the creation of causal network itself is more difficult and more general approach dealing with large amount of ambiguous data might be necessary.

In addition to the issues in estimations described above, remaining issues for developing part agents include warranty of reused part [28], security and privacy [29], infrastructure to help the promotion of reuse. Application to various practical parts and products other than HDD is necessary to evaluate the effectiveness of the proposed scheme.

6 CONCLUSION

In this paper, we propose a framework for part agent to promote reuse of parts. To overcome the uncertainty that cannot be predicted in the design phase, a fundamental mechanism is proposed to select a life cycle path based on the information of life cycle. As an example for the estimation of life cycle path, a method to select a reused part appropriate for user's operations is developed. Bayesian network that represents causal relations of events with conditional probability is applied to estimate the probability of failure. Future work is also discussed.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] Hauschild, M., Jeswiet, J. and Alting, L., 2005, From Life Cycle Assessment to Sustainable Production: Status and Perspectives, in: Annals of CIRP, Vol. 54, No. 2: 535–555.

[2] Sakai, K., 2007, Ricoh's Approach to Product Life Cycle Management and Technology Development, in: the Proceedings of the 14th CIRP Conference on Life Cycle Engineering. June 11–13, 2007. Tokyo, Japan: 5-9.

[3] M. Goedkoop et al., 1999, Product Service Systems Ecological and Economic Basics, Report for Dutch Ministries of Environment and Economic Affairs.

[4] Borriello, G., 2005, RFID: Tagging the World, in: Communications of the ACM, Vol. 44, No. 9: 34–37.

[5] Hitachi Ltd., Hitachi Develops a New RFID with Embedded Antenna μ-Chip, http://www.hitachi.com/New/cnews/030902.html (accessed on 2 May, 2012).

[6] Suzuki, M., Sakaguchi, K. and Hiraoka, H., 2001, Life Cycle Support of Mechanical Product Using Network Agent, in: Inasaki, I. (ed.), Initiatives of Precision Engineering at the Beginning of a Millennium, Kluwer Academic Publishers, 912–916.

[7] Hiraoka, H. and Iwanami, N., 2005, Network Agent's Advice for Promoting the Reuse of Mechanical Parts, in: the Proceedings of EcoDesign 2005, Tokyo, Japan: 2C-1-2F.

[8] Fukuda, N., Hiraoka, H. and Ihara, T., 2006, Supporting the Reuse of Parts Based on Operation Histories of Products and Preference of Consumers, in: the 11th International Conference on Precision Engineering, Tokyo, Japan: 59-63.

[9] Hiraoka, H., Fukuda, N. and Hanatani, T., 2007, Handling the Variety for Reuse of Mechanical Parts, in: the Proceedings of EcoDesign 2007, Tokyo, Japan: C3-2-3F.

[10] Hanatani, T., Fukuda, N. and Hiraoka, H., 2007, Simulation of Network Agents Supporting Consumer Preference on Reuse of Mechanical Parts, in: the Proceedings of the 14th CIRP Conference on Life Cycle Engineering, Tokyo, Japan: 353-358.

[11] Hiraoka, H., Hanatani, T. and Tanaka, A., 2008, Life Cycle Simulation of Mechanical Parts with Part Agents for Promoting their Reuse based on User's Preferences, in: the Proceedings of the 5th International Conference on Product Lifecycle Management, Seoul, South Korea: 206.

[12] Hiraoka, H. and Tanaka, A., 2009, Simulator for Reuse of Mechanical Parts with Network Agents, in: International Journal of Automation Technology, Vol. 3, No. 1: 77–83.

[13] Nakada, T., and Hiraoka, H., 2009, Network agents for supporting consumers in the lifecycle management of individual parts, in: the Proceedings of the 6th International Conference on Product Lifecycle Management, Bath, UK.

[14] Hiraoka, H., Nishida, K. and Tanaka, A., 2009, Life Cycle Simulation for Promoting the Reuse of Parts Using Part Agents, EcoDesign 2009, V-27.

[15] Hiraoka, H., Ito, K., Nishida, K., Horii, K. and Shigeji, H., 2011, Development of Part Agents for the Promotion of Reuse of Parts through Experiment and Simulation, Glocalized Solutions for Sustainability in Manufacturing, Proceedings of the 18th CIRP International Conference on Life Cycle Engineering: 419-424.

[16] Shigeji, Y., Kawaharada, H. and Hiraoka, H., 2011, A Life Cycle Simulation for Part Agents that Proposes a Management of Parts Based on Consumer's Satisfaction, EcoDesign 2011: G1-12.

[17] Jun, H. B., Kiritsis, D. and Xirouchakis, P., 2007, Research Issues on Closed-Loop PLM, in: Computers in Industry 58: 855–868.

[18] Wikipedia, S.M.A.R.T., http://en.wikipedia.org/wiki/S.M.A.R.T. (accessed on 2 May, 2012).

[19] Kondoh, S., Tateno, T. and Matsumoto, M. 2009, Multi-agent simulation of component reuse focusing on variations in user preference, CIRP J. of Manufacturing Science and Technology, 1: 287-293.

[20] Umeki, N., 2011, Quality Information Service. http://homepage1.nifty.com/QCC/index.html (in Japanese) (accessed on 2 May. 2012).

[21] Asano, T., 2000, Introduction to practical multivariate analysis. The 2nd edition, Kodansha, Japan (in Japanese).

[22] Wikipedia, k-means clustering, http://en.wikipedia.org/wiki/K-means_clustering (accessed on 2 May. 2012).

[23] Wikipedia, Analytic Hierarchy Process, http://en.wikipedia.org/wiki/Analytic_Hierarchy_Process (accessed on 2 May. 2012).

[24] Pinheiro, E., Weber, W.D., and Barroso, L.A., 2007, Failure Trends in a Large Disk Drive Population, in: the Proceedings of the 5th USENIX Conference on File and Storage Technologies, San Jose, CA: 17-28.

[25] Lange, D., and Oshima, 1988, M., Programming and Deploying Java™ Mobile Agents with Aglets™, Addison-Wesley.

[26] Pombo, J., Ambrósio, J., Pereira, M., Lewis, R., Dwyer-Joyce, R., Ariaudo, C. and Kuka, N, 2010, A study on wear evaluation of railway wheels based on multibody dynamics and wear computation, Multibody System Dynamics, 24: 347-366.

[27] Arita, M., Kawaharada, H. and Hiraoka, H., 2012, Simulation on wear of a reused part that consider deviation of product's motion due to deterioration of the part, ICPE2012 (to appear).

[28] Anityasari, M., Kaebernick, H. and Kara, S., 2007, The Role of Warranty in the Reuse Strategy, 14th CIRP Conference on Life Cycle Engineering: 335-340.

[29] Ohkubo, M., Suzuki, K. and Kinoshita, S., 2005, RFID Privacy Issues and Technical Challenges, in: Communications of the ACM, Vol. 44, No. 9: 66–71.

[30] Komoto, H., Masui, K. and Kondoh, S., 2012, A simulation method of dynamic systems applied to backcasting scenario design, The Philosopher's Stone for Sustainability, Proc. of the 4th CIRP International Conference on Industrial Product-Service Systems, pp.333-338.

[31] Kondoh, S. and Komoto, H., 2012, Reuse/sharing business design method considering the difficulties for product transfer, The Philosopher's Stone for Sustainability, Proc. of the 4th CIRP International Conference on Industrial Product-Service Systems, pp.363-368.

[32] Hiraoka, H., Ueno, T., Arita, M., Shigeji, Y., Horii, K and Kawaharada, H., 2012, Promoting reuse of mechanical parts using part agents, The Philosopher's Stone for Sustainability, Proc. of the 4th CIRP International Conference on Industrial Product-Service Systems, pp.387-392.

[33] Komoto, H., Tomiyama, T., Nagel, M., Silvester, S., and Brezet, H., 2005, Life Cycle Simulation for Analyzing Product Service Systems, Proc. of EcoDesign 2005, 2B-1-2F.

[34] Kunii, E., Fukushige, S. and Umeda, Y., 2011, Development of CAD System for Life Cycle Scenario-Based Product Design, Glocalized Solutions for Sustainability in Manufacturing, Proc. of the 18th CIRP International Conference on Life Cycle Engineering, pp. 118-123.

[35] Wada, H., Kishita, Y., Mizuno, Y., Hirosaki, M., Fukushige, S. and Umeda, Y., 2011, Proposal of a Design Support Method for Sustainability Scenarios 1st Report: Designing Forecasting Scenarios, Glocalized Solutions for Sustainability in Manufacturing, Proc. of the 18th CIRP International Conference on Life Cycle Engineering,pp. 189-194.

[36] Motomura, Y. and Iwasaki, H., 2006, Bayesian Network Technology – Modeling of Users and Customers and Uncertainty Reasoning, Tokyo Denki University Publisher (in Japanese).

Selective Disassembly Planning for Sustainable Management of Waste Electrical and Electronic Equipment

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Abstract

Waste Electrical and Electronic Equipment (WEEE) are one of the most significant waste streams in modern societies. Full disassembly of WEEE is rarely an ideal solution due to high disassembly costs. Selective disassembly, which prioritizes operations for partial disassembly according to the legislative and economic considerations of specific stakeholders, is becoming an important yet still challenging research topic in recent years. In this paper, a Particle Swarm Optimization (PSO)-based selective disassembly planning method embedded with customizable decision-making models has been developed. The developed method is flexible to handle WEEE to meet the various requirements of stakeholders, and is capable to achieve optimized selective plans. Practical cases on Liquid Crystal Display (LCD) televisions have been used to verify and demonstrate the effectiveness of the research in application scenarios.

Keywords:

Disassembly planning; WEEE; LCD

1 INTORDUCTION

The mounting demand for new products has brought more manufacturing activities worldwide in recent years. This rapid development, however, has been hindered by the increasing concerns on the scarcity of natural resources and environmental issues. Statistics show that from 1985 the resource consumption on the global level has been higher than the ecological capability of the Earth. It has been estimated that the required bio-capacity of two Earths is necessary to satisfy the need of the development in 2050 according to current production and consumption trends [1].

On the other hand, more and more products after services are filled up in landfills. Among them, Electrical and Electronic Equipment (EEE) after services, that is, Waste Electrical and Electronic Equipment (WEEE), are becoming one of the major and challenging waste streams in terms of quantity and toxicity. For instance, there are approximately 7 million tons of WEEE generated in Europe per year [2]. In China, 1.1 million tons of WEEE are generated per year [3]. Due to the rapid technical innovations and shorter usage lifecycle of EEE, WEEE are growing much faster than any other municipal waste streams. To keep the Earth cleaner, End-of-Life (EoL) recovery strategies are critical to shape the future of WEEE lifecycle management patterns. Among the strategies, remanufacturing is viewed as a “hidden green giant” and attracting escalating attentions of researchers and practitioners [4-7]. Remanufacturers seek to bring some components of products after their services back into ‘as new’ condition by carrying out necessary disassembly, overhaul, and/or repairing operations for re-use to extend lifecycles. There are two driving forces for industries in adopting the relevant technologies and practices, i.e., stricter legislative pressure for environmental protection and better profit margins from remanufacturing. The explanations are expanded below.

- The WEEE Directive has been enacted and implemented from 2003 in Europe, and the equivalent Directives have been developed in different countries of the world. Further proposals for tighter WEEE Directives have been suggested to regulation bodies with an aim to make products and components after services more recyclable, reusable and remanufactureable (i.e., reducing the waste arising from WEEE, improving and maximizing recycling, reuse and other forms of recovery of waste from WEEE, and minimizing the impact on the environment from their treatment and disposal);
- According to the WEEE Directives, a producer (manufacturer, brand owner or importer)’s responsibility is extended to the post-consumer stage of WEEE, instead of stopping at selling and maintenance (i.e., Extended Producer Responsibility – EPR [8-9]. The EPR is aimed at encouraging producers especially manufacturers to provide cradle-to-grave support to reduce environmental impacts, such that they work closely with remanufacturing industries to recover maximum values and reduce environmental toxicity/hazardousness. For instance, the remanufacturing legislative initiatives are underway in the EU and USA to ensure Original Equipment Manufacturers (OEMs) and suppliers to provide free access to remanufacturing information facilities in global chains [10];
- Good remanufacturing planning and management can effectively balance economic and environmental targets, and bridge gaps between the shorter innovation cycles of EEE and the extended lives of components of WEEE. Remanufacturing industries in the EU and worldwide have been recently growing quickly because of better economic return values. There are numbers of successful cases in industries, including single use cameras (Eastman Kodak and Fuji Film), toner cartridges (Xerox), personal computers (IBM, HP, Toshiba, Reuse network-Germany), photocopiers (Fuji Xerox–Australia, Netherlands and UK), commercial cleaning equipment (Electrolux), washing machines (ENVIE-France), mobile phones (Nokia, ReCelluar-USA, Greener solution-UK).

Disassembly planning, which is used to determine sensible disassembly operations and sequencing, is critical in remanufacturing. Effective disassembly planning can significantly improve the recycling and reuse rates of components and materials from WEEE to ensure maximum value recovery. For a set of WEEE, there could be a number of different sequences of disassembly operations leading to different decision-making models according to the perspectives and criteria of stakeholders [11]. As thus, it becomes difficult for remanufacturers to solely depend upon their experiences to plan disassembly operations so as to recover a larger proportion of components and fulfill environmental targets at a reasonable cost. In the past years, research has been carried out to address the issues of disassembly. The previous research can be generally summarized as the following two categories:

- Disassembly for design. Disassembly approaches for EEE such as consumer electronic products have been developed to use smart materials like Shape Memory Polymers (SMPs) in the design of embedded releasable fasteners to facilitate the disassembly processes of the products [12-17]. Design for remanufacturing/disassembly principles have been spread among Japanese manufacturers since products with the principles are more profitable in this context than those that were not designed with this purpose [5, 18-19];
- Disassembly planning and operation sequencing. Typical disassembly operations based on manual, semi-automatic and automatic processes and the associated tool-kits were summarized [5]. Based on disassembly operations and the precedence constraint relationships among the disassembly operations, sequencing rules and intelligent and/or meta-heuristic reasoning algorithms were applied to deduce an optimal plan from a large pool of candidate solutions [11, 20-22]. In recent years, remanufacturers are facing many challenges to disassemble WEEE due to their high customization and diversity, high integration level, and more complex assembly processes. Current economic analyzes have demonstrated that a full disassembly is rarely an optimal solution and necessary owing to high disassembly cost. Selective disassembly, which prioritizes operations to implement partial dismantling of WEEE so as to take account of the legislative and economic considerations and meet the specific requirements of stakeholders, is a promising alternative and has therefore become a new research trend [5].

Attributing to booming personalized and mass-customized EEE, it is still challenging to apply the developed methods to increasingly diversified and personalized WEEE to make sensible decisions and meet different stakeholders' perspectives. In this paper, a Particle Swarm Optimization (PSO)-based selective disassembly planning method with customizable decision making models has been developed. The method is adaptive to various types of WEEE, flexible for customized decision modeling and making for different stakeholders, and capable for achieving optimized solutions during disassembly planning. Industrial cases on Liquid Crystal Display (LCD) televisions have been used to verify and demonstrate the effectiveness of the developed method.

2 SELECTIVE DISSASEMBLY PLANNING APPROACH

Disassembly of WEEE involves different stakeholders, such as environmental regulators and remanufacturers, which will lead to develop different decision-making models. For instance, according to the WEEE Directive, WEEE regulators will check whether remanufacturing companies are able to recycle at least 75% of WEEE by weight and remove/recover all the hazardous materials. In other words, at least 75% of WEEE are required to be dismantled to a component level, and all the components containing hazardous materials need to be taken apart from WEEE for further recycling and processing. Apart from fulfilling these fundamental environmental targets, remanufacturers would also improve the economic efficiency by prioritizing valued components during disassembly. In Figure 1, an example of LCD WEEE is used to illustrate the above scenario.

In order to develop a selective disassembly planning method that is suitable for stakeholders to process various types of WEEE and meet their specific requirements, it is imperative to define customizable decision-making models. The models (Disassembly indices and Objective) developed in this research are described in following formulas.

In the formulas, three symbols will be used frequently and they are explained here first.

n	The number of the total disassembly operations in a plan of a set of WEEE
m	The number of the disassembly operations in a selective disassembly plan
$Position(Oper(i))$	The position (sequence) of the ith disassembly operation in a disassembly plan

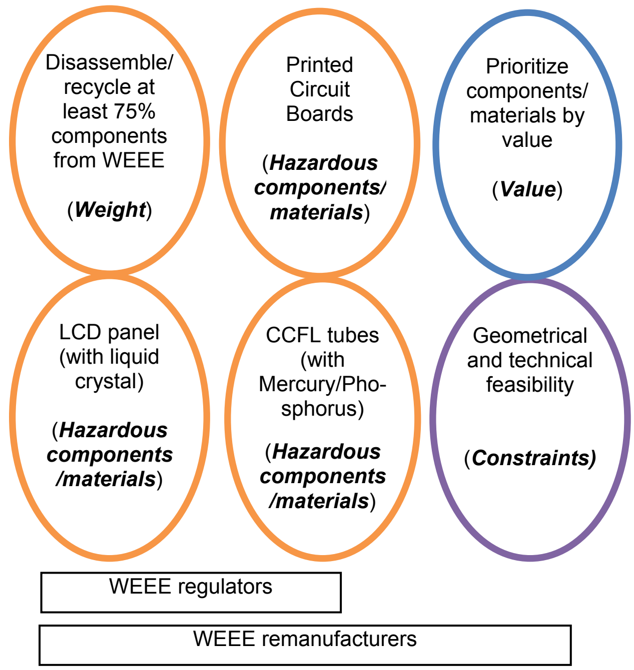


Figure 1: Criteria for different decision-making models.

Selective Disassembly Plan (DP) and Disassembly Operation ($Oper(i)$)

A set of WEEE can be fully disassembled using a disassembly plan. The number of all the operations in the plan is n. A Selective Disassembly Plan (DP), which consists of a set of disassembly operations, which is a part of the above complete operations. The number of the selected operations is m, and the i^{th} operation is denoted as $Oper(i)$. DP can be represented as:

$$DP = \bigcup_{i=1}^{m} (Oper(i), Position(Oper(i))) \quad (1)$$

where $\bigcup$ represents the set of disassembly operations, and $m \le n$.

For instance, there are a set of disassembly operations $Oper(1), Oper(2), Oper(3), Oper(4)$, and their positions in DP are 4,2,1,3 (e.g., $Position(Oper(1)) = 4$), so that the sequence of the operations in DP is $Oper(3), Oper(2), Oper(4), Oper(1)$.

Meanwhile, $Oper(i)$ has some properties related to the environmental and economic targets defined as follows.

Hazardousness ($H(Oper(i))$) and Hazardousness Index ($Index\_H$)

Hazardousness of the i^{th} disassembly operation is to indicate the level of hazardousness contained in the component(s) removed by the operation from the WEEE. It can be represented in a qualitative means, i.e., high, relatively high, medium, and low, and converted to a quantitative means accordingly, such as (5,3,1,0) for (high, relatively high, medium, low). $Index\_H$ of a set of WEEE is to indicate the accumulated hazardousness contained in the component(s) removed by the disassembly operations in the WEEE. $Index\_H$ can be computed as below:

$$Index\_H = \sum_{i=1}^{m}(H(Oper(i)) * Position(Oper(i))) \quad (2)$$

A smaller $Index\_H$ will be beneficial. The function of multiplying $H(Oper(i))$ and its position $Position(Oper(i))$ in DP is to ensure that the disassembly operations with higher hazardousness (i.e., $H(Oper(i))$) are arranged in earlier positions in DP to achieve a smaller $Index\_H$.

For instance, the hazardousness of $Oper(1), Oper(2), Oper(3), Oper(4)$ are (high, low, medium, relatively high) respectively, which can be converted to (5, 0, 1, 3). The positions of the operations in DP are (4, 2, 1, 3). Therefore, the hazardousness index of DP is (5*4+0*2+ 1*1+3*3) = 30. If the positions of the operations are re-arranged as (1, 4, 3, 2), then the hazardousness index is (5*1+0*4+1*3+3*2) = 14. The latter is lower than the former since the operations with higher hazardousness are arranged earlier in the latter. In Objective defined later on, a weighted minimum hazardousness index will be pursued to ensure the operations to remove the most hazardous components will be arranged as early as possible to improve the efficiency of hazardousness removal in a selective disassembly plan.

Potential Recovery Value ($V(Oper(i))$), Disassembly Time ($T(Oper(i))$) and Potential Value Index ($Index\_V$)

$V(Oper(i))$ of the i^{th} disassembly operation is to indicate the potential recovery value of the component(s) disassembled from the WEEE by the operation. The disassembled component(s) could be re-usable so that $V(Oper(i))$ can be represented as the depreciation value of the equivalent new component(s). $T(Oper(i))$ represents the time spent for the disassembly operation $Oper(i)$. $Index\_V$ of a set of WEEE is to indicate the accumulated potential value index by the disassembly operations in the WEEE. $Index\_V$ can be computed as below:

$$Index\_V = \sum_{i=1}^{m}((V(Oper(i)) / T(Oper(i)) * Position(Oper(i))) \quad (3)$$

A smaller $Index\_V$ will be beneficial. $V(Oper(i))/T(Oper(i))$ represents the potential value recovery efficiency of $Oper(i)$. The function of multiplying $V(Oper(i))/T(Oper(i))$ and its position $Position(Oper(i))$ in DP is to ensure that the disassembly operations with higher $V(Oper(i))/T(Oper(i))$ are arranged earlier to achieve a smaller $Index\_V$ so as to achieve a higher efficiency of potential value recovery for a selective disassembly plan.

Weight Removal ($W(Oper(i))$) and Weight Removal Index ($Index\_W$)

$W(Oper(i))$ is to indicate the level of the removed weight by the i^{th} disassembly operation from the WEEE. It can be represented by the weight of the component(s) disassembled by the operation. $Index\_W$ of a set of WEEE is to indicate the accumulated weight removal index by the disassembly operations in the WEEE. $Index\_W$ can be computed as below:

$$Index\_W = \sum_{i=1}^{m}(W(Oper(i)) * Position(Oper(i))) \quad (4)$$

Similarly, a smaller $Index\_W$ will be beneficial. The function of multiplying $W(Oper(i))$ and its position $Position(Oper(i))$ in DP is to ensure that the disassembly operations with higher $W(Oper(i))$ are arranged earlier to achieve a smaller $Index\_W$ in order to improve the efficiency of weight removal in a selective disassembly plan.

Decision Making Objective and Optimization Algorithm

Disassembly decision-making will be modeled as an optimization problem. The Objective can be customized to address different requirements of stakeholders through weight setting by users. The Objective is represented below:

$$Mimimise(w1 * Index\_H, w2 * Index\_V, w3 * Index\_W) \quad (5)$$

where $w_1 - w_3$ are the weights. Different weights can be set by different users to reflect .varied priorities of the three indices. A higher weight means more attentions will be paid to that index, and a zero value means such index will not be considered. In order to rationalize the model, the three indices are required to be normalized to be in the same measurement scale. The normalization process is illustrated in case studies.

The different selection and optimization sequencing of disassembly operations for a set of WEEE usually brings forth a large search space. In this research, an improved algorithm based on a modern intelligent algorithm, i.e., PSO, has been applied to facilitate the search process. A classic PSO algorithm was inspired by the social behavior of bird flocking and fish schooling [23]. Three aspects will be considered simultaneously when an individual fish or bird (particle) makes a decision about where to move: (1) its current moving direction (velocity) according to the inertia of the movement; (2) the best position that it has achieved so far; and (3) the best position that its neighbor particles have achieved so far. In the algorithm, the particles form a swarm and each particle can be used to represent a potential disassembly plan of a problem. In each iteration, the position and velocity of a particle can be adjusted by the algorithm that takes the above three considerations into account. After a number of iterations, the whole swarm will converge at an optimized position in the search space. A classic PSO algorithm can be applied to optimize the disassembly planning models in the following steps:

(1) Initialization

- Set the size of a swarm, e.g., the number of particles “Swarm_Size” and the max number of iterations “Iter_Num”;
- Initialize all the particles (a particle is a disassembly plan DP) in a swarm. Calculate the corresponding indices and Objective of the particles (the result of the objective is called fitness here);
- Set the local best particle and the global best particle with the best fitness.

(2) Iterate the following steps until “Iter_Num” is reached

- For each particle in the swarm, update its velocity and position values;
- Decode the particle into a disassembly plan in terms of new position values and calculate the fitness of the particle. Update the local best particle and the global best particle if a lower fitness is achieved.

(3) Decode global best particle to get the optimized solution

However, the classic PSO algorithm introduced above is still not effective in resolving the problem. There are two major reasons for it:

- Due to the inherent mathematical operators, it is difficult for the classic PSO algorithm to consider the different arrangements of operations, and therefore the particle is unable to fully explore the entire search space;

- The classic algorithm usually works well in finding solutions at the early stage of the search process (the optimization result improves fast), but is less efficient during the final stage. Due to the loss of diversity in the population, the particles move quite slowly with low or even zero velocities and this makes it hard to reach the global best solution. Therefore, the entire swarm is prone to be trapped in a local optimum from which it is difficult to escape.

To solve these two problems and enhance the capability of the classic PSO algorithm to find the global optimum, new operations, including crossover and shift, have been developed and incorporated in an improved PSO algorithm. Some modification details are depicted below.

(1) New operators in the algorithm

- Crossover. Two particles in the swarm are chosen as Parent particles for a crossover operation. In the crossover, a cutting point is randomly determined, and each parent particle is separated as left and right parts of the cutting point. The positions and velocities of the left part of Parent 1 and the right part of Parent 2 are re-organized to form Child 1. The positions and velocities of the left part of Parent 2 and the right part of Parent 1 are re-organized to form Child 2;
- Shift. This operator is used to exchange the positions and velocities of two operations in a particle so as to change their relative positions in the particle.

(2) Escape method

- During the optimization process, if the iteration number of obtaining the same best fitness is more than 10, then the crossover and shift operations are applied to the best particle to escape from the local optima.

3 CASE STUDIES OF WEEE RECYCLING

Televisions can be generally classified into six groups: CRT (Cathode Ray Tube), LCD, PDP (Plasma Display Panel), LED (Light Emitting Diode), RP (Rear Projection) and DLP (Digital Light Projection). The LCD televisions have been developed quickly over the past decades and they are now the market leader sharing the biggest market (e.g., the global market figures for the LCD televisions are forecasted to surpass $80 Billion in 2012 [24]).

A LCD television produces a black and colored image by selectively filtering a white light. The light is typically provided by a series of Cold Cathode Fluorescent Lamps (CCFLs) at the back of the screen. The LCD televisions studied here are produced by the Changhong Electronics Company, Ltd. from China, which is the biggest television producer in China. The company provides information about LCD televisions of the type of LC24F4, such as the Bill of Materials (BoMs), exploded view, mass of each parts and the detailed assembly processes (see Figure 2).

A LCD television is typically assembled by three main parts: front cover assembly part, back cover assembly part and base assembly part. Among them, the front cover assembly part is composed of a surface frame, a remote control receiver board, a control button board, a main board, a power supply board, a Low-Noise Block (LNB) converter board (optional), and a DVD ROM (optional). The mass of the LC24F4 LCD television is 5963.8 Grams. Among the component/material composition, the PCBs (Printed Circuit Boards, which are mainly main boards and power supply boards) and LCD screens are quite complex in terms of structure and recycling. Other components/materials include cables, wires, pins, switches and rubbers. The cables, wires, pins and switches consist of plastics that are usually Polyvinyl Chloride (PVC), nonferrous mainly Copper and Aluminum. Current EoL disposal for LCD televisions is typically landfill or incineration, and this form of disposal restricts the ability to recover potentially reusable materials from waste LCD televisions, e.g., components to be reused or remanufactured, and recycled materials like Steel, Aluminum, Copper, etc. Due to the increasingly significant market share of LCD televisions, it is imperative to apply effective methods to plan the disassembly of LCD televisions.

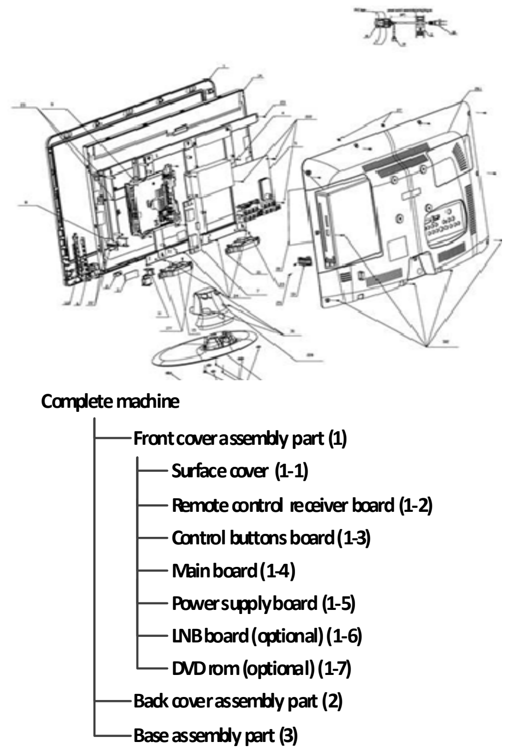


Figure 2: A LCD television and part of its structure views.

In the disassembly planning process of LCD televisions, it needs to address environmental, economic and feasibility issues. Environmental regulators need to ensure that specific targets with regard to the remanufacturing and recycling of LCD televisions are adhered to, and remanufacturers expect to isolate components that can generate higher potential re-use values from the overall assembly in a timely and efficient manner to ensure that labor overheads are maintained as low as possible.

The hazardous materials contain substances that are harmful to humans or directly harmful to the environment. Some hazardous materials are parts of LCD televisions, such as PCBs, which often contain Tin, Lead, Cadmium and capacitors containing Polychlorinated Biphenyls, and the LCD screen, which contains fluorescent tubes with Mercury and liquid crystals.

According to the WEEE Directives, components in WEEE with hazardous materials need to be disassembled and then recycled (e.g., The EU WEEE Directive states that PCBs greater than 10 cm^2 need to be removed from WEEE). It is also required to disassemble at least 75% components from a set of WEEE. In a LCD television, key components contribute significantly to the overall weight of the LCD so that they should be handled first to improve disassembly efficiency. Meanwhile, another key issue to achieving successful recycling is to ensure that there is an economic gain from the disassembly process.

Based on the BoMs of the LCD television of the type of LC24F4, the process of disassembly can be planed. Each disassembly operation is defined with several properties, such as disassembly operation number, disassembly operation time, component(s) (name, amount, and mass) to be disassembled by each operation, and potential recovered component(s)' mass, potential value and hazardousness.

An initial plan:

Different disassembly plans can be created. One of these chosen is (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20). Its physical disassembly process is shown in Figure 3. This plan is called "an initial plan" to be used in the following scenario for a comparison with an optimized plan for a better understanding of the optimization process.

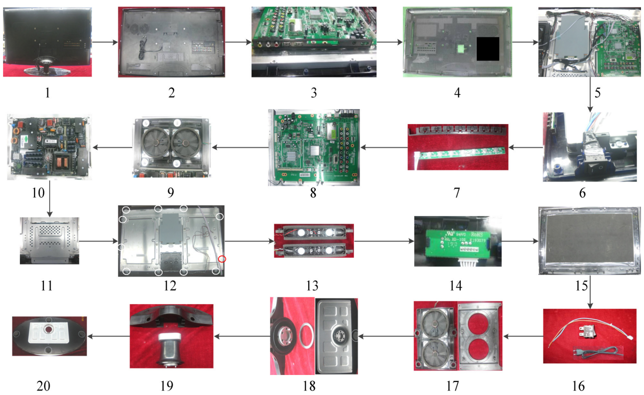


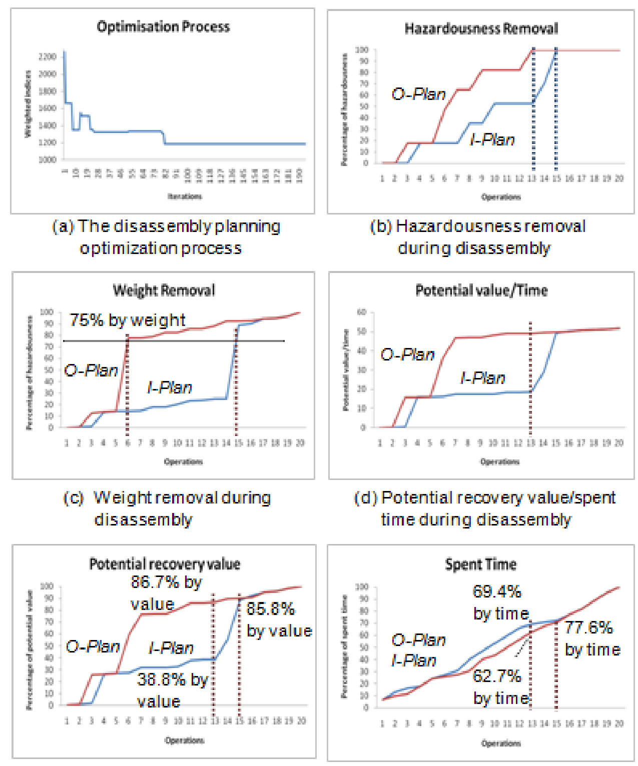
Figure 3: Disassembly plan of a LCD (an initial plan).

Selective optimized plan:

It is aimed to determine a selective optimization disassembly plan (part of the full disassembly plan) to meet the environmental protection targets (100% hazardousness removal and 75% component disassembled for the whole WEEE) and achieve the optimized potential recovery value. The disassembly planning selection and optimization process is shown in Figure 4 (a), in which *I-Pan* and *O-Plan* stand for the initial and optimization plans respectively. During the computation process, results were normalized, i.e., the index result of each operation was converted as the percentage of the overall results of all the operations. The results in the Y axis were also accumulated for the operations. The hazardousness removal, weight removal and potential recovery value for the initial plan (the initial plan is shown in the previous Figure 3) and an optimized plan are shown in Figure 4 (b), (c) and (d) respectively. In (b), a 100% hazardousness removal target will be achieved after 13 disassembly operations for the optimized plan, In (c), a target to achieve 75% component disassembled by weight (of the total weight of the WEEE) took 6 operations for the optimized plan,. In (d), the result of potential recovery value divided by spent time for each operation is shown, which is a target to achieve the most potential recovery value within the shortest time. To meet the environmental protection targets of removing 100% components with hazardous materials and 75% components by weight to be disassembled, the first 13 disassembly operations were selected from the optimized plan as the selective optimized plan. Meanwhile, the potential recovery value and spent time for this plan was optimized in this selective plan.

In (b) and (c), it can show that the initial plan will take 15 disassembly operations to achieve 100% hazardousness removal, and also 15 operations for 75% components by weight to be disassembled. Therefore, 15 operations are necessary to achieve the environmental protection targets. Therefore, the optimized plan will have 2 less operations. The potential value/time in (d) can be separated and interpreted in (e) and (f). It shows that with the selective optimized plan, the potential recovery values during the disassembly process are 86.7% (of the total potential value of all the disassembled components in the WEEE) for 13 operations, and 38.8% and 85.8% for the initial plan after 13 and 15 operations respectively. With the selective optimized plan, the time spent during the process were 62.7% (of the total time spent to disassemble the WEEE) for 13 operations, and 69.4% and 77.6% for the initial plan after 13 and 15 operations respectively.

Therefore, if the 13 operations are selected for both plans, it can be observed that significant potential value is recovered (86.7% vs 38.3%) while less time spent with the optimized solution (62.7% vs 69.4%). If the 13 operations and 15 operations are selected for the two plans respectively, a better potential recovery value (86.7% vs 85.8%) while about 15% time of the total disassembly time can be saved with the optimized solution (62.7% vs 77.6%). Assume 15% labor time of disassembling a single set of LCD WEEE stands for 200 seconds, about 6 hours for 100 sets of the LCD WEEE will be saved.



(a) The disassembly planning optimization process
(b) Hazardousness removal during disassembly
(c) Weight removal during disassembly
(d) Potential recovery value/spent time during disassembly
(e) Potential recovery value during disassembly
(f) Spent time during disassembly

Figure 4: Selective optimization plan.

4 CONCLUSIONS

WEEE have been increasingly customized and diversified, and the selective disassembly planning of WEEE to support remanufacturing decision-making is an important but challenging research issue. In this paper, an effective selective disassembly planning method has been developed to address the issue systematically. The characteristics and contributions of the research include:

- An improved PSO algorithm-based selective disassembly planning method with customizable decision-making models has been developed in a systematic means. In the method, the customizable decision-making models embedded with adaptive multi-criteria to meet different stakeholders' requirements have been designed to enable the method flexible and customizable in processing WEEE effectively;
- Based on the intelligent optimization algorithm, the developed method is capable to process different types of WEEE based on

a generic and robust process and achieve selective optimized disassembly plans efficiently;

- Industrial cases on LCD WEEE have been successfully carried out to verify the effectiveness and generalization of the developed research. Application scenarios have been set and analyzed to validate and demonstrate that this research is promising for practical problem solving.

In the future, a more intelligent mechanism needs to be developed to generate and incoperate disassembly constraints from the functions and semantics of the BoMs of EEE automatically and accurately (e.g., not all the assembly constraints will be used to generate disassembly constraints due to the different functions and semantics during EEE assembly and WEEE disassembly). With the mechanism, disassembly plans of WEEE will be generated from the design stage of EEE to support Design for Remanufactureability/Sustainability in a more efficient means.

5 ACKNOWLEDGEMENT

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6 REFERENCES

[1] Jovane, F.; Yoshikawa, H.; Alting, L.; Boer, C.R.; Westkamper, E.; Williams, D.; Tseng, M.; Seliger,G.; Paci, A.M. (2008): The Incoming Global Technological and Industrial Revolution Towards Competitive Sustainable Manufacturing, in: CIRP Annals – Manufacturing Technology, Vol. 75, pp.641-659.

[2] Walther, G.; Steinborn, J.; Spengler, T.S.; Luger, T.; Herrmann, C. (2010): Implementation of the WEEE-Directive - Economic Effects and Improvement Potentials for Reuse and Recycling in Germany, in: International Journal of Advanced Manufacturing Technology, Vol. 47, pp.461-474.

[3] Hicks, C.; Dietmar, R.; Eugster, M. (2005): The Recycling and Disposal of Electrical and Electronic Waste in China – Legislative and Market Responses, in: Environmental Impact Assessment Review, Vol. 25, pp.459-47.

[4] Kopacek, B.; Kopacek, P. (1999): Intelligent Disassembly of Electronic Equipment, in: Annual Reviews in Control, Vol. 23, pp.165-170.

[5] Duflou, J.R.; Seliger, G.; Kara, S.; Umeda, Y.; Ometto, A.; Willems, B. (2008): Efficiency and Feasibility of Product Disassembly: a Case-based Study, in: CIRP Annals – Manufacturing Technology, Vol. 57, pp. 583-600.

[6] Kernbaum, S.; Heyer, S.; Chiotellis, S.; Seliger, G. (2009): Process Planning for IT-equipment Remanufacturing, in: CIRP Journal of Manufacturing Science and Technology, Vol. 2, pp.13-20.

[7] Hatcher, G.D.; Ijomah, W.L.; Windmill, J.F.C. (2011): Design for Remanufacturing: A Literature Survey and Future Research Needs, in: Journal of Cleaner Production, Vol. 19, pp.2004-2014.

[8] Mayers, C.K. (2007): Strategic, Financial, and Design Implications of Extended Producer Responsibility in Europe: A Producer Case Study, in: Journal of Industrial Ecology, Vol. 11, pp.113-131.

[9] Sander, K.; Schilling, S.; Tojo, N.; van Rossem, C.; Vernon, J.; George, C. (2007): The Producer Responsibility Principle of the WEEE Directive, in: DG ENV. Study Contract N° 07010401/2006/449269/MAR/G4, https://ec.europa.eu/environment/waste/weee/pdf/final_rep_okopol.pdf, (2007), (accessed on 28.11.2012).

[10] Giuntini, R.; Gaudette, K. (2003): Remanufacturing: the Next Great Opportunity for Boosting US Productivity, in: Business Horizons, November-December, pp.41-48.

[11] Kara, S.; Pornprasitpol, P.; Kaebernick, H. (2006): Selective Disassembly Sequencing: A Methodology for the Disassembly of End-of-life Products, in: CIRP Annals – Manufacturing Technology, Vol. 55, pp.37-40.

[12] Masui, K.; Mizuhara, K.; Ishii, K.; Rose, C. (1999): Development of Products Embedded Disassembly Process Based on End-of-life Strategies, in: Proceedings of the EcoDesign'99: 1st International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, pp.570-575.

[13] Chiodo, J.D.; Harrison, D.J.; Billett, E.H. (2001): An Initial Investigation into Active Disassembly using Shape Memory Polymers, in: Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 215, pp.733-741.

[14] Jones, N.; Harrison, D.; Billett, E.; Chiodo, J. (2004): Electrically Self-powered Active Disassembly, in: Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 218, pp.689-697.

[15] Braunschweig, A. (2004): Automatic Disassembly of Snap-in Joints in Electromechanical Devices, in: Proceedings of the 4th International Congress Mechanical Engineering Technologies'04, Varna, pp.48-56.

[16] Hussein, H.; Harrison, D. (2008): New Technologies for Active Disassembly: Using the Shape Memory Effect in Engineering Polymers, in: International Journal of Product Development, Vol. 6, pp.431-449.

[17] Ijomah, W.L.; Chiodo, J.D. (2010): Application of Active Disassembly to Extend Profitable Remanufacturing in Small Electrical and Electronic Products, in: International Journal of Sustainable Engineering, Vol. 3, pp.246-257.

[18] Sundin, E.; Lindahl, M.; Ijomah, W.L. (2009): Product Design for Product/service Systems – Design Experiences from Swedish Industry, in: Journal of Manufacturing Technology Management, Vol. 20, pp.723-753.

[19] Dindarian, A.; Gibson, A.A.P.; Quariguasi-Frota-Neto, J. (2012): Electronic Product Returns and Potential Reuse Opportunities: A Microwave Case Study in the United Kingdom, in: Journal of Cleaner Production, Vol. 32, pp.22-31.

[20] Santochi, M.; Dini, G.; Failli, F. (2002): Computer Aided Disassembly Planning: State of the Arts and Perspectives, in: CIRP Annals – Manufacturing Technology, 51(2), pp.507-529.

[21] Lambert, A.J.D. (2002): Determining Optimum Disassembly Sequences in Electronic Equipment, in: Computers & Industrial Engineering, Vol. 43, pp.553-575.

[22] Kuo, T.C. (2012): Waste Electronics and Electrical Equipment Disassembly and Recycling Using Petri Net Analysis: Considering the Economic Value and Environmental Impacts, in: Computers & Industrial Engineering, to appear.

[23] Kennedy, J.; Eberhart, R. (1995): Particle Swarm Optimization, in: Proceedings of IEEE International Conference on Neural Networks, IV. pp.1942-1948.

[24] Ryan, A.; O'Donoghue, L.; Lewis, H. (2011): Characterising Components of Liquid Crystal Displays to Facilitate Disassembly, in: Journal of Cleaner Production, Vol. 19, pp.1066-1071.

After Sales Strategies for the Original Equipment Manufacturer of Electric Mobiles

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Abstract

In the opinion of industry, politics and science, the electric mobility becomes increasingly important in future of the automotive sector. With the resulting replacement of internal combustion engines, there are changing conditions for the stakeholders in the automotive industry. Therefore, new suppliers and even competitors are entering the market and the value chain will be changed. Particularly the automotive aftermarket is concerned by the electric mobility which is because of its high margins and stable revenues a very important sector. All players in this market have to rethink their after sales strategies to exist in this highly competitive sector. In this article the new market conditions and the consequences for the stakeholders in the automotive aftermarket are shown. Additionally after sales strategies that meet the requirements of the electric mobility are shown and analyzed.

Keywords:

After Sales Management; End-of-Life Strategies; Electric Mobility

1 INTRODUCTION

Since several years electric mobility is one big topic in economy and research. [1], [2] In the opinion of industry, politics and science the electric mobility becomes increasingly important in the future of the automotive industry. Many Stakeholders of the automotive sector see a huge market, especially since the end of the internal combustion technology for cars is foreseeable. One major reason for this is the limited resources of crude oil. In addition there are other special reasons for changes in the automotive sector e.g. new legislative measures since the electric cars have a positive effect on carbon dioxide emission, if the energy is gained by renewable energy. [3] With the resulting replacement of the internal combustion engines, conditions for stakeholders in the automotive industry will change.

An electric vehicle may be defined as a road vehicle with electric propulsion. There are different technologies like battery electric vehicles, hybrid electric vehicles or fuel-cell electric vehicles [2], which will be not distinguished in this paper. Although the electric mobility has currently not yet taken hold in the market, the projected growth rates are significant. For example, McKinsey expects market shares in large cities between five and sixteen percent for electric vehicles in new registrations in 2015. [4] As another reason for changes in the market, grants of governments have a high impact on this market, e.g. research promotion. [2], [5]

But only the primary market the sales market is exposed to these new influences due to the electric mobility. Particularly the automotive after sales service with its high margins [6] is affected by the electric mobility. Figure 1 shows the differences and the advantages that a good after sales service can provide for the enterprises. While the after sales service is relatively resistant against economic downtimes, the sales business often reacts with a dramatical sales collapse as a result of the crisis. In addition the after sales service provides a close contact to the customer because he comes more than a single time to a workshop for the service and maintenance of his car.

A big problem for the stakeholders in the automotive aftermarket is that neither the factors that influence the after sales are known properly, nor the useful after sales strategies which consider the requirements of electric mobility have been identified in a structured way. Therefore, this paper deals with the new market conditions in the automotive aftermarket due to the increasing relevance of electric mobility. In the first step, the automotive after sales service with the relevant stakeholders is shown. Also the consequences for the stakeholders in the automotive aftermarket caused by the changes of the electric mobility are shown. In the next step, the relevant strategies for the automotive after sales service sector are pointed out. Finally, the strategies are analyzed and assessed by adequate key factors.

	Sales	After Sales Service
Independency of economic situation	Very high	Low
Margin	Low	High
Behavior in times of crisis	Profit and sales collapse	Stable
Forecast horizon	Short product life cycles	Long service intervals
Contact to customer	Singular customer contact	Intensive, long lasting contact
Gathering customers needs	Limited	Good, due to intensive contact with the customer
Growth and innovation potential	Often already limited	High

Figure 1: Sales vs. After Sales Service.

2 AUTOMOTIVE AFTER SALES SERVICE

In the following part of the paper the structure of the automotive after sales market is shown in detail. For a better understanding of the automotive aftermarket, the market structure and the relationship of its stakeholders are shown in figure 2.

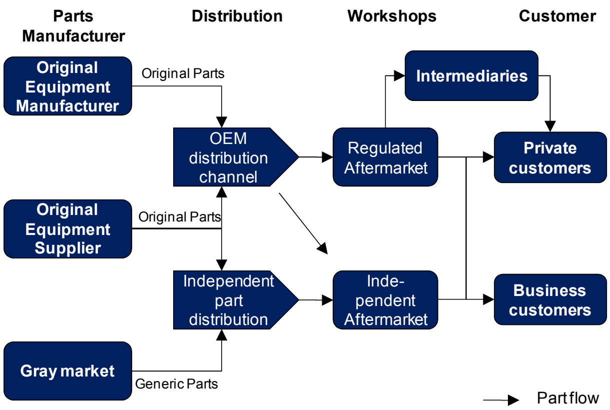

Figure 2: Structure of the automotive aftermarket.

This market can roughly be divided in four levels: the parts manufacturer level, the distribution level, the workshop level and the customer level. At each level in the after sales market there is a variety of stakeholders with differing interests.

First there are the automotive manufacturers (original equipment manufacturers / OEMs), suppliers (Original Equipment Suppliers / OES) and the gray market which are acting in the parts manufacturer level. [7] These stakeholders are the providers of the spare parts for after sales market. While the OEM and OES sell relatively expensive original equipment spare parts the gray market manufacturer normally dispose the so called generic parts. [8] The stakeholders of the gray market often only provide the generic spare parts which have high sales volumes. Generic parts are much cheaper spare parts which are often copied from the original equipment spare parts. The parts are sold via two distribution channels the OEM distribution channel for the original parts and the independent part distribution channel for the generic parts. At the workshop level, parts are sold and the services such as car repairs or car maintenance services are offered. The workshop level becomes more and more important due to several reasons. For example there is the possibility for direct customer contact, which allows to identify the needs of the customers contemporarily. Therefore, they are able to sell additional services to the customers. The workshop level itself can be divided on the one hand in the regulated aftermarket, where the car dealerships of the OEMs as well as workshops with a contractual commitment to the OEMs are settled. On the other hand there is the independent aftermarket. The independent aftermarket represents large workshop chains and small independent garages. [7] They offer services for various automotive brands and their service scope varies widely. For example, there are specialized workshops on glass repairs, tires, paint or workshops which provide the complete maintenance and repair services. Between the workshop level and the customer level acts a connecting group of stakeholders the so called intermediaries. Intermediaries can be assigned neither to the customers nor to the workshop level of the automotive after sales sector. Examples for intermediaries are assurance companies which determine the services carried out in a workshop. Therefore intermediaries can have a high impact on the automotive aftermarket. The last level in the automotive After Sales market is the customer level. These stakeholders are the most important players in the automotive market. Customers can be separated private and business customers, which also contain fleet customers.

3 CHANGES IN THE AUTOMOTIVE AFTER SALES SERVICE

As the result of the increasing electrification of the cars different effects in the automotive aftersales market could be identified. Hence there is a need to develop new strategies which can compansate the declines in the after sales business. Significant changes, which are caused by the trend towards electric mobility are shown in figure 3.

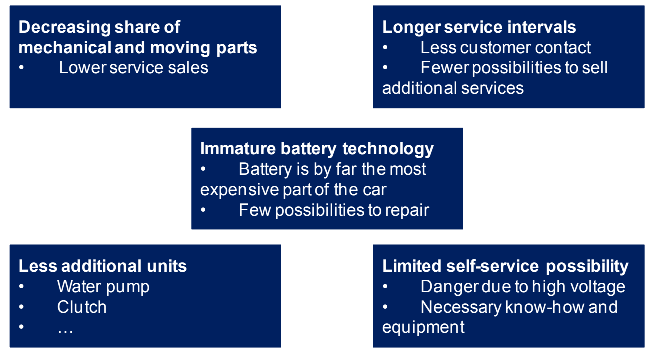

Figure 3: Changes in the automotive After Sales market [8].

Decreasing share of mechanical and moving parts

Compared to conventional cars with internal combustion engines, the share of used mechanical and moving parts will be significantly lower in electric cars. Due to its simpler construction there is no need for many mechanical and moving parts. According to estimates, the number of parts may fall by up to 90%. [9] Examples for moving parts which are no longer needed are fan belts or timing chains. These parts are to a large extent wear parts and require regular maintenance. Therefore, these parts have a large share of the profit in the automotive aftermarket.

Longer service intervals

Consequences from the first aspect are longer service intervals for electric mobiles. The small number of wear parts in the car and the electric engines do not require high frequencies of regular inspections. Therefore, it can be expected that the number of visits in the workshop due to the maintenance friendly construction of the electric cars will decline. The possibility of a continuous contact with customers in the workshops is significantly reduced due to this development. Hence it is more difficult to sell additional services (e.g. winter check, etc.) to the customer. [9]

Immature Battery Technology

Currently, the main weakness in the field of electric mobility is the energy supply and storage. The battery technology can be seen as a bottle neck because it reduces the range of the car. Thus the key element for electrically powered vehicles will be the battery. Also in the area of the after sales service the battery technology leads to problems. In lead-acid batteries, the energy density is very low. In addition, these batteries have a high weight. The batteries of the second generation are often based on the lithium-ion technology which have a much higher energy density and therefore would rather meet the requirements of electric mobility. This second generation of batteries however is very expensive which causes higher total costs of ownership. Another problem is the short life of the existing battery technologies in comparison to the whole car. The range is estimated to 75,000 to 150,000 kilometers at a weight of 400 kilograms. [10] It is therefore likely that the customer will be constrained to replace the batteries in the second third of the cars life cycle. Since the batteries are the most expensive wear part in an electrically powered vehicle, it is possible that the replacement of the battery pack is not cost-effective. This would lead to a reduced life of the entire vehicle. Associated therewith, the large number of repairs which occur in the last third of the cars life cycle will not occur.

Less additional units

Resulting from the changed vehicle technology, new systems must be installed in automobiles (e.g. more powerful air conditions to cool the batteries). However, many systems are no longer needed. Especially clutch, exhaust systems or oil pumps are examples for obsolete parts in electric mobiles. Since these systems can fail and thus could be potential spare parts, this has a negative impact on the after sales service from manufacturer's perspective. [8]

Limited self-service possibility

Arisen from the increasing share of electronics in the vehicles new apprenticeships such as mechatronics were developed to ensure the service in the workshops. In addition, electronic diagnostic equipment with appropriate software is required for the repair of electric vehicles expensive. Electric mobility will reinforce these trends so that the customer could not do the maintenance and repairs on his own. Furthermore, because of the high voltage technology it is very dangerous and risky for laymen to perform repair services by themselves.

The changes of the automotive aftermarket due to the rising share of electric mobility were shown in the last part. These changes have impact on all the stakeholders in the automotive aftermarket. The changes are summarized in figure 4.

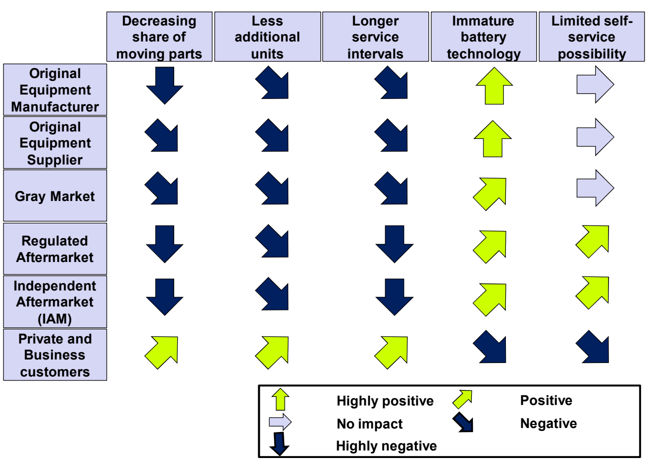

Figure 4: Impacts on the stakeholders [8].

The figure shows that the main profiteers of the development in the after sales service caused by the rising share of electric mobility are the customers because electric vehicles are less maintenance intensive and the service intervals are longer than the in cars with combustion engines. On the other hand the providers of spare parts are the loser of the development in the after sales service. Only the immature battery technology could have a positive effect.

In summary, it can be stated that the OEMs have to rethink their existing strategies in the automotive aftermarket to be as successful as currently.

4 ASSESSMENT OF FUTURE AFTER SALES STRATEGIES FOR E-MOBILITY

In the last part of the paper the changes in the automotive after-sales market as a result of the increasing share of electric cars was worked out in detail. It became clear that the OEMs have to adapt their existing strategies to the new situation. In recent years several different strategies to cope with the challenges in the automotive aftermarket occurred. Some of these strategies were developed especially for the after sales market and some were developed for the sales business. However the lines between sales business and after sales business in the automotive sector blurred gradually. In the following part of the paper, therefore selected strategies are presented and will be assessed from the OEM's point of view.

4.1 Future Strategies

A new strategic adjustment for the automotive after sales can have a positive impact on business success. However, the success of the chosen strategy is not easily foreseeable by the OEM. The success of a strategy rather depends on many environmental factors and its implementation. For example, the same strategy will not be successful for an OEM that builds premium class cars on the one hand and on the other hand for an OEM that builds middle class cars.

However, in the automotive aftermarket, some new strategies have proven to be promising for an aftermarket with an increasing number of electric cars. These strategies are illustrated in figure 5.

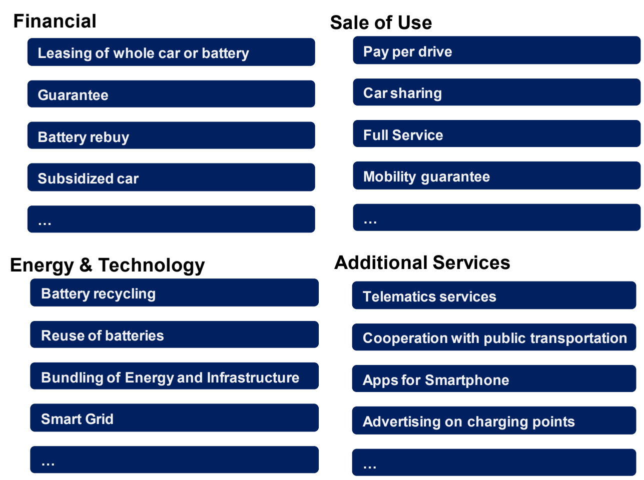

Figure 5: Changes in the automotive After Sales market.

The Strategies for the automotive aftermarket are gathered from the publications in the relevant literature and are related to the introduction of electric mobility.

In the first step of the assessment process the strategies are clustered into four categories to get a better review basis for the assessment of the strategies in the second step.

Financial

Recently, financial strategies have reached special attention in the automotive sector since the acceptance of the customers for financial services is grown. In this category strategies like leasing services or guarantee prolonging services are listed. These strategies are not exclusively developed for electric vehicles but the financial services seem to be an adequate strategy especially for the automotive aftermarket of electric cars. The price of electric cars will raise appreciably are, because of the high costs for research and development and expensive resources (e.g. rare earths) used to build these cars. In addition, the OEMs can use the financial strategies to compensate disadvantages due to the additional price of the battery technology. The first OEMs which have put electric cars on the market are using already the strategy of battery leasing. Thereby the electric cars are sold to the customers and the batteries have to be leased separately.

Sale of Use

In the second category, the focus lies on selling the use of a product instead of the actual product. One strategy in this category is the mobility guarantee. This strategy for the automotive aftermarket is particularly suitable for electric cars because they have the disadvantage of a limited driving distance. Through this, electric cars are often unattractive to the customer, so that the acceptance of the electric car is reduced. In the context of mobility guarantee, the customer will be offered temporary alternatives to his own electric car to be able to do long distance rides. For this, the OEM developed a car with an conventional combustion engine available for the customer. Likewise car sharing services fall into this category. The strategy of car sharing especially fits to electric cars because customers can park the cars at specific points where the charging infrastructure is given. Between the uses by different customers, the car can be charged at these fixed parking areas.

Energy &Technology

In the third category, the strategies are merged which have technological requirements before they can be implemented. Also, strategies that deal with the supply of the needed energy for driving the electric cars are in this category. For example the strategy bundling of energy and infrastructure allows the OEM to sell a specific charging infrastructure to the customer (e.g. wall box) and in addition the customer gets a special energy contract of an affiliated energy provider of the OEM. It is possible to offer the advantage of a simple electricity billing by combining the normal billing at home with the billing of the electric mobility for the customers.

Additional Services

In the last category, the after sales strategies are combined which especially due to the introduction of electric cars provide additional service profits. For example it is possible for the OEM to develop smart phone applications, which allow to control the charging management of the electric cars through mobile phones. Likewise, special telematic services are offered.

4.2 Assessment of Future Strategies

According to Johnson et al. there are four main impact factors for good business models (Customer Value Proposition, Key resources, Profit formula, Key Processes) [12]. To review the mentioned after sales strategies adequate key factors are needed that can assess the ability of the strategies for the after sales market of electric cars. These impact factors are derived from the impact factors of Johnson et al. The result are the following impact factors for the assessment of the strategies:

- Customer tie
- Ressource intensity
- Profit Potential
- Implementation Process

Customer tie is derived from the factor customer value and it is very important for an after sales strategy because recently many new stakeholders enter the automotive after sales market because of its high margins. The OEMs for example can use a contractual obligation to tie the customer and do all services and maintenance on the electric vehicle.

The resource intensity indicates if a strategy needs high initial and continuous efforts e.g. costs for a required infrastructure. This impact factor is very important because without the needed key resources the strategy would not work properly or may not be reasonable from economic point of view.

Profit potential indicates if the assessed strategy has the potential to put the OEMs in the place to make profit by using this strategy. This key factor is not very easy to assess since the profit depends on many other factors that are not capable of being influenced by the OEMs themselves.

The last impact factor is supposed to rate the difficulty of the implementation process. It assesses the pre-conditions that are needed for implementing the strategy. E.g. a strategy where special process knowledge is needed by the workshop staff would be rated more difficult than strategies which can be implemented without special knowledge.

Every presented after sales service strategy was assessed by a team of after sales experts. The result of this assessment is shown in figure 6. In the following part the results are described.

Financial Strategies

In summary, it can be stated that for OEMs the financial strategies offer a good way to retain the customer as early as possible to the company which is important to continue to operate successfully in the competitive after sales business. Financial strategies additionally do not have any resource requirements which makes it easy to implement them. Unfortunately, they partially have the disadvantage to offer only mediocre potential for profit. Rather the strategies are focused on helping to bind the customer to the company and to generate long-term revenues. From the perspective of implementing this strategies that are very useful as it requires excluding any contracts concluded with third parties. Any additional technological or infrastructural pre-conditions such as the construction of special facilities are not required.

Energy & Technology

In the second category, Energy and Technology can be one good way to find a good customer loyalty. The good rating can be justified because for the strategies smart grid or bundling of energy and infrastructure contracts to the customers exist. On the other hand strategies are listed that only have a medium ability to bind the customer e.g. the reuse of batteries. However the OEM can use the strategies of the battery reuse and the battery recycling to make profit. For this however, new technological requirements are needed. In particular the process expertise and the equipment for the implementation of these strategies leads to considerable effort that make the implementation very complicated. Therefore, energy and technology strategies from the implementation view for the automotive aftermarket are comparatively difficult.

Sale of Use

The third category includes after sales strategies where the use instead of the product is paid for by the customer. [13] By considering the high price of an electric car these strategies seem to be particularly promising because usually the user pays only for the needed output. Sale of use strategies are often not exclusively attributable to the after sales business but rather as an entire business model for the whole life-cycle of a car. However, simultaneously it comes in touch with the after sales business and the strategies also generate after sales revenues.

Future strategies / Impact Factors	Customer Tie	Ressource Intensity E.g. Infrastructure	Profit Potential	Implementation Process
Financial				
Leasing of whole car or battery	+	+	+	+
Guarantee	+	+	+	+
Battery rebuy	O/+	+	-	+
Subsidized car	-	+	-	+
…	…	…	…	…
Energy & Technology				
Battery recycling	O	-	+	-
Reuse of batteries	O	-	+	-
Bundling of Energy and Infrastructure	+	-/O	O	-
Smart Grid	+	-	O/+	-
…	…	…	…	…
Sale of Use				
Pay per drive	+	O	+	-/O
Car sharing	+	O	+	-/O
Full Service	+	+	O	O
Mobility guarantee	+	-	O	-/O
…	…	…	…	…
Additional Services				
Telematics services	+	-	+	-
Cooperation with public transportation	O/+	+	+	O
Apps for Smartphone	O	-/O	O/+	-/O
Advertising on charging points	O	-	+	-
…	…	…	…	…

\+ = Positive impact, O = Medium impact, - No (or negative) impact

Figure 6: Assessment of the strategies.

Sale of use strategies are generally rated positive in binding of the customer. Part of the strategies are contractual obligations between the customers and the OEMs which tie the customer to the company. For example the customer needs to register at a car sharing provider before using car sharing services. Depending on this the customer only pays for the distance or time he drives or has to pay monthly fees.

Depending on the regarded strategy there are different impacts of the factor needed resources. Considering the strategy of full service, in which for a certain time all service charges for maintenance and repair works are incorporated in the purchase price. Therefore, this strategy is not very resource intensive. However, for the car-sharing strategy, special parking areas and car pools must be created including the infrastructure for charging electric cars. The strategies offer moderate to good potential for new profit and sales volume. A reason for that is the decreased buying power of the customers so that they could not buy an electric car that has higher total costs of ownership. [14] At the same time, especially in large cities, the interest in car sharing increases. In this way, the sale of use strategies offer a good way to make additional sales. Assessing the key factor implementation process of the sale of use strategies, they are not really easy to be realized since there are many pre-conditions like infrastructure investments.

Additional Services

Strategies of this category are useful for binding the customer to the OEM by providing additional services which are in particular possible due to electric cars. The customer tie is rated middle to good because often there is no contractual form of agreement between customers an OEM. Merely, this could be found e.g. if the OEM makes telematic services only available with a contractual obligation. The rating of the factor resource intensity depends on the strategy. It is for example very expensive to install the infrastructure to collect telematic data compared to develop applications for smart phones. Regarding to the revenue potential of the other strategies (e.g. telematics services) can be assessed very good. [15] Despite the negative development due to the electric cars by using these strategies, additional revenue can be generated. The implementation process must be classified negative because by using this strategy often considerable process deployment pre-conditions are needed. Other strategies e.g. cooperation with public transportation need collaborations with third party enterprises which are often difficult to build up.

In conclusion the introduction of electric cars causes a severe cut in the profit-rich after sales business. Especially in the field of spare parts supply a significant decline in revenues will be noticeable. The outlined strategies can help OEMs to reduce this decline. Whether the strategies can compensate for the anticipated loss, remains to be seen. The success of the strategies depends from various environmental factors. However, it is certain that the OEM have to adapt their existing after sales strategies if the electric mobility is implemented widely.

5 SUMMARY

The present paper deals with the upcoming challenges in the automotive aftermarket due to the rising share of electro mobility. Therefore, the market structure of the automotive after sales service is shown. In addition, all relevant stakeholders as well as the impact on the stakeholders in this market is shown. Due to several reasons, in particular the OEMs are affected negatively. Subsequently, the stakeholder have to adapt or expanse their existing after sales strategies. Therefore, relevant strategies for the automotive after sales service were identified and clustered.

Based on this, the most important factors for the assessment of the strategies were derived in a structured way. In the final section of the paper the possible after sales service strategies for the Original Equipment Manufacturer were assessed. The results of this paper can be used as a guideline for OEMs to rethink their strategies for the future automotive aftermarket.

6 REFERENCES

[1] Chan, C.C.,Y. Wong, S., Bouscayrol, A., Chen, K. (2009): Powering Sustainable Mobility: Roadmaps of Electric, Hybrid, and Fuell Cell Vehicles, in: Proceedings of the IEEE, Vol. 97, No. 4, April 2009.

[2] German National Platform for Electric Mobility (NPE) (2012): Progress Report of the German National Platform for Electric Mobility (Third Report). Berlin, May 2012.

[3] Galus, M. D., Andersson, G. (2008): Demand Management of Grid Connected Plug-In Hybrid Electric Vehicles (PHEV), in: IEEE Energy2030, Atlanta, GA USA, 17-18 November, 2008.

[4] McKinsey (2010): Elektromobilität in Megastädten: Schon 2015 Marktanteile von bis zu 16 Prozent. Study by McKinsey Consultants, 2010.

[5] Valentine-Urbschat, M., Bernhart, W. (2009): Powertrain 2020 – the future drives electric, Study by Roland Berger Strategy Consultants, 2009.

[6] A.T. Kearney (2009):A.T. Kearney: Aftermarket 2020 Survey. Issue 1, 2009.

[7] CBI Ministry of Foreign Affairs of the Netherlands (2012): Trade structure and channels for automotive parts and components. URL: www.cbi.eu, 11.11.2012.

[8] Antia, K. D., Bergen, M., Dutta, S. (2004): Competing with Gray markets. MIT Solan Management Reviw, Fall 2004, pp.63 – 69.

[9] Dombrowski, U., Engel, C., Schulze, S. (2011): Changes and Challenges in the After sales service due to the Electric Mobility, in: Proceedings of the IEEE International Conference on Service Operations and Logistics, and Informatics 2011, 10.-12.06.2011, Peking, China.

[10] Frischknecht, R., Flury, K. (2011): Life cycle assessment of electric mobility: answers and challenges. In: The International Journal of Life Cycle Assessment 16 (2011) 7, S. 691–695.

[11] Diez, W. (2010): Zeitenwende im Automobilservice. URL:http://automechanika.messefrankfurt.com/frankfurt/de/besucher/events/AM-Academy.html, 03.10.2010.

[12] Johnson, M., Christensen, C., Kagermann, H.(2008): Reinventing Your Business Model. Harvard Business Review December 2008, p.59 – 68.

[13] Schröter, M., Buschak, D., Jäger, A. (2010): Nutzen statt Produkte kaufen. Mitteilungen aus der ISI Erhebung, Ausgabe 53, April 2010.

[14] Dombrowski, U., Engel, C., Schulze, S. (2011): Scenario Management for Sustainable Strategy Development in the Automotive Aftermarket. In: Proceedings of the CIRP Conference on Industrial Product Service Systems, Braunschweig, 2011

[15] Gebauer, H. (2009) The Aftermarket in the Automotive Industry - How to Optimize Aftermarket Performance in Established and Emerging Markets.

Operational Challenges in the Automotive Recycling Business: A System Dynamics Perspective

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Abstract

Despite advances in automotive recycling policies and technologies, achieving 95% recovery potential in real world terms remains a major challenge. The purpose of this paper is to explore the root causes for this system-level impediment. The paper finds that the five basic operational challenges facing the automotive recycling business are not only the major hurdle in attaining full recycling potential, they also underline the sustainability of the industry. The paper then concludes that in order to sustain the industry and improve the recycling performance, policy makers and industry stakeholders should regard these challenging areas as leverage points into the system.

Keywords:

Automotive Recycling; End of Life Vehicles; System Dynamics

1 INTRODUCTION

In the recent decade auto manufactures have focused on the recyclability of End of Life Vehicles (ELVs) aiming for a 95% recycling target including re-use, recycling and recovery. Examples of these are the use of recyclable materials, finding more cost-effective ways to dismantle vehicles, and developing processes that assist in parts segregation for recycling [1].

ELV-specific government policies and industry strategies were also adopted in several countries (the EU, Japan, and most recently Korea and China), all aiming to reduce the environmental impact of ELVs by encouraging higher recyclability. But despite these advances and efforts, and the vehicle being by default one of the most recyclable complex products in the world, reaching that recyclability target seems to have become more difficult than originally perceived [2,3].

So why exactly does auto recycling, from a systems point of view remain far from achieving its target? And how could we leverage the system more effectively towards it? This research was set about to answer these simple questions by studying the business of auto recycling. The underlying assumption is that auto recyclers are the key stakeholders in the system because their main business activity is the dismantling of ELVs and the resale of used parts/materials. The Australian auto recycling industry, which remains unregulated, is treated as a case study.

In this paper we first provide a snapshot of the Australian auto recycling industry, we then highlight each of the five key challenging areas that emerged from qualitative and quantitative data gathered from stakeholder interviews. Each area of interest is treated as a problem context of its own and presented in a System Dynamics (SD) stock and flow model. The paper rounds off with a discussion and the real world implications of this study.

2 BACKGROUND

2.1 Auto Recycling

In terms of environmental value addition, and despite being a pure economic activity, auto recycling is perhaps the most significant stage in the reverse life cycle of automobiles. It involves the recovery of re-usable parts and segregation of recyclable parts and materials for further processing.

Automakers have been thriving to minimize the environmental impact of new vehicles across all stages of the lifecycle, including end of life. Measures were taken to include recycled and recyclable materials into new vehicles, parts that are easier to disassemble and processes that allow for easier segregation of materials for further recycling. Across several countries and regions like the European Union, Japan, Korea and others, 95% recyclability for ELVs has become a standard goal to aim for.

However, achieving this goal is far from reality. In Australia the estimated current ELV recyclability rate is around 70% [4] and is estimated to decrease if business continues as usual [5]. This decrease may be attributed to the lack of economic value seen in materials recovery, the relative low cost of energy and landfilling [5]. But even in the case of Germany, one of the leading countries in ELV recycling, where the cost of energy and landfilling is high and business cases for recovering low yield materials exist, the ELV recovery rate was last reported in 2009 to be around 87% [3].

It can be said that at a global level and from a systems perspective, achieving the recycling target would seem almost impossible unless all countries recycle their ELVs efficiently and in an environmentally sound manner. Furthermore, the Australian case warrants further investigation as it trails behind other developed nations in terms of ELV recycling and presents unique opportunities for policy and business development in this arena.

2.2 The Australian Auto Recycling Industry

The Australian auto recycling industry can be characterized as a set of well-established auto recycling enterprises with varying business models, workforce size and turnover. There are around 800 enterprises across Australia, employing about 3400 workers and generating approximately $1.1 Billion Australian Dollars in annual revenue [6]. Most are small businesses (less than 20 employees) and have been operating for 20 years on average [7].

Revenue comes from a variety of streams. Depending on the business model, the most significant ones are the retail of used parts to the smash repair industry and the public, retail of scrap

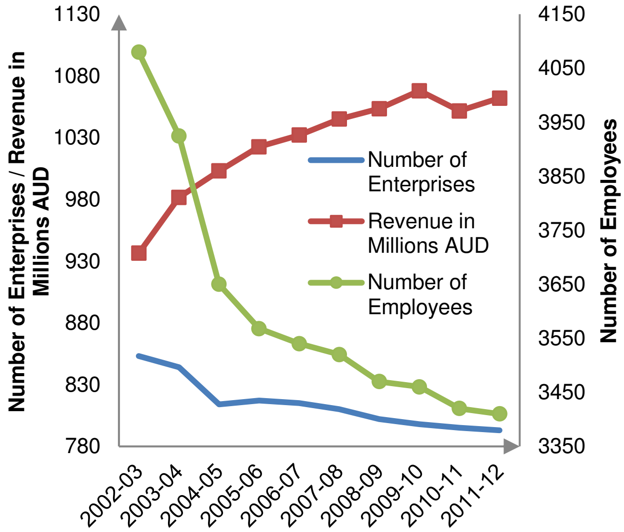

Figure 1: Overview of the Australian auto recycling industry.

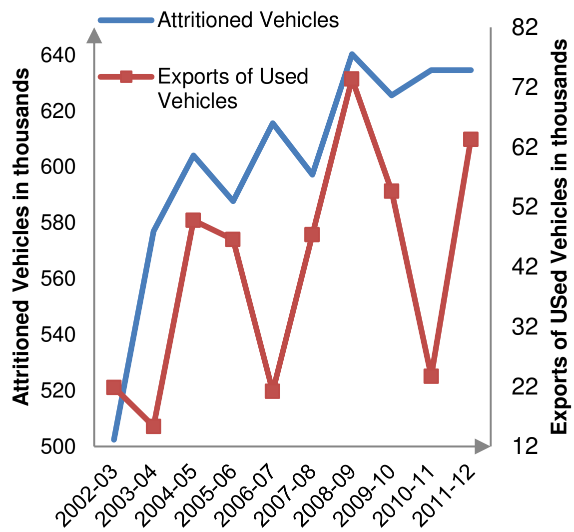

Figure 2: Attritioned and exported used vehicles.

metal to metal recyclers, and automobile related services such as vehicle servicing/repairs to the public. It is estimated that the industry handles about 610,000 ELVs annually [7]. These are damaged and old vehicles sourced through salvaged car auctions from the auto insurance industry. ELVs are also sourced directly from the public and in limited numbers imported from countries like Japan and the UK. The industry is similar to other manufacturing industries where raw input materials represent the most significant costing factor.

Over the past decade the industry has shrunk both in terms of number of enterprises and workforce size (7% and 16% decline respectively) while revenue has increased by 13% (Figure 1) [6]. During the same period the Australian vehicle fleet grew by almost 31% (from 12.8 to 16.7 million vehicles) [8,9] and the number of estimated ELVs that were handled by the industry grew by 22% from 500 to 610 thousand ELVs (Figure 2 - attritioned vehicles data is used instead as ELV data is unavailable) [4,6].

Meanwhile used car exports per year has grown by a staggering 190% (from 21 to 63 thousand vehicles) [10,11]. More importantly, the population has grown by almost 14% (from 19.8 to 22.6 million people) [12,13]. When taking these indicators into perspective, the industry revenue increase can be seen as insignificant. The industry is in fact in decline [6] and its sustainability is facing uncertainty.

On a different front, the industry remains unregulated despite the efforts made over the years by industry associations and large operators to adopt policies and standards. The lack of specific licensing requirements for auto recycling allows backyarders or outsiders to compete with legitimate operators when sourcing ELVs and supplying parts to the public. Policing and enforcement of environmental and licensing requirements is proving difficult as they vary significantly among states and local jurisdictions. To further complicate the matter, policing and enforcement responsibility is shared among several agencies.

An important question that comes to mind here is: Given all these limitations and threats, how could the Australian auto recycling industry be leveraged towards a shared ELV recyclability target?

In order to address this question we first need to better understand how the current Australian auto recycler operates.

3 METHOD

This study adopts SD [14] as a research framework to enhance our understanding of the auto recycling business in Australia. Thirteen semi-structured stakeholder interviews were conducted in 2010 and 2011 to collect qualitative and quantitative data about the current state of affairs in auto recycling. Interviewees included stakeholders from the auto recycling industry, car auctions industry, industry associations and enforcement. The gathered data was processed using a novel approach [15]. Five areas of operational challenges emerged, each having its own problem context [16]. A SD stock and flow model was developed to replicate the behavior of the main factors. Required data was either sourced from industry intelligence reports or estimated based on known trends.

4 OPERATIONAL CHALLENGES

In this section, the stock and flow models of the five operational challenges are presented and described.

4.1 Supply of ELVs

ELVs are the essential feedstock for the auto recycling industry. Not all attritioned vehicles get into the stream (Figure 3). They could be valued as scrap metal and hence acquired directly by the metal recycling industry. The remaining ELV stock on the market is either exported overseas or acquired by auto recyclers. In the latter case, the ability to acquire ELVs was found to be strongly causally linked to the auto recycling industry profit (or in other words available cash) and the available yard space. Auto recyclers may dispose of older ELVs to free up space and to acquire more ELVs. Demand for ELVs, driven by the number of auto recyclers (and backyarders), is a major determinant for the ELV cost of purchase which in turn affects the industry profit.

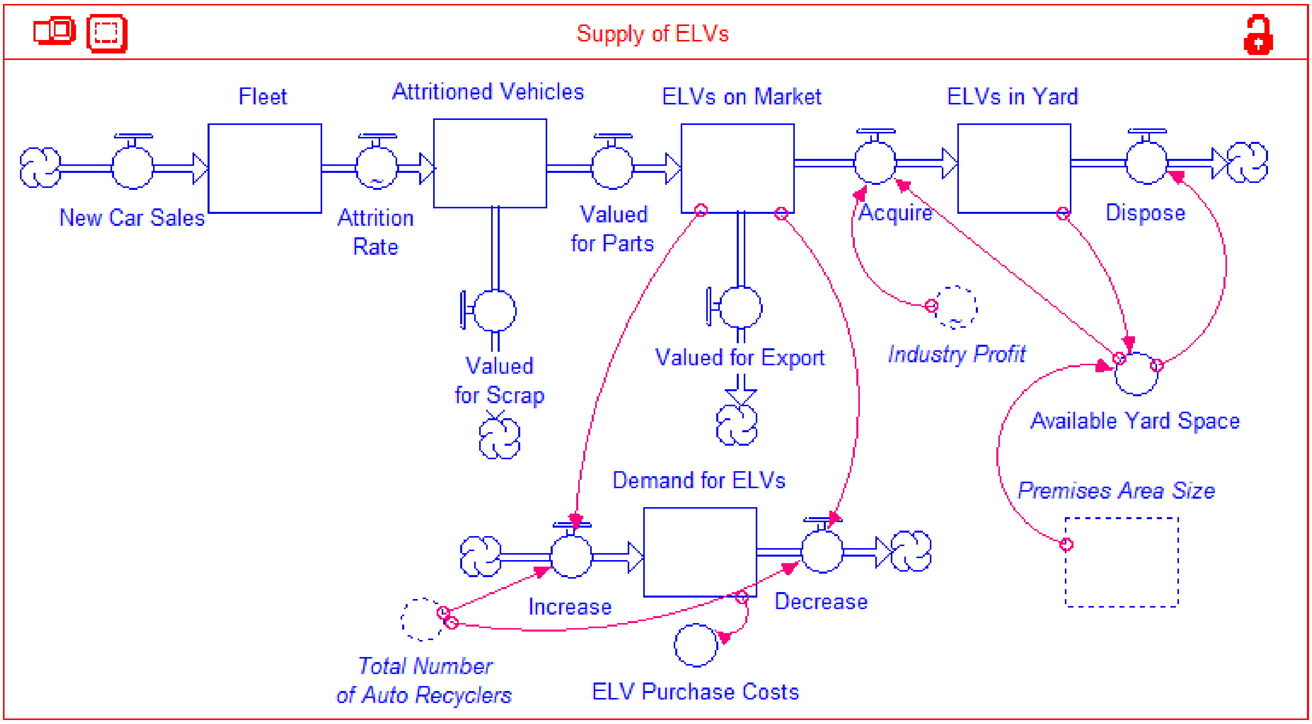

Figure 3: Supply of ELVs operational challenge.

Auto recyclers are constantly trying to balance between keeping their profits in check and being able to source ELVs in a cost effective manner, given their premises area constraints. The lack of licensing and regulations means that the current trend of ELVs heading to export markets and to backyarders will undermine the ability of legitimate auto recyclers to source ELVs, and hence stay in business.

4.2 Demand for Used Parts

As mentioned earlier, the current auto recycling activity in Australia relies on meeting the demand for used parts. Revenue from the sale of scrap metal to metal is minimal and inconstant because auto recyclers only dispose of scrap metal arising from dismantling when the yard capacity is reached or when the fluctuating price of scrap metal is right (about 200 AUD per ton).

Auto recyclers need to turn over significant number of ELVs (in excess of 1000 p.a.) for revenue from scrap metal sale to appear significant. Given that the average auto recycling enterprise turns over about 760 ELVs, it is hence safe to limit the scope of this model to the parts retail aspect. The demand for used parts comes primarily from the smash repair industry and has been stagnant over the past decade [17].

Though there are several business models for dismantling, we found that on average the dismantling activity is both driven and limited by the available shelf space and the number of ELVs in the yard (Figure 4). Auto recyclers were found to carry large inventories of ELVs and dismantled parts to maximize revenue potential as demand for used parts is difficult to predict. Operating under these

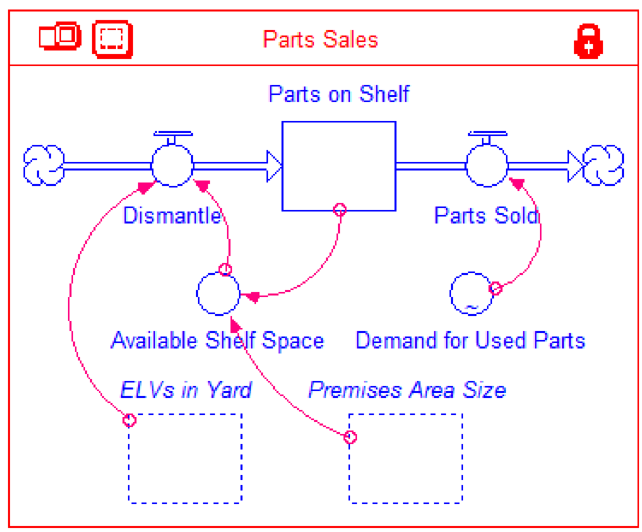

Figure 4: Parts sales operational challenge.

conditions means that the main revenue stream for auto recycling enterprise is constantly under threat from over stocking for sporadic demand.

4.3 Premises

The third challenging operational area is the facilities or premises management. Stocking of ELVs is a space demanding operation especially with the current norms of maintaining large inventories (both parts and ELVs). Enterprises have to adapt their facilities size to maintain profits. This includes both expanding and shrinking (Figure 5).

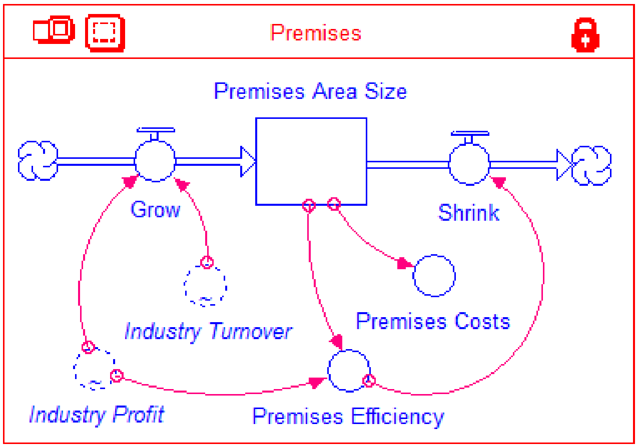

Figure 5: Premises operational challenge.

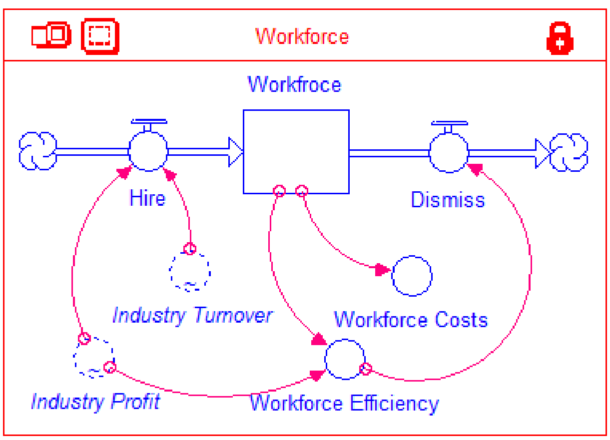

Figure 6: Workforce operational challenge.

4.4 Workforce

Similar to the premises management area discussed above, is the human resources management challenge. Auto recyclers adapt their workforce depending on their turnover and profits (Figure 6). This adjustment, however, happens frequently throughout the year.

4.5 Industry Image

Industry outsiders, or backyarders, are competing with legitimate operators at the level of ELV sourcing as well as at the level of parts resale to the public. The ability of the industry to increase turnover and maintain profit is hindered. The environment and the industry reputation are also severely affected because of the current issues with licensing and enforcement.

The figures for backyarders are unknown as some appear on the market and fold within days or weeks. But based on the perceptions of the interviewees and their experiences at salvage car auctions, there could be as many backyarders as legitimate auto recycling enterprises. Some backyarders, encouraged by the current non-specific licensing requirements, are occasionally driven to legitimize their operations to keep up with legitimate competitors in the area.

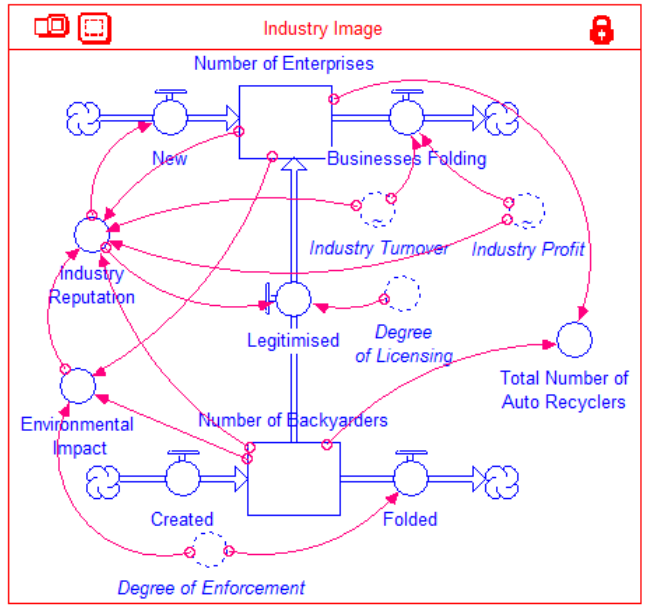

Figure 7: Industry image operational challenge.

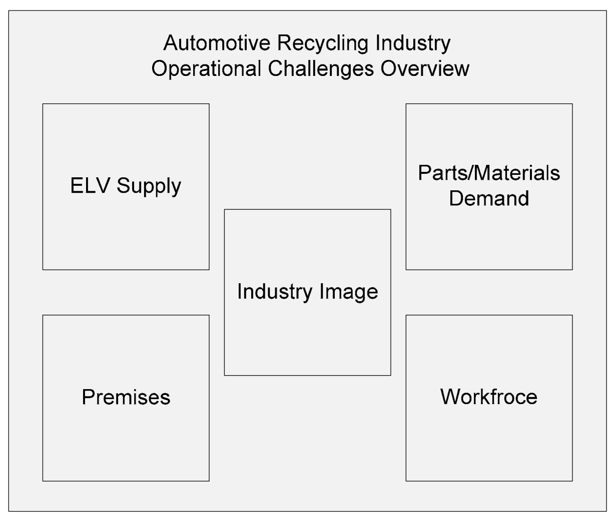

Figure 8: Overview of the identified dynamic areas.

5 DISCUSSION

Maintaining an auto recycling enterprise has become a challenge under the current climate given the current reliance of auto recyclers on revenue from used parts retail. As we were developing the models it became clear that all five operational areas (Figure 8) are dynamically interconnected. For example, the potential for the industry to source ELVs was found to be closely linked to the prevalence of backyarding, the industry capacity in terms of workforce and premises and the demand for used parts. This dynamic interconnectivity in combination with the observed current trends led us to identify a common denominator: the sustainability of the auto recycling industry.

In treating auto recycling as a business activity, we were able to identify threats and shortfalls in the current processes. Profit driven strategies appear to be the current norm. Environmental protection is a secondary non-explicit strategy and a by-product of the auto recycling activity. It is thus safe to deduce that, provided business continues as usual, the current business and industry structures are inept to deal with an industry-wide strategy such as achieving a certain recycling target. This finding resonates with previous observations made on the German auto recycling industry [18] almost a decade ago when a new set of EU-wide ELV regulations were implemented.

The industry in Germany has adapted to change and is viewed as one of the best practice examples; achieving the same in Australia may be an unrealistic endeavor given that the sustainability of the industry is threatened under current trends. An ELV-specific policy or strategy aiming to achieve a 95% ELV recyclability target must leverage upon the highlighted operational challenges in the auto recycling industry. In other words, the policies need to be adapted to the current business models and structures and not the other way around.

6 CONCLUSION

This paper presented a SD perspective of the challenging operational areas in the auto recycling industry in Australia. The lessons learnt from this process can be summarized as follows:

- The sustainability of the auto recycling activity in Australia is under threat due to the lack of regulations and because of the current profit-driven strategies pursued by auto recyclers.
- Achieving maximum recycling potential is contingent upon a policy that leverages all five operational challenges areas.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] Kanari, N., Pineau, J., Shallari, S. (2003): End-of-life vehicle recycling in the european union, in: Journal of Manufacturing, Volume 55 number 8, pp. 15-19.

[2] El Halabi, E., Doolan, M., Newell, B. (2008): A Global Comparison of End-of-Life Vehicles Policies, in: Meeting the Challenges to Sustainable Mobility, ICSAT 2008, RMIT Publishing, Melbourne.

[3] BMU (2011): End-of-Life Vehicle Reuse/Recycling/Recovery Rates in Germany, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, available online: http://www.bmu.de/files/english/pdf/application/pdf/altfahrzeuge_2009_en_bf.pdf.

[4] Environment Australia (2002). Environmental Impact of End of Life Vehicles: An Information Paper. Commonwealth Department of Environment and Heritage.

[5] Hedyati, M., Subic, A. (2008): Indicative Comparison Between the End-of-life Vehicle Recovery Rate in Australia and the International Best Practices, in: Meeting the Challenges to Sustainable Mobility, ICSAT 2008, RMIT Publishing, Melbourne.

[6] IBISWorld (2011): IBISWorld Industry Report F4624 Motor Vehicle Dismantling and Used Part Dealing in Australia.

[7] El Halabi, E., Doolan, M. (2012): New insights into the Australian Automotive Recycling Business, in: Sustainable Automotive Technologies 2012, Springer, pp. 325-329.

[8] Australian Bureau of Statistics (2006): Motor Vehicle Census, cat. no. 9309.0, ABS, Canberra.

[9] Australian Bureau of Statistics (2012): Motor Vehicle Census, cat. no. 9309.0, ABS, Canberra.

[10] Department of Foreign Affairs and Trade (2008): [Unpublished raw data] Australia's Exports of Used Cars.

[11] Department of Foreign Affairs and Trade (2012): [Unpublished raw data] Australia's Exports of Used Cars.

[12] Australian Bureau of Statistics (2006): Australian Demographic Statistics, Mar 2006, cat. no. 3101.0, ABS, Canberra.

[13] Australian Bureau of Statistics (2012): Australian Demographic Statistics, Mar 2012, cat. no. 3101.0, ABS, Canberra.

[14] Sterman, J. D. (2000): Business Dynamics: Systems Thinking and Modeling for a Complex World, McGraw-Hill, Boston.

[15] El Halabi, E., Doolan, M. (2012): Extracting Variables and Causal Links from Interview Data, in: Proceedings of the 30th International Conference of the System Dynamics Society, available online: http://www.systemdynamics.org/conferences/2012/proceed/papers/P1293.pdf.

[16] El Halabi, E., Doolan, M. (2012): Causal Loops in Automotive Recycling, in: Proceedings of the 56th Annual Meeting of the ISSS, accepted for publication.

[17] IBISWorld (2011): IBISWorld Industry Report G5323 Smash Repairing in Australia.

[18] Lucas, R. (2001): End-of-Life Vehicle Regulation in Germany and Europe: Problems and Perspectives, Wuppertal Institute for Climate Environment and Energy, available online: http://www.wupperinst.org/uploads/tx_wibeitrag/WP113.pdf.

A Basic Study on the Effectiveness of Counterplans to Promote Take-back of Mobile Phones

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Abstract

In Japan, the next targets of recycling can be small sized home appliances. It is said that those products may contain considerable amount of rare metals and rare earths. Although social experiments to discuss a new legislation are ongoing, the results suggested the collection rate will be very low without counterplans to promote take-back. The paper discusses counterplans to enhance take-back. It also estimates customers' acceptances of the plans, based on a questionnaire. By comparing the tendencies, the paper tries to evaluate the effectiveness of the plans. Finally, it proposes a strategic way to increase material recovery from mobile phones.

Keywords:

Rare metals; take-back law; mobile phones

1 INTRODUCTION

Electrical and electronic equipment (EEE) are popular in recent world and have large impacts on environment. In Japan, it is well-known that there are legislations that require consumers to take back designated products to recycling facilities. About the four designated products, the collection rate which means the actual collected amount of e-waste among the potential e-waste emissions had been around 50% for long. But recently, it is said that the rate has reached to 70% [1]. Although a certain portion of e-waste is exported [2], stored in home, or illegally dumped [3], the social system for large e-waste recycling is basically working well. As an extension of current laws for recycling, it has been discussed to cover small and medium sized EEE [4]. Since it is said that those small and medium sized e-waste contain considerable amount of precious metals and rare earth elements, collection and recycling of those e-waste is becoming a national concern of Japan now. Social experiments [4] to collect those products have been carried out in some regions of Japan. As the result of the social experiments, the average collection rate was only 3.8%. The collection rate might be improved when the legislation launches. However, without effective counterplans to enhance the collection rate, the new recycling system cannot be very effective, in the aspect of reducing the amount of rare metals and rare earths consumptions. Thus, the objective of this study is to analyze statistics of e-waste recycling and try to find appropriate strategies to handle used mobile phones. In order to find proper strategies which will be really accepted by consumers, a questionnaire to consumers will be carried out.

2 E-WASTE FLOW ANALYSIS

2.1 Basic e-waste Flow Model

There are existing studies [5] about the e-waste flow in Japan. Especially for the domestic e-waste flow of PCs, there is a study [6] which investigated the flow precisely, with quantitative information. Based on the existing surveys, it is possible to illustrate a general e-waste flow not limited to PCs. Without considering outflow of e-waste and recycled materials to overseas, the simplified e-waste flow can be illustrated as Figure 1. The boxes show the activities or subjects for activities and lines show the corresponding flows between the subjects. The dotted lines show that there are time delays.

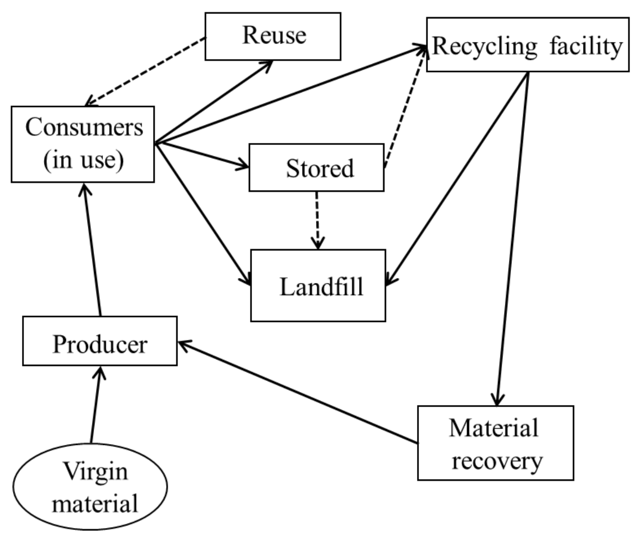

Figure 1: Simplified e-waste flow.

2.2 Factor Definitions

The objective of this study is to know the effect of various factors of e-waste flow such as collection rate, recycling rate, and so on, to reduce the environmental impact of the total system. Thus, in order to make a quantitative analysis on the illustrated e-waste flow model, factor definitions are necessary. Table 3 shows the list of the defined factors.

2.3 Calculation of Material Usage

By using the e-waste flow shown in Figure 1 and defined parameters, it is possible to calculate the amount of necessary materials theoretically. Consumption amount of material j for product i can be expressed by equation (1)

Parameter name	Meaning
$M_i(y)$	Amount of production of product *i* in year *y* (ton)
R_{ij}	Ratio of material *j* contained in product *i*
Rc_i	Ratio of collected e-waste of product *i*
Rl_i	Ratio of landfilled e-waste of product *i*
Rs_i	Ratio of stored e-waste of product *i*
Ru_i	Ratio of reused e-waste of product *i*
Rsc_i	Ratio of collected e-waste after storage of product *i*
Rsl_i	Ratio of landfilled e-waste after storage of product *i*
Rss_i	Ratio of stored e-waste after the first period of storage of product *i*
$Rssc_i$	Ratio of collected e-waste after 2 periods of storage of product *i*
t_i	Average length of storage for product *i* (year)
Rr_{ij}	Ratio of recovery of material *j* in product *i*

Table1: Definition of factors in e-waste flow.

$$\begin{aligned} Cm_{ij}(y) &= M_{ij}(y)\times R_{ij} - M_{ij}(y-t_i)\times R_{ij}\times Ru_i \\ &- M_{ij}(y-t_i)\times Rc_i\times R_{ij}\times Rr_{ij} \\ &- M_{ij}(y-2t_i)\times Rs_i\times Rsc_i\times R_{ij}\times Rr_{ij} \\ &- M_{ij}(y-3t_i)\times Rs_i\times Rss_i\times Rssc_i\times R_{ij}\times Rr_{ij} \end{aligned} \quad (1)$$

$Cm_{ij}(y)$: Consumption amount of material *j* for product *i*

3 CASE STUDY FOR MOBILE PHONES

3.1 Deviation of Production

Generally speaking, collection rates of small sized e-waste were insufficient [4]. Social experiments showed the collection rate can be less than 5%, without any counterplans. There might be some different reasons of the low collection rates. One reason is that small-sized EEE especially mobile phones are becoming more and more popular as it is shown in Table 2. Thus, some of the mobile phones have not reached the end-of-life stages in current situation yet. And since the product is small, it is easy to store the used products in homes even if consumers don't use them anymore.

Number of products per a home (mil. unit)				Average life in 2007 (year)
2005	2006	2007	2008	
1.80	1.95	2.04	2.09	2.9

Table 2: Deviation of production amount of mobile phones.

3.2 Material Recovery Calculation

Again the existing survey [4] reports that certain amounts of precious metals and rare earths are contained in small-sized EEE, especially in printed circuit boards (pcb), motors, liquid crystal displays, and so on. Table 4 shows the amounts of some of the rare earths contained in the 9 major small-sized EEE plus audio, in tons. (First 3, Co, Ta, W are not rare earths in the original definition.) It also indicates how much percent of the annual usage of those materials can be covered by recycled materials if the collection rate reaches 100%. The data show that for some materials, considerable portions of annual consumptions can be covered by recycled materials from mobile phones. Based on this analysis, Palladium and Tantalum can be the targets to recover through recycling of mobile phones, since it can caver 1% of annual usage in Japan. Table 5 shows the data about base metals and rare metals, in the same contexts. The table suggests that Gold and Silver should be focused, in the aspect of the coverage of annual consumptions. Table 4 indicates that, in the aspect of Ta, more than 1% of annual usage of Gold can be covered by recycling all the recyclable products. In the aspect of base metals recovery, mobile phone is also important in some materials.

	Pd	Ta	W	Nd	Dy	La
Amount (ton)	0.55	4.12	3.44	3.93	0.08	1.22
Potentail to cover annual usage in Japan (%)	1.12	1.04	0.05	0.10	0.02	0.01

Table 4: Potential of mobile phone on rare earths recovery.

	Au	Ag	Cu	Zn	Pb
Amount(ton)	2.1	12.2	486	9.6	18.9
Potentail to cover annual usage in Japan(%)	1.01	0.54	0.03	0.00	0.00

Table 5: Potential of mobile phone on metal recovery.

Based on the statistics of annual production shown in Table 2, amounts of productions of mobile phones can be simulated by equations from (2) to (5).

$$M_{1j}(y) = M_{1j}(2005)\times 1.05^{y-2005} \quad (2)$$

$$M_{2j}(y) = M_{2j}(2005)\times 1.15^{y-2005} \quad (3)$$

$$M_{3j}(y) = M_{3j}(2005)\times 1.15^{y-2005} \quad (4)$$

$$M_{4j}(y) = M_{4j}(2005) \quad (5)$$

Based on the results of social experiments, basic values of Rc_i, Rs_i, Rsc_i and average storage time t can be assumed as Table 6. Rc_i are based on the experimental results shown in Table 1. Rs_i were assumed by simply thinking 30% of the products will be landfilled as incombustible trashes. However, mobile phones are not treated like that, since information security issues are concerned. Plus, the stored rate will be higher for digital cameras, since the products are easy to store in home. Rsc_i is double of Rc_i and $Rssc_i$ is double of Rsc_i, since we assumed storage in homes will become much harder after years. And t is assumed to be same as product lives. In the basic calculation, product reuse rate; Ru_i, is set to 0.

Rc_i	Rs_i	Rl_i	Rsc_i	Rss_i	$Rssc_i$	t
0.05	0.95	0	0.1	0.9	0.2	3

Table 6: Assumed values of ratios and stored length.

3.3 Effect of Material Recovery

Based on the equations from (1) to (5), and tables from 6 to 8, amount of the recycled material for every i (i=1 to 4) and every j (j=1 to 4) can be calculated. Figure 2 shows the monetary values recovered through material recycling of mobile phones, as of 2012. Vertical axis shows the potential recoverable value in million JPY. Figure 3 shows the same calculation about TMR (total material requirement). The vertical axis shows the TMR in tons which basically indicates environmental impact to be reduced. Both viewgraphs indicate that Gold is the most valuable material which can be recovered from mobile phones and most of the value or potential to reduce environmental impact depend on Gold recovery. In addition, it is also important to think some counterplans to collect used mobile phones from the market as much as we can.

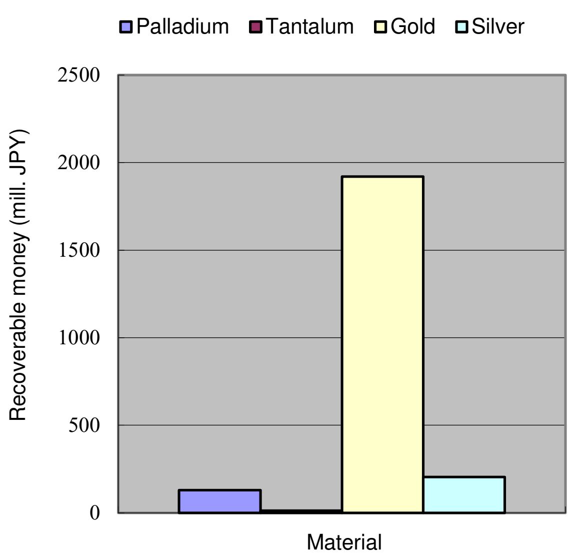

Figure 2: Recoverable monetary values.

4 COUNTERPLANS TO ENHANCE COLLECTION RATE

4.1 Basic Scenarios

Aforementioned social experiments suggested that there are some barriers for consumers to bring back their used EEE to recycling-bins. Thus, counterplans should eliminate those mental barriers of consumers. In addition, there are some other methods to reduce TMR. Especially for mobile phones, these counter-plans including both social methods and technical methods can be listed.

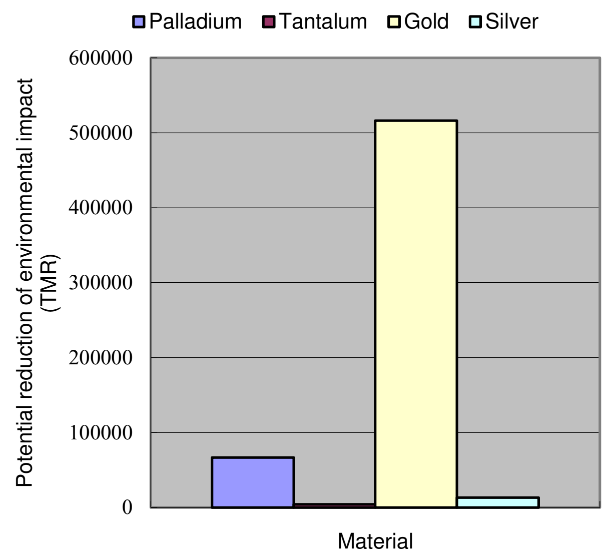

Figure 3: Potential reduction of environmental impact in TMR.

Social plans:

1. Since the mobile phones are small, it is not difficult to store in home. If there is a certain amount of deposit per phone, consumers may bring it back to shops.
2. If equipment to erase the information electronically or physically is set together with the recycling bins, consumers may put their used phones in the bins.
3. There was no big advertisement of the recycling social experiments. If there is an announcement in the TV, consumers may bring their used mobile phones to the recycling bins.
4. If there is a business model to replace used mobile phones to new phones, consumers will bring their used phones to the shops. Collected phones can be refurbished and reused.

Technical plans

5. In current system, consumers need to bring used equipment by themselves. If recyclers come to pick them up, it will be easier to put to recycling.

:

6. Technological development may reduce amount of rare earths containing in small-sized EEE, by replacing those materials by normal materials.
7. Technological development can increase material recovery rates of rare earths.
8. Technological development can increase material recovery rates of precious metals.

There is no quantitative information to predict the effect of above-mentioned counterplans. Though, qualitative effects on parameters can be assumed like Table 7.

4.2 Comparison of the Counterplans Based on Consumers' Perception

In predicting the effect of each counterplan, the key is whether the counterplan will be preferred by consumers' or not. Especially for

Number of counterplans	Scenarios
1	Many of consumers will bring back used phones at the time of purchase. Other consumers will store for long.
2	Some of consumers will put used phones in the recycling bins. Collection rate after storage will be the same.
3	Many of consumers will put used phones in the recycling bins. However, collection rate after storage will be the same.
4	Most of consumers will bring back used phones at the time of purchase. 10% of them can be reused. On the other hand, product life time will decrease to 2 years.
5	Some of consumers will hand used phones to the recyclers. Collection rate after storage won't change.
6	Amount of rare earths and base metals used in the mobile phones will be reduced to 90% in the new products.
7	By technological development, material recovery rates of rare earths will increase to 60% from 0%. Plus, collection rate will increase to 10%.
8	By technological development, material recovery rates of base and rare metals will increase to 90% from 80%. Plus, collection rate will increase to 10%

Table 7: Possible effects of the counterplans.

the social methods, the consumers' acceptance is the key factor to evaluate the effects. In order to know the perceptions of the counterplans, a questionnaire was made to the consumers. Although most of the consumers have changed their mobile phones, no one has known the afore-mentioned social experiment. However, most of the people said they would bring their used products to recycling bins, if a proper method is provided. Table 8 shows the data obtained by the questionnaire about the preference of the social counterplan 1 through 5. In the table, numbers of people who answered "very positive" and "partially positive" are shown correspondingly. We assumed who answered two positive categories would bring back their used phones, if the corresponding counterplans are provided. For example, 75% people were positive to counterplan 1 which is to prepare a certain amount of deposit to the product. Therefore, the paper assumed that 75% of consumers will bring back their used products to recycling facilities or recycling bins.

4.3 Modified Scenarios

The next step is to assume the effect of each countermeasure to enhance collection rate quantitatively. As it was mentioned in the former section, by applying these steps to all the plans, Table 9 can be assumed.

Counterplans	Very positive	Partially positive	Ratio of positive perception (%)
1	35	25	75
2	8	19	34
3	1	5	8
4	45	20	81
5	1	1	3

Table 8: Priority of the counterplans.

Number of counterplans	Scenarios
1	75% of consumers will bring back used phones at the time of purchase. Other consumers will store for long.
2	34% of consumers will put used phones in the recycling bins. Collection rate after storage will be the same.
3	8% of consumers will put used phones in the recycling bins. Collection rate after storage will be the same.
4	81% of consumers will bring back used phones at the time of purchase. 10% of them can be reused. On the other hand, product life time will decrease to 2 years.
5	3% of consumers will hand used phones to the recyclers. Collection rate after storage won't change.

Table 9: Concrete scenarios.

Based on equation (1) and parameters shown in Table 6, effect of each counterplan in reducing TMR can be calculated. Figure 4 shows the effects of each counterplans, when the scenarios shown in Table 9 has been realized, comparing to the situation without recycling. The calculation results suggest that the counterplan 4 in which a business model to encourage consumers to bring their used mobile phones to shops in order to replace them to new phones, might be effective in reducing total TMR of mobile phones productions.

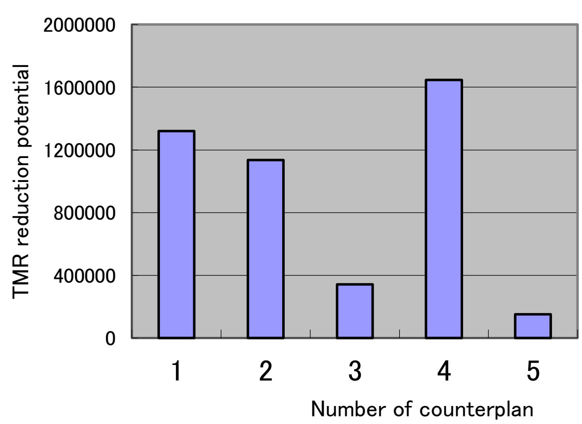

Figure 4: Potential of counterplans to reduce TMR.

4.4 Comparison of Counterplans

The basic survey suggested that the counterplan with the business model to discount new mobile phones is the most preferred counterplans by consumers. However, some technical methods are possible as suggested in Table 9. Since the purpose of this paper is to compare technical methods and social methods to reduce environmental impact, these two categories should be examined on the same aspect. Figure 5, shows the basic comparison between social counterplans and technical counterplans. In the figure, red bars show technical counterplans.

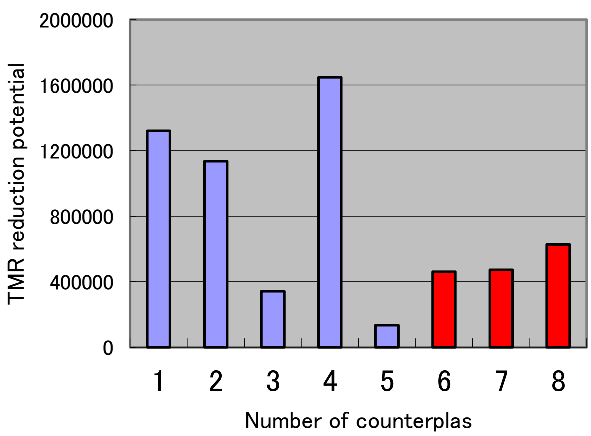

Figure 5: Comparison of different types of counterplans.

The figure basically suggests that best three social counterplans (1,2 and 4) would be more effective than technical counterplans. However, real comparison should be based on the cost-effect analysis. For the technical counterplans, the afore-mentioned report [4] provides the basic cost-effect analysis. On the other hand, it is difficult to estimate the costs of social counterplans. But for some of the plans, costs to realize the plans can be roughly estimated

Counterplan 1:

By assuming the annual number of end-of-life mobile phones is 2 million and 75% of the consumers will bring back their used products, the number of recyclable mobile phones is 1.5 million units. If the deposit per product is 500 JPY, the total cost will be 750 million JPY per year.

Counterplan 2:

By assuming the price of the security device is 0.5 million JPY per unit and number of recycling bins is 4000 all over Japan (3 per cities, 2 per towns and 1 per villages), the total estimated cost is 2,000 million JPY.

Counterplan 3:

Average price for TV advertisement is 1-2 million JPY per a 15 seconds spot. Thus, if the number of annual spots is 1200 times (1 per day, 300 days, 4 channels), the total cost will be about 1,200 million JPY.

Counterplan 5

Another report [7] from Japanese agency tells that number of public waste-collecting vehicles in Japan is about 50 thousand. By assuming the cost to run a recycling van is 50 thousand JPY per one operation and 10% of the vehicles run once per month, total annual cost will be 3,000 million JPY.

Counterplan 7:

In the report, the total cost of recovering 90% of rare metals is estimated to be 1,300 million JPY, when the collection rate is 10%

Counterplan 8:

In the report, the total cost of recovering 60% of rare earth materials is estimated to be 1,700 million JPY, when the collection rate is 10%.

For counterplan 4 and 6, cost estimation is difficult.

Figure 6 shows the comparison of cost-profit ratio of above-mentioned 6 counterplans.

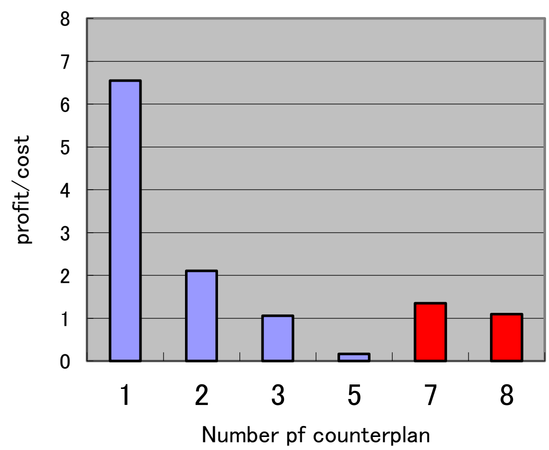

Figure 6: Cost-profit analysis of counterplans.

Although the effects of the counterplans were compared under very rough assumptions, the best plan seems to be plan 4, in reducing TMR. On the other hand, based on another calculation, it was suggested that counterplan 1 would have the best cost-profit rate among 6 plans in which the costs can be estimated. Basically, it was predicted that the counterplans 1 and 4 that are preferred from consumers can be effective in reducing environmental impact and promoting a better circulation of e-waste.

5 CONCLUSIONS

In this paper, the report from Japanese governmental agencies in order to establish social system for small-sized EEE recycling was analyzed. In order to find what is the most important materials to be recovered from used mobile phones, the analysis and calculations were carried out. As a result, most of the potential reduction of TMR depends on material recovery of Gold.

The paper also discussed some possible counterplans to increase collection rate, reuse rate and material recovery amount, or to decrease material consumption. It was suggested that increasing collection rate greatly is the most effective way to reduce TMR and some business models to give incentives to consumers might be necessary. To know the acceptance of each counterplan by consumers, a questionnaire was carried out. The result shows most of the consumers would bring back their used product, if a proper method to give consumers incentives is provided.

Generally speaking, this type of analysis along with actual data published in the report can be a powerful tool to evaluate the material flow of e-waste and to design social systems to handle the e-waste.

As future work, to clarify the relations between counterplans and e-waste flow factors will be necessary to obtain practical and useful strategies. In addition, cost-profit analyses of all the counterplans are indispensable. More practical and precise examinations of business models will be necessary too.

6 REFERENCES

[1] Association for Electric Home Appliances, (2012): Annual Report of Home Appliances Re-cycle –FY2011, pp.19-21. (In Japanese).

[2] Yoshida A,.Terazono, A. (2010): Reuse of secondhand TVs exported from Japan to the Philippines, Waste Management, 30, pp. 1063-1072

[3] Association for Electric Home Appliances, (2012): Annual Report of Home Appliances Re-cycle –FY2011, pp.67. (In Japanese).

[4] Ministry of Environment, Ministry of Economy, Trade and Industry, (2011): Report of the study group about recovery of the rare metal and proper processing of used small household appliances.

[5] Terazono, A. et. al. (2006): Current status and researches on e-waste issue in Asia, Journal of Material Cycles and Waste Management, 8(1), pp.1-12.

[6] Yoshida, A.,, Tasaki, T., Terazono, A. (2007) : Material Flow of Used PCs in Japan: Proceedings of IEEE International Symposium of Electronics and Environment, pp46-55.

[7] Ministry of Environment, (2011): Waste management in Japan -as of fiscal year 2009-. (In Japanese)

Collecting End-of-Life Mobile Phones in Jakarta: A Pilot

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Abstract

Currently mobile phone is one of the products that have the most rapid technology development. This leads to an increasing number of mobile phone consumption around the world, and also in Indonesia. However, this consumption also resulted in a problem in its end-of-life management. This paper aims to test the actual consumer behavior in recycling their end-of-life electronics, especially mobile phones, compared to previously conducted survey. The test was performed through a pilot project. Three locations in Jakarta Greater Area were selected as the pilot location. There are three performance indicators used in this research, which are participation rate, return rate, and cost. The pilot project showed that although people were willing to recycle, in fact they are still reluctant to contribute. Furthermore, compared to the existing network using the informal sector, this collection method is still less economical.

Keywords:

Reverse Logistics; Pilot Project; End-of-life management; WEEE

1 INTRODUCTION

The European Unions classified the waste of electronics and electrical equipments (WEEE) into 10 categories. Among those categories, WEEE is mostly populated by items in Category 3, IT and telecommunications equipment. Every year various associations and market research companies gather world sales statistics for these products. In 2011, as reported by the Electronics Take Back Coalition, the largest sale worldwide was occupied by cell phones with 1.59 billion units, followed by 352.8 million units of computers and 248 million units of televisions.

In Indonesia, a study conducted by the Ministry of Communication and Information Technology reported that 87.64% of people owned a cellular phone while only 33.64% owned a computer. With the rapid development in mobile technology, it is imminent that mobile devices will soon replace a large number of computers.

Based on a short survey conducted by Wibisono [1] among university students in Indonesia, the usage life of mobile phones is less than 2 years before it is replaced by a new one. US EPA also reported that in US, compared to computers (40%), monitors (33%) and televisions (17%), mobile phones have the lowest recycling rate of 11%. With these trends, in a few years there will be a massive amount of mobile phones discarded.

E-waste management is a new notion in Indonesia. Used electronics are usually traded by informal sectors and government has not regulates its management. Similar findings were found in Kenya [2], Uganda [3], India [4] and South American countries [5]. The collection of e-waste is conducted by informal sectors. Furthermore, e-waste take-back system design approaches in developed countries are varied between countries [6-9]. As explained by Gregory et al [7], the take-back system comprises of collecting, processing and system management. The collection could be conducted by government, retail, OEM or commercial entity. There are different types of collection methods, such as permanent drop-off, special drop-off event, door-to-door pick up, permanent and scheduled curbside collection, trade-in and mail-in collection [7, 10].

Nokia provided 6000 collection points distributed in 100 countries worldwide. They actively campaign to schools, office buildings and phone retailers to provide education on the importance of recycling old mobile phones and its benefit. In Finland, Norway, UK and USA, phone users can return their old phones by registering online, print the prepaid post label and send it to Nokia official recycling centre without incurring any fee [11]. Sony Ericsson conducted similar program since 2008. Until now there are 500 collection points in 8 countries. The result showed that in 2010 Sony collected 1.5 million EOL phones to be recycled. This figure covers around 3% of Sony's mobile phone sales in 2010 [12]. In Australia, MobileMuster, as the product stewardship program of the telecommunication industry, have collected old mobile phones since 2009. Since then, the number of phones collected per annum has tripled from 257,000 units in 2009 to 839,000 units in 2010-2011 [13].

The objective of the pilot project is to raise awareness on e-waste and understand the society involvement on e-waste collection program, especially end-of-life mobile phones, analyze the feasibility of a sustainable e-waste collection program and the requirement of such program. Three performance indicators are used to analyze this project, which are return rate, participation rate and cost.

The paper is structured as follows. Firstly, the preparation for the pilot project is described. Then, the actual collection of end-of-life mobile phones in Jakarta is explained. To verify the reason behind the participation of the donators, a survey was performed. The result from the survey and the pilot project are analyzed in Section 4. Finally, a conclusion is drawn and some suggestion for future research is

2 METHOD

This study aims to understand the feasibility of conducting an e-waste collection program in Indonesia through a pilot project. To limit the scope of the study, Jakarta Greater Area (Jabodetabek) is chosen as the object of the study.

Preliminary research on the willingness to recycle and customer behavior towards e-waste was conducted. It is then followed by a project cost analysis. The gathered information was then used to plan for the pilot project. The framework of this research can be seen in Figure 1.

The performance of the project was measured by project participation rate, product return rate and cost. The result of this project is compared to the result from Nokia [14] and Sony Ericsson [15]. Their worldwide collection resulted in 3% for both participation and return rate. Participation rate and product return rate are calculated based on Equation 1 and 2:

Participation rate = the number of donors/total sample population that location X 100% (1)

Product return rate = The number of old phones collected/total sample population X 100% (2)

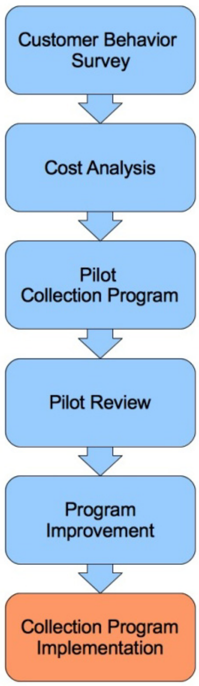

Figure 1: Collection program framework.

3 PREPARATION FOR THE E-WASTE COLLECTION PILOT PROJECT

Willingness to recycle and cost are two major issues in preparing for the e-waste collection pilot project. Since recycling has not become a common practice in Indonesia, a survey was conducted to find the consumer behavior and analyzed the willingness of the people to recycle end-of-life electronic household waste [2], [3]. The questionnaire was distributed to 180 respondents, spread in five regions in Jakarta Special Capital Region, which are West, North, East, South and Central Jakarta.

The consumer behavior in Jakarta Special Capital Region is identified with two variables. The first variable is the current society involvement in recycling and the second variable is the willingness to be involved in the future. Each of the variables consists of eight indicators. The indicators for current society involvement in recycling are:

- Respondents do not have workplace environmental policy
- Respondents do not have workplace electronic waste policy
- Respondents awareness of e-waste comes from media and environmental campaign by an organization
- Respondents behavior towards end-of-life electronics is discard or donate
- The criteria for buying an electronic product are save energy and reliable
- The reason which inhibit respondents to recycle end-of-life electronics is the lack of understanding on the benefit of recycling e-waste
- The perception on recycling is advantageous to the environment
- E-waste management is the responsibility of all parties

Meanwhile, the variables for willingness to be involved in the future are:

- Respondents might be interested to be involved in recycling electronic products in the next 5 years
- Products which will be recycled by respondents, if there is such procedure, are gadgets such as mobile phones, MP3 players, and PDA
- Respondents are willing to pay to recycle gadgets in the range of US$ 0.50 -2.50
- Respondents are willing to pay to recycle small size appliances in the range of US$ 0.50 -2.50
- Respondents are willing to pay to recycle medium size appliances in the range of US$ 0.50 -2.50
- Respondents are willing to pay to recycle large household appliances in the range of US$ 5 -10
- The most preferred location for e-waste collection is shopping malls.

Some of the important findings from the survey were used directly in the pilot project preparation. The survey found that people need more information about the benefit of recycling e-waste. It also found that gadgets are the type of product that is more likely to be recycled than other appliances. Additionally, the respondents preferred to drop off their e-waste at shopping malls rather than any other means and places.

The second part of the preparation was to determine if it is financially sustainable to collect e-waste. A field survey was carried out to estimate the cost of a project. There are two approaches used in the field survey. The first approach was by gathering information from the informal sector while the second approach utilizes cost analysis method.

The field survey discovered that currently there is a network of informal sector that trades waste from computers and mobile phone parts [16]. This network comprises of scavengers, dealers, brokers, service centers, recyclers and also overseas dealers. However, as explained previously in [17], the processing method currently conducted by these informal recyclers is hazardous and harmful to human health and the surrounding environment. The survey also found that these informal sectors processes and trades waste from computer and mobile phone parts. Waste from computer parts are traded in the price range of $0.30 to $7 per unit for motherboard, processors, hard disk, depending on the type while PCB from mobile phones for 20c per unit or around $15 to $18 per kg [16].

The cost analysis method calculated projected collection cost around Jakarta Greater Area [18]. As suggested from the preliminary survey, shopping malls becomes the target of the study. The calculated project cost was composed of rental fee at shopping malls and office buildings, advertising fee, equipments, transportation and man-hour. There were 21 locations surveyed, comprises of 16 shopping malls and 5 office buildings. Table 1 shows the project cost summary for collection at shopping malls and office buildings whereas Table 2 shows the range of cost for malls and offices with and without using a warehouse. An option of omitting the warehouse cost is included in here since the size of e-waste collected from old phones is insignificant to the cost.

	Malls	Office
Location	$600-1700	$50-500
Transportation	$50	
Storage Box	$38	
Labor	$140	
Advertising	$360	
Warehouse	$11,000	
TOTAL	$11,588	

Table 1: Project cost summary.

	With a warehouse		Without a warehouse	
	Malls	Office	Malls	Office
Range min	$12,188	$11,638	$1,068	$518
Range max	$13,288	$12,088	$2,168	$968

Table 2: Project cost range.

This projected cost is the result from cost analysis of various scenarios of e-waste collection in shopping malls and office buildings. The average unit cost collected is US$14.2, which ranges from US$3.4 to $83, depending on the scenario and estimated number of participants. The average unit cost collected from office building is estimated around US$50.

4 PILOT PROJECT

The e-waste collection pilot project was specified for EOL mobile phones. Mobile phone is chosen for the study due to several reasons. Based on the survey on the willingness to recycle behavior, most people are willing to recycle their gadgets and mobile phones. Mobile phones and gadgets are small; therefore require minimum space for storage and minimum handling. Consequently, resulted in minimum cost.

The pilot project was conducted in three areas in three different period. The first one was conducted in a university in Tangerang, as part of Jakarta Greater Area in 2010. The second event was conducted in an office building in West Jakarta in 2011. The last one was also in an office building in South Jakarta in 2012. These collection events were conducted as a one-time event and each event occurred for a week.

The campaigns were mainly utilizing posters, banners, flyers, social media, internal emails and personal network. No certain advertising technique were applied in this project and the event campaign mostly occurred a few days before the event and at time of event. To limit the population of the respondent, the posters, banners and flyers were only distributed on the location of the event to keep the project impartial. The accuracy of the population was maintained to reflect the performance measurement, which is the participation rate and return rate. Posters of the events are shown in Figure 2

The collection booth is consisted of a table, two chairs and a collection box. The box is made of clear acrylic with a dimension of 100 mm x 100 mm x 1000 mm. It was made clear to raise awareness from people and invite participation. The location of the booth was varied in each event. At the university, the booth was located in the faculty office. The traffic in that area was light. At the office building in West Jakarta, the booth was located in front of an elevator leading to the office cafeteria and the traffic in that area was quite high, especially during lunchtime. Meanwhile, at the office building in South Jakarta, the booth was located at the reception area of an office. The traffic was also mild.

(a) University, 2010 (b) Office Building, 2011 (c) Office Building, 2012

Figure 2: Posters of collection events at three locations.

There are two different scenarios used in the project. The major difference between the scenarios is the incentive system. In the first scenario, for every old phone donated, the donor would be included in a raffle to win shopping vouchers. In the second scenario, the incentive is directly given to the donors for every phone collected. The first scenario was implemented in the first and second event at Tangerang and West Jakarta while the second scenario was implemented in the office building in South Jakarta.

The cost estimated for the project was streamlined from the projected cost analysis. Some of the cost items were eliminated due to the nature of the pilot project. The cost estimated for the project is around US714 which consists of supplies such as the acrylic box, locks, banners, posters, brochures, stickers, supplies for the post collection surveys, and incentives in the form of shopping vouchers or goodies. Cost items such as transportation, labor and warehouse was removed since labor was replaced with volunteers and warehouse was not required.

5 RESULTS AND DISCUSSION

The results of the collection event are varied. The differences are caused by several factors such as location, nature of work of the population, top management commitment and many others, which will be discussed in this section. The total population of each event were 900, 450 and 538 people, respectively for Tangerang, West Jakarta and South Jakarta.

Initially, based on the result of the field survey, there were five office buildings approached to be used as collection points. However, from five only one agreed. Building managers seemed to be reluctant to participate in such events. Some hesitated because of the "waste" might affect the image of their building. This seems to correspond to one of the survey result on indicators of current society involvement in recycling, where majority of the respondents do not have workplace environmental policy.

The buildings that agreed to participate have shown interest in community services and social services activities. Corporate Social Responsibility was one of their reasons to participate in this project. Their eagerness in participating in this event was not only shown in conducting this event but also by sponsoring it. Their sponsorship was in the form of incentives for the respondents. Therefore, it can be concluded that e-waste collection can only be successful with the commitment from the building or companies or by combining with CSR programs or used as CSR programs for companies.

Figure 3 shows the number of product returns and participants in three locations. From the number, collection event at South Jakarta office building has the highest amount of phones collected and the highest number of participants. It also achieved the highest amount of return and participant rate (Figure 4), which are 15.43 % return rate and 6.69% participation rate. This shows that all three events surpassed the 3% rate target, based on the Nokia and Ericsson collection events [14, 15].

Two major contributors to the result are commitment from the management and the incentive system. There is commitment from the top management in the office buildings to promote this event and ensure its success. Encouragement to participate in the event was spread from top down and the respondents were not only come from those who have medium and high income but also from lower rank staffs such as cleaners and janitors.

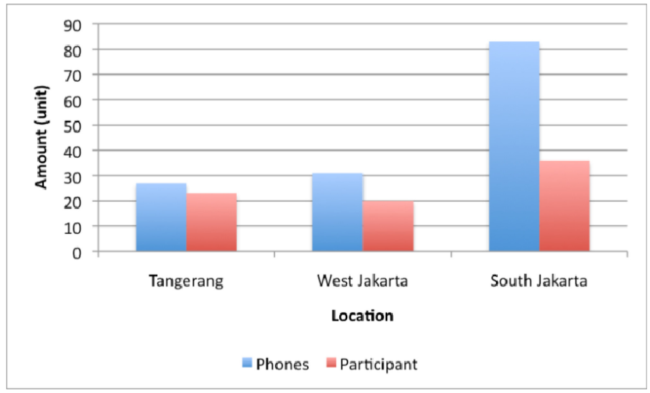

Figure 3: Number of product returns and participants in three locations.

The incentive system was also a dominant factor in the willingness to recycle. The direct incentive used in the third event was an attractive scheme that increases the participation rate. Furthermore, collaboration with charity event also a contributing factor. Many respondents were more attracted on getting the incentives rather than to actually recycle their e-waste.

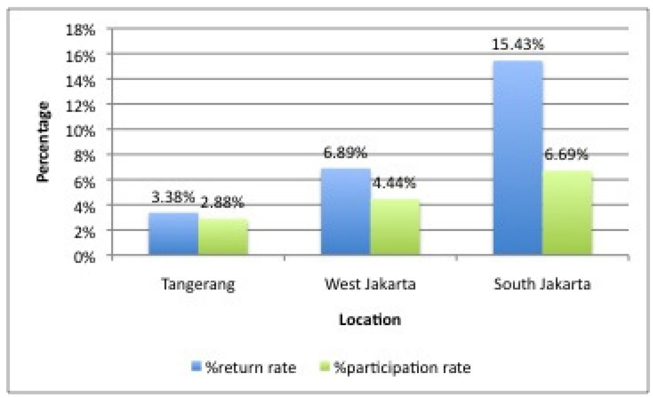

Figure 4: Percentage of product return rate and participation rate in the three locations.

Publication and education on e-waste are also an important factor that affected the result. During the collection event at West Jakarta office building, the booth was strategically located in front of the elevators leading to the cafeteria compared to the event in the university. Thus, during lunchtime, the traffic was high and the booth attendee was able to explain about e-waste and raise awareness of the population. This fact shows that publication and education is an important factor to the success of e-waste collection program. A more direct education on e-waste is necessary.

The cost incurred during the events was around US$650 and was lower than the budget of US714. This is because there was no rental fee incurred in the event, as it was part of the sponsorship. Souvenirs for the incentives were also reduced due to the sponsorship from the office buildings. The unit cost of the phone was around $13 for the first two events and was significantly reduced to $2 for the third event. The reduction was caused by the lower setup cost for the third event and high number of product return rate. However, if they are compared to the unit cost of buying from the informal sector, the collection cost is still higher.

Based on the three events, the time when people are most likely to participate was during mid morning (10:00 – 13:00) and in the afternoon (13:00-14:30). People also tend to participate during midweek or two to three days after the commencement of the event. Thursdays and Fridays have the highest return rate regardless on the start time of the event.

A post event survey was conducted to evaluate the events. Based on the questionnaire distributed, it was found that majority of the population knows about the event. More than 90% knows about the event and more than 80% learned from the banners and posters at the booth (Figure 5). It was found that more than 55% still keep their old phones at home (Figure 6) although more than 70% claimed that they know about the danger of e-waste. This seems to be an opportunity for e-waste collection program, especially because more than 96% of people said that they have never participated in an e-waste collection program before. The respondents also said that if they decided to recycle or donate their old phones, they would prefer to trade in their phones, recycle it to the producers and to donate it to their family or relatives.

Overall, there were some challenges encountered during the pilot project. The biggest challenge was to find participating building or company. Being part of a Corporate Social Responsibility in a company or producers would be the best chance for conducting this type of event. There was also a misconception about EOL phones and the habit of keeping old phones. Some negative perception was also received regarding these events. People still need to be educated on the issue of e-waste and publication is imperative.

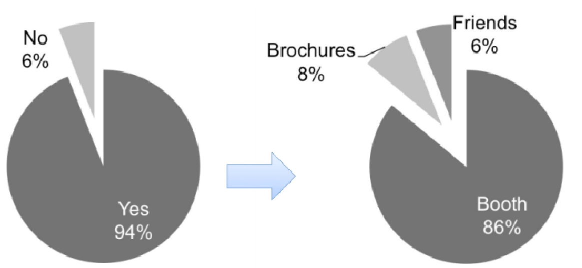

Figure 5: Public event awareness.

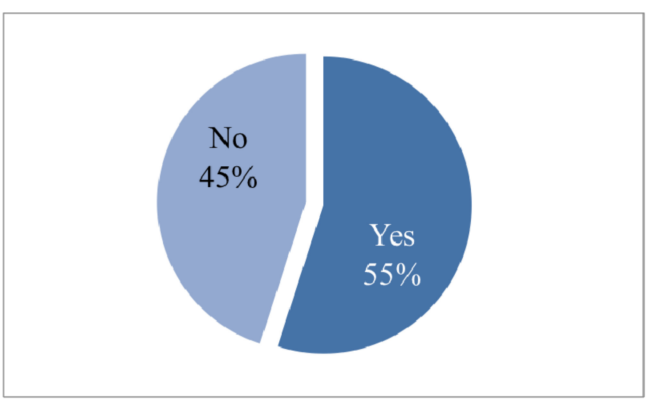

Figure 6: EOL phones ownership.

6 CONCLUSION

To conclude, all events conducted were successful and achieved more than 3% participation and product return rate. The average products return rate was 8.56% and the average of participation rate was 4.67%. The unit cost of collecting these EOL phones are still higher than those from informal sectors however these events can raise people's awareness regarding the issue. The feasibility of a collection program as a business unit is still questioned. This program shows more suitability as corporate social responsibility activity that employs volunteers.

Further study on other parts of the city is still required to comprehend the issue. Some measures to improve the performance are increasing publicity, partnership with companies and government body or telecommunication industries.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] Wibisono, D. (2010): Dimensi Kualitas Preferensi Handphone di Kalangan Mahasiswa Teknik Industri UPH, Bachelor of Engineering, Industrial Engineering, Universitas Pelita Harapan, Karawaci.

[2] Waema, T. and Mureithi, M. (2008): E-waste Management in Kenya Kenya ICT Action Network (KICTANet), Nairobi, Kenya

[3] Wasswa, J. and Schluep, M. (2008): e-Waste assesment in Uganda: A situational analysis of e-waste management and generation with special emphasis on personal computers Uganda Cleaner Production Center, Empa, Kampala/Uganda, St. Gallen/Switzerland

[4] Sinha-Khetriwal, D., Kraeuchi, P., and Schwaninger, M. (2005): A comparison of electronic waste recycling in Switzerland and in India, in: Environmental Impact Assessment Review Environmental and Social Impacts of Electronic Waste Recycling, Vol. 25, No. 5, pp. 492-504.

[5] Boeni, H., Silva, U., and Ott, D. (2008): E-Waste Recycling in Latin America: Overview, Challenges and Potential, in: Proceedings of *2008 Global Symposium on Recycling, Waste Treatment and Clean Technology*, Cancun, Mexico.

[6] Glazebrook, B. and Beling, C. (1999): Analysis of five residential/consumer end-of-life electronics collection programs, in: Proceedings of *Electronics and the Environment, 1999. ISEE -1999. Proceedings of the 1999 IEEE International Symposium on*, pp. 292-297.

[7] Gregory, J., Magalini, F., Kuehr, R., and Huisman, J. (2009): E-Waste Take Back System Design and Policy Approaches United Nations University/StEP Initiative 2009

[8] Daan, C. (1999): End-of-Life Electronic Equipment Pilot Collection Program Summary Report - Alachua County, Florida Center for Environmental Communications, Andover

[9] Howley, J. (2004): End-of-Life Electronic Equipment Pilot Collection Program: Summary Report- Hernando County, Florida Hernando County's Solid Waste and Recycling Division, Brooksville, FL

[10] Hanafi, J., Kara, S., and Kaebernick, H. (2008): Reverse Logistics Strategies for Mobile Phone Waste Collection, in: International Journal of Logistics Management, Vol. 19, No. 3, pp. 367-388.

[11] Nokia. (2011, 12 October 2011): Where to Recycle. Available: http://www.nokia.com/environment/recycling/where-and-how-to-recycle

[12] Sony. (2012, 01 November 2012): Sustainability | Recyclng | Performance | Sony Smartphones. Available: http://blogs.sonymobile.com/about-us/sustainability/recycling/performance/

[13] MobileMuster. (2011): 2010-11 - Annual Report Australian Mobile Telecommunications Association

[14] Nokia. (2011, 12 October 2011): Global consumer survey reveals that majority of old mobile phones are lying in drawers at home and not being recycled. Available: http://press.nokia.com/

[15] Sony Ericsson. (2011, 13 October 2011): Berkelanjtuan. Available: http://sonyericsson.com/

[16] Melini, E. (2010): Studi Kelayakan untuk Pengembangan Fasilitas Daur Ulang Sampah Komputer di Daerah Jabodetabek, Master of Engineering, Graduate Program in Industrial Engineering, Universitas Pelita Harapan, Jakarta.

[17] Hanafi, J., Kristina, H. J., Jobiliong, E., Christiani, A., Halim, A. V., Santoso, D. P., and Melini, E. (2011): The prospects of managing WEEE in Indonesia, in: Proceedings of *Glocalized Solutions for Sustainability in Manufacturing - Proceedings of the 18th CIRP International Conference on Life Cycle Engineering*, pp. 492-496, Braunschweig, Germany.

[18] Tunggono, L. T. (2011): Analisi Biaya Pengumpulan e-waste di DKI Jakarta: Studi kasus pengumpulan di mal dan gedung perkantoran, B.E., Departement of Industrial Engineering, Universitas Pelita Harapan, Tangerang.

Systematic Product Inspection and Verification to Improve Returned Product Recovery

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Abstract

Management of products and resources at end-of-life (EoL) includes recovery of product for reuse, remanufacturing for reviving parts and component, recycling for material contents and responsible disposal. The decisions are affected greatly by the mix of product varieties, recovery technologies, economic value, social and environmental impacts. An informed EoL product recovery decision can be accomplished when recovery aspects are better integrated in design and manufacturing phase. This paper introduces an efficient returned product assessment framework for original equipment manufacturer (OEM), where the assessment refers to design and manufacturing results. However, this integration poses challenging problem of decisions subject to uncertainties. A detailed and systematic product inspection and verification approach is proposed in this paper. It guides a decision maker to solve product recovery selection problem with optimized recovery value. This method is demonstrated with returning hair dryer.

Keywords:

End-of-life (EoL); Product Recovery; Waste Management

1 INTRODUCTION

The world population is currently growing by approximately 30% or 1.6 billion people between 1990 and 2010 [1]. With the trend of growing population, there is a tendency of humankinds consume more natural resources, such as forests, fish, fossil fuels, water and so on. The increased demand for natural resources are in danger of resources vanishing from planet faster than the rate of regeneration. Nations need increasing amounts of energy and raw materials to produce economic growth, however, the costs of supplying energy and materials are burgeoning. In many cases, lower quality resources with high impact to environment and high extraction cost remain happen. This has raised the concern on better utilization of natural resources through proper management of EoL product, where it largely encourages sustainable manufacturing by recovering valuable embodied energy and material back as input resources.

Product in EoL phase in this paper refers to returning of product when it no longer satisfies the initial purchaser or user needs. This paper mainly covers the EoL phase, on how the systematic recovery

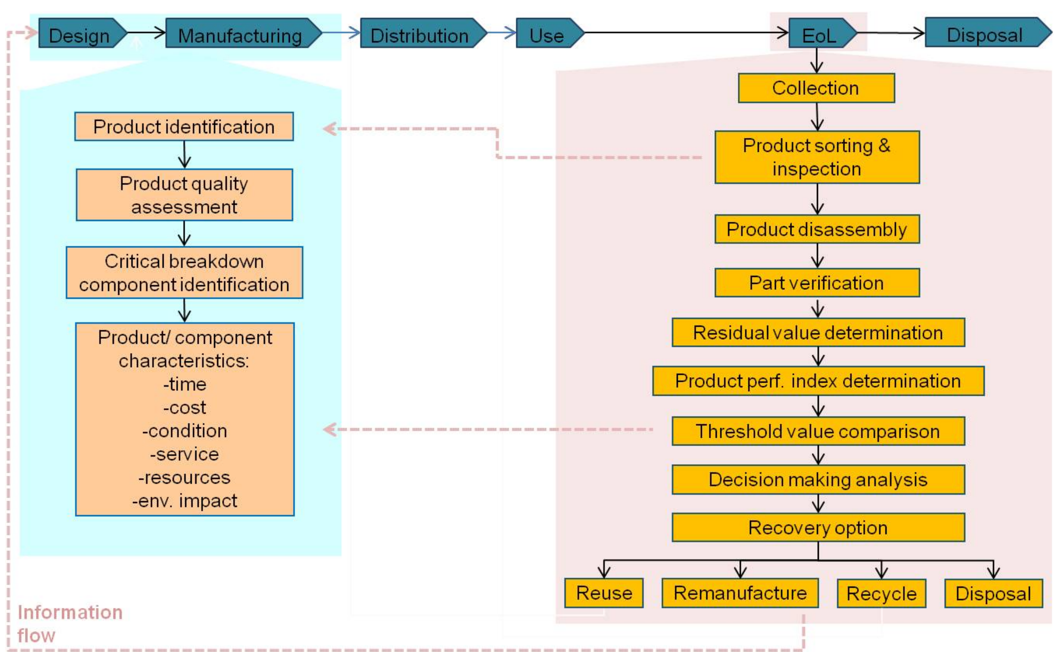

Figure 1: Product life cycle framework.

process could make informed decision to optimize recovery values from returned product. The recovery values such as time spent to manufacture new product, material and energy used and cost spent on resources that could be salvaged from durable product rather than being thrown away. Section 2 presents the outline of product life cycle framework for consumer goods, focusing on collection of product returns, returned product sorting and inspection process, product disassembly and part verification. The methodology will be illustrated using hair dryer as an example in Section 3. Different scenarios of product returns are explained in section 4 to demonstrate their impacts. Section 5 concludes on how the assessment results assist in making informed decision for returned product recovery and thus improve recovery values.

2 METHODOLOGY

Figure 1 shows the product life cycle framework for consumer product [2]. Stages in pentagon boxes demonstrate the primitive open loop product life cycle, where most of the EoL product ended up in landfill or incinerator. The way of ignorant disposal resulted in loosing up valuable resources and scarifying enormous space for landfill. Also, each of the product life cycle phase does pose certain effect on the total environmental performance. For example, extraction of material for manufacturing, emission of GHG to the environment during usage and transportation that used up energy for product distribution and waste collection after EoL. Therefore, this paper proposed a closed-loop system, focusing on maximizing product recovery values in EoL phase. A systematic process as stated in the boxes start from EoL phase would lead to a decision for product recovery, such as reuse, remanufacture, recycle or disposal. Information learned from the processes, such as product collection, sorting, inspection and verification are essential in determining the returned product status and its remaining value before decision is made. The details will be explained next. Solid line in Figure 1 shows material flow within the system, it forms a closed-loop system that brings back the embedded materials and energy in a used product to the new product life cycle. At the same time, knowledge learned from the recovery process could feedback to product design stage as common sharing platform, dotted line in the figure shows the information flow. With the knowledge of EoL consequences in mind, a more efficient practice will be inherited in the next design cycle for better environmental performances and profitable product.

2.1 Product Collection

Collection is the very first and important stage in recovery process, where original products are collected and transported back to product recovery facility for rework. There are four primary types of returns: *i) supply chain returns*, *ii) warranty returns*, *iii) end-of-lease returns* and *iv) end-of-life returns*. From the source of product returns obtained, it is seen that the reason for discarding able to precisely estimate the state of the product when it is returned. The collection cost and environmental impact from the transportation is significant in this step, and thus affects the decision make in recovery process. After collecting all returned products, they will be going through product sorting and inspection, as shown in Figure 2.

i) *Supply chain returns* could be unsold products returned from retailer or vendor. It might cause product obsolescence due to excess purchase or shipment because of errors in sales estimation. However, the products are never sold and unused. It is easy to predict the condition of the products, and most likely the products are in perfect condition.

ii) *Warranty returns* are the products returned by consumers against defects in material and workmanship or fail units within a certain period of time specified by manufacturer or retailer. Consumers are required to verify the product warranty eligibility before it is sent back to the manufacturer/retailer. This information is crucial to the manufacturer regarding to the state of the product. In the case of consumers with no expertise to confirm if the products fail, manufacturer would accept the returned products in order to maintain customer relationship. Since the product has been used in a limited timeframe, it is often possible to estimate the condition of the product.

iii) *End-of-lease returns* refer to the returning of leased product when the lease schedules are expiring. At the end of the leasing period, the old equipment is often replaced by a new unit and usually comes with maintenance service in the contract. In this case, up-to-date product information is available during product maintenance. However, the complete identity of the product could not be confirmed as there is a mixture of old and new parts in the reconditioned equipment. Therefore, it is rather difficult to accurately predict overall product performance.

iv) The last type of product returns is *end-of-life* product, which is discarded by consumer when the product no longer satisfies the consumer needs. In fact, the EoL product may be still functioning, but a better performing model exert a pull on influencing consumer behavior. Thus, returning of EoL product before end of it useful life has been the trend in recent decade. A majority of EoL product is discarded at civic amenity sites, and then it will be sent to independent recycler. Thus, OEM should largely encourage product take back program by returning of EoL product to the retailer so that distributor could collect back the original product when it allocates new product to the shops.

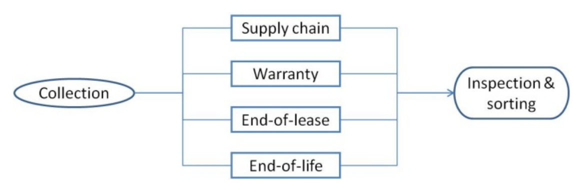

Figure 2: Types of product returns.

This paper will study the cost and environmental impact based on two types of product returns: supply chain returns and end-of-life returns (show in Figure 3). Several assumptions have been made for product collection in this paper:

1) 3.3ton short distance trucks are used for all goods delivery/collection [Source: Gabi (GLO: Solo truck)]

2) All truck performance in similar condition

3) The truck from storage/collection center responsible to collect product from distribution center and retailers.

4) Returned product will be collected back when new order delivers to storage/ distribution centers/ retailers

5) End users abide by product take back regulation by returning origin EoL goods to retailer by themselves

As refer to Figure 3, the cost incurred in supply chain and EoL returns includes transportation cost and driver's pay, as shown below.

$$Total\ cost = \sum_{i=1}^{n} D_i.\frac{Fuel\ cost}{Unit\ distance} + \sum_{i=1}^{n} T_i.\frac{Labor\ cost}{Trip}$$

where

$D_i = distance\ [km]$

$T_i = Number\ of\ trip$

$$\frac{Fuel\ cost\ [S\$]}{Unit\ distance\ [km]} = \frac{Fuel\ consumption\ [\iota]}{Unit\ distance\ [km]} \times \frac{Fuel\ cost\ [S\$]}{Unit\ fuel\ [\iota]}$$

The impact of gas emission from fuel consumption in the vehicle is measured by total direct GHG $(CO_2, CH_4 \; and \; N_2O)$, calculated as follow. (Gas emission in upstream production of fuel is not included in the emission factor.)

$$Total\ GHG\ emission = \sum_{i=1}^{n} D_i \times \frac{Fuel\ consumption}{Unit\ distance} \times Direct\ GHG\ emission\ factor$$

where

$D_i = distance\ [km]$

$Direct\ GHG\ emission\ factor = 2.6763 kg.CO_2/litre$ [2]

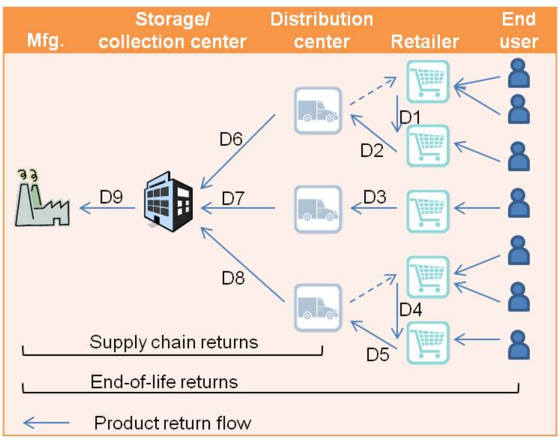

Figure 3: Product return flow.

Figure 3 shows product return flow where EoL returns are the products brought back by end users to retail shops, and the collector collects the products from retailer and distribution centers to storage center, then send back to manufacturing factory. The EoL returns trip inclusive of supply chain returns product. Table 1 shows an example of distance for collection locations, which will be using in the computation in following section.

Distance (km)	D1	D2	D3	D4	D5	D6	D7	D8	D9
	10	10	20	10	10	20	20	20	10

Table 1: Distance of collection location.

2.2 Product Sorting and Inspection

After getting back the original product, sorting and inspection is the next critical step to filter out malfunction product, show in Figure **4**. In this process, market demand followed by technology level of the returned product will be assessed first owing to the ease of detectability and minimal operating time and cost. The complication of detectability, time and cost taken are subsequently increasing in power test, aesthetic check and functional test (refer to calculation in Table 2). Thereby, the more test a product taken, the higher inspection cost acquired. Meanwhile, returned product that fails at the earlier test could be prevented from accumulating cost in the later test. For instance, an EoL product which obsoletes in the market could be quickly decided for product disassembly. All the test results are referring to the available information in manufacturing database and also company guideline for product acceptance.

Figure 5 shows the product life cycle of a product which facilitates in determining the stage of current sales fall into. This data should be available from the manufacturer's sales department and it would guide the decision maker to predict product demand in the market. If the product demand in the market is high, it is important to check for the state of technology level. Figure **6** shows the competitive advantage and technology revolution of a product. The competitive advantage could be determined by the product performance, number of inventions, level of invention or profitability. Meantime, the evolution of emerging technology for similar product should be observed so that boundary of competitive value could be estimated. For example, if the emerging technology s-curve overlaps with current technology, the returned product with high competitive advantage could consider for product recovery and then resell to the secondary market. On the other hand, products which are in low demand or not competitive in the market will be further disassembled for valuable parts recovery. Similarly, products that fail in power test, aesthetic check and functional test will be dismantled.

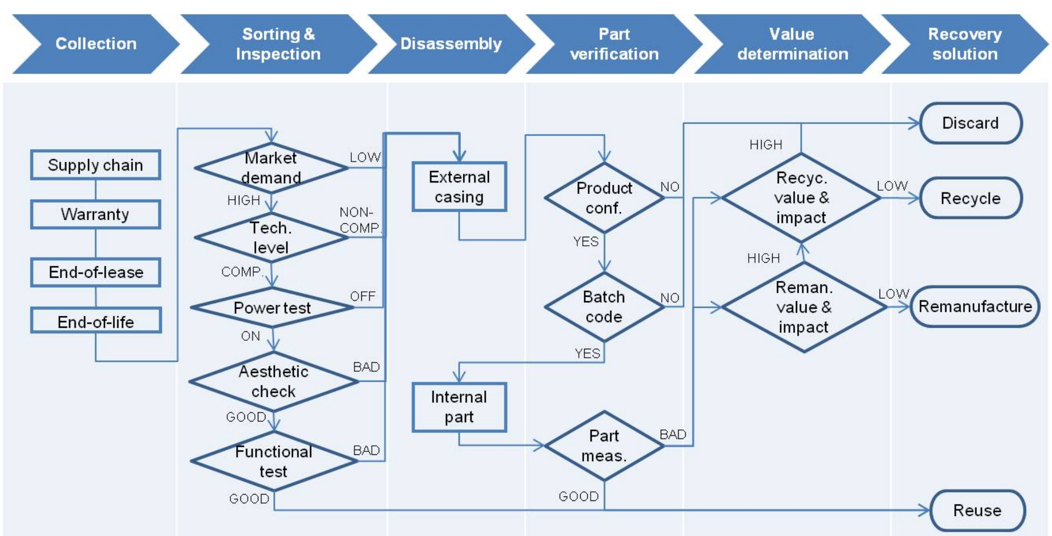

Figure 4: Flow chart for product assessment.

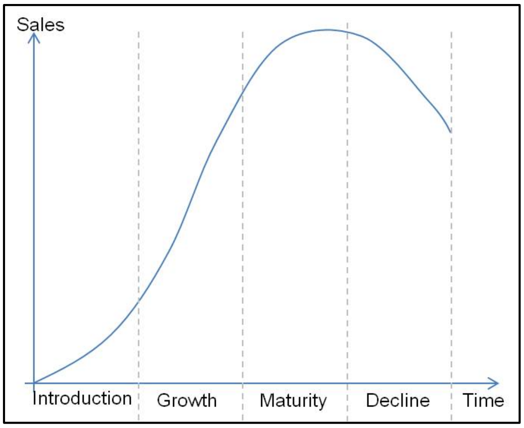

Figure 5: Product life cycle.

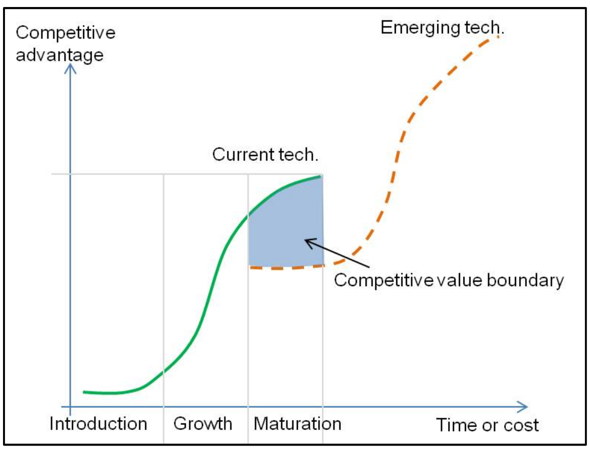

Figure 6: Technology revolution of a product.

2.3 Product Disassembly

There are two levels of product disassembly: external casing disassembly and internal part disassembly. External casing disassembly is first executed when it receives rejects from sorting and inspection process. In this step, it allows decision maker to ensure the configuration of the origin product. If the product configuration and batch code of the parts are all right, the product will be further dismantled. The internal parts of the product will be separated and measurement on durable parts will be done.

2.3 Part Verification and Value Determination

After the external casing is taken out, the returned product is checked for the right configuration and manufacture origin. If the product configuration or parts origin is mismatched, product will be discarded away. Otherwise, the good parts will be further dismantled to assess for valuable parts recovery opportunity. Valuable parts will be measured for the dimension or tested in detail, and the perfect one will be decided for reuse. This is the ideal recovery option as there will be no additional time, cost and resources needed to recover the part. On the contrary, part dimensions that are not within the required range will consider for remanufacturing of that part or recycling for material. The recovery options depend on remanufacturing and recycling value (cost, time, raw material) taken and impact to the environment. If both the remanufacturing value and impact is low, where most of the embedded energy and resource are possible to recover, remanufacture would be the best recovery solution. The part is appropriate for recycling if the recycling process cause lower value and impact compare to product discard.

3 CASE STUDY

Two scenarios are demonstrated in this paper to illustrate product assessment flow for the product returns: 1) Supply chain returns and 2) EoL returns. Hair dryer is used as an example in the scenarios. The total cost of recovery and environmental impact caused by each scenario are calculated in per month basis. The details show in Table 2 specifies the breakdown cost for returned hair dryer assessment. The labor pay is set based on skill required in executing the test and equipment cost is estimated by spreading the cost evenly over 5 years life. Moreover, power consumed by electrical appliances is computed based on typical value in Singapore household appliances. The results from both scenarios will be discussed and explained in the next section.

Scenario 1: Supply chain returns

The returned products in this case are mainly unsold unit due to overstock, therefore the products are most likely still in new condition. However, the returned products are mandatory going through physical and functional tests to validate its performance before decision is made. The assessment flow for supply chain returns is shown in Figure 7. The supply chain returns pass through the tests show in bubble background boxes. In this scenario, for instance the product demand is high with certain level of competitive advantage, the product in good appearance and well functional. As the result, the product is acceptable for reuse.

The total recovery cost will be the value calculated based on (1).

$$Total\ recovery\ cost = Collection\ cost + Factory\ rental + Equip.cost + Labor\ cost + Utility\ cost \quad (1)$$

<u>Parameters for cost of diesel consumption</u> [Source: Gabi]
Type of truck (capacity): 3.3t Solo truck
Journey condition: 50% outside of town; 50% within town
Load per truck: 85% full
Product type per truck: 20% from supply chain; 80% from EoL
Number of trip/month: 4
<u>Electricity tariff</u> [Source: Singapore Power, last updated Oct'12]
Low tension supplies, domestic: 29.18 ¢/kWh [4]

The environmental impact caused by the recovery process is based on calculation (2).

$$Total\ GHG\ emission = (Electricity\ consumption \times electricity\ grid\ emission\ factor) + (Fuel\ consumption \times GHG\ emission\ factor) \quad (2)$$

where

$Electricity\ grid\ emission\ factor$ [3],

$$1kWh\ electricity = 0.5716\ kg\ CO_2e/kWh$$

$Direct\ GHG\ emission\ factor$ [2],

$$1\ litre\ of\ diesel = 2.6763kgCO_2e/litre$$

Scenario 2: End-of-life returns

The condition of returned products in this scenario varies from short period used product due to unsatisfaction to a long age used EoL

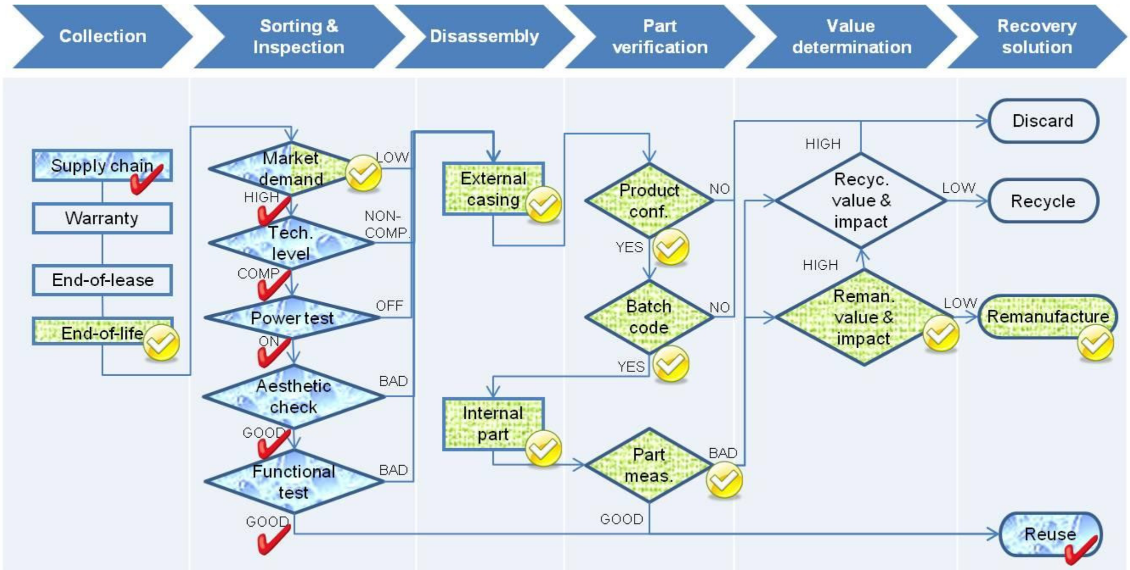

Figure 7 Scenario 1: Assessment flow for supply chain returns (in bubble background with red ticks); Scenario 2: Assessment flow for EoL returns (in hatch background with yellow circular ticks).

Process	Item required	Skill required	No. of worker	Salary/ worker [S$]	Equip. cost [S$]	No. of hr/mo.	Utility [kWh]
Market demand	-Electricity -Computer	Elementary					
Tech. level	-Electricity -Computer	Elementary	1	800	33.33	160	43.2
Power test	-Electricity	Elementary			-	40	60
Aesthetic check -Structural -Surface -Color	-Electricity -Computer -Spectrophotometer	Elamentary Intermediate	1 1	800 1000	33.33 250	160 160	43.2 8
Functional test -Fan speed -Temperature	-Electricity -Computer -Sensor -Thermometer	Intermediate	1	1000	33.33 8.33	160 160	43.2 240
External dis. -Casing	-Electricity -Screw driver	Elementary			2.5	40	2
Internal dis. -Motor -Heating element -Blower	-Electricity -Screw driver	Elementary	1	800		60	3
Product config.	-Electricity -Computer	Elementary					
Batch code	-Electricity -Computer	Elementary					
Value & impact checking -Reman. -Recycle	-Electricity -Computer	Elementary	1	800	33.33	160	43.2
Part testing/ meas. -Motor -Heating element -Blower	-Electricity -Computer -Motor tester -Digital vernier caliper	Intermediate Elementary	1 1	1000 800	33.33 8.33	160 160	43.2 240

Table 2: Breakdown details of recovery process steps.

product. Thereby, product assessment for EoL returns is prime important in verifying product state, in order to maximize product recovery value. Boxes in hatch background shows in Figure **7** are the assessment step for EoL return product. In this case, EoL product which is obsolete in the market will be sending to disassembly process, and then going for parts verification. The total recovery cost and environmental impact cause by EoL product recovery are calculated using (1) and (2).

4 DISCUSSION

Figure **8** as follow shows the total recovery cost for supply chain and EoL returns. Product from EoL returns incurred slightly lower recovery cost than supply chain returns. It is because of early detection of inappropriate EoL product for reuse in the market has prevented adding up the cost from subsequent tests in the inspection process. However, collection (transportation) cost is higher for EoL returns due to higher fuel consumption are required for bigger amount (80% EoL product) of return product. The result also illustrates cost of utility and rental is the major components contribute to product recovery expenditure. On the other hand, result in Figure **9** tells EoL product recovery causes higher impact to the environment. This is owing to higher fuel consumption for larger amount of EoL returned product and longer collection journey. In Scenario 1 (Figure **7**), product reuse is advisable for its higher selling value although the recovery cost is high. For the case in Scenario 2, if the cost of remanufacturing and GHG emission from that process is lower than recycling cost and impact, EoL returned product is prudent to go for remanufacturing.

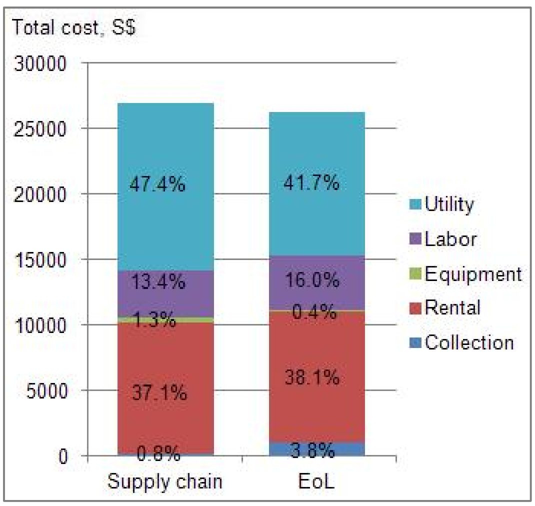

Figure 8: Total recovery cost for supply chain and EoL returns.

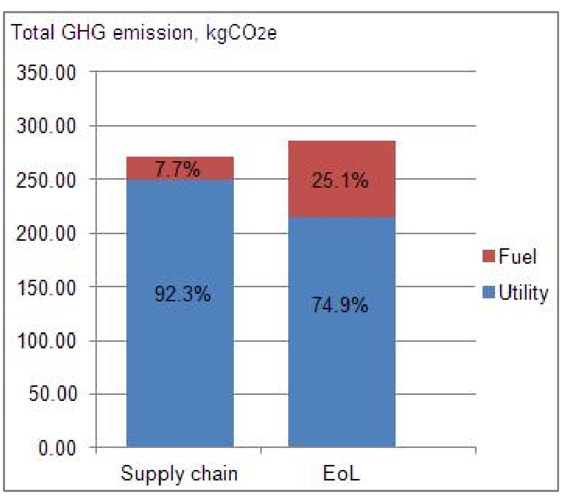

Figure 9: Total GHG emission for supply chain and EoL returns in product recovery process.

5 CONCLUSION

The framework described above consists of product collection, product sorting and inspection, product disassembly and part verification process. It is a systematic approach that aids in improving returned product recovery value, such as shorter time in deciding product recovery option, productive process that reduce operation cost and efficient method that brings down environmental impact. It saves the product recovery time by utilizing available data from design and manufacturing process. At the same time, the proposed framework able to close the product life cycle loop by sharing the knowledge learned in recovery process to product designer. Nevertheless, the proposed methodology is workable provided product take back program is widely implemented in all regions. Besides, take back regulations should be closely monitored by the government.

For further product recovery improvement, determination of product/part residual value could be done. This allows OEM has better prediction and management on returning source of materials and components back to the manufacturing process. In addition, environmental improvements are viable via dematerialization, and regular advancement in recovery process leads to more environmentally benign technology. Overall, efficient product recovery management enables sustainable manufacturing and economy growth.

6 REFERENCES

[1] World Population Prospects: The 2010 Revision, Highlights and Advance Tables, 2011, United Nations: New York.

[2] Yen Ting Ng, Hui Mien Lee, Wen Feng Lu and Jonathan Sze Choong Low, (2012): Improving E-waste Recovery with Energy Efficiency Information of Products, in: Electronics Goes Green, Berlin, Germany, Paper B6.4.

[3] Guidelines to Defra/ DECC's GHG Conversion Factors for Company Reporting, 2012.

[4] Information on Emission Factors, April 2012, National Environment Agency: Singapore

[5] Electricity Tariff Revision, September 2012, Singapore Power Services: Singapore

Life-Cycle Assessment for Plastic Waste Recycling Process: Based of the Network Evaluation Framework

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Abstract

With the increasing application of plastic products in consumption, plastic waste has become a serious problem with huge environmental impact. In order to analyze the recycling process of plastic waste, a network model is established in this paper. Based on this model, an evaluation framework and Life-Cycle Assessment indicator system are built to denote the actual situation of plastic waste recycling industry in China. With the evaluation of the environmental impact, efficiency and economy cost for different recycling technology selections and output scales, an evaluation framework is presented to optimize the design of plastic waste recycling process to reduce the environmental impact, and increase output efficiency.

Keywords:

Plastic waste; Life-cycle Assessment; recycling

1 INTRODUCTION

With the increasing application of plastic products in consumption, the amount of plastic waste was more than one third of total consumption of plastic in China. The total consumption of plastic was up to 60 million tons, which was about 25% of global consumption in 2011. Furthermore, the phenomenal growth of the plastics industry during the past several years has resulted in a vast amount of various kinds of plastics produced every year.

In order to solve this problem, many methods have been proposed for the recycling of plastic waste: Y. Barba-Guti´errez[1] used LCA to analyze different electrical and electronic waste. It is shown that under certain circumstances, the environmental impact of these recycling could be even higher than impact of non-collection. Kunihiko TAKAHASHI1[2] assessed different recycling options for plastic wastes from discarded mobile phones by LCA, and found that mechanical recycling of plastics is more attractive treatment option in environmental terms than incineration for energy recovery. M. Bientinesi[3] put forward a compare of waste brominated plastic, and demonstrates that the thermal treatment of staged-gasification was more energy efficient than co-combustion. Hakan Stripple[4] developed an environmental improvement of plastics for hydrophilic catheters in medical care. Chao Feng[5] presents an analysis of the color TV set and found that the environmental burdens which arise from color TV sets are mainly due to air emissions derived from fossil fuel utilization.

In order to increase efficiency of plastic waste recycling, a systematic and scientific recycling process model should be established for analysis of “hotspots”. Poonam Khanijo Ahluwalia[6] presents a multi-objective model that used to evaluate management cost and reuse time span or life cycle of various streams of computer waste for different objectives of economy, perceived risk and environmental impact. Jörg Winkler[7] compares a selection of six different models, the model-comparison revealed show high variations and are not negligible in LCA. In some cases the high variations in results lead to contradictory conclusions concerning the environmental performance of the waste management processes. Thomas H. Christensen[8] brought out the use of EASEWASTE (a new computerized LCA-based) model for integrated waste management. The results shown that waste management systems can be designed in an environmentally sustainable manner where energy recovery processes lead to substantial avoidance of emissions and savings of resources. Seong-Rin Lim[9] developed a mathematical optimization model to synthesize existing distributed and terminal WTPs into an environmentally friendly total wastewater treatment network system (TWTNS) from a life cycle perspective. Chang-Chun Zhou[10] presented artificial neural networks and genetic algorithm approach to process Multi-objective optimization of material selection for sustainable products. It was validated by an example that the system can select suitable materials to develop sustainable products. Takanobu Kosugi[11] merged an integrated assessment model and a Life-cycle Impact Assessment (LCIA) model to simulate the external costs of global environmental damage.

In researches mentioned above, most of models focus on a specific material and established by particular experimental data of a certain product, such as PET bottle or TV set. And the situation of different country has not been taken into consideration. In China, because many plastic recycle enterprises are low scale volume companies with simple equipments, it is very important to do systematic research for plastic recycling process, especially the relationship between LCA result and technology-equipment selection.

2 GENERAL DESCRIPTION

Plastic waste recycling is a complex process including lots of operation steps, such as Collection, Disassembly, Break, Sorting, Washing, Separation, Delalogenation, Physical Modification, Chemical Modification, Energy Recovery, Landfill, etc. It also involves variety of techniques with physical and chemical changes, which consume energy and resources, then generate new products and environmental impact. Operation steps of plastic waste recycling can be shown in Table 1.

2.1 IPO Model and Operation Step for Plastic Waste Recycling

In order to build a framework to describe plastic waste recycling process and environment impact result, the “IPO” (Input- Process-Output) model [12] can be used to denote Input-Output flow and LCA

ID	Type	Operation Unit	Optional Technology
1	Pre-Operation	Collection	-
2		Disassembly	Manual, Mechanical
3		Break	Impact Low-temperature, Shear Ultrasonic
4		Sorting	Gravity, Turbine, Wind Shaking, Electromagnetic Sorting
5		Washing	-
6		Separation	Gravity, Turbine, Wind Shaking, Electromagnetic Sorting
7	Mechanical Recycling	Delalogenation	-
8		Physical Modification	Extrusion
9		Re-Manufacture	Extrusion, Heating Blends, Blow Molding, …
10	Chemical Recycling	Chemical Modification	Supercritical Fluid
11	Energy Recovery	Energy Recovery	-
12	Final Disposal	Landfill	

Table 1: Operation Steps of Plastic Waste Recycling.

calculation model for each operation step in recycling process. For each operation step, material inputs can be regarded as Input Flow. Input Flow mainly includes two parts: Materials output from previous operation step, and new additive materials added. Materials produced by operation step can be regarded as Output Flow. Output Flow means Material that can be used by next operation step.

For each operation step, different operation technologies may be used. And for a certain operation technology, different equipments can be selected to fit different producing scale volume. Different design scenario of technology and equipment will cause different LCA results. Here, Energy and cost can be regarded as LCA input elements. Noise, Solid waste, water waste and Air emission can be regarded as LCA output elements. If using a 'Layer' to denote an operation step, the IPO model of a layer can be shown as Figure 1.

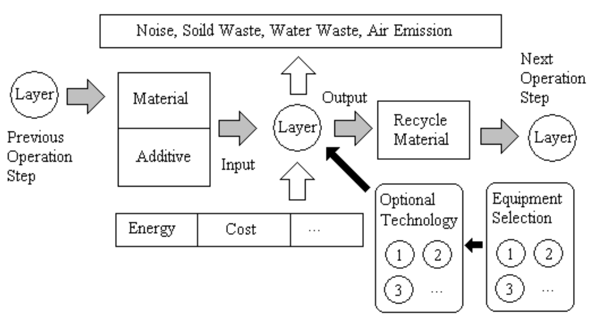

Figure 1: The IPO model for an operation step in recycling process.

2.2 Relationship between Neighboring Operation Steps

As shown in Figure 1, each operation step of plastic waste recycling process has many optional scenarios of technology and equipment selection. Since an operation step can be regarded as a 'Layer', then each technology-equipment scenario can be regarded a 'node' in operation step layer. For whole plastic waste recycling process, a network-based model with lots of layers and nodes can be used to denote the logistical and mathematical relationships between different operation steps. This network-based model can be shown as Figure 2.

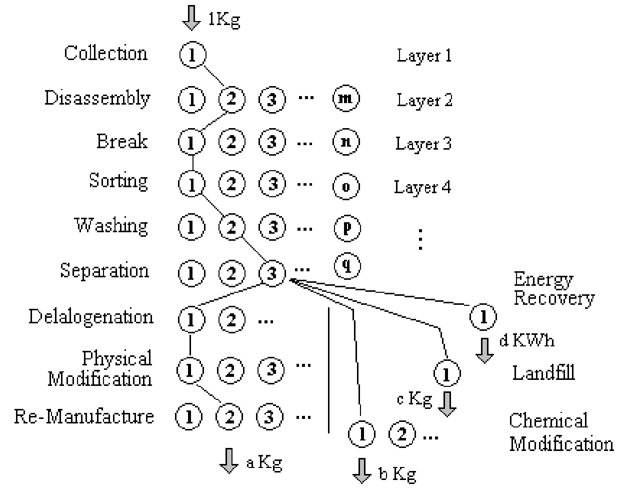

Figure 2: Network-based framework.

2.3 Operation Technology Design and Equipment Selection

In figure 2, 12 layers are designed to denote 12 operation steps of plastic waste recycling process. In each layer, some nodes are used to denote all optional technologies for this operation step. When a company wants to build recycling system for plastic wastes, to some extent it must design a flowing line to link certain nodes in different layers. This flowing line linked the nodes of different layers can be regarded as a systematic scenario of technology selection for plastic waste recycling process.

For each technology node in different layer, there are lots of optional equipments can be selected. Parameters such as output scale, energy consumption, efficiency and cost should be taken into consideration for equipments selection.

Then with network-based model shown in Figure 2, a mathematic model can be designed to analyze situation for different selection of technology process and equipment. This mathematic model can directly denote the relationship between the Inputs for plastic wastes and recycled outputs for materials and energy. And this relationship can be described as:

Input: 1 Kg plastic waste input –

Process: Certain operation process scenario

Output: Recycled material and energy (a Kg recycled material, b Kg chemical modification product, c Kg final disposal, d KWh energy recovery).

2.4 Mathematic Model

In order to denote relationship between input and output of network-based model, relationship between nodes in neighboring layers should be designed. This mathematical relationship between nodes of neighboring two-layers can be shown as Figure 3.

$P_n(i)$: Node *i* of Layer *n*;

m: The number of nodes in Layer *n-1*;

P: The number of nodes in Layer *n+1*;

$X_n(i)$: Material input of the node $P_n(i)$, Kg;

$Y_n(i)$: Material Output of the node $P_n(i)$, Kg;

$W_{n,i\text{-}j}$: The correlation coefficient between node *i* of Layer *n* and node *j* of the Layer *n-1*, from 0 to 1;

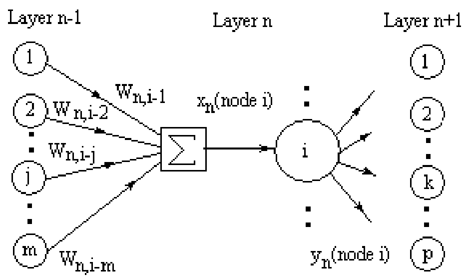

Figure 3: Mathematical relationship between nodes.

According to the Figure 3, the mathematical relationship between the neighboring layers can be expressed as:

$$X_n(i) = \sum_{j=1}^{m} W_{n,i-j} \cdot Y_{n-1}(j) \tag{1}$$

$$Y_n(i) = f(X_n(i)) \tag{2}$$

Here, formula (2) means the relationship between $X_n(i)$ and $Y_n(i)$ of node *i* in layer *n*. This relationship can be summarized as a function decided by the situation of technology and equipment selected.

In formula (1) and (2), parameter $W_{n,i-j}$ and function $f(x_n(i))$ can be regarded as the most important contents in network-based model.

Parameter $W_{n,i-j}$ denotes the relationship between different operation technologies in neighboring steps. If the output of node k (operation technology k) in layer n-1 can be used as input of node t (operation technology k)_in layer n, $W_{n,i-j}$=1, otherwise $W_{n,i-j}$=0.

Function $f(x_n(i))$ denotes the output efficiency of equipment selection for node *i* in layer n.

Parameter $W_{n,i-j}$ and function $f(x_n(i))$ can be summarized by experiments or real produces for plastic waste recycling. For example, Figure 4 shows the usage of parameter $W_{n,i-j}$ and function $f(x_n(i))$ for operation step of 'Sorting'. There are 6 different technologies can be selected in Sorting step, such as P4(1) to P4(6). Parameters in Figure 4 denote the separation efficiency of different separation technology for different materials such as PP, PE, PVC, PS, ABS, etc.

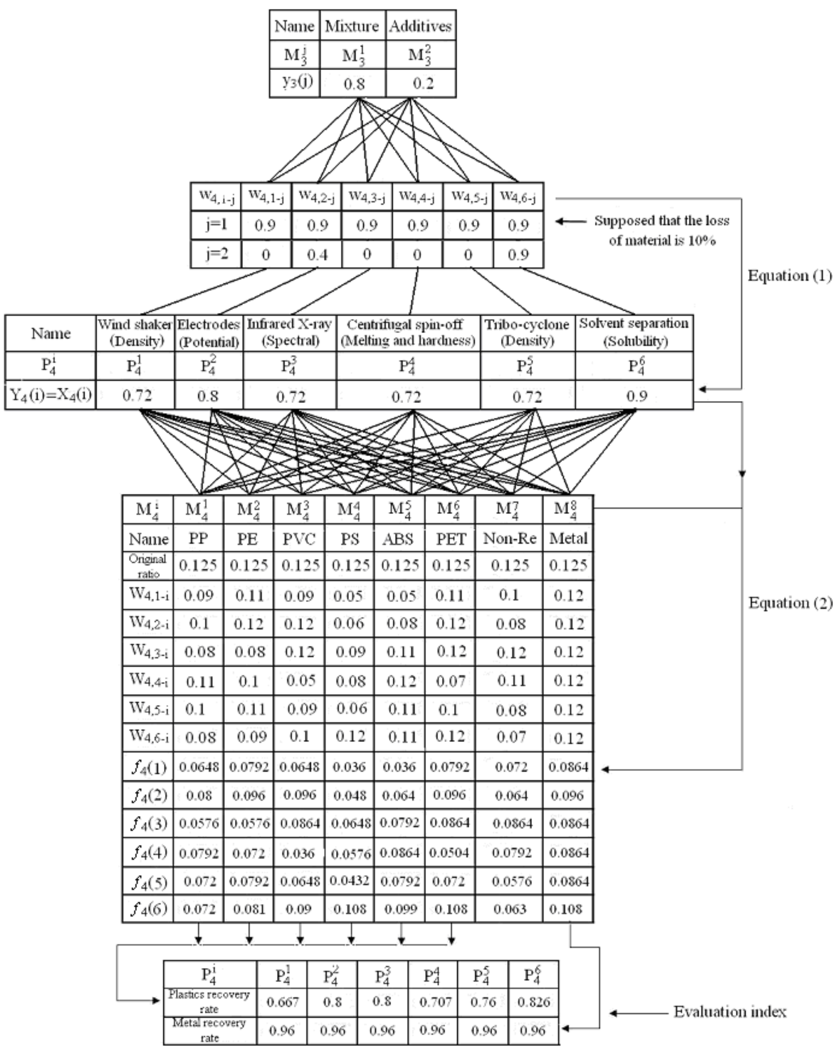

Figure 4: Parameters in network-based model for operation step of Sorting.

3 LCA EVALUATION INDICATOR

For plastic waste recycling process, LCA evaluation indicators can be summarized into two parts: LCA input elements and LCA output elements.

$EI_n(i)$: LCA input elements of the node *i* of layer *n*;

$EO_n(i)$: LCA output elements of the node *i* of layer *n*.

LCA input elements mean consumption factors, such as cost and energy. LCA output elements include 29 evaluation parameters as shown in Table 2.

The LCA elements for node *i* in layer *n* can be summarized as:

$$EI_n(i) = \{Cost,\ Energy\ Consumption\}$$

$$EO_n(i) = \{Solid\ Waste,\ Liquid\ Waste,\ Exhaust,\ Noise\} \quad (3)$$

Here:

$Solid\ Waste = \{S_1, S_2, \ldots, S_6\}$

$Liquid\ Waste = \{L_1, L_2, \ldots, L_{10}\}$

$Exhaust = \{G_1, G_2, \ldots, G_{12}\}$

$Noise = \{N\}$

Category	State	Pollution Sources	Pollution Factor	Measures Taken
SOLID WASTE	S1	Metal cutting and smelting	Metal slag metal debris	Artificial collection Absorption filter filters
	S2	Gas filtration and adsorption	The fine dust containing metals Used activated carbon	Solvent treatment Confined burning
	S3	Separation of dissolved solvent	Insoluble polymer Metal particles	Burning, Separation of smelting
	S4	Depolymerization	Carbonization of polymer Between coking products	Artificial removal of Smash burning
	S5	Solid-phase extrusion extruder	Intermediate product, ash	Dust buried
	S6	Heating blends	Inorganic ash	Absorption collection
LIQUID WASTE	L1	Hydrofluoric acid cleaning	Fluorine-containing cyanide solution	Decomposition catalyst recycling
	L2	Hydrothermal dissolution circuit board	Phenol-containing organic ester solution	Distillation extraction recovery
	L3	Broken grinding	Broken lubricants, abrasive	Filter Recycling
	L4	Solvent evaporation condensation	Liquid Methyl ethyl ketene solution	SDE
	L5	Proportion sorting	Waste water	Filtration purification Absorption
	L6	Halogen free hot points	Wastewater containing halogen	Chemicals Brine purification
	L7	Supercritical fluid extraction dehalogenation	Wastewater containing halogen	Chemicals Brine purification
	L8	Chemical reduction dehalogenation	Spent alkali metal ammonia solution	Chemical Filter recycling
	L9	Chemical mechanical dehalogenation	Spent solution containing flame retardants	Extractive distillation separation
	L10	Recovery of fire retardant	Final waste	Dilution decomposition
EXHAUST	G1	Cutting, smelting	Gas metal dust	Absorption filter filters
	G2	Demolition of refrigeration equipment	Containing CFC emissions	Activated carbon adsorption, condensation recovery
	G3	Dismantling of CRT	Lead and phosphor emission	Activated carbon adsorption filters
	G4	Broken plastic products	Blowing agent CFC-11 emissions	Activated Carbon Adsorption
	G5	Solvent recycle	Emissions of volatile organic solvents	Solvent Chemical Absorption Activated Carbon Adsorption
	G6	Shaker light wind electric election Separator smash	Plastic metal mixed dust	Bag house Dust Collector
	G7	Heating centrifugal separation	Plastics volatile organic gases	Activated Carbon Adsorption
	G8	Polyurethane depolymerization	Oxides of nitrogen sulfide	Scrubber alkaline absorption
	G9	Separation of metal smelting	Metal dust gases, sulfide	Separation, absorption filter
	G10	Removal of fire retardants	$HCl\ NO_X\ SO_X\ CO_2$	Alkaline solution to absorb
	G11	Extruder Chemical dehalogenation	Solvent evaporation gas HCl	Extractive distillation absorption
	G12	Blending, extrusion Blow molding, foaming	Exhaust, dust	Absorption filters, bag collection
NOISE	N	Air compressor, grinder Crusher, grinding machine	Noise db	Sound insulation, noise reduction, shock absorption

Table 2: LCA Output Elements for Plastic Waste Recycling.

Then LCA result for the whole network-based model for plastic waste recycling process can be described as:

$$LCA\ result=\{\sum_{n=1}^{k}\sum_{i=1}^{m_n} EI_n(i),\ \sum_{n=1}^{k}\sum_{i=1}^{m_n} EO_n(i)\} \quad (4)$$

Here, k: the number of layers. (The number of operation steps in recycling process).

m_n: the number of nodes in layer n.

Then, the LCA evaluation framework for plastic waste recycling can be built as shown in Figure 5. With the support of Technology Database, Equipment Database and LCA Indicator System, evaluation framework can be used to make analysis for different recycling operation process for different plastic wastes. And this framework can also be used to analyze plastic waste recycling market situation of environmental impact and cost input for a certain country.

Furthermore, with a proper optimization methodology, company designer can use this framework to optimize the design of operation process scenario.

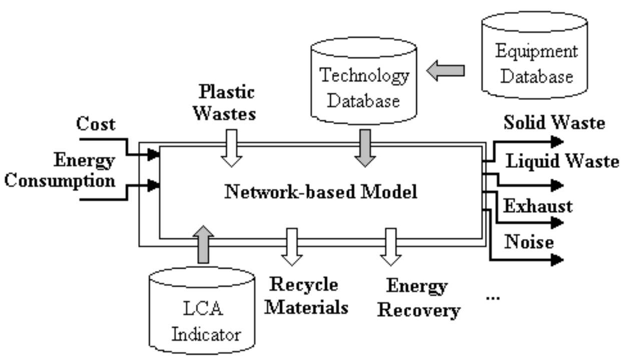

Figure 5: Evaluation Framework for Plastic Waste Recycling.

4 CASE STUDY

With the network-based model and evaluation framework, the total LCA results can be calculated. In this paper, China market of plastic waste recycling is select as the case study. In this case study, LCA situation for each step of plastic waste recycling will be calculated and analyzed. With the analysis result, improvement method will be discussed.

According to the average market price and statistics of China Plastics Processing Industries in 2011. The cost and energy consumption of typical processes of plastic waste recycling technology are shown in Table 3.

Category	Price (RMB)	Power (kwh)	Performance Indicator
Jaw Crusher	4500-7500	13	800-1200Kg/h
Impact Crusher	12000-20000	11	250-350Kg/h
Composite Crusher	6000-14000	30	700-1000Kg/h
Magnetic Separator	30000	20	5t-8t/h
Electrostatic Separator	19000-30000	10	200-500Kg/h
Ball Mill	10000-20000	1.5	1t-3t/h
Cryogenic Crusher	75000-100000	5	100-300Kg/h
Wind Shaker	10000-15000	1.1	1.6t/h
Hydraulic Separator	8000	1.1	8-15t/h
Dryer	42000	6	2t/h
Washing Machine	9000-30000	4	1000-1500Kg/h
Twin-screw Extruder	320000	110	550Kg/h
Single Screw Extruder	35000	47	75-125Kg/h
Foaming Machine	178000	15	100-500Kg/h
Exhaust Filters	36000		
Activated Carbon Filters	50000-60000		
Sewage Treatment Equipment (small)	68000-80000		2m3/h
Sewage Treatment Equipment (Medium)	1000000-4000000		20-300m3/h
Complete Sets of Solid Waste Process	880000-3000000		

Table 3 Statistics for plastic processing equipment and disposal equipment.

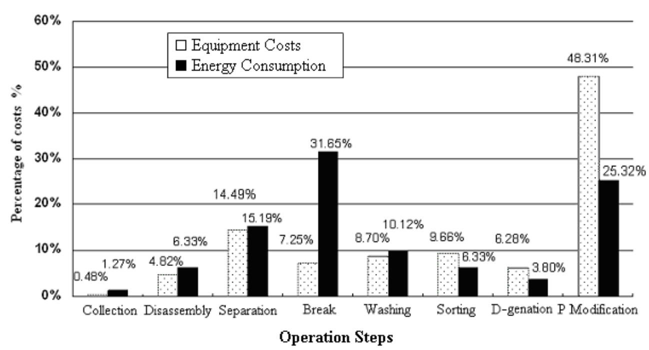

Figure 6: Cost and Energy Consumption Situation of Plastic Waste Recycling.

Because most of plastic recycling industries in China select the mechanical recycling technology, only operation steps of mechanical recycling are taken into consideration in case study. With the LCA analysis, LCA input for normal situation of plastic waste recycling is shown as Figure 6, and LCA output for normal situation of plastic waste recycling is shown as Figure 7. In order to facilitate analysis and comparison, only indicators of solid waste, Liquid Waste, and Exhaust are select in LCA analysis.

According to Figure 6 and Figure 7, it can be found that operation of Washing and Sorting cause most of Liquid Waste in recycling process. And liquid waste can also be regarded as a major environmental impact of plastic waste recycling. It is important to develop new technology of cleaning and sorting to minimize the liquid waste output.

For solid waste, operation of sorting can be regarded as important factor. It is urgent to integrate sorting process to reduce the volume of solid waste discharging.

According to Figure 7, it can be found that Dehalogenation cause most of air pollution. The Dehalogenation should be paid more attention to research new technology way.

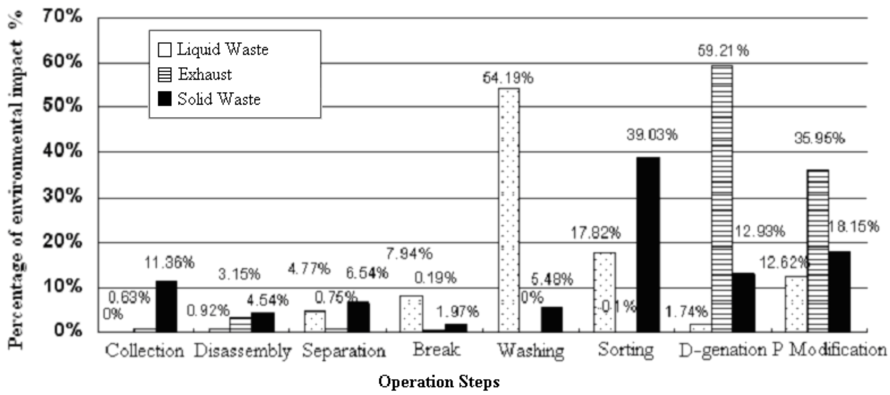

Figure 7: Environmental impact Situation of Plastic Waste Recycling.

5 CONCLUSION

In this research, a Network-based model is presented to analyze the whole process of plastic waste recycling. With the model, all process of recycling including Waste Collection, Disassembly, Material Separation, Break, Sorting, Dehalogenation and Physical Modification, etc. can be analyzed by an integrated LCA system to evaluate the cost, Energy consumption and environmental impact.

This network-based model can be used to make LCA analysis for different design scenarios of recycling technology selection. Furthermore, it can also be used to make optimization for the best recycling processes selection to reduce environment impact.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] Y. Barba-Guti´errez, B. Adenso-D´ıaz, M. Hopp, (2008): An analysis of some environmental consequences of European electrical and electronic waste regulation. J Resources, Conservation and Recycling 52, pp481–495

[2] Kunihiko TAKAHASHI, Gjergj DODBIBA, (2007): Assessing Different Recycling Options for Plastic Wastes from Discarded Mobile Phones in the Context of LCA. J Resources Processing 54, pp29–34

[3] M. Bientinesi, L. Petarca, (2008): Comparative environmental analysis of waste brominated plastic thermal treatments. J Waste Management, doi:10.1016/j.wasman.2008.08.004

[4] Hakan Stripple, Robert Westman, (2008): Development and environmental improvements of plastics for hydrophilic catheters in medical care: an environmental evaluation. J Journal of Cleaner Production doi:10.1016/j.jclepro.2007.12.006

[5] Chao Feng, Xiao Qian Ma, (2008): The energy consumption and environmental impacts of a color TV set in China. J Journal of Cleaner Production doi:10.1016/j.jclepro.2008.03.007

[6] Poonam Khanijo Ahluwalia, Arvind K. Nema, (2007): A life cycle based multi-objective optimization model for the mamagement of computer waste. J Resources, Conservation and Recycling 51, pp792–826

[7] Jo¨rg Winkler, Bernd Bilitewski, (2007): Comparative evaluation of life cycle assessment models for solid waste management. J Waste Management 27, pp1021–1031.

[8] Thomas H. Christensen, Gurbakhash Bhander, (2007): Experience with the use of LCA modeling (EASEWASTE) in waste management. J Waste Manage& Research 25,pp257–262.

[9] Seong-Rin Lim, Jong Moon Park, (2009): Environmental impact minimization of a total wastewater treatment network system from a life cycle perspective. J Journal of Environmental Management 90, pp1454–1462

[10] Chang-Chun Zhou, Guo-Fu Yin, and Xiao-Bing Hu, (2008): Multi-objective optimization of material selection for sustainable products: Artificial neural networks and genetic algorithm approach. J Materials & Design, doi:10.1016/j.matdes.2008.06.006

[11] Takanobu Kosugi, Koji Tokimatsu, (2009): Internalization of the external costs of global environmental damage in an integrated assessment model. J Energy Policy 37, pp2664–2678

[12] Tan X.C, Liu.F, Liu DC, (2007): Research on the diagnosis and improvement method of a process route in an enterprise production process in terms of sustainable development III. J International Journal of Advanced Manufacturing Technology, Vol.33, No.11-12, pp 1256-1262, August

Product Clustering for Closed Loop Recycling of Flame Retardant Plastics: A Case Study for Flat Screen TVs

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Abstract

Closing material loops for the housing of electronic equipment remains a particular technical challenge because of the common use of Flame Retardant (FR) plastics. Within an industrial collaboration, series of experiments were setup to demonstrate the technical and economic feasibility of closed loop recycling of back covers of End-of-Life Flat screen TVs (FTVs). The results of these experiments show that the used type of plastic and FR is strongly producer dependent. Therefore, this paper proposes to cluster FTVs based on product brand to facilitate closed loop recycling of PC-ABS and HIPS-PPO with phosphorous FRs.

Keywords:

Recycling; Flame Retardant Plastics; LCD TVs

1 INTRODUCTION

Worldwide a total number of approximately 1 billion Liquid Cristal Display (LCD) FTVs has been sold in 2012 [1]. In addition, the average lifetime of TVs decreased in 2012 to 6,9 years [1]. This high number of FTVs put on the market combined with the shortening lifespan will result in a fast increasing number of FTVs reaching its End-of-Life (EoL). In Europe, due to legislation, LCD FTVs have to be collected separately and processed in a dedicated recycling line, since many LCD FTVs use mercury containing Cold Cathode Fluorescent Lamps (CCFLs) as backlighting [2].

According to recent studies, LCD TVs contain about 30% plastics [3, 4]. On average, 15% of these plastics are used in the front cover and 45% in the back cover, which can be disassembled with limited effort. However, these housing plastics often contain FRs because of manufacturers' safety policy or because of legislation. For example, European legislation obliges the use of FR in FTV housings from 2010 onwards (EN 60065:2002/A11:2008).

According to the European legislation, all phosphorous based FR (PFR) plastics can be reapplied. On the other hand, the European legislation on Restriction of Hazardous Substances (RoHS) classifies the Bromine based FRs (BrFR) polybrominated biphenyl (PBB) and polybrominated diphenyl ethers (PBDEs) as hazardous. However, PBB and PBDEs were only produced until 2002, while LCD TVs were only produced after this date. Accordingly, the by RoHS legislation restricted BrFRs are not found in LCD TVs. Nonetheless, since the European Waste Electrical and Electronic Equipment (WEEE) Directive states that a separate treatment of bromine containing plastics is compulsory [5], the separation of housing plastics based on FR is required prior to recycling. However, commonly used separation techniques cannot differentiate between plastics with PFRs and BrFRs. As a result, in Europe incineration with energy recovery is currently the most adopted EoL treatment for plastics containing FRs [5].

Nevertheless, from an economic perspective closed loop recycling of plastics with PFR is an opportunity, since this allows selling these plastics at a higher value. The EoL treatment of FR plastics could possibly shift from incineration with energy recovery, with a cost of 160 €/tonne, to a profit generating activity [6]. Moreover, from an environmental perspective, closed loop recycling is the preferred EoL option for plastics [7]. Compared to incineration with energy recovery, up to 40% of the environmental impact can be reduced by recycling plastics [8].

In consequence, the question to be addressed is whether closed loop recycling of plastic housings containing PFRs is technically and economically feasible. Prior laboratory research has demonstrated that most FR plastics maintain their properties after multiple-pass recycling [9, 10]. However, little is known about the feasibility of separating PFR plastics from WEEE on an industrial scale for the purpose of closed loop recycling. Therefore, within the framework of the collaborative project PRIME [11] with TP Vision, the TV development site for Philips, and a Van Gansewinkel pre-processing plant [11], series of experiments were set up to verify the recyclability of PFR plastic housings. Since back covers can be disassembled with limited effort and contain 75% of the housing plastics present in FTVs, this research focuses on closed loop recycling of back covers of EoL LCD FTVs with PFR. The results of these experiments demonstrate that clustering FTVs based on product brand can facilitate closed loop recycling of Polycarbonate-Acrylonitrile Butadiene Styrene (PC-ABS) and High Impact Polysterene–Polyphenylene (HIPS-PPE) with PFR.

2 CURRENT PLASTIC RECYCLING PROCESSES

In Europe, direct cooperation between manufacturers or retailers and recyclers is a rare phenomenon. As a result, recyclers seldom have access to information about material content and product architecture of the products they process. This implies that the information associated with the product is gradually lost after the point-of-sale, which is one of the major obstacles for efficient value recovery from EoL products [12]. Consequently, in Europe FTVs are in most cases treated in a size reduction based process, as shown in Figure 1.

In this treatment, after the mercury extraction and magnetic and eddy current separation, a plastic dominated mix remains. From this plastic mix, low density plastics, such as High Impact Polystyrene

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(HIPS) or Acrylonitrile Butadiene Styrene (ABS), can be extracted for reapplication by means of sink-floatation techniques. The remaining plastic mix contains many different types of heavy plastics with FRs or Glass Fibers (GF) and plastics used in the LCD module for diffusing and polarizing the light, such as Polyethylene Terephtalate (PET), Polymethyl Methacrylate (PMMA) and Polycarbonate (PC). However, because of various density overlaps between these higher density plastics, they cannot be separated based on density [13]. As a result, in Europe these plastics are commonly incinerated with energy recovery.

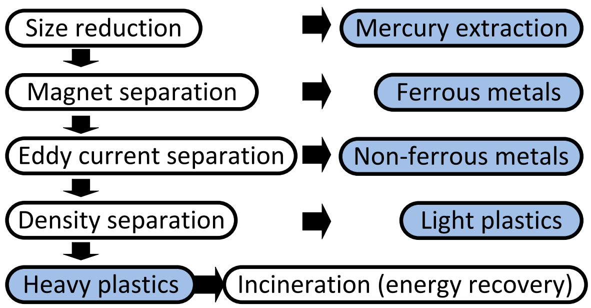

Figure 1: Recycling processes applied in a conventional EoL treatment procedure for LCD FTVs.

The analysis of 111 LCD TVs of the current waste stream in Belgium indicates that the concentration of HIPS and ABS without FRs in LCD TVs represents only 21%, as shown in Figure 2. Due to this low presence of HIPS and ABS, density based separation of these plastics is currently barely economically viable. As a result the plastic mix derived from processing FTVs is in some cases incinerated with energy recovery without further processing, or exported outside Europe for the purpose of recycling. For example, China imported 8,36 million tonnes of scrap plastics in 2011 for reapplication in the domestic market, of which about one third was imported from Europe [14].

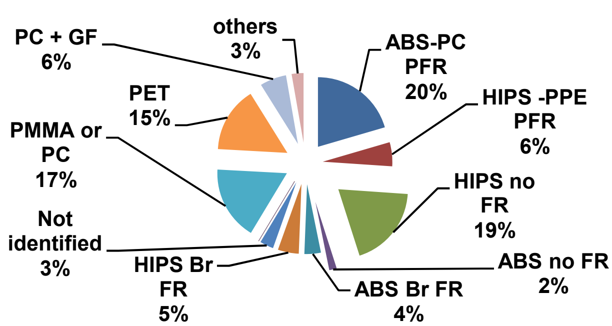

Figure 2: Commonly used plastics and FR types in LCD FTVs.

Besides density based sorting techniques, advanced post-shredder separation processes, which can separate shredder residue based on optical material properties, have recently been developed. Currently, most of these processes still have difficulties with separating black plastics based on plastic type, whereas 93% of the current FTV housings are black [13]. Also, the separation based on type of FR by these optical sorting techniques is currently not possible for shredder residue. However, all housing plastics of FTVs put on the European market from 2010 onwards can be expected to contain FRs. Also, the analysis of the current FTV waste stream indicated that already 15% of the analyzed FTVs contain plastics with BrFR and 45% with PFR, as shown in Figure 3. Therefore, these separation techniques are rarely applied for the separation of FR plastics.

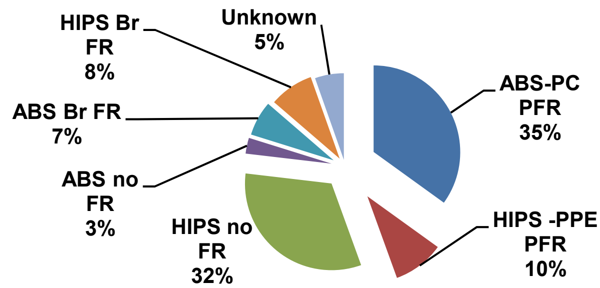

Figure 3: Commonly used plastics and FRs in LCD FTV back covers.

Furthermore, for the reapplication of recycled plastics, a purity of about 98% is generally required to prevent degradation of the physical properties of plastics [13]. In addition, the European RoHS legislation requires high separation efficiencies in order to limit the concentration of hazardous elements, such as Bromine for which the maximum concentration in plastics put on the European market is 1000ppm. Due to these high separation requirements and low efficiency of advanced separation techniques, these techniques are rarely applied for the separation of PFR plastics.

3 FR PLASTIC IDENTIFICATION AND PRODUCT CLUSTERING

In an industrial setting one of the main challenges for recycling plastics from WEEE is to identify the applied type of plastic and FR with a high reliability. Once the applied FR and plastic type is identified, products can be clustered based on their material content to facilitate a dedicated treatment for the product cluster. In general, the main advantage of clustering products based on material properties is that the entropy of the material mix can be reduced, which can facilitate the separation of materials. In addition, by clustering products the separation efficiencies can improve due to a higher presence of the target material. Since FR plastics cannot be recycled post-shredder with the current technologies, the goal in this case is to cluster FTVs based on FR type used in the product housing to enable to only disassemble plastic back covers of FTVs with PFRs.

Products containing plastic components can be clustered based on the in-mold indicated FR and plastic type. However, prior studies have indicated that a significant number of plastic components are mismarked [15]. Another drawback of clustering based on in-mold indication is that all products need to be disassembled to enable to identify them, since most components are marked on the inside.

Another possibility is to identify every product and to cluster products based on manufacturers' information. However, prior experiments performed in collaboration with TP Vision, the FTV development site of Philips, have indicated that over time different variants of a specific FTV product model have often been produced, using different types of plastics. The problem with these product variants is that they cannot be differentiated based on serial number, since this information is not tracked by the manufacturer. In addition, 6 % of the analyzed EoL Philips FTVs could not be identified because of missing or damaged label, which corresponds with the results of prior research [16]. Accordingly, a separation based on manufacturers' information cannot be applied for clustering EoL FTVs.

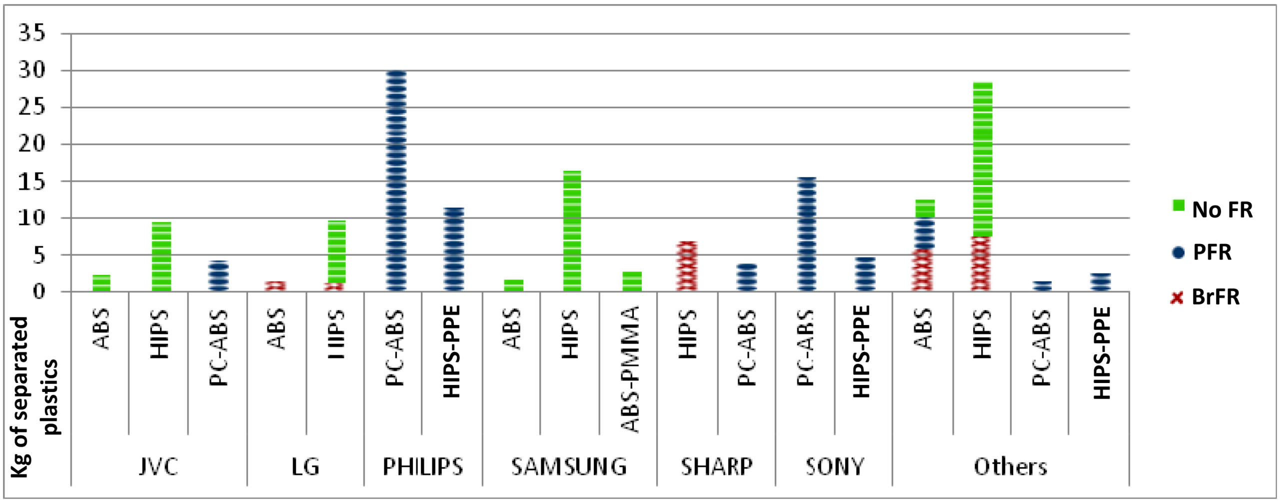

Figure 4: Plastic types and FRs used by different brands in the back covers of EoL FTVs collected in 2011.

Products can also be clustered based on material analysis. Therefore, experiments with two analyzing techniques for large black FR plastic components were conducted. The evaluated techniques are the so-called Sliding-Spark SPectroscopy (SSSP) and the Fourier Transform InfraRed analysis (FTIR) [17, 18]. The SSSP is an analysis method which thermally vaporizes a small amount of the plastic surface by using high-voltage sparks, which also activates the different elements present in the plastic to emit a specific and measurable radiation. FTIR is an analysis method which can identify chemical bonds in a molecule by producing an infrared absorption spectrum. For both methods all dust and coatings should be removed from the sample surface, for example by scratching with a knife. Also direct contact with the plastic for a time span between 1 and 30 seconds is required [18]. In this experiment the analysis results of 111 plastic back covers of different brands of EoL LCD FTVs from the Belgian collection system were compared with the results of an X-Ray Fluorescence analysis (XRF), which was only able to detect BrFRs and uses electromagnetic radiation to activate the bromine in the plastic to emit a measurable radiation. In addition, the FTIR and SSSP analysis were compared with the plastic type indicated in the mold and the available manufacturers' information. The results of this experiment indicate that 95% of all plastics can be identified with a high certainty. However, a combination of both the SSSP and the FTIR is required, since the SSSP only has a high reliability for identifying FRs. Hence, the FTIR analysis is still needed to separate the different types of FR plastics.

The results of this analysis also indicate that both Philips and Sony have only been using PC-ABS and HIPS-PPE with PFR for the housings of FTVs, and that in the analyzed waste stream about 85% of PFR plastics is used in products of these brands, as shown in Figure 4. Accordingly, when treating Philips and Sony FTVs separately, the housing plastics of these products only need to be separated based on plastic type. To facilitate the separation of PC-ABS and HIPS-PPE with PFR, this paper proposes to disassemble the back covers and to separate these components based on FTIR analysis. Another possibility is to use density separation for these plastics. In this case, disassembly of the back covers is also required, since there is an overlap in density between these housing plastics and other plastics used in the LCD module. A small scale experiment with about 40 samples demonstrated the feasibility of separating HIPS-PPE and PC-ABS by means of a sink-float process. However, the efficiency of this separation process and the required purity of both plastics for closed loop recycling still need to be evaluated.

The main advantage of a brand based clustering strategy is that EoL products can be sorted at high speed based on limited visual inspection with only a limited need of advanced plastic identification techniques. Moreover, when other manufacturers also start to systematically use only plastics with PFR, their products could be treated in a similar way when clustered based on other product properties, such as production date. Another advantage is that this clustering strategy enables to separate and recycle only plastics of known origin, which can help to convince producers to apply recycled plastics when they are reluctant to use recyclates from bulk mixed waste [18].

4 TECHNICAL FEASIBILITY OF CLOSED LOOP PFR PLASTIC RECYCLING

To demonstrate the technical feasibility of recycling PC-ABS and HIPS-PPE with PFR on an industrial scale, different experiments were setup. In addition, it was attempted to further improve the properties of recycled PC-ABS and HIPS-PPE with PFR by removing impurities, originating from labels or tapes, by means of a micro sieving process prior to regranulating the plastics.

In the performed series of experiments 111 plastic back covers were manually disassembled from the Belgian FTV waste stream. From these plastic back covers, 30 were identified as PC-ABS and 8 as HIPS-PPE by means of the analysis described in the prior section. In total, about 50 kg PC-ABS and 15 kg HIPS-PPE of back covers were disassembled. From these back covers all screws and attached components, except the product labels or tapes, were removed. Thereafter, the back covers were ground into particles smaller than 5mm and all remaining ferrous components were removed by means of a magnetic separation process. Surprisingly, still a substantial amount of ferrous material was separated within this process. Furthermore, no other pre-cleaning activities were performed, despite the high amount of dust which was present on the back covers.

	Recycled PC-ABS with PFR						Recycled HIPS-PPE with PFR		
		100% Recycled				15% recycled		100% Recycled	
	Virgin	No sieve	0,5 mm	0,25 mm	0,16 mm	0,25mm	Virgin	No sieve	0,25 mm
Pb (ppm)	< 1000	7,6	/	/	/	/	< 1000	/	/
Br (ppm)	< 1000	118	/	/	/	/	< 1000	/	/
Vertical burn test	V0	V1	/	/	/	/	V0	/	/
Candle flame test	Pass	Pass	/	/	/	/	Pass	/	/
Impact test (with ball)	Pass	Pass	/	/	/	Pass	Pass	/	/
Aesthetic properties	Pass	Fail	/	/	/	Pass	Pass	Fail	Pass
Charpy Impact test (J)	> 5	3,8	3,8	5,7	6,1	/	6,0	2,3	2,4
Tensile test (Mpa)	61,5	55,3	56,1	56,7	56,8	/	61,0	38,1	42,5
Strain at break (%)	12,17	6,77	7,72	9,05	7,98	/	8,00	16,96	18,80

Table 1: Mechanical and chemical properties of virgin and recycled PC-ABS and HIPS PPE with PFR (/ = not tested).

From these three batches and from the residual plastics fraction, test bars were injection molded and assessed by means of tensile and Charpy impact tests. As shown in Figure 5, the sieving of the recycled plastics reduces the amount of impurities in the fraction area. As indicated in Table 1, the plastics sieved with a 0,25 and a 0,16 mm sieve provided the best results for the tensile and impact tests. However, the shorter strain at break of the batch obtained with the 0,16 mm sieve indicates a possible degradation of the plastic. In addition, the strands of the 0,16 mm sieve broke several times during processing, which will lead to problems in an industrial setting. Therefore, the 0,25 mm sieve was used to obtain a batch of PC-ABS and HIPS-PPE with PFR for further experiments.

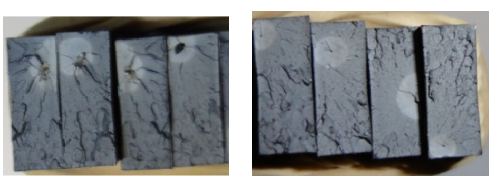

Figure 5: Contaminations in the fracture area of non-sieved (left) and 0,25mm sieved (right) recycled HIPS-PPE with PFR.

Both from the sieved and non-sieved recycled PC-ABS, new back covers were produced. First, a back cover was made from non-sieved 100% recycled PC-ABS, which contained Figure 6silver lines and polluted spots. These defects were probably caused by insufficient drying of the plastics prior to remolding and the presence of impurities in the recycled materials. Thereafter, a back cover was injection molded utilizing 15% recycled and sieved PC-ABS and 85% virgin material, since this blend is assumed to be the most likely industrial application of recycled PC-ABS with PFR. As shown in Figure 6 this back cover has good aesthetic properties. From the sieved and non-sieved recycled HIPS-PPE small test plates were injection molded, as shown in Figure 7. This figure shows that similar aesthetic improvements for HIPS-PPE are achieved by sieving the plastics.

In addition, the 100% recycled non-sieved PC-ABS with PFR was chemically analyzed to check whether the presence of hazardous substances is in line with the RoHS directive. Also, by means of vertical burn and candle flame tests, the flammability of the recycled plastic was evaluated. Furthermore, mechanical material properties were evaluated of the 100% recycled PC-ABS and HIPS-PPE with PFR by means of tensile and Charpy tests [19]. The results of these tests, shown in Table 1, indicate that the flammability levels dropped from V0 to V1 for PC-ABS with PFR. However, with the V1 flammability level the legal requirements for FTV back covers are still met. Also, the impact resistance and tensile strength of the recycled and sieved PC-ABS with PFR are about 25% and 10% lower than the virgin material. For the HIPS-PPE with PFR a stronger degradation of about 30% in tensile strength and 50% in impact resistance is demonstrated. This could be due to material degradation during both the product use phase and the recycling process or due to the residual presence of small material impurities.

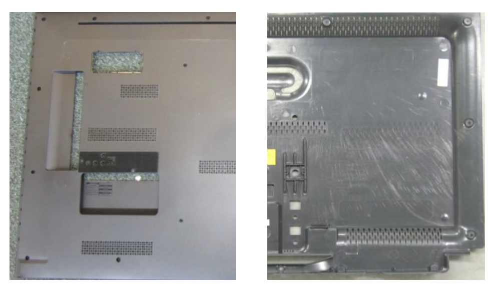

Figure 6: Back cover of 15% recycled 0,25mm sieved and 85% virgin PC-ABS with PFR (left) and back covers of 100% recycled non-sieved PC-ABS with PFR (right).

Figure 7: 100% recycled 0,25mm sieved (left) and non sieved (right) HIPS-PPE with PFR.

Brand sorting	10	s / 2,18 kg back cover * 35% Philips or Sony * 25 €/h	91	€ / tonne	7%
Plastic identification	60	s / 2,18 kg back cover * 25 €/h	191	€ / tonne	14%
Manual disassembly	120	s / 2,18 kg back cover * 80% efficiency * 25 €/h	478	€ / tonne	36%
Regranulating			350	€ / tonne	26%
Plastic cleaning			150	€ / tonne	11%
RoHS compliance testing			50	€ / tonne	4%
Transport to moulder			14	€ / tonne	1%
Total operating cost for joint recycling of PC-ABS (74%) and HIPS-PPE (26%) with PFR.			1.324	€ / tonne	100%

Table 2: Cost break down for recycling PC-ABS and HIPS-PPE with PFR from FTVs.

Based on these test results, the TP Vision engineers consider producing FTV housings from 100% recycled PC-ABS with PFR feasible. On the other hand, a mix of 15% recycled with 85% virgin HIPS-PPE with PFR is assumed required for reapplying this material in FTVs, due to the higher material degradation of HIPS-PPE compared to PC-ABS with PFR. Further analysis will be required to determine the cause of this material degradation. Nonetheless, it can be concluded that closed loop recycling of PC-ABS and HIPS-PPE with PFR is technically feasible and that when these plastics are sieved with a 0.25 mm sieve they can be reapplied with good aesthetic properties.

5 ECONOMIC FEASIBILITY OF CLOSED LOOP PFR PLASTIC RECYCLING

For the economic analysis reported in this paper only the additional processes to a size reduction based scenario are considered, as shown in Figure 8. Accordingly, all the process costs required for separating and recycling PC-ABS and HIPS-PPE with PFR of back covers of Philips and Sony FTVs are taken into account and only allocated to these fractions. It should be noted that by manually disassembling the back cover, access is facilitated to other components, such as PCBs, which can be recycled with higher efficiencies after manual disassembly [20]. However, to evaluate the economic feasibility of disassembling internal components, the optimal depth of disassembly should be determined. In this analysis, abstraction is made from such an optimized scenario and a direct cost analysis limited to closed loop recycling of PC-ABS and HIPS-PPE with PFR is presented.

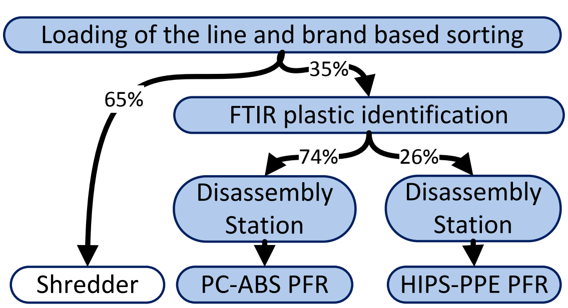

Figure 8: Proposed clustering strategy based on FTV brand for PC-ABS and HIPS-PPE with PFR.

In Figure 8, the cost per tonne for closed loop recycling PC-ABS and HIPS-PPE with PFR coming from Philips and Sony LCD FTV back covers of the Belgian waste stream is calculated. Both the presented disassembly and identification times are based on time studies. For clustering the FTVs based on product brand, a required time of 10 seconds per FTV is assumed and the percentage of Philips and Sony FTVs is based on the analysis of 111 FTVs. For the cost of manual disassembly a labour cost of 25 €/hour, a productivity of 80 % and a disassembly time of 2 min to remove the back cover and the hereon attached components is used. Furthermore, the plastic identification cost is calculated considering a total sample preparation and analysis time of 1 min. The percentage of PC-ABS and HIPS-PPE present in Philips and Sony FTVs is based on the results of performed experiments. The other costs of cleaning, regranulating, ROHS compliance testing and the possible additional transporting costs are estimated based on discussion with different industrial partners.

The calculations indicate that closed loop recycling is economically feasible for both plastics, since the total processing cost of 1324 euro per tonne for recycling PFR plastics is only about 50% of the price of virgin plastics. The price of virgin PC-ABS varies between 2930 and 3010 €/tonne and of HIPS-PPE between 2130 and 2148 €/tonne [14, 21]. However, these plastic prices depend, to some extent, on the sold volume and the required additives, such as FR. In addition, the cost of 160 €/tonne for incinerating plastics with energy recovery can be avoided by recycling the PFR plastics [6]. Also, the initial removal of the back covers decreases the amount to be treated in a size reduction based process.

To determine the rate of return on investment for the required plastic analysis equipment and disassembly stations, data about the volume of arising EoL FTVs are lacking. Furthermore, producers and recyclers face a "chicken and egg" dilemma, since producers will not use recycled materials when they are uncertain about a steady supply of high quality plastics. On the other hand, recyclers will not invest in recycling processes for FR plastics unless they are certain that a market for these plastics exists. To overcome this dilemma and to lower the initial risk of investment for recyclers, cooperation between producers and recyclers is required, as is created within the PRIME project [11]. Such collaboration also generates opportunities for improving the product design in order to facilitate product identification and disassembly, thus enabling to drastically lower the main costs of plastic recycling. For example, the application of identification techniques, such as RFID, QR-codes or bar-codes, can facilitate product sorting and disassembly embedded design and active disassembly can significantly reduce the required disassembly time, as proposed in prior research [12, 16, 22, 23].

6 SUMMARY

The results of the presented plastic analysis indicate that the type of applied plastic and FR is strongly producer dependent. Therefore, experiments were performed in which products were clustered based on brand name to facilitate recycling of PFR plastics. The results of these experiments demonstrate that closed loop recycling of PC-ABS and HIPS-PPE with PFR is technically feasible when applying the proposed clustering strategy. Moreover, these experiments show that sieving the plastics at 0,25mm prior to the regrinding process significantly improves the physical and aesthetic properties.

Furthermore, the performed cost analysis demonstrates that recycling PC-ABS and HIPS-PPE with PFR is economically feasible, since the total recycling operation cost per tonne is approximately 50% of the virgin price of these plastics. The main cost in the proposed recycling process is the disassembly cost, which can be reduced by improving product design. This cost can also be allocated differently, since removing the back cover increases the economic feasibility of manually disassembling PCBs. Accordingly, future work will focus on improving the product design and on determining the optimal depth of disassembly considering product characteristics.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] DisplaySearch. (2012). Available: http://www.displaysearch.com

[2] "Directive 2012/19/EU.". Available: http://ec.europa.eu/

[3] J. Huisman, F. Magalini, R. Kuehr, C. Maurer, E. Delgado, E. Artim, J. Szlezak, and A. Stevels, "2008 Review of Directive 2002/96 on Waste Electrical and Electronic Equipment (WEEE)," United Nations University2008.

[4] J. Cryan, K. Freegard, L. Morrish, and N. Myles, "Demonstration of Flat Panel Display recycling technologies," WRAP Project, 2010.

[5] F. Vilaplana and S. Karlsson, "Quality Concepts for the Improved Use of Recycled Polymeric Materials: A Review," Macromolecular Materials and Engineering, vol. 293, pp. 274-297, 2008.

[6] S. Salhofer, M. Spitzbart, and K. Maurer, "Recycling of LCD Screens in Europe - State of the Art and Challenges," in Glocalized Solutions for Sustainability in Manufacturing, ed: Springer Berlin Heidelberg, 2011, pp. 454-458.

[7] M. Patel, N. v. Thienen, E. Jochem, and E. Worrell, "Recycling of plastics in Germany," Journal of Resources Conservation & Recycling, pp. 65 - 90, 2000.

[8] G. Dodbiba, K. Takahashi, J. Sadaki, and T. Fujita, "The recycling of plastic wastes from discarded TV sets: comparing energy recovery with mechanical recycling in the context of life cycle assessment," Journal of Cleaner Production, vol. 16, pp. 458-470, 2008.

[9] R. B. Dawson and S. D. Landry, "Recyclability of flame retardant HIPS, PC/ABS, and PPO/HIPS used in electrical and electronic equipment," in Proceedings of the IEEE International Symposium on Electronics and the Environment, 2005, pp. 77-82.

[10] Cefic and EFRA, "Recycling and disposal End of life of products containing flame retardants," ed: European Chemical Industry Council, 2006.

[11] PRIME. Available: http://www.mipvlaanderen.be/en/webpage/134/prime-eng.aspx

[12] A. K. Parlikad and D. Mc Farlane, "RFID-based product information in end-of-life decision making," Control engineering practice, vol. 15, p. 1348, 2007.

[13] L. Tange, J. Van Houwelingen, W. Hofland, F. Kohl, M. Kearns, P. Salemis, and N. Mendad, "Recycling of plastics containing flame retardants in electronic waste, a technical and environmental challenge for a sustainable solution," in PMI Conference, Ghent, Belgium, 2012.

[14] PIE. (2012). Plastic Information Europe. Available: http://pieweb.plasteurope.com/

[15] Q. Xiuli, J. A. S. Williams, and E. R. Grant, "Viable plastics recycling from end-of-life electronics," IEEE Transactions on Electronics Packaging Manufacturing, vol. 29, pp. 25-31, 2006.

[16] K. A. Hribernik, M. Stetencron, and C. Hans, "Intelligent Products to Support Closed-Loop Reverse Logistics, Glocalized Solutions for Sustainability in Manufacturing," in 18th CIRP International Conference on Life Cycle Engineering, 2011, p. 486.

[17] M. Bennett, L. Edwards, L. Goyos-Ball, R. Hilder, P. Hall, L. Morrish, R. Morton, and N. Myles, "Separation of mixed WEEE plastics," WRAP Project, 2009.

[18] K. Freegard, G. Tan, and R. Morton, "Final project report: Develop a process to separate brominated flame retardants from WEEE polymers," 2006.

[19] P. Vanegas, J. R. Peeters, T. Devoldere, D. Cattrysse, and J. R. Duflou, "Closed loop recycling of Philips TV housing plastics," presented at the I-SUP 2012 Conference, Brugge, Belgium, 2012.

[20] P. Chancerel, C. E. M. Meskers, C. Hageluken, and V. S. Rotter, "Assessment of Precious Metal Flows During Preprocessing of Waste Electrical and Electronic Equipment," Journal of Industrial Ecology, vol. 13, pp. 791-810, 2009.

[21] Resin pricing - Commodity Thermoplastics. Available: http://plasticsnews.com

[22] J. R. Duflou, G. Seliger, S. Kara, Y. Umeda, A. Ometto, and B. Willems, "Efficiency and feasibility of product disassembly: A case-based study," CIRP Annals - Manufacturing Technology, vol. 57, pp. 583-600, 2008.

[23] J. R. Peeters, P. Vanegas, W. Dewulf, and J. R. Duflou, "Active Disassembly for the End-of-Life Treatment of Flat Screen Televisions: Challenges and Opportunities," in EcoDesign, Kyoto, Japan, 2012, pp. 535-540.

E-waste Assessment in Malaysia

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Abstract

The exponential growth of e-waste contributes to a rapid increase in the amount of e-waste contaminants in landfills. In this study, the waste produced from the recycling of mobile phones will be quantified, highlighting the driving factors that affect the amount of waste reaching landfills. A system dynamics approach was adopted to understand the flow of mobile phone e-waste in an e-waste recycling facility in Malaysia. The analysis found that the efficiency of mobile phone PCBs' precious metals recovery is 13.62%. The analysis also demonstrated that public awareness has the greatest impact in reducing contaminants.

Keywords:

E-waste recycling; end-of-life mobile phones; landfill; system dynamics

1 INTRODUCTION

Waste is a growing problem in many countries [1]. One of the contributors of increasing waste generation is the fast-growing electrical and electronic waste [2]. Global technology enhancement has led to the rapid growth of electronic and electrical equipment (EEE). This is demonstrated by the rapid rate of technological development in electronic devices, especially mobile devices, personal computers and laptops. There is a high market demand driving the economic growth and sales of EEE due to the world's rapid population expansion [3]. Furthermore, the increasing demand of electronic equipment is directly related to the rising importance of technology to the global economy [4].

A study by the Economics Intelligence Unit (EIU) on the manufacturing of electronics in Asia [3], found that developed nations have gradually shifted the manufacturing of electronic technology to East and Southeast Asia due to the lower cost of labour in those countries, thus greatly transforming Asia into an important electronic manufacturing location. Currently, Asia is the largest supplier of the world's electronic products providing 67% of total global production. In the year 2000, the market demand for domestic electrical appliances in Asia was US $18.6bn, or nearly 10% of the world's demand, as shown in Figure 1. The exponential growth of market demand has led to a forecast by the EIU that the demand in Asia for electronic products will be US $159bn, or 22% of world demand, by the year 2014.

The increasing demand of EEE will result in the escalating amount of electronic devices or waste of electronic and electrical equipment (WEEE). E-waste is defined here as electronic and electrical equipment which is no longer useful to the holder or reaches its end-of-life and is disposed of [5]. Nevertheless, there is no standard definition for e-waste. EEE can be both a good business prospect and also an emerging global crisis to the environment if not disposed of properly. Monitors, televisions and mobile phones are some of the common electronic devices that contribute to e-waste generation.

The amount of e-waste generated in Malaysia in 2008 was around 688,000 metric tonnes, which was forecasted to be 1.11 million metric tonnes in 2020 [6]. These figures do not include the hidden trade of e-waste such as illegal imports from developed countries. The exponential growth of e-waste has led to increasing concern about its environmental impacts. Inappropriate e-waste disposal is detrimental to the environment and the population's health. Furthermore, the low level of public awareness has contributed the overflow of e-waste produced in Malaysia. Hence, studies on e-waste system's behaviour in Malaysia are important to identify the driving factors of the e-waste issues, such as government legislation [7] and the efficiency of e-waste recycling processes [6].

This paper aimed to trace the materials flow in an e-waste recycling plant and to find the driving factors to minimise e-waste that ends up in landfill. A system dynamics approach will be used to explore the systemic structure of e-waste recycling in a firm in Malaysia. The modelling of mobile phone's path will be the focus in this paper. Based on those models, tracking of input and output materials flow, key variables, leverage points, and the limiting factors that influence waste flow will be proposed to provide possible solutions for the current e-waste problem in Malaysia.

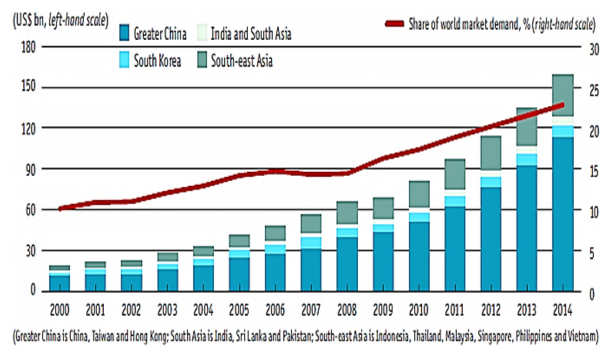

Figure 1: Market demand for domestic electrical appliances in Asia (exclude-Japan) [3].

2 E-WASTE IN MALAYSIA

Malaysia is one of the key countries that receives and dispatches e-waste [6]. According to the guidelines for classification of used EEE in Malaysia, e-waste is defined as waste from electrical or electronic appliances that consist of components such as: accumulators; mercury-switches; glass from cathode-ray tubes and other activated glass or polychlorinated biphenyl-capacitors; and components contaminated with cadmium, mercury, lead, nickel, chromium, copper, lithium, silver, manganese or polychlorinated biphenyl [8]. The quantity of e-waste generated each year is increasing exponentially as shown in Figure 2.

2.1 E-waste Management in Malaysia

E-waste recycling in Malaysia is managed by two divisions: the formal and informal sectors. The formal sector consists of licensed recycling firms, who either fully or partially recover e-waste. Firms in the formal sector appropriately manage e-waste according to the

Department of Environment (DOE) guidelines and regulations [15]. The informal e-waste recycling sector often uses lower efficiency techniques in processing and extracting valuable components [11]. Moreover, their main goal is to retrieve only valuable materials. Most of the informal recycling activities are carried out at “backyard” facilities who apply the most primitive processes [12].

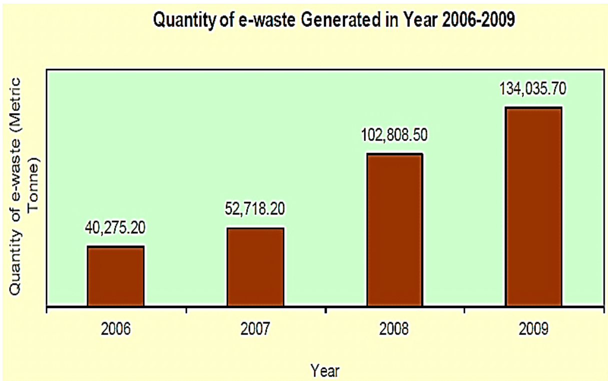

Figure 2: Quantity of E-waste Generated in Malaysia in Year 2006-2009 [10].

Most e-waste ends up in the informal sector because of its monetary incentives, regulation gaps, economic interdependence and their social reality [13]. It is a challenge for the government to control informal e-waste recycling activities, whose environmental impact is greater due to improper processing procedures [12]. Moreover, the downstream of e-waste recycling in the informal sector is difficult to be traced and involves transnational movements of illegal e-waste to and from other countries [14]. Another issue that arises from the flow of e-waste to the informal sector is the competition between the formal and informal recycling sectors for access to e-waste [12], which largely determines the final disposal of e-waste in the country.

Conversely, formal licensed e-waste recycling companies appropriately manage e-waste. Presently, there are 20 full recovery facilities and 132 partial recovery facilities in Malaysia [15]. All of the recovery facilities are owned by private companies. The main techniques or technologies used to recover precious metals from e-waste in Malaysia are wet chemical processes and electrolysis [16].

2.2 Obsolete Mobile Phones

Mobile phones are one of the fastest growing waste streams because of their short average life span, quick technology evolution, and affordability among consumers [17]. The mobile phone penetration rate in Malaysia is around 106% due to multiple subscriptions [18]. This indicates the ability to own more than one mobile phone per user and high demand in the mobile phone market. Furthermore, the mobile phone average life span is about three years [19]. The high demand among consumers and the short average life span imply that more obsolete mobile phones will be generated in future. However, initiatives to recycle part of the components of mobile phones such as mobile phone batteries have been carried out by the DOE and some manufacturers, including Nokia and Sony Ericsson, since 2002 [20]. The Penang E-waste Project studied mobile phone material flows. The results of the study are shown in Figure 3.

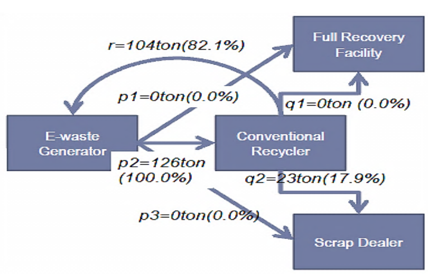

Figure 3: Simplified Mobile Phones Flow in Penang in 2011 [16].

3 METHOD

This study explored the e-waste recycling system through a case study on mobile phones at a formal recycling plant in Malaysia. Information was gathered through two phases: a survey questionnaire via email to understand the overall operation, and an on-site visit to gather information through tours of the facilities and interview sessions.

3.1 E-waste Modelling Process

A system dynamics approach was adopted to explore the systemic structure of the Malaysian firm’s e-waste processes. This technique was used because of the dynamic and transforming complexity of the e-waste system in Malaysia. System dynamics assists in developing conceptual and virtual models by identifying the variables in the system and their relationships. Initially, a more generic approach was taken, only modelling the general e-waste path to clearly understand the overall e-waste flow in Malaysia. The focus of the problem was the waste produced by the recycling process, which defined the boundary of the system being explored. The materials flow of mobile phone waste was identified and captured in stock and flow diagrams. An example of a stock and flow diagram can be seen in Figure 4.

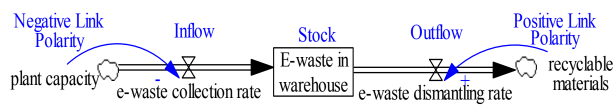

Figure 4: E-waste Stocks and Flows with Influence Diagram[1].

The initial diagram was expanded to further classify the specific processes that created the various stocks and flows of materials that undergo the different chemical processes. The detailed tracking of materials helped identify the data that was needed.

The next step was to formulate a dynamic hypothesis which was based on the behaviour of the documented e-waste system. Modelling tools were used to simulate the e-waste system according to the outlined problem and its boundary. A model boundary chart was developed to determine which factors were to be included and also helped to minimise the complexity of the model. Maps of the causal structure were then developed based on the preliminary hypotheses and key variables. A negative link polarity indicates that when the cause increases, the effect decreases whereas a positive link polarity shows that when the cause increases, the effect increases as shown in Figure 4. The generated influence diagrams were then reviewed by industry personnel and altered and changed where necessary.

The data obtained was used to evaluate the e-waste model and was used to assess how well the conceptual model reflected the virtual model. The conceptual and virtual model of mobile phones’ waste path was examined closely and the modelling process was revised

[1] When the plant achieved the maximum capacity, the e-waste collection rate will be reduced because the plant no longer able to receive more e-waste to be recycled (negative link polarity). When more recyclable materials are used to manufacture electronic products, more e-waste can be dismantled, thus increasing the dismantling rate (positive link polarity).

based on the feedback obtained. A positive loop identifier (the sign in the middle of a loop) indicates the reinforcing loop whereas a negative loop identifier indicates the balancing loop of the variables which circulate in the same direction of the loop. The key variables that drive the e-waste system and leverage points were identified using a feedback loop analysis on the stocks and flows of mobile phone.

4 E-WASTE FLOW ASSESSMENT IN A MODEL RECYCLING PLANT IN MALAYSIA

The following section uses data captured during 2011 from the Malaysian recycling firm. The generic e-waste stock and flow diagram is shown in Figure 5. E-waste is collected and sorted for further dismantling. After dismantling, the e-waste undergoes chemical processes to retrieve valuable materials. The waste is then sent to a different firm for treatment. The defined e-waste problem boundary is shown in Figure 5. This e-waste flow is generic for all types of e-waste in the formal recycling facility.

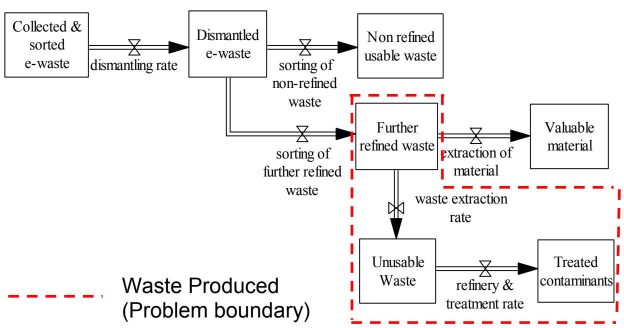

Figure 5: Generic e-waste flow with defined problem boundary.

The e-waste collected by the Malaysian firm passes through four main stations: the warehouse, mechanical plant, chemical plant, and waste treatment plant. Each respective station plays a specific role in the recovery of materials from e-waste. The warehouse stores, sorts, and dismantles the e-waste. A large space is needed to store the e-waste collected, especially WEEE that comes in large volume and a variety of sizes such as server base station (large size), printers and computers (medium size) or mobile phones and cables (small size). These components are disassembled and recyclable materials are collected. Next, the collected Printed Circuit Boards (PCBs) are categorised and transferred to the mechanical plant or chemical plant depending on the characteristics of the PCB: whether the recoverable materials are 'apparent' (easy to get to) or 'hidden' (not easy to get to). The PCBs then go through the precious metal processes in the chemical plant and the leftover waste from the chemical processes is treated at an external waste treatment plant. The high level e-waste process flow is shown in Figure 6. Because it has been sorted, the e-waste can be processed quickly and efficiently upon arrival. While this project focuses on mobile phones, and in particular their PCBs, a similar flow applies to other e-waste products.

4.1 Mobile Phone Flow Analysis and Overall Recovery

The stocks and flows of mobile phone materials generated reference the amount of mobile phone obtained in the year of 2011, which had a total of 12 collections. The general stock and flow diagram of mobile phones and their PCBs from collection is shown in Figure 7.

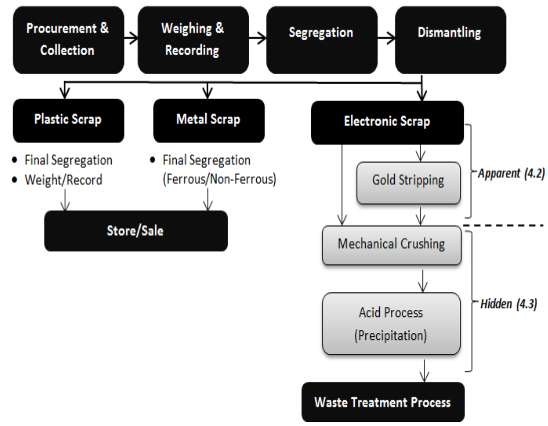

Figure 6: High Level E-waste Process Flow at the Malaysian Firm.

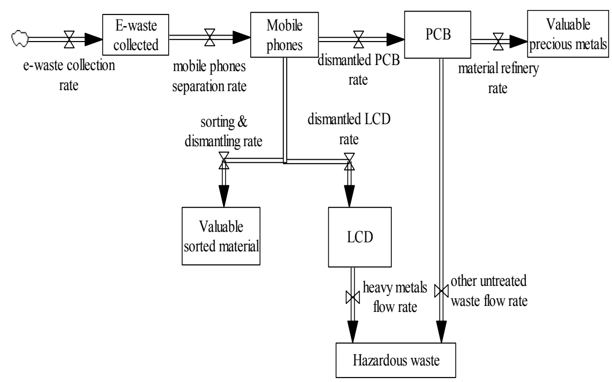

Figure 7: Stock and Flow Diagram of Mobile Phone Materials at the Malaysian Firm.

After the warehouse, the dismantled pile of PCBs goes through the apparent and hidden PCB processes to recover apparent and hidden valuable materials. The percentages of valuable precious metals and waste of mobile phone PCBs from both groups of processes are shown in Table 1: 54.5% of the outputs of the recovery process are valuable materials and 45.5% of outputs are waste.

Valuable Precious Metals		Waste	
Gold	0.022%	Fibre Waste	41.500%
Palladium	0.005%	Tin & trace metal	4.000%
Copper	52.500%	-	
Iron	2.000%	-	

Table 1: The overall mobile phone PCB material composition.

4.2 Stocks and Flows of Apparent PCB Process

The apparent PCB process is a chemical stripping process used to remove gold from the surface of PCBs. The dissolution, which includes the gold, is then purified. The stock and flow diagram of the apparent PCB process is shown in Figure 8.

There were 22.74 kg of dismantled PCBs that underwent the apparent process. The amount of alkaline (waste) solution produced from the stripping process was 3.452 kg. The purification process produced a further 3.448 kg of waste solution and 4.252 g of gold (99.9% purity).

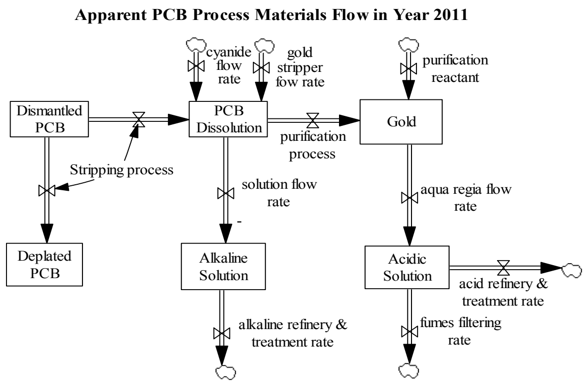

Figure 8: The Apparent PCB Process Materials Flow in the Malaysian Firm.

4.3 Stocks and Flows of Hidden PCB Process

The hidden PCB process is an acid chemical process used to recover precious metals contained in de-plated PCBs such as copper, palladium, and hidden gold. The stock and flow diagram of hidden PCB process is shown in Figure 9. 22.736 kg of de-plated PCBs were crushed and ground in the mechanical plant, before undergoing the two different types of dissolution in chemical processes shown. The estimated amount of powdered PCBs after the separation of ferrous metals using magnetic separator was 22.281 kg. The powdered PCBs are then mixed with nitric acid solution and copper/palladium precipitation agents who sum up to 62 kg to form powdered PCB Dissolution I. After the precipitation process, about 11.94 kg of precious metals retrieved, 50.06 kg of waste produced and 10.34 kg of solid filtered material proceeded to the next dissolution process, Dissolution II. In Dissolution II, 5.25 g of aqua regia solution and the gold precipitation agent are added according to the proportion of gold in the powdered PCBs. The total amount of Dissolution II which was about 10.35 kg produced two outflows: precipitated gold (0.75 g) and waste flow (10.35 kg).

4.4 Efficiency of Recycling Facility

The amount of dismantled mobile phone PCBs was 22.74 kg with an estimated 65.48 kg of processing chemicals added (such as precipitation agents for copper, palladium and gold; aqua regia solution; and alkaline cyanide solution) for the hidden and apparent process. After the mobile phone PCBs underwent the hidden and apparent processes for respective precious metals recovery, 11.95 kg of precious metals was retrieved (stripped gold, precipitated copper, palladium and gold) and 75.82 kg of waste was generated. The overall efficiency of precious metals recovery for mobile phone PCBs was 13.62%. The efficiency of apparent and hidden chemical processes was 0.74% and 16.15% respectively. From these figures, the efficiency of chemical processes for precious metal recovery from PCBs seems low and indicates a high waste being produced in the recovery processes. The total amount of mobile phone related materials was 857.68 kg. From this amount, 821.92 kg of usable materials are disassembled. The efficiency of disassembled valuable materials was 95.8%, which is relatively high. Based on the whole mobile phone recycling processes, the firm has a recycling plant efficiency of 97.2%

$$\eta_{\text{recycling efficiency}} = \frac{\text{precious materials (kg)}}{\text{total inputs (kg)}}$$

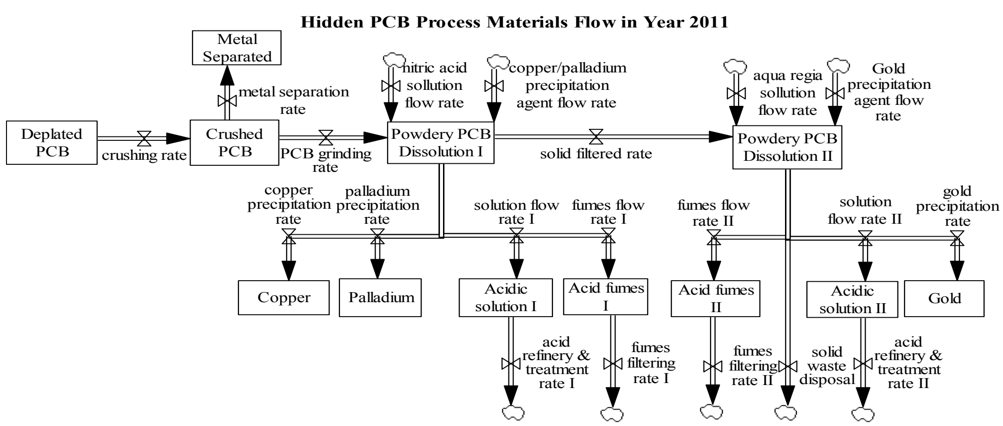

Figure 9: Hidden PCB Process Materials Flow in the Malaysian Firm.

Process	Useful Material Recovered (mass)	Efficiency
Precious metal recovery	11.95	13.62%
Hidden process recovery	25.51	0.74%
Hidden process recovery	11.94	16.15%
Disassembled materials	821.92	95.8%
Recycling plant efficiency	821.92 + 11.95	97.2%

Table 2: Plant Efficiencies.

4.5 Heavy Metals and Other Waste Products

The Malaysian waste treatment plant does not have the facilities to treat and refine hazardous waste such as solidified cyanide, heavy metal sludge, and fibre waste. Instead, the hazardous waste collected is sent to another waste management company for further treatment before disposal in landfill. In this paper, the material flows captured were based on the waste produced from the recycling processes in the Malaysian firm. The amount of produced waste flow after undergoing further waste treatment in another company is not traced. Among the items sent to the secondary facility are dismantled Liquid Crystal Displays, which contain toxic materials such as mercury in the liquid crystalline substances. The displays undergo a process called solidication or cementation. The waste is first mixed with solidified product at a bunker. It is then moved to a tipper lorry and mixed with additional solidified product. The mixture (cementation product) is then transported to a secure, authorised landfill where it is poured into the landfill and left to set as a solid concrete slab. The main objective of this cementation process is to fix the heavy metals into concrete to prevent them leaching into the ground water and the environment. Images of this process can be seen in Figure 10.

(a) Mixture of heavy metal materials and solidified products at tipper lorry. (b) Final disposal of cementation product at reserve area in secure landfill.

Figure 10: LCD Waste Treatment [21].

5 INFLUENCES OF MOBILE PHONE PCB RECYCLING

The recycling plant is effective in the recovery of usable materials; however, waste is still a problem. Therefore, the external system of mobile phone recycling is analysed to identify the driving factors of this problem. The recycling of mobile phones in the Malaysian firm comprises of two main inflows which are the PCBs that come from dismantling and the processing chemicals that are used during the apparent and hidden chemical processes. Conversely, precious metal recovery and waste products are the major outflows. The precious metals recovered are the firm's main source of revenue which offsets the high level of expenditure on chemical waste treatment. The simplified stock and flow diagram of mobile phone PCB recycling can be seen in Figure 11.

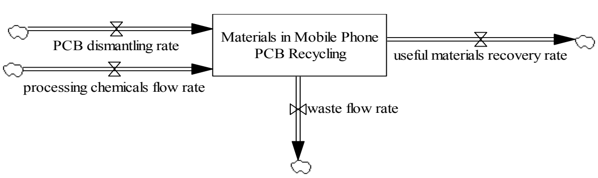

Figure 11: Useful Materials Recovery of Mobile Phone PCB in 2011.

5.1 Mobile Phone Collection

The mobile phones collected in the recycling plant have a tremendous impact on the PCB dismantling rate. The higher the number of mobile phones collected, the greater amount of PCB material can be recycled and the more efficient the plant will be (economies of scale).

The collection of mobile phones is influenced by four main variables: incentives, product turnover, manufacturer end-of-life (EOL) product take back, and public awareness. Incentives are always a driving factor to encourage more people to recycle their used mobile phones. These can be monetary incentives or as a trade-in during the purchase of a new mobile phone. Moreover, high product turnover increases mobile phone collection rates. The product turnover changes according to the average life usage of mobile phones, consumers' market demand and the second-hand market creating a material delay in mobile phone collection for recycling. Public awareness on e-waste collection among Malaysians is still low. Therefore, more mobile phones could be collected if public awareness on e-waste was increased through education, campaigns, or setting up more e-waste collection centres in convenient areas.

The two balancing loops of the recycling cost and incentives loops are shown in Figure 12. The cost variable indicates the upfront recycling cost that must be borne by the manufacturers. It will be used by the manufacturers for future take back schemes, such as the cost of mobile phone collection directly from consumers' home. The availability of such take back services will increase public awareness and encourage the return of used mobile phones to their manufacturers. Another alternative method to increase the mobile phone collection would be through monetary incentives. Nevertheless, the incentives offered will increase the upfront recycling cost. When the recycling cost increases, the manufacturers will decrease incentives offered to reduce future recycling costs.

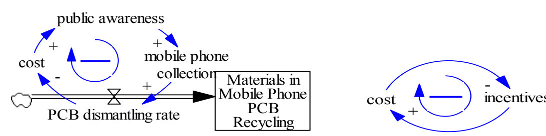

Figure 12: Balancing loops of mobile phone collection.

5.2 Waste Generated

There are a few variables influencing the waste flow rate as represented in Figure 13.

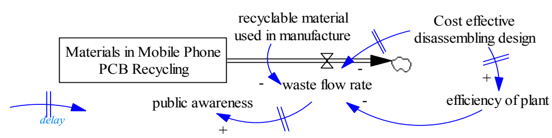

Figure 13: Influences on the waste generated from mobile phone recycling in Malaysia.

The influential factors of the waste flow rate are the recyclable materials used in manufacture, cost effective disassembly design, and the efficiency of the plant. When more recyclable materials are used in manufacture, the more usable materials can be retrieved during the recycling of mobile phones and thus less waste generated. A higher efficiency of recycling plant further reduces the waste flow stream by maximising the recovery of usable materials. Moreover, cost effective disassembly design will produce less waste flow since more materials are recycled with cost effective recycling processes, increasing the recycling plant efficiency. Nevertheless, its influence on the waste flow rate and efficiency of a facilty will take some time because of the inherent delay of mobile phones in the market. The increasing amount of waste ending up in landfill disposal will have an influence on the public awareness when it creates implications to public health. However, an information delay occurs as the waste flow rate has no direct impact on the public awareness unless it reaches a critical level.

5.3 Environmental Law Enforcement

The allowable chemical concentration variable is influenced or influencing other variables as described in Figure 14.

Environmental law enforcement can be measured through the concentration of chemical released to the environment. The allowable chemical concentration that can be released is greatly influenced by public awareness. As public awareness increases, the government will be pressured to take legal action to control the e-waste flow generated. Such action could include a reduction in the allowable chemical concentration that can be released to the environment.

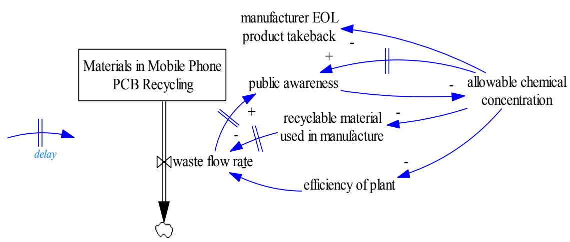

Figure 14: Influences of allowable chemical concentration that can be released in Malaysia.

Mandated Extended Producer Responsibility (EPR) can also help reduce chemicals that leech into the environment from landfill by ensuring more mobiles are collected. EPR among manufacturers, such as product take back schemes, increase EOL product take back, ensuring more mobiles are recycled and less potentially toxic material enters landfills. Nevertheless, the influence of EPR on the waste stream will take several years because of the inherent delay of mobile phones in the market. EPR is a voluntary initiative by manufacturers who are not mandated by current environmental policy in Malaysia [7]. Furthermore, law enforcement on e-waste legislation will increase the efficiency of a plant. Scrap dealers or informal recycling facilities which are commonly found in Malaysia [22] will be pressured to increase their plant efficiency to the same level as full recycling facilities in order to continue their business. The law enforcement balancing loops with public awareness act as pushing factors to further increase the efficiency of a plant and recyclable material used in manufacture (see Figure 14).

6 DRIVING FACTORS TO MINIMISE WASTE PRODUCTION

6.1 Phase 1: Incentive Reinforcing Loop

In the first phase, the key variables and leverage points to intervene in the e-waste system appear to be the incentives and manufacturer EOL product take back variables. These variables drive mobile phone collection rates while reinforcing the public awareness on e-waste. Nevertheless, the recycling plant capacity is the limiting factor because the plant could only handle a fixed amount of capacity despite more mobile phones being collected, as shown in Figure 15.

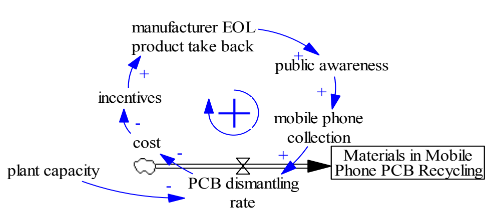

Figure 15: Incentive - Reinforcing Loop.

6.2 Phase 2: Law Enforcement and Public Awareness Loop

In the second phase, both the public awareness and environmental law enforcement have a significant impact in driving the system. Nevertheless, law enforcement, such as new policies and legislation, creates significant delays in reducing the waste in landfill as shown in Figure 16. Conversely, by increasing public awareness levels, the mobile phone collection increases through voluntary incentives or manufacturer take back which has an immediate sustainable impact and drives the environmental law enforcement as well as shown in Figure 17. Therefore, it appears that the central variable that will drive the whole system efficiently is public awareness.

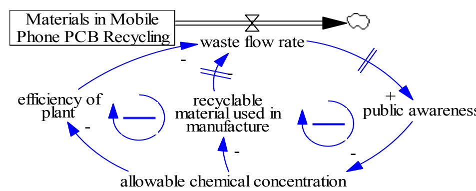

Figure 16: Law Enforcement - Reinforcing Loop.

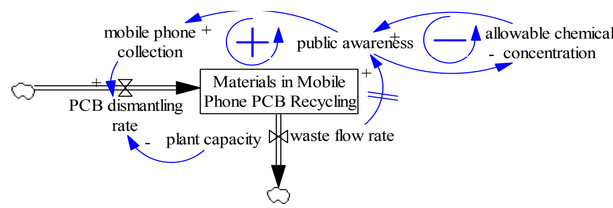

Figure 17: Public Awareness - Reinforcing and Balancing Loop.

7 CONCLUSION

The efficiency of mobile phone PCBs' precious metals recovery appears low, at only 13.62% from an environmental perspective. This is especially the case with the apparent chemical process since even more waste is produced. Nevertheless from an economic perspective, the firm is proficient in recovering precious metals with high purity from mobile phone PCBs, about 99.9% which generates profitable revenue and offset the cost of partial waste treatment.

The e-waste contaminant flows that end up in landfills are influenced by the amount of e-waste flow into the full recovery facilities, informal recyclers, public awareness, and government legislation related to e-waste. Therefore, the driving factors to minimise waste production are:

Incentives - The incentives given will increase the mobile phone collection into full recycling facilities in the initial phase.

Law Enforcement - Law enforcement related to e-waste reduces the toxic concentration that can be released to the environment.

Public Awareness - The public awareness will reduce the amount of e-waste ends up in landfills and reduce the toxicity of waste.

The variable that influences the system to reduce long term waste production in Malaysia is public awareness. Increased public awareness is a key variable for reducing environmental damage caused by chemicals from mobile phones and their recycling processes.

8 REFERENCES

[1] Heidi, O-K, Deepali, S-K, Max, S & Heinz, B 2005: Global Perspectives on E-waste, ScienceDirect, vol 25, no. 5, pp. 436-458.

[2] Pinto 2008: E-waste hazard: The impending challenge, Indian J Occup Environ Med., vol 12, no. 2, pp. 65-70.

[3] EIU 2011: 'Rising Consumption Rising Influence', The Economist.

[4] Macauley, M 2003: Dealing with electronic waste: modeling the costs and environmental benefits of computer monitor disposal.

[5] UNEP 2007: E-waste Volume 1, United Nations Environment Programme.

[6] Tengku-Hamzah, TAA 2011: Making Sense of Environmental Governance: A Study of E-waste in Malaysia, Doctoral Thesis, Durham University, Durham E-Theses, Durham.

[7] Agamuthu, P & Victor, D 2011: Policy Trends of Extended Producer Responsibility in Malaysia, Waste Management & Research, p. 9.

[8] DOE 2010: Guidelines for the Classification of used Electrical and Electronic Equipment in Malaysia.

[9] Fenny, WNY & Goh, SB 2012: E-Waste Management in Malaysia, Department of Environment Malaysia, Putrajaya.

[10] Ab. Halim, N 2011: Country Presentation-Malaysia: E-waste Management in Malaysia, Presentation, Department of Environment Malaysia, Putrajaya.

[11] Herat, S & Agamuthu, P 2012: E-waste: A Problem or An Opportunity? Review of Issues, Challenges and Solutions in Asian Countries.

[12] Williams, E 2005: International activities on E-waste and guidelines for future work, Appearing in Proceedings of the Third Workshop on Material Cycles and Waste Management in Asia, National Institute of Environmental Sciences, Tsukuba.

[13] Chi, X, Streicher-Porte, M, Wang, M & Reuter, M 2011: Informal Electronic Waste Recycling: A Sector Review with Special Focus on China, ScienceDirect, vol 31, no. Waste Management, pp. 731-742.

[14] Kojima, M 2005: Transboundary Movements of Recyclable Resources in Southeast Asia, pp. 85-94.

[15] DOE 2012: List of Contractor.

[16] Awang, AR 2012: E-Waste Management in Malaysia, Department of Environment Malaysia, DOE, Putrajaya.

[17] L.Funk, J 2004: The Product Life Cycle Theory an Product Line Management: The Case of Mobile Phones, IEEE Transactions on Engineering Management, vol 51, no. 2, pp. 142-152.

[18] Evans, P 2010: Malaysia: Telecoms, Mobile and Broadband, Publication, Malaysian Communications & Multimedia Commission.

[19] PGE 2008: The E-waste Inventory Project in Malaysia.

[20] DOWA 2007: The Report of Investigation on International Recycling Networks for Mobile Phones in Asian Region.

[21] Source 2012: Kualiti Alam Sdn. Bhd., Malaysia.

[22] Saeed, MO, Hassan, MN & Mujeebu, MA 2009: 'Assessment of municipal solid waste generation and recyclable materials potential in Kuala Lumpur, Malaysia', *ScienceDirect*, vol 29, no. 7, pp. 2209-2213.

Methodology for an Integrated Life Cycle Approach to Product End-of-Life Planning

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Abstract

The planning of cost-effective strategies to manage products at end-of-life (EoL) is still a major challenge for manufacturers. Different methods have been developed to tackle this challenge but they have mainly approached it from a third-party remanufacturer or recycler perspective. Our work instead focuses on closed-loop supply chains where an integrated lifecycle approach to EoL planning is necessary. By applying a product structure-based methodology, we demonstrate how interrelationships between the EoL and other life cycle stages in a closed-loop supply chain can be captured during the EoL planning process. Its application is demonstrated using a dive torchlight example.

Keywords:

EoL strategy; EoL management; closed-loop supply chain

1 INTRODUCTION

Extended producer responsibility (EPR) is an environmental policy in which the responsibility of managing a product's end-of-life (EoL) is placed on the manufacturer. Its main motivation is to help alleviate the burden of waste management on local governments; while encouraging manufacturers to take ownership of managing the entire life cycle of their products especially the EoL stage [1]. With increasing global adoption of EPR laws, the pressure is now on manufacturers to play a more active role in product EoL management. However, a more active role also brings more challenges.

One of the main challenges still faced by manufacturers is planning cost-effective strategies to manage their products at EoL. Existing methods to solve this EoL planning problem have applied mathematical optimisation techniques, such as dynamic programming [2,3], integer programming [4] and linear programming [5,6]. EoL modelling methods have also been developed to great extents to tackle this problem [7-10]. All these methods have proved to be effective tools for EoL planning, but their approach has been mainly isolated and disconnected from other life cycle stages.

For manufacturers, a total and integrated life cycle perspective must be applied to EoL planning. This is because interrelationships exist between EoL activities in the reverse supply chain and the mainstream production in the forward supply chain. For instance, an interrelationship between the EoL stage and mainstream production is created in a closed-loop supply chain when recovered resources from collected cores (used products) at EoL is channelled back into the mainstream production as forward material [11].

Figure 1 illustrates the interrelationships that can exist between product life cycle stages in a closed-loop supply chain scenario. In scenarios such as this, any EoL decisions made cannot be only focused on improving processes at the EoL stage while neglecting the impact of these decisions on processes upstream in the supply chain. Therefore, it is especially important for manufacturers in closed-loop supply chains to take an integrated life cycle approach to product EoL planning.

In this paper, we propose a product structure-based methodology and demonstrate how using this methodology, an integrated life cycle approach to EoL planning can be achieved. Our proposed methodology enables us to incorporate multiple life cycle considerations, which is a critical characteristic of closed-loop supply chains, in the EoL planning process. It also allows us to breakdown complex EoL planning problems into smaller and simpler sub-problems to be solved.

Using a dive torchlight example, we will demonstrate the procedures and application of the product structure-based methodology in the EoL planning domain. In this example, certain configurations of EoL options available to the components in the dive torchlight will result in a closed-loop supply chain scenario. This means that the impact of EoL planning decisions for the dive torchlight cannot be considered just for its EoL stage alone but also for all other stages of its life cycle. Although our methodology is not limited to just

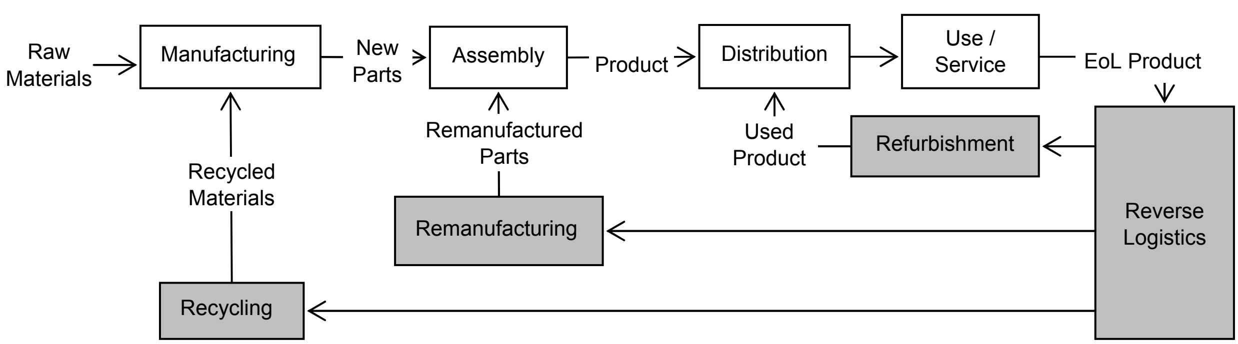


Figure 1: A closed-loop supply chain with refurbishment, remanufacturing and recycling operations.

economic cost aspects, the scope of this study is only focused on the minimisation of life cycle costs.

2 METHODOLOGY FOR PRODUCT END-OF-LIFE PLANNING

A critical characteristic of a closed-loop supply chain is the recovery of resources from collected used products at EoL to be put back into the mainstream production. Therefore, for an EoL plan to be relevant to closed-loop supply chain scenarios, it is imperative that this characteristic is included and reflected in the analysis during the EoL planning process. This can be done by applying the product structure-based methodology for EoL planning.

The product structure-based methodology enables a total and integrated life cycle analysis of a product by breaking down complex modelling problems into smaller sub-problems. It allows multiple life cycle attributes at every level of a product to be incorporated while still maintaining the integrity of the overall model [12]. The framework for EoL planning using the product structure-based methodology is shown in Figure 2. Based on this framework, the following sections describe how this methodology is applied for an integrated life cycle approach to EoL planning.

2.1 Mapping of Integrated Life Cycle Based on Product Structure

The first and most important step in our methodology is to representatively decompose the structure of a product into its modules and components. This can be done based on the product's bill of materials (BOM). With the decomposed product structure, every of its module and component are mapped to five main life cycle stages: production, distribution, use, EoL collection and EoL processing. Because EoL planning is the objective of our work here, it is also necessary for EoL options of every disassembly level (i.e. modules and components) to be identified in the process. Using a dive torchlight example, an integrated life cycle map (with identified EoL options) based on its product structure is illustrated in Figure 3.

In a decomposed product structure, the product is represented by a root node (i.e. the node without parents), its modules by intermediary nodes (i.e. nodes connected between root and leaf nodes), and its primary components by leaf nodes (i.e. nodes without children). Structural relationships between product, modules and components are represented by lines connected between nodes. EoL options identified for every disassembly level of the product are represented by circled alphabets under their respective nodes. They are mapped to the EoL collection and EoL processing stages.

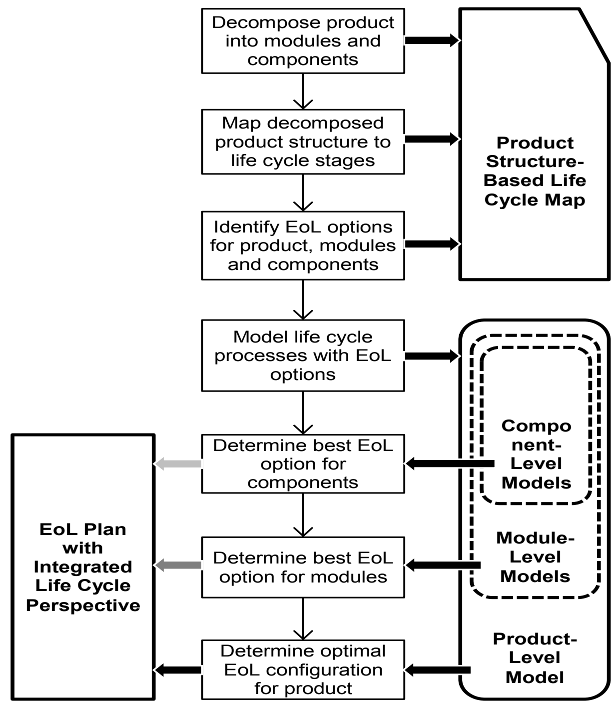
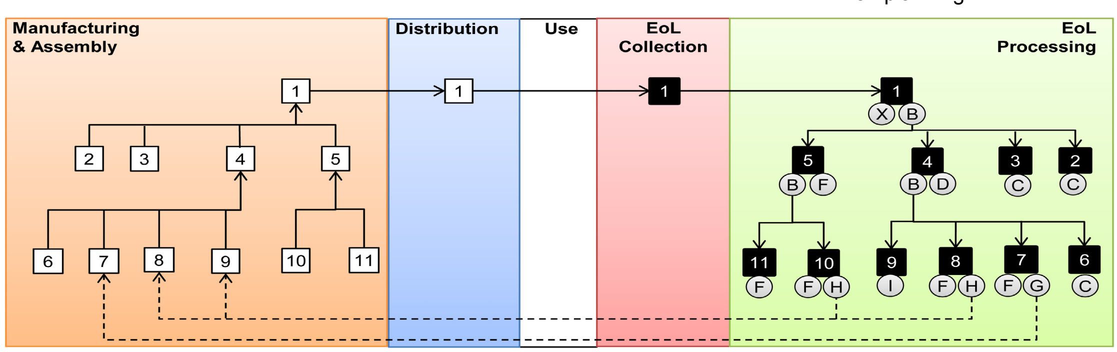


Figure 2: Framework for an integrated life cycle approach to product EoL planning.



Part	Name
1	Dive Torchlight
2	O-Rings
3	Batteries
4	Head Module
5	Body Module
6	Lens
7	Bulb Holder
8	Bulb Housing
9	LEDs
10	Batteries Housing
11	Copper Wires

EoL Option	Description
X	No Take-Back
B	Disassemble
C	Incineration (MSW)
D	Mechanical Treatment
E	Plastic Recycling (Open-Loop)
F	Scrap Metal Recycling (Open-Loop)
G	Steel Recycling (Closed-Loop)
H	Aluminium Recycling (Closed-Loop)
I	LED Reuse (Closed-Loop)

Figure 3: Integrated life cycle map of a dive torchlight with identified EoL options based on its product structure.

In the context of our work, the term EoL option is not confined to the general categories of reuse, remanufacture, recycle and disposal. An EoL option can also be distinguished based on the type of technology, facility location or even setup to meet a certain EoL requirement or objective. For instance: the EoL option of selling scrap aluminium to third-party recyclers versus the EoL option of smelting scrap aluminium to be reused in the mainstream production (closed-loop aluminium recycling). For a module which can be disassembled further, its EoL option will include a disassembly (or similar) option. This crucially allows for the consideration of partial product disassembly in the final EoL plan.

2.2 Modelling of Integrated Life Cycle with End-of-Life Options

Once a product structure has been decomposed and mapped to its life cycle stages, and EoL options for every of its disassembly level identified, we can proceed to model the product's integrated life cycle. Using the product structure-based methodology, the model is able to incorporate at specific nodes, characteristics of closed-loop resource recovery (i.e. recovered resources at EoL channelled back into mainstream production) when the corresponding EoL options are selected. This ensures that any potential offset (from closed-loop resource recovery) in resource requirements at life cycle stages upstream is accurately reflected in the analysis [12].

Since the theme of this paper is planning cost-effective EoL strategies, modelling work done here is focused on economic cost aspects only. However, it is worth pointing out that our proposed methodology is not limited to economic cost modelling alone. The same concept can be applied in environmental impact modelling studies of closed-loop supply chains as well.

The life cycle (economic) cost pertaining to any node (i.e. product, module or component) in a product structure is the sum of the costs at the production, distribution, use, EoL collection and EoL processing stages plus the life cycle costs of any of its child nodes (modules or/and components). This can be generally expressed as:

$$\begin{aligned} C_{\text{Life\_Cycle},\,i} &= C_{\text{Production},\,i} + C_{\text{Distribution},\,i} + C_{\text{Use},\,i} \\ &+ C_{\text{EoL\_Collection},\,i} + C_{\text{EoL\_Processing},\,i} \\ &+ C_{\text{Child\_Nodes},\,i} \end{aligned} \quad (1)$$

where i represents the index of a node in a product structure and C the annual cost.

To illustrate the economic cost modelling procedure, the body module (node 5) of the dive torchlight example, its batteries housing component (node 10) and copper wire component (node 11) are used as the subjects for modelling in this section. The expanded view of the life cycle processes of the body module and its components are shown in Figure 4. There are two EoL options available for the body module, i.e. disassembly (EoL option B) and scrap metal recycling (EoL option F). Therefore, expanding on equation (1), life cycle costs of the body module with EoL option B can be expressed as:

$$\begin{aligned} C^{\text{B}}_{\text{Life\_Cycle},\,5} &= C_{\text{Production},\,5} + C^{\text{B}}_{\text{EoL\_Processing},\,5} \\ &= C_{\text{Body\_Module\_Assembly}} \\ &+ C_{\text{Body\_Module\_Disassembly}} \\ &+ C_{\text{Life\_Cycle},\,10} + C_{\text{Life\_Cycle},\,11} \end{aligned} \quad (2)$$

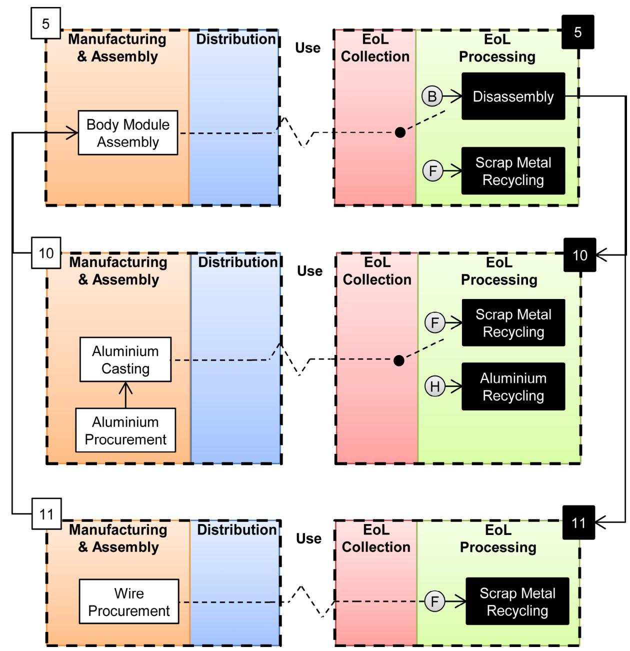


Figure 4: Expanded view of life cycle processes for the body module, and its batteries housing and copper wire components.

and with option F as:

$$\begin{aligned} C^{\text{F}}_{\text{Life\_Cycle},\,5} &= C_{\text{Production},\,5} + C^{\text{F}}_{\text{EoL\_Processing},\,5} \\ &= C_{\text{Body\_Module\_Assembly}} \\ &+ C_{\text{Body\_Module\_Scrap\_Metal\_Recycling}} \\ &+ C_{\text{Production},\,10} + C_{\text{Production},\,11} \end{aligned} \quad (3)$$

Life cycle cost of the batteries housing component with EoL option F can be expressed as:

$$\begin{aligned} C^{\text{F}}_{\text{Life\_Cycle},\,10} &= C_{\text{Production},\,10} + C^{\text{F}}_{\text{EoL\_Processing},\,10} \\ &= C_{\text{Aluminium\_Procurement}} + C_{\text{Aluminium\_Casting}} \\ &+ C_{\text{Battery\_Housing\_Scrap\_Metal\_Recycling}} \end{aligned} \quad (4)$$

and with option H as:

$$\begin{aligned} C^{\text{H}}_{\text{Life\_Cycle},\,10} &= C_{\text{Production},\,10} + C^{\text{H}}_{\text{EoL\_Processing},\,10} \\ &= C_{\text{Aluminium\_Procurement}} \times R_{\text{Aluminium\_Offset}} \\ &+ C_{\text{Aluminium\_Casting}} \\ &+ C_{\text{Aluminium\_Recycling}} \end{aligned} \quad (5)$$

where $R_{\text{Aluminium\_Offset}}$ is the factor for material offset from closed-loop recycling of the aluminium, which can be derived based on the allocation procedures for closed-loop recycling in ISO 14040/44 [13,14]. Life cycle cost of the copper wire component with scrap metal recycling at EoL (option F) can be expressed as:

$$\begin{aligned} C^{\text{F}}_{\text{Life\_Cycle},\,11} &= C_{\text{Production},\,10} + C^{\text{F}}_{\text{EoL\_Processing},\,11} \\ &= C_{\text{Copper\_Wire\_Procurement}} \\ &+ C_{\text{Copper\_Wire\_Scrap\_Metal\_Recycling}} \end{aligned} \quad (6)$$

Similarly, life cycle models for the rest of modules and components in the product structure can be developed by following the procedures as described.

2.3 End-of-Life Planning through a Bottom-Up Analytical Approach

In order to configure a cost-effective EoL plan, the best EoL option at every disassembly level of a product based on economic cost performance, must be selected. However, as recovery volume changes, so does costs at EoL. In the case of closed-loop supply chains, the costs at upstream of the life cycle are affected as well. But the rate at which costs change with respect to recovery volume varies for different EoL options. Therefore, the optimality of an EoL plan is dependent on the recovery rate of the product at EoL. Because of recovery rate uncertainties, it is important to ensure that an EoL plan is robust enough to accommodate to 'expected' fluctuations in recovery volume. In this section, we explain how results generated from the model are used to configure an optimal EoL plan with regards to change in recovery rate (or collection volume).

Using our proposed methodology, configuring an optimal EoL plan for a product requires a bottom-up analysis of the product's EoL options. This is basically the concept of 'granularising' the overall EoL planning problem at the product-level into smaller manageable sub-problems at the module- and component-levels. By finding solutions to these sub-problems, it is then possible to combine these solutions to find the overall solution to the problem at product-level. For instance, within the body module (node 5), there are two components: the batteries housing (node 10) and copper wire (node 11). Hence, before the EoL options for the body module can be analysed, the analyses for its components (batteries housing and copper wire) must first be completed.

Since the batteries housing and copper wire components are both leaf nodes (as defined in the product structure of the dive torchlight example), the bottom-up analysis can start at either one of these components. Figure 5 and 6 are the EoL option analyses for the batteries housing and copper wire components respectively. Analytical results for these components are then combined to generate the analytical results for the body module. Figure 7 shows the EoL option analysis for the body module embedded with the composite analytical results of the batteries housing and copper wire components. These results together with completed analytical results of the other nodes in the dive torchlight's product structure are used in the product's final EoL plan configuration. This final EoL plan will be further discussed in the following section.

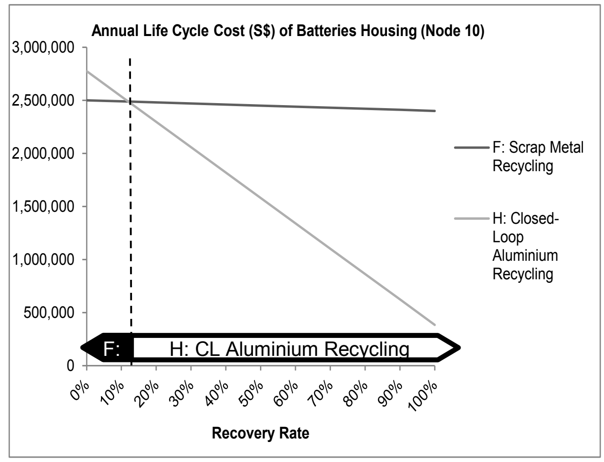


Figure 5: EoL options analysis (of F: scrap metal recycling or H: closed-loop aluminium recycling) for the batteries housing.

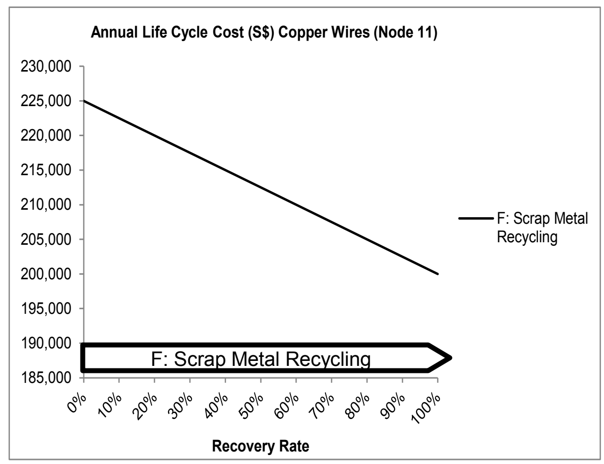


Figure 6: EoL options analysis (of F: scrap metal recycling) for the copper wire component.

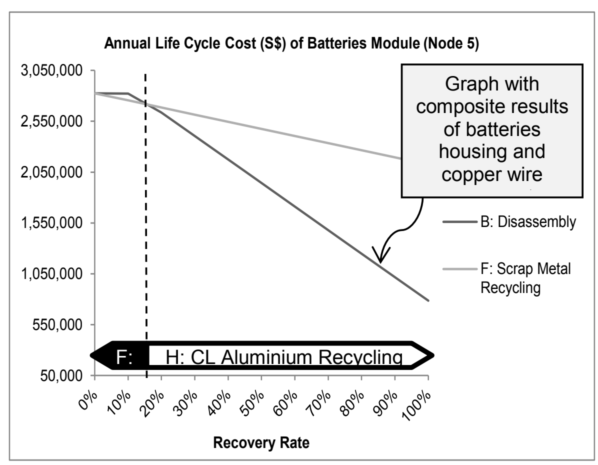


Figure 7: EoL option analysis for the body module embedded with the composite analytical results of the batteries housing and copper wire components.

3 APPLICATION EXAMPLE: EOL PLANNING FOR A DIVE TORCHLIGHT

To maintain the consistency of our presentation, the application of our proposed methodology is demonstrated using the dive torchlight example which has already been used throughout the earlier sections of this paper. Cost data for this case study are mainly estimated from information of material and component prices available online. Whenever possible, cost data are estimated based on information from component and equipment suppliers. The case study is also localised to the Singapore context, i.e. costs of facility (building and rental space), equipment, utilities (electricity water and gas) and labour are based on the local Singapore market rate. Other key assumptions made for the case study are summarised in Table 1.

Parameters	Value
Product Distribution Volume	1,000,000 units a year
Distribution Price	S$20.00 per unit
Planning Horizon	3 years
Market	South East Asia region
Distribution/Collection Network	Centralised (Singapore)
Return Policy	20% rebate per unit returned

Table 1: Key assumptions made for the case study of the dive torchlight.

From the EoL plan in Figure 8, the arrowed bars at node 1 indicate that product take-back will only become desirable (in monetary terms) for the manufacturer above 80% recovery rate (averaged over 3 years). This is provided a closed-loop reuse of LEDs in (remanufactured) torchlights, recycling of steel from the bulb holder, and recycling of aluminium from the bulb and battery housings are incorporated in the reverse supply chain. The reason for this is by selecting these EoL options, a substantial cost offset is gained from alleviating the cost of raw materials and capacity requirements in the forward supply chain. Otherwise, selection of the alternative (less cost-effective) EoL options is not able to justify, in terms of cost performance, the decision to carry out product take-back in scenarios whereby no take-back laws apply to the manufacturer.

In the scenario whereby product-back is mandatory, the EoL plan serves as a robust EoL strategy guide for the dive torchlight manufacturer. It provides a guide for the manufacturer to pursue the most cost-effective EoL strategy to manage an EoL product based on its forecasted recovery volume or over a range of expected recovery rates. A resource recovery path can be derived by following a top-down view (from product to modules to components) of the EoL plan. For instance, at early introduction stage of the product (dive torchlight) when forecasted recovery rate (for the first 3 years' average) is less than 12.5%, it can be interpreted from the EoL plan that to maximise monetary returns, the manufacturer should follow a resource recovery path of: 1(B) to 2(C),3(C),4(B),5(F); and 4(B) to 6(C),7(F),8(F),9(I); whereby the numbers refer to the nodes and letters in () refers to the EoL options. This means that the manufacturer should setup their operations to disassemble returned torchlights down to their bulb holders and housings to be sold as scrap metal, and reuse functioning LEDs in new products. Conversely, body modules should not be disassembled further as they can be directly sold for scrap metal and there is no benefit from further disassembly.

In scenarios whereby a manufacturer has already invested in a setup for product take-back, the EoL plan is able to provide them with an indicator on which area of the EoL strategy more attention is needed. For instance, if the dive torchlight manufacturer has already setup their operation for full disassembly and recovery of the product, the EoL plan indicates that the manufacturer should focus on improving processes that are 'recovery volume demanding' such as the closed-loop recycling of steel from bulb holders (>65% to achieve desirability), or even the product collection process itself to bring down the recovery rate requirement to achieve profitability for product take-back.

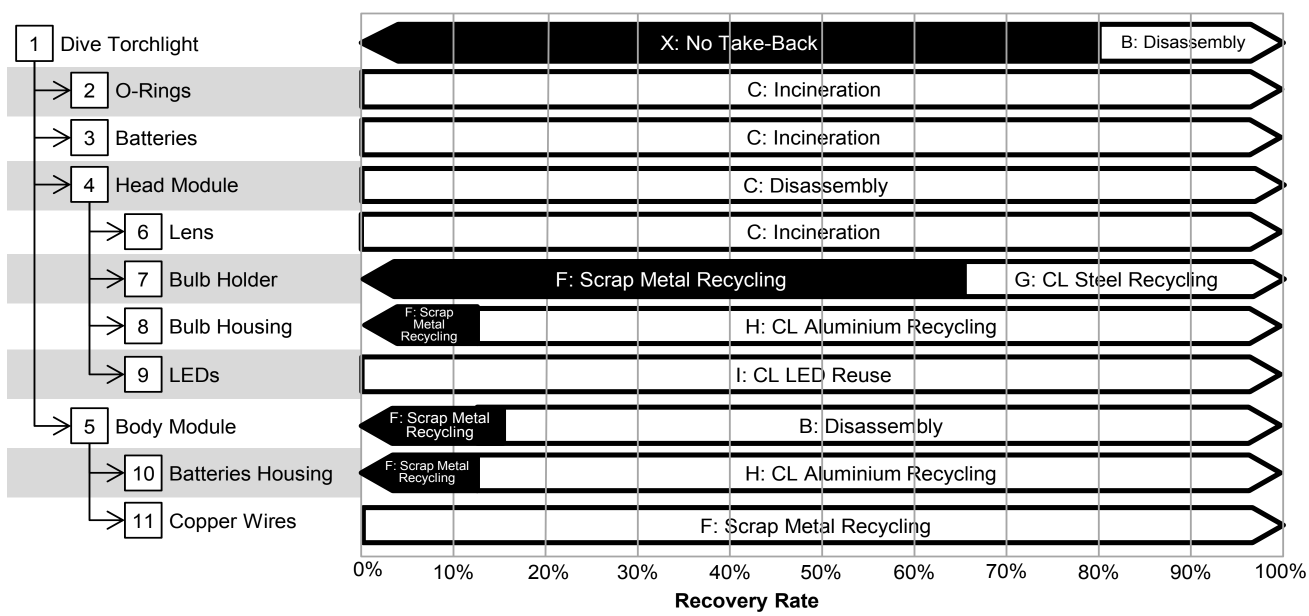


Figure 8: EoL plan for the dive torchlight based on life cycle cost performance. (The direction a bar is pointing indicates the point at which the corresponding EoL option is desirable, and in single EoL option cases, must be selected at the particular disassembly level).

4 CONCLUSION

In summary, an integrated life cycle approach to EoL planning is necessary to give manufacturers in closed-loop supply chains a holistic management of their products at EoL. To help them do this, we proposed a product structure-based methodology to enable EoL planning with an integrated life cycle perspective. The application of our proposed methodology in the EoL planning domain was demonstrated on a hypothetical case of a closed-loop supply chain for a dive torchlight product.

In this case study, the EoL plan was able to indicate to the dive torchlight manufacturer that while keeping product recovery rate at above 80%, product take-back operation becomes profitable (lower total life cycle cost) through closed-loop reuse of LEDs, and closed-loop recycling of steel and aluminium materials. The EoL plan was also able to provide a guide to the manufacturer, on the most cost-effective EoL strategy to pursue based on forecasted recovery volume, or over a range of expected recovery rates. Last but not least, the EoL plan was able to provide an indicator to the manufacturer on which processes are potential opportunities to reduce costs.

Through the application example using the dive torchlight case study, we showed how EoL planning with an integrated life cycle perspective can be achieved using the product structure-based methodology. It demonstrated how critical characteristics exhibited in closed-loop supply chains for multiple life cycle products can be factored in during the EoL planning process. Most importantly, we showed how using the product structure-based methodology, a complex EoL planning problem, such as the one for the LED torchlight, can be solved through a breakdown of the overall problem into smaller manageable sub-problems.

5 REFERENCES

[1] Organisation for Economic Co-operation and Development (OECD): Extended Producer Responsibility, available online at: http://www.oecd.org/env/environmentalpolicytoolsandevaluation/extendedproducerresponsibility.htm

[2] Krikke, H.R., van Harten, A., Schuur, P.C. (1998): On a Medium Term Product Recovery and Disposal Strategy for Durable Assembly Products, International Journal of Production Research, Vol. 36, pp. 111-140.

[3] Teunter, R.H., Bayindir, Z.P., Heuvel, W.V.P. (2006): Dynamic Lot Sizing with Product Returns and Remanufacturing, International Journal of Production Research, Vol. 44, pp. 4377-4400.

[4] Das, S., Yedlarajiah, D. (2002): An Integer Programming Model for Prescribing Material Recovery Strategies, in: Proceedings of the IEEE International Symposium on Electronics and the Environment, San Francisco, CA, pp. 118-122.

[5] Willems, B., Dewulf, W., Duflou, J.R. (2006): Can Large-Scale Disassembly be Profitable? A Linear Programming Approach to Quantifying the Turning Point to Make Disassembly Economically Viable, International Journal of Production Research Vol. 44, pp.1125-1146.

[6] Tan, A., Kumar, A. (2008): A Decision Making Model to Maximise the Value of Reverse Logistics in the Computer Industry, International Journal of Logistics Systems and Management, Vol. 4, 297-312.

[7] C.M. Rose, Stevels, A., Ishii, K. (2000): A New Approach to End-of-Life Design Advisor (ELDA), in: Proceedings of the IEEE International Symposium on Electronics and the Environment, San Francisco, CA, pp. 99-104.

[8] Huisman, J., Ansems, T., Feenstra, L., Stevels, A. (2001): The QWERTY Concept, A Powerful Concept for Evaluating the Environmental Consequences of End-of-Life Processing of Consumer Electronic Product, in: Proceedings of the 2nd International Symposium on Environmentally Conscious Design and Inverse Manufacturing (EcoDesign'01), pp. 929-934, Tokyo, Japan.

[9] Gonzalez, B., Adenso-Diaz, B. (2006): A Bill of Materials-Based Approach for End-of-Life Decision Making in Design for Environment, International Journal of Production Research, Vol. 43, pp. 2071-2099.

[10] Gregory, J., Atlee, J., Kirchain, R. (2006): A Process-Based Model of End-of-Life Electronics Recycling, in: Proceedings of the IEEE International Symposium on Electronics and the Environment, pp. 138-143, Scottsdale, AZ.

[11] Asif, F.M., Bianchi, C., Rashid, A., Nicolescu, C.M. (2012): Performance Analysis of Closed-Loop Supply Chain, Journal of Remanufacturing, Vol. 2:4, available online at: http://www.journalofremanufacturing.com/content/2/1/4/.

[12] Low, J.S.C., Lu, W.F., Lee, H.M., Song, B. (2012): Methodology for Modelling the Eco-Efficiency of Closed-Loop Product Life Cycles, in: Proceedings of Electronics Goes Green 2012+ (EGG), pp.1-6, Berlin, Germany.

[13] ISO 14041: Environmental Management – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis.

[14] ISO 14049: Environmental Management - Life Cycle Assessment - Examples of Application of ISO 14041 to Goal and Scope Definition and Inventory Analysis, 2000.

Sustainable Metal Management and Recycling Loops: Life Cycle Assessment for Aluminium Recycling Strategies

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Abstract

The benefit of knowing the exact chemical composition of metal scrap plays a significant role from metallurgical point of view in recycling processes. Thus, the focus of this paper is to identify opportunities for more efficient scrap management, in order to minimize quality loses and primary material consumption during recycling. By moving to compositionally closer recycling loops, higher recycling values by reducing the need for primary metal and alloying elements addition, can be achieved. A Life Cycle Assessment (LCA) was performed, focusing on aluminium scrap, in order to validate, estimate and compare the environmental impact of different recycling options and the effect of scrap separation strategies. Furthermore, a metric to compare the 'quality' in terms of recyclability of the various metal flows is proposed.

Keywords:

Aluminium recycling; Life Cycle Assessment; Cascade recycling; Quality losses; Resource efficiency

1 INTRODUCTION

Metals can be regarded as one category of regenerative waste streams with a high potential for a more sustainable management, due to their high economic value, the large quantities that are used (enabling economies of scale) and their distinctive feature of good recyclability. Nevertheless, today this potential is not adequately used since many related challenges remain to be tackled: the relatively big number of alloys, the accumulation of impurity elements, the inefficient scrap pre-separation, along with the thermodynamics limitations of impurity removal during the final metallurgical processing stage.

For mixed waste flows, in order to achieve the goal of minimizing contaminations and maximizing efficient use of resources, the compatibility of materials combinations for recycling processes needs to be taken into account during disassembly and separation processes at the End-of-Life (EoL) treatment [1]. In principle metals are infinitely recyclable, but in practice, recycling is often inefficient. This can be explained by the accumulation of unwanted elements, the inefficient pre-melt separation as well as the thermodynamics barriers preventing the refinery of certain elements. Since many elements have similar thermodynamic behavior during the smelting process of metallic materials, the melt technologies and chemical separation of many impurity elements are often very energy-intensive or essentially impossible. For example, the three layer electrolytic process for the aluminium refining (removing Si, Fe, Mg, Cu, Zn and Cr from aluminium) requires 17-18 kWh/kg, while the primary production requires 14 kWh/kg [2]. Moreover, other advanced melt separation technologies for the case of aluminium (Al) are still in a research or early development stage [2].

Recent studies, based on chemical thermodynamic analysis of the distribution of elements during metallurgical processing for various base metals (Al, Fe, Cu, Zn, Pb, Ti and Mg) [2-6], indicate which elements can be removable (in the slag or gas phase) and how far the impurity levels can be controlled. The impurity removal from the melt in most cases can be performed either through oxidation in the slag phase or by evaporation in the gas phase.

Nowadays, dilution with high purity metal inputs of difficult to remove impurity elements, or down-cycling strategies are widely used in the metal industry. Although both strategies effectively resolve the refining limitations, they are pushing the problem of material recyclability to the future. Moreover, from economic point of view, the increasing cost of high purity metal additions in the case of dilution; or the reduced product value in the case of down-cycling; form incentives to seek for more efficient quality preserving solutions. Quality and dilution losses during metal recycling are extensively analyzed for the case of ferrous metals recycling [7] and by means of exergy analysis for the case of aluminium recycling [8].

Improved scrap separation strategies and management by moving from open to compositionally closer recycling loops, can provide a more environmentally friendly solution minimizing the need for impurity dilution and quality loses. Moreover, by recovering the locked up value in the scrap composition, this strategy can positively affect the recycling economics. Finally, a more different approach focusing on solid state / meltless recycling of aluminium scrap can provide significant environmental benefits, mainly by avoiding metal losses [9].

2 ALUMINIUM SCRAP REFINING – QUALITY METRIC

2.1 Refining Options for Aluminium Scrap

Impurity control and removal is a much bigger challenge for aluminium [2, 3, 5] and magnesium [4] compared to other base metals, like copper and ferrous materials. Thus, the main focus of this paper is to improve the secondary aluminium production efficiency by improved pre-melt control of the quality of the scrap streams. Alumium is widely used with the addition of few elements in an alloy form. The properties of the various alloys depend on the elements added and their concentration. Typical alloy elements for aluminium are: Silicon (Si), Iron (Fe), Copper (Cu), Zinc (Zn), Magnesium (Mg), Manganese (Mn) and Chromium (Cr). More than 450 alloy designations/compositions have been registered by the Aluminium Association Inc. [10]. These alloys are mainly categorized into two major categories regarding the concentration of alloying elements: i) high purity wrought alloys (often with less than 5 wt.%) produced by remelters and used by extruders and rolling mills, and; ii) cast alloys with much higher compositional tolerance limits for alloying elements (often above 10 wt.%).

Nakajima et al. [3, 5] examined the distribution of various elements in the gas, slag and metal phases for simulated aluminium remelting. They concluded that among the 45 examined elements (most of them occur as tramp elements), only Mg, Ca and Be can be removed in the slag phase by oxidation and Zn, Cd and Hg can be removed in the gas phase by evaporation. The residual 39 elements remain in the metal phase and their removal is very difficult or technically impossible. These results also show that for the typical alloying element of aluminium (Si, Fe, Mg, Cu, Mn, Zn and Cr), only Mg and Zn can be removed. Mg can be removed through oxidation by transferring to the slag phase and Zn through evaporation in the gas phase. Oxidation is the main mechanism and the most widely used to remove impurities. An experimental study supported these results for the Mg removal, with removal of nearly half of the magnesium content after remelting with a salt flux treatment [11]. Zn can be recovered thought distillation technologies [2]. In particular one study showed that a distillation process can reduce the Zn content of the aluminium melt from >3 wt.% to less than 0.1wt.% [12].

2.2 Quality Metric for Metal Scrap Stream and Alloys

Based on the thermodynamic analysis results for the various base metals on impurity removal [2-6], in this paper a quality metric is proposed to compare the recyclability of various scrap metal streams. This quality metric is defined by Equation 1:

$$Quality\ metric = 100 - \sum_{i=1}^{n}(e_{i,m}) - \sum_{j=1}^{m}(c_j * e_{j,sg}) \qquad (1)$$

where e_m is the concentration wt.% of the elements that remain in the metal phase and cannot be removed to any appreciable extend during smelting; e_{sg} represents the concentration wt.% of the elements that can be removed either in the slag or gas phase, multiplied by a removability factor c for each element. The factor c was set at 0 when the element can be fully removed from the melt in the slag or gas phase and to 0.5 when there are some limitations in the removability. For the elements that remain in the metal phase after remelting the value of c is 1. Lower values of this metric indicate limited options for cascade recycling and a higher dilution need to up-cycle to higher purity. This metric can also be used to compare the quality of alloys of the same series. For the case of aluminium refining and its typical alloying elements, only Mg can be removed in the slag phase, irrespective of its concentration [5]; so the factor c will be 0. But for Zn, since it can be removed in the gas phase depending on its concentration (the removal is difficult at low concentrations) [5], this factor was set to 0.5. In Figure 1 the maximum compositional limits of representative alloys from the different wrought and cast aluminium alloy families are shown [10]; combined with the quality metric in term of recyclability for the specific compositions. Al 99.7 according to the chemical composition specifications of London Metal Exchange (LME) for high grade aluminium contract [13] is considered equivalent to primary aluminium. Cast alloys (like 355.0, 380.0) can be considered as low quality alloys in terms of recyclability due to the higher alloy elements content than wrought alloys.

3 SCRAP CATEGORIES AND VALUES

Since the alloy element removal during remelting of aluminium is very difficult for most of the elements, it is crucial to more efficiently control their concentration in the scrap streams before re-melting. Generally, as the origin of the scrap becomes less certain, the composition uncertainty increases. Thus the advantage to easily separate and collect scrap streams from industrial processes where the chemical composition is usually well known should be fully utilized. Moreover, for mixed scrap streams, usually from post-consumer waste, physical, chemical and pre-melt operations are nowadays available and capable not only to separate ferrous and non-ferrous components from each other; but also to separate between aluminium wrought and cast alloys (like by means of the hot crush process) and furthermore by its alloy or alloy series (like color ID/etching and spectrographic techniques) [2]. Finally an improved scrap management can also target in selectively collecting products that are mainly from specific alloy series (e.g. window frames scrap from the construction sector that are mainly made from the 6XXX wrought alloy series).

Kevorkjjan investigated the opportunities, the challenges and the recycling economics of the wrought aluminium production [14]. Compositional separation of the scrap streams before remelting plays a significant role from metallurgical point of view; and since there are also economic benefits from this separation, nowadays regional standards are established in order to control the scrap quality. In the European Community, DIN EN 13920 [15] identifies 15 different categories of aluminum scrap, specified in part by their overall element composition. Similar scrap categories can be found also in other countries. Clearly, any scrap dealer or trader supplying scrap according to these standards can set a higher price and therefore obtain a commercial advantage. Table 1 shows representative average values for selected scrap categories of EN DIN 13920 [15] in relation with the primary aluminium value at the London Metal Exchange [14]. The Al content/purity of the scrap is the main factor that affects the scrap price. But the aluminium content is not the only determining factor. The mixing of alloy families and thus alloying elements, the form of the scrap (e.g. turnings or solid parts),

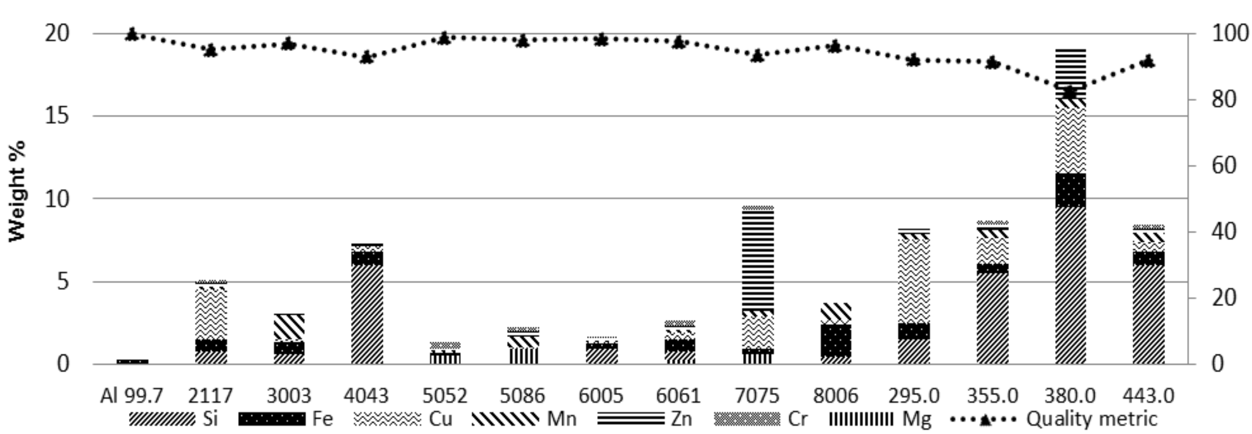

Figure 1: Maximum compositional limits of representative aluminium alloys from different series [10] and their quality metric value.

the presence of various contaminations (tramp elements, foreign material and organic impurities) and scrap availability also affects the scrap value. In general separated scrap batches have higher values; especially for wrought alloys as they can be utilized as high purity raw material in the wrought aluminium production, effectively substituting primary material production. But what are the environmental benefits of compositionally separated scrap for the secondary aluminium production? In order to answer this question this paper examines the recycling options and the future challenges together with a life cycle assessment of various case studies.

DIN EN 13920 categories	Scrap Description	Al Content (%)	Average Price* (% LME)
DIN EN 13920-4	One single wrought alloy	97.2	95-99
DIN EN 13920-5	two or more wrought alloys of the same series	97.2	80-85
DIN EN 13920-10	Used Al beverage cans	94	55-60
DIN EN 13920-12	Turnings, one single alloy	95.3	80-85
DIN EN 13920-13	Mixed turnings, two or more alloys	84	75-80

* The reported scrap values are only indicative

Table 1: Average scrap price of selected scrap categories [14,15].

4 METHODOLOGY

In Figure 2 the chosen system boundary for the analysis is presented. The functional unit that was used is 1 kg of the target aluminium alloy from the secondary aluminium production. For the case studies four scrap composition examples (see Table 2), based on different alloy mixing scenarios, were assumed. The recycling process aims at the production of a specific aluminium alloy as output. Primary aluminium (Al99.7) was considered for the dilution of the alloy elements that remain in the metal phase during remelting (Si, Fe, Cu, Mn, Cr) [5] as it is also the practice today. For these elements the removal from the melt is very difficult. In order to meet the target alloy compositional limits, the minimum dilution needed for the alloy element that has the maximum difference from the alloy composition limits was calculated. The elements Mg and Zn were excluded from this analysis since they can easily be extracted from the melt (Mg in the slag phase through a flux treatment and Zn in the gas phase by distillation) [5]. For these two elements dilution is not always necessary and it was assumed that they can be refined from the melt according to a preset target in order to meet the composition limits. All the results were normalized based on the functional unit (1 kg of produced alloy). Furthermore, in order to adjust the alloy composition after dilution, the addition of all the typical alloying elements (that are also diluted in the melt) was included. The best case scenario of minimum dilution and required addition of alloy elements to meet the boundary alloy composition limits is modeled for all the case studies. The degree of dilution for each case is given by the ratio of primary Al in the melt. Secondly, more efficient scrap utilization can also replace the alloy elements addition, which also significantly affects the impact per kg of the produced alloy.

The effort in the recycling process should be to minimize this primary material ratio (minimize primary aluminium consumption) and secondly alloy elements addition; as it negatively affects the recycling economics and the overall environmental impact per kg of produced alloy. This goal can be achieved by utilizing scrap with closer composition to the target alloy (for closed recycling loops) or by appropriately mixing different scrap alloy (for open recycling loops) without exceeding the maximum compositional limits of the target alloy.

The ReCiPe LCIA method (Endpoint Europe H/A) and data from the Ecoinvent database [16] were used to model the case studies. This was particularly the case for the primary liquid aluminium production, the modified process of remelting casting and alloying of new scrap into secondary Al, and the alloying element production (for Fe, Si, Cu, Mn and Cr).

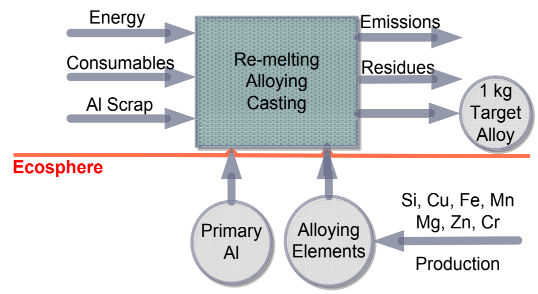

Figure 2: System boundary and functional unit.

Scrap batch compositions	Si wt.%	Fe wt.%	Cu wt.%	Mn wt.%	Cr wt.%
1. Single alloy 6061	0.600	0.700	0.275	0.150	0.195
2. Same alloy series (50% 6061, 50% 6005)	0.675	0.525	0.188	0.125	0.148
3. Mixed wrought alloys (25% of each: 6061 ,6005 ,5086 ,2117)	0.638	0.563	0.769	0.225	0.136
4. Mixed wrought & cast alloys (25% of each: 6061, 5086, 295.0, 355.0)	1.775	0.700	1.531	0.363	0.149

Table 2: Examined scrap batches and their typical alloy element composition, excluding Mg and Zn [13].

5 RECYCLING OPTIONS – CASE STUDIES

Nowadays, the challenge of the very limited options for refining of aluminium is successfully resolved either by dilution of the difficult to handle impurities with high purity metal inputs; or by cascade recycling to lower purity alloys (e.g. to cast quality). Since there is limited scrap availability and high demand of cast alloys, both of these strategies are effective solutions nowadays. But will these strategies continue to be sustainable in the future? For the first option, the major challenge is that wrought Al production heavily depends on primary Al consumption. Wrought alloys have very limited ability to tolerate elements in their composition. Mixed scrap streams contain too many alloying elements to be absorbed into a wrought product. Well defined composition separation and more efficient pre-melt sorting, especially for the high purity wrought alloys, will result in the reduction of the primary aluminium and alloying element consumption. This will reduce the overall environmental impact of their production by decoupling it from the primary aluminium consumption.

Because of the high demand for cast alloys, down-cycling of downgraded mixed aluminium scrap to ‘recycle friendly’ cast alloys, is a common strategy nowadays. Cast alloys act as a sink in the aluminium cascade chain, but will there be a market for these products in the future? While cast alloys are mainly used in the transportation sector, wrought alloys have a much wider range of applications [17]. The European Aluminium Association (EAA) reports that 73% of castings in Western Europe are used in the transport sector. Data from Japan also show that cast and die cast alloys are mainly used in the automobile sector, with main application in engine manufacturing [5]. A recent study of Hatayama et al. [18] showed that the introduction of electric vehicles will result in a decrease of the demand for cast alloys, generating 6.1 Mt of scrap in 2030, which cannot be recycled due to the high concentration of alloying elements. Furthermore they illustrated that scrap sorting of end-of-life vehicles significantly lowers the generation of un-recycled scrap and reduces the primary Al requirements by 15-25% [18]. Within these case studies examples of the recycling options for four different scrap batches, based on different alloy mixing scenarios (from a single wrought alloy to a mix of wrought and cast alloys) are modeled. The composition of the investigated scrap streams is calculated based on the average values of alloy element composition limits for the selected alloys [9]. Table 2 presents the chemical composition of the examined scrap batches. Magnesium and zinc are excluded since they can be easily extracted from the melt. The recycling options that were investigated are:

- Downgrading to lower purity
- Maintain quality
- Up-cycling to higher purity (by dilution with primary Al)

The different recycling pathways are presented in Figure 3. Closed (as the chemical composition of the scrap-final product remains the same) and open recycling loops are compared based on their environmental performance. The single alloy strategy can be applied either for industrial scrap or for old scrap streams with improved scrap sorting.

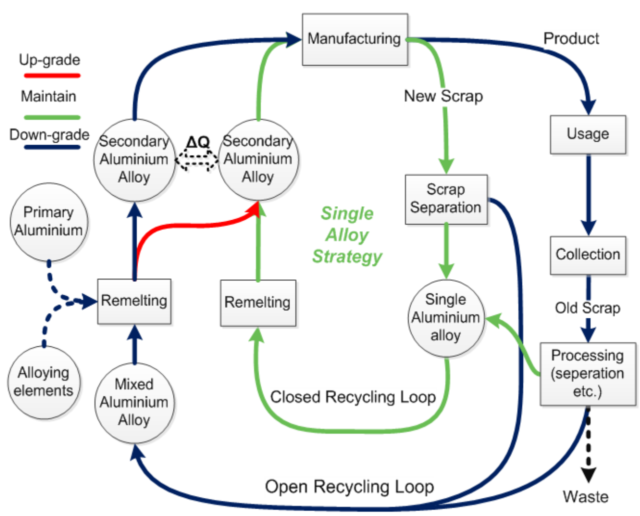

Figure 3: Recycling options and corresponding pathways.

5.1 Downgrading

Nowadays, the cascade recycling strategy (represented by the blue line in Figure 3) is widely used within the metal recycling industry, in order to handle the problems of alloy mixing, accumulation of unwanted elements, and the limits in impurity refining during remelting. Recycling of the metal scrap to lower quality alloys is done in open recycling loops. For the case of aluminium, a number of “recycle friendly” cast alloys (e.g. 355.0 and 380.0 cast alloys listed in Figure 1) with wider compositional limits for alloy elements, have been developed to facilitate recycling. Figure 4 presents the overall normalised impact for the production of 1 kg of the 355.0 cast alloy with cascade recycling of the different scrap batches listed in Table 2. Down-cycling of scrap batches 3 and 4 provides clear environmental benefits compared to the up-cycling option of producing the higher purity 6061 alloy by dilution. These benefits can be explained by the reduction (for scrap batch 4) or prevention (for scrap batch 3) of the dilution losses. For scrap batch 3 we can 100% utilize the scrap to produce the 355.0 alloy, adding only alloy elements to meet the composition limits. Yet, scrap batches 1 and 4 still contain dilution losses, since the iron contamination has to be diluted from 0.7% to 0.6% which is the composition limit for the 255.0 alloy. Summarised data regarding the environmental impact of down-cycling the scrap batches for producing the 355.0 cast alloy can be found in Table 3.

For scrap batch 1 and 2 the main impact contribution comes from the addition of primary Al since the melt needs to be diluted. Moreover, the results also indicate that the alloy element addition impact is lower for less ‘pure’ scrap batches (see Table 3). The higher the alloy content is in a scrap stream, the higher the potential is to efficiently replace alloy element addition in downcycling recycling loops. Raw material consumption of alloying elements (like copper, silicon, manganese etc.), is also an important impact contribution factor; and thus the effort should be to substitute them with the scrap alloy content. By appropriate blending of different scrap qualities or specific alloy scrap the alloy elements concentration of the final scrap batch can be brought closer to the target alloy composition; and thus minimizing the overall environmental impact per kg of produced aluminium alloy.

Target alloy 355	Scrap batch 1	Scrap batch 2	Scrap batch 3	Scrap batch 4
Degree of dilution [%]	16.7	0	0	16.7
Impact contribution of primary aluminium addition [%]	67.5	0	0	74.1
Alloying elements addition impact [mPt]	57.5	58.0	42.7	33.9
Impact/kg [mPt]	266.0	86.8	71.4	242.0

Table 3: Environmental impact for the production of 1 kg of 355.0 alloy utilizing the various scrap batches (ReCiPe Europe H/A).

5.2 Maintain Quality - Single Alloy Strategy

When the scrap input and the target alloy are the same alloy, there is no need for dilution. In consequence this represents the best case scenario. The environmental impact per kg of produced alloy is minimal and can be mainly attributed to the energy requirements of the recycling processes. The single alloy strategy (illustrated by the green line in Figure 3) represents the closest compositional recycling loop, avoiding dilution and quality loses. This case is presented in Figure 4 for the recycling of scrap batch 1 (single alloy 6061) to the same alloy. Only a small correction in the Mg and Zn content is assumed (half of the average alloy content), as these elements can be partially lost during remelting. The environmental impact per kg of produced alloy is 46.7 mPt. Maintaining the scrap quality by avoiding mixing alloys and utilizing single alloys scrap for the production of the same alloy should be the first choice, but this is not always possible since there are a relative big number of alloys. For some very widely used alloys a single alloy strategy can provide significant environmental and economic benefits if they are used in a closed recycling loop for the production of the same alloy. Furthermore, Figure 4 shows a slightly different case for scrap batch 2 (same alloy series example of 50% 6061 and 50% 6005). By

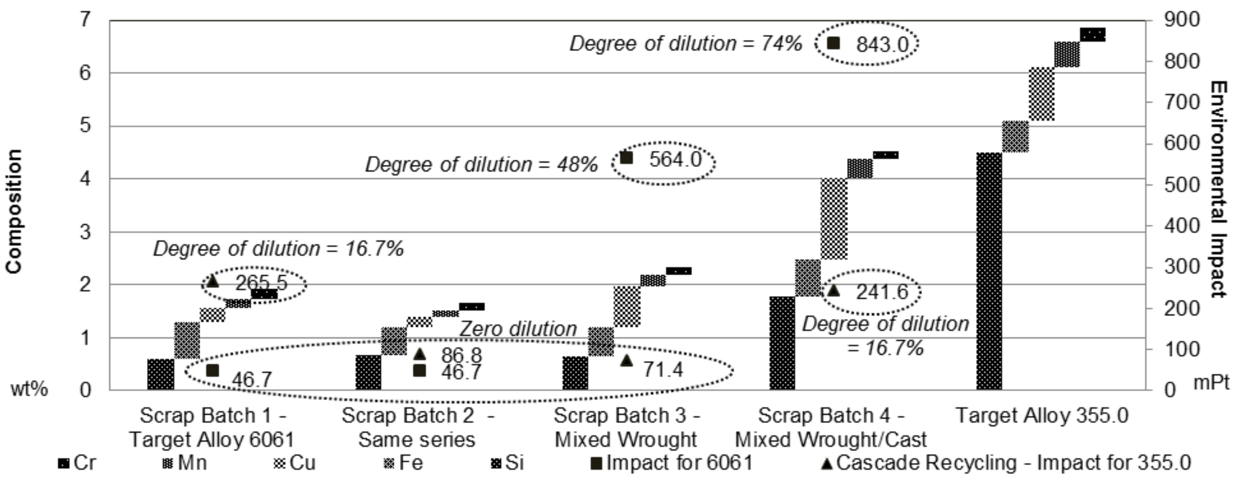

Figure 4: Impact per kg of 6061 alloy for the different scrap batches of Table 2.

mixing these two alloys in this ratio we are still in the 6061 alloy composition limits. Therefore there is no composition adjustment. In fact the 6005 content of the scrap acts as dilutant to the 6061 content.

5.3 Upgrading / Dilution of Impurity Elements

The last recycling option that is examined is the 'upgrading' of scrap batches 3 and 4 (presented in the Table 2) into a target alloy with higher quality. The selected target alloy is the commonly used wrought alloy AA6061 which also is used to examine the single alloy strategy. To meet the alloy compositional limit, dilution of the impurity element that has the maximum difference from the compositional limit for the specific alloy with primary Al (Al 99.7) is assumed. Afterwards, in order to adjust the alloy composition (since all the elements are diluted), an addition of the rest alloying elements was included into the analysis, simulating the recycling process as it is today. Figure 4 illustrates the normalized overall environmental impact for the production of 1 kg of secondary aluminium 6061 alloy utilizing scrap batches 3 and 4. Table 3 lists the overall impact per kg for the target alloy AA6061 in order to fully utilize the different scrap batches; as well as the impact contribution of dilution and alloy element addition.

For scrap batch 3, representing an example of a mixture of wrought alloys, the required degree of dilution of the melt with primary Al in order to dilute Cu (from 0.769 wt% to the alloy composition limit of 0.4 wt.%) is 47.97%. Finally, for scrap batch 4, the degree of dilution needed in order to meet the alloy specification is even higher at 73.88% (dilution of Cu from 1.535 wt.% to 0.4 wt.%). Generally by moving to higher accumulation of an alloy element in a scrap stream, the dilution loses for up-cycling to higher purity alloy are also higher. For scrap batch 3 91.5% dilution is needed and for scrap batch 4 even 94.3% as the copper concentration increases. This very high degree of dilution is the reason why mixed wrought, mixed cast or mixed wrought/cast alloys cannot effectively replace primary aluminium for the wrought aluminum production.

Finally the environmental impact per kg of recycling of a single series scrap stream (example of 50% of 6005 and 50% of 6061 Al alloys of scrap batch 2) into two target alloys of the same series was investigated. When the target alloy is the AA6061, the regeneration impact is 47.6 mPt since we still are within the composition limits of the 6061 alloy. However, when the recycling process targets the production of the AA6005 alloy, the degree of dilution should be at least 46.7% in order to dilute the copper concentration from 0.188 wt% to the maximum composition limit for the specific alloy of 0.1%. Thus the impact for the production of 1 kg of the 6005 (listed in figure1) alloy fully utilizing scrap batch 2 is 550.9 mPt. The primary Al consumption has an impact contribution of 91.2%; and the alloy elements addition (in this case of Si) represents 3.4% of the overall impact. This option represents an up-cycling since the target is to end-up with a higher quality alloy than the quality of the scrap. Even by collecting alloys by their series, still we cannot always avoid the dilution of the melt.

Target alloy 6061	Maintain Quality		Up-cycle to 6061	
	Scrap batch 1	Scrap batch 2	Scrap batch 3	Scrap batch 4
Degree of dilution [%]	0	0	48.0	73.9
Impact contribution of primary addition [%]	0	0	91.5	94.3
Impact contribution of alloying elements addition [%]	39.5	39.5	3.3	2.3
Impact/kg [mPt]	46.7	46.7	564.0	843.0

Table 4: Overall impact per kg for the production of AA6061 alloy and the impact contribution from the resource addition.

6 PRE-MELT SEPARATION STRATEGIES

The single alloy strategy (maintaining the quality) is the best solution from environmental perspective since it has the minimum impact per kg of produced alloy. Technically, by remelting and casting the same alloy is obtained. However, a small amount of Mg and Zn can be lost due to oxidation [10] and evaporation [11] respectively. By separately collecting scrap (by its alloy) to be used in closed recycling loops for the production of the same alloy, quality and dilution losses are avoided. Furthermore, clean single wrought alloy scrap has a higher value in the scrap market, nearly close to the primary Al; and can be sold in the EU according to the specification of the DIN EN 13920-4 scrap category [13]. Since separating scrap by its specific alloy is not always possible due to the relative large number of alloys [9], the second best option, especially for the high quality wrought alloys, is to separate them according to their alloy series (DIN EN 13920-5 scrap category). By following this strategy, mixing of different alloy elements from different series is avoided. This strategy can lead to the reduction of the primary requirement for dilution since no new elements are added from mixing alloy series. Separated scrap batches according to alloy series can be used more efficiently for the production of the same series alloy. For example, in the 3XXX series, the manganese that is used as alloying element remains in the metal phase during remelting. Thus the refining of this element is very difficult and unless the 3XXX series alloys were separated during pre-processing, the resulting metal would be unsuitable for 95% of all aluminium applications [5]. The last preferable sorting option should focus at least to separate wrought and cast alloys.

7 DISCUSSION

This paper presents an approach to determine, from environmental point of view, the optimal scrap input for the recycling process depending on the target alloy. The environmental impact to put the scrap metal back to different product systems represents indirectly also the recycling cost of each option. The single alloy strategy is the best sorting strategy since quality losses and the need for dilution with high purity metal inputs are avoided. Furthermore, since most metals are not used in their elemental form but rather in an alloy form, more precisely compositionally separated scrap streams of the same metal have a higher potential for replacing primary metal during recycling. Lower purity scrap streams have higher potential in replacing alloying elements addition in open recycling loops. Proper pre-melt mixing of alloy-specific scrap batches in order to bring the scrap composition closer to the final product composition, can serve to reduce environmental impact, since limited alloy corrections need to be made after melting.

The difficulty of the aluminium purification and the practical compositional tolerance limits that exist for the aluminium alloys (especially for wrought alloys), indicate the importance of improved pre-melt sorting and the control of impurities in the disassembly process. Dilution or cascade recycling can effectively provide a solution to this problem nowadays, but is not a sustainable solution for the future. The effort in recycling should be to minimise this environmental impact. Cast alloys can easily absorb mixed scrap streams, but are practically difficult to be recycled in anything else than a cast alloy. Scrap separation technologies or a selective sorting strategy focusing on specific product systems (like window frames, that are mainly from the 6XXX alloy series), can provide economic as well as environmental opportunities by improving the old scrap sorting aiming at lower dilution ratios and thus to higher primary aluminium substitution. Moving to compositional closer recycling loops, and improving the chemical separation and melt technologies will help to mitigate the current challenges in aluminium recycling.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

[1] Castro, M.B.G., Remmerswaal, J.A.M., Reuter, M.A., Boin, U.J.M. (2004): A thermodynamic approach to the compatibility of materials combinations for recycling, Resources, Conservation and Recycling, Vol. 43, pp. 1–19.

[2] Gaustad, G, Olivetti, E., Kirchain, R. (2012): Improving aluminum recycling: A survey of sorting and impurity removal technologies, Resources, Conservation and Recycling, Vol. 58, pp. 79-87.

[3] Nakajima, K., Takeda, O., Miki, T., Matsubae, K., Nagasata T. (2011): Thermodynamic analysis for the controllability of elements in the recycling process of metals. Environmental Science Technology, Vol. 45, pp. 4929–4936.

[4] Hiraki, T., Takeda, O., Nakajima, K., Matsubae, K., Nakamura, S., Nagasaka, T. (2011): Thermodynamic criteria for the removal of impurities from end-of-life magnesium alloys by evaporation and flux treatment, Science and Technology of Advanced Materials, Vol. 12, 035003 (10p).

[5] Nakajima, K., Takeda, O., Miki, T., Matsubae, K., Nakamura, S., Nagasaka, T. (2010): Thermodynamic analysis of contamination by alloying elements in aluminum recycling, Environmental Science Technology, Vol. 44, pp. 5594–5600.

[6] Lu, X., Hiraki, T., Nakajima, K., Takeda, O., Matsubae, K., Zhu, H.M., Nakamura, S., Nagasaka, T. (2012): Thermodynamic analysis of separation of alloying elements in recycling of end-of-life titanium products, Separation and Purification Technology, Vol. 89, pp. 135-141.

[7] Nakamura, S., Kondo, Y., Matsubae, K., Nakajima, K., Tasaki, T., Nagasaka, T. (2012): Quality- and dilution losses in the recycling of ferrous materials from end-of-life passenger cars: input-output analysis under explicit consideration of scrap quality, Environmental Science Technology, Vol. 46(17), pp. 9266-9273.

[8] Amini, S.H., Remmerswaal, J., Castro, M.B., Reuter, M.A. (2007): Quantifying the quality loss and resource efficiency of recycling by means of exergy analysis, Journal of Cleaner Production, Vol. 15, pp. 907−913.

[9] Paraskevas, D., Kellens, K., Renaldi, Dewulf, W., Duflou, J.R. (2012): Resource efficiency in manufacturing: Identifying low impact paths, 10th Global Conference on Sustainable Manufacturing (GCSM2012), Istanbul, pp. 271-276.

[10] Davis, J.R. (1998): Chemical Compositions and International Designations for Aluminum Alloys, Metals Handbook Desk Edition, Second Edition (ASM International), pp. 426-436.

[11] Mashhadi, H.A., Moloodi, A., Golestanipour, M., Karimi, E.Z.V. (2009): Recycling of aluminium alloy turning scrap via cold pressing and melting with salt flux, Journal of Material Processing Technology, Vol. 209 (7), pp. 3138–3142.

[12] Ohtaki, M., Arakawa, T., Murata, F. (2000): A new proposal of continuous agitationvacuum distillation process (CAVP) to remove Zn from aluminum scrap melt. In Fourth international symposium on recycling of metals and engineered materials. TMS: The Minerals, Metals, and Materials Society; 2000.

[13] LME, Special Contract Rules for High Grade Primary Aluminium,http://www.lme.com/downloads/metalsspecs/LME_Specifications_for_Primary_Aluminium_111010.pdf

[14] Kevorkjjan, V. (2010): The Recycling of Standard Quality Wrought Aluminum Alloys from Low-grade Contaminated Scrap, JOM, Vol. 62 (8), pp. 37-42.

[15] “EN 13920: Aluminium and Aluminium Alloys—Scrap” ,European Committee for Standardization, 2003.

[16] Classen, M., Althaus, H.-J., Blaser, S., Doka, G., Jungbluth, N., Tuchschmid, M. 2009: Life Cycle Inventories of Metals, Final report ecoinvent data v2.1 No.10, Swiss Centre for LCI, Dübendorf, CH.

[17] European Aluminium Association (2006): Aluminium Recycling in Europe the Road to High Quality Products.

[18] Hatayama, H., Daigo, I., Matsuno, Y., Adachi, Y. (2012): Evolution of aluminum recycling initiated by the introduction of next-generation vehicles and scrap sorting technology, Resources, Conservation and Recycling, Vol. 66, pp. 8-14.

Framework for Modeling the Uncertainty of Future Events in Life Cycle Assessment

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Abstract

One limitation of Life Cycle Assessment is that it relies on the expectation of what will happen to a product as predicted at the point of creation. However, changes in technology, the economy, and end-of-life treatment practices may alter future emissions. This paper describes a study done to develop a model to improve the accuracy of estimated emissions by incorporating uncertainty into the expected impacts of a product by considering events that alter the phases that have not occurred. A case study using this model on a laptop shows use phase GHG emissions reduced by up to 55% in one scenario.

Keywords:

Life Cycle Engineering; Uncertainty

1 INTRODUCTION

Life Cycle Assessment (LCA) is a leading technique used to determine the environmental impacts of a product or process. Results from LCA evaluations are presented with an assumed level of accuracy. However, the methodology relies heavily on the predictions of events that have not yet occurred. Specifically, it is up to the organization conducting the LCA to make assumptions about the future frequency and duration of product use and what will happen to the product at the end of its useful life. These expected events are not guaranteed to occur, yet very little research has been dedicated to incorporating their uncertainty into assessments.

Assumptions made about the use phase are significant, and for many products this phase accounts for the majority of impacts. For instance, the dominant contributor to the CO2 emissions of a Volkswagen Golf A4 is the fuel consumed during the use phase, which makes up around 77% of the life cycle emissions [1]. For a cotton t-shirt, the use phase laundering is responsible for 78% of the energy that is required, and 82% of the greenhouse effect that is created for the product [2]. Dell reports that the energy needed for the use phase results in 65% of the product carbon footprint of a laptop used in China [3], and 90% of a server operated in United States [4].

However, there are events that can occur which disrupt the assumed useful life of the average product. The estimated lifetime of many products is based on the average time before the next technology is released rather than when the product will no longer be useful. However, technological disruptions can occur that are beyond the scope of the average evolution of technology. Substitutive technologies may cause people to buy new products before old products have reached the end of their expected life. For instance, in the transition from videocassettes tapes to DVDs many consumers purchased a DVD player despite the fact that their VCR continued to work. As a result of the proliferation of the new standard, consumers that wanted to continue using VCRs would have increasing trouble using the old technology, as supporting industries, like tape manufacturers, died off. In other cases, complementary technologies alter the way consumers are expected to use existing products, and hence the impacts associated with them. Netbooks, smartphones, and tablets, such as Apple's iPad, do not fully replace laptop and desktop computers, but they have altered the purpose and frequency with which consumers use them [5,6].

Policies can also cut the useful time of a product short. For example, in the state of California, statue SB 33 was passed in 1984 as the standard under which cars must qualify to pass a smog check. If a car cannot meet this standard, the state offers an incentive to retire the gross polluting vehicle through its Voluntary Accelerated Vehicle Retirement program [7]. This retirement program can cut the life time of the car short, reducing the expected use time and emissions down from original estimates. Another example of policies that impact expected emissions is the sourcing of energy. Most LCAs rely on the current "energy mix," or the proportion of the energy being generated by various energy producing technologies, to estimate the expected emissions from energy demand over the use phase of the product at an assumed location. The proportion of renewable energy sources in the energy mix is largely dictated by legislation. Over time new means of power production with different associated emission will go online, and change the actual emissions that were projected for the use phase.

Other events can prolong the average use phase of products. In many instances, it is not economically feasible for consumers and companies to invest in new equipment. In slow economic times, companies may not have the capital to upgrade equipment, even if it is operationally and financially advantageous to do so; instead they will get along with the available devices on hand that are still operational. For instance, with the post-2008 recession, businesses may not have the financial resources available to refresh their computer hardware at the rate that they had anticipated when they first modeled the expected life time of the computers they purchased years ago.

In this paper we aim to improve the accuracy of the estimated emissions of a Life Cycle Assessment by including predictable disruptions to the life cycle, thereby increasing the meaningfulness of LCA results. First we provide a framework to incorporate the uncertainty associated with such events into the LCA of any given product sold at a certain point in time. Then, we present a case study which applies this theoretical framework to empirical data from existing LCAs. Specifically, the possibility of a recession and the release of a complementary product are incorporated into previous studies conducted on a laptop. Finally, we discuss results and draw some main conclusions.

2 PROPOSED METHODOLOGY

For this study, we consider future uncertainty by incorporating specific events that may disrupt the expected course of the average product. The impacts of such events are determined by evaluating their likelihood and consequences over the duration of the lifecycle phase in which they occur. We begin by assessing the estimated time that any of these products are expected to be in use. This period spans from when the product is first released on the market until the last product sold reaches its end of the life. In other words, it includes not just the estimated lifetime of the product but, also, the amount of time that the products are on the market.

Once we have established the period of consideration, we next identify events that could change the expected use or disposal of products over this span of time. These events will be referred to as lifecycle disturbances. Disturbances can either increase or decrease the expected impacts of a product. Examples of disturbance events include: a recession; a change in policy; the introduction of, or change to, a complementary technology which alters how consumers use the product; the development of a substitutive technology which displaces the product; and the development, or proliferation, of an end of life processing technique. Additional events beyond these examples could exist, and are dependent on the individual product. The example we use in this study will focus on disturbances during the use phase.

For each event, data is needed to determine the likelihood that it will take place and its impact if it does occur. Historic Data is used to model the probability that an event will occur over time. This data may be complex to obtain or estimate. If the historic data needed to model an event is not available, it is suggested that either the definition of the event is expanded to include other occurrence of a similar type or correlated data is used as a proxy. The case study that follows discusses some possible source for this data. However, determining the most suitable data for all possible events is beyond the scope of this paper, and we will reserve this task for future work.

The future uncertainty of the use phase can be modeled in a scenario-based framework. Let $A=\{\alpha_{1,}\ \alpha_{2,}\ \alpha_{3\ldots}\ \alpha_n\}$ be the set of all events that could affect the use time of the initial product and $U(\beta)$ be the use time when a set of events $\boldsymbol{\beta} \in \boldsymbol{P}(\boldsymbol{A})$occurs, where $\boldsymbol{P}(\boldsymbol{A})$ is the power set of *A*, which includes all of the subsets of *A*. Then, with an estimation of the probability that β occurs, $\mathbf{Pr}(\boldsymbol{\beta})$, we can calculated the expected duration of use during the use phase with the following equation:

$$\mathbf{E}[\mathbf{use\ time}] = \sum_{\boldsymbol{\beta}\in\boldsymbol{P}(\boldsymbol{A})} \boldsymbol{U}(\boldsymbol{\beta}) * \mathbf{Pr}\,(\boldsymbol{\beta}) \quad (1)$$

3 LAPTOP CASE STUDY

3.1 Introduction

Laptops serve as a good illustration for some of the potential unexpected disturbances that can take place over the life span of a product. There are several external events that can affect the rate at which consumers replace their laptops. Compared to other items, the obsolescence of high tech products is determined by the developments within the industry, rather than the functional life of a device. Also, the electronics industry in particular has recently been subjected to an increasing number of regulatory and voluntary market standards, including EPEAT, WEEE, Energy Star, and RoHS, which has intensified the generational differences between products.

3.2 Determining the Factors of Unexpected Disturbances

Period of Consideration

There are many estimates for the average duration of the use time of a laptop in LCA studies. IVF [8] estimates that a laptop lasts 5.6 years, Deng et al. [9] assumes that it is used for 2.9 years based on a survey, while O'Connell, and Stutz [3] evaluate the replacement time to be 4 years. For this study, the Dell figure of 4 years is used. This number is based on Energy Star's Typical Energy Consumption (TEC), which is also used to approximate the average use of the laptop. According to this standard, we assume that a laptop spends 60% of the time turned off, 30% being used, and 10% in sleep mode.

Meanwhile, we assume that the sales period, or the amount of time a laptop is on the market, is one and a half years. This is based on the assumption that laptop models are updated annually, though in actuality it can be less frequent. We add another six months to account for the fact that models are sold beyond the release date of the next version, until the remaining inventory is sold. With this figure, the sales period and the refresh rate combine to 5.5 years.

Identify Events

Given the scale of this study, we limit the disruptive events considered for a laptop to a recession and the release of a complementary technology. These two events have actually taken place in recent years and serve to illustrate the potential effects of disruptive events on impacts.

Predicting the Possibility of a Recession

Several factors make it difficult to predict when a recession will occur. The incidence of a recession is determined largely by changes in the gross domestic product (GDP). Yet, GDP serves as a poor predictor of the turning points of economic cycles [10]. Data from common economic indicators, like the GDP, lags months or even quarters behind the present day, making it difficult to determine even the current economic conditions. In addition, because recessions are rare, the corresponding data needed to adequately forecast them is limited [11].

When assessing the various recession forecast models that are currently available, several researchers have found them to be insufficient [10–12]. To our knowledge none of the existing models have been able to identify the start date of every recession correctly, without also providing false signals for downturns that do not come about. While researchers continue to refine the existing models [13–15] and explore alternative variables [16–18], Harding [12] notes that the unconditional probability would often serve as a better predictor than some of the models that have been proposed.

For this study, we must develop a method to determine the likelihood that a recession will occur at the point when laptop owners first begin to purchase newer replacement products to the point when the last customer is expected to refresh their hardware. The limitations of existing models, as well as their focus on shorter horizons, presently make them a poor candidate for estimating the probability of a recession many years into the future. However, with the correct variables, existing recession forecasting techniques, such as the differences in yield curves, and linear probability, univariate, and multivariate models, may later prove to be suitable methods to predict recessions farther on the horizon.

Instead we utilized data points from the National Bureau of Economic Research (NBER) to obtain the length of time between recessions in the United States, in order to determine the parameters of a probability distribution. We estimated the probability of a recession occurring from the third year of the period of consideration onward, as devices begin to reach the end of their life, using the Weibull distribution with fitted parameters. We define the time between recessions as the duration from the end of previous recession to the beginning of the next recession. These time intervals between events can be fitted to Weibull distribution. The shape parameter of the Weibull distribution represents whether the hazard rate function is increasing, decreasing, or constant over time. Changes in the hazard rates function over time indicate whether the next event will be more or less likely to occur as time goes on. The parameters of the Weibull distribution are estimated using Maximum-Likelihood Estimation (MLE). Despite the small amount of data points, we obtained a near 45% line in Q-Q plot, as shown in Figure 1, where the Q-Q plot is used to measure if two distribution are similar to each other or not. With the MLE estimator of the distribution, we can then calculate the probability that a recession will occur during a certain period of time, given the end time of the previous period.

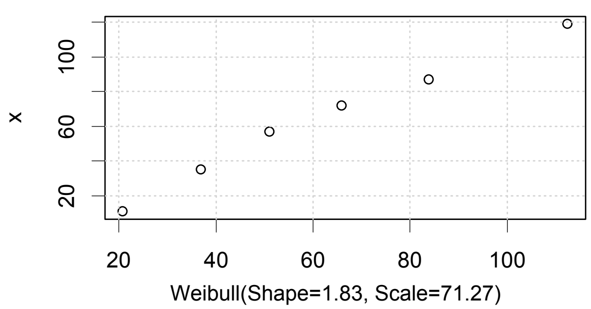

Figure 1: Q-Q Plot of the Fitted Weibull Distribution and the History Recession Data.

While the traditional definition of a recession is two consecutive quarters of shrinking GDP [19], NBER identifies recessions based on business cycles that begin the first day of a period following a peak through the last day of the period of the trough. More specifically, NBER defines a recession as "a significant decline in economic activity spread across the economy, lasting more than a few months, normally visible in real GDP, real income, employment, industrial production, and wholesale-retail sales [20]." Only data from the most recent decades was used, as researchers have suggested that the economy has become less volatile and that recessions have become less frequent and severe in recent decades [21–23].

Predicting the Impact of a Recession

We assume that if a recession occurs at the time when laptop owners are expected to begin purchasing new replacement devices, they will put off their purchase for a year on average. Under this assumption, the laptop is assumed to be in use for 5 years. Using data from Deng et al., the effects of an additional year of use will be another 34.76 CO_2e (kg) provided no other disturbance events take place.

Predicting the Possibility of a Complementary Product

The continuous development of technology leads to better and more functional products. Over the course of this development, complementary products are introduced. Eventually these products may evolve to replace the initial product. This phenomenon has been observed in various technologies, such as computers and video playing and recording devices. At any point in time the reduction in the use of the initial product due to the new complementary product can be modeled for period t as shown in the equation below: The proportional reduction in period *t* is:

$$R(t) * \min\{a(t)/S(t), 1\}, \tag{2}$$

where for period *t*, *R*(*t*) is the proportion reduction in the use of the initial product amongst those who purchase the complementary product, *a*(*t*) is the number of people who adopt the complementary product, and *S*(*t*) is the number of people who own the original product.

The number of people who adopt the new product, denoted *a*(t), may be small initially, before it becomes successful and is purchased at a much faster rate. Bass [24] developed a model to estimate the adoption of new technologies. His model describes the diffusion process of new products based on communication theory and the spread of word of mouth. According to the Bass diffusion model, a small group of people are innovators, who like to try new products, while others are imitators that only purchase a new product when they hear positive reviews from others that own it. Over time, the whole potential market gradually adopts the new product as more and more imitators hear about it. Since the development of the model, the diffusion of word of mouth has accelerated, due to the development of the internet and the use of technology in social interactions.

Many researchers have extended upon the Bass diffusion model and developed methods to estimate the parameters of those models using sale data. Readers are referred to [25,26] for more details and extensions of the Bass model. In general, the model consists of three parameters: the coefficient of innovation, *p*, the coefficient of imitation, *q*, and the potential market size, *m*. For this study, we utilize the nonlinear least squares (NLLS) approach proposed by [27] to estimate the parameters.

Note that the parameter *m* can be estimated using either previous sales data or a specific number based on an educated estimate. For the tablet, we use both initial sales data for the nascent product, as well as diffusion data on other technologies to estimate *m*. In the United States there is a large difference between the number of people who have adopted various technologies. It was estimated that that 52% of adults owned a laptop in 2010, while 77% owned either a laptop or a desktop in 2012 [28]. These figures equate to 40% and 58% of the overall populations in 2010 and 2012, respectively. Given their price point and ease of use, we believe that tablets are more accessible products than traditional PCs, and as a result will become more popular. Since tablets require very little technical know-how, they could potentially become devices owned by children and the elderly—a group who have traditionally been the most reluctant to adoption new technologies. In fact, tablet manufacturers, such as Apple [29], Samsung [30], Acer [31], and Amazon [32] have already started pilot programs for testing tablets in classrooms. Cellular phones, which have previously been a product with a high rate of penetration, can give an idea of the potential adoption rate of tablets. In 2010, 85% of adults in the United States owned a cell phone. Given this information, we will assume that the potential market size for tablets is 65% of the overall national population that is expected in 2017.

In our study, tablet PCs are viewed as new complementary product to laptops. The nonlinear least square method is used to estimate the adoption rate of tablet PCs using sales data of tablets from 2010 to 2012. Due to the availability of sales data of the whole tablet market, we estimated the 2010 sales according to [33] and the 2011 and 2012 sales using a combination of the sales number and the market share of Apple ipad and Samsung galaxy [34,35]. The 2012 Q4 ipad sales are estimated from global data and scaled to a figure for the U.S. [36]. We assume that this data is an accurate measure of adoption for tablets. The adoption curve of tablet PCs is shown in Figure 2.

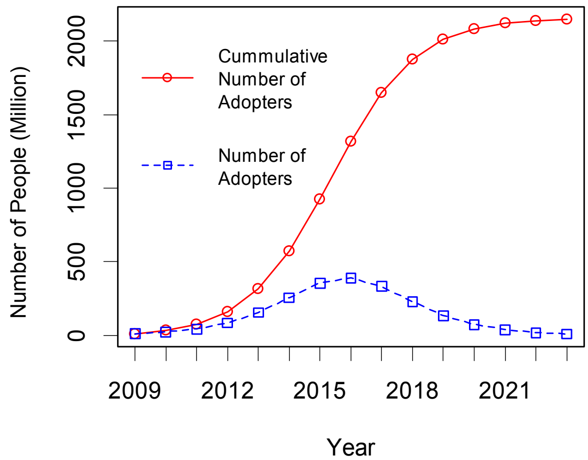

Figure 2: Estimated Adoption Curve for Tablet PC.

Surveys have shown that more than 30% of people who own both a tablet and a PC have reduced their usage of traditional devices [5]. However, these surveys do not indicate the amount of time by which these individuals have reduced their use. According to a report by Morgan Stanley [5], consumer PC usage decreased by 20% from 2008 to 2010. The report also suggests that, at present, tablet use is still limited to content consumption, such as web browsing, photo viewing, and music listening, while working, producing, and communicating, or creating content such as writing, spreadsheets, and edited photos, is still reserved for the PC. They calculate that around 75% of PC usage consists of content consumption. As a result, we assume that an increasing amount of desktop and laptop usage will be replaced by tablets, especially as more powerful hardware and software is developed. However, because of their small screen size and lack of a keyboard, PCs will still continue to be used for certain types of activities.

For the sake of simplicity, we will assume $R(t)$ to be a simple linear function with an upper bound:

$$R(t) = \min\{0.1^*t, 0.8\}. \quad (3)$$

For the number of people who own laptops at time t, denoted $S(t)$, we assume 52% is the saturate rate of laptop for U.S. adults, which is the actual total proportion of adults who owned the device in 2010 [37]. We assume that this rate will continue into the future, and we can estimate the exact number for $S(t)$ based on projections for the U.S. adult population [38].

3.3 Total Impacts of Events

We considered three scenarios to investigate how lifecycle disturbances can affect the use phase impacts of an LCA. First, impacts are benchmarked without the inclusion of any of these events using U.S. greenhouse gas emissions factors [39] and the LCA results of [3] and [9]. Then, impacts that incorporate future uncertainty are assessed for products that are released at two respective points in time: the years 2009, prior to the release of the iPad and the subsequent adoption of tablets, when the possibility of this event was still uncertain; and the present year, 2012, when the release of tablet is no longer being a possible uncertainty. Since the likelihood that a disruptive event will occur changes over time, the impacts for a single product will differ based on when it is released. As a result, the inclusion of this type of uncertainty differentiates competing products based on a temporal aspect.

In the second scenario, we consider a new laptop that was launched on the market in August 2009, from the perspective of that point in time. In 2009, there were indications within the industry that a new product category was coming in the near future. In general, the history of innovations within the computer industry shows that fundamentally different technologies take on average about 10 years of development before they matures into a successful format that a large number of consumers can afford. In 2009, the personal computer industry had gone about that long, since the last big technology, laptops, had taken off. Additionally, for the two decades leading up to this point, the computer industry had been developing new mobility products, and had released technologies such as personal digital assistants (PDA) and netbooks. The iPhone and subsequent smartphones had been hugely successful, offering users increased access to some of the functions of a PC in a mobile device. Similarly, an iPod with Wi-Fi and multi-touch interface had hit the market in 2007. Rumors of the iPad were escalating [40]. All of this evidence suggested that there was going to be a new mobile product, and this product could displace some the functional uses of desktops and laptops.

For the 2009 scenario, we assume that the probability of a new product being introduced in 2010, 2011, or 2012 is each 30%. There is also 10% chance that there would be no new complementary product coming during the planning periods. Once the new product is launched on the market, we assume the reduced use time of the laptop depends on the adoption rate of the new product.

In the third scenario, we consider an LCA study that would be conducted in 2012 for a new laptop that is going to be launched in January 2013. For this scenario, the tablet has already been introduced, so the risk is low that there will be another complementary product coming on the market that will potentially displace the PC in the short term. Then the only uncertain event in this scenario is the recession. Note that the use time of laptops here requires an adjustment due to the adoption of tablet PC as well.

As mentioned earlier, a recession only affects the use time of a product when it happens in the last portion of the period of consideration. Hence, we assume that if there is a recession during the time between the third year and the fifth and a half year, the actual use time of a laptop increases for one year on average. The probability of a recession during a certain period can be estimated using the Weibull distribution with fitted parameters.

To simplify the analysis, we assume that the events we considering are independent of each other. In real life, with more information available, such as the correlation between the technology development and recession, the joint probability of dependent events can be estimated. With the assumption of independence, we calculate the probability and the corresponding use time of each event and obtain the expected greenhouse gas emissions using the U.S. energy mix [39] for the three scenarios, as are shown in Figure 3. The one standard deviation error bars for the 2009 and 2010 scenarios are also in the figure.

Our results show that the expected carbon footprint for the scenarios that consider future events differs from the benchmark scenario significantly. In our case study, due to the high probability of new complementary technology, we observe a much lower use phase energy consumption and GHG emissions compared with the benchmark scenario. Use phase greenhouse gas emissions are 24-55% lower than the benchmark scenario, contributing 20-33% to the overall LCA emissions reported by O'Connell and Stutz [3], as opposed to their estimates of 47%. Also, we observe that the standard deviation for the 2012 scenario is smaller than that of 2009 scenario because there are fewer uncertain events in the 2012 scenario.

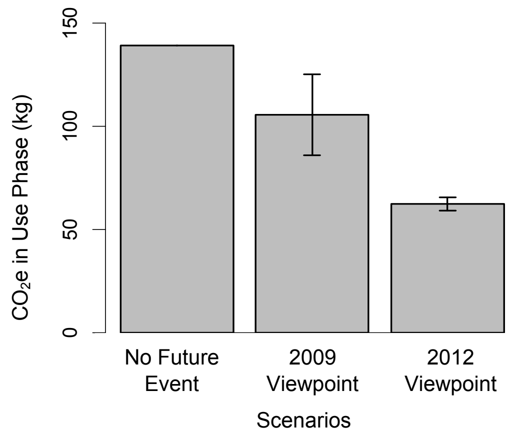

Figure 3: Expected CO2e for Scenarios.

For products that consume energy during the use phase, the energy consumption is usually a significant proportion of the total life cycle energy consumption. As demonstrated in our case study, future event scenarios could alter LCA result.

4 CONCLUSIONS

The uncertainty of Life Cycle Assessment is a very important factor to consider in order to ensure the accuracy of estimated emissions and meaningfulness of LCA results. However the uncertainty associated with expected events, including the use phase, which is known to be an important part of many products, has not been discussed. In this paper, we propose a model to incorporate uncertainty into the expected impacts of a product by considering disturbance events that may alter the phases that have not yet occurred. A case study using this model was performed on a Dell Laptop computer, based on the LCA results of [3] and [9]. We considered the impacts of two possible disturbance events, a recession, and the release of a new technology, and how such events affect the use of the average laptop.

The impacts of including such uncertainty were shown to alter results significantly, reducing use phase greenhouse gas emissions by 55% in one scenario. They also illustrate that the impacts of a single product can change significantly based on temporal aspects. While data and parameter uncertainty is commonly incorporated into LCAs, through statistical techniques such as sensitivity and Monte Carlo analysis, discussions about contextual or choice uncertainty, which deals with the definitions, system boundaries, and assumptions made while conducting the LCA are less prevalent [41]. Our results show that the assumptions made about the impacts of expected events, which have not yet occurred, are significant and can lead to an inaccurate assessment.

Given the scope and time constraints of this paper, we were only able to consider two events and provide a basic estimation of their probabilities. The proposed methodology would provide the most accurate results if all possible disturbance events that could impact the results of a LCA were considered. This illustrates that one drawback of the methodology is that there are no readily available resources for companies to identify such events, or obtain an easy estimates of their likelihood. Companies may be limited in the time and resources they can dedicate to exhaustively and accurately conduct such research. On the other hand firms have access to additional forecasting reports of their industry, which may provide better data for estimating the probability of events.

The case study presented in this work represents only two possible events that can disturb the expected lifecycle. The impacts of other events that might affect the use time of a product need to be explored in forthcoming work to substantiate the validity of our proposed model. In addition, the application of the model to other products will be attempted, to see if findings also hold true. Work dedicated to finding the most appropriate resources to estimate the possibility of events would also improve our confidence in the validity of these results. A possible prospect for future study includes a database constructed for identifying events and their probabilities which would aid others in incorporating the uncertainty of expected emissions into future LCA studies.

5 REFERENCES

[1] Schweimer G. W., and Levin M., (2000), Life cycle inventory for the Golf A4, Research, Environment and Transport.

[2] Laursen S. E., Hansen J., Knudsen H. H., Wenzel H., Larsen H. F., and Kristensen F. M., (2007), EDIPTEX: Environmental assessment of textiles, Danish Environmental Protection Agency, working report, **24**.

[3] O'Connell S., and Stutz M., (2010), Product carbon footprint (PCF) assessment of Dell laptop-Results and recommendations, Sustainable Systems and Technology (ISSST), 2010 IEEE International Symposium on, pp. 1–6.

[4] Stutz M., O'Connell S., and Pflueger J., (2012), Carbon footprint of a dell rack server, Electronics Goes Green 2012+ (EGG), 2012, pp. 1 –5.

[5] Morgan Stanley, (2011), Tablet Demand and Disruption.

[6] The Nielsen Company, (2011), Connected Devices: How We Use Tablets in the U.S.

[7] CA Air Resources Board, (2011), Car Scrappage - Voluntary Accelerated Vehicle Retirement [Online]. Available: http://www.arb.ca.gov/msprog/avrp/avrp.htm. [Accessed: 08-Dec-(2012)].

[8] TREN E., (2005), Preparatory studies for Eco-design Requirements of EuPs „LOT 3-Personal Computers (desktops and laptops) and Computer Monitors. Final Report ". European Commission DG TREN, Preparatory studies for Eco-design Requirements of EuPs, Contract TREN D, **1**, pp. 1–8.

[9] Deng L., Babbitt C. W., and Williams E. D., (2011), Economic-balance hybrid LCA extended with uncertainty analysis: case study of a laptop computer, Journal of Cleaner Production, **19**(11), pp. 1198–1206.

[10] Smirnov S., (2011), Discerning “Turning Points” with Cyclical Indicators: A few Lessons from “Real Time”Monitoring the 2008–2009 Recession, Higher School of Economics Research Paper No. WP2/2011/03.

[11] Rudebusch G. D., and Williams J. C., (2009), Forecasting Recessions: The Puzzle of the Enduring Power of the Yield Curve, Journal of Business & Economic Statistics, **27**(4), pp. 492–503.

[12] Harding D., and Pagan A., (2010), Can We Predict Recessions?, 6th Eurostat Colloquium on Modern Tools for Business Cycle Analysis.

[13] Dueker M., (2005), Dynamic Forecasts of Qualitative Variables, Journal of Business & Economic Statistics, **23**(1), pp. 96–104.

[14] Kauppi H., and Saikkonen P., (2008), Predicting U.S. Recessions with Dynamic Binary Response Models, Review of Economics and Statistics, **90**(4), pp. 777–791.

[15] Chauvet M., and Piger J., (2008), A Comparison of the Real-Time Performance of Business Cycle Dating Methods, Journal of Business & Economic Statistics, **26**(1), pp. 42–49.

[16] Estrella A., and Mishkin F. S., (1998), Predicting U.S. Recessions: Financial Variables as Leading Indicators, Review of Economics and Statistics, **80**(1), pp. 45–61.

[17] Owyang M., Piger J., and Wall H., (2012), Forecasting national recessions using state level data, Federal Reserve Bank of St. Louis Working Paper No.

[18] Wright J., (2006), The yield curve and predicting recessions.

[19] Shiskin J., (1974), The Changing Business Cycle; POINTS OP VIEW, The New York Times.

[20] Hall R., Feldstein M., Frankel J., Gordon R., Romer C., Romer D., and Zarnowitz V., (2003), The NBER’s Business-Cycle Dating Procedure, Business Cycle Dating Committee, National Bureau of Economic Research.

[21] Kim C.-J., and Nelson C. R., (1999), Has the U.S. Economy Become More Stable? A Bayesian Approach Based on a Markov-Switching Model of the Business Cycle, The Review of Economics and Statistics, **81**(4), pp. 608–616.

[22] McConnell M. M., and Perez-Quiros G., (2000), Output Fluctuations in the United States: What Has Changed Since the Early 1980’s?, The American Economic Review, **90**(5), pp. 1464–1476.

[23] Stock J. H., and Watson M. W., (2010), Estimating Turning Points Using Large Data Sets, National Bureau of Economic Research.

[24] Bass F. M., (1969), A new product growth for model consumer durables, Management Science, **15**(5), pp. 215–227.

[25] Bass F. M., (2004), Comments on “A New Product Growth for Model Consumer Durables”: The Bass Model, Management Science, **50**(12), pp. 1833–1840.

[26] Mahajan V., Muller E., and Wind Y., eds., (2012), New-Product Diffusion Models, Springer.

[27] Srinivasan V., and Mason C. H., (1986), Nonlinear Least Squares Estimation of New Product Diffusion Models, Marketing Science, **5**(2), pp. 169–178.

[28] Mitchell A., Rosenstiel T., and Christian L., (2012), Mobile Devices and News Consumption: Some Good Signs for Journalism, the Pew Research Center.

[29] Apple - Education - iPad makes the perfect learning companion [Online]. Available: http://www.apple.com/education/ipad/. [Accessed: 08-Dec-(2012)].

[30] Samsung and Khan Academy Launch Pilot Tablet Program, Education Week - Digital Education [Online]. Available: http://blogs.edweek.org/edweek/DigitalEducation/2012/10/samsung_and_khan_academy_launc.html?cmp=SOC-SHR-FB. [Accessed: 08-Dec-(2012)].

[31] Acer-EUN Tablet Pilot - Acer-EUN’s Educational Netbook Pilot [Online]. Available: http://1to1.eun.org/web/acer/tablet-pilot. [Accessed: 08-Dec-(2012)].

[32] Kindle Education [Online]. Available: http://www.amazon.com/gp/feature.html?ie=UTF8&docId=1000412651. [Accessed: 08-Dec-(2012)].

[33] Tablet PC sales in the U.S. 2010-2015 | Forecast [Online]. Available: http://www.statista.com/statistics/200248/forecast-of-tablet-pc-sales-in-the-united-states-from-2010-to-2015/. [Accessed: 07-Dec-(2012)].

[34] Apple vs. Samsung Trial Forces Companies to Open Up the Books, AllThingsD [Online]. Available: http://allthingsd.com/20120809/apple-vs-samsung-trial-forces-companies-to-open-up-the-books/. [Accessed: 07-Dec-(2012)].

[35] Net Applications [Online]. Available: http://www.netmarketshare.com/2012/02/01/The-iPad-s-Competition-Still-Small-but-Growing-. [Accessed: 08-Dec-(2012)].

[36] Apple Q4 2012 hardware sales: By the numbers | ZDNet, ZDNet [Online]. Available: http://www.zdnet.com/apple-q4-2012-hardware-sales-by-the-numbers-7000006435/. [Accessed: 08-Dec-(2012)].

[37] Zickuhr K., (2011), Generations and their gadgets, Pew Research Center.

[38] U. S. Census Bureau D. I. S., 2008 National Population Projections [Online]. Available: http://www.census.gov/population/projections/data/national/2008.html. [Accessed: 07-Dec-(2012)].

[39] The U.S. Environmental Protection Agency, eGRID [Online]. Available: http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html. [Accessed: 07-Dec-(2012)].

[40] The Apple Tablet: a complete history, supposedly, Engadget [Online]. Available: http://www.engadget.com/2010/01/26/the-apple-tablet-a-complete-history-supposedly/. [Accessed: 08-Dec-(2012)].

[41] Finnveden G., Hauschild M. Z., Ekvall T., Guinée J., Heijungs R., Hellweg S., Koehler A., Pennington D., and Suh S., (2009), Recent developments in Life Cycle Assessment, Journal of Environmental Management, **91**(1), pp. 1–21.

Life Cycle Assessment and Life Cycle Costing – Methodical Relationships, Challenges and Benefits of an Integrated Use

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Abstract

Due to discussions on climate change, environmental pollution, exhaustible energies and resources ecological efficiency has gained importance as one decisive objective beside economic efficiency. As a concept for sustainability appraisals, life cycle engineering addresses both of the efficiency dimensions basing on two pillars: life cycle assessment (LCA) and life cycle costing (LCC). LCA and LCC are often applied independent from each other and thus, significant relationships between ecological and economic efficiency remain unconsidered. Therefore, the paper investigates mutual points of contact and methodical relationships and presents a procedure model for an integrated use of LCA and LCC.

Keywords:

Life Cycle Assessment; Life Cycle Costing; Multi Criteria Decision Making

1 INTRODUCTION

In recent years, growing concerns about climate change, environmental pollution and exhaustible energies and resources have led to a shift of paradigms and priorities from the exclusive tracking of economic objectives to a consideration of ecological objectives like greenhouse gas reduction, conservation of natural resources, etc. Referring to this shift, life cycle engineering (LCE) is a concept for life cycle wide sustainable design, aiming at an economically as well as ecologically sustainable development, manufacturing, operation and disposal of products and production technologies.

In LCE, life cycle assessment (LCA) and life cycle costing (LCC) are the two major approaches for sustainability analyses and appraisals. LCA especially addresses the environmental burdens of a product by the systematic "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" [1]. But, due to its exclusive focus on ecological aspects, it does not regard economic effects of ecologically sustainable products or production technologies design. This can be achieved by LCC. The economical approach aims at revealing the overall costs and cost trade-offs caused by a specific product or production technology during its life cycle [2]. Though both approaches are used for life cycle wide sustainability appraisals, they are often applied independent from each other. Thus, significant trade-offs between economic and ecological consequences of a product throughout its life cycle remain disregarded [3].

But, that such trade-offs are important can be demonstrated by regarding the relevance of ecological objectives in managerial decision making. According to [4], three basic strategies of pursuing ecological objectives (Figure 1) can be distinguished depending on their positioning in an organizations hierarchy of goals:

- Defensive strategy: Environmental measures remain at a minimum by tracking ecological objectives simply in order to fulfill regulatory requirements and societal expectations.
- Middle strategy: Pursuing ecological objectives to improve the fulfillment of success goals (e. g., because of potentials for cost savings or revenue growth).
- Offensive strategy: Viewing ecological efficiency as stand-alone objective coequal to other success and performance objectives (based on sustainability and social responsibility thinking).

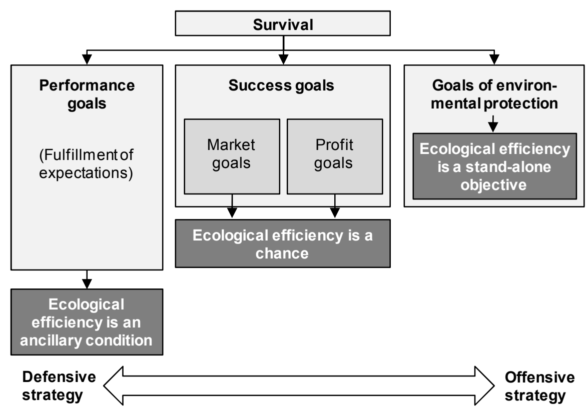

Figure 1: Strategy-related positioning of ecological objectives (ecological efficiency) in a company´s goal system (derived from [4]).

The existence of the strategies coincides with the fact that ecological and economic goals may be competing or complementary. So, integrating LCA and LCC is essential for the planning of environmental measures by identifying trade-offs between the achievement of ecological and economic goals and appraising measures with respect to both goal dimensions in a consistent way. This will, e. g., justify the ecological measures competing for capital resources by appropriately assessing their economic consequences throughout the products life cycle [5]. Additionally, a LCA-LCC integration may help to realize accessible synergy effects concerning data acquisition and analysis. Striving for an integrated assessment, an overview of LCA and LCC is presented (section 2). Based on that, a procedure model for integrated LCA-LCC studies is introduced (section 3). In this context, relevant relationships, emerging methodical questions as well as challenges are discussed. The final section summarizes and gives an outlook on future research (section 4).

2 LIFE CYCLE ASSESSMENT AND LIFE CYCLE COSTING

2.1 Fundamentals of LCA

Life cycle assessment is a general procedure (specified in [1]) for identifying and quantifying the environmental impacts of a product system by following the product life cycle from cradle-to-grave. It can be used to detect environmentally critical areas of a product system and to compare environmental (dis)advantages of alternatives. Thus, it aims at revealing ecological improvement possibilities and facilitates the design of eco-friendly products, production processes and strategies. Figure 2 shows its four phases which are briefly described in the following.

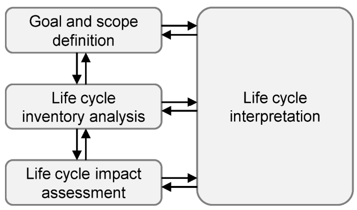

Figure 2: Phases of life cycle assessment [1].

In the first phase, *goal and scope definition*, the study's purpose and the considered product system are specified. This includes:

- the intended application and audience of the study,
- the product, its function and the corresponding functional unit,
- the system boundaries according to the product, the unit processes and the life cycle phases to be studied,
- the methods (e. g., for impact assessment and allocation), assumptions and limitations which are applied for the study.

These items form the basis for system modeling in subsequent phases and should therefore be defined as precise as possible.

Based on the settings of phase 1, *life cycle inventory (LCI) analyses* are generated to quantify relevant input and output flows of the product system. For this purpose, all activities and unit processes (the smallest process element) as well as the flows between them (energy, materials, products, waste, emissions, etc.) are modeled. Afterwards, quantitative (amount of each type of input and output) and qualitative (descriptions of technology, conditions of emission measurement, etc.) data are collected. For the numerical data, further steps of normalization, transformation and allocation (for allocation methods see [1] [6]) are usually required to link them to the reference flow of the functional unit and to calculate the environmental loads of each activity and unit process. The functional unit expresses the performance of a product system in quantitative terms (e. g., 500 m² heated area). It serves as a reference basis the input and output flows are related to with the help of a reference flow. This flow specifies the amount of process outputs needed to fulfill the aspired performance of the product system [1].

In phase 3, the significance of the quantified environmental burdens is determined by *life cycle impact assessment* (LCIA). Here, the environmental loads are assigned to selected impact categories (climate change, human toxicity, etc.). The impact categories are usually defined in the goal and scope definition, but are specified in LCIA according to the information collected in LCI (for different impact categories and their further specifications see [6]). In any case, double counting should be avoided by selecting impact categories which are mainly independent from each other. The same applies for the assignment of LCI data to impact categories [6]. After assigning LCI data to impact categories, appropriate indicators are chosen for each category (e. g., global warming potential [kg CO_2 equivalents per functional unit]), which reflect the aggregated contribution of all environmental loads to the specific type of impact category. The various category indicators (e. g., global warming, acidification, eutrophication potentials) represent the environmental profile of the product system. By further steps of normalization and weighting they can be expressed in one environmental score (similar to utility value analysis [7]). So, in LCIA the multitude of LCI parameters is transferred to more comprehensible and therewith comparable results. Since impact assessment requires well-founded information about environmental mechanisms, also ready-made LCIA models (e. g., eco-indicator'99, EPS method) can be of support. Such models provide impact categories, equivalence factors and principles for normalization or weighting to determine the environmental impacts of a product system in form of a single index or set of category indicators [6].

The final phase of LCA is *life cycle interpretation.* This phase is based on findings of LCI and/or LCIA and aims at drawing conclusions about the ecological efficiency of products and process technologies and at deriving improvement recommendations (e. g., alternative designs). For this purpose, completeness and consistency of the LCA-study are checked and significant parameters and issues are identified by performing sensitivity analyses [1].

2.2 Fundamentals of LCC

As a method for cost management, LCC aims at detecting and evaluating all monetary consequences (e. g., cost, revenue, cash flows) related to an object and its life cycle from the perspective of an economic decision maker (producer, consumer) [8]. It can be applied for selection problems (e. g., concerning product and production technology designs) and for identifying cost drivers [9]. Especially in managerial literature, a variety of LCC models exists. In general, these models refer to specific types of objects with a main focus on products (and services) and non-consumable resources (e. g., machinery, software) [13]. Beyond that, LCC is discussed in engineering standards [9] [10], regarding products and production facilities, outlining LCC basics and giving advice for practical application. Besides, LCC overlaps with total cost of ownership (TCO) approaches [11]. Taken as a whole, these models provide basic life cycle descriptions for several objects including different characteristics, methods, and procedures for systematic appraisals of life cycle wide monetary consequences.

To provide an overview of main steps and aspects of LCC, a procedure model for technical and economic life cycle evaluations proposed by [12] (Figure 3) will be used. This relatively abstract and ubiquitously applicable model refers to life cycle-related decisions for complex systems. It summarizes the common basis of existing LCC models, systematically incorporates the elements of decision theory (target measures, alternatives, etc.), and can also be adapted for integrated LCA-LCC studies. As shown in Figure 3, the procedure model is subdivided into two modeling levels, system and sub system level. The latter was introduced to reduce the complexity of the problem. Since the steps are identical for both levels, they are only explained for the system level.

The economic life cycle valuation of an object starts with the definition of evaluation goals and scope [S0]. Here, the purpose of the study is specified and possible decision alternatives and basic evaluation concepts are selected. Concerning the latter, methods of investment appraisal come to the fore, since LCC is mainly applied for long-term investment decisions. Depending on the consideration of time-related effects, static and dynamic methods can be distinguished. Static methods base on simplifying assumptions about representative average periods, but neglect differences in the timing of costs and other monetary measures (for reasons of simplification only the term cost is used here) and related effects (e. g., interest).

Dynamic methods are rather recommended. They resolve this deficit by including several periods and financial mathematics to adequately consider time-related effects. Thus, the value resulting from long-term investment is represented more realistically [7].

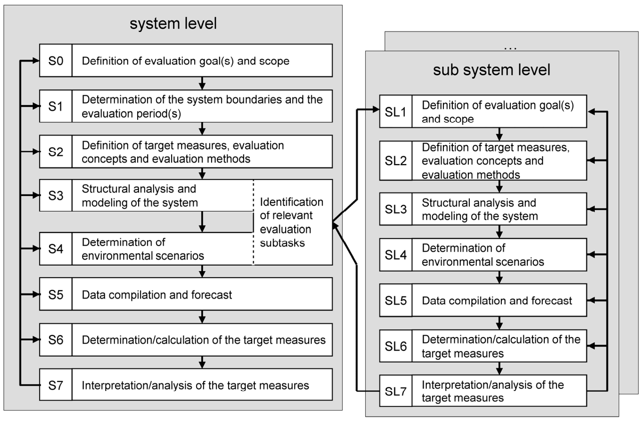

Figure 3: Procedure for life cycle evaluation (adapted from [12]).

In the next step, the system boundaries and evaluation period(s) are determined [S1]. This refers to the life cycle phases relevant for the study and the inclusion of upstream and downstream phases and related monetary effects. For subdividing and modeling, general life cycle models as in [13] can be used. Beyond that, a supplementary specification of time segments, e. g., on an annual basis, is often required. This forms a fundament for the assignment of costs to the point in time at which they presumably occur.

Based on these specifications, the target measures and accounting methods are defined [S2]. With respect to the discussion on dynamic investment appraisal [S0], financial target measures, such as net present value (NPV) or internal rate of return, are focused. Especially the NPV method is preferred as the scientifically most accepted dynamic method. The NPV represents the value of all future cash inflows (CIF_t) diminished by the cash outflows (COF_t) and discounted to the point in time (t), when investment decisions have to be made (usually the beginning of a planning period in $t=0$). Using a discounting factor q^{-t} (with $q = 1 + i$ and i as rate of return), the NPV can be expressed as follows [7]:

$$\mathrm{NPV} = \sum_{t=0}^{T} (\mathrm{CIF}_t - \mathrm{COF}_t) \cdot q^{-t} \tag{1}$$

Afterwards, the structure of the relevant system is analyzed and the respective processes, activities and available alternatives are modeled [S3]. For systematically decomposing the system, product and process breakdown structures have to be developed.

The cost caused by the processes and activities depend on a multitude of influencing factors. They could be of internal (conditions of technical equipment) or external (competitors, current law, etc.) origin. To include these factors adequately, different environmental scenarios (environmental in a wide sense covering technological, economical and ecological facets, etc.) are defined in [S4]. For analyzing the current and future outcomes of influencing factors and their impacts on each other and on cost, system-analytical methods (e. g., MICMAC method, scenario analysis) are applied.

The findings about the processes, activities and influencing factors form the basis for estimating the economic consequences, especially for forecasting cost items [S5]. In order to achieve transparency in the cost and to gain results with high explanatory value, costs are typically distinguished by content and time. To support this differentiation, cost breakdown structures can be used [8].

After the costs have been forecast, the available alternatives are evaluated by calculating the target measure(s) [S6] defined in [S2].

Finally, the outcomes have to be analyzed with respect to the goals and alternatives [S7]. Since cost estimation and forecast involve uncertainties, additional sensitivity analyses are recommended.

3 TOWARDS AN INTEGRATED USE OF LCA AND LCC

After both approaches have been described, integration aspects are discussed. However, first approaches for an integrated view do already exist. Especially, cost aspects are included in LCA studies and cost effects of environmental impacts in LCC (see below). But, these approaches are not really mature and support a concerted economic-environmental decision making only insufficient.

Following the procedure model introduced in section 2, goal-, methodical- and data-related relationships as well as challenges central for LCA-LCC integration are discussed. In particular, the following points are picked up: goals of the study (e. g., decision support, reporting); aspects of scope definition like target measures (cost, ecological efficiency), life cycle concepts, functional units; system boundaries and system modeling approaches; database aspects as well as means and methods for the analysis and interpretation.

[S0] Goal and scope definition

The first step in LCA and LCC is the definition of the goal(s) and the scope of the study. Basically, here, the object(s) of the study, the functional unit and the intended application (e. g., for economic-ecological sustainability assessment), the reasons (e. g., design decisions in product development) and the target audience (e. g., CEO, public authorities) have to be specified. For a common LCA-LCC survey, the basic goal and scope settings for both concepts must not contradict to enable decision makers to prepare decisions concerning the life cycle wide economic and environmental success of their products, processes, or services.

Though in literature, combined LCA-LCC analyses can be found, the compatibility of the concepts has to be discussed with respect to their general scope, in particular, the type of life cycle concept used, the modeling of time and the definition of a functional unit in LCA.

(1) First, for an LCA-LCC integration it has to be clarified how much LCC is already in LCA and vice versa. LCA aims at revealing ecological consequences of product systems. LCA approaches already apply economic information like prices, averaged accounting data, etc. in two different ways. First, it serves as a base for allocating input and output data to co-products and wastes [1]. Second, it is used to monetize LCA results [3]. Then, relevant cost or cash flows can be either integrated via an additional economic impact category [14] or by aggregating all effects to an overall LCC measure (e. g., average yearly costs, NPV, internal rate of return, etc.) [15]. Unfortunately, most of the LCA contributions do not specify the concrete applied target measure or calculation method. But, though cost and other monetary figures may serve as a means of analyzing and interpreting ecological impacts, this is – at least in most of the published cases – not done according to the classical economic LCC interpretation (section 2.2). The analyses remain ecologically intended, other monetary consequences are not considered.

In contrary, LCC ideally considers all life cycle wide monetary consequences of a product, technology, etc. This should also comprise the consequences from ecological effects. However, this principle guideline can be implemented in different ways:

1. by only including the cost of materials, energies, auxiliaries, and perhaps cost or revenues of co-outputs or wastes (“pure LCC”);

2. in addition to (1), by explicitly including differentiated internal eco cost and revenues. They may comprise cost of ecological issues (environmental management, certification cost, etc.), cost incurred by ecological accidents (i. a., forced clean-up costs), taxes on emissions and resource consumption [16], and so on;
3. by also considering external eco cost in order to estimate the effects of a possible future internalization of these cost.

However, in each of the cases, the aim of the analysis is an economical one. Ecological effects are only seen as cost or revenue drivers or components (middle strategy in Figure 1) and not as stand-alone targets (offensive strategy in Figure 1).

In an integrated study neither ecological nor economic values alone would be a good basis for decision making, there must be minimum two separate measures, and these have to be based on a concerted evaluation basis.

(2) Therefore, an essential precondition for meaningful results is the compatibility of the evaluation goals. From the descriptions in section 2 can be concluded that both approaches contribute to the identification, assessment, and comparison of products and production technologies, appropriate design strategies, etc. What differs might be the underlying intention. LCC aims at the determination of the economic success of single products (absolute profitability), the relative profitability of products or the continual controlling of cost, cash flow or success over a product's life. In contrary, LCA studies are rather directed to fulfill publicity requirements like environmental reporting, or they are applied for ecologically intended design decisions (like resource efficiency improvements, material or production technology selection). Compared to LCC, LCA results can only support decisions about the relative eco-friendliness (equivalent to relative profitability) of product systems. Since every product alternative will concern ecology to some degree, there cannot be decisions with respect to the absolute eco-friendliness of a single product – the omission alternative (no realization of the product at all) would always be favorable. However, the absolute degree of environmental impacts can be determined. But this information is not really meaningful in decision making without any reference value.

(3) A further integration aspect is the life cycle concept. In both concepts, the life cycle of an object is modeled as an object system. This object system is subdivided into unit processes. In LCA literature is often stated that unit processes represent phases or more detailed sections of the system life cycle (raw material acquisition to waste treatment), while process decomposition in LCC usually follows a product-oriented economic life cycle (i. a., market introduction, growth, etc.) [17]. However, the use of a certain life cycle concept seems not to be a characteristic of LCA or LCC, since LCC does not necessarily have to be based on such an economic life cycle. In contrary, the mentioned standards and the TCO approach refer to a system-related life cycle with manufacturing, use and disposal phase. Therefore, the life cycle concepts do not seem to be an integration barrier – the challenge is rather the selection of adequate life cycle phases dependent on the goals, object system and functional unit.

(4) As described, the functional unit serves as reference unit to set a standardized basis for the comparability of LCA results. It can be an object function (pairs of hands dried by air dryer or towel [1]), a defined object system (e. g., a car body for trains with a useful life of 25 years and an intended mileage of 7,500,000 km [18]) or the output of an object system (e. g., a passenger kilometer, 1 TJ electricity). Though in LCC the term functional unit does not exist, the examples below show that similar reference units can be used: (i) to identify the life cycle cost of air dryer and towel, the pairs of hands dried would be a relevant information for comparisons; (ii) the life cycle cost of train car-bodies are calculated for different numbers of pieces manufactured [18]; (iii) life cycle cost of a car can be scaled down to cost per passenger kilometer. These are all examples where LCA and LCC can be related to the same functional unit. So, for an integrated LCA-LCC, only an appropriate reference unit has to be chosen.

(5) Another problem arises from the fact that the functional unit refers to a product that is typically embedded in a complex company system together with other products. They share many of the resources (e. g., facilities, equipment, energy) what causes the problem that neither costs nor ecological burdens can be allocated to the products according to the causer-pays-principle. To deal with this problem, simplified allocation rules from cost accounting theory can be used in LCC and transferred to LCA [2].

[S1] Determination of system boundary and evaluation periods

From the previous discussion and with respect to **system boundaries** and basic **limitations** determination, three LCA scope scenarios (LCA 1 – LCA 3) – partly corresponding with LCC scope scenarios – can be derived. They should be briefly described.

Often, an LCA study does not refer to a cradle-to-grave, but only to a gate-to-gate study [1]. That means, (1) only a part of the life cycle is analyzed (e. g., use phase), and (2) a phase-specific functional unit (e. g., ton kilometer for transport) is used. LCA's with limitations like that often evaluate only environmental impacts directly caused in the respective phase and for the respective functional unit. That would mean: in a use phase scenario only the direct impacts of the product use are considered; impacts from previous phases (e. g., manufacturing) or to subsequent phases (e. g., waste disposal) are beyond the system boundary (*LCA 1*). For LCC, this is a less realistic scenario, since this approach explicitly aims at concerning different life cycle phases in decision making.

LCC analyses usually include cost of upstream (represented by acquisition cost) and downstream phases (e. g., represented by liquidation values). So, for a highly integrated use, the scope/system boundary in LCA would have to be extended to environmental impacts caused by the product system in phases previous and subsequent to the use phase (*LCA 2*). Up to now, e. g., impacts of human resources and capital equipment are usually not covered [19]. From this it follows that decision makers possibly neglect relevant ecological effects and do not choose the most eco-friendly product. Thus, it has a lot to commend an extension of the boundary. Another reason would be that if all environmental impacts could be monetized (all external cost are internalized), a company would include these total ecological cost in its cost and price calculations.

From the life cycle concept discussion follows that LCA can also be based on the integrated life cycle and made for a series of product units being produced, sold, etc. over time (*LCA 3*). When regarding this scope in LCC, temporal and quantity effects (e. g., learning curve effects, inflation rates, price changes) should be included to model the economic consequences realistically. Some of these aspects may be taken up in LCA: consumption reduction is relevant for ecological evaluations; consumption-dependent environmental loads and their (relative) weighting factors may change over time. Steady state models are not constructive to grasp such effects; this is already recognized in LCA literature [20]. Thus, to anticipate changes in the environmental impact potential, time dependent environmental data should be included for an integrated study. However, this raises two questions: Firstly, environmental loads and their impacts have to be forecast over time (see [S5]) which would be a difficult task in data collection. Secondly, periodical impacts have to be aggregated to a life cycle wide value – either by calculating average values or by modeling the change of environmental burdens over time analog to discounting monetary measures. However, the dynamization of LCA is still an open research question.

[S2] Target measures, evaluation concepts and methods

In this step, the target measures for a joint LCA-LCC study and the concepts and methods to calculate them are chosen. This selection can largely be handled independently from each other. Only two points are worth mentioning: Firstly, the double counting of effects (e. g., the inclusion of a specific environmental impact in an eco-indicator and as a cost driver) should either be avoided or made aware. Secondly, a method for the joint evaluation for both economical and ecological results has to be defined (see also [S7]).

[S3] Structural analysis and modeling of the system

In this step, the product system is analyzed with respect to the set goals, scope and target measures, to design an appropriate system model. The resulting model has to meet the LCC and LCA requirements and must provide a basis for data compilation and forecast.

Basically, for LCA studies, process-based, input-output-based or hybrid modeling methods are known [21]. With a process-based approach product components and unit processes (or flows) are decomposed and modeled in detail. Since there is often no good cost-benefit ratio for detailed process analyses, input-output (I/O) analysis can be conducted on the basis of (macro-)economic flow data bases (e. g., by statistical agencies and national governments) [21]. In practice, often hybrid approaches are used: internal process chains are modeled in high detail; aspects beyond via I/O models.

Similar to process-based LCA studies, breakdown structures for products and processes are developed in LCC [9] [22]. Product decomposition is a prerequisite for modeling life cycle-related processes (manufacturing, assembly, etc.). The level of detail for process modeling depends on the purpose of the study and the available information. But in general, reliable cost estimations require a comparatively high level of detail. So, highly detailed process descriptions (e. g., up to single operations) are often necessary. For this, the use of generic process models is recommended. They support the structuring of processes along the life cycle as well as in hierarchical order [22].To conclude, product and process models could be used as mutual basis for integrated LCA and LCC studies.

Additionally, flow models as known from flow cost accounting (FCA), can be applied. Originally developed for monetary appraisals of resource inefficiencies, FCA bases on the evaluation of material and energy flows. Therefore, the data compiled in FCA are similar to those required in LCA and (to some degree) in LCC. Consequently, FCA flow models and FCA in general could be a starting point for integrated LCA-LCC studies and might contribute to reducing the efforts for data compilation. The close connection of FCA and LCA is visible at the example of the software Umberto®. Initially developed for LCA on the basis of flow models, it also supports monetary assessments as generated in FCA [23]. But, FCA is more an as-is analysis than a multi-period assessment method. Its applicability for LCC should therefore be enhanced, e. g., by integrating life cycle-relevant as-is and forecast data as suggested in [24].

[S4] Definition of environmental scenarios

As mentioned in section 2.2, environmental and monetary consequences caused by the considered product system depend on a multitude of influencing factors. These factors have to be identified, analyzed and forecast, and relevant scenarios defined. In this regard, internal information systems (e. g., PDA, cost accounting) as well as external information sources come to the fore. They form a basis to determine current and future outcomes (maybe in form of best, probable and worst case scenarios) of influencing factors by providing relevant data (like prices, number of pieces to be manufactured or sold, condition and utilization of machinery, process parameters, etc.). Usually, the outcome of influencing factors and their impacts on the ecological or economic performance of a system also depends on the interrelations between these factors. To analyze and forecast such interrelations as well as the behavior of the influencing factors and the system over time in more detail, techniques like MICMAC-method [25], system dynamics [26] or scenario analysis [27] are useful.

Some parts of the environmental scenarios form a common basis for LCA and LCC. However, influencing factors considered as relevant in both cases might differ (e. g., future prices are essential for LCC, but often not for LCA). Therefore, self-contained modeling and evaluation processes (e. g., with respect to different impact categories in LCA) can be realized at the sub system level (Figure 3).

[S5] Data compilation and forecast

In this step, the economic and ecological consequences of alternative product systems are collected based on a variety of data. Here, a synergy potential exists: If flow models or input-output models are used in LCA the compiled data (flow quantities, etc.) provide a part of the data needed in LCC. In particular, the quantity bases for material or energy cost and, additionally, co-products and wastes are thereby generated (for an overview of the potential of LCI for the determination of LCC relevant cost see [28]). Furthermore, the more types of environmental costs are included in LCC, the greater the common database for the integrated use (Figure 4).

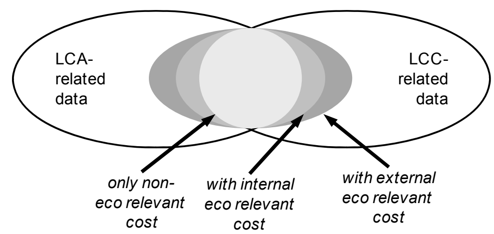

Figure 4: Data relationships between LCA and LCC analyses.

Other cost-types like environmental management, product development and marketing cost cannot be derived from the LCI data. They have to be compiled and forecast otherwise, if needed. The synergy potential primarily arises from the use of LCI data for LCC. In the opposite direction, the impulse for multi-period analyses stemming from LCC seems to be worth mentioning.

[S6] Calculation of the target measures

The sixth step does not pose any challenges for an integrated use. Here, the target measures are calculated on the basis of the compiled and forecast data. In LCA terminology, this step corresponds with the LCIA where performance indicators for the predefined impact categories are calculated [1]. In LCC terminology, in this step the LCC target measure (NPV) is calculated.

[S7] Interpretation/analysis of the target measures

In the last step, the results of the LCA-LCC study are analyzed, conclusions drawn, recommendations made, and limitations listed for the economic-ecological decision making. Beyond that, the validity of the results and input data is checked, for instance with help of sensitivity analyses. Here, a challenge is the coexistence of monetary and non-monetary target measures that may not be transferred into each other. This results in a multi-criteria decision making (MCDM) problem if there is no dominant – ecologically and economically favorable – alternative. To handle this problem, different approaches can be used:

- Classical MCDM approaches (e. g., utility value analysis, AHP, ANP) that weight the results against each other with respect to set goals and their relative relevance for the intended decision.
- LCA contributions dealing with that challenge: Huppes and Ishikawa presented a framework for eco-efficiency analyses by mapping the environmental burden to the economic value of technology domains in an efficiency diagram [29].
- An approach for industrial-related LCA-LCC studies comes from Pecas et al. [30]. They propose a framework for life cycle integrated performance based on best alternative performance mapping. It is implemented via a three-dimensional diagram composed of a functional/technical, environmental, and economic performance dimension.

4 SUMMARY AND OUTLOOK

Summarizing, a generic approach for the integration of LCA and LCC has been outlined as a contribution to well-founded economic-ecological decision making. Thereby, points of contact, necessities of coordination (e. g., a concerted goal and scope definition) as well as potentials and possible pitfalls of integration have been revealed.

However, some methodical questions have not yet been addressed in detail. One aspect – in particular coming from LCC theory – is the integration of economic revenues and environmental benefits. Up to now, the relevance of the latter has not been discussed. A second aspect concerns the problem of cost and environmental burden allocation to single products – resulting from the fact that most of the companies manufacture and sell different products that share many resources. Further research has also to be done with respect to integration details, especially, the dynamic models in LCA and LCC and the analysis of flow (cost) accounting as a potential tie between the two worlds of modeling.

5 ACKNOWLEDGMENTS

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6 REFERENCES

[1] International Standardization Organization (2006): ISO 14040 International Standard. Environmental management – Life cycle assessment – Principles and framework, Geneva, CH.

[2] Götze, U. (2010): Kostenrechnung und Kostenmanagement. 5th ed., Springer, Berlin [German].

[3] Norris, G. A. (2001): Integrating Life Cycle Cost Analysis and LCA, in: Int. J. LCA, Vol. 6, No. 2, pp. 118-120.

[4] Steger, U. (1993): Umweltmanagement. Erfahrungen und Instrumente einer umweltorientierten Unternehmensstrategie. 2nd ed., Gabler, Wiesbaden [German].

[5] Shapiro, K. G. (2001): Incorporating Costs in LCA, in: Int. J. LCA, Vol. 6, No. 2, pp. 121-123.

[6] Baumann, H., Tillman, A.-M. (2004): The hitch Hiker's Guide to LCA. An orientation in life cycle assessment methodology and application, Studentlitteratur, Lund, Sweden.

[7] Götze, U., Northcott, D., Schuster, P. (2008): Investment appraisal. Methods and models. Springer, Berlin.

[8] Dhillon, B. S. (1989): Life Cycle Costing. Techniques, Models and Applications, Gordon and Breach, New York.

[9] Deutsches Institut für Normung (2006): DIN EN 60300-3-3: Zuverlässigkeitsmanagement. Teil 3-3: Anwendungsleitfaden – Lebenszykluskosten, Beuth, Berlin [German].

[10] Verein Deutscher Ingenieure (2005): VDI-Guideline 2884: Purchase, operating and maintenance of production equipment using Life Cycle Costing (LCC), Beuth, Berlin.

[11] Ellram, L. M. (1995): Total cost of ownership: an analysis approach for purchasing. in: International Journal of Physical Distribution & Logistics Management, Vol. 25, No. 8, pp. 4-23.

[12] Götze, U., Koriath, H.-J, Kolesnikov, A., Lindner. R., Paetzold, J. (2012): Integrated methodology for the evaluation of the energy- and cost-effectiveness of machine tools, in: CIRP JMST, Vol. 3, No. 5, pp. 151–163.

[13] Höft, U. (1992): Lebenszykluskonzepte. Grundlage für das strategische Marketing- und Technologiemanagement. Erich Schmidt Verlag, Berlin [German].

[14] Ferguson, T. M.; Norman J.; McLean, H. L. (2005): Moving Toward Sustainable Design through the Utilization of Economic Input-Output-Based Life Cycle Assessment Methods, in: CDEN International Conference, 2005. Kananaskis, AB.

[15] Huppes, G.; Rooijen, M. van; Kleijn, R.; Heijungs, R.; de Koning, A.; Oers, L. van (2004): Life Cycle Costing and the Environment. Report of a project commissioned by the Ministry of VROM-DGM for the RIVM Expertise Centre LCA.

[16] Steen, B. (2005): Environmental costs and benefits in life cycle costing, in: Management of Environmental Quality: An International Journal, Vol. 16, No. 2, pp. 107-118.

[17] [Hunkeler, D.; Rebitzer, G. (2003): Life Cycle Costing - Paving the Road to Sustainable Development, in: Int. J. LCA, Vol. 8, No. 2, pp. 109-110.

[18] Schwach Castella, P. et al. (2009): Integrating life cycle costs and environmental impacts of composite rail car-bodies for a Korean train, in: Int. J. LCA, Vol. 14, No. 5, pp. 429-442.

[19] Bundesumweltministerium, Bundesumweltamt (1995): Handbuch Umweltcontrolling, Vahlen, München [German].

[20] Reap, J.; Roman, F.; Duncan, S.; Bras, B. (2008): A survey of unresolved problems in life cycle assessment, Part 2, in: Int. J. LCA, Vol. 13, No. 5, pp. 374-388.

[21] Rebitzer, G. et al. (2004): Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications, in: Environ. Internat., Vol. 30, No. 5, pp. 701-720.

[22] Götze, U.; Hertel, A.; Schmidt, A.; Päßler, E.; Kaufmann, J.: Integrated framework for life cycle-oriented evaluation of product and process technologies – conceptual design and case study, in: Henriques, E.; Peças, P.; Silva, A. (Eds.): Technology and Manufacturing Process Selection: The Product Life Cycle Perspective (accepted).

[23] Schmidt, A.; Hache, B.; Herold, F.; Götze, U. (2012): Material Flow Cost Accounting with Umberto, in: Neugebauer, R.; Götze, U.; Drossel, W.-G. (Eds.): Energy Related Balancing and Evaluation in Production Engineering – Methods and Examples, Wissenschaftliche Scripten, Auerbach, pp.49-65.

[24] Götze, U.; Bierer, A.; Sygulla, R. (2013): Die Flusskostenrechnung und ihre Integration in die traditionelle Kostenrechnung. in: Seicht, G. (Ed.), Jahrbuch für Controlling & Rechnungswesen 2013, LexisNexis, Vienna, pp. 49–72 [German].

[25] Godet, M. (1986): Introduction to la Prospective. Seven key ideas and one scenario method, in: futures, Vol.18, No. 2, pp. 134-157.

[26] Richmond, B. (1994): Systems thinking/system dynamics. Let`s just get on with it, in: System Dynamics Review, Vol. 10, No. 2-3, pp. 135-157.

[27] Schnaars, S. P. (1987): How to develop and use scenarios, in: Long Range Planning, Vol. 20, No. 1, pp. 105-114.

[28] Rebitzer, G. (2005): Enhancing the Application Efficiency of Life Cycle Assessment for Industrial Uses. Swiss Federal Institute of Technology, Lausanne, CH.

[29] Huppes, G.; Ishikawa, M. (2005): A Framework for Quantified Eco-Efficiency Analysis, in: J. Ind. Ecol., Vol. 9, No. 4, pp. 25-41.

[30] Pecas, P.; Ribeiro, I.; Henriques, E. (2013): LCE: a framework for an informed and sustainable decision-making process. In: Neugebauer, R. et al. (Eds.): Energy related balancing and evaluation of production engineering – methods and examples, Wissenschaftliche Scripten, Auerbach, pp. 231-248.

Developing IAM for Life Cycle Safety Assessment

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Abstract

This publication discusses aspects of the development of an impact assessment method (IAM) for safety. Compared to the many existing IAM's for environmentally oriented LCA, this method should translate the impact of a product life cycle on the subject of safety. Moreover, the method should be applicable within Simapro. Besides the usual subjects, like the definition of effects and interventions, specific solutions had to be found for classification. Besides a dedicated impact assessment method for safety, also new data cards have to be developed to describe the necessary product characteristics to account for geometric and kinematic dependencies.

Keywords:

LCA; methods; safety; education

1 INTRODUCTION

Contrary to what many people still assume, sustainability incorporates much more than 'just' the environment. The familiar interpretation of People-Planet-Profit already shows the broader scope of sustainability. Concerning the Planet part, many tools to account for the environment have been developed. The most common one is the life cycle assessment, in short LCA [1], [2], [3].

Increasingly, the 'profit' part of sustainability is getting more attention. Applying a product life cycle approach to the profit side of sustainability results in the development of tools for life cycle costing, quite similar to the environmental LCA.

To account for the sustainability aspect concerning the 'people', tool development seems to be lacking behind. This part of sustainability is traditionally left to the 'soft sciences'. Methods to incorporate the people part of sustainability usually emerge on a more ethical and social level. Applying the theory for life cycle assessment to relate the impact of product life cycle to human life (and society) is not yet common practice.

While the mentioned aspects of sustainability are commonly considered a more academic concern, industry embraces the possibilities of the product life cycle approach in their business developments [4]. Also the spin-offs of this LCA approach are breaking ground. Indicators like the carbon footprint and even the water footprint are examples of the more familiar spin-offs. Besides, the use of environmental product declarations (EPD's) in business-to-business relations increases continuously. An increasing number of governments (e.g. American national and state government departments) demands the use of EPD's to support price offers for e.g. office furniture and supply acquisition.

Next to the development and application of these more general tools, the demand for specific tools increases as well. This ranges from dedicated assessment methods for very specific industry branches (for example the packaging industry and the textile industry) to tailor-made LCA tools and supportive methods for companies.

These recent developments lead to a research on developing impact assessment methods (IAM) in general. The focus is not the development of additional environmental oriented impact assessment methods, but rather the development of IAM's to apply the theory to LCAs for different engineering aspects. In this publication, results of exercises, or 'experiments' for the development of an IAM dedicated to safety is discussed.

2 PROBLEM DESCRIPTION

Both in industry and in academia, the need to assess the impact for a specific engineering aspect in a product's life cycle is evident. The theory of life cycle assessment has to become applicable to more than just the environmental domain. In the specific case for this publication, the need for a safety oriented impact assessment method is identified. Since the research context includes Simapro [5] as LCA simulation software, performing life cycle assessments with a focus on safety relied on the adaptation of this tool. This despite the fact that from the start, Simapro was expected to have limited possibilities.

Indeed, the existing elements available in Simapro and in the accompanying libraries were, unfortunately, not directly suitable for safety oriented life cycle assessments. Therefore, a new impact assessment method dedicated to assess the impact on safety had to be developed. To support this new method, specific data cards had to be developed

It is well-nigh impossible to leave the required developments to 'traditional' experts in life cycle assessments. Firstly, they are mainly trained against an environmental background. Secondly, if they work with Simapro, they are all too familiar with the existing elements that are available in the tool. As such, their environmental expertise could be a disadvantage in developing an impact assessment method for safety. As a sheer practicality, it is traditionally also difficult to free enough time and funding to mobilize LCA experts.

To overcome these obstacles, the assignment to develop a safety oriented impact assessment method was given to a number of student teams. All team members had a good understanding of the general theory of LCA, whereas they did not have a pre-bias for the environmental aspects (yet). As engineering students, they had a good understanding of the necessary technical aspects of product life cycles and they are creative enough to find adequate solutions and workarounds. During the assignments, the teams were supervised and supported by LCA and IAM experts.

3 THEORY OF DEVELOPING AN IAM

3.1 LCA versus IAM

Although most product engineers should be familiar with life cycle assessments, it might be helpful to explain the relations between a life cycle assessment and the necessary impact assessment method. A LCA mainly is a method to assess the impact a product life cycle has on a certain subject. It describes the different steps that have to be undertaken:

- Goal definition with the functional unit.
- Inventory of the necessary product data to model the life cycle.
- Profiling phase to translate the interventions into graphs.
- Evaluation to interpret the results.
- Indicate the possibilities for improvements.

In the profiling phase, an impact assessment method is applied to transform the interventions resulting from the product life cycle model into contributions to the required effects. That is the reason why the applied impact assessment method determines the effects describing the subject of interest of the LCA. Figure 1 displays possible elements in an impact assessment method. As can be expected from the discussion above, all well-known impact assessment methods describe the impact on the environment. Some of the more familiar method include the CML 2002 [6], the Eco-indicator '95 [7], the Eco-indicator '99 [8] and the ReCiPe [9].

3.2 Structure of an Impact Assessment Method

Earlier research has already addressed the structure of impact assessment methods more extensively [10]. Basically, in developing an impact assessment method two distinctive approaches can be followed. The linear approach starts at the level of interventions and successively continues with the transformations into effects, damages and finally, single score indicators. The top-down approach starts at the level of the required indicator score and works backwards in the different transformations of damages, effects and finally arriving at the level of interventions.

Both approaches will give rise to similar problems. The final transformation in the process is often the most problematic. In the linear approach, this is the transformation from effects into a single indicator score. Quite often, subjective weighing factors are necessary for this transformation to account for the relative differences between the effects. In the top-down approach the transformation of interventions into the effects can causes difficulties. The transformation from the interventions that can be related to product life cycle characteristics into the effects need increasingly subjective factors. Since the effects are often expressed in terms of a higher order of classification (the level of end points) it is often difficult to scientifically substantiate those transformation factors.

3.3 Anticipated Difficulties in Developing a Safety IAM

Unfortunately, it is not possible to simply switch to a different impact assessment method to obtain results on a different subject. As long as the main subject of the LCA is the same, a variety of impact assessment methods can be applied to calculate the impact. Obviously, the mentioned environmental impact assessment methods have most interventions in common.

If the life cycle inventory (LCI) is executed to model a product life cycle for the environment, the associated interventions will not be suitable for an impact assessment method on safety. It is not just a matter of the type of interventions, but important differences also occur on the level of modeling the product life cycle characteristics. Databases dedicated to environmental aspects are mostly based on materials and processes to transform those materials. Of course, common processes for transport and energy supply are described in those databases as well. In this kind of database (such as the Eco-invent [11], franklin and ETH) the structure in which the associated interventions are connected to the described characteristic is based

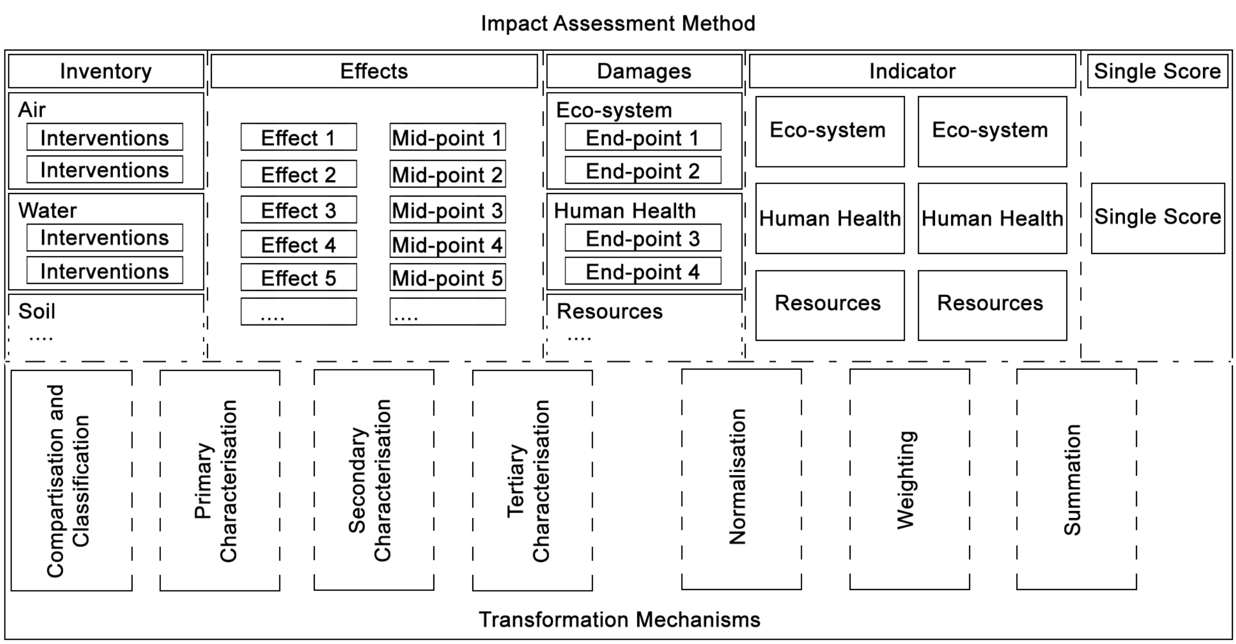

Figure 1: An overview of the different aspects of impact assessment methods.

on the original classification methods based on environmental compartments as described in CML 92.

In the development of an impact assessment method for a subject other than the environment, the relevant interventions will differ from the environmental interventions as well. Additionally, the preferred classification method and associated compartments can be different, as will be the aspects that describe the characteristics of the product life cycle on that particular subject. For example, geometric characteristics are more important for a safety oriented LCA as compared to an environmental oriented LCA. While the shape or angle of an edge will not influence the environmental impact, it can make a crucial difference for the associated interventions for the impact on safety. Consider for example the differences between a dull versus a sharp 'cutting' edge. In dealing with these difficulties, the young, nimble and non-predisposed minds of Master students can develop creative solutions.

4 PROJECT SET-UP

4.1 Background

For both the Master's programs in Mechanical Engineering as well as in Industrial Design Engineering a course is available focusing on product life cycles and LCA as an engineering tool. Although the background of the students and the set-up of the courses differ, both groups of students work on similar problems in their final assignment.

The Mechanical Engineering students do have prior knowledge on LCA's from their bachelor studies. Yet, often the groups are extended with students that have completely different backgrounds (international exchange students, or different bachelor studies). This course follows a rather classic approach of teaching LCA's and product life cycles. The lectures are set up in relation to the steps of the LCA procedure, starting with goal definition and finishing with a lecture on product life cycle improvements.

The master course for Industrial Design Engineering is based on a back-to-front teaching approach (as presented at the 12th LCE conference [12]). These students did not have a preparatory course on LCAs in their Bachelor's program. On the other hand, these students already have developed a broader understanding of the relations between products and humans.

In both courses, the procedures of a LCA and the relation to impact assessment methods is discussed using the available environmental impact assessment methods as examples. The familiar Eco-Indicator '95 method is used as a primary example with side steps to other methods to explain differences.

4.2 Student Assignment

In both courses, the final assignments for the student teams have a similar structure. Teams of 5 to 8 students develop an impact assessment method to calculate the impact of a certain product's life cycle on a subject different from the environment. Some of these teams received safety as the subject for their IAM. The products were different each year, yet, to keep the level of complexity manageable, they are always very simple powered consumer products. Obviously, the goal of the assignments was not a numerically accurate LCA of that product, but rather the solutions and approaches needed to develop an impact assessment method for safety.

The teams had to write a report on the development of their impact assessment method from a theoretical viewpoint. As a proof of principle, the teams also needed to implement their impact assessment method into Simapro 7. Besides the report on the IAM development, each team delivered a second report on the application of their method in a simulated LCA study. In total, the results from 11 different student teams over the past 3 years are relevant for this publication.

4.3 Differences in Life Cycle Modeling

In the development of impact assessment methods, the usual problems arose: the definitions and boundary for the effects, the level of classification, the calculation of the characterization factors, determining normalization factors and of course the use of weighing factors for constructing single indicator scores. As compared to the development of yet another environmental impact assessment methods, some additional problems emerged that are specific for safety oriented impact assessment methods.

Product Characteristics for Environment

Many LCA practitioners are familiar with modeling a product life cycle during the life cycle inventory process. In such a product life cycle model, the product is described by means of the materials and processes involved. The geometry of the product could determine the required production processes. Based on this product life cycle model, an extensive table of interventions is constructed containing all substances crossing the system boundary between the life cycle and its surrounding.

Product Characteristics for Safety

An important difference between an environmental life cycle assessment and safety oriented life cycle assessment are the product characteristics that describe the life cycle. For safety, the geometry and interaction between components are much more important as compared to the material aspects. Whether a sharp edge is materialized in steel, glass or aluminum is for the safety intervention less important than the length and edge angle. How two components move relative to each other is important if limbs can be caught and squeezed between such components. Whether your finger is cut-off between two steel parts or two wooden parts is relatively unimportant.

Compared to the usual environmental life cycle assessments, not only different effects and interventions have to be determined. Also a new approach towards modeling a product life cycle is needed. To be able to model the relevant product characteristics, different aspects of the product need to be taken into account during the inventory phase for a safety oriented LCA. Section 6 discusses possible solutions.

5 DEVELOPING IAM ON SAFETY

5.1 Classification

One of the first aspects to determine when developing an impact assessment method on safety is the definition of both safety and the accompanying effects describing the notion of safety. Similar to the environmental impact assessment methods, the safety impact assessment methods do not actually describe how safe a product's life cycle is, but rather the impacts reducing safety caused by the product life cycle. In this project, safety impact is considered as 'harm to the human body'. Since the higher order effects of classification resulting in a decreased human health due to emission of possible toxic substances is already covered in environmental impact assessment methods, these long term effects were not included in the safety impact assessment methods. To quote the students; '*when these kind of health problems are necessary to be included, it could be transferred from the already existing methods like ReCiPe, including the effect definition, the interventions and the characterization factors.'*

For the safety impact assessment method it therefore seemed appropriate to focus on physical, and in some case even mental, damages to the human body that could be allocated directly to the product life cycle, while disregarding damages related to environmental issues.

Considering the common practice in safety analyses, the notion of safety can be described by the exposure to a certain threat or hazard, the risk of that threat and the possible consequences of that threat [13].

$$Risk = Exposure \times Hazard \qquad (1)$$

However, this equation is related to a more predictive approach for the safety of individuals. Since life cycle assessment is rather an analytical approach to calculate the actual damages caused by a completed product life cycle, the predictive approach is less suitable. In analogy with the environmental methods, the interventions are expected to have occurred (on average). It is not so much calculating what the risk is for an individual to be cut by a sharp edge, but rather to account for the number of cuts due to the existence of that sharp edge.

Obviously, the classical approach toward safety and calculating risks could be used in determining characterization factors and even form an approach for modeling safety in certain data cards. The resulting interventions themselves are occurrences rather than chances.

5.2 Effects (End Point)

Although a minority of the teams decided on a top-down approach for their impact assessment method, 9 teams used a more or less linear approach. In the top down approach, the teams almost automatically embraced the higher order classification to determine endpoint effects. This resulted in damage categories like ‘days hospitalized’, ‘inability to function (or lost work days)’ and ‘permanent invalidity’. The analogy with the damage categories like human health, eco systems and resources with their units as DALY, PDF’s and MJ surplus energy comes to mind. These teams adopted the existing Eco-indicator ’99 or ReCiPe endpoint method as a template for their safety method. However, in this publication the focus is mainly on the midpoint approach as described below.

5.3 Effects (Midpoints)

The majority of the teams applied a rather linear development approach to their method. Defining the interventions and developing the effects was a combined integrated process. This resulted in effects of a lower order level of classification, similar to the Eco-indicator ’95 and the ReCiPe midpoints. The different teams all considered similar effects. Sometimes definitions and units differed between the teams. In general, the following categories of effects were used to describe the impact of a product life cycle on the human body (between brackets the type of characterization);

- Skin damages (specific cut)
- Burns (defined type and size of burn)
- Muscle damage (strain of specific muscle)
- Bone fractures (defined bone fracture)
- Damage to sensory organs (the loss of a specific sense)
- Organ damage (loss of a specific organ)
- Invalidity & amputations (loss a specific limb)
- Fatalities (number of deaths)

For organ damage, the teams choose the loss of a specific organ like lung or kidney since the complete failure of that specific organ would not automatically result in a fatality (like the complete loss of the heart function will result in a deceased).

Due to the broad range of traumas covered by these basic effects, teams often divided certain effects in several smaller or more specific effects to avoid difficulties during characterization. This solution is also often applied in existing environmental impact assessment methods, for example the distinction between summer smog and winter smog in the Eco-indicator ’95.

The nonphysical issues related to human health appeared problematic for most teams. They did appreciate the concept of mental problems related to product life cycles, but had a hard time to construct characterization factors. Associating mental problems to product life cycles appeared to have difficulties similar to higher order effects of classification. Even when these effects were accounted for in the theoretical model of the impact assessment method, it was rarely utilized in the method modeled in Simapro.

5.4 Characterization

Once the effects and the reference units had been defined, other relevant classified interventions needed to be characterized. For certain interventions, the characterization factor could be determined in a straightforward approach. The severity of a cut could be expressed in a series of default cuts of a standard unit length, acknowledging that 10 small cuts would not equal a single cut 10 times that unit length. A similar approach was applied for the difference of superficial and deep cuts. Even special sets of cuts were described to be able to account for muscle or organ trauma. This resulted in interventions that would contribute to multiple effects with different characterization factors. Although the emphasis was not on the numerical validity of the characterization factors, but rather on the discussion of how to characterize those kind of interventions to the more general effect, the students took this process very seriously. They familiarized themselves with the methods used by professionals in healthcare, trauma treatment, emergency and by rescue workers, but also with methods and terminology used in insurance companies and industrial branch organizations. A well-known example is the method to classify types of burns, in first, second and third degree burns. In the developed impact assessment methods, burn types were often expanded to distinct thermal, chemical and electrical burns, but also to account for abrasions and similar skin damages.

5.5 Compartments

As a result of the increased knowledge about trauma to the human body, the students realized that a further distinction was necessary in this process of classifying the interventions. Although the teams sometimes decided on different types of classes, the solution to apply ‘compartments’ as another type of classification was quite similar. Using this type of classification to be able to apply variations in characterization factors for similar interventions is common practice in environmental assessment methods. In fact, intervention compartments are already used to structure the interventions in the appropriate data cards. In many databases (e.g. Ecoinvent), the environmental interventions are already allocated to certain emission compartments, for example emissions to air, to soil, to water and from raw materials. For the impact assessment method on safety, these compartments could be used to classify interventions to different user types (from children, to professional, to consumer, to service engineer, etc.) or using different age groups since different trauma interventions can have different consequences to different age groups. As all parents know, young children heal remarkable quickly. However, some damages (like amputations) can not heal at all. But permanent damage, like amputations, in a child’s life will have a bigger impact over time. A similar line of thought is possible for elderly people: cuts and especially fractures take much longer to heal. A different approach towards utilizing the compartment classes are different body parts, although that was often solved more practically by using specific intervention types.

Compartments in Simapro

Unfortunately, in Simapro, it is not possible to add, or adjust the already available compartments. This is understandable, since the defined compartments are integrated with the individual data cards in libraries. On the other hand, a solution is conceivable, since existing data cards need to be copied into the current project before data can be changed, or interventions can be added. Such copied data cards could be extended by adding the desired compartments. In practice this problem was avoided by using the available compartments while ignoring compartment names. This work around resulted in the use of emissions to air as the compartment for children, while the emissions to water was used for adult consumers and emissions to soil for professionals, etc. By allocating the interventions to the target compartment different characterization factors could be applied depending on that compartment.

5.6 Normalization

The normalization of the results is quite important. Beside the benefit of being able to express all the impacts of the different effects into a common unit, the norm, it is also useful for interpreting the values. The value of the calculated effect scores are hard to interpret without a common norm as a reference. In the familiar environmental impact assessment methods, the impact for a certain area, with or without the number of inhabitants, is generally used as a norm. Some of the teams tried to develop a similar norm for their safety method. Often they had to rely on data from the Dutch institute for statistics (CBS) to construct a safety norm for the average Dutchman expressed in average impacts on the different effects. On the other hand, a more benchmark like approach was sometimes applied. The development teams applied their method on a factious reference product, like a chainsaw or a food processor to determine the impact of that reference product on the effects. From discussions with the student teams, it appeared that in general they preferred a reference product for their normalization instead of a reference impact as is commonly applied in many environmental impact assessment methods.

5.7 Weighing and Indicator Scores

Construction of weighing factors in order to account for differences in importance between effects always leads to discussion. Yet, especially weighing factors related to the described safety effects caused heated debates among the students. As expected, a lot of ethical aspects played an important role, often resulting in an unsolvable philosophical discussion. Ultimately, the teams adopted one of two approaches to tackle this problem.

The first approach is to construct multiple sets of weighing factors to be selected by the LCA researches to match the goal of the research. Although the sets were more extensive and detailed, a similarity to the different views in the Eco-indicator ’99 and the ReCiPe methods can be recognized.

The other approach was a more clinical approach to adopt the methods of insurance companies in determining their reimbursements / compensation payments after accidents to and invalidity of their clients. In these sets of weighing factors the students tried to avoid the personal and ethical aspects of weighing.

The general opinion among the students was, however, that it is far more important that the weighing factors applied in a certain life cycle assessment should be determined beforehand in co-operation with the target group and the initiator.

6 MODELING PRODUCT LIFE CYCLES FOR SAFETY

As already mentioned in section 3.3, besides the obvious aspects of the impact assessment method, an important issue is how to modeling a product life cycle for safety.

For well-known and common processes, the appropriate interventions could be added to the data cards for those processes, similar to the development of data cards for environmental oriented LCA’s. In fact, the existing environmentally oriented data cards describing common process could be extended with the safety interventions, scaled to the unit of that data card. For example, the safety interventions during injection molding of a million kg’s of plastics could be determined from research. The relevant interventions could be a series of cuts, burns, fractures, and even amputations (getting fingers caught in the mechanisms). These amounts of interventions could then be scaled back for the injection molding of 1 kg of plastics and added to the suitable classification compartments. The same approach could be applied to expand the other processes to model the production and end of life phases of a product.

That the majority of the impacts on safety occur during the use phase, is to be expected. In many cases, the use phase for safety need to be more extensively modeled as compared to the environmental LCAs. While only the power consumption and consumables are modeled in the use phase for the environment, even the use phase of inert products like a kitchen knife or a stepladder need to be modeled for safety.

To be able to model the relevant product characteristics during usage, the different development teams constructed data cards describing these characteristics, for example the occurrence of a hot surface reachable by a user. The temperature or hazard of this surface could be defined in the name, while the surface area could be used to scale this characteristic. A similar approach can be taken to describe sharp edges and even kinematic aspects. However, especially while modeling the usage of a product, the time dependencies become important again. Or, more specific, the exposure to the hazard will determine the amount of associated interventions.

This time dependency has led to two distinct approaches to describe product characteristics in the use phase of the life cycle. The first is similar to the method to model for example transport. To describe certain characteristics, new units are introduced to combine exposure and hazard. In the example of the hot surface, the unit could then be ‘dose x area ’, or more specific the time the user can interact with that surface multiplied by the surface area. This can also be applied for sharp edges, with a unit ‘length x time’ and even for the kinematic aspects in units of frequency times ‘enclosed area’ (to describe the hazard of a limb being caught between two moving parts).

The other approach depends much more on the quality of the life cycle inventory process. In this case, data cards were constructed to describe the actual occurring interventions. For example, a data card to model the number of paper cuts of approximately 1 cm lengths. This type of data card could even be specified for different sets of people (children, consumers, professionals, etc.) in order to apply the earlier discussed use of classification compartments (see section 5.5). Although this approach allows for more control during modeling of the use phase, it depends on the necessary insight of the researches. Both approaches, however, strongly depend on the quality and availability of statistical data.

7 CONCLUSION

Although the development of an impact assessment method to calculate the impact of a product life cycle on safety is not a straightforward process, it is feasible. This includes the necessary development of the interventions having an impact on the human body and the necessary transformation mechanisms to determine the impact on different effects, the development of a reference norm and the weighing factor to be able to construct single score indicators. In order to apply the impact assessment method, data cards have to be adjusted and developed to be able to model the appropriate product characteristics. A new type of data cards is required, especially to describe the human-product interactions during the use phase of the life cycle.

8 FUTURE WORK

As a result of the difficulties in modeling the required product characteristics during the use phase of the life cycle, the applicability of the unit process in life cycle inventories [14] is interesting to research. Closely connected to this will be investigations to develop a taxonomy to describe human-product interactions. Also the actual development of an impact assessment method and supportive data cards will be subject of ongoing research.

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10 REFERENCES

[1] Wenzel, H, Hauschild, M, Alting, L (1997): Environmental Assessment of Products, Volume 1 methodology, tools and case studies in product development, Chapman & Hill, first edition, London, UK

[2] Nederlands Normalisatie-instituut (2006): NEN-EN-ISO 14040 Environmental management - life cycle assessment - Principles and framework (ISO 14040:2006, IDT): Nederlands Normalisatie-instituut, Delft.

[3] Nederlands Normalisatie-instituut (2006): NEN-EN-ISO 14044 Environmental management - life cycle assessment - Requirements and guidelines (ISO 14040:2006, IDT): Nederlands Normalisatie-instituut, Delft.

[4] Krebbekx, J, Wolf, W, de (2011): FME Duurzaamheidskompas: A publication by Berenschot, Agentschap NL and FME CWM, Utrecht, The Netherlands.

[5] Simapro 7.23 LCA software; PRé Consultants b.v., Amersfoort, The Netherlands; 2012

[6] Heijungs, R, et al (1992); Environmental Life Cycle Assessment of products (Guide & Backgrounds). 1992; Leiden, Centre of Environmental Science; 1992

[7] Goedkoop M.J.(1995); De Eco-indicator 95, Final report; NOH report 9523; PRé Consultants b.v.; Amersfoort (NL); July; 1995; ISBN 90-72130-77-4

[8] Goedkoop, M.; Spriensma, R (2001): The Eco-Indicator 99 A damage oriented method for Life Cycle Impact Assessment, by: PRé Consultants; available from: http://www.pre.nl/eco-indicator99/ei99-reports.htm

[9] CML PRé; RIVM; Radboud Universiteit Nijmegen; CE Delft (2009): ReCiPe 2008; A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level: available from: http://www.lcia-recipe.net/.

[10] Toxopeus, M, Kickert, V, Lutters, E. (2011): Developing Impact Assessment Methods: an approach for addressing inherent problems, in: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering (LCE2011), pp. 581-586, Braunschweig, Germany

[11] Frischknecht, R, Jungbluth N, (2007): Overview and methodology, ecoinvent report no.1. Swiss Centre for Life Cycle Inventories, Dübendorf, Switserland.

[12] Toxopeus, M, Lutters, E, Meijer, M, Houten, F, van (2005): Teaching LCA Back to Front, in: Proceedings of the 12th CIRP International Conference on Life Cycle Engineering (LCE2005), Paper 011, Grenoble, France

[13] Ropeik, David (2002). *Risk*. New York, New York, USA: Houghton Mifflin Company. ISBN 0-618-14372-6.

[14] Kellens, K.; Dewulf, W.; Overcash, M.; Z. Hauschild, M.; Duflou, J.R. (2011): Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI) – CO2PE! Initiative (cooperative effort on process emissions in manufacturing. Part 1: Methodology description, in: International Journal of Life Cycle Assessment, Vol. 17, pp: 69-78

Multi-Layer Stream Mapping as a Combined Approach for Industrial Processes Eco-efficiency Assessment

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Abstract

Nowadays achieving sustainable development is a global concern. The issue of unsustainability can be related to population growth and excessive consumption of natural resources. To tackle these issues, several management tools and methodologies have been developed in the last years, to assess, analyse and improve the environmental and economic performance of production systems. This work presents an approach based value stream mapping in order to assess and improve energy efficiency, environmental performance and financial performance of a production system. The developed approach can be applied to any industry or production system, where all the unit processes involved are identified and the inputs/outputs of each unit system quantified and easily perceived. Key environmental performance indicators and the corresponding eco-efficiency ratios arise as outcomes of this approach, in which a Multi-Layer Stream Mapping (MSM) with visual management attributes is created.

Keywords:

Multi-Layer Stream Mapping; Eco-efficiency; Value Stream Mapping; Performance Indicators; Visual Management

1 INTRODUCTION

In the whole history of mankind, sustainability was never as meaningful and important as it is nowadays. This fact collides with population growth; the scarcity of resources and their rising prices; the national and international environmental policies becoming stricter [1]. However, measuring sustainability and assessing sustainability evolution is an ambiguous and difficult task. In the 90's the World Business Council for Sustainable Development (WBCSD), established a framework to assess eco-efficiency, which embraces the economic and environmental dimensions, leaving out the social dimension that is part of the sustainability structure [2]. The WBCSD identified the following elements of eco-efficiency:

1. Reduce material intensity
2. Reduce energy intensity
3. Reduce dispersion of toxic substances
4. Enhance recyclability
5. Maximise use of renewable resources
6. Extend product durability
7. Increase service intensity

The purpose of eco-efficiency is to maximise value creation and minimize environmental burdens [3]. Eco-efficiency measures the relationship between economic growth and environmental pressure, and is generally expressed by the ratio between economic value and environmental influence, represented by:

$$\text{Eco-efficiency} = \frac{\text{Product or service value}}{\text{Environmental influence}} \quad (1)$$

Equation 1 - Eco-efficiency Ratio [3]

Eco-efficiency, as a management philosophy, has been adopted by many companies, including major economic groups such as 3M, Dow Chemicals, Toyota, BASF, etc. [2]. These companies believe that eco-efficiency goes a step further then corporate responsibility, and by embracing an eco-efficient mind-set, the outcomes are an asset for the company. For example, Toyota uses an approach based on environmental values, which reinforces their competitiveness and improves their eco-efficiency performance [4].

The framework developed by WBCSD can be used by any business to assess and measure progress towards economic and environmental sustainability [3].However, this framework lacks a simple and discrete approach in order to analyze and assess unit processes that are part of the production system.

The goal and main focus of this work is to present a combined use of an alternative tool, Value Stream Mapping (VSM), and demonstrate its suitability to assess environmental and energy performance of unit processes and production systems in a fast and flexible manner. This approach can be both very practical and useful for:

- Top management decision support
- Defining priorities
- Identifying inefficiencies in an easy manner
- Identifying Key Environmental Performance Indicators (KEPI)
- Assessing eco-efficiency performance
- Identifying improvement actions

Secondly, this work attempts to demonstrate the importance of presenting environmental issues and eco-efficiency performance in a simple manner, through visual management maps and layouts, in order to simplify top management understanding of the KEPI's and their suitability for decision making and overall awareness.

2 APPROACH

There are several methods, management tools and decision support approaches that aim to maintain or increase production while reducing costs, raw materials consumption, energy consumption, the amount of emitted effluents, waste generated, etc.

However, this paper presents a framework that combines Value Stream Layers (from Value Stream Mapping assessment) with visual management attributes, thus transforming the concept and the understanding of eco-efficiency into something more quantifiable, simpler, concise and directly applicable to any production system or process sequence.

This need arises since the existing eco-efficiency tools and methods are not always directly applicable to every product and/or production system, and often addressed as “isolated stage analysis”.

The other reason that sustains the need of such approach is related to the lack of fast visual management attributes in most methods and tools used for eco-efficiency assessments.

Visual communication is an important aspect for any management board or project manager, managerial esthetics highlights the critical roles of visual elements in modern management [5].

Therefore, the approach presented by this work presents the data and performance results in a fast assessable visual format. The outcome and results are diagrammatical and intuitive representation of managerial concepts. This helps to amplify cognitive ability or reduce complex cognitive work, consequently humans can derive better and faster the overview information, than if presented in a textual/numerical format [6]. Spatial positions or colors provide similarity amongst different features than do texts or numbers, which is one of the key reasons why human beings can be visually attentive to certain symbols and identify visual patterns [6].

Thereby, in order to fulfill the visual management attributes, the Key Environmental Performance Indicators and the global performance results are represented in Dashboards, thus taking into account that the primary purpose of a dashboard is to display all of the required information on a single screen/layout, clearly and without distraction, in a manner that can be quickly and objectively assimilated by top management, stakeholders and project managers thus allowing them to see the necessary information at a glance and make an informed decision [7].

The combined use of Value Stream Layers of a Value Stream Map emerges in order to “see beyond” the global environmental and financial performance of a production system in a simpler manner and enables the understanding of the eco-efficiency assessments, and at the same time simplifies the identification and quantification of specific inefficiency situations.

In order to assess the environmental, financial and global performance of a production system and also identify and quantify the inefficiencies and misuses, this framework starts from the classic bathtub curve of Value Stream Mapping.

Value Stream Mapping

The Value Stream Mapping (VSM) approach adopts a flow perspective rather than an activity-based perspective on how work gets done (Figure 1).

It includes metrics to gauge certain types of waste/inefficiencies in the supply chain [8, 9].

According to Rother and Shook’s approach [10], a value stream consists in the collection of all actions (actions that add value and actions that don’t) that are required to bring a product or a group of products through the main flows, starting with raw material and ending with the customer [8, 11]. To map a value stream, the first step is to choose a product family as the target for improvement and then map its current state (while walking along the current production system). In other words, it consist in capturing a snapshot of how thing are actually done, consequently creating the current state map. The following step is to create the future state map, which is a picture of how the system should look after the inefficiencies in it have been removed [8, 11, 12].

The primary goal of this tool is to identify all types of waste in the value stream flow and processes in order to take actions to try and eliminate these, by analyzing the Value Stream Maps (VSM) [9, 11].

Kuhlang and Edtmayr [9] have studied the application and use of an extended value stream map (Figure 2), although their extended stream map does not consider multiple aspects of different nature (as for environmental, economic and global performance aspects). Their goal was to reduce lead time (wastes) by using an extended value stream map that also considers, for example, the area occupied by each machine or industrial element.

The lean tool here presented arises in this framework because it can be a practical and useful way to identify actions that do not add value to the final product and to identify inefficiency and wasteful situations. In this approach, Value Stream Maps are used to quantify in detail not only the time spent but also to identify: costs, emissions, energy consumption, resource consumption, waste generated, etc., of all unit processes. Unlike the usual VSM that just maps out individual process times and stocks, or areas and transport in the extended version by Kuhlang and Edtmayr [9], the idea here is to assess overall eco-efficiency performance, using a VSM bathtub curve for each environmental and financial aspect, or any kind of variable, originating a Multi-Layer Stream Mapping (MSM) for overall performance assessment.

The ratios and key performance indicators can be easily quantified in terms of: consumption of energy and resources, emission, waste generated and costs of each unit process, allowing the user to calculate the efficiency of utilization of various resources and production time. This facilitates the task of identifying improvement actions that are necessary or which can be implemented. This approach also helps to better understand how the production system interacts along its sequence.

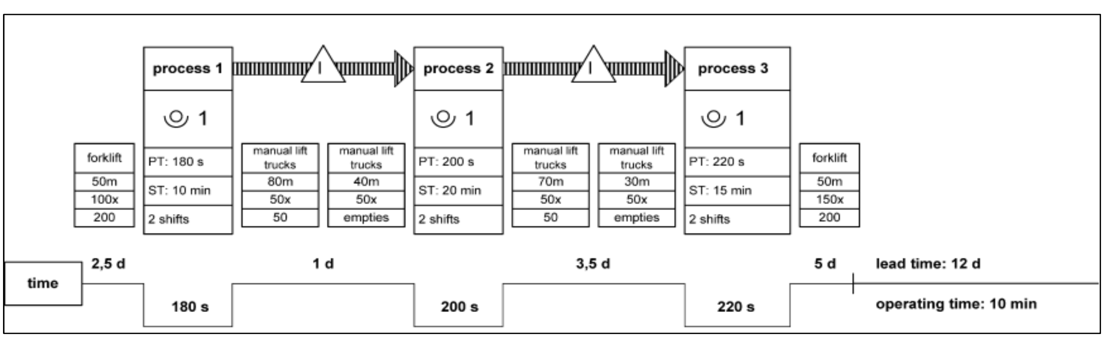

Figure 1: Common Value Stream Map for production time assessment [9].

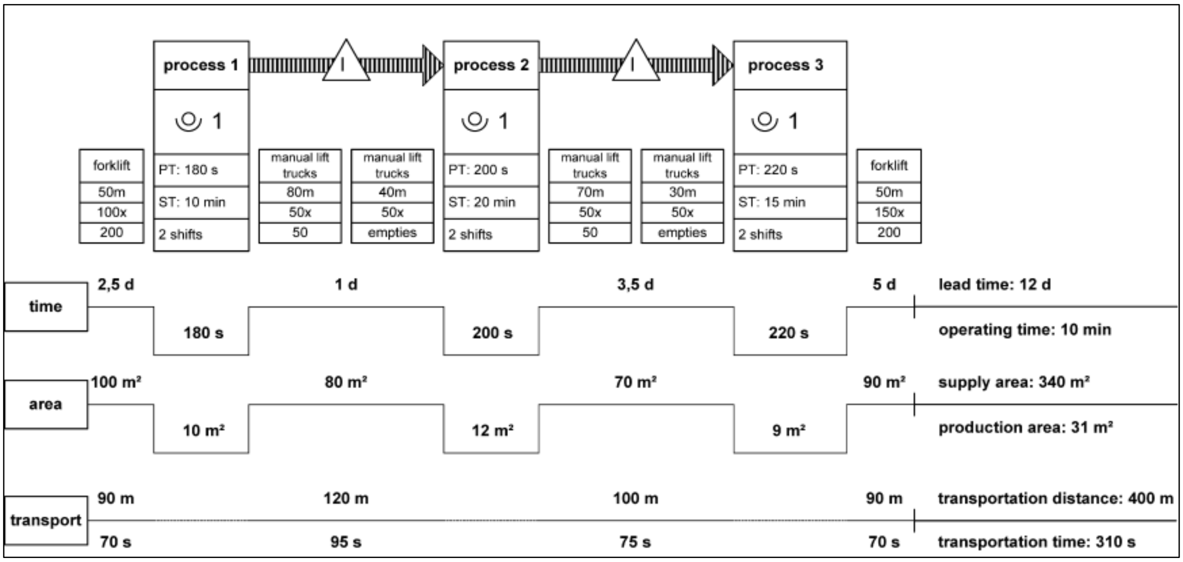

Figure 2: Extended Value Stream Map [9].

3 MULTI-LAYER STREAM MAPPING DESCRIPTION

The Multi-Layer Stream Mapping (MSM) consists in replicating the approach used for Value Stream Mapping, but allowing the addition of multiple layers (stream flows) that embrace environmental and economic aspects, or other key variable, in order to assess eco-efficiency performance.

Figure 3 characterizes an example of the application of the MSM approach.

The values located below of the MSM line are those which do not add value to the product (Lead Stages), i.e. representing the "waste/misuses" of time, money or resources. On the other hand the values that are presented above the VSM line (Process Stages) are those that add value to the product, thus representing the “useful consumption” of stream flow that can be analyzed in order to assess, evaluate and quantify production efficiency and eco-efficiency performance aspects.

One key feature of the MSM approach consists in considering dimensionless ratios, so the higher the result for the ratio, the better the performance of the energy, mass or time flow or other key variable of a process or system. It should be noticed that the MSM approach can assess, quantify and analyze environmental aspects (energy consumption, emissions, raw material consumption etc.), economic aspects and productions aspects one by one. This is possible if the stream under analysis follows in the direction of the processes stream (raw direction in the diagram), the final result of the stream variable metric will be represented by φ （Figure 3).

Besides assessing individual streams, it is also possible to quantify the efficiency performance of unit processes (P_1, P_2, P_N), by following the Multi-Layer Stream Mapping direction P_1 φ （column direction of the diagram in Figure 3).

Finally, the overall efficiency of a process sequence or system can be evaluated by calculating the average (or other weighted formula) of the several φ of the processes. This evaluation is again possible since the results of each φ, of each process, are dimensionless.

The results of φ in both directions (Process Stream Analysis and Multi-Layer Stream Mapping) are Key Performance Indicators. Therefore by analyzing and mapping environmental aspects as streams, the outcome is a Key Environmental Performance Indicator. The process variables that can be assessed according to this approach are unlimited. For instance, the following environmental aspects can take place as assessing variables:

- Energy Consumption
- Raw Material consumption
- Fuel Consumption
- CO_2 Emissions
- Waste Generation
- (…)

Beside these environmental aspects, other specific cost flows can be added, i.e. a cost flow to assess the costs of energy consumption only, or raw material only, thus allowing to assess specific eco-efficiency indicators (since product value and environmental influence are specific).

The eco-efficiency performance can be evaluated, by following the Multi-Layer Stream Mapping direction (column direction of the diagram in Figure 3). This approach provides a wide range of eco-efficiency evaluation data, due to the possibility of assessing the eco-efficiency performance of a process stage that adds value to the product (Figure 3 - equation (a)) and/or asses the eco-efficiency performance of the stage that does not add value (Figure 3 - equation (b)). The global eco-efficiency performance of a process can also be assed (Figure 3 - equation (c)). It’s worth mentioning that when assessing global eco-efficiency performance several environmental aspects (Environmental Influences) can be added to the denominator of the equations (c),(f) and (i) in Figure 3, in turn the overall eco-efficiency performance of the process will arise as an outcome of this approach.

Multi-Layer Stream Mapping Features

In order to facilitate the identification of major inefficiencies and assess, evaluate and quantify eco-efficiency performance, visual management interpretation for each unit process is highlighted according to their efficiency score (Figure 4).

The global efficiency performance of the process is presented by highlighting only the main process flow and omitting the bathtub lines in order to present a final MSM dashboard in a simplified way and in an even more understandable manner (Figure 5).

For the color labels four classes were considered. The first efficiency class represents the range from 90% to 100% (green highlight); the second efficiency class from 70% to 90% (yellow highlight); the third from 40% and 69% (orange highlight); and the final efficiency class is for less than 40% (red highlight). It is noteworthy to emphasize that the yellow and orange classes have a variation of approximately 50%, while the green class has a variation of 10% (see Figure 6).

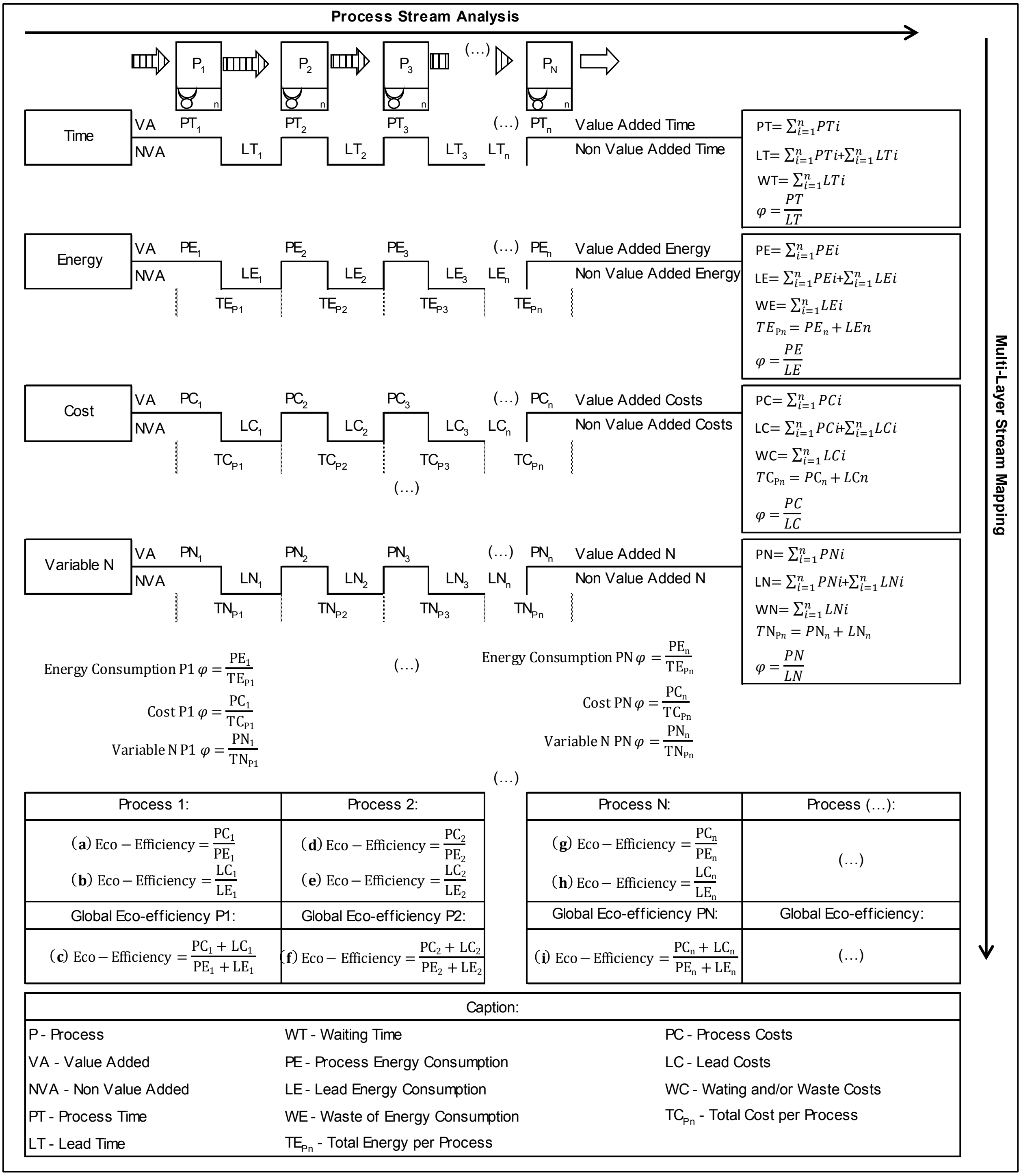

Figure 3: Multi-Layer Stream Mapping Approach.

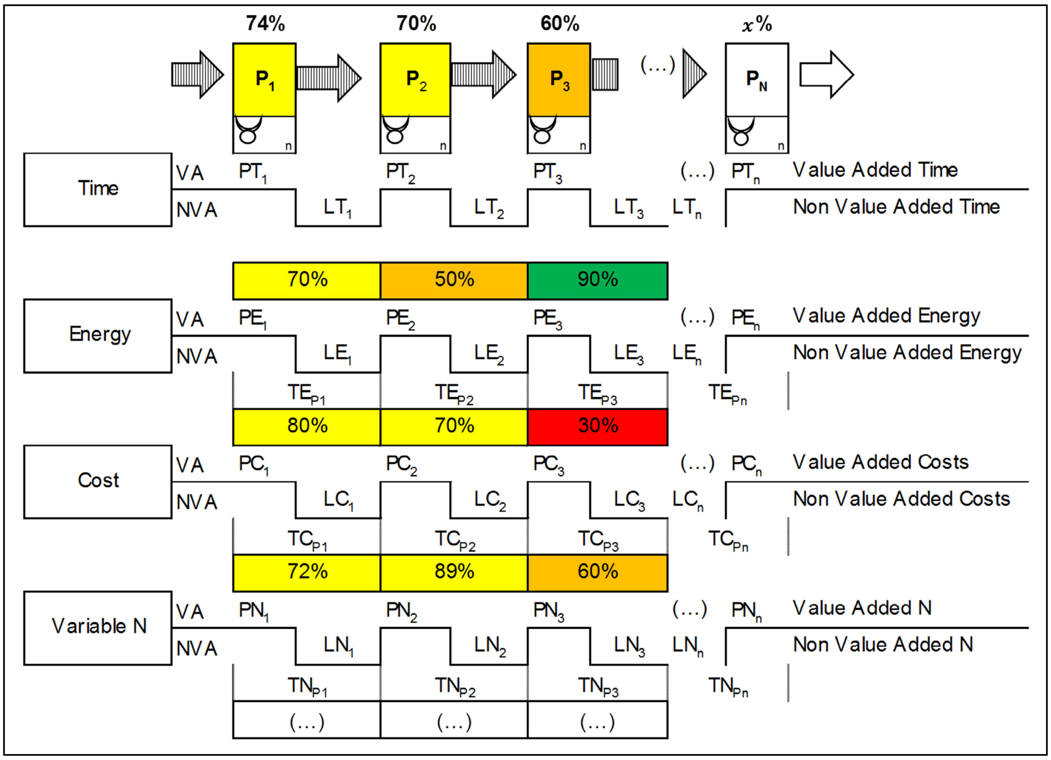

Figure 4: Global efficiency dashboard (Example).

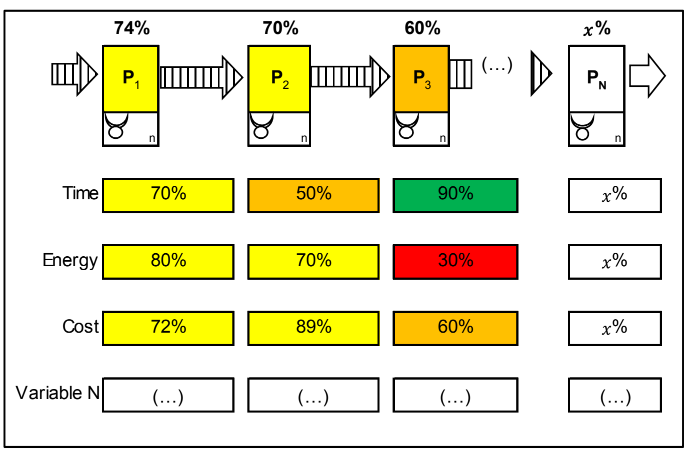

Figure 5: Final efficiency dashboard (Example).

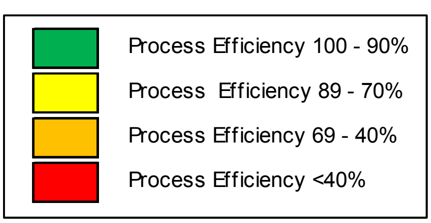

Figure 6: Color labels ranges for the MSM diagram.

Figure 4 is a schematic output of this approach that can be used to assess and evaluate both data and key performance aspects. The identification of KEPI takes place by assessing the results of the global efficiency dashboard, in which these key indicators are represented by the total value of each process, in each stream (i.e. TE_{P1}, TE_{P2}, TC_{P1},TN_{Pn} as presented in Figure 3). The final efficiency simplified dashboard (Figure 5) represents the efficiency results for each process and layer stream, as it can also represent the overall color indicator for each variable and for the overall industrial process sequence. The results obtained in each stream represent, in the presented case, an average value of the efficiency for each unit process, and this is determined by the overall average value of each unit process taking into account all streams related to the process.

Another relevant aspect is that in this approach all inefficiencies and misuses are accounted in the non-value added stages. Usually these stages represent transportation time or pauses during productions. Therefore, when using the MSM approach, transportation data should be added to the other misuse/waste data in order to properly assess the efficiency of a transportation process. In that case, if the goal is to know with greater accuracy the transportation efficiency, then one should add another layer stream (by adding a new variable) or by drilldown the MSM approach (Figure 7).

4 APPLICABILITY AND STRENGTHS

The MSM approach, like the traditional VSM, can be used to identify which processes and/or streams are less efficient, thus contributing for decision support and allowing continuous improvement to environmental and financial key performance indicators.

This approach can also be used for process reengineering evaluation, since in some cases the unit processes, or even the whole production system of a factory, have good operational results, but the efficiency is not as high as it could be. Therefore, using this approach to scrutinize “how”, “where”, and “how much” can a unit process and/or a production system improve its financial, environmental and performance aspects, is of great importance for decision-making.

A drilldown approach of the MSM can be executed, as cited before, in order to, for instance, assess and identify inefficiencies and misuses that occur along a production system, at a unit process or in one particular stage of a production system.

One other strong point in this approach is related to the versatility of the outcomes. In Table 1 it is noticeable that the outcome features of this approach are suitable for presenting the data in a dashboard or scorecard format, since its purpose, users, updates, data and display features are very widespread. This results from the MSM construction simplicity, that is supported by applying a lean tool (VSM) and a lean thinking approach that highlights the value (for any kind of process variable) in a process sequence or system.

Moreover, the target users for the MSM diagrams analysis can be simultaneously the top and middle managers, or even the production line workers, since its mathematical concepts and visual attributes are straightforwardly understandable.

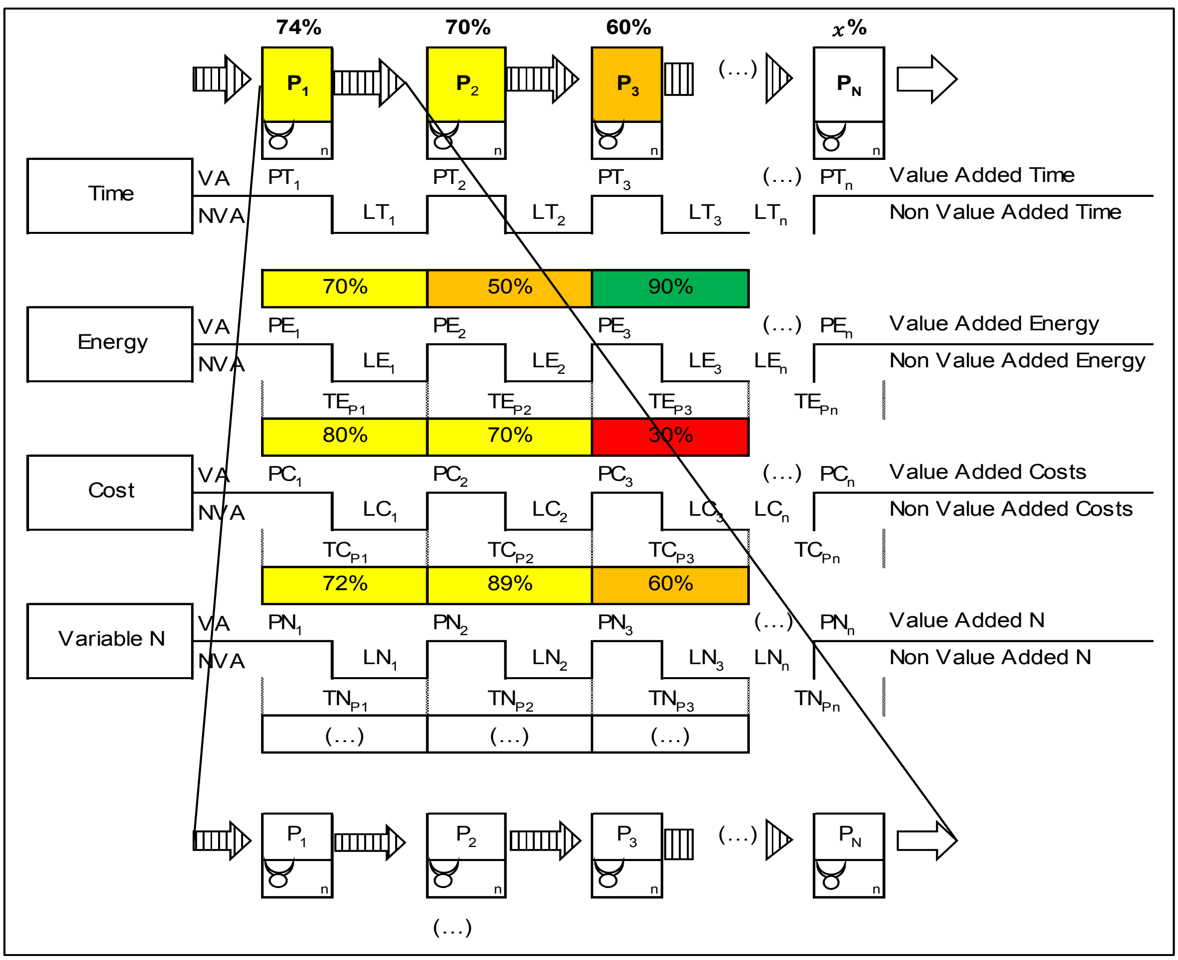

Figure 7: Multi-Layer Stream Mapping Drilldown.

Feature	Dashboard	Scorecard	MSM outcomes
Purpose	Measures performance	Charts progress	Measures performance and Charts progress
Users	Supervisors, specialists	Executives, managers, and staff	Supervisors, specialists, executives, managers, and staff
Updates	Right-time feeds	Periodic snapshots	Periodic snapshots
Data	Events	Summaries	Events and Summaries
Display	Visual graphs, raw data	Visual graphs, comments	Visual graphs, raw data and comments

Table 1: Features of Dashboards and Scorecards [7] compared with Multi-Layer Stream Mapping approach.

5 CONCLUSION

This paper presents a new approach, so called Multi-Layer Stream Mapping (MSM) that brings a new perspective on how eco-efficiency assessments results can be quantified by a discreet method in order that a process sequence or a system can be easily displayed and perceived in a multi-variable diagram. Variables such as energy, raw material consumption and cost can be straightforwardly mapped, as well as composed metrics, such as key environmental performance indicators, financial and production efficiency metrics, or other kind of relevant metrics for the analysis.

Due to the visual management attributes integration and its mathematical simplicity, based on the well-known VSM lean tool, the MSM can be viewed as a promoter for the importance of assessing, evaluating and quantifying environmental aspects of an industrial process or plant, in order to improve global industrial performance. By assessing global performance and considering environmental variables, together with time and cost variables, MSM can improve economic performance. With this approach, many environmental aspects, viewed as costs, can be reduced or eliminated from the process if it is assessed that they don't add value to the product.

Additionally, the demonstrated versatility of the MSM approach, besides giving a whole new dimension to eco-efficiency assessment perception, can be extended and applied with similar good results to the analysis of the performance of other general processes/systems. Other possible applications of the MSM approach can be investigated, such as in project management, logistics, economics, or even in financial systems analysis.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] WBCSD, World Business Council for Sustainable Development, *Vision 2050: The new agenda for business*, 2010: Geneva.

[2] Lehni, Markus, Schmidheiny, Stephan, and Stigson, Björn, *Eco-efficiency: creating more value with less impact*, 2000: Geneva.

[3] Verfaillie, Hendrik A. and Bidwell, Robin, *Measuring Eco-Efficiency—A Guide to Reporting Company Performance*, 2000, World Business Council for Sustainable Development WBCSD: Geneva.

[4] UNESCAP, United Nations Economic and Social Commission for Asia and the Pacific, *Eco-efficiency: A Practical Path to Sustainable Development*, 2007, United Nations publication.

[5] Zhang, Kang, *Using visual languages in management.* Journal of Visual Languages & Computing, 2012. **23**(6): p. 340-343.

[6] Russell, Alan D., Chiu, Chao-Ying, and Korde, Tanaya, *Visual representation of construction management data.* Automation in Construction, 2009. **18**(8): p. 1045-1062.

[7] Kerzner, Harold, *Project Management Metrics KPIs and Dashboards*, 2011, John Wiley & Sons, Inc.

[8] Arbulu, Roberto J., D.Tommelein, Iris, D.Walsh, Kenneth, and C.Hershauer, James, *Value stream analysis of a re-engineered construction supply chain.* Building Research & Information, 2003. **31**(2): p. 161-171.

[9] Kuhlang, P., Edtmayr, T., and Sihn, W., *Methodical approach to increase productivity and reduce lead time in assembly and production-logistic processes*. CIRP Journal of Manufacturing Science and Technology, 2011. **4**(1): p. 24-32.

[10] Shook, John and Rother, Mike, *Learning to See: Value Stream Mapping to Add Value and Eliminate MUDA.* 1999.

[11] Abdulmalek, Fawaz A. and Rajgopalb, Jayant, *Analyzing the benefits of lean manufacturing and value stream mapping via simulation: A process sector case study.* International Journal of Production Economics, 2007. **107**(1): p. 223-236.

[12] Braglia, Marcello, Carmignani, Gionata, and Zammori, Francesco, *A new value stream mapping approach for complex production systems.* International Journal of Production Research, 2006. **44**(18-19): p. 3929-3952.

A Binary Linear Programming Approach for LCA System Boundary Identification

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Abstract

One of the very first steps in conducting life cycle assessment (LCA) is system boundaries identification. A binary linear programming (LP) model is proposed to identify boundary between significant and insignificant processes in a LCA study. The proposed model is designed based on Relative Mass-Energy-Economic (RMEE) methodology. There are two types of objective function that can be solved by the proposed model, (1) to minimize number of processes considered in LCA or (2) to maximize cut-off criteria values. A numerical example and sensitivity analysis are provided to verify the applicability of the proposed model.

Keywords:

LCA; System Boundary; Linear Programming

1 INTRODUCTION

LCA is a tool used to assess environmental impact of a product. The assessment is conducted over life cycle of the product, from material extraction to end-of-life treatment. Figure 1 presents a general product life cycle [1].

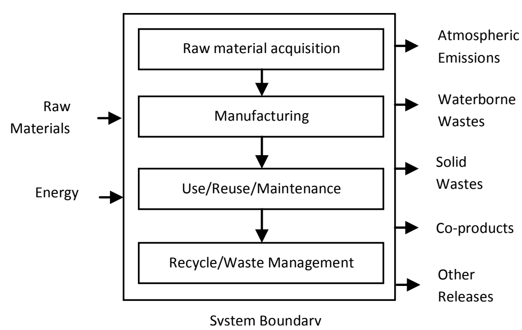

Figure 1: General Product Life Cycle [1].

As shown by Figure 1, box labeled as "system boundary" is a general system boundary of a LCA study. According to Tillman et al. [2] and Guinee et al. [3] there are 5 types of system boundary in LCA:

a) boundary between technical system and environment,

b) geographical area,

c) time horizon,

d) production of capital goods,

e) boundary between life cycle system of studied product and connected life-cycle systems of other products, and

f) boundary between significant and insignificant processes.

This paper concentrates on boundary between significant and insignificant processes. Defining boundary between significant and insignificant processes is not easy because when goals and scope are defined the significant and insignificant data are unknown [4].

2 EXISTING APPROACHES

Many LCA studies select system boundary qualitatively without a scientific basis. However, several methods have been proposed to guide practitioners in identifying LCA system boundary. For example, the use of percentage of mass to define system boundary can be found in Hunt et al. [5]. Criteria to stop are mass ratios. If ratio of mass used is 0.01, it means that if ratio of mass of an input to total mass of a process is less than 0.01 then this input is not considered in the system boundary. This approach is reasonable. However it does not quantify the significant of an input to the whole life cycle of a product.

Since data availability is also one of the difficulties in conducting LCA, the use of data availability in determining system boundary can be found in Mann et al. [6]. The weakness of this approach is that it has no scientific basis.

ISO standard [7] also provides guideline to identify LCA system boundary. It uses environmental significance as the criteria to select system boundary and requires impact assessment to be done before the system boundary is defined. This makes this methodology ineffective in practice.

Other approaches can be found in Raynolds et al. [8] and known as Relative Mass-Energy-Economic (RMEE) method. The following criteria are used by this method to cut system boundary [8].

$$M_{Ratio} = \frac{M_i}{M_{Total}} \quad (1)$$

$$E_{Ratio} = \frac{E_i}{E_{Total}} \quad (2)$$

$$E_{Ratio} = \frac{E_i}{E_{Total}} \quad (3)$$

$$\$_{Ratio} = \frac{\$_i}{\$_{Total}} \quad (4)$$

If $M_{Ratio} > Z_{RMEE}$ then process i is inside system boundary, else outside system boundary.

If $E_{Ratio} > Z_{RMEE}$ then process i is inside system boundary, else outside system boundary.

If $\$_{Ratio} > Z_{RMEE}$ then process i is inside system boundary, else outside system boundary.

Z_{RMEE} is boundary cut-off ratio ($0 < Z_{RMEE} < 1$). $M_i, E_i, \$_i$ are mass, energy and economic value of input i . $M_{Total}, E_{Total}, \$_{Total}$ are total mass, energy and economic value of the functional unit. Figure 2 shows RMEE procedure [8].

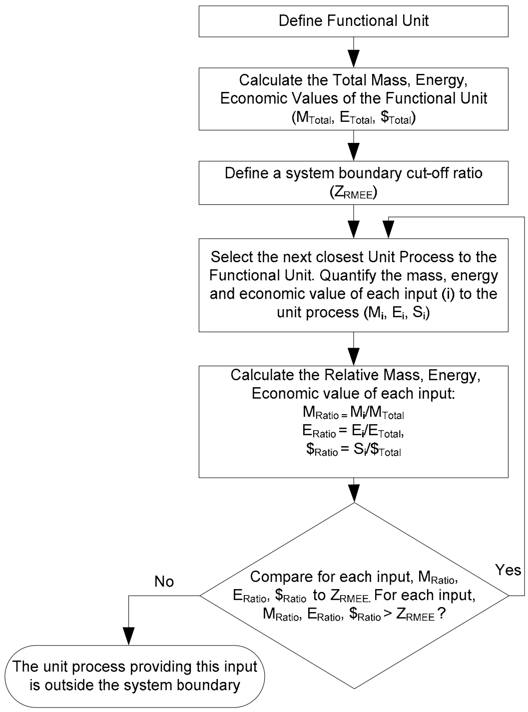

Figure 2: RMEE procedure [8].

RMEE method is quantitative, repeatable and streamlined. However this method does not incorporate data accessibility as one of the criteria to identify system boundary. Furthermore, RMEE also does not facilitate sensitivity analysis. If the cut-off ratio changes then the RMEE procedure has to be done all over again. Another question about RMEE is that how the value of the cut-off ratio is determined.

This paper formulates RMEE method as a binary LP model. In the proposed LP, the difficulties to collect inventory data are considered. Data collection cost is used to quantify those difficulties. In order to answer the question how cut-off ratio is defined, available budget to conduct LCA study is used as a constraint to determine how good cut-off ratio we can obtain. Moreover, since it is a mathematical programming approach then sensitivity analysis can be conducted easily.

3 BINARY LP MODEL TO IDENTIFY LCA SYSTEM BOUNDARY

3.1 Variables and Parameters

Let w, x, y, z be variables representing material extraction, manufacturing, use, and end-of-life phase respectively.

Suppose that w, x, y, z contain $i_1 = 1,2,..;\ j_1 = 1,2,..;\ k_1 = 1,2,...;$ and $l_1 = 1,2,...$ number of processes respectively and are denoted as $w_{i_1}, x_{j_1}, y_{k_1}$ and z_{l_1}. Similarly, suppose that $w_{i_1}, x_{j_1}, y_{k_1}$ and z_{l_1} have $i_2 = 1,2,...;\ j_2 = 1,2,...;\ k_2 = 1,2,...$ and $l_2 = 1,2,...$ number of processes respectively and are denoted as $w_{i_1 i_2}, x_{j_1 j_2}, y_{k_1 k_2}$ and $z_{l_1 l_2}$. Again, suppose that $w_{i_1 i_2}, x_{j_1 j_2}, y_{k_1 k_2}$ and $z_{l_1 l_2}$ contain $i_3 = 1,2,...;\ j_3 = 1,2,...,k_3 = 1,2,...$ and $l_3 = 1,2,...$ number of processes respectively and are denoted as $w_{i_1 i_2 i_3}, x_{j_1 j_2 j_3}, y_{k_1 k_2 k_3}$ and $z_{l_1 l_2 l_3}$

Of course the number of variables can grow indefinitely, for simplification, let's say that they grow up to $i_n = 1,2,..;\ j_n = 1,2,...;\ k_n = 1,2,...$ and $l_n = 1,2,....$ so that the last processes are denoted as $w_{i_1 i_2 i_3 \dots i_n}, x_{j_1 j_2 j_3 \dots j_n}, y_{k_1 k_2 k_3 \dots k_n}$ and $, z_{l_1 l_2 l_3 \dots l_n}$.The grow of those variables can be represented as a tree, shown by Figure 3.

All variables are binary (can only have a value of 0 or 1). If the value of a variable is 0 then the process represented by that variable is not inside system boundary, otherwise, if its value is 1 then the process represented by that variable is inside system boundary. Therefore, it can be expressed as, $w_{i_1}, x_{j_1}, y_{k_1}, z_{l_1};\ w_{i_1 i_2}, x_{j_1 j_2}, y_{k_1 k_2}, z_{l_1 l_2};\ w_{i_1 i_2 i_3}, x_{j_1 j_2 j_3}, y_{k_1 k_2 k_3}, z_{l_1 l_2 l_3};$ $w_{i_1 i_2 i_3 \dots i_n}, x_{j_1 j_2 j_3 \dots j_n}, y_{k_1 k_2 k_3 \dots k_n}, z_{l_1 l_2 l_3 \dots l_n} \in \{0,1\}$. Furthermore, w, x, y and z are equal to 1 because they are the main life cycle stages and have to be included in the system.

Suppose that mass inputs for material extraction, manufacturing, use and waste treatment are $\alpha^w, \alpha^x, \alpha^y$ and α^z; energy inputs for material extraction, manufacturing, use and waste treatment are $\beta^w, \beta^x, \beta^y$ and β^z; the economic values of processes in material extraction, manufacturing, use and waste treatment are $\gamma^w, \gamma^x, \alpha^y$ and γ^z ; and inventory data collection costs are $\delta^w, \delta^x, \delta^y$ and δ^z.

Therefore, for example, parameters for w_{i_1} are $\alpha^w_{i_1}, \beta^w_{i_1}, \gamma^w_{i_1}$ and $\delta^w_{i_1}$ and parameters for $w_{i_1 i_2 i_3}$ are $\alpha^w_{i_1 i_2 i_3}, \beta^w_{i_1 i_2 i_3}, \gamma^w_{i_1 i_2 i_3}$ and $\delta^w_{i_1 i_2 i_3}$. All parameters must be defined per functional unit of the studied system.

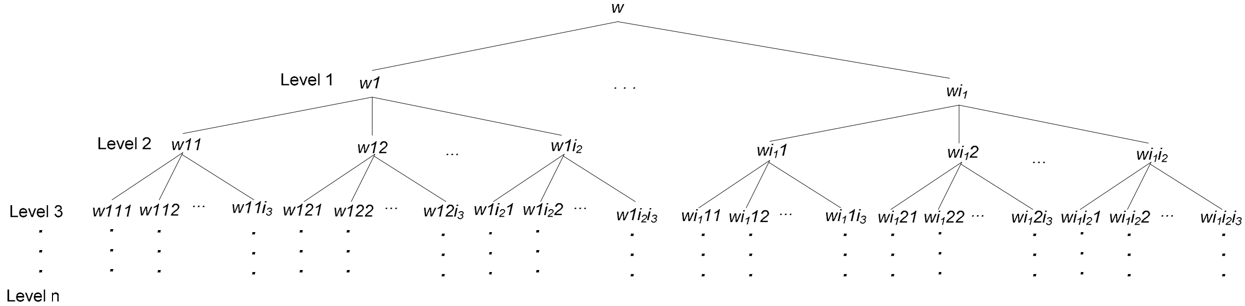

Figure 3: Variables or process tree for material extraction (w).

It is also defined that M_c, E_c, C_c are the cut-off criteria for material input, energy input and economic value, where $0 < M_c < 1, 0 < E_c < 1$ and $0 < C_c < 1$. If $M_c = 0.95$, it means that the ratio of sum of mass in the system boundary to total mass flowing in the system is 95%. The same meaning is also applicable for E_c and C_c. The closer those values to 1 the better the cut-off criteria. Finally B is total budget available to conduct a LCA study.

In the following section, objective functions and constraints are defined. For the purpose of simplification and because of limited space, variables included in the model are only up to level 3 (with 3 subscripts).

3.2 Objective Functions

There are two types of objective functions that can be selected, to minimize the number of processes considered in the LCA or to maximize cut-off criteria values. Equation (5) is the objective function formula for number of processes minimization and equation (6) is the objective function formula for cut-off criteria maximization.

$$Min\ Z = \sum_{i_1=1}^{m_1} w_{i_1} + \sum_{i_1=1}^{m_1}\sum_{i_2=1}^{m_2} w_{i_1 i_2} + \sum_{i_1=1}^{m_1}\sum_{i_2=1}^{m_2}\sum_{i_3=1}^{m_3} w_{i_1 i_2 i_3} + \sum_{i_1=1}^{n_1} x_{j_1} + \sum_{j_1=1}^{n_1}\sum_{j_2=1}^{n_2} x_{j_1 j_2} + \sum_{j_1=1}^{n_1}\sum_{j_2=1}^{n_2}\sum_{j_3=1}^{n_3} x_{j_1 j_2 j_3} + \sum_{k_1=1}^{0_1} y_{1_1} + \sum_{k_1=1}^{o_1}\sum_{k_2=1}^{0_2} y_{i_1 i_2} + \sum_{k_1=1}^{0_1}\sum_{k_2=1}^{0_2}\sum_{k_3=1}^{0_3} y_{k_1 k_2 k_3} + \sum_{l_1=1}^{p_1} z_{l_1} + \sum_{l_1=1}^{p_1}\sum_{l_2=1}^{p_2} z_{l_1 l_2} + \sum_{l_1=1}^{p_1}\sum_{l_2=1}^{p_2}\sum_{l_3=1}^{p_3} z_{l_1 l_2 l_3} \quad (5)$$

$$Max\ Z = \frac{1}{3}\left(M_c + E_c + C_c\right) \quad (6)$$

Where,

$$M_c = \frac{1}{\alpha_{Total}}\left(\sum_{i_1=1}^{m_1} \alpha_{i_1}^{w} w_{i_1} + \cdots + \sum_{l_1=1}^{p_1}\sum_{l_2=1}^{p_2}\sum_{l_3=1}^{p_3} \alpha_{l_1 l_2 l_3}^{z} z_{l_1 l_2 l_3}\right) \quad (7)$$

$$E_c = \frac{1}{\beta_{Total}}\left(\sum_{i_1=1}^{m_1} \beta_{i_1}^{w} w_{i_1} + \cdots + \sum_{l_1=1}^{p_1}\sum_{l_2=1}^{p_2}\sum_{l_3=1}^{p_3} \beta_{l_1 l_2 l_3}^{z} z_{l_1 l_2 l_3}\right) \quad (8)$$

$$C_c = \frac{1}{\gamma_{Total}}\left(\sum_{i_1=1}^{m_1} \gamma_{i_1}^{w} w_{i_1} + \cdots + \sum_{l_1=1}^{p_1}\sum_{l_2=1}^{p_2}\sum_{l_3=1}^{p_3} \gamma_{l_1 l_2 l_3}^{z} z_{l_1 l_2 l_3}\right) \quad (9)$$

$\alpha_{Total}, \beta_{Total}$ and γ_{Total} are total mass input, energy input and economic value in the studied system.

3.3 Constraints

If the selected objective function is equation (5) then the constraints are the following.

$$\sum_{i_1=1}^{m_1} w_{i_1} \le Mw \quad (10)$$

$$\sum_{i_2=1}^{m_2} w_{i_1 i_2} \le M w_{i_1},\ \forall\, i_1 \quad (11)$$

$$\sum_{i_3=1}^{m_3} w_{i_1 i_2 i_3} \le M w_{i_1 i_2}, \forall\, i_1 i_2 \quad (12)$$

$$\sum_{i_1=1}^{n_1} x_{j_1} \le Mx \quad (13)$$

$$\sum_{j_2=1}^{n_2} x_{j_1 j_2} \le M x_{j_1},\ \forall\, j_1 \quad (14)$$

$$\sum_{j_3=1}^{n_3} x_{j_1 j_2 j_3} \le M x_{j_1 j_2},\ \forall\, j_1 j_2 \quad (15)$$

$$\sum_{k_1=1}^{o_1} y_{k_1} \le My \quad (16)$$

$$\sum_{k_2=1}^{o_2} y_{k_1 k_2} \le M y_{k_1},\ \forall\, k_1 \quad (17)$$

$$\sum_{k_3=1}^{o_3} y_{k_1 k_2 k_3} \le M y_{k_1 k_2},\ \forall\, k_1 k_2 \quad (18)$$

$$\sum_{l_1=1}^{p_1} z_{l_1} \le Mz \quad (19)$$

$$\sum_{l_2=1}^{p_2} z_{l_1 l_2} \le M z_{l_1},\ \forall\, l_1 \quad (20)$$

$$\sum_{l_3=1}^{p_3} z_{l_1 l_2 l_3} \le M z_{l_1 l_2}, \forall l_1 l_2 \quad (21)$$

$$\frac{1}{\alpha_{Total}}\left(\sum_{i_1=1}^{m_1} \alpha_{i_1}^{w} w_{i_1} + \cdots + \sum_{l_1=1}^{p_1}\sum_{l_2=1}^{p_2}\sum_{l_3=1}^{p_3} \alpha_{l_1 l_2 l_3}^{z} z_{l_1 l_2 l_3}\right) \ge M_c \quad (22)$$

$$\frac{1}{\beta_{Total}}\left(\sum_{i_1=1}^{m_1} \beta_{i_1}^{w} w_{i_1} + \cdots + \sum_{l_1=1}^{p_1}\sum_{l_2=1}^{p_2}\sum_{l_3=1}^{p_3} \beta_{l_1 l_2 l_3}^{z} z_{l_1 l_2 l_3}\right) \ge E_c \quad (23)$$

$$\frac{1}{\gamma_{Total}}\left(\sum_{i_1=1}^{m_1} \gamma_{i_1}^{w} w_{i_1} + \cdots + \sum_{l_1=1}^{p_1}\sum_{l_2=1}^{p_2}\sum_{l_3=1}^{p_3} \gamma_{l_1 l_2 l_3}^{z} z_{l_1 l_2 l_3}\right) \ge C_c \quad (24)$$

$$\sum_{i_1=1}^{m_1} \delta_{i_1}^{w} w_{i_1} + \cdots + \sum_{l_1=1}^{p_1}\sum_{l_2=1}^{p_2}\sum_{l_3=1}^{p_3} \delta_{l_1 l_2 l_3}^{z} z_{l_1 l_2 l_3} \le B \quad (25)$$

$$w_{i_1}, w_{i_1 i_2}, w_{i_1 i_2 i_3}, x_{i_1}, x_{i_1 i_2}, x_{i_1 i_2 i_3}, y_{i_1}, y_{i_1 i_2}, y_{i_1 i_2 i_3}, z_{i_1}, z_{i_1 i_2}, z_{i_1 i_2 i_3} \in \{0,1\} \quad (26)$$

Inequalities (10) until (21) are linking constraints which mean that values of some variables depend on value of a certain variable. For example, suppose that process w_{11} and w_{12} are selected then process w_1 has to be selected because process w_{11} and w_{12} are inside process w_1. The number M represents an upper bound of any sum of the variables in the model. In other words M is at least as large as any sum of the variables we can feasibly get. Inequalities (22), (23) and (24) are constraints for cut-off criteria. Inequality (25) is budget constraint and (26) is binary constraint. If the selected objective function is equation (6) then the constraints are formulas (10), (11), (12), (13), (14), (15), (16), (17), (18), (19), (20), (21) and (26).

4 NUMERICAL EXAMPLE

Suppose that we want to do LCA study for the system represented by Figure 4. Mass, energy, and cost to collect inventory data is given by Table 1. Mass and energy values given are per functional unit. Information regarding economic values of a process is not given therefore it is not considered. Our objective is to identify system boundary and maximize overall cut-off criteria. Budget available to conduct LCA study is 400. Note that this example is not a real case study. The purpose of the example is just to demonstrate and verify the model.

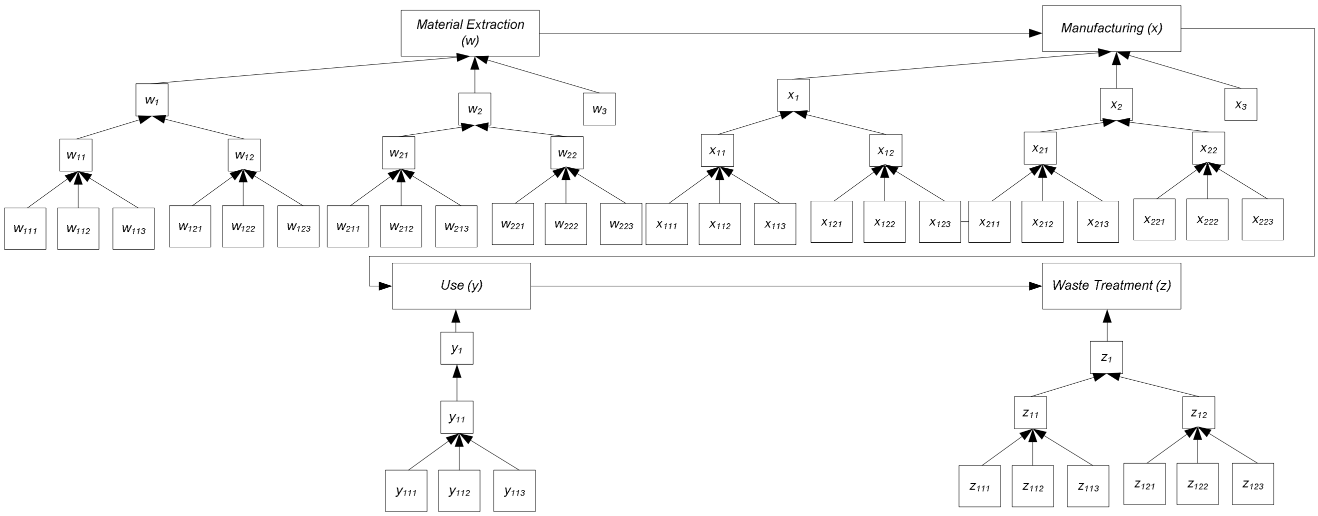

Figure 4: System for the numerical example.

Life cycle stage	***Process (Level 1)***	***Mass***	***Energy***	***Cost***	***Process (Level 2)***	***Mass***	***Energy***	***Cost***	***Process (Level 3)***	***Mass***	***Energy***	***Cost***
w	w_1	2	91	1	w_{11}	6	27	19	w_{111}	10	92	15
									w_{112}	10	28	15
									w_{113}	0	50	3
					w_{12}	7	79	11	w_{121}	1	93	6
									w_{122}	2	91	9
									w_{123}	1	45	15
	w_2	3	79	12	w_{21}	8	7	2	w_{211}	1	20	15
									w_{212}	8	58	4
									w_{213}	8	88	17
					w_{22}	5	98	16	w_{221}	1	18	12
									w_{222}	3	77	12
									w_{223}	0	65	6
	w_3	9	5	4								
x	x_1	8	27	10	x_{11}	2	19	4	x_{111}	3	96	3
									x_{112}	9	49	20
									x_{113}	7	33	1
					x_{12}	6	99	14	x_{121}	5	36	5
									x_{122}	0	77	2
									x_{123}	9	59	4
	x_2	1	20	0	x_{21}	7	85	8	x_{211}	6	70	10
									x_{212}	10	94	8
									x_{213}	3	15	7
					x_{22}	5	58	8	x_{221}	0	15	8
									x_{222}	10	75	9
									x_{223}	7	76	9
	x_3	5	64	19								

Table 1: Data.

Life cycle stage	*Process (Level 1)*	*Mass*	*Energy*	*Cost*	*Process (Level 2)*	*Mass*	*Energy*	*Cost*	*Process (Level 3)*	*Mass*	*Energy*	*Cost*
y	*y₁*	*2*	*2*	*20*	*y₁₁*	*9*	*5*	*13*	*y₁₁₁*	*4*	*68*	*15*
									y₁₁₂	*1*	*48*	*17*
									y₁₁₃	*2*	*15*	*13*
z	*z₁*	*3*	*13*	*2*	*z₁₁*	*2*	*69*	*20*	*z₁₁₁*	*2*	*52*	*7*
									z₁₁₂	*9*	*83*	*20*
									z₁₁₃	*5*	*70*	*4*
					z₁₂	*5*	*53*	*17*	*z₁₂₁*	*6*	*26*	*18*
									z₁₂₂	*1*	*78*	*6*
									z₁₂₃	*9*	*79*	*1*

Table 1: Data (*continued*).

The binary linear programming model is the following.

$$Max\ Z = \frac{1}{2}\left(M_c + E_c\right)$$

where,

$$M_c = \frac{\begin{array}{c}2w_1 + 3w_2 + 9w_3 + 8x_1 + x_2 + 5x_3 + 2y_1 + 3z_1 + 6w_{11} + \cdots + \\ 2x_{11} + \cdots + 9y_{11} + \cdots + 2z_{11} + \cdots + 10w_{111} + \cdots + 9z_{123}\end{array}}{\begin{array}{c}2+3+9+8+1+5+2+3+6+\cdots+ \\ 2+\cdots+9+\cdots+2+\cdots+10+\cdots+9\end{array}}$$

$$E_c = \frac{\begin{array}{c}91w_1 + 79w_2 + 5w_3 + 27x_1 + 20x_2 + 64x_3 + 2y_1 + 13z_1 + 27w_{11} \\ + \cdots + 19x_{11} + \cdots + 5y_{11} + \cdots + 69z_{11} + \cdots + 92w_{111} + \cdots + 79z_{123}\end{array}}{\begin{array}{c}91+79+5+27+20+64+2+13+27 \\ +\cdots+2+\cdots+9+\cdots+2+\cdots+10+\cdots+9\end{array}}$$

$Subject\ to,$

$w_1 + w_2 + w_3 \le Mw$

$x_1 + x_2 + x_3 \le Mx$

$y_1 \le My$

$z_1 \le Mz$

$w_{11} + w_{12} \le Mw_1$

$w_{21} + w_{22} \le Mw_2$

$x_{11} + x_{12} \le Mx_1$

$x_{21} + x_{22} \le Mx_2$

$y_{11} \le My_1$

$z_{11} + z_{12} \le Mz_1$

$w_{111} + w_{112} + w_{113} \le Mw_{11}$

$w_{121} + w_{122} + w_{123} \le Mw_{12}$

$w_{211} + w_{212} + w_{213} \le Mw_{21}$

$w_{221} + w_{222} + w_{223} \le Mw_{22}$

$x_{111} + x_{112} + x_{113} \le Mx_{11}$

$x_{121} + x_{122} + x_{123} \le Mx_{12}$

$x_{211} + x_{212} + x_{213} \le Mx_{21}$

$x_{221} + x_{222} + x_{223} \le Mx_{22}$

$y_{111} + y_{112} + y_{113} \le My_{11}$

$z_{111} + z_{112} + z_{113} \le Mz_{11}$

$z_{121} + z_{122} + z_{123} \le Mz_{12}$

$$\begin{pmatrix} w_1 + 12w_2 + 4w_3 + 10x_1 + 0x_2 + 5x_3 + 20y_1 + 2z_1 + 19w_{11} \\ + \cdots + 14x_{11} + \cdots + 13y_{11} + \cdots + 2z_{11} + \cdots + 15w_{111} + \cdots + 1z_{123} \end{pmatrix} \le 400$$

$$w_1, w_2, w_3, x_1, x_2, x_3, y_1, z_1, w_{11}, \cdots, x_{11}, \cdots, y_{11}, \cdots, z_{11}, \cdots, w_{111}, \cdots, z_{123} \in \{0,1\}$$

The solutions of this simple problem are the following.

$w = x = y = 1$ because they are the main life cycle stages.

$w_1 = w_2 = w_3 = 1,$

$x_1 = x_2 = 1, x_3 = 0,$

$y_1 = 1, z_1 = 1,$

$w_{11} = w_{12} = w_{21} = w_{22} = 1$

$x_{11} = x_{12} = x_{21} = x_{22} = 1$

$y_{11} = 1,$

$z_{11} = z_{12} = 1,$

$w_{111} = w_{112} = w_{113} = 1,$

$w_{121} = w_{122} = 1, w_{123} = 0,$

$w_{211} = 0, w_{212} = w_{213} = 1,$

$w_{221} = 0, w_{222} = w_{223} = 1,$

$x_{111} = x_{112} = x_{113} = 1,$

$x_{121} = x_{122} = x_{123} = 1,$

$x_{211} = x_{212} = x_{213} = 1,$

$x_{221} = 0, x_{222} = x_{223} = 1,$

$y_{111} = 1, y_{112} = y_{113} = 0,$

$z_{111} = z_{112} = z_{113} = 1,$

$z_{121} = 0, z_{122} = z_{123} = 1.$

$$Z = \frac{1}{2}\left(M_c + E_c\right) = \frac{1}{2}\left(0.93 + 0.91\right) = 0.92.$$

Total budget spent is 400 and the selected boundary is shown by Figure 5.

Suppose that we vary the budget from 375 to 575. The change in objective function value with respect to budget change is given by Figure 6 that shows when the budget reaches 535 it is possible to consider all processes in the system.

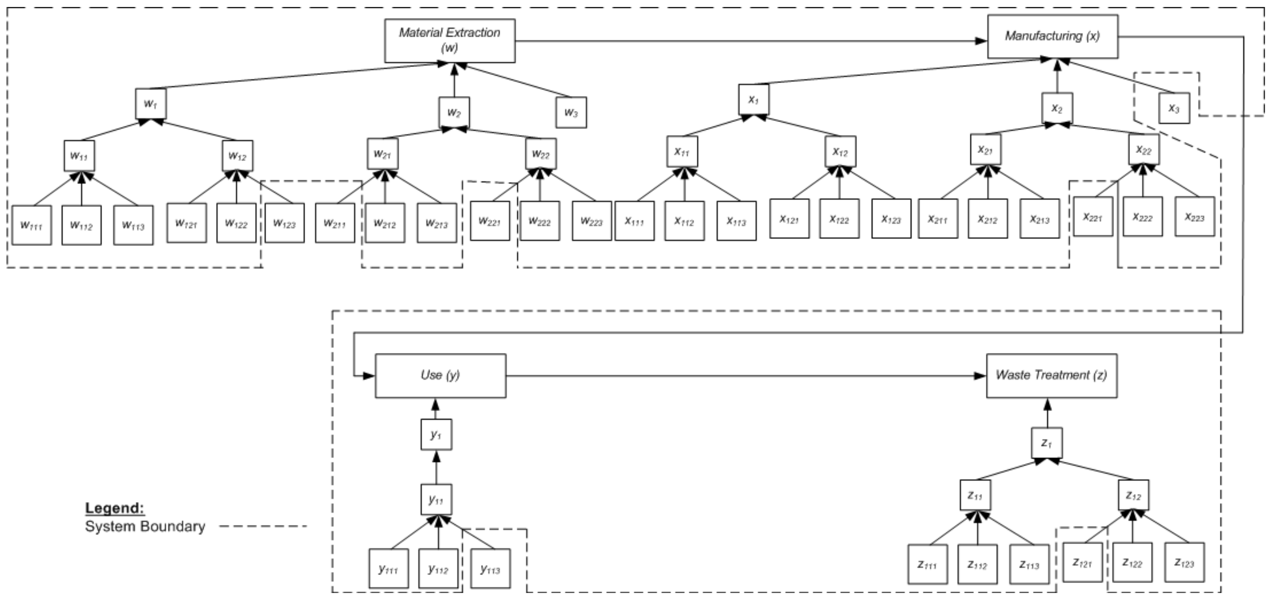

Figure 5: Selected system boundary.

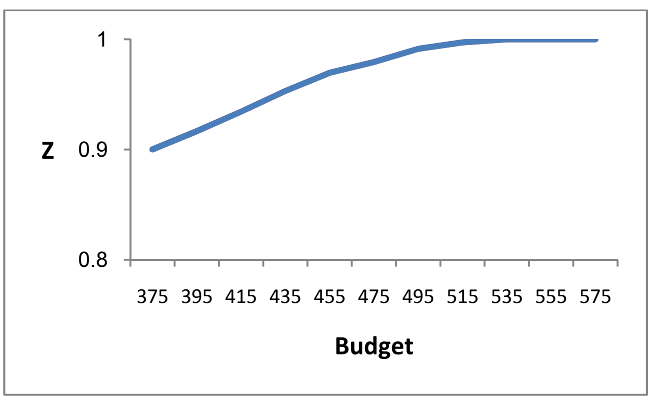

Figure 6: Change in objective function value with respect to budget change.

5 CONCLUSION

A binary linear programming approach to select system boundary of a LCA study is proposed. The proposed method is based on RMEE methodology presented in Raynolds et al. [8]. The main differences between the proposed methodology and RMEE are (1) RMEE is a repetitive approach; our approach is an optimization approach, (2) in our approach cut-off ratios are determined based on data accessibility (cost to collect inventory data); in RMEE the cut-off ratio is given, and (3) since our approach is a mathematical programming model therefore sensitivity analysis is easy to be done.

In the future, it is expected that computer software will be developed based on this methodology so that practitioners can easily determine their LCA boundary based on their available budget, mass flow, energy flow and economic values of the processes.

6 REFERENCES

[1] US Environmental Protection Agency (EPA), (2006): Life Cycle Assessment: Principles and Practice, EPA, Cincinnati, Ohio.

[2] Tillman, A. M., Ekvall, T., Baumann, H., Rydberg, T. (1994): Choice of System Boundary in Life Cycle Assessment, in: Journal of Cleaner Production, Vol. 2, No. 1, pp. 21 – 29.

[3] Guinee, J. B., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H. A., de Bruijn, J. A., van Duin, R., Huijbregts, M. A. J. (2002): Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Series: Eco-efficiency in Industry and Science, Kluwer Academic Publishers, Dordrecht.

[4] Finveden, G., Hauschild, M. Z., Ekvall, T., Guinee, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S. (2009): Recent Developments in Life Cycle Assessment, in: Journal of Environmental Management, Vol. 91, No. 1, pp. 1 – 21.

[5] Hunt, R. G., Sellers, P. L., Craig, K. L. (1992): Resource and Environmental Profile Analysis: A life-cycle Environmental Assessment for Products and Procedures, in: Environmental Impact Assessment Review, Vol. 12, No. 3, pp. 245 - 296.

[6] Mann, M. K., Spath, P. L., Craig, K. L. (1996): Economic and Life Cycle Assessment of an Integrated Biomass Gasification Combined Cycle System, in: Proceeding of the 31st Intersociety Energy Conversion Engineering Conference (IECEC), pp. 2134 - 2139, Washington DC, USA.

[7] ISO 14041, (1998): Environmental Management - Life Cycle Assessment - Goal and Scope Definition and Inventory Analysis, International Organization for Standardization.

[8] Raynolds, M., Fraser, R., Checkel, D. (2000): The Relative Mass-Energy-Economic (RMEE) Method for System Boundary Selection, in: International Journal of Life Cycle Assessment, Vol. 5, No. 1, pp. 37 – 46.

Lifecycle Oriented Ramp-Up – Conception of a Quality-Oriented Process Model

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Abstract

The ramp-up phase is a central point in the life cycle of a product. Numerous interdependent sections of a company link for the first time within this phase. There are many interdependent decisions in a dynamic and interdisciplinary environment, and turbulences emerge expressed by insufficient or inaccurate information about the current project status. Many identified problems cannot be analysed in detail regarding their causes or relevance, because one lacks a deep understanding of the system and suitable analysis tools. Instead of proactive problem prevention there do evolve spontaneous and unsecured actions. Studies demand future research to focus on developing systematic problem solving processes and explicit action schemes, increasing transparency and information flow by deriving quality-oriented approaches, a methodical organization of the ramp-up phase, holistic integration and connection of supporting methods. To face these challenges a process model is required, which allows for a holistic organization of the production ramp-up in terms of proactive quality management. This model enables companies to visualize, harmonize and align their projects and processes to reach and facilitate production systems' efficiency. Hence, the focus of this paper is on a process model for a quality-oriented production ramp-up containing three essential modules: system planning, evaluation and control.

Keywords:

Quality Management; Modelling; Ramp-up; Life Cycle Management

1 INTRODUCTION

In present times companies face enormous challenges. With ongoing globalization, companies have to compete with more competitors and deal with expanding individual customer requirements. Competition is becoming more complex, especially for the automotive, the mechanical engineering and the electrical engineering industry. Entrepreneurial success depends on producing and developing according to new market requirements. As a reaction to meet these customer requirements, the pace of innovation is accelerated, product lifecycles are getting shorter and the variety of different product variants is increased [1][2].

Thus the ramp-up phase – the phase between development and serial production – becomes more important, because it is passed through more often. In the automotive industry for example, the number of ramp-up processes of OEMs has tripled in the last two decades [3]. At the same time, the variety of different vehicle versions has increased by 61 percent between 1999 and 2005 [4].

These tendencies are of major economic importance. Automotive experts affirm that with efficient ramp-ups potentials up to five percent of the car model's return can be achieved. A delayed product launch results in lost sales which cannot be compensated for due to shorter product lifecycles, especially since prices are higher shortly after entering the market. Furthermore resources are bound in finding and implementing solutions generating additional costs. According to the BMBF research project "Fast Ramp-up", there is 15-35 percent potential for savings in the production ramp-up depending on the respective industry [5].

A vital cause for delays is fulfilling quality requirements. Most product flaws and defects originate from the early product phases, development and ramp-up. In contrast, 50 percent of the defects are first detected and dealt with in the production phase [6][7].

In most cases problems with the production ramp-up are not mastered. According to an international study, 60 percent of all ramp-ups in the European automotive industry missed their technological and/or economical goals [8]. The example of a German middle class car released in 1997 shows the drastic effect of delay: 50,000 cars could not be delivered on time resulting in lost profits of 15 million euro or 5 percent of the company's annual profit.

Therefore, the goal for the ramp-up is to enable on schedule, frictionless and safe production, while complying with the targeted goals for quality and costs. Educing from the BMBF research project "Fast Ramp-up", there are three fields that demand for research:

- The development of supporting models, tools, and methods for ramp-ups
- The improvement of organization and planning of ramp-ups
- The conception of controlling mechanisms in order to make measures and their effects more transparent.

2 THE PRODUCTION RAMP-UP

In order to develop a model for a quality-oriented production ramp-up, a comprehensive introduction to the field of observation – production ramp-ups in terms of Quality Management – is necessary. The following is a description of production ramp-ups as well as its implied tasks, objectives and challenges.

2.1 The Phases of Production Ramp-Ups

The production ramp-up specifies the period between the completion of the product or serial development and the achievement of peak production [9]. This period is distinguished by transferring a preproduction model from the development stage into the stage of serial production [10].

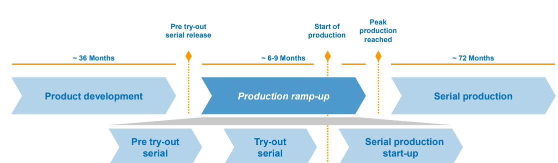

Figure 1: Production ramp-up.

In literature, stages of the production ramp-up are not described consistently. In the automotive industry, the serial production ramp-up begins after the pre try-out serial release and consists of three main stages: pre try-out serial, try-out serial and serial production start-up (see Figure 1) [2][5]. The production ramp-up is finished as soon as the planned peak production is reached and serial production begins. Process optimization, employees' qualifications and early problem diagnosis are in the focus of the pre try-out serial and the try-out serial phase, when prototypes are built. In the serial production start-up phase the first customer-ready product is created.

The acceleration of the production ramp-up is shown by the ramp-up curve. The ramp-up curve demonstrates the functional coherence between the production output per time unit and the production ramp-up time [7]. The change from the predecessor to the successor product can be either abrupt (block method) or continuous (step method) [11]. The serial production start-up phase ends as soon as the planned peak production has reached a stable and dependable production output rate. Due to the novelty of the product, the poor understanding of the production process and the inevitable integration of new suppliers, the production ramp-up represents a critical stage.

Control of the complex and critical stages of the production ramp-up is an important precondition for a holistic and continuous ramp-up management. An effective and efficient ramp-up management concentrates on all activities needed for planning, controlling and execution of the production ramp-up under consideration of all up- and downstream processes [5]. Therefore, key suppliers involved in the product development process need to be integrated into the production ramp-up as well. In a short period of time, ramp-up management needs to make a lot of interdependent decisions in a dynamic and interdisciplinary environment [6][9]. Major drivers of complexity are non-transparent situations and functional relations, as well as differences between global and local aims of the various groups involved in the three ramp-up phases**.**

2.2 Fields of Action

Concerning the previously shown coherences, several different fields of action within the ramp-up exist. Kuhn distinguishes between five fields of action for successful ramp-up management [5].

The first field of action is the planning, control and organization for which models are useful to master complexity. Current modelling approaches include single and multi-project management, enhanced data processing support, simulations, and also evaluation and process models. Secondly, ramp-up processes need to be robust, meaning the production process must be easily adjustable to later product or capacity changes and insusceptible to errors. The biggest issues with this are the maturity level of new technologies and parallel development of control mechanisms. The third field of action is ramp-up change management. Assemblies or single components of prototypes often require changes e.g. due to quality problems. These changes need to be planned, implemented and communicated. Additionally, different company departments and external parties such as suppliers or partners need to be coordinated. Cooperation and reference models are suitable, making data and processes transparent for all involved parties. The last field of action is building a ramp-up specific, company-wide system for knowledge management in order to conserve knowledge for follow-up projects. This paper focuses on the first field of action, the need for improved planning, evaluating and controlling approaches and models.

3 QUALITY-ORIENTATED FRAMEWORK

After a brief overview of serial production ramp-up processes, the associated quality and cost related challenges, this chapter addresses a holistic quality management framework. Starting with a derivation for the need of such framework in general, the Aachen Quality Management Model is introduced as a basic structure for organizational ramp-up modelling.

3.1 Need for a Holistic Framework

Generally, a framework, which enables a holistic image of all company activities rather than only focusing on single aspects, is needed for the creation of an entrepreneurial quality management [12]. Derived from the goals and challenges of the production ramp-up, new modelling demands for quality management emerge. Based on the characterizing terms for the performance measurement dimensions of production systems, a framework has to cover all relevant aspects to identify organizational losses. Therefore, it also needs to consider strategic objectives, entrepreneurial conditions and corporate skills.

Existing explaining and evaluating models like the ISO 9004:2007 series, or evaluating models like the EFQM Model, only emphasize an increase of the overlap rate of customer demands and product features. The company orientations, respectively the company's capabilities, are not taken into account [13]. Due to their primarily value-adding-oriented view of the process, these models are further lacking appropriate structures to carry information into adjoining or prospective product generations as well as their corresponding development processes [14]. In fact, the consideration of lifecycles has not been operationalized yet.

3.2 The Aachen Quality Management Model

The Aachen Quality Management Model provides a scope of action, which allows for the design of the entrepreneurial quality management for a company by considering strategic objectives, entrepreneurial conditions and resources in the product life cycle (see Figure 2) [15].

The constituting elements of the Aachen Quality Management Model are management, quality stream and resources & services. Thereby, management mainly includes pursuing strategies and goals efficiently, forming organizational structures and establishing a management system to support the process organization.

The quality stream, being the core element of the model, refers to the processes within a company. The quality stream consists of two structural elements: the quality forward chains and the quality backward chain. The quality forward chains include the proactive and preventive measures per product group. The quality backward chain organizes the reactive and corrective actions for all product groups. Control loops between the quality forward chains of different product groups and the quality backward chain enhance the model with elements of continues improvements. The third element of the model, the resources & services, reflects the company's capabilities [12].

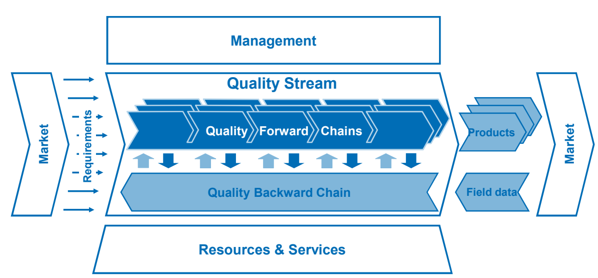

Figure 2: The Aachen Quality Management Model

On the path to the waste-free fulfilment of customer demands, the illustration of information relations between different product groups and their creation processes is an essential requirement to identify informative losses [16]. Within the Aachen Quality Management Model, these information relations are displayed by product and process overlapping in the quality stream. Therefore, every single forward chain is linked to the backward chain via control and improvement loops, so that holistic and bidirectional information architecture can be illustrated in the quality stream. Hereby, it is possible to transfer field data from current products to the early phases of the lifecycle of new product generations. One essential requirement to increase the maturity of new developments and, therefore, to immediately fulfil customer demands, is to extend the simple process orientation by also considering the lifecycle of a product.

4 CONCEPTION OF A QUALITY-ORIENTATED PROCESS MODEL

Process models work with establishing interrelations based on detected interactive grounds between apparently seeming independent fields. Within the framework of total quality management, they take numerous factors into consideration, namely the company's quality, working quality, potential quality, product quality and process quality. Those factors are set between the customer's needs, referring to input variables, as well as the customer's satisfaction as output.

Hence, process models model a company's internal processes, making them visual for the purpose of analyzing and explaining sources of interference within the context of quality management.

4.1 Conception of an Explanatory Model

Explanatory models, as opposed to description models and decision models, focus on causes of operating processes within a company, especially reasons for certain disruptions.

In a first step, relevant influence factors are to be identified with the purpose of interrelating them afterwards while aiming at establishing a whole reaction network based on detected assumptions.

Nevertheless, when it comes to create an appropriate explanatory model, investigations and inquiries need to be conducted first, delivering essential and basic information for further modelling.

Method

All models, particularly designed within the framework of this conception, are based on actual subjects of inquiry as well as on the conducted explorative-empirical investigation results. The latter provide different contextual aspects and contents with reference to given phase. The stress could be reduced during the *phase of orientation*. The reduction of stress was due to the author's casual and colloquial presentation of the subject and the aim of the paper. Furthermore, the focus was on creating a reliant and trustful atmosphere, making it easier to gather sensitive and company-internal information afterwards. Relevant issues, mentioned in chapter, were addressed during the *period of information gathering*. The main intention was to form a uniform concept of term as a basis, since equal meanings happen to be labeled quite differently which, as a result, causes miscommunication, resulting in misunderstanding within a company. The *completion phase* was anticipated to be a reflection, identifying quality-relevant key activities.

Modeling of Effective Interactions

The epistemological explanatory model (see figure 3) was derived from actual subjects of inquiry along with explorative-empirical based investigation results. It functions as a model-to-be for the structured and systematic run through of a try-out production phase, describing three fields of activity while elaborating on their interactive relation.

The main element of this model is the try-out production phase, which needs to be structured first. These structuring and planning activities take place with reference to the output of production, management advices and adaptional needs, left over from preceding trials.

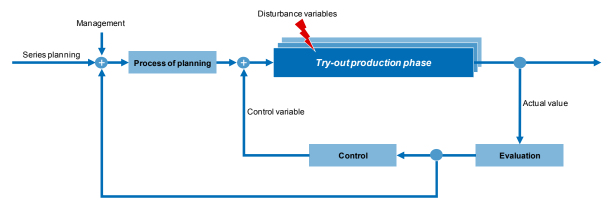

Figure 3: Epistemological explanation model.

However, the whole try-out process per se is subject to internal and external disturbance variables. In order to reduce these it is mandatory to evaluate and identify phase relevant process parameter, regulating disturbance factors if necessary.

4.2 Transformation of Inter-related Effects

Research has shown that there is a tremendous need for a systematic organization of series production. Due to the process immanent complexity, it is necessary to make the involved organizational steps as transparent as possible. Since it is illusionary to think of series production as problem-free, the systematic organization needs to rely on usage-based reaction-sceneries and strategies.

With reference to what research and investigation has presented so far, there are several requirements for each model which need to be fulfilled for the purpose of making it work, namely the three quality criteria: validity, reliability and functionality.

In the following, such a systematic organization of series production is introduced by applying IDEF0-modeling to the given context.

Syntax of Transformation Procedure

The construction-orientated design of the process model is based on the IDEF0-method (Integration Definition for Functioning Modeling). The IDEF0-method as such is based on SADT-logic (Structured Analysis and Design Technique) and is suitable when it comes to visualize production-related activities and model business processes.

The standard modeling language relies on the Black-Box-Principle, decompozating a given system starting with its highest abstraction form and going into more detail in succession. The system itself is regarded as being part of a larger process, including defined in- and output information which are themselves interrelated. A single function step is visualized using rectangles. Various function steps result in process chains (see figure 4).

The IDEF0-methods allows for top-down processes to be visualized according to any given situation with regard to any favored detail level. Additional concepts, approaches and methods contribute to the model's distinctness.

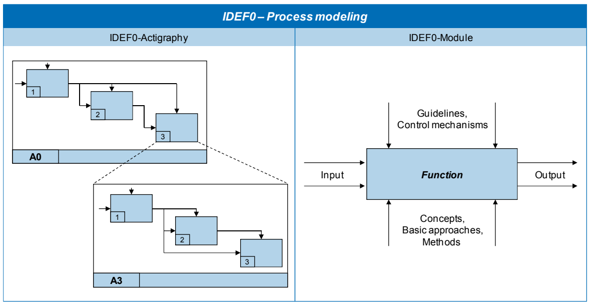

Figure 4: IDEF0-modeling.

4.3 Quality-Orientated Approach for Managing the Production Ramp-Up

The production ramp-up processes regarding the needs of product development and production management have been studied in detail. A holistic approach from a quality management point of view has, however, not yet been addressed and needs to be designed.

The aim regarding this need is to develop a comprehensive process model for a quality-oriented management of production ramp-ups. According to basic philosophies of quality management, the approach can be divided into three steps, namely planning module, evaluation module and control module (see Figure 5). Each module consists of specific activities, which will be described and elaborated in the following chapter.

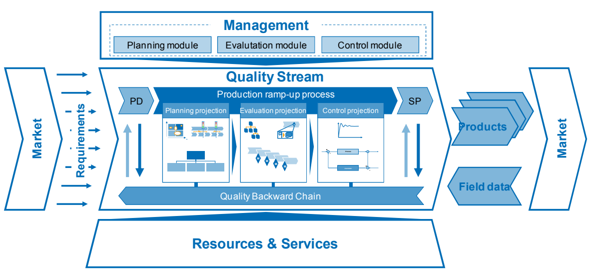

Figure 5: Conception of a process model for a quality-orientated ramp-up.

Planning Module

In a first step, the planning module takes the claim that the serial production ramp-up can be viewed as a predictable and controllable socio-technical system into account. The module's target is to ensure a systematic, forward-looking "think-through" of the ramp-up which has to be viewed as a business process. Therefore, central points of the planning module are the preparation and systematic organization of the production ramp-up. In doing so, it is necessary to elaborate all significant parts and sub systems and make them available to succeeding modules.

Starting with a strategic system planning, based on a top-down approach, the definition of the ramp-up system follows, building the foundation of all further activities. Quality-oriented process planning assists in the design of quality creating processes. Thus, proactive as well as reactive processes are to be constructed ramp-up specifically. In order to implement quality-suitable organizational structures, the planning module contains the development of purposeful organizational structures. In addition to operational structure related aspects, it is vital to build up appropriate organizational structures in order to guarantee a smooth and frictionless arrangement and realization of the production ramp-up.

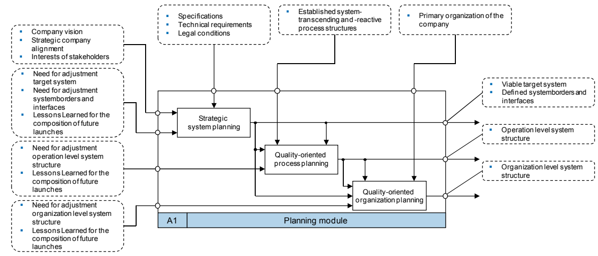

Figure 6: IDEF0-planning module.

Evaluation Module

Another demand the model has to fulfil is enabling decision makers to identify and evaluate ramp-up relevant problems. This demand is met within the framework of the evaluation module, which in essence is aimed at providing quality-relevant information. In contrast to the planning module, the evaluations module's information production and distribution is not on demand, but enables the continuous evaluation of the ramp-up process. The module's target is to increase the transparency of business processes by illustrating quality-relevant information for performance evaluation purposes. Apart from deriving information distribution requirements and maintaining an inventory of sensors, the module identifies key figures for quantitative representation of performance. In another activity a planning evaluation takes place, which continuously evaluates structures initialized in the planning module and which proactively influences future ramp-ups via the retrograde gain of knowledge. Impulses to encourage this are to be made on the basis of the already established reporting system. Central evaluation figures represent system, process and product quality.

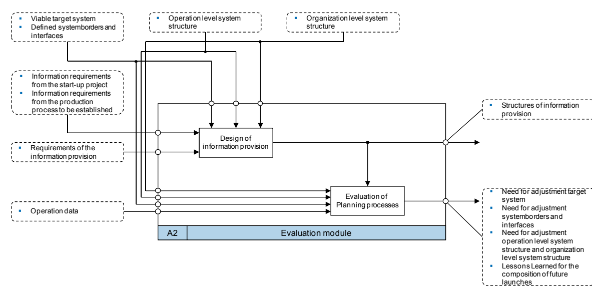

Figure 7: IDEF0-evalutaion module.

Control Module

According to numerous practical analyses, disturbances result from planning mistakes on the one hand and from unpredictable delays and modifications on the other hand. This makes adequate structures necessary that enable instant reactions on problems or disturbances. This way the model meets the requirements, providing mechanisms for quality-oriented controlling to decision makers. Hence, the control module's aim is to conceive structures which provide the ramp-up system with robustness regarding dynamic influences by allowing short-term reactions to disturbance variables.

The first activity of this module allows the allocation of control, which empowers the identification of to be regulated process variables as well as dimensioning and placing controlling structures. Within the scope of the second activity, the construction of the previously allocated control structures takes place, which also minimizes the turbulence related adjustment of these structures over time.

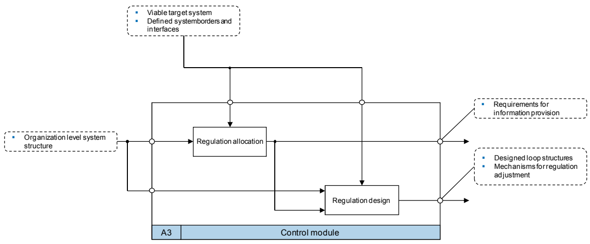

Figure 8: IDEF0-control module.

5 SUMMARY

Objective target of this paper was to introduce an outline for a process model to design a quality-oriented production ramp-up. Based on a description and resulting problems of the ramp-up phase, an overview about future fields of action in the context of ramp-up research was given first. It is especially Quality Management's task to support this highly dynamic, interdisciplinary, and interdependent phase with planning and controlling approaches. In this regard, the Aachen Quality Management Model with its texturing elements provides a suitable framework for explaining and shaping the ramp-up phase. With the integration of the planning, evaluation and controlling modules into the management layer of the Aachen Quality Management Model, the process model focuses on organizational aspects in particular. The projection executed by the modules and their activities allows the actual operationalization of previously planned activities within the Quality Stream by the use of the layer resources and services. Detailed elaborations of the modules as well as their activities are in the focus of current research.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] Fleischer, J., Lanza, G., Ender, T., Schmalzried, S., Giemsch, P. (2006). Verkürzung von Produktionsanlaufprozessen durch effiziente Inbetriebnahmeprozesse. wt Werkstattstechnik: 96. Jg., No.9, 688-692.

[2] Tücks, G. (2010). Ramp-Up in der Automobilindustrie, 1. Aufl., Apprimus Verlag, Aachen, Germany.

[3] Schuh, G., Kampker, A., Franzkoch, B. (2005). Anlaufmanagement. Kosten senken – Anlaufzeiten verkürzen – Qualität sichern. wt Werkstattstechnik: 95. Jg., No.5, 405-409.

[4] Abele, E., Elzenheimer, J., Rüstig, A. (2003). Anlaufmanagement in der Serienproduktion. ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb: 98. Jg., No.4, 172-176.

[5] Kuhn, A. H., Wiendahl, H.-P., Eversheim, W., Schuh, G. (2002). Fast ramp up: Schneller Produktionsanlauf von Serienprodukten. Verlag Praxiswissen, Dortmund, Germany.

[6] Schmitt, R., Pfeifer, T. (2010). Qualitätsmanagement. Strategien, Methoden, Techniken. 4. Aufl., Hanser Verlag, München, Germany.

[7] Baumgarten, H., Risse, J. (2002). Logistikbasiertes Management des Produktentstehungsprozesses. Technische Universität Berlin, Germany.

[8] Straube, F., Fitzek, D. (2004). Logistikorientierung optimiert Serienanläufe. Branchenreport Automobilzulieferer: 90-91.

[9] Schuh, G., Stölze, W., Straube, F. (2008). Anlaufmanagement in der Automobilindustrie erfolgreich umsetzen. Ein Leitfaden für die Praxis. 1. Aufl., Springer Verlag, Berlin, Germany.

[10] Wiesinger, G., Housein, G. (2002). Schneller Produktionsanlauf von Serienprodukten – Wettbewerbsvorteile durch ein anforderungsgerechtes Anlaufmangement. wt Werkstattstechnik online: 92. Jg., No.10, 505-508.

[11] Laick, T. (2003). Hochlaufmanagement – Sicherer Produktionshochlauf durch zielorientierte Gestaltung und Lenkung des Produktionsprozesssystems. 1. Aufl., FBK, Kaiserlautern, Germany.

[12] Schmitt, R.; Schmitt, S. (2009): Lifecycle Management – A New Entrepreneurial Approach for Quality Management. In: LCE 2009. Life Cycle Engineering in the Sustainability Age, Bd. 1 (Ed.: Waguih ElMaraghy). Windsor: University of Windsor, 221–227.

[13] Gucanin, A. (2003). EFQM-Modell auf dem Prüfstand. Forschungsergebnisse über Schwächen des EFQM-Modells für Excellence. QZ - Qualität und Zuverlässigkeit: Vol.48, No.2, 109-110.

[14] Achilleos, M., Ioannou, G. (2000). The development of an ISO 9000 Quality Management System to meet the requirements of the European Foundation for Quality Management (EFQM) Model - The Cyprus Telecommunications Authority's Case. 2000 Proc. 10th Mediterranean Electrotechnical Conf., 128-131.

[15] Schmitt, R., Betzold, M., Hense, K. (2007). Das Aachener Qualitätsmanagement Modell. In Masing Handbuch Qualitätsmanagement (Ed.: Schmitt, R., Pfeifer, T.). Carl Hanser Verlag, München, Germany, 38-41.

[16] Feng, L., Luo, M., Ren, J. A. (2007). Study on Integrated Quality Management System for the Lifecycle of Virtual Enterprise. Proc. WiCom 2007 International Conference on Wireless Communications, Networking and Mobile Commputing. Shanghai, China, 5074-5078.

Method for Rapid Estimation of Carbon Footprint Involving Complex Building Inventory Data – A Case Study

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Abstract

The process of performing carbon footprint assessment for buildings often involves the collection of vast amount of life cycle inventory data. It is not uncommon for the bill-of-material of buildings to exceed 100 items. Furthermore, the nature of the bill-of-material is a mixture of component (individual identifiable materials) and composite (mix of several materials) data, which introduces further complexities during data processing. The matching of emission factors to the appropriate activity data is a time-consuming process and therefore reliable emission results will be delayed when data gap is encountered. This paper aims to resolve the issues faced when conducting carbon footprint assessment involving complex dataset. A method is proposed for activity data screening and rapid emission estimation to enable the timely reliable estimations of the final emission results even where data gap in the emission factor exists. Further error analysis enables practitioners to focus data collection effort based on expected error of the inventory data items. Cut-off criteria may therefore be specified on this basis in order to manage data collection efforts.

Keywords:

Carbon Footprint; Emission Factor; Central Limit Theorem; Inventory Data

1 INTRODUCTION

1.1 Background

Activities associated to the building and construction industry often involves the vast consumption of the earth's resources in the form of materials and energy, resulting in the release of pollutants into the biosphere [1]. Throughout the life cycle of each material that forms a building, it would have undergone the stages of raw material extraction from the earth, to the multiple intermediate stages of transportation and material processing, and finally, the construction of a building. Mitigating the release of greenhouse gases into the atmosphere has been a growing issue in the area of sustainability.

Recognizing such issues, the local building and construction industry in Singapore has developed carbon footprint measurement and management strategies. The first step to carbon management would be able to accurately measure the carbon emissions during the building's lifecycle. This has resulted in the development of The Carbon Index specific to the construction industry in Singapore [2, 3]. Carbon footprint reporting has also been brought up to pace by the Building and Construction Authority (BCA) of Singapore with its inclusion in the latest Green Mark Scheme [4]. These recent developments illustrate the rising interest in the building and construction sector in the area of carbon footprint quantification and reporting.

1.2 Problem

With the progress in the requirements of carbon footprint reporting, organizations in the construction industry embarking on carbon footprint studies, however, still face major hurdles, especially when the bill-of-materials (BOM) of buildings commonly forms the main bulk of the data collection and processing efforts.

Several surveys conducted on LCA practitioners have pointed that data collection is the biggest challenge commonly faced when conducting life cycle studies. Cooper and Fava (2006) [5] states that inventory data collection process, is cited by approximately two-thirds of LCA practitioners as the most time-consuming and costly part of LCA. Follow up surveys done by Teixeira and Pax (2011) [6] also showed consistent results on the barriers of conducting LCA.

In order to address these challenges, previous studies have proposed carbon footprint streamlining methods such as data grouping [7] and algorithmic approach to streamline carbon footprint quantification [8]. Predictive emission factors in combination with structured data and uncertainty analysis were also proposed to deal with tremendous data requirements for simultaneous multi-product carbon footprinting [9].

In the context of carbon footprinting for buildings, the largest problems associated to data collection are the complexity and size of dataset being handled and the difficulty in collecting complete data in a timely manner.

The rate at which a carbon footprint study can be conducted is limited by the availability of timely and complete data. This poses tremendous practical challenges as data associated to the construction of a building is decentralized among several individual sub-contractors. In reality, the required data is not available simultaneously from all anticipated sources. It is common for a practitioner to have only obtained partial data for the entire building's BOM after numerous iterations of data collection attempts. Even after the entire BOM is completely collected, the details of each item in the BOM may still be left unavailable. An example would be the unavailability of the disaggregation of an item's weight in terms of major contributing materials. In the absence of complete data, the carbon footprint study suffers from data gaps which compromise on completeness. This eventually leads to delays in the delivery of the carbon footprint results and findings. Notwithstanding tremendous challenges faced during the conduct of carbon footprint studies of buildings, practitioners may also be required to be able to deliver carbon footprint estimates for purposes such as, but not limited to, budget estimation for carbon offsetting of building projects, justification for design decisions and addressing stakeholder's concerns by providing quick initial estimates for benchmarking purposes. Working with limited data is a scenario commonly faced by LCA practitioners. While providing the final carbon footprint results is not possible at this stage, estimations can still be made by using expert judgement. There is neither a formalized method for performing estimations nor any definition of what expert judgement entails. That leads to subjectivity in determining the basis of estimation and scope of expert judgements.

Conventional methods of quantification, while ensuring transparency, completeness, relevance and reliability required by the carbon footprint standards [10, 11], also introduce complexities as a consequence. The process of carbon footprint quantification when applied on products with a small number of assemblies and sub-assemblies, are often manageable in terms of the data collection and processing efforts requirements. In such an instance – quantifying the product carbon footprint of a plastic bottle, for example – the process can hence be completed in a relatively short amount of time. However, when handling carbon footprinting of a product such as a building, a complex set of data is required to estimate the activities involved during the construction of the building. As a result, the required time and effort for the carbon footprint study increases. This involves the process of data collection, data processing and data validation, often on data size exceeding 100 items. Further expertise is also required to examine each activity data point individually and correspondingly match with their appropriate emission factor (EF). The matching process may also involve further efforts through the form of conducting interviews and questionnaires to gather expert knowledge to ensure EFs are utilized appropriately and fairly. Matching of EFs to the appropriate activity is a manual process which not only requires intensive work, but also relies on specialised knowledge and expert judgement. Very often, there are multiple data sources available in the practitioner's database of EF for a single activity. For instance, there could be over 70 possible values of EFs for concrete production. Selection of the best possible match would require details on the specifications of the concrete such as its strength class, and, the type and proportion of cement replacement used. Such detailed data might not be available until the later stages of the study.

2 AIMS

The main aim of this work is to propose a method for rapid estimation of the carbon footprint under data limitations and complex datasets. It is recognized that under conditions of limited data availability, a carbon footprint study that fulfils the principle of completeness may not be possible. However, valuable data can still be inferred in such circumstances with the collected existing data. The method also aims to reduce the demands on data processing during the process of deriving the estimates. The initial estimates produced can then be further refined to arrive at the final results.

3 METHOD

3.1 Premise and Definition

The challenges faced during the matching of EFs to the corresponding activities can be overcome by providing a preliminary estimate of the EFs instead of attempting to guess suitable EFs amongst the numerous EFs available under situations of limited data availability. In order to provide a reasonable estimate of EFs, a definition of what is deemed as a *reasonable estimate* must be first established. In this study, a *reasonable estimate* of EF is defined as the mean industry EF for a particular activity. For instance, a *reasonable estimate* for the EF of concrete production is the mean EF taken across the entire global industry of concrete producers. With this definition established, it can be further developed as a basis to simplify and reduce the complexities in handling large datasets involved in the carbon footprint study of a building to provide rapid estimation.

3.2 Contextualization of the Central Limit Theorem (CLT)

The Central Limit Theorem (CLT) states that when random samples is drawn from a population of any distribution shape, with finite mean (μ) and variance (σ), the corresponding sampling distribution of the sample means will approach a normal distribution as the sample size (n) increases. The mean of the sampling distribution will have a mean equivalent to the population mean (μ) and a corresponding variance of $\frac{\sigma^2}{n}$ [12].

The CLT in principle enables the inference of useful information such as the mean of the population, which is generally an unknown, without direct measurement of the entire population through the conduct of random sampling. This proves to be a particularly useful property of the CLT which enables it to be contextualised for the

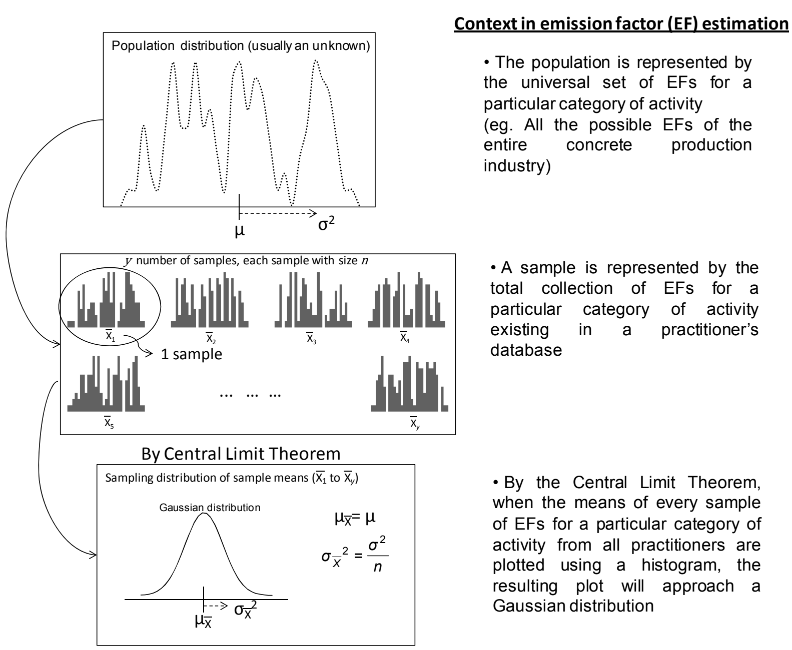

Figure 1: Illustration of contextualization of the CLT for EF estimation.

estimation of the mean industry EF for a particular activity. As mentioned above, this work deems a *reasonable estimate* of an EF, based on the mean industry EF for a particular activity; hence, CLT is applied to evaluate reasonable estimates for EFs.

An illustration of the CLT being used for such a context is shown in Figure 1. All the possible EFs of a particular activity are taken to be the entire population. Additionally, the individual EFs existing in the practitioner's database corresponding to the same activity represent a sample of EFs taken from the population. Taking, for instance, the case of concrete production, all the possible EFs of concrete production from all possible concrete producers represent the entire population of concrete production EFs, while the EFs of concrete production available in the practitioner's database is a sample of EFs drawn from the entire population of EFs for concrete production. Each EF in the population is assumed to be independent of each other.

Although the sampling distribution of the sample mean is inaccessible to each individual practitioner, the sample mean is the best available estimate at hand, and the value is approximately close to the sampling mean. In practical terms, from the perspective of an individual practitioner, the set of EFs available for data analysis is the practitioner's own database collection. Therefore, the entry point of EF estimation is EFs drawn from the practitioner's database, forming a single sample. The mean of this set EFs can then be easily calculated as the practitioner's database is the most readily available data source. The sample of EFs is treated as a random sample taken from the population of which the sample is supposed to describe.

Another issue to be addressed is the scope definition of the EFs sample. Determining the items belonging to a sample can be conducted through several means such as grouping the EFs in terms of material types (eg. steel, plastic) and other common properties. This is similar concept employed by the *grouping technology* employed by Rugrungruang (2010) [7], whereby the EFs can be grouped in a similar manner as in the case of a complex BOM highlight in the previous study.

Although the sampling distribution of the sample means cannot be obtained from the perspective of a single practitioner, knowledge of a single sample mean is still useful in determining confidence intervals regarding the population mean.

This work limits the scope of discussion to the evaluation of the embodied carbon emissions of buildings, as it is the main carbon footprint contributor during the construction phase of buildings. However, the same concept can also be applied to other sources of emissions and also other products where large life cycle data inventory is expected.

3.3 Full Conventional Method

The full conventional method of computing the carbon footprint of a building while observing the principles of transparency, completeness and reliability also demands rigorous data collection and processing procedures. As illustrated in Figure 2 (left), the process of computing the embodied emissions of a building can be summarized into four steps. Starting with the completion of the BOM (Step 1), every item must be examined to identify the specific raw material that makes up the item in question. Once the specific raw materials are identified, the proportion of each raw material has to be estimated and recorded (Step 2). For each identified raw materials on the list, the practitioner has to collate all possible EFs for selection based on material names, specifications, production process technology, production geography, *et cetera* (Step 3). Finally, once the data are filtered and appropriately matched, the final data aggregation is done to derive the carbon footprint for the embodied materials (Step 4).

3.4 Proposed Rapid Estimation Method

The proposed rapid estimation method aims to estimate a carbon footprint value without the need of a rigorous process. The purpose of this process is not meant to compute the final carbon footprint value, but rather, it aims to retrieve useful information about the final results through inference. As illustrated in Figure 2 (right), the proposed rapid estimation takes place in four major steps. With the same starting point as the conventional method, the BOM is collected (Step 1). However, the specificities in the BOM may be missing, for instance, if an item is identified to be made of 80% plastic and 20% steel, neither the specific type of plastic nor the specific grade of steel is required at this stage. Next, the BOM is reduced by disaggregating items and collecting them into *Material Class* bins (Step 2). Collectively, the *Material Class* bins forms a vector, storing the weights of each identified generic class of materials. Each *Material Class* bin has a predefined EF, forming another vector to represent the EFs of all the *Material Classes*. Finally (Step 3), to arrive at a preliminary estimate of the carbon footprint, a dot product is performed between the weight vector and EF vector. If further accuracy is required, an error analysis and data refinement step can be performed (Step 4) to arrive at a revised estimate.

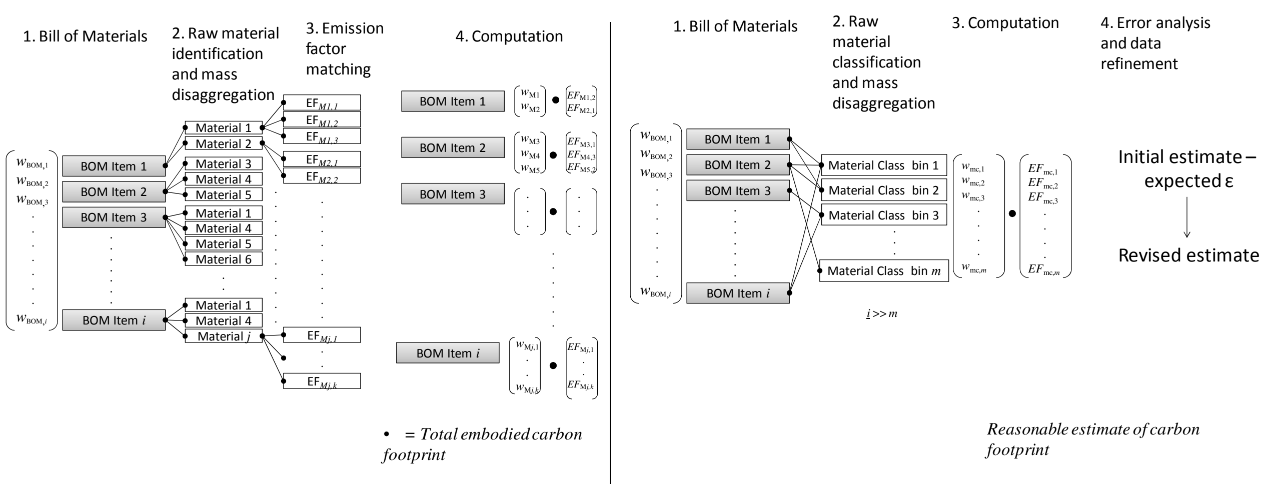

Figure 2: Conventional method (left) and rapid estimation method (right) for carbon footprint.

3.5 EF Estimators

Applying the concept of the proposed rapid estimation method, data preparation has been done accordingly. Data is collected from several libraries – Inventory of Carbon & Energy[13], ecoinvent[14], IDEMAT 2001[15], ETH-ESU 96[16], BUWAL[17], World Steel Association[18], PE International[19], Franklin USA 98[20], Plastics Europe[21], International Stainless Steel Forum[22] and SIMTech's in-house studies. Prototype *Material Class* bins are defined, with the EF means($\bar{X}$) and coefficient of variation (C_v) shown in Table 1 below. This table forms the basis of EF estimation used in the following case studies.

Material Class bin	Data Sample Size (*n*)	Mean ($\bar{X}$)	Coefficient of Variation (C_V)
Aluminium	31	7.471	0.379
Asphalt	5	0.076	0.491
Cement	26	0.606	0.640
Ceramics	8	1.006	0.373
Clay	7	0.401	0.633
Concrete	79	0.119	0.457
Copper	4	2.860	0.466
Glass	11	1.334	0.458
Mortar	10	0.252	0.393
Other Metals	11	3.683	0.468
Paint	10	2.034	0.514
Plaster	6	0.310	0.818
Plastics	23	3.954	0.104
Rubber	13	2.679	0.665
Sand	7	0.007	0.327
Sealants & Adhesives	11	5.791	0.183
Stainless Steel	10	4.798	1.738
Steel	55	1.831	1.049
Stone, Gravel	12	0.113	0.207
Wood	10	0.848	0.709

Table 1: Emission factor estimators.

4 CASE STUDIES

4.1 Case Background

Two building construction projects – Project A and Project B – are used as case study for the rapid estimation method to estimate their embodied carbon emissions from the BOM data. Project A is the construction of a commercial retail mall while Project B is the construction of an industrial building.

In order to make a comparison, the results of the embodied carbon emission done manually with the full conventional method are used as the benchmark. Therefore, the error in the results is the difference between the rapid estimation method and the full conventional method of calculation.

4.2 Initial Estimation

The initial results from the rapid estimation method are compared to the results from the manual calculation for the two projects.

A plot of actual manually calculated results against estimated emissions by rapid estimation method is shown in Figure 3 to illustrate the trends between the two sets of results. The corresponding correlation coefficient of the two sets of results is 0.9976. The final results are summarized in Table 2 below.

Comparatively, the rapid estimation method produces an average absolute error of approximately 20% for the two projects. With this level of error, the initial estimations obtained from the rapid estimation method can only be employed to infer an approximate gauge of magnitude for the carbon footprint results.

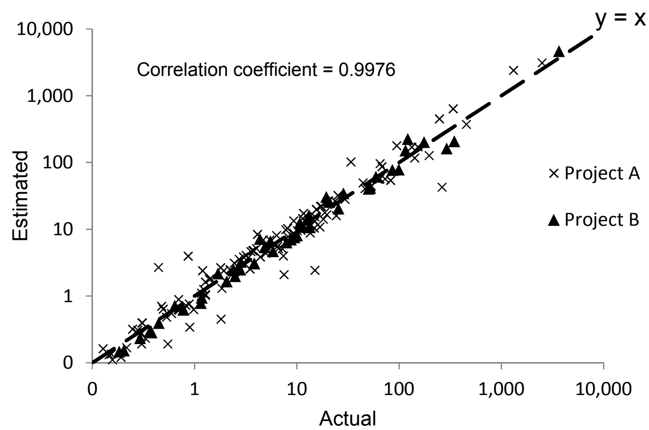

Figure 3: Comparison of actual vs. estimated emissions.

Carbon footprint (Normalized)	Project A	Project B
Initial estimation	125.8	86.8
Manual calculation	100	100
Absolute error (%)	26%	13%

Table 2: Results summary of the initial estimation and manual calculation.

However, as there is linear relationship between the estimated and actual results, the estimated results can still be used for purposes such as determining the relative contributions from each emission source and data refinement prioritization to yield more accurate results to assist practitioners in the earlier stages of their carbon footprint studies.

4.3 Error analysis for Data Refinement

The data is re-examined to determine ways of reducing the error. Two indicators for the measurement of error are defined – expected relative error and actual absolute relative error. The expected relative error represents estimation for the expected deviation away from the mean value of the results for each item in the BOM. It is calculated as follows:

$$Expected\ relative\ error\ (pre-normalized)_i = \frac{\sum_{j=1}^{M} w_{i,j} \times EF_{i,j} \times CV_{i,j}}{\sum_{i=1}^{N}\sum_{j=1}^{M} w_{i,j} \times EF_{i,j}}$$

where:

w represents weight

i is an item in the BOM

j is the *Material Class* bin

N is the total number of items in the BOM

M is the total number of *Material Class* bins

CV is the coefficient of variation for the *Material Class j* of the i^{th} item in the BOM

The expected relative error is then normalized with the estimated carbon footprint done with the rapid estimation method to give a total sum of 1 (or 100% in percentage scale) for all the items in the BOM.

$$Expected\ relative\ error_i = \frac{Expected\ relative\ error\ (pre-normalized)_i}{\sum_{i=1}^{N} Expected\ relative\ error\ (pre-normalized)_i}$$

where:

i is an item in BOM

N is the total number of items in the BOM

The actual absolute relative error provides a similar measure in error, taking the difference between the estimated values and the actual values of the carbon footprint as a basis.

$$Actual\ absolute\ relative\ error\ (pre-normalized)_i = \frac{|(Estimated\ CF\ of\ item\ i\ in\ BOM - Actual\ CF\ of\ item\ i\ in\ BOM)|_i}{Total\ actual\ CF}$$

where:

i is an item in BOM

CF represents carbon footprint

$$Actual\ absolute\ relative\ error_i = \frac{Actual\ absolute\ relative\ error\ (pre-normalized)_i}{\sum_{i=1}^{N} Actual\ absolute\ relative\ error\ (pre-normalized)_i}$$

where:

i is an item in BOM

N is the total number of items in the BOM

In reality, only the expected relative error can be calculated to forecast errors, while the actual absolute relative error is calculated retrospectively (i.e. after the full conventional method of calculation is completed). However, both values are presented for the purpose of the comparison and illustration of the predictive capability of the expected relative error.

Each item in the BOM is subsequently assigned to an error band based on the expected relative error. The error bands are classified by the author based on the order of magnitude as shown in Table 3.

Relative error (%)	Error band
less than 1%	Low
1 - less than 10%	Medium
10% and above	High

Table 3: Error bands.

The result of the expected relative error is plotted against the actual absolute relative error for every data point in the BOM. The error bands for the data points (actual and predicted) are reflected in Figure 4.

Analysis of the two sets of data points showed a correlation coefficient of 0.9348. Therefore, the expected relative error provides a good measure to infer the actual error after the conduct of the rapid estimation method. Based on the error bands of each data point, error "hotspots" can be identified which assist practitioners prioritize and focus on data that falls within the high error band. Practitioners can now easily identify data that require further refinement from the computed values of expected relative error. If the expected relative error is more than 10%, it falls in the "high" error band, hence more resources should be channelled to ensure higher data quality for those data points. Data points, having an expected relative error of between 1% and 10%, are classified within the "medium" error band. These data points can be revisited once the practitioner has refined data in the high priority. On the other end of the scale, if the expected relative error is less than 1%, it reflects that the data point has little effect on the final carbon footprint results, and therefore placing the data in low priority.

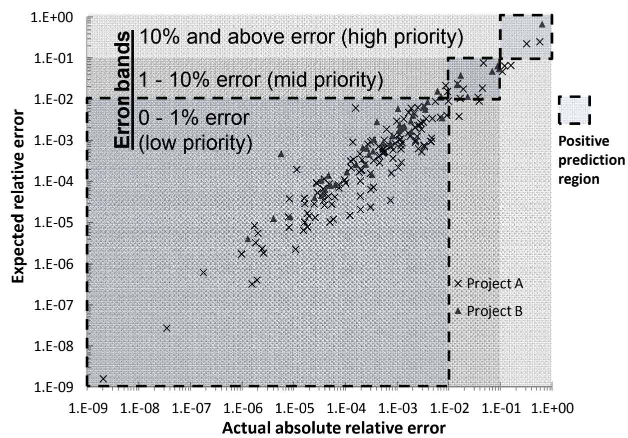

Figure 4: Classification of errors using error bands.

Table 4 shows the performance of the expected relative error in inferring the actual error "hotspot" from the data in the case studies. For 95% of the BOM items (encompassed in the dotted region in Figure 4), they are correctly placed in the error bands such that their respective predicted error bands is equivalent to the actual error bands. 2.5% of the BOM items however are being over predicted (points lying above dotted region in Figure 4), whereby the predicted error band is higher than that of the actual error bands, while the remaining BOM items suffers from under prediction (points lying below the dotted region in Figure 4), whereby the predicted error is lower than the actual error bands. However, it is noted that all the data that lie in the high error band are categorized correctly.

Error banding outcome	Frequency (%)
Positive prediction of error band	94.92%
Over prediction of error band	2.54%
Under prediction of error band	2.54%

Table 4: Prediction performance of error band classification.

4.4 Manual Refinement and Revised Estimation

Following the error banding outcome, BOM items of which expected relative error fall in the high error band are identified. The EFs of these BOM items are then revaluated and refined to select a more specific EF that better fit the item in question. A total of two BOM items from Project A and one BOM item in Project B are identified to be in the high error bands. These data that are deemed to have high error based on its predicted error band are then revised with the practitioner's manual decisions and input. The final revised estimation results are shown in Table 5.

After the items in the high error band are identified and re-evaluated with manually assigned EF that best fit the items' specifications, the revised estimates showed a significant drop in the difference between the carbon footprint from the estimates and the manually calculated results. The absolute error for both projects on average is approximately 4%, which is significantly lower than the initial 20%.

Carbon footprint (Normalized)	Project A	Project B
Revised estimate	104.5	103.2
Manual calculation	100	100
Absolute error (%)	4%	3%

Table 5: Revised estimates.

5 DISCUSSION

5.1 Data reduction for Initial Estimation

The main advantage of rapid estimation is the reduction of the number of data points involved in the calculation of the product carbon footprint. For the purpose of rapid carbon footprint estimation, it is recognized that the amount of data processing effort should be kept low, while preserving a reasonable amount of accuracy. The number of data points handled for Project A and Project B are compared in and Table 6.

Illustration of the number of data points involved in Project A & Project B				
	Step 1	**Step 2**	**Step 3**	**Step 4**
Conventional	197	240	7,591	480
Rapid Estimation	197	20	40	240

Table 6: Illustrative comparison of reduction in data points.

The conventional calculation method takes a data expansion approach to calculate the carbon footprint. This approach suffers from a data multiplicative effect. With a starting number of 197 items in the BOM (Step 1), every data has to be examined and disaggregated in terms of their basic material composition. On the average, each item contains of approximately 1.2 basic materials, therefore, increasing the number of data points to 240 (Step 2). Subsequently, for each basic material, there could possibly be more than a single EF value for the practitioner to select and match. Therefore, all the possible EF has to be complied for matching with the materials in question. Depending on the type of materials and data availability, the number of EFs available for each material varies. In the case studies, an average of about 32 EFs is available for selection for each material. Iterating the procedure for the materials for each BOM item, the amount of data points handled rapidly rises – 7,591 in this case (Step 3). Finally, once the EFs are filtered and paired with the respective materials, the data points handled will settle to twice the number of materials (Step 4).

The rapid estimation method, however, takes a data reduction approach to derive reasonable estimates of carbon footprints. Taking the same 197 items of data in the BOM (Step 1), each item is disaggregated and collected in their respective *Material Class* bins (Step 2). The resultant number of data point in this step is equivalent to the number of *Material Classes* being defined. In this work, 20 *Material Classes* are being defined. Proceeding on, each *Material Class* have a corresponding pre-defined estimated EF, therefore, the number of data points is 40 (Step 3). Further error analysis and data refinement requires the examination of each material in the BOM (Step 4), hence, the number of data points is equivalent to the number of basic materials identified.

In comparison of the two approaches, the rapid estimation method has markedly reduced the data processing demands on the practitioner, potentially reducing data processing time by over 90%. At the same time, the results obtained were within 4% of that being manually calculated using the conventional method.

5.2 Data Prioritization

A recommended guideline, though not a requirement, for conducting a carbon footprint study is to perform a data prioritization process. Usually this process is carried out based on existing previous studies, and in the case whereby previous studies are not available, estimations must be made [10]. Therefore, the results derived from the proposed rapid estimation method can be utilized as a starting point to conduct data prioritization if a previous study of a particular product in question is not available.

Based on the results of the rapid estimation, significant contributors to the carbon footprint can be identified. Thereafter, efforts of data collection efforts can be focused in collecting data that have significantly higher impact on the results to reduce the uncertainty in those items. Conversely, data of negligible consequence to the final carbon footprint results can also be identified. Cut-off criteria can also be established to reduce the total data collection efforts of the carbon footprint study. Such an approach would enable practitioners to cut the time in data processing and focus their efforts on essential tasks (i.e. collecting data with significant impact) which necessarily demand more data examination and expertise.

It can be seen in the case study that with the combination of the proposed rapid estimation methods together with the error analysis and data refinement, the estimated carbon footprint results are brought to 4% of the actual manually calculated results, down from an average of 20% from both case studies.

5.3 Limitations

The main assumption for the rapid estimation method is based on the CLT and hence is subject to the assumptions of the theorem. It is assumed that the samples are drawn randomly from the population. Such assumption may pose challenges when the practitioner's database data points do not adhere to random sampling due to improper definition of the sample. Therefore, practitioners have to clearly define the scope that the samples represent to determine if the sample is a suitable estimator for the study in question. For instance, data points bounded by geographic location may reflect well on that specific geographic location it is taken from but will not be a good estimator if the same data points were to be utilized to represent a global average. Therefore, careful delineating and selection of the items belonging to a sample requires sound technical expertise.

The case study utilizes a prototype of the EF estimators, of which the ratio of EF data points to EF estimators is on average 17:1. However, it is noted that there are as low as four data points in the estimation of a single EF estimators in the case of copper. The small number of data points in estimating the EF estimators poses a limitation on the accuracy of estimations. This limitation however, can easily be overcome by increasing the ratio of EF data points to

EF estimators. Further improvement can also be made on the EF estimators by re-categorizing or adding more categories to minimize sample standard deviations.

5.4 Future Works

The requirement for a careful selection of data to be classified as a sample belonging to a *Material Class* bin is identified as one of the limitations as it requires expert judgment. Therefore, criteria based selection can be explored to optimize the process of selecting of data points for the *Material Class* samples. The establishment of such procedures will further decrease the subjectivity of the classification process and increase the robustness of the method.

Data in life cycle assessment or carbon footprint studies exists as a large network of interlinked data points instead of separate individual entities. While this current work mainly discusses the technique of rapid estimation in the context of buildings' BOM, similar concept can also be expanded to characterize activity data. The variations in the activity data varies vastly and contain much larger types of categories from distance estimation for transportation to process input energies *et cetera*. They in turn form a vast network of interlinked data points, associating the various activities to categories of EF. When such networked relationships between data points are established, the rapid estimation method can be applied to rapidly predict the carbon footprint results, reducing the time required to establish a baseline estimate of environmental performance.

5.5 Conclusion

In order to address data collection and processing issues in carbon footprint quantification, a rapid estimation method is established for the purpose of carbon footprint estimation. This method utilizes the mean EF for materials classified under the same category as a starting point. A technique of error analysis for data prioritization, coupled with practitioners' manual decisions is discussed and applied to further enhance the accuracy of the estimates. The two case studies on average illustrated a final estimate of approximately 4% difference between the results from manual calculations and that derived from the rapid estimation method. At the same time, the number of data points involved during data processing has been reduced by over 90%. Similar concept can be applied on the activity inventory data for estimation. In order for the methods to be more effective, the networked relationships between activity data and emission factor must be studied and established. Once established, a full predictive model can be developed.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] G. P. Hammond and C. I. Jones, "Embodied energy and carbon in construction materials," in *Institution of Civil Engineers - Energy 161*, 2008.

[2] National University of Singapore, "Construction Carbon Index," NUS, 2012. [Online]. Available: https://www.carbonindexcalculator.com/. [Accessed 14 November 2012].

[3] Singapore Institute of Surveyors and Valuers, "The Carbon Index," Singapore, 2008.

[4] Building and Construction Authority, "BCA Green Mark Assessment Criteria," BCA, Singapore, 2012.

[5] J. S. Cooper and J. A. Fava, "Life-Cycle Assessment Practitioner Survey," *Journal of Industrial Ecology,* vol. 10, no. 4, pp. 12-14, 2006.

[6] R. Teixeira and S. Pax, "A Survey of Life Cycle Assessment Practitioners with a Focus on the Agri-Food Sector," *Journal of Industrial Ecology,* vol. 15, no. 6, pp. 817-820, 2011.

[7] F. Rugrungruang, B. Song, Z. Yeo and H. K. Gwee, "A method for applying LCA for eco-performance improvement of complex products," in *8th International Symposium and Environmental Exhibition: Going Green – Care Innovation 2010*, Vienna, Austria, 2010.

[8] R. S. Ng, Z. Q. Yeo, C. W. P. Shi, F. Rugrungruang and B. Song, "An Algorithmic Approach to Streamlining Product Carbon Footprint Quantification: A Case Study on Sheet Metal Parts," *International Journal of Automation Technology,* vol. 6, no. 3, pp. 312-321, 2012.

[9] C. J. Meinrenken, S. M. Kaufman, S. Ramesh and K. S. Lackner, "Fast Carbon Footprinting for Large Product Portfolios," *Journal of Industrial Ecology,* vol. 16, no. 5, pp. 669-679, 2012.

[10] British Standads (BSI), "PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services," 2011.

[11] Greenhouse Gas Protocol, "Product Life Cycle Accounting and Reporting Standard," GHG Protocol, 2011.

[12] W. DeCoursey, Statistics and Probability for Engineering Applications, Elsevier Science (USA), 2003.

[13] Sustainable Energy Research Team (SERT), "Inventory of Carbon & Energy," University of Bath, Bath, UK, 2011.

[14] Swiss Centre for Life Cycle Inventories, "Ecoinvent Lifecycle Database".

[15] Delft University of Technology, "IdeMat LCI database," Netherlands.

[16] ESU-services, "ETH-ESU 96 libraries," ESU-services, Zürich, Uster.

[17] Swiss Packaging Institute, "BUWAL Library," Swiss Packaging Institute, Switzerland.

[18] World Steel Association, "World Steel Association life cycle assessment".

[19] PE International, "PE International lifecycle database," PE International.

[20] Franklin USA 98, "Franklin USA LCI library," Sylvatica.

[21] Plastics Europe, "PlasticsEurope Eco-profile," Plastics Europe.

[22] International Stainless Steel Forum, "ISSF Life Cycle Inventory and Analysis," ISSF.

Product Benefit as a Key for Assessing Resource Efficiency of Capital Goods

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Abstract

For assessing the resource efficiency of capital goods, a life cycle oriented approach is essential. The following paper presents an approach to assess the resource efficiency and especially the product benefit, which is introduced as a key factor for the efficiency calculation. The interdependencies of measures within the three product life cycle pillars "production", "product", and "use phase" have to be taken into account. Resource efficiency of capital goods is determined by its long use phase and is highly dependent on the respective application profiles. The product benefit for the customer has to be compared to the needed resources.

Keywords:

Resource Efficiency; Product Life Cycle; Product Benefit

1 INITIAL SITUATION

The long use phase and the application profiles of capital goods determine the resource efficiency. For a life cycle oriented approach, the used resources in all phases have to be taken into account. The life cycle of a capital good consists of the three pillars "production", "product", and "use phase". Measures to reduce the use of resources are specifically applied to single areas or processes within a single pillar. They neither consider the effects on the other pillars nor on the product benefit.

According to the efficiency, which is defined as ratio between output and input [1, 2], resource efficiency in this paper is defined as ratio between the product benefit (output) and the use of resources (input) over the whole life cycle. Due to restrictions and immeasurable risks in accessibility of resources, the approach focusses especially on energy and material. This paper presents an approach for assessing the product benefit as key factor in order to assess life cycle oriented resource efficiency. This methodology is suitable for evaluating different measures for increasing resource efficiency in consideration of their effects on the generated product benefit (numerator of resource efficiency formula) as well as on the use of resources within the three pillars "production", "product", and "use phase" (denominator of resource efficiency formula). The methodology is illustrated by an example of the capital goods industry. In particular, this example shows how to determine the product benefit depending on different application profiles of a capital good. Finally, the proposed methodology will be discussed and suggestions for further research will be given.

2 STATE OF THE ART

2.1 Resource Efficiency in Capital Goods Industry

In general, capital goods have a long lifetime and are applied to generate a value for the customer. The products require lots of resources and a high reliability. According to that, the limitation of raw materials, legal conditions, and the rising resource awareness lead to resource efficiency as a competitive factor.

The limitation of resources is represented by the static range, which depends on the current reserve [2]. It is highly dynamic and is determined by several factors, e.g. varying demand, new technologies, or new explorations, which cannot be considered yet. Consequently, different sources exist that present different values depending on the publication date for the static range [3, 4, 5, 6].

Law makers in different countries recognized the importance of resource efficiency. This results in different legal conditions which vary within the countries. They consider for example emission standards [7, 8, 9, 10], energy restrictions [11], or subsidies for certain resources.

As a result, resource efficiency is getting more and more important for capital goods and is finally inevitable.

2.2 Existing Approaches to Assess Resource Efficiency

In order to assess resource efficiency, it is necessary to analyze the impact of measures over the whole life cycle. Existing approaches are based on the collection of input and output parameters and focus a certain aspects, like machine [12], production [2,13], product use [14], etc. Input parameters are usually material and energy. Output parameters are for example products, waste, or emissions [15]. These approaches are based on balancing the input and output parameters. These parameters are for example emissions for the life cycle assessment (LCA) [16], energy for the cumulated energy demand (KEA) [17], and energy or material for energy or material stream analysis [18].

2.3 Existing Approaches for the Assessment of Product Benefit

The success of selling products depends on the performance of customer requirements. That implies a certain value of the purchased product for the customer [19]. This value is often difficult to define and to assess [19]. According to this, the term of the customer benefit was established. It is a measure for customer's satisfaction of need and is always assessed under consideration of the costs [20]. The assessment of the customer benefit is applied in the field of Value Based Marketing and aims at deriving product attributes from the customer's requirements [21]. The customer's requirements can be classified [21], for example into quality and functionality, competitiveness, safety, or fun factor [20]. The attributes are divided into basic, performance, and excitement attributes [21].

There are several approaches to identify those attributes. They are based on interviews with the customer, as for example the Field-Value-in-Use Assessment [20], direct or indirect interviews [21], focus group value [20, 21] or importance ratings [21]. A widespread approach is the conjoint analysis [20, 22]. Within this approach, different product profiles are presented to the customer. The customer assesses the whole configuration and not only single attributes.

The aforementioned approaches are marketing methods to gather customers' needs and to derive requirements for the product development. The product attributes are in general given by the interviewer. Consequently, the quality of the interviews is highly dependent on the choice of the interviewer and the interviewed customers [23]. Additionally, interdependencies between attributes are not taken into account. The customer benefit is always considered in correlation to the costs for the customer. In contrast to the customer benefit, the product benefit depends on the utility function and the product lifetime. In addition to that, the product benefit is considered in correlation to the use of resources during the whole life cycle and results in the resource efficiency. Therefore, the existing approaches are not suitable for assessing the product benefit.

2.4 Interim Conclusion and Objectives

Improvement measures for resource efficiency may lead to overcompensation over the life cycle due to independencies within the pillars. The objectives of the following approach are the consideration of the reference to the product benefit, a life cycle orientation, and the assessment of improvement measures with consideration of interdependencies between the life cycle pillars. Therefore, a suitable methodology to assess the product benefit is presented within this paper.

3 ASSESSMENT APPROACH

The approach is separated into two parts: the basic model (1) of the approach consists of the description of the life cycle pillars, the resource efficiency calculation, and the definition of the product benefit. The assessment of resource efficiency (2) contains the assessment of the current resource efficiency and the assessment of improvement measure impacts on the resource efficiency.

3.1 Basic Model

Life cycle pillars

The calculation of life cycle oriented resource efficiency is based on a general assessment model (see Figure 1). In order to take each part of the product life cycle into account, the model consists of three pillars: the production, the product itself and the product use. The transportation of the product or pre-products is also included by a cross-pillar function. The interdependencies between the pillars are an important issue for gathering the impact of measures on the whole life cycle. The assessment method focusses on the use of the resources energy and material.

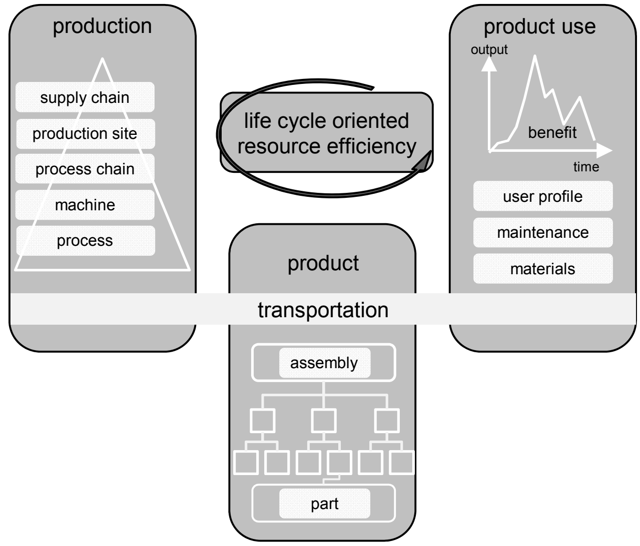

Figure 1: General assessment model.

The **production pillar** includes all manufacturing steps from the raw material production to the final product. According to the systems theory, the production pillar focusses different levels: supply chain, factory, process chain, machine, and process. Changes within a level can have impacts on superior or subordinate levels as well as on preceding or following areas.

Within the **product pillar**, the product itself is the main object. The product consists of different sub-systems, which in turn consists of assemblies of parts. All these components determine the product properties like e.g. power or weigth.

The pillar **product use** is determined by two factors: the product benefit and the used resources.

Resource efficiency calculation

In order to calculate the resource efficiency, the total amount of used resources is taken into account for the pillars. It is balanced against the product benefit. Thus, resource efficiency R_{eff} is described as

$$R_{eff} = B_p / R_u \quad (1)$$

The product benefit B_p depends on the utility function U(t) which is conducted over the whole lifetime L_t and is defined as:

$$B_p = \int_0^{Lt} U(t) \quad (2)$$

The use of resources R_u is the total amount of material and energy which is needed during the life cycle.

$$R_u = R_{production} + R_{product} + R_{productuse} + R_{transport} \quad (3)$$

Product benefit

The product benefit is the essential factor in order to assess resource efficiency over the whole product life cycle. Customers buy capital goods in order to generate a specific value (transportation, soil cultivation, energy generation, etc.). Consequently, only value creating functions are considered in order to determine the product benefit. Therefore, excitement attributes (design, entertainment system, etc.) are less relevant and not taken into account. Beside the basic attributes, the performance attributes are of main interest in order to determine the utility function of capital goods and to derive the product benefit.

The product benefit is the utility function over the product lifetime. A specific product output rate (performance) of a capital good at each time results in the utility function U(t) (see Figure 2).

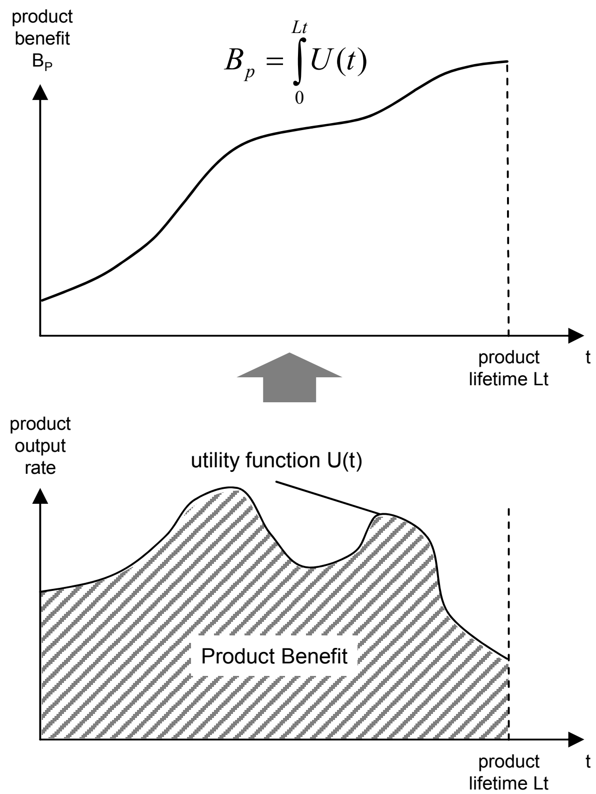

Figure 2: Product benefit.

In order to assess the product benefit, the utility function has to be determined related to the product lifetime. The utility function is determined by the usage, the availability, and the performance attributes of the product (see Figure 3).

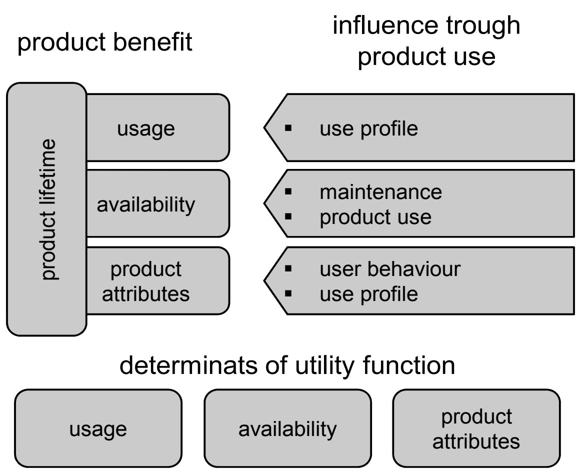

Figure 3: Interdependency between product benefit and product use.

The usage is determined by the use profile in the product use. The maintenance on the one hand and the way the product is used on the other hand, determine the availability of the product. It is assumed that the product attributes remain the same as at the beginning of the product use. These attributes can be changed during the use phase through the user behavior and the use profile.

3.2 Assessment of Resource Efficiency

The procedure of the resource efficiency assessment consists of three steps (see Figure 4): the data collection, the measurement analysis and the assessment of the new resource efficiency.

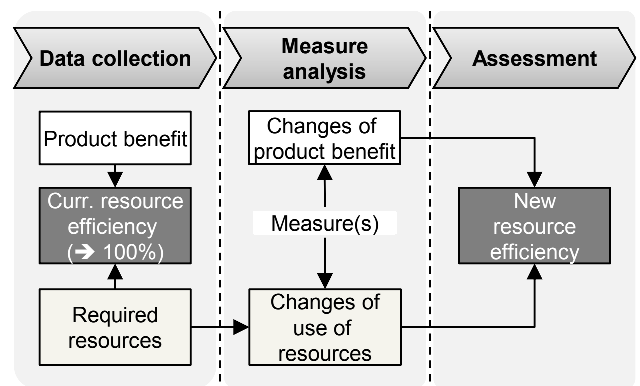

Figure 4: Procedure of resource efficiency assessment.

At first, all necessary values have to be determined in the data collection phase. The evaluation of the current status of ressource efficiency is the main aspect of this phase. According to aforementioned equation 1, two input values are needed: the use of resources in all pillars (equation 2) and the product benefit (equation 3). The result is the current resource efficiency which is equated with 100%.

To evaluate the impact of a measure on resource efficiency, the changes for the values are gathered in the measure analysis phase. Depending on the measure, the product benefit or the use of resources can be constant. But the interdependencies across the pillars can cause a change of different factors. Finaly, the new resource efficiency is calculated. The result is a percentage which has to be compared to the initial 100% of the current resource efficiency.

Assessment of resource efficiency

The factors in the product use determine the utility function. Consequently, these factors are used to derive the relevant attributes for a classification of use profiles. For the assessment of resource efficiency, the product benefit is deduced for the different classes of use profiles. After that, the use of resources is gathered for the different types of resources (production, product, product use, and transport). The resource efficiency is the quotient of the product benefit (output) and the use of resources (input). It is set to 100% as initial point (see Figure 5).

	classes of use profiles		
	A	B	C
$B_{P,Lt}$	product benefit A	product benefit B	product benefit C
$R_{production}$	use of resources in production		
$R_{product}$	resources in the product		
$R_{productuse}$	$R_{productuse,A}$	$R_{productuse,B}$	$R_{productuse,C}$
$R_{transport}$	$R_{transport,A}$	$R_{transport,B}$	$R_{transport,C}$
R_{eff}	= 100%	= 100%	= 100%

Figure 5: Assessment of resource efficiency.

Assessment of improvement measures

The resource efficiency of 100% is the initial point for assessing improvement measures. The objective is to assess, how this value will be changed by improvement measures. Two kinds of measures can potentially improve the product benefit (see Figure 6): measures to increase the utility function and measures to extend the product lifetime. Measures to increase the utility function affect the use (e.g. change workload), the availability (e.g. maintenance), or the product attributes (e.g. efficient components or consumables). The lifetime can be extended through a more robust product or a changed use of the product with less wear.

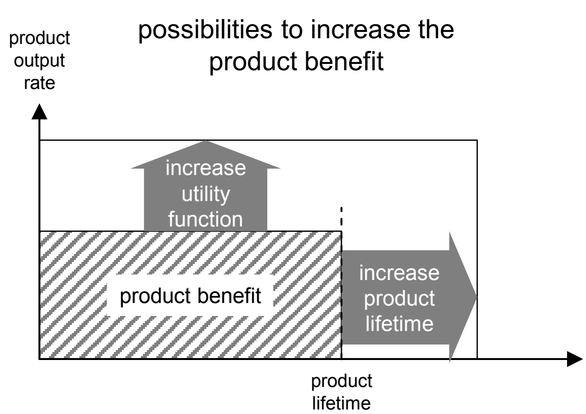

Figure 6: Influence on product benefit.

Two effects have to be deduced in order to assess the resource efficiency of improvement measures: the effects on the product benefit P_B and the effects on the use of resources R_u over the life cycle. Therefore, the effects of measures on the product benefit and the use of resources are analyzed. Based on that, the resource efficiency, influenced by the improvement measures, is calculated (see Figure 7).

	current (c)	measure (m)
$B_{P,Lt}$	$B_{P,c}$	$\Delta B_{P,m}$
$R_{production}$	$R_{production}$	$\Delta R_{production}$
$R_{product}$	$R_{product}$	$\Delta R_{product}$
$R_{productuse}$	$R_{productuse}$	$\Delta R_{productuse}$
$R_{transport}$	$R_{transport}$	$\Delta R_{transport}$
Σ	R_u	ΔR_u
$R_{eff,c}$	= 100%	
$R_{eff,m}$	$= \frac{100\% + \Delta B_{P,m}}{100\% + \Delta R_u}$	

Figure 7: Assessment of measures.

4 USE CASE

The presented approach will be illustrated by an use case. Therefore, a wind mill for energy generation is taken as example.

4.1 Initial Situation

The considered wind mill has a height of 120 meters and is located closed to the coast. It runs approximately 2500 hours per year with a performance of 2 MW. The average lifetime is about 25 years.

4.2 Assessment of Product Benefit

In order to assess the resource efficiency, the product benefit and the use of resources are gathered.

Resource efficiency

The product lifetime of the considered windmill is approximately 25 years. Within this time it is able to generate energy. The utility function of the wind mill equals the energy generation. The performance of the wind mill is 2 MW which can be performed for 2500 hours a year. Consequently, the product benefit of the considered wind mill is 125.000 MWh within its lifetime. 5000 MWh are necessary to produce and to maintain the wind mill. This includes the production of raw materials, the production and assembly, transport, and maintenance. Related to equation (1), the resource efficiency is the product benefit divided by the use of resources. This value represents the current resource efficiency of 100%.

Assessment of improvement measures

The aim is to improve the resource efficiency by suitable measures. Therefore, an adaptation of the manufacturing process in order to improve surface quality of the bearing has to be analyzed. The idea is to manufacture a surface at a higher quality by improving the manufacturing processes of the bearing. This requires more resources and time but it has the potential to improve the overall resource efficiency.

The additional abrasive processes to improve the bearing require additional energy of 1,44 MJ which equals 0,4 KWh. The resulted surface has two effects on the product quality: on the one hand it increases the effectiveness by 1% through the reduction of friction and on the other hand it increases the lifetime about 2% by the increased quality (see Figure 8). This measure enables an additional generation of 3775 MWh.

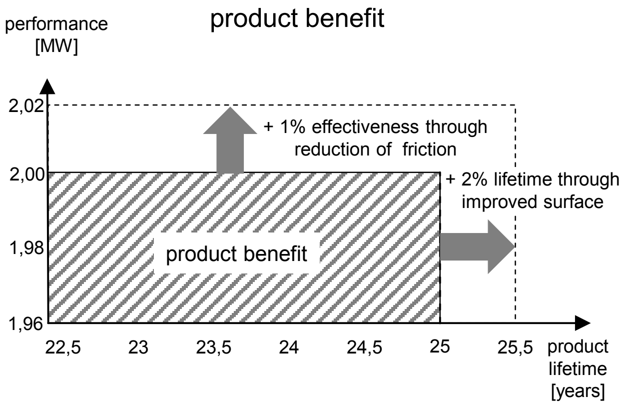

Figure 8: Product benefit.

The additional energy which is generated is much higher compared to the additional required energy through the manufacturing process. But to assess the effects on the resource efficiency, these values have to be considered in equation (1).

$$R_{eff} = \frac{B_{P,m} / B_{P,c}}{R_{U,m} / R_{U,c}}$$

$$R_{eff} = \frac{128775 MWh / 125000 MWh}{5000{,}0004 MWh / 5000 MWh}$$

$$R_{eff} = 103{,}02\%$$

The measure results in an improvement of the resource efficiency of 3%. Consequently, the measure has a positive effect on the resource efficiency and it is recommended to implement it.

5 CONCLUSION AND OUTLOOK

In this paper, an approach for a life cycle oriented assessment of resource efficiency is presented. Therefore, the product benefit is the key factor. The assessment of measures is based on a comparison between the use of resources and the product benefit before and after taking measures. A detailed methodology for the assessment of the product benefit is presented. The use case shows that an increase of used resources through additional abrasive processes can lead to increased resource efficiency over the whole life cycle anyway.

In order to provide the relevant data and to improve the approach, supporting software tools as for example product life cycle management (PLM) or enterprise resource planning (ERP) have to be extended. It has to be investigated, how the approach can be integrated into existing business process, such as product development, development of production systems, engineering change management, and continuous improvement.

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6 REFERENCES

[1] DIN Deutsches Institut für Normung e.V. (editor) (2005): ISO 9000: Quality management systems - Fundamentals and Vocabulary. trilingual version. Beuth, Berlin/Germany.

[2] Duflou, J. R., Sutherland, J. W., Dornfeld, D.; Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M., Kellens, K. (2012): Towards energy and resource efficient manufacturing: a process and system approach. In: CIRP Annals – Manufacturing Technology, Vol. 61, No. 2, pp. 587–609.

[3] Ashby M, Jones D (2006) Engineering Materials 1 - An introduction to properties, applications and designs. Elsevier Ltd.

[4] Bundesministerium für Wirtschaft und Technologie (2006) BMWI Energierohstoffbericht. http://www.bmwi.de/BMWi/Redaktion/PDF/E/energierohstoffbericht,property=pdf,bereich=bmwi,sprache=de,rwb=true.pdf. Accessed 20 March 2012.

[5] Bundesagentur für Geowissenschaft und Rohstoffe (2006) Trends der Angebots- und Nachfragesituation bei mineralischen Rohstoffen. www.rwi-essen.de/media/content/pages/publikationen/rwi-projektberichte/PB_Mineralische-Riohstoffe.pdf. Accessed: 20 March 2012.

[6] United States Geological Survey (USGS) (2012) Commodity - Statistics and Information. Statistics and information on the worldwide supply of, demand for, and flow of minerals and material. Accessed 09 March 2012.

[7] European Union (2007) Regulation No 715/2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6). Official Journal of the European Union. http://ec.europa.eu/. Accessed 20 March 2012.

[8] European Union (2004) Directives 97/68/EC and amendments 2001/63/EC, 2002/88/EC, 2004/26/EC No 715/2007. Directives on emissions from non-road mobile machinery. Official Journal of the European Union. http://ec.europa.eu/enterprise/sectors/mechanical/documents/legislation/emissions-non-road/index_en.htm. Accessed: 20 March 2012.

[9] California Air Resources Board (CARB) (2012) The California Low-Emission Vehicle Regulations. http://www.arb.ca.gov/msprog/levprog/cleandoc/cleancomplete_lev-ghg_regs_12-10.pdf. Accessed 16 March 2012.

[10] Environmental Protection Agency (EPA) (2012) Emission Standards Reference Guide. http://www.epa.gov/otaq/standards/allstandards.htm, Accessed: 16 March 2012.

[11] European Union (2006) Directive 2006/26/EC on energy end-use efficiency and energy services. Official Journal of the European Union. http://ec.europa.eu/. Accessed 20 March 2012.

[12] Neugebauer, R., Wabner, M., Rentzsch, H., Ihlenfeld, S. (2011): Structure principles of energy efficient machine tools. CIRP Journal of Manufacturing Science and Technology. Vol. 4, No. 2, pp 136-147.doi:10.1016/j.cirpj.2011.06.017.

[13] Bunse, K., Vodicka, M., Schönsleben, P., Brülhart, M., Ernst, F. O. (2011): Integrating energy efficiency performance in production management – gap analysis between industrial needs and scientific literature. In: Journal of Cleaner Production, Vol. 19, No. 6-7, pp667-679.

[14] Dogan, E., Steg, L, Delhome, P. (The influence of multiple goals on driving behavior: The case of safety, time saving, and fuel saving. In: Accident Analysis & Prevention, Vol. 43, No. 5, pp-1635-1643.

[15] Schmidt, M. (2011): Energie- und Stoffstromanalyse. RKW Rationalisierungs- und Innovationszentrum der Deutschen Wirtschaft e.V. Kompetenzzentrum, Faktenblatt: 1/2011.

[16] DIN Deutsches Institut für Normung e.V. (editor) (2006): DIN EN ISO 14040: Environmental Management – life cycle assessment – Principles and framework. trilingual version. Beuth, Berlin.

[17] VDI Verein Deutscher Ingenieure e.V. (editor) (2012) VDI-Richtlinie 4600: Cumulative energy demand (KEA) - Terms, definitions, methods of calculation. Issue German/English. Beuth, Berlin.

[18] Erlach K, Westkämper E (editor) (2009) Energiewertstrom – Der Weg zur effizienten Fabrik. Fraunhofer Verlag, Stuttgart.

[19] Plank, R. E., Ferrin, B. G. (2002): How manufacturers value purchase offering – An exploratory study. In: Industrial Marketing Management. Vol. 31, pp 457-465.

[20] Anderson, J., Narus, J.A., Narayandas, D. (2009): Business Market Management: Understanding, Creating and Delivering Value. Upper Saddle River, NJ: Prentice Hall.

[21] Homburg, C.; Beutin, N. (2000): Value-Based Marketing: Die Ausrichtung der Marktbearbeitung am Kundennutzen. Mannheim, 2000.

[22] Green, P. E., Rao, V. R. (1971): Conjoint measurement for quantifying judgement data. In: Journal of Marketing Research, Vol. 8, pp. 355-363.

[23] Lilien, G. J., Grewal, R., Bowman, D., Ding, M., Griffin, A., Kumar, V., Narayandas, D., Peres, R. Srinivasan, R., Wang, Q. (2010): Calculating, creating, and claiming value in business markets: Status and research agenda. DOI 10.1007/s11002-010-9108-z.

Least-Cost Technology Investments in the Passenger Vehicle and Electric Sectors to Meet Greenhouse Gas Emissions Targets to 2050

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Abstract

This paper presents an optimization-based model to compute least-cost-to-society strategies for technology deployment and retirement in the passenger vehicle and electric power generation sectors to meet greenhouse gas (GHG) reduction targets set by the Intergovernmental Panel on Climate Change (IPCC) through 2050. The model output provides a timeline and technology quantities to be deployed or retired early for years 2011 through 2050, as well as annual and total costs-to-society and GHG emissions. Model inputs include costs of deploying or retiring incumbent and elective GHG-reducing technologies, as well as numerous scenarios for energy prices and technology costs. On top of constraints on GHG emissions, as well as scenario constraints for retirement and market factors, the model framework provides the ability to investigate the effect of additional constraints such as renewable portfolio standards and increases in corporate average fuel economy. Ultimately, the framework is targeted in scope to operate in a broader policy discussion capable of quantitatively evaluating existing or proposed policy measures for any country or geographic region. The paper describes the model framework and its various components, along with its relevance and application in technology policy. It also presents the mathematical formulation of the linear programming model that runs at the core of the framework. Results are presented from application of the framework to the U.S. automotive market operating under IPCC GHG constraints to determine technology deployment and retirement trajectories for automotive technologies through 2050 under various future scenarios.

Keywords:

Transportation and Energy Policy; Greenhouse Gas Mitigation; Technology Diffusion

1 INTRODUCTION

Curbing greenhouse gas (GHG) emissions at a global level to keep the rise in Earth's average temperature compared to pre-industrial times below 2 °C has been identified as an initiative needing urgent attention by the governments of most developed and developing countries at the Kyoto Summit in 1997. In response to governmental regulations arising from this climate change mitigation initiative, as well from the business opportunities created by a move towards a "green" economy, a surge has occurred in the development of several technologies and practices to curb GHG emissions in all economic sectors. Of these economic sectors, the ones that contribute significantly to climate change are the automotive and power generation sectors, which together are responsible for about 40% of global and 60% of U.S. GHG emissions [1].

Environmental sustainability, of which GHG mitigation is a quintessential part, can be successfully achieved only when ecologically driven technologies and practices are deployed through an economically sound technology deployment and technology management policy. To this effect, studies in the literature have examined the automotive and power generation sectors individually from a technology and technology policy perspective to suggest GHG mitigation strategies for these sectors [2], [3]. Other studies have assessed the role of fuel switching [4] and reducing demand through energy efficiency [5] in GHG mitigation. With the introduction of electric vehicles and biofuels, it is now common knowledge that the power generation, automotive, and fuel technology sectors are all interdependent. There is thus a need to design an effective and robust GHG mitigation policy framework for the automotive and power generation sectors that collectively examines their environmental impacts and economics together. Such a systems-level framework for assessment and design of technologies and technology policy has not yet been investigated, and this study aims to begin bridging that critical gap in the literature.

The framework proposed in this study uses current technology and fuel options in both the automotive and power generation sectors with regards to their costs GHG reduction potential in the use phase, and determines least-cost-to-society trajectories for technology deployment (considering fuel switching) in these sectors under an emission reduction constraint such as the one suggested by the Intergovernmental Panel on Climate Change (IPCC). The future costs and emission reduction potentials of technologies and fuels are informed by policy inputs to the framework such as Renewable Portfolio Standards that mandate electric utilities to have a certain percentage of renewable fuel-powered plants in their portfolio, and the Corporate Average Fuel Economy (CAFE) standards which regulate fuel economy of vehicles in the US. Additionally, the framework also provides an avenue to include market factors by taking into account the market penetration of various technologies, and demand for mobility and electric energy, both in the present and future based on observed data and analysis of consumer and producer preferences. The cost-minimization method can determine costs for individual regulation as well as joint regulation of the automotive and power generation sectors to assess which approach under the given set of input data and assumptions will cost least in achieving GHG reduction targets.

By incorporating emissions constraints, market share constraints, technology costs, early retirement level constraints, and other factors, the framework evaluates current GHG mitigation policies to see if they can achieve their targets with cost and market considerations. The framework can also be applied to design more cost efficient and market feasible technology policy by quantitatively defining levels of regulation on fuel economy, subsidies, rebates,

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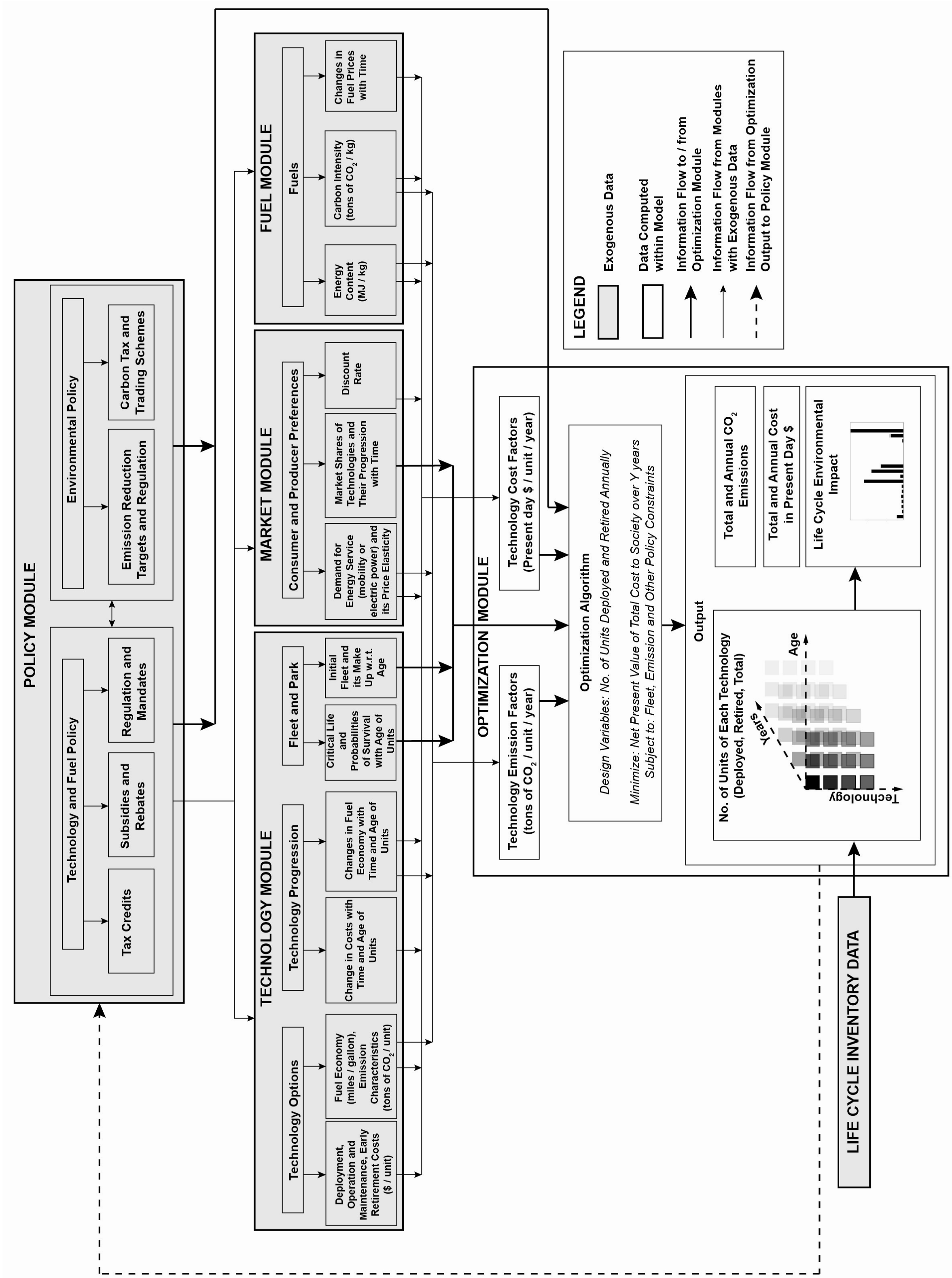

Figure 1: Model framework with inputs, outputs, and information flows across different modules.

taxes and other policy instruments along with their time-frame of implementation for both sectors resulting in the least total cost to society. Such information can inform policy-makers about investments that need to be made in the short term to keep costs of meeting GHG mitigation targets lower while taking the long-term technology and cost perspective, rather than acting on a series of shorter-term and likely more expensive policy measures that arise from political pressure or global warming-driven natural calamities. Additionally, the framework elucidates the environmental trade-offs resulting from a GHG-centric climate change policy by using life cycle inventory data for passenger car and power generation technologies considered in the analysis to evaluate magnitudes of non-GHG mid point impact assessment metrics.

From a global perspective, the framework also facilitates a quantitative comparison of investments in GHG mitigation technologies and early retirement of fuel inefficient units in developed countries vis-à-vis similar investments in developing countries under a carbon-trading scenario.

The following section describes the high-level function and details of the various components of this systems-level GHG mitigation policy framework as applied to the automotive and power generation sectors. It also provides a mathematical description of the optimization formulation that is at the core of the framework. This is followed by a discussion on results from implementing the framework for the US automotive market. Conclusions and future work are outlined in the last section.

2 METHODOLOGY

2.1 Model Overview

The framework used in this study contains five modules, which are: i) Policy Module, ii) Technology Module, iii) Market Module, iv) Fuel Module, and v) Optimization Module.

Figure 1 shows these modules along with a brief description of their inputs, outputs, and information flows. The basic principle behind the framework is to use cost and emission characteristics of various technologies in the passenger vehicle and/or electric utility sectors, projected trends in cost and emission characteristics, and market penetration as exogenous inputs to a cost minimization problem acting under emission and other constrains set by environmental regulations and market factors. The cost that is minimized is the net present value of the total cost to society, i.e. it includes amounts spent by consumers, producers, and the government. The framework can be applied to passenger vehicle sector and the electric power generation (utilities) sector in separate as well as joint regulation scenarios. The following paragraphs describe each module in detail.

2.2 Policy Module

This module can be used either determine the total cost of a set of existing greenhouse gas mitigation policies based on a set of technology and market assumptions, or to develop new greenhouse gas mitigation policies that result in the least cost to society. More specifically, on the technology side this module provides values for parameters such as tax credits, subsidies, and mandates as inputs to the other modules. On the environmental policy side, this module mainly defines the annual emission targets that the sector(s) under consideration should meet. It also has the capability to define costs from carbon tax or carbon trading schemes in which emission targets are not treated as hard constraints but instead a violation penalty is added to the total cost in the Optimization Module. This module also instructs the Optimization Module whether both the passenger vehicle and utilities sectors are to be separately regulated or jointly regulated.

2.3 Technology Module

This module is comprised of the Technology Options, Technology Progression, and Fleet and Park sub-modules. The Technology Options sub-module contains data on fuel efficiency, deployment costs, and operation and maintenance costs for various technology options that are the subject of the analysis. The Technology Progression sub-module contains trends with respect to time and age of a unit in the characteristics of technologies from the Technology Options sub-module. Data on these trends can be gathered from the literature or can be assumed in a scenario-based study. The Fleet and Park sub-module provides data on new (fleet) and old (park) technology units, and their age-wise distribution based on sales records from past years. In the model used in this framework, data from these three sub-modules is used to calculate Emission Factors (***EFs***) in tCO_2/ unit/year and Cost Factors (***CFs***) in \$/unit/year as a function of time and age for units of all technologies in consideration. If the ***N*** technology options are indexed by ***i***, the current age of each technology is indexed by ***j*** with ***T*** being the maximum age of any technology, and the number of years into the analysis is indexed by ***k*** with ***Y*** being the duration of the planning period, then EF(i,j,k) is given by

$$EF(i,j,k) = Fuel\ Efficiency\ (i) \times \left(FE_{improve}{}^{k}\right) \times \left(FE_{reduce}{}^{j}\right) \times Demand(i,k) \times Carbon\ Intensity\ (i,k) \quad \text{(Eq. 1)}$$

where, ***Fuel Efficiency*** is mass or volume of fuel per unit demand of energy service (e.g. gallons/mile), ***Carbon Intensity*** is the amount of CO_2 produced when a unit mass or volume of fuel is used for energy generation (e.g. tons of CO_2/gallon), and ***$FE_{improve}$*** and ***FE_{reduce}*** are the annual improvements and reductions respectively in fuel efficiency as a function of time and age. Similarly, for new and old units,

$$CF(i,j,k) = \{Deployment\ Cost\ (i) \div Cheap\ Rate(i,k)\} + \left\{Fuel\ Efficiency\ (i) \times \left(FE_{improve}Factor^{k}\right) \times \left(FE_{reduce}Factor^{j}\right) \times Demand(i,k) \times Fuel\ Cost\ (i,k)\right\} + \{Maintenance\ Cost(i,k)\} \quad \text{(Eq. 2)}$$

and for units retired before their critical age (early retirement),

$$CF_{\ retired}(i,j,k) = Retirement\ Cost(i) \times \left(Expensive\ Rate^{k}\right) \times \left(Cheap\ Rate^{j}\right) \quad \text{(Eq. 3)}$$

where ***Cheap Rate*** and ***Expensive Rate*** are factors that correspond to decrease and increase in retirement costs as age and time increase respectively. ***EF*** and ***CF*** can be pre-calculated in the model and stored form use by the Optimization Module.

2.4 Market Module

This module contains data on current and projected market shares for all the technologies considered in the Technology Module. Additionally, it also contains data on electricity demand, vehicle miles travelled, and discount rate assumed for net present value calculations.

2.5 Fuel Module

This module provides data inputs to the Technology Module as well as the Optimization module. The Fuel Module contains data on the heating value or energy content, carbon intensity (tCO_2/unit of fuel consumed for energy), price and price trends of various fuels for technologies in considerations. This module allows for creation of scenarios with fuel-switching, price shocks, and price reductions due to expansion of resource base (e.g. discovery of a Shale gas reserves or Arctic oil-drilling due to climate change).

2.6 Optimization Module

This framework uses a linear optimization model to calculate the minimum total cost to society to comply with environmental regulation and market constraints. Two major reasons for choosing a linear formulation over a non-linear one are that a feasible solution is guaranteed to be the global optimum, and the computation time is significantly lower. The cost minimization problem can be defined as:

$$\min_x f^T x \quad \text{(Eq. 4)}$$

Subject to

$$Ax \leq B \ (Inequality\ Constraints) \quad \text{(Eq. 5)}$$

$$A_{eq}x = B_{eq} \ (Equality\ Constraints) \quad \text{(Eq. 6)}$$

$$lb \leq x \leq ub \ (Bounds) \quad \text{(Eq. 7)}$$

Where,

$$x = Column\ vector\ of\ design\ variables\ given\ by$$

$$x_p = new(i,k)\ \forall\ p = i + N(k-1) \in [1, NY],\quad i \in [1,N], k \in [1,Y] \quad \text{(Eq. 8)}$$

$$x_p = retired(i,j,k)\ \forall\ p = NY + i + N(j-1) + NY(k-1) \in [NY+1, NY+NYT],\quad i \in [1,N], j \in [1,T], k \in [1,Y] \quad \text{(Eq. 9)}$$

2.6.1 Inequality Constraints – Fleet and Emissions

In its very basic formulation, the inequality coefficient matrix ***A*** comprises of design variable coefficients that impose the constraint that the total number of units (old and new) should be non-negative. Depending on the year ***k*** and age ***j***, the number of total units can be expressed as a linear combination of the initial fleet, new units deployed, and units retired early as follows.

$\forall\ j < k,$

$$old(i,j,k) = \left\{new(i,k-j) \times \prod_{m=0}^{j-1} P(i,m)\right\} - \left\{\sum_{m=1}^{j-1} retired(i,m,k-j+m) \times \prod_{n=m}^{j-1} P(i,n)\right\} - retired(i,j,k) \quad \text{(Eq. 10)}$$

$\forall\ j > k,$

$$old(i,j,k) = \left\{initfleet(i,k-j) \times \prod_{m=j-k}^{j-1} P(i,m)\right\} - \left\{\sum_{m=j-k+1}^{j-1} retired(i,m,m-j+k) \times \prod_{n=m}^{j-1} P(i,n)\right\} - retired(i,j,k) \quad \text{(Eq. 11)}$$

$\forall\ j = k,$

$$old(i,j,k) = \left\{initnew(i) \times \prod_{m=0}^{j-1} P(i,m)\right\} - retired(i,j,k) - \left\{\sum_{m=1}^{j-1} retired(i,m,m) \times \prod_{n=m}^{j-1} P(i,n)\right\}, \quad \text{(Eq. 12)}$$

Here, ***initfleet*** is an array containing number of old units of all technologies and ages in the year before the first year of the analysis and ***initnew*** is a vector containing new units of all technologies deployed in the year before the first year of the analysis. ***P(i,j)*** is the probability that a unit of technology type ***i*** and age ***j*** will survive. Age = 0 implies that the unit is a new unit. There will thus be ***NYT*** number of rows, each defining the non-negativity constraint for ***old(i,j,k)***. Based on these equations and converting the three-dimensional formulation to one-dimensional (for multiplication with the design vector) using

$$row\ index = i + N(j-1) + NY(k-1), \quad \text{(Eq. 13)}$$

coefficients in a given row (i.e. given constraint) of the ***A*** matrix and ***B*** vector, corresponding to new and retired units defined by Eqs. 10, 11 and 12, are populated.

To introduce emission constraints, additional rows of coefficients must be added to the ***A*** matrix and ***B*** vector after the non-negativity constraints given by Eqs. 10, 11 and 12. A year-by-year emission constraint is denoted by

$$E(k) \leq Target\ (k)$$

i.e., $$\left\{\sum_{i=1}^{i=N}\sum_{j=1}^{j=T} old(i,j,k) \times EF(i,j,k)\right\} + \left\{\sum_{i=1}^{N} new(i,k) \times EF(i,0,k)\right\} \leq Target(k) \quad \text{(Eq. 14)}$$

where ***EF*** is a three-dimensional emission factor matrix containing values in tons of CO_2/unit/year of a given technology ***i*** and age ***j*** in a given year ***k***, pre-calculated based on the data and assumptions from the policy and technology modules. There will be constant terms (i.e. terms independent of design variables ***x***) generated from the ***initfleet*** and ***initnew*** terms when using Eq. 10 and Eq. 11 respectively. These constant terms will be subtracted from the row of ***B*** vector corresponding to the constraint in generating these terms (i.e. depending on ***i***, ***j***, and ***k***). If market penetration is to be considered, annual technology market share constraints can be added to the inequality constraint set by calculating their contribution to the ***A*** matrix and ***B*** vector in a manner similar to the emission constraints by extracting coefficients from the following equations.

$$Total\ units(i,k) \leq Market\ Share(i,k) \times Total\ Demand\ (k)$$

i.e., $$\sum_{j=1}^{j=T} old(i,j,k) + new(i,k) \leq Market\ Share(i,k) \times Total\ Demand(k) \quad \text{(Eq. 15)}$$

Since inequality constraints are defined as $\boldsymbol{Ax} \leq \boldsymbol{B}$, rows of ***A*** and ***B*** representing constraints of type $\boldsymbol{Ax} \geq \boldsymbol{B}$ must be multiplied by negative 1.

2.6.2 Objective Function – Net Present Value of Total Cost

Similar to the manner in which the emission constraint is defined, the coefficients of the objective function column vector ***f*** are determined by the formulas

$$f(k) = \left\{\sum_{i=1}^{i=N}\sum_{j=1}^{j=T} old(i,j,k) \times CF(i,j,k)\right\} + \left\{\sum_{i=1}^{i=N} new(i,k) \times CF(i,0,k)\right\} + \left\{\sum_{i=1}^{i=N}\sum_{j=1}^{j=T} retired(i,j,k) \times CFret(i,j,k)\right\} \quad \text{(Eq. 16)}$$

$$f = \sum_{k=1}^{k=Y} f(k)/(1+r)^{k-1} \quad \text{(Eq. 17)}$$

where ***CF*** is a three-dimensional cost factor matrix containing values in \$/unit/year of a given technology ***i*** and age ***j*** in a given year ***k***, pre-calculated based on the data and assumptions from the policy and technology modules, and ***r*** is the discount rate for net present value calculations. Constant terms from Eqs. 10 and 11 are accounted for by adding them to the total cost at the end of the optimization. Leaving them out of the objective function does not affect the value of the optimizer ***x****, since the solution for $\mathbf{min}_x \boldsymbol{f^T x}$ is the same as the solution for $\mathbf{min}_x \boldsymbol{f^T x} + \boldsymbol{c}$.

2.6.3 Equality Constraints – Total Demand

In the simplest formulation of the optimization problem, the equality constraints consist of the yearly demand for total number of units in the market. These constraints are given by the equation

$$\sum_{i=1}^{i=N}\sum_{j=1}^{j=T} old(i,j,k) + \sum_{i=1}^{i=N} new(i,k) = Total\ Demand(k) \quad \text{(Eq. 18)}$$

Additional equality constraints such as hard constraints on market shares of a certain technology imposed by regulations such as Renewable Portfolio Standards can also be imposed using the formulation in Eq. 15 with an equality sign.

2.6.4 Bounds

A non-negativity lower bound ***lb*** applies to all design variables and is defined by defining a null column vector of length ***NY(1+T)***, which is the length of the design vector. Upper bounds ***ub*** can also be applied to some or all design variables by defining another column vector of length ***NY(1+T)*** and setting numerical upper bounds for desired variables and those for remaining design variables to infinity.

2.6.5 Joint Regulation of Passenger Vehicle and Utility Sectors

As discussed in Section 2.2, the framework provides the ability determine the cost of separately or jointly regulating the passenger vehicle and utilities. The discussion in Section 3 so far focuses on separate regulation. In the case of joint regulation, the design vector will be of length $N_1Y_1(1+T_1) + N_2Y_2(1+T_2)$, where the subscript 1 is for the passenger vehicle sector and subscript 2 is for the utilities sector. It is implied that the passenger vehicle sector design variables precede the utilities sector design variables, although this arrangement can also be reversed. The calculation of ***f***, ***A***, ***Aeq***, ***B***, and ***Beq*** can proceed individually for both sectors as in the previous discussion on separate regulation. After this, the matrices and vectors for both sectors can be combined as follows to give the resulting joint regulation matrices and vectors.

$$A = \begin{bmatrix} \begin{bmatrix} & \cdots & \\ \vdots & A_{pass.\ veh.} & \vdots \\ & \cdots & \end{bmatrix} & \begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 0 \end{bmatrix} \\ \begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 0 \end{bmatrix} & \begin{bmatrix} & \cdots & \\ \vdots & A_{utilities} & \vdots \\ & \cdots & \end{bmatrix} \end{bmatrix} \quad \text{(Eq. 19)}$$

$$B = \begin{Bmatrix} B_{pass.veh.} \\ B_{utilities} \end{Bmatrix} \quad \text{(Eq. 20)}$$

Joint regulation ***Aeq*** can also be combined in the same way as ***A*** and ***Beq***, ***lb*** and ***ub*** can be combined in the same way as ***B***. The emission constraint then becomes

$$\left\{\sum_{i=1}^{i=N_1}\sum_{j=1}^{j=T_1} old(i,j,k) \times EF(i,j,k) + \sum_{i=1}^{i=N_1} new(i,k) \times EF(i,0,k)\right\} + \left\{\sum_{i=1}^{i=N_2}\sum_{j=1}^{j=T_2} old(i,j,k) \times EF(i,j,k) + \sum_{i=1}^{i=N_2} new(i,k) \times EF(i,0,k)\right\} \leq Target_1(k) + Target_2(k) \quad \text{(Eq. 21)}$$

where ***Target₁*** and ***Target₂*** are the GHG emission targets for the automotive and utilities sector respectively. It should be noted that joint regulation thus simply changes the emission constraint leaving the other constraints unchanged.

In addition to these modules, the framework also uses a life cycle inventory database for the technologies and fuels considered in the analysis to evaluate the environmental tradeoffs resulting from a GHG mitigation-based policy approach.

3 PRELIMINARY RESULTS AND DISCUSSION

The optimization framework described in the previous sections was implemented in MATLAB for the passenger vehicle sector under regulation by emission mitigation targets set for this sector by the Intergovernmental Panel for Climate Change (IPCC). In this model, the electric sector is treated as exogenous. The U.S. passenger vehicle market was modeled as being composed entirely of mid-size light duty vehicles (LDVs). Time horizon for the cost minimization analysis was chosen to be from 2011 to 2050. Four LDV powertrain types namely Conventional Gasoline Engine (CV), Hybrid Electric (HEV), Battery Electric (BEV), and Plug-in Hybrid Electric (PHEV) were considered as present and future technology options for the analysis. Four different scenarios were examined and their costs compared to the case where no emission constraints exist, were estimated using the optimization model.

Scenario 1: Cost minimization without consideration for market shares. Salient assumptions for this scenario include discount rate of 10%, baseline vehicle without any emission reduction technologies costs $20,000 and has a fuel economy of 26 mpg, annual improvement of 2% in fuel economy of gasoline driven engines (including hybrids and plug-in hybrids), annual gasoline price increase of 3%, and roughly 12000 vehicle miles driven per year [6] (this demand is assumed to be inelastic). To account for reduction in emissions from electric charging due to cleaner power generation while keeping the model linear, reduction in carbon intensity of electric charging was assumed to follow the slope of the IPCC target curve for the utilities sector. Total number of vehicles on the road is assumed to increase annually at 1%.

***Scenario 2*:** Cost minimization under the same set of assumptions as in Scenario 1, but with the additional constraint that market share of CVs cannot fall by more than 3% in a year compared to the previous year, and the total number of units retired at the end of a year cannot exceed 7.25% of the total number of units on the road. These constraints are imposed to reflect the expected gradual decline in CVs due to the existing high consumer preference for them [7], and more realistic scrapping rates in the absence of take-back programs offered by manufacturers or the government. The 7.25% figure is based on total passenger car data from [8] and car scrappage data from [9] for the year 2010.

***Scenario 3*:** Cost minimization under the same set of assumptions as in Scenario 1, but with the added assumption that battery manufacturing will become cheaper annually by an average of 6% until 2025 [10], after which costs will stabilize.

Scenario 4: Cost minimization under the same set of assumptions as in Scenario 1, but with a discount rate of 4%. This scenario is used to assess the effect that people's valuation of expenditure in the future has on the least cost trajectory.

Results from Scenario 1 are shown in Figure 2. Under this scenario, IPCC targets are met every year and the total cost to society is estimated to be $889 billion over 40 years. It is interesting to note that although it is possible to meet IPCC targets, a high fleet

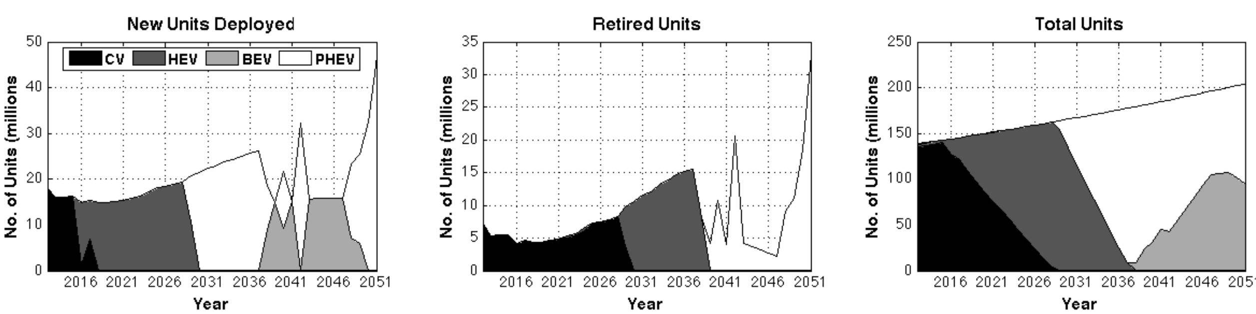

Figure 2: Results showing new units deployed, units retired, total units, and GHG emissions from 2011 to 2050 in Scenario 1 (Baseline). Cost of compliance with IPCC targets is $889 billion over 40 years.

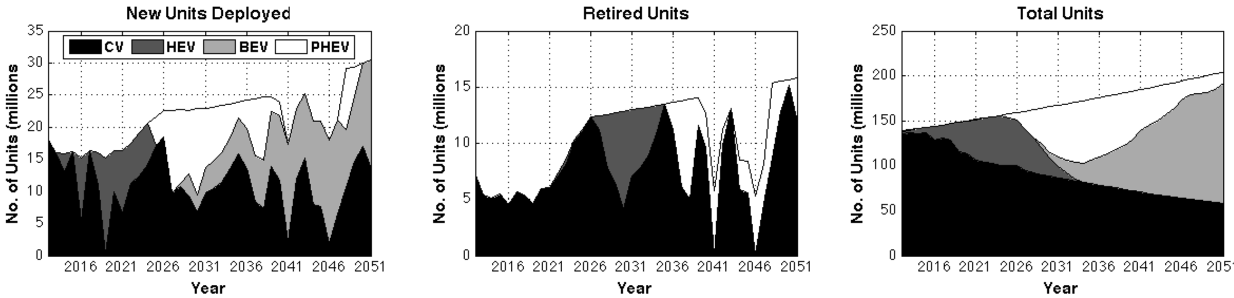

Figure 3: Results showing new units deployed, units retired, total units, and GHG emissions from 2011 to 2050 in Scenario 2 (Baseline with market share and retirement constraints). Cost of compliance with IPCC targets is $1.26 trillion over 40 years.

turnover through early retirement of relatively unclean old units plays a significant role in achieving these targets. Most years show a retirement of over 10 million units, which is about 40% more than the number of vehicles scrapped in 2010. The results show a switch from CVs to HEVs around 2015 for new vehicles deployed. This outcome is quite likely given the introduction of hybrid versions of most passenger cars by their manufacturers at prices that are comparable to, or are projected to become comparable to those of CVs in the next few years.

PHEVs start getting deployed around 2027, and BEVs get deployed around 2036 as the electric charging grid becomes cleaner from deployment of more renewables. BEVs are deployed later as emission target levels further decrease and the high cost of BEVs becomes justified. PHEVs account for the largest market share for nearly all years after 2035. New HEVs are not deployed after 2030, indicating that HEV technology acts as a transition technology until electric grids used to charge PHEVs and BEVs become clean enough.

Scenario 2 is also able to comply with IPCC targets. Figure 3 shows that BEVs are deployed sooner than Scenario 1 in 2027. CVs stay in the fleet through 2050 due to the imposed market share constraint, although electric vehicles hold a majority of the market share beyond 2030. The cost of compliance in this scenario increases to $1.26 trillion (an increase of 41% compared to Scenario 1), and most of this increase likely comes from higher costs of deploying more BEVs to compensate for the loss in emission reduction from more CVs on the road.

Due to reduced battery costs in Scenario 3, new vehicles deployed are all battery-based, with HEVs being deployed right away. PHEV and HEV deployment is similar to that in Scenario 1 as shown in Figure 4. PHEVs also continue to have a significant market share in years beyond 2020 due to lower costs and better emission characteristics than CVs. According to this scenario, there will be no CVs on the road beyond the year 2031. The cost of compliance is estimated to be $225 billion over 40 years, which is significantly lower (by over 74%) than the cost in the first two scenarios. Breakthroughs in battery technology that can reduce their costs can therefore play a pivotal role in the passenger vehicle sector meeting its IPCC emission targets at low costs.

New unit deployment results for Scenario 4 shown in Figure 5 indicate that the decision to deploy new units is sensitive to the discount rate assumed in the analysis, with a higher discount rate (meaning future $ are less valuable) leading to a preference for deploying more (cheaper) CVs initially and PHEVs over BEVs after 2030. Early retirement of existing vehicles on the road is also observed to decrease.

It is also observed that the model is not very sensitive to fuel costs. This is likely because under the assumptions in this model, gasoline prices ($4/gallon in 2011), and electricity prices (12 cents/kWh in 2011) are assumed to increase at a rate lower than the discount rate. Thus, the decision to deploy a certain vehicle technology unit depends more on the production or purchase cost, than its operation and maintenance cost. This could mean higher deployment of CVs than predicted by this model in the short to medium term due to significant improvements in their fuel economy under stricter regulation. To ascertain as to which parameters impact the least-cost trajectories and their cost, a more comprehensive sensitivity analysis is to be performed on this model so that policies that align with the behavior of these parameters can be designed.

The technology trajectories under all scenarios examined here predict a significant increase in battery-based technologies in the passenger vehicle sector. Although achieving IPCC targets through

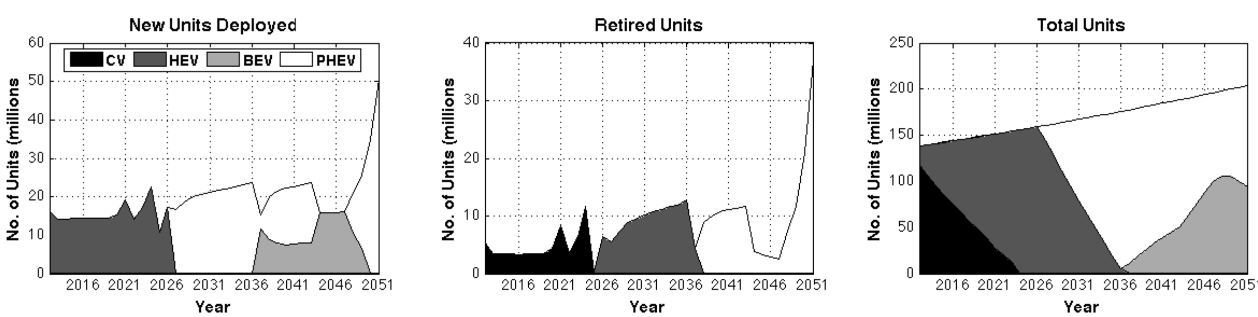

Figure 4: Results showing new units deployed, units retired, total units, and GHG emissions from 2011 to 2050 in Scenario 2 (Baseline with decreasing battery manufacturing costs). Cost of compliance with IPCC targets is $225 billion over 40 years.

reductions in the use phase emissions is possible, it should be noted that battery technology poses significant concerns in terms of resource availability and end-of-life management strategies. A proper life cycle assessment and recycling strategy review is thus needed before large investments can be made in charging stations and other infrastructure to support the predicted growth in battery-based vehicle technologies.

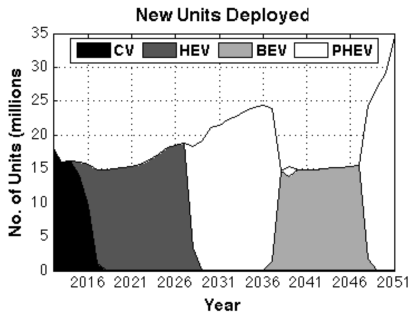

Figure 5: New units deployed under Scenario 4 (Baseline with lower discount rate).

4 CONCLUSION AND FUTURE WORK

Model results generally indicate that meeting IPCC targets is still possible for the U.S. automotive sector, but to do so at low costs, older units will have to be retired before their maximum life in considerably higher than existing numbers. When consumer preferences and market penetration of battery-based vehicle technology are taken into account, the cost of compliance with IPCC target is expected to rise significantly. Conventional vehicles are likely to remain in the fleet in the near future due to improvements expected in their fuel economy and their low costs. Hybrid electric vehicles can act as a transition technology to plug-in and battery electric vehicles that are deployed when the grid that charges them is improved in its emission characteristics

Future work will entail application of the framework to the utilities market to estimate least cost-to-society under separate as well as joint regulation with the passenger car sector to meet IPCC targets. Total compliance costs and costs for the automotive sector are expected to be lower when both sectors are jointly regulated because investments can be focused on the utilities sector which has a lower cost per unit of CO_2 reduced. Additionally, a study on the role of increased natural gas utilization in the electric, and potentially the transportation sector as NG prices decline, will also be conducted using the framework. Based on the outcomes of these studies along with a thorough uncertainty analysis, general technology diffusion trends and specific policy measures for both sectors needed to achieve least-cost GHG-mitigation will be elucidated.

5 REFERENCES

[1] Metz B., Davidson O.R., Bosch P.R., Dave R., Meyer L.A., (2007), "Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change", *Cambridge University Press*, Cambridge, United Kingdom and New York, NY, USA.

[2] Venkatesh A., Jaramillo P., Griffin W.M., Matthews H.S., (2012), "Implications of Near-Term Coal Power Plant Retirement for SO_2 and NO_X and Life Cycle GHG Emissions", *Environ. Sci. Technol. 46* (18), pp. 9838-9845.

[3] Shiau C.-S.N., Kaushal N., Hendrickson C.T., Peterson S.B., Whitacre J.F., Michalek J.J., (2010), "Optimal Plug-In Hybrid Electric Vehicle Design and Allocation for Minimum Life Cycle Cost, Petroleum Consumption, and Greenhouse Gas Emissions", *J. Mech. Des. 132*, 091013.

[4] Delarue E., D'haeseleer W., (2008), "Greenhouse Gas Emission Reduction by Means of Fuel Switching in Electricity Generation: Addressing the Potentials", *Ener. Convers. Manage. 49* (4), pp. 843-853.

[5] van Vuuren D.P., den Elzen M.G.J., Lucas P.L., Eickhout B., Strengers B.J., van Ruijven B., Wonink S., van Houdt R., (2007), "Stabilizing Greenhouse Gas Concentrations at Low Levels: An Assessment of Reduction Strategies and Costs", *Climate Change 81* (2), pp. 119-159.

[6] U.S. Dept. of Transportation, *Office of Highway Policy Information*, "Table VM-1: Annual Vehicle Distance Traveled in Miles and Related Data – 2010", Accessed from, http://www.fhwa.dot.gov/policyinformation/statistics/2010/vm1.cfm, on December 5, 2012.

[7] Ewing G.O., Sarigöllü E., (1998), "Car Fuel-Type Choice Under Travel Demand Management and Economic Incentives", *Transpn. Res.-D 3* (6), pp. 429-444.

[8] U.S. Dept. of Transportation, *Bureau of Transportation Statistics*, "Light Duty Vehicle, Short Wheel Base and Motorcycle Fuel Consumption and Travel", Accessed from, http://www.bts.gov/publications/national_transportation_statistics/html/table_04_11.html, on December 5, 2012.

[9] U.S. Dept. of Transportation, *Bureau of Transportation Statistics*, "Motor Vehicles Scrapped", Accessed from, http://www.bts.gov/publications/national_transportation_statistics/html/table_04_58.html, on December 5, 2012.

[10] *Bloomberg New Energy Finance* (April 16, 2012), "Electric Vehicle Battery Prices Down 14% Year on Year", Accessed from http://www.bnef.com/PressReleases/view/210, on December 5, 2012.

Development of a New Methodology for Impact Assessment of SLCA

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Abstract

In this study, a new method for social impact assessment was developed based on the UNEP/SETAC Guidelines for SLCA of products. As quantitative indicators, we collect country-specific statistics data from Taiwanese governments as performance reference points (PRP) to assess the social impact of each indicator of a specific product. Moreover, the quantitative indicators are used to assess social performance and effort in terms of five measures: policy, communication, approach, record, and response. The proposed model of impact assessment for SLCA in this study can facilitate a social impact assessment of a specific product.

Keywords:

Social Impact Assessment; Quantitative and Semi-quantitative Indicators; Performance Reference Points (PRPs)

1 INTRODUCTION

With the emergence of corporate social responsibility (CSR) in accordance with stakeholders' needs, different tools for social impact assessment have been developed. However, these tools are generally aimed at guiding and supporting the work at an organization or at a project level [1]. To understand the social impact of products, social life cycle assessment (SLCA) was introduced. Recent studies related to SLCA are being conducted, tested, and evaluated by researchers worldwide [2-9]. The recently published "UNEP/SETAC Guidelines for social life cycle assessment of products" [10] states that the ultimate objective of developing the SLCA is to promote improvements of social conditions for the stakeholders in the life cycle. Even if various studies have utilized the Guidelines to develop stakeholders, subcategories, and indicators for assessing social impact, [2-4] [9] [11] no consistent or specific method of social impact assessment is proposed in the Guideline or in previous literature. With respect to social impact assessment, most studies used relative comparison analysis among products for social impact [2-3] [11], mainly qualitative and semi-quantitative indicators for determining social performance [4] or only the generic product chain for identifying social hotspots [9].

To overcome these limitations, a novel method for social impact assessment in this work is proposed. For quantitative indicators, the statistics data of social indicators at the country-level are considered as performance reference points (PRPs) to assess the social performance of each indicator for specific sites or organizations. This methodology can facilitate understanding of the social impact of a specific product. On the other hand, qualitative indicators are essential for SLCA. Thus, five management measures are utilized to assess social impact. This study aims to assess the social impact of specific- products or organizations to aid managers in making decisions on the social impacts of product development and research.

2 LITERATURE REVIEW

A number of studies have followed the UNEP/SETAC Guidelines for SLCA of products to establish a framework for analyzing and assessing social impacts. The UNEP/SETAC Guidelines provide guidance on the assessment of product life cycle social impact and present an effective framework representing the consensus of an international group of experts in this field [12]. Although the Guidelines provide the foundation for the selection of social indicators, the specific methodology as well as case studies remains limited [11] [13-14]. Typical social impact assessments of SLCA based on the UNEP/SETAC Guidelines are given below.

To improve the sustainable performance of products, Franze and Ciroth [4] investigated the social and environmental impacts of an eco-labeled notebook during its entire life cycle. Their study aimed to apply the UNEP/SETAC Guidelines for SLCA on a complex product. Five stakeholder categories, 31 subcategories, and 88 indicators were identified to be relevant to the study. In SLCA, both impacts and the performance of considered sectors and companies are assessed. Therefore, the assessment is split into two phases. The first phase assesses the performance of the sectors and companies based on the status of the indicators that consider the performance of the sector/ company in relation to the situation in the country/region. The second phase assesses the impacts of company/sector behavior with regard to the selected impact categories. Finally, social hot spots were identifies in every life cycle stage of the notebook for comparison of different product alternatives.

Foolmaun and Ramjeeawon [2] proposed a new methodology to compare the environmental and social impact of four selected disposal alternatives of used polyethylene terephthalate (PET) bottles. To determine the more socially beneficial disposal options, social impacts were determined based on the UNEP/SETAC Guidelines for SLCA of products. The functional unit for LCA was defined as the disposal of 1 ton of used PET bottles to the respective disposal facilities, as well as SLCA. Three stakeholder categories (worker, society, and local community), eight sub-category indicators (child labor, fair salary, forced labor, health and safety, social benefit/social security, discrimination, contribution to economic development, and community engagement) and 11 social indicators were identified to be relevant to the study. To overcome the barrier of unavailable information, a questionnaire was employed for data collection using "yes" or "no" questions. Through the conversion of inventory results into percentages, a score from zero to four is assigned to each indicator by classifying the percentage of five categories. This methodology aims at converting qualitative inventory information into quantitative social and socio-economic inventory data and then aggregating them using a scoring system. Finally, the scores obtained for each sub-category are summed up to a single score for comparing different disposal alternatives. Considering the different disposal alternatives for PET bottles, the score was multiplied by the percentage it represents in the combined scenario to yield the final single score.

Traverso et al. [3] proposed the life cycle sustainability dashboard (LCSD) in the case study of Photovoltaic (PV) modules for comparing the life cycle sustainability assessment (LCSA) results of three different PV modules: a German 2008 module, a German 2009 module, and an Italian 2008 module. With respect to the development of the SLCA method, their study selected the stakeholder of worker group and six sub-categories, namely, discrimination, child labor, wages, working hours, social benefits, and health conditions in terms of the UNEP/SETAC SLCA Guidelines. Workers are important stakeholders, and they are directly related to the product chain and management level in the production line. In total, 19 indicators were selected under six subcategories for social life cycle impact assessment (SLCIA). Considering the same functional unit for different compared products, 1 m2 of PV modules has been used as a functional unit. All data on each social indicator from site-specific inventories of production facilities were related to a functional unit to identify the social performance of the product. As an example of the wages subcategory, benefits for family, average wage of female workers, average wage of male workers, and minimum wage of a worker per functional unit (€/m2) are used to determine the social performance of three PV modules. Along with the quantitative values of each social indicator, the LCSD was employed to show the relative score and position among three PV modules for a decision maker to obtain a clear picture of the social impact of products.

In a case study of a laptop computer, Ekener-Petersen and Finnveden [1] proposed a new impact assessment method called social hotspots methodology to identify social hotspots in the product system of a generic laptop based on the UNEP/SETAC Guidelines to assess the social and socio-economic impacts of products. The functional unit in the study was a laptop with generalized features and with a typical product system for such a computer. The case study sought to include six life cycle stages of the product system from "cradle to grave," as well as the impacts on all relevant stakeholders as suggested by the UNEP/SETAC Guidelines. Following this principle, the stakeholder and related subcategories assumed to be most affected in each phase were identified, including five stakeholders (worker, society, local community, consumer, and value chain actors), 31 subcategories, and 54 indicators. In gathering information, they focused on country-specific data for the indicators, and minimal sector-specific information was inventoried. For the social impact assessment, they developed a new approach by combining two actions in the data collection spreadsheet. First, they divided the countries into groups with very large activity, large activity, and moderate activity. Second, they highlighted the countries with values in the high end of the range of possible values for each specific indicator. The world minimum and maximum values on the indicator were then identified, after which the countries with values in the highest quartile in the range, indicating severe impacts, as well as the countries with values in the second highest quartile in the range, indicating quite severe impacts, were identified. To prevent potential identification as a social hotspot, the most severe score was chosen as the social impact if the indicators scored differently in one subcategory. The results revealed some hotspots, some hot countries, and some hot issues, all indicating a risk of negative social impacts in the product system of a laptop.

Vinyes et al. [11] utilized LCSA to compare the sustainability of three domestically used cooking oil (UCO) collection systems through schools (SCH), door-to-door (DTD), and urban collection centers (UCC). The functional unit of this study is the collection of the UCO generated in a neighborhood of 10,000 inhabitants for one year in the city of Barcelona. With respect to the development of the SLCA methodology, three stakeholders, eight subcategories, and 11 indicators have been used to develop the assessment framework of social impact based on the UNEP/SETAC Guidelines. The selected social indicators in this study were determined according to the functional unit, data and information available, geographic location, and characteristics and limitations of the three collection systems. To calculate the social impact of each indicator, the data were obtained from entities and organizations that are currently applying these UCO collection systems to Catalonia. The value obtained for all indicators were then transformed into contribution percentages. These percentages were calculated by comparing the values that each collection system has obtained for the same indicator. According to the percentage of contribution assigned, scores from 1 to 5 were given to each social indicator: one point for percentage a contribution of 1% to 20 %, two points for 21% to 40 %, three points for 41% to 60 %, four points for 61% to 80 %, and five points for 81% to 100 %. After scoring all the indicators, a total score is calculated for the SLCA assessment of the three UCO collection systems.

3 NEW METHODOLOGY FOR SLCA

The UNEP/SETAC SLCA Guidelines have been widely used to recognize the stakeholders, subcategories, and indicators of social impact assessment [1-4] [11]. Having followed the UNEP/SETAC Guidelines, only one stakeholder of workers was determined primarily because workers are important stakeholders who are directly related to the product chain. Moreover, the development of and data available on social impact assessment in Taiwan are limited. In this study, eight subcategories within the stakeholder of workers were found, including freedom of association and collective bargaining, child labor, forced labor, fair salary, working hours, equal opportunity/discrimination, health and safety, and social benefits.

As highlighted by [2], SLCIA involves the linking of inventory data to particular SLCIA subcategories and impact categories (classification) as well as the determination or calculation of subcategory indicator results (characterization). However, no scientific classification model of social life cycle inventory parameters exists and neither is there any internationally accepted impact assessment method available [4]. In this study, the authors introduce a new methodology of SLCIA that comprises quantitative and qualitative indicators for each subcategory.

The data inventory of each quantitative indicator from specific sites or organizations is obtained and calculated. Meanwhile, the statistics data of each social indicator at the country-level from Council of Labor Affairs (CLA) and Directorate-General of Budget, Accounting, and Statistics, Taiwan, are acquired as PRPs. The social performance of each indicator for specific sites or organizations can be assessed with respect to the PRP, such as regional/country/sector's statistics data on social issues. This process is fully supported by Vinyes et al. [11], who determined that geographical location is of major importance in SLCA. A score from 1-5 is given to each indicator according to the proportion between the social performance of inventory data and PRP (Table 2). For the positive indictor, the scale of the score is defined as 1 point for a proportion less than 25%, 1.5 points for 25%-50%, 2 points for 50% to 75%, 2.5 points for 75-100%, 3 points for a 100% proportion, 3.5 points for 100%-125%, 4 points for 125% to 150%, 4.5 points for 150%-175% and 5 points for more than 175%.

Stakeholder	Subcategories	Indicators
Worker	Freedom of association and collective bargaining	Rate of labor dispute involvement (%)
		Rate of union organization (%)
		Assistance of the trade union management and operation
		Express provision of protection for the trade union
	Child labor	General child labor risk
		Apprenticeship programmers or similar educational programmers supervised by other competent authorities
		Dangerous working age limit
	Forced labor	Dispute over work hours (%)
		Dispute over wages (%)
		Risk management and control for forced labor
	Fair salary	Per month average wages _ Male (NT $)
		Per month average wages _ Female (NT $)
		Per month average wage _ manufacturing (NT $)
		Commitments and safeguards for fair wages
	Working hours	Per month average working hours _ Male (hours)
		Per month average working hours _ Female (hours)
		Weekly overtime hours _ Male (hours)
		Weekly overtime hours _ Female (hours)
		Implementation of the extension of working hours management
	Equal opportunities /discrimination	Labor force participation rate_ male (%)
		Labor force participation rate_ female (%)
		Participation rate of indigenous people in the labor force (%)
		Participation rate of indigenous people and disabled population (%)
		Rate of the cases of appeal for gender equality in employment (%)
		Rate of the cases of appeal for sexual harassment (%)
		Rate of the cases of appeal for measures of promoting equality in employment (%)
		Female wage to male wage ratio (%)
		Equal opportunity employment system
		Implementation of the system of non-discrimination
	Health and safety	Disabling frequency rate
		Disabling severity rate
		Rate of deaths attributed to occupational injury (%)
		Hazard identification, risk assessment, and determination of control measures
		Competence, training, and awareness
		Emergency preparedness and response
	Social benefits/social security	Rate of contribution of the labor pension (%)
		Number of retirement pension payments (%)
		Dispute over labor insurance benefit payments (%)
		Provision of a complete employee benefits system

Table 1: SLCA indicators for Workers.

On the other hand, for the negative indicator, the scale of score is 1 point for more than 175%, 1.5 points for 150%-175%, 2 points for 125% to 150%, 2.5 points for 100-125%, 3 points for 100% proportion, 3.5 points for 75%-100%, 4 points for 50% to 75%, 4.5 points for 25-50%, and 5 points for less than 25%. While the PRP in terms of labor regulations, for negative indicator, the social performance of indictors is assigned a zero score when the data indicates that the social indicator violates the requirements of labor regulations. An example of the rate of labor dispute involvement, using the statistics data at the country level (0.0053%) as PRP to assess the social performance (0.0024%) of a specific organization, a percentage of 45.3% is acquired, which falls within the range of 25% to 50%, indicating a score of 4.5 as a negative indicator.

In SLCA, quantitative, semi-quantitative, and qualitative data are used and integrated according to the [16]. This practice is consist with [17], who stated that the violation of labor rights are complex and therefore difficult to measure using traditional quantitative single indicators. Their study proposed multi-criteria indicators to address the complexity of labor rights issues for assessing the effort (will and ability) of a company to manage individual issues. Through the integration of appropriate managerial measures of communication, existing guidelines, practices, and continuous active control, values for the implementation degrees of each of the three management efforts are identified to be applied in the processing of management measure scores. For the qualitative indicator in this study, the authors develop a new framework considering five measures to assess efforts on social performance according to the study of [17]. The scoring of a company's management effort for each indicator follows basic rules for scoring the implementation degrees as 0 (not implemented), 0.5 (partially or implementation is not completely), and 1 (fully implemented). The Simultaneous fulfillment of each of the five criteria is crucial for the effective implementation of a measure. Therefore, the criteria are assessed separately, and the results are combined into an aggregated score for a social indicator.

Indicators (negative)	PRP	Company data	Percentage (100%)	Score	
				Positive indicators	Negative indicators
Rate of labor dispute involvement	0.0053%	0.0024%	<25	1	5
			25-50	1.5	4.5
			50-75	2	4
			75-100	2.5	3.5
			100	3	3
			100-125	3.5	2.5
			125-150	4	2
			150-175	4.5	1.5
			>175	5	1

Table 2: Scores of quantitative indicators for SLCA.

Efforts on social issues		Degree	Indicator 1	……	Indicator n
Policy	Establishment of policies that support integration of the measure into daily work	0			
		0.5			
		1			
Communication	Communication of commitment for the integration of the measure into daily work	0			
		0.5			
		1			
Approach	Performance of systematic active control of the integration of the measure into daily work	0			
		0.5			
		1			
Record	All active communication and responses are recorded	0			
		0.5			
		1			
Response	A system for handling complaints and suggestions has been established to ensure response	0			
		0.5			
		1			
Total score					

Table 3: Scores of qualitative indicators for SLCA.

4 CONCLUSIONS

The life cycle-based conceptual framework and operational model incorporating social performance into LCA has been presented. For effective social impact assessment, the stakeholder of workers, eight subcategories, and 39 indicators were identified based on the UNEP/SETAC Guidelines of SLCA of products. In this study, a new methodology to determine the characteristics of SLCIA comprising of both quantitative and qualitative social indicators for each subcategory was introduced. Compared with previous investigations, the proposed methodology has the following contributions to social impact assessment and to the development of SLCA: First, a new characteristic model of quantitative indicators for assessing social impact with emphasis on the statistics data of social performance at the country-level as PRPs for the determination of the social impact of specific products or organizations was introduced. This model facilitates understanding and determination of the social impact of a single product instead of conducting a relative comparison analysis of social impact among different products. Second, five measures were recognized and regarded as management tools for the assessment of the social impact of qualitative indicators. A hybrid model integrating these two methodologies was applied in the SLCA, which has been rarely utilized in previous studies.

5 REFERENCES

[1] Ekener-Petersen, E.; Finnveden, G. (2012) Potential hotspots identified by social LCA—part 1: a case study of a laptop computer. Int J Life Cycle Assess, DOI: 10.1007/s11367-012-0442-7.

[2] Foolmaun, R. K.; Ramjeeawon, T. (2012) Comparative life cycle assessment and social life cycle assessment of used polyethylene terephthalate (PET) bottles in Mauritius. Int J Life Cycle Assess, DOI: 10.1007/s11367-012-0447-2.

[3] Traverso, M.; Asdrubali, F.; Francia, A.; Finkbeiner, M. (2012) Towards life cycle sustainability assessment: an implementation to photovoltaic modules, Int J Life Cycle Assess, Vol. 17, pp. 1068–1079.

[4] Franze, J.; Ciroth, A. (2011) A comparison of cut roses from Ecuador and the Netherlands. Int J Life Cycle Assess, Vol. 16, pp. 366–379.

[5] Benoît, C.; Aulisio, D.; Norris, GA.; Hallisey-Kepka, C.; Overakker, S.; Vickery, G. (2011a) A social hotspot database for acquiring greater visibility in product supply chains: overview and application to orange juice. In: M. Finkbeiner (ed) Towards life cycle sustainability management, DOI: 10.1007/978-94-007-1899-9_6.

[6] Macombe, C.; Feschet, P.; Garrabé, M.; Loeillet, D. (2011) 2nd International seminar in social life cycle assessment—recent developments in assessing the social impacts, of product life cycles. Int J Life Cycle Assess, Vol. 16, pp. 940–943.

[7] Reitinger, C.; Dumke, M.; Barosevcic, M.; Hillerbrand, R. (2011) A conceptual framework for impact assessment within SLCA. Int J Life Cycle Assess, Vol. 16, pp. 380–388.

[8] Ciroth, A.; Franze, J. (2010a): Social LCA of an Ecolabeled Notebook, presentation, Informal EU Meeting on Sustainable Consumption and Production and Integrated Product Policy Brussels, pp. 6-7.

[9] Ekener-Petersen, E.; Moberg, Å. (2012) Potential hotspots identified by social LCA—part 2: Reflections on a study of a complex product. Int J Life Cycle Assess, DOI: 10.1007/s11367-012-0443-6.

[10] Benoît, C.; Mazijn, B. (eds) (2009) Guidelines for social life cycle assessment of products, UNEP/SETAC Life Cycle Initiative, ISBN: 9789280730210.

[11] Vinyes, E.; Oliver-Solà, J.; Ugaya, C.; Rieradevall, J.; Gasol, C. M. (2012) Application of LCSA to used cooking oil waste management. Int J Life Cycle Assess, DOI: 10.1007/s11367-012-0482-z.

[12] Benoît, C.; Norris, GA.; Valdivia, S.; Ciroth, A.; Moberg, A.; Bos, U.; Prakash, S.; Ugaya, C.; Beck, T. (2010) The guidelines for social life cycle assessment of products: Just in time! Int J Life Cycle Assess, Vol. 15, pp.156–163.

[13] Klöpffer, W. (2006) The role of SETAC in the definition of LCA. Int J Life Cycle Assess (Special Issue), Vol. 1, pp. 116–122.

[14] Hauschild, M. Z.; Dreyer, L. C.; Jørgensen, A. (2008) Assessing social impacts in a life cycle perspective—lessons learned. Annals of the CIRP, Vol. 57, pp.21–24.

[15] Ciroth, A.; Franze, J. (2011) LCA of an Ecolabeled Notebook—consideration of social and environmental impacts along the entire life cycle, Berlin 2011, available on http://www.greendeltatc.com/ uploads/media/LCA_laptop_final.pdf.

[16] UNEP/SETAC (2009) Guidelines for social life cycle assessment of products. United Nations Environment Programme.

[17] Dreyer LC, Hauschild M, Schierbeck J (2010a) Characterisation of social impacts in LCA part 1: development of indicators for labour rights. Int J Life Cycle Assess, Vol. 15, pp. 247–259.

A Manufacturing Informatics Framework for Manufacturing Sustainability Assessment

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Abstract

Manufacturing firms that wish to improve their environmental performance of their product, process, and systems are faced with a complex task because manufacturing systems are very complex and they come in many forms and life expectancies. To achieve desired product functionalities, different design and material can be selected; thus the corresponding manufacturing processes are also changed accordingly. There is direct need of assessment tools to monitor and estimate environmental impact generated by different types of manufacturing processes.

This research proposes a manufacturing informatics framework for the assessment of manufacturing sustainability. An EXPRESS information model is developed to represent sustainability information such as sustainability indicators and their associated weighting and uncertainty factors, material declaration information, and hazardous condition information, etc.

This information model is tested with industrial products to validate its completeness and correctness. This information model serves as the first step of establishing close association of sustainability information with product design specification. In the next phase of research, investigation will be conducted to integrate sustainability information model and existing standardized product design model ISO 10303 AP 242.

Keywords: Manufacturing process; Environmental impact; Life Cycle Assessment; Information Model

1 INTRODUCTION

Sustainability is a multi-disciplinary field that involves the areas of ecology, economic development, and social equity [1]. The manufacturing industry is often cited as the cause of many environmental and social problems, yet it is acknowledged as the main mechanism for change through economic growth [2]. It is clear that the world is moving forward aggressively to achieve sustainable design and manufacturing with life cycle considerations. Industry is confronted with the challenge of designing sustainable products and manufacturing processes. The ones who first develop and employ such technologies will gain a competitive advantage in the market place [3]. Many sustainable development strategies [4-8] have been proposed by government agencies and academia since the late 1990s. Research in sustainable manufacturing field can be categorized into the following four main themes [9, 10]: a) Life-Cycle Assessment (LCA) [11-15], b) design-for-X principles and design for sustainability [16-25]; c) end-of-life studies [26-31]; and d) energy efficiency monitoring and studies [32-35].

LCA considers all environmental impacts associated with a product or a service from its inception to the end of its life. It can be broken down in five main stages; namely the material extraction, manufacturing, transportation, use, and disposal. International standards for industrial life cycle assessment, such as ISO 14040-14043, have been published in the past decade. These standards lay out the rules that industry should follow for conducting and reporting life cycle assessment. Considering the diversity and complexity of most manufacturing products, LCA methodologies are hampered by two main challenges: a) the diversity and variations in materials, processing techniques, usage durations, and disposal routes; and b) excessive implementation time. Most LCA research is specifically developed for one particular material or product. In industrial setting, LCA is very data-intensive and requires months to complete. Furthermore, LCA is not connected to business perspectives, and thus it does not measure the value of sustainability practice without additional product cost estimation and optimization factors.

Design for Sustainability (DfS) aims at designing or re-designing a product in order to reduce its environmental impact within one particular stage of the product life cycle. It complements design-for-X principles. Design for manufacturing methodologies have been used with a focus on cutting both the production lead time and cost. That, in turn, may lead to a reduction in energy consumption. Design for disassembly, for remanufacturing, and for recycling fall under the umbrella of “design for end-of-life”. Design for durability and for energy efficiency is to minimize material usage such as raw material and fossil fuel. While LCA is intended to determine material and energy flows and to assess the resulting environmental impacts, DfS utilizes information and results from LCA to improve product and process design. One key problem with DfS and LCA is the lack of a close connection and integration with other design, management, and manufacturing tools. Energy efficiency research focuses more specifically on – energy consumption monitoring and estimation. These research fields are segmented and they are specific for certain products, materials or processes. The lack of manufacturing system and sustainability information integration hampers the widespread adaptation of the best sustainability practices in the manufacturing industry.

2 INFORMATION MODELS OF PRODUCT DESIGN AND MANUFACTURING PROCESSES

In recent years, information technology has become increasingly important in the manufacturing enterprise. Effective information sharing and exchange among computer systems throughout a product’s life cycle has been a critical issue [36]. Information modeling is a technique for specifying the data requirements that are needed within the application domain [37]. An information model is a representation of concepts, relationships, constrains, rules, and operations to specify data semantics for a chosen domain of discourse [38]. The advantage of using an information model is that it can provide a sharable, stable, and organized structure of information requirements for the domain context. There are different practices in developing an information model. The underlying methodologies for the recent modeling practices are based on three approaches: the Entity-Relationship (ER) approach, the functional modeling approach, and the Object-Oriented (O-O) approach. Based on these approaches, there are many information models existing in manufacturing industry such as UML models, XML models, IDEF1X models, etc. Amongst these information models, the STEP and STEP-NC information models are the most advanced and standardized ones.

STEP and STEP-NC standards have been developed by ISO committee to provide the basis for product design, machining standardization, and integration of part inspections with machining. The information is modeled in EXPRESS language. The purpose of STEP is "to specify a form for the representation and unambiguous exchange of computer-interpretable product information throughout the life of a product" [39]. STEP permits different implementation methods to be used for storing, accessing, transferring, and archiving product data. STEP Application Protocol (AP) 203 edition 1 [40] and edition 2 [41] (Configuration Controlled 3D Designs of Mechanical Parts and Assemblies) provides the data structures for the exchange of configuration-controlled 3D designs of mechanical parts and assemblies. AP 203 is but one part of the entire ISO 10303 product data standard. It does not present itself as the data standard for configuration management of a product throughout its entire life cycle. The AP is centered on the design phase of mechanical parts and the high-level information entities are shown in Figure 1.

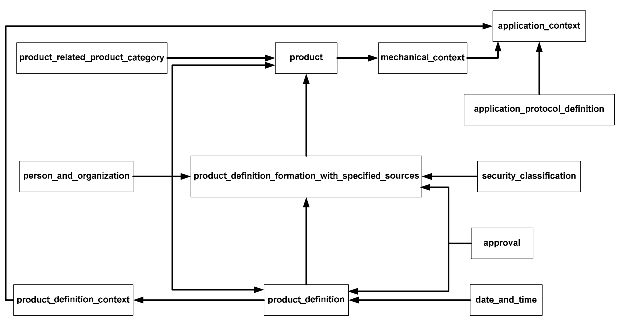

Figure 1: High-level information entities in STEP AP203.

Other APs of STEP information models carry the product design data in AP 203 forward through the product life cycle. STEP-NC represents a common standard specifically aimed at NC programming, making the goal of a standardized CNC controller and NC code generation facility a reality [42]. It provides CNC with a detailed and structured data interface that incorporates feature-based programming where a range of information is incorporated such as the features to be machined, tool types used, operations (workingsteps) to perform, and process plan (workplan) to develop [43] as shown in Figure 2. The feature information in STEP-NC can be obtained by processing the product design geometry in STEP AP 203 through a feature recognition process. The material information and Product Lifecycle Management (PLM) information in STEP AP 203 associated to the design geometry can also be passed onto the manufacturing features in STEP-NC, which in turn associates to the manufacturing process parameters such as machine tools, tool-path, cutting strategy, etc. In this way, the design geometry, material, PLM information is connected to the manufacturing process level.

By providing the high level information to machining systems, STEP-NC will not only eliminate the costly and inefficient process of data post-processing, it will also establish a unified environment for the exchange of information between product design, machining process planning and inspection. It enables the realization of a closed, STEP-NC based machining process chain with data feedback and a consolidated data structure at each level [44, 45]. Industrial use of STEP/STEP-NC has shown evidence of significant cost saving, higher quality, and reduced time-to-market. It may become a major building block in e-economy, the effort to unite manufacturing businesses among corporate partners, distant suppliers, and across divers computer environments [24].

3 ISSUES OF INTEGRATING LCA IN PRODUCT DESIGN STAGE

Due to the complexity of manufacturing products and their manufacturing processes, conducting LCA for one product alone is a very time-consuming process. Furthermore, because of the various software and hardware tools involved in a product design and manufacturing process, the quality of LCA data is also a pressing issue for industry to accept current LCA results. The various data format in design and process planning software also contributes to the difficulties of integrating LCA information into product design stage. This section discusses these issues in detail.

3.1 Quality and Quality of Data in LCA Process Modeling

Product systems are complex and the manufacturing firms encounter serious problems when using LCA in the design situations for many reasons. Firstly, the large number of parts and the diversity of materials and processes involved inside a product system are true barriers to effective implementation of LCA in the design phase [46, 47]. Collecting and processing all the data needed for modelling the product life cycle does make compiling the inventory a very time consuming task which also requires a lot of efforts [48]. In addition, these elements are not fully available earlier in the design phase [49].

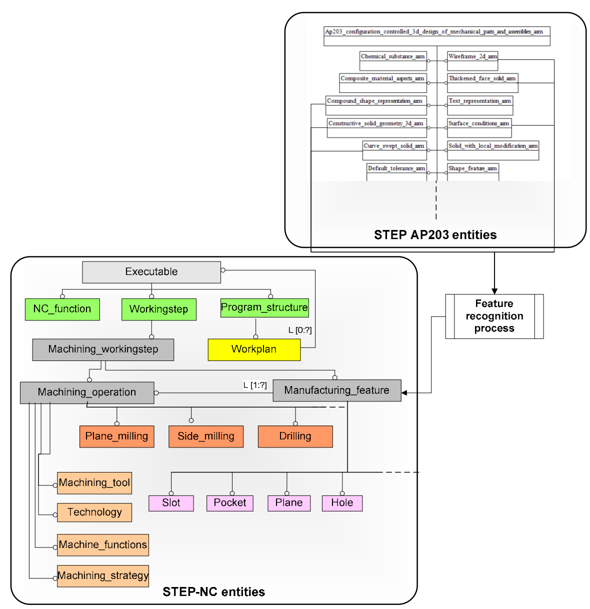

Figure 2: An example of STEP-NC information model in EXPRESS-G diagram.

Secondly, it is often difficult to be exhaustive in terms of all the processes, data and parameters of product life cycle modelling as required by LCA procedure [50]. In fact, conducting LCA approach requires that the following four aspects must be taken into account:

1) The level of "depth and detail" of data required in the application(s),

2) The breadth and completeness of the study: life cycle stages, drawn system boundary, inventory and impact category indicators used to meet the intended application(s),
3) The degree of openness and comprehensiveness in the presentation of the results, and
4) The data sources and quality (i.e., are secondary data sources sufficient for the study or primary data required, or a mix of both sources? How much confidence should the users have in the data manipulated and in the study's conclusions?

Also, in LCA, the "functional unit" establishes the process parameters. Unfortunately, in real-life complexity, the utility of a product cannot be reduced to the expression of one or two specifications of use [51]. However, this rationalization of real-life complexity is acknowledged by qualifying the LCA system boundary as "rigid", as either not all the existing parameters can be reduced to a few numbers and inserted into the process model. This LCA data management is therefore often conducted with a certain degree of subjectivity [52] and polluted by a lack of comprehensiveness in terms of data sources [53]. Indeed, data sources can also contribute to inaccuracy, as it is well known and acknowledged that data used in generic processes may be based on averages, unrepresentative sampling, or outdated measures. Additionally, it is also well known that depending on the scope definition, the considered system boundary may be different from one LCA practitioner to another regarding a product life cycle modelling. Thus, it is never possible to obtain an exact life cycle inventory [54].

3.2 LCA Adaptation in the Product Design Stage

Many LCA software tools are commercially available, but SimaPro from Pré Consultants and GaBi from PE International have been around for many years, and are widely used by life cycle assessment professionals. The user interface for both of these products is challenging in terms of intuitiveness.

Concerning the modelling philosophy, GaBi could be qualified as a "process modelling approach", as it requires users to build a "process-tree" to connect materials, energy and processes to parts. After building the product system in GaBi, users can check if inputs and outputs match up for the assemblies.

SimaPro could be qualified as a "product modelling approach", as the users are required to enter in data for the product, before switching to a flow chart view to easily see the relative impacts from materials and processes.

Both tools can all the same display inputs/outputs and impacts categories in what appear to be every conceivable format, but the users are responsible for their choices, according to their preferred working philosophy and also related to the nature of the product system needed to be studied. For example, does the product system contain a large amount of parts but involving a few number of processes diversity? Does the product system, whatever the number of components, contain a large diversity of materials and manufacturing processes?

Table 1 shows a summary of the relevant advantages and drawbacks from our usage observation of the two software tools described above. It is noticed that we do not intended to compare these tools about commercial aspects such as their costs or the required hardware materials.

Behind the choice of LCA tools and softwares, making the LCA method and these sophistically softwares adapted into the design situations is also a veritable challenge. It is due to the problem of time and several efforts needed. Indeed, modelling the product through understanding the implications of system boundaries and the problem of vocabulary gaps between the design and LCA languages make this appropriation impossible for people lacking experience in LCA [55]. Precisely, modelling the product life cycle requires high levels of environmental expertise and specific vocabularies (e.g. unit flow, elementary flow…) to be able to map the product life cycle's interaction with the environment, in terms of extractions and rejects. These notions are still fuzzy among the actors of the design universe [56]. Moreover, interpreting the complete and detailed results of LCA is often not helpful in a business context [57], since this kind of information can only be understood by an LCA expert, who is not often the decision-maker in the manufacturing firms. It is therefore extremely unrealistic to ask the design actors to model the product directly in LCA software and to interpret the results by themselves.

	GaBi	SimaPro
Advantages	Possibility to use parameters for the calculation and modelling; Implemented sensitivity analysis tool (Monte-Carlo Analysis), scenario analysis, parameter analysis; Easy to identify the critical life cycle stage and associated processes, in terms of impacts; Possibility to create different types of diagrams; High quality LCI database, professional database, wide range data sets cover many industrial branches.	More intuitive interface; Quickly learning how to work; Real-time analysis of impact assessment results; Easy to identify the most impact contributor in terms of part/component; Support damage categories in impact assessment methods; Possibility to create easily his assessment methods; Implemented Ecoinvent databases.
Drawbacks	Do not include the reputed Ecoinvent databases in the professional version; Results visualisation and exploitation are complicated; Less intuitive interface.	Sophisticated analysis option for the assessment results (sensitivity analysis, impacts contribution on each life cycle stages…).

Table 1: Advantages and drawbacks of most commonly used LCA software.

4 PROPOSED MANUFACTURING INFORMATICS FRAMEWORK FOR THE INTEGRATION OF LCA AT DESIGN STAGE

In order to integrate LCA information into the product design stage, necessary information must be properly represented and associated to the product PLM information. In the proposed research, a case study was first conducted to examine what LCA information should be modelled. Composite parts give interesting examples on a simple piece such as a pedal crank developed with recycled carbon fibres for thermoset organic matrix composite as shown in Figure 3. During the design, product models have to integrate materials information such as matrix composition, reinforcement type (glass, carbon, aramid, and natural), their architecture (unidirectional, woven) and the structure composition (orientations of the different layers in the depth of the product). Other information like inserts or coating completes the bill of material.

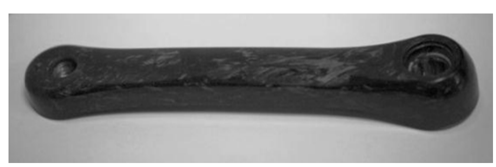

Figure 3: Natec pedal crank made with recycled Carbon Firers Reinforcements (developed with recycled fibres at I2M) [30].

Currently in STEP AP 203, only very limited material information is modelled as shown in the following entities:

```
ENTITY Material_identification;
   material_name : STRING;
   items : SET[1:?] OF material_item_select;
END_ENTITY;

TYPE material_item_select = SELECT
   (Anisotropic_material,
    Braided_assembly,
    Coating_layer,
    Isotropic_material,
    Laminate_table,
    Part_view_definition,
    Substance_view_definition,
    Woven_assembly);
END_TYPE;

ENTITY Composite_material_identification
   SUBTYPE OF (Material_identification);
DERIVE
   composite_material_name : STRING :=
      SELF\Material_identification.material_name;
END_ENTITY;
```

To associate composite material information to a product design, the following entities were developed in this research. The new entities are written in bold.

```
TYPE material_item_select = SELECT
   (Anisotropic_material,
    Braided_assembly,
    Coating_layer,
    Isotropic_material,
    Laminate_table,
    Part_view_definition,
    Substance_view_definition,
     Woven_assembly
     Composite_material);
END_TYPE;
```

```
ENTITY Composite_material
ABSTRACT SUPERTYPE OF (ONEOF
(carbon_fibre_reinforced_composite,
glass_reinforced_composite,
thermoplastic_composites));
   name:                STRING;
   matrics:             composite_matrix;
   resins:              composite_resin;
   reinforcement:       composite_reinforcement;
END_ENTITY;

ENTITY composite_matrix
ABSTRACT SUPERTPYE OF (ONEOF (mud, cement,
polymers, metals, ceramics));
   name:                STRING;
END_ENTITY;

ENTITY composite_resin
ABSTRACT SUPERTYPE OF (ONEOF (polyester_resin,
vinylester_resin, epoxy_resin,
shape_memory_polymer_resin));
   name:                STRING;
   material_property:   STRING;
END_ENTITY;

ENTITY composite_reinforcement
ABSTRACT SUPERTYOP OF (ONEOF (glass_fibre,
carbon_fibres, aramid_fibres, boron_fibres));
   name:                STRING;
   architecture:        fibre_architecture;
END_ENTITY;

ENTITY fibre_architecture;
ABSTRACT SUPERTYPE OF (ONEOF
(short_fibre_reinforced,
continuous_fibre_reinforced));
   name:                STRING;
   direction:           fibre_directions;
END_ENTITY;

ENTITY fibre_directions;
SUPERTYPE OF (ONEOF (continuous_aligned,
discontinuous_aligned, discontinuous_random,
unidirectional, woven));
END_ENTITY;
```

Manufacturing data must also been included in order to ensure the product / material / process combined design in the case of composite parts. Promoting recycled carbon fibres eco-design [58] imposes to access to material data (from end of life scenario and properties) at the early stage of the design. It means developing a specific data storage for material properties (depending to the recycling process) and properties models prediction (based on the different type of fibres) as illustrated on Figure 4.

Currently in STEP AP 203, the limited material information, shown above in unbold entities, is not associated to design geometry. The material information is defined only for annotation display. In order to fully integrate material information with design process, the association between product geometry and its material must be semantic. Today no integrated environment allows taking all these facets into consideration. And the next step is to compare, for an expected set of functions, the n-plet [59] in order to optimise both technically, but also environmentally with specific focus such as material resources minimization (mix of less material and improved end of life possibilities), energy optimisation and/or pollution reduction. These multi objective optimisation needs to handle all these data, models, life stages, functional unit definition in a coherent environment and at the early stage of product development.

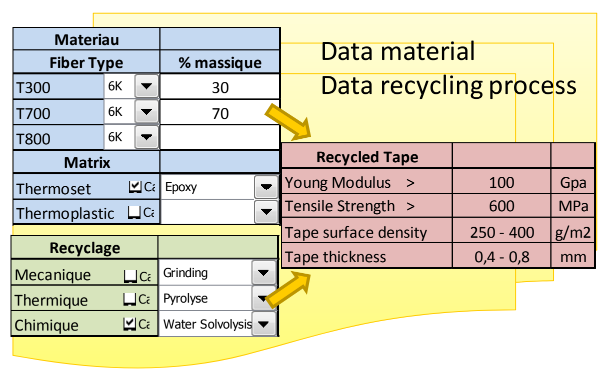

Figure 4: Recycling End of Life scenario and product/material properties evaluation tool.

STEP and STEP-NC is the most suitable information structure framework that needs to be enriched by the environmental aspects of the product/process data as shown in Figure 5. Eventually, with the proposed information framework, LCA related information is integrated to the design and process planning aspects of product development. The LCA knowledge and data accumulated throughout a product life cycle can be fed back to the product design stage to improve new product development and to reduce environmental impact.

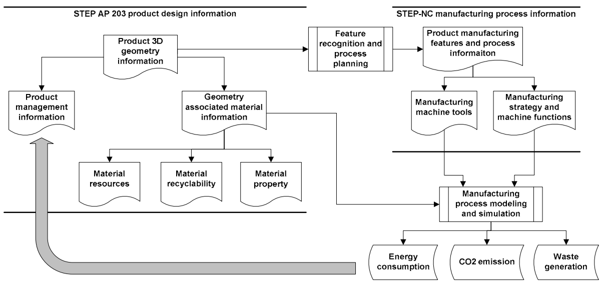

Figure 5: Proposed information framework for integrating LCA in product design stage.

5 FUTURE WORK AND CONCUSIONS

The research reported in this paper is the very beginning stage of developing an information framework to support the integration of LCA at the product design stage. A simple case study was conducted to examine what composite material information should be defined in association with product design information. The next steps of the proposed research are:

1) data structure:
    - Identify all the Product Life Phases (from Fife Cycle Analysis) needs in terms of environmental data versus the existing data into STEP,
    - Identify a dynamic ontology of environmental data for product development. This will give, for every stage of the product development, the expected environmental data that must be integrated in the product data,
    - Structure the data and evaluation models to propose, usable simulation results (technical and environmental) for decision making, depending of product/process definition enrichment, and
    - Propose a STEP extension for End of Life support.
2) Data acquisition
    - Start low level implementation (at the process level for the manufacturing phase) in order to start enriching STEP with environmental concepts and to start creating data base for process evaluation and optimization,
    - Develop design approach and integrated tools specification based on STEP for Environmental Friendly Development for some simple case study. Some interoperability problems must be identified between product development models and tools and, Life Cycle Assessment Software and Database.

Sustainable product design and manufacturing is the future of today's manufacturing industry. Sustainability research in manufacturing industry has been conducted in several different approaches from life cycle assessment, to design for sustainability, and to energy efficiency analysis. These research fields are segmented and they are specific for certain products, materials or processes. The lack of manufacturing system and sustainability information integration hampers the widespread adaptation of the best sustainability practices in the manufacturing industry. In order to provide product designer with comprehensive material and environmental related information at the design stage, a complete information structure must be developed to associate sustainability information with product design information and product manufacturing process. This research proposes to develop such an information framework based upon STEP and STEP-NC information models. An initial case study was conducted to identify composite material information that should be defined for product design.

6 REFERENCES

[1] Sreenivasan, R., A. Goel, and D.L. Bourell. *Sustainability issues in laser-based additive manufacturing*. 2010.

[2] Baldwin, J.S., et al., *Modelling manufacturing evolution: Thoughts on sustainable industrial development.* Journal of Cleaner Production, 2005. **13**(9): p. 887-902.

[3] Hoffman, A.J., et al., *The Green Conversation*, in *Harvard business review*. 2008. p. 58-62.

[4] Baas, L., *Cleaner production and industrial ecosystems, a Dutch experience.* Journal of Cleaner Production, 1998. **6**(3-4): p. 189-197.

[5] Frosch, R.A., et al., *The industrial ecology of metals: A reconnaissance.* Philos Trans R Soc London Part A, 1997. **355**: p. 1335-1347.

[6] Grant, J., *Planning and designing industrial landscapes for eco-efficiency.* Journal of Cleaner Production, 1997. **5**(1-2): p. 75-78.

[7] Lowe, E.A., *Creating by-product resource exchanges: Strategies for eco-industrial parks.* Journal of Cleaner Production, 1997. **5**(1-2): p. 57-65.

[8] Von Weizsäcker, E., A.B. Lovins, and L.H. Lovins, *Factor Four: Doubling Wealth, Halving Resource Use*. 1997.

[9] Mayyas, A., et al., *Design for sustainability in automotive industry: A comprehensive review.* Renewable and Sustainable Energy Reviews, 2012. **16**(4): p. 1845-1862.

[10] Seliger, G., M.M.K. Khraisheh, and I.S. Jawahir, eds. *Advances in Sustainable Manufacturing*. 2011, Springer.

[11] Ashby, M., et al., *Life-cycle cost analysis: Aluminum versus steel in passenger cars.* Materials and the Environment, 2009: p. 161-245.

[12] Pennington, D.W., et al., *Life cycle assessment Part 2: Current impact assessment practice.* Environment International, 2004. **30**(5): p. 721-739.

[13] Saur, K., J.A. Fava, and S. Spatari, *Life cycle engineering case study: Automobile fender designs.* Environmental Progress, 2000. **19**(2): p. 72-82.

[14] Stodolsky, F., A. Vyas, and R. Cuenca, *Lightweight materials in the light-duty passenger vehicle market: Their market penetration potential and impacts center for transportation research.* Life-cycle Thinking, 1995.

[15] Ungureanu, C., *Design for Sustainability: Product Life-cycle Analysis in Aluminum Auto Body Applications*. 2007, University of Kentucky.

[16] Barker, S. and A. King, *Organizing reuse managing the process of design for remanufacture (DFR).* POMS 18th Annual Conference, 2007.

[17] Bulucea, C.A., et al., *Building awareness of sustainable automobile manufacturing within industrial ecology framework.* Proceedings of the International Conference on Urban Sustainability, Cultural Sustainability, Green Development Green Structures and Clean Cars, 2010: p. 149-153.

[18] Coulter, S., et al., *Designing for material separation: Lessons from automotive recycling.* Proceedings of the 1996 ASME Design Engineering Technical Conferences and Computers in Engineering Conference, 1996.

[19] Dantec, D., *Analysis of the cost of recycling compliance for the automobile industry*. 2005, Massachusetts Institute of Technology.

[20] Hammond, R., T. Amezquita, and B. Bras, *Issues in the automotive parts remanufacturing industry: Discussion of results from surveys performed among remanufacturers.* International Journal of Engineering Design and Automation, 1998. **4**(1): p. 27-46.

[21] Jawahir, I.S., et al., *Design for sustainability (DFS): New challenges in developing and implementing a curriculum for next generation design and manufacturing engineers.* International Journal of Engineering Education, 2007. **23**(6): p. 1053-1064.

[22] Mildenberger, U. and A. Khare, *Planning for an environment-friendly car.* Technovation, 2000. **20**(4): p. 205-214.

[23] Van Schaik, A. and M.A. Reuter. *The effect of design on recycling rates for cars part 1- Theory*. 2005.

[24] Warburg, N., C. Hemam, and J.D. Chiodo, *Accompanying the (re)design of products with environmental assessment (DfE) on the example of ADSM.* International Symposium on Electronics and the Environment, 2001. Proceedings of the 2001 IEEE, 2001.

[25] Yuksel, H., *Design of automobile engines for remanufacture with quality function deployment.* International Journal of Sustainable Engineering, 2010. **3**(3): p. 170-180.

[26] Govetto, S., et al., *End-of-life vehicle recycling based on disassembly.* Determining the Environmental Impact of Disposal, Recycling and Remanufacturing Strategies, 2008. **12**(2): p. 153-156.

[27] Jayal, A.D., et al., *Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels.* CIRP Journal of Manufacturing Science and Technology, 2010. **2**(3): p. 144-152.

[28] Jody, B.J., E.J. Daniels, and E. Sundin, *Product and process design for successful remanufacturing.* End-of-life Vehicle Recycling: The State of the Art of Resource Recovery from Shredder Residue, 2006.

[29] Palmer, J., et al., *Disassembly-Oriented Assessment Methodology to Support Design for Recycling.* Mechanical Recycling of Automotive Composites for Use As Reinforcement in Thermoset Composites, 2009. **43**(1): p. 9-14.

[30] Perry, N., et al., *Improving design for recycling - Application to composites.* CIRP Annals - Manufacturing Technology, 2012. **61**(1): p. 151-154.

[31] Sundin, E., *Product and Process Design for Successful Remanufacturing*, in *Department of Mechanical Engineering*. 2006, Linköpings Universitet: Linköping.

[32] Sun, Z. and L. Li, *Opportunity Estimation for Real-Time Energy Control of Sustainable Manufacturing Systems.* IEEE Transactions on Automation Science and Engineering, 2012.

[33] Tanaka, K., *Review of policies and measures for energy efficiency in industry sector.* Energy Policy, 2011. **39**(10): p. 6532-6550.

[34] Thiede, S., C. Herrmann, and S. Kara. *State of research and an innovative approach for simulating energy flows of manufacturing systems*. 2011.

[35] Vijayaraghavan, A. and D. Dornfeld, *Automated energy monitoring of machine tools.* CIRP Annals - Manufacturing Technology, 2010. **59**(1): p. 21-24.

[36] *Information Technology for Manufacturing*, in *National Research Council Report*. 1995, National Research Council

[37] Lee, Y.T., *An overview of information modeling for manufacturing systems integration*, in *NISTIR 6382*. 1999, National Institute of Standards and Technology.

[38] Chen, P.P., *The entity relationship model: Towards a unified view of data.* ACM Trans. on Database Systems (TODS), 2004. **1**(1): p. 1976.

[39] ISO, *ISO 10303-1: Industrial automation systems and integration - Product data representation and exchange - Part 1: Industrial Automation System and Integration - Product Data Representation and Exchange Part 1: Overview and Fundamental Principles.* 1994.

[40] ISO, *ISO 10303-203: Industrial automation systems and integration - Product data representation and exchange - Part 203: Application Protocols: Configuration controlled 3D design.* 2007.

[41] ISO, *ISO 10303-203:2009: Industrial automation systems and integration - Product data representation and exchange - Part 203: Application protocol: Configuration controlled 3D design of mechanical parts and assemblies.* 2009.

[42] ISO, *ISO 14649-1, Data model for Computerized Numerical Controllers: Part 1 Overview and fundamental principles.* 2002.

[43] Zhao, Y.F., S. Habeeb, and X. Xu, *Research into integrated design and manufacturing based on STEP.* International Journal of Advanced Manufacturing Technology, 2009. **44**(5-6): p. 606-624.

[44] Xu, X., Andrew, Y. C., ed. *Advanced Design and Manufacturing Based on STEP*. 2009, Springer.

[45] Xu, X., et al., *STEP-compliant process planning and manufacturing.* International Journal of Computer Integrated Manufacturing, 2006. **19**(6): p. 491-494.

[46] Koffler, C., L. Schebek, and S. Krinke, *Applying voting rules to panel-based decision making in LCA.* International Journal of Life Cycle Assessment, 2008. **13**(6): p. 456-467.

[47] Fitch, P.E. and J.S. Cooper, *Life cycle energy analysis as a method for material selection.* Journal of Mechanical Design, Transactions of the ASME, 2004. **126**(5): p. 798-804.

[48] Bretz, R., *SETAC LCA workgroup: Data availability and data quality.* International Journal of Life Cycle Assessment, 1998. **3**(3): p. 121-123.

[49] Schiffleitner, A., et al. *ProdTect - Life cycle design and concurrent engineering in the automotive industry*. 2008.

[50] ISO, *ISO 14040:2006: Environmental management -- Life cycle assessment -- Principles and framework.* 2006.

[51] Millet, D., et al., *Does the potential of the use of LCA match the design team needs?* Journal of Cleaner Production, 2006. **15**(4): p. 335-346.

[52] Leroy, Y., *Development of a methodology to reliable environmental decision from life cycle assessment based on analysis and management of inventory data uncertainty*. 2009, Ecole Nationale Supérieure d'Arts et Métiers: Chambéry, France.

[53] Ayres, R.U., *Life cycle analysis: A critique.* Resources, Conservation and Recycling, 1995. **14**(3-4): p. 199-223.

[54] Bala, A., et al., *Simplified tools for global warming potential evaluation: When 'good enough' is best.* International Journal of Life Cycle Assessment, 2010. **15**(5): p. 489-498.

[55] Dewulf, J. and H. Van Langenhove, *Exergetic material input per unit of service (EMIPS) for the assessment of resource productivity of transport commodities.* Resources, Conservation and Recycling, 2003. **38**(2): p. 161-174.

[56] Millet, D., et al., *The firm faced to sustainable development: Change of paradigm and learning process.* L'entreprise face au développement durable: Changement de paradigme et processus d'apprentissage, 2003. **11**(2): p. 146-157.

[57] Rebitzer, G., *Enhancing the application efficiency of life cycle assessment for industrial uses.* International Journal of Life Cycle Assessment, 2005. **10**(6): p. 446.

[58] Perry, N. and W. Uys, *Knowledge integration based on road mapping and conceptual framework approach to ease innovation management.* International Journal of Computer Applications in Technology, 2010. **37**(3-4): p. 165-181.

[59] Mayyas, A., et al., *Using Quality Function Deployment and Analytical Hierarchy Process for material selection of Body-In-White.* Environmental Product Declaration, 2011. **32**(5): p. 2771-2782.

“LCA to Go” – Environmental Assessment of Machine Tools According to Requirements of Small and Medium-Sized Enterprises (SMEs) – Development of the Methodological Concept

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Abstract. The goal of the “LCA to go” project is to spread the use of LCA across European SMEs. For the sector of machine tools, a webtool will be developed to help SMEs carry out environmental assessments. Requirements to this tool were analysed through a survey, as well as research into case studies, standards and legislation. The simplified environmental assessment methodology follows a two step approach including a rough assessment of the Cumulative Energy Demand an a detailed analysis focusing on the most relevant life cycle phases. The progress to robust results is tracked using simplified Data Quality Indicator, which are proposed in this paper.

Keywords: Environmental assessment methodology; cummulative energy demand; data quality indicator; machine tools; SMEs

1 INTRODUCTION

The increasing interest in environmental impacts of products over the whole life cycle is reflected by the numerous existing standards and ongoing activities. Large sized companies have enough budget and workforce to cope with these environmental requirements, but what about SMEs? The objective of the project “LCA to go” is to develop an open source webtool for SMEs, enabling them to perform a sector specific life cycle based environmental assessment. It provides tailor-made solutions to integrate simplified life cycle approaches into daily business processes. Among others, one sector in the “LCA to go” project focuses on is Industrial machines and more specifically machine tools.

2 APPROACH

This paper shows the development of the methodology concept for the environmental assessment of machine tools. To identify an appropriate methodolgical concept based on LCA, Carbon Footprint, Energy Efficiency Index etc. a SMEs needs assessment in form of a survey, research on current case studies of environmental assessments of machine tools and an analysis of current and future legislation and standards have been conducted (Figure 1).

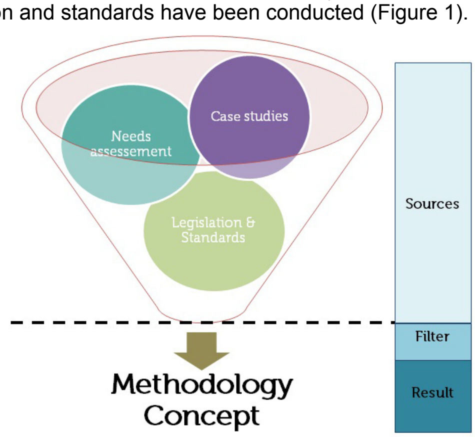

Figure 1: Development of methodological concept [1].

2.1 Needs Assessment

22 SMEs, specialized in machine tool manufacturing, responded to a survey, which helpded define the needs of the European SMEs in this sector. The survey showed that environmental issues are already anchored in SMEs, but often only in form of cleaner production and theoretical knowledge around environmental assessment methods. Only 2 companies had performed an LCA once and only 36% of respondents knew that machine tools are use-intensive products (because of energy consumption in operation). 23% thought that disposal is the most problematic life cycle phase for their product (Figure 2).

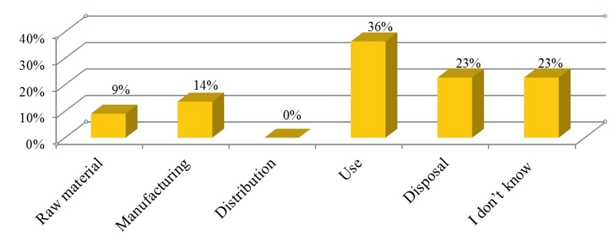

Figure 2: Survey answers to the question “What is the most problematic life cycle phase of a machine tool?” [1].

Nevertheless, the SMEs pointed out that the software tool should focus on energy aspects and support them in fulfilling legal requirements. A voluntary environmental label, focusing on energy efficiency, and to be used as an environmental communication instrument, was of greatest interest to the respondents. The SMEs also indicated that the tool should help improve product quality, and its environmental performance, which is expected to reduce manufacturing costs while helping them prepare for future customer demands. Furthermore, the assessment of innovative products should be possible, without complete life cycle data sets.

2.2 Case Studies

Case studies on environmental assessment of machine tools give the scientific perspective by providing environmental profiles from which the most relevant environmental aspects can be derived.

In the case studies, different methods have been applied in LCAs of machine tools (CML, Ecoindicator 99, and Cumulative Energy Demand). Machine tools usually have a high weight (> 5 tons) and an average lifetime of about 10 years operating in a 2 or3 shift regime. The result of the environmental assessment showed that the energy consumption during the use phase accounts for 55-90% of the total environmental impact of machine tools. Figure 3. shows the environmental profile for an injection moulding machine. In this case, the use phase is broken down into the main operations driving the energy consumption. It becomes apparent that the tempering unit is centrally important, accounting for nearly 50% of the total energy consumption in the use phase.

Research further showed that in some cases, the raw material use also has a relevant environmental impact, in less use intensive machines, such as a press brake, operated in a one shift regime, where the materials used in the machine account for in 40% of the total. This indicates that the environmental impact of a machine tool relay highly on the use scenario.

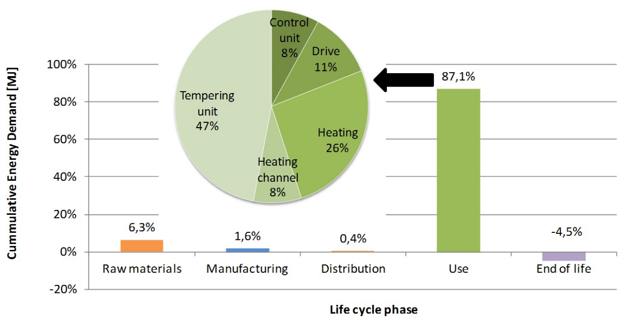

Figure 3: Environmental Profile of an injection moulding machine [2].

2.3 Legislation and Standards

To ensure that the developed web tool is widely applied, the methodology should be coherent with current and future legislation and standards.

Machine tools are already in focus of several environmentally driven legislative initiatives. The European Commission (EC) has started a Product Group Study related to the Ecodesign Directive [3] to identify and recommend ways on how to improve the environmental performance of machine tools. This pressure from the EC resulted in two further initiatives driven by the industry. These are the ISO 14955 [4] and the Self-Regulation Initiative (SRI) [5], concentrating on the environmental assessment of machine tools. The SRI and the ISO standard focus on the evaluation of the energy efficiency of machine tools. As such the most relevant machine components are identified, by allocating the energy consumption to the individual functional components. Further, the German Society on Numeric Control (NCG) [6] proposed a standardized method to measure the energy usage, allowing for the calculation of an Energy Efficiency Index (EEI).

All mentioned initiatives and standards focus on the energy consumption during the use phase of a machine tool. Product Category Rules for preparation of an Environmental Product Declaration are also under development, where the entire life cycle is considered [7].

3 METHODOLOGICAL CONCEPT

3.1 Environmental Assessment Method

The preparatory work showed that several aspects must be considered in the development of the methodology. Table 1 summarizes the aspects on the basis of the three defined information sources: the needs assessment, the case studies and the legislation.

To fulfill these key requirements, the general methodology of the tool follows a two-step approach. To gain an understanding of the overall environmental profile of the machine tool the user carries out a first rough assessment. The resulting information on the Cumulative Energy Demand (CED) over the entire life cycle, informs the user of the environmental hotspots and the underlying data quality. In the second step the user will be able to add more detailed information to the most relevant phases, allowing a more detailed assessment of the CED and the derivation of improvement measures.

Main questions	Sources	Key aspects for methodology
On which **environmental aspect(s)** should the assessment focus?	Case studies, Needs assessment,	Energy consumption, materials consumption
What kind of **environmental assessment** should be provided?	Case studies, Needs assessment	Cumulative Energy Demand (MJ), Energy Efficiency Index (kWh/production unit)
What kind of **environmental communication** instrument should be used?	Needs assessment, Legislation	Energy savings, EEI, CED
How robust and complete are the **environmental results**?	Needs assessment, Case studies	Full assessment with incomplete data, Data Quality Indicators define robustness

Table 1: Main questions leading to methodological key aspects (excerpt) [1].

Emphasis has been put on the tool's user-friendliness and its ability to produce a result with very limited data. It was however understood, that the tool must be able to produce more accurate results with increasing depth of input data. This level of precision and depth is tracked using a Data Quality Indicator.

Additionally for environmental communication a voluntary environmental label, focusing on energy efficiency, is of most interest. SMEs want to inform their business clients about energy savings of machines compared to reference products.

According to the case studies the material and the use phase are most relevance, Manufacturing, Distribution and End of Life show just minor environmental impacts. To avoid a shift in environmental impact from one to another life cycle phasethe entire life cycle of a machine tool is modelled in the tool. The methodology therefore provides the possibility to include the less relevant phases with minimum effort for the user while offering the possibility of adding in depth information where needed.

The CED has been chosen as an appropriate assessment method for the machine tools. The CED is an appropriate approach to assess impacts from material and resource consumption, leading to aggregated results, expressed in MJ. It allows for the comparison of the relative impact of the phases while remaining easy to understand for SMEs. In comparison to other environmental assessment methods the advantage of the CED methodology is manageable data and time effort, which was a main criterion for SMEs using an environmental assessment method. Moreover it delivers easy to understand results, even for users who have low experience in the field of environmental assessment.

3.2 The Data Quality Indicator

A major limiting factor in the application of Life Cycle Assessments is the quality of data used in the calculations [8]. Data Quality Indicators (DQI) are therefore of central importance to assess and improve the quality of LCAs [9], as well as enhancing the understanding of the specific data quality problems, which may subsequently be useful in improving the data collection strategy [10].

Comprehensive approaches dealing with data quality, such as the application of the Pedigree matrix as described by Weidema & Wesnaes (1996) [10] or stochastic approaches as identified by Coulon et al. (1997) [8] have been developed. No matter which model or method is applied, one issue that cannot be addressed is the adequacy of the data used with regards to the goal of the study [10].

The Pedigree matrix proposed by Weidema & Wesnaes (1996), is widely applied in different tools and has been adapted for use in the GHG Protocol [11] and Sima Pro [12]. In this matrix five DQIs are identified namely: Reliability, Completeness and correlations in Time, Geography and Technology. The goal of the "LCA to go" approach is to develop an easy to use web tool tailored for SMEs and therefore the above presented pedigree matrix would be too comprehensive. Especially the intended users (product developers, existing & potential clients, etc.) would find this approach difficult to apply and time intensive, as all five DQIs would have to be declared for each data input.

The proposed approach therefore focusses on a holistic assessment of the data quality in each life cycle stage, by combining the five aforementioned Data Quality Indicators to a single indicator, whose score is described on a scale as either Robust, Indicative or Illustrative [13] as highlighted and defined in detail in Table 2.

DQIs acc. to Weidema & Wesnaes (1996)		**Simplified DQI score**
		Robust
		Description: Conclusions from such datasets are as reliable as reasonably possible. [13]
Reliability	Simplified DQI definition	Data from measurement or verified data provided by a third party (including laboratory test data for performance forecasts, and physical specifications)
Completeness		Data from an adequate number of sites, or from the dedicated process / product / site under study, over an adequate period (to even out normal fluctuations)
Temporal correlation		Data is less than half a typical product life cycle old
Geographical correlation		Data from area or region of study
Further technological correlation		Data applies to specification, processes, materials and/or technology under investigation
		Indicative
		Description: Any data manipulation used includes some assumptions or unavoidable approximations that could unintentionally reduce accuracy. Accuracy is, however, judged such that meaningful but qualified conclusions could be drawn. [13]
Reliability	Simplified DQI definition	*Data that is partly based on assumptions (qualified estimate based on industrial insights), may also contain data from measurement and/or provided by a third party*
Completeness		*Representative data from an adequate number of sites over a shorter period or from a smaller number of sites over an adequate period*
Temporal correlation		*Data is between half and a full typical product life cycle old*
Geographical correlation		*Data from area with similar production conditions as the area under study*
Further technological correlation		*Data applies to related processes, materials and/or technology under investigation*
		Illustrative
		Description: Data manipulations for the analysis contain an element of speculation or significant assumption [13] and there are significant data gaps.
Reliability	Simplified DQI definition	*Estimate data not based on measurement or provided information, use of default data entries*
Completeness		*Data from / estimates for a small number of sites over a short period*
Temporal correlation		*Data is older than a typical product life cycle or age is unknown*
Geographical correlation		*Data from area with different production conditions or area unknown*
Further technological correlation		*Data applies to unknown processes, materials and/or technology*

Table 2: Single DQI according to [13] for the "LCA to go" approach on the basis of five DQIs form [10].

This description and definition of those three parameters is depended on the product in focus of the assessment and therefore have to be specified for the different sectors in focus in this LCA to go project.

The data quality has generally to be defined for each data used in the assessment. For simplification reasons in this LCA to go approach this data quality assessment has to be done just for each life cycle stage. The user (self evaluation) will be asked to indicate the overall data quality for each life cycle phase by selecting one of the three possible scores: Robust, Indicative or Illustrative. All criteria listed per simplified DQI score have to be met; else the next lower level has to be chosen. These DQI scores apply only to the user entries, not for the generic background data: Neither is it possible to determine at the time of dataset implementation, how suitable the dataset will be for any given later application by the user, nor is a typical SME user in the position to judge the background data quality for his application case. The proposed method will follow the overall requirement to be "to go", meaning easy to use, fast and intuitively understandable.

The description of the DQI scores will have to be clearly defined for each sector. Presented in Table 3 is the definition of the DQI scores for the Industrial machine tool sector. The tailored description will enable the user to quickly identify the appropriate DQI score and provide information on the necessary steps to improve the score should this be needed.

Robust	Data from measurement according to a measurement standard or verified data provided by a third party. Data gathered over an adequate period of time and over different machine states to even out fluctuations. Data applies to the machine model under investigation. Data applies to the area/region Data is less than 6 years old.
Indicative	Data partly based on assumptions. Data gathered over a shorter period or for select machine states. Data applies to at least the previous model of the same machine. Data applies to an area/region with similar production conditions. Data is less than 15 years old.
Illustrative	Estimate data not based on measurement or provided information. Data gathered over very short periods or a single machine state. Data applies to older model of the machine or similar model from a different manufacturer. Data may apply to a different (or unknown) area/region. Data is older than 15 years or the age is unknown.

Table 3: Single DQI specified for machine tools.

The output of the tool should link the results of the environmental assessment to the quality of the input data (as highlighted in Figure 4 below. This will enable the user to quickly identify which areas of data collection, if any, need to be improved and whether the result is robust. This is of central importance when deriving improvement measures for the product under investigation.

3.3 Rough Assessment of Hot-spots Using the CED

The goal in the first step is to identify the most relevant environmental phases of the machine tool life cycle. Using only limited data input, the dominant environmental life cycle phase can be recognized. Based on these results a detailed assessment can be conducted in the second step.

In the Material phase a rough estimation of the CED will be calculated. The total weight of the machine is used to calculate a first estimate based on a general material dataset. The user can refine this very roughly by providing rough weight information on up to five major materials or supplier parts if available.

In the Manufacturing phase, an estimate for the energy consumption in the manufacturing process is calculated by the tool based on the total weight of the machine. If rough information on the energy consumption in this phase is available, the user can overwrite this estimate. E.g. apportionment of electricity bill to machines produced.

In the Distribution phase, the user simply distinguishes between overland and overseas shipping and has the option of adding the weight of any packaging.

The main focus lies in the definition of the use scenario in the Use phase. In this first rough assessment, the user must declare the electrical power consumption of the machine in three different operating states: Producing, Ready and Standby. The interface further contains three pre-defined use scenarios (1-shift, 2 shift, 3-shift), which the user can modify using an intuitive interface.

In the End of Life phase the user has the option to define a simple disposal scenario, by defining percentage shares for the three waste streams: Recycling, Incineration, Landfill.

Results of the rough assessment will be presented as shown in Figure 4 enabling users to quickly recognize the environmental hotspots and identify the quality of the underlying data. Most life cycle phases have just illustrative data quality. In the use phase, where 95% of the total environmental impact occur the data quality is higher and assigned as “indicative”. If a higher data quality is needed e.g. the assessment should be used for product improvement a second assessment step is recommended.

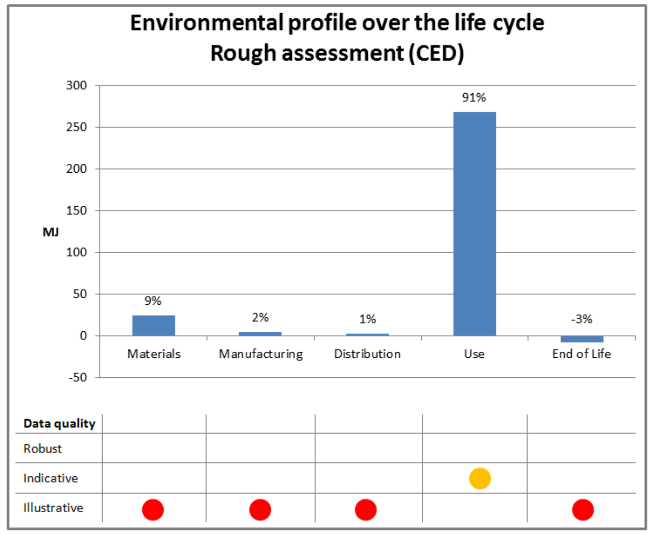

Figure 4: Result presentation of the rough assessment containing information on the DQI.

3.4 Second Step: Detailed Assessment with CED

Conducting an environmental assessment is an iterative process. The initial rough assessment is followed up by a more detailed assessment where the users focus their efforts on the most life cycle phases. With the help of the result from the rough assessment, the areas, which need further attention, can be easily identified. The tool offers the capability to add more detailed data to all five life cycle phases. The results generated in the detailed assessment will provide the basis for environmental improvements to the machine tool.

As uncovered in the needs assessment and case studies, the material phase can be of great importance in certain cases, depending on the use scenarios. Materials also gain relative importance when large quantities of rare elements are incorporated in machine tools or if the customers request a material declaration. Moreover increasing costs of materials or future legislation could bring these aspects more into focus. This has been taken into account in the detailed assessment through the incorporation of supplier parts and increased levels of input depth. For each material a dataset is available. The more materials are declared (in % of the total weight) the higher the accuracy of the results will be.

Following the results of the case studies, the Manufacturing and Distribution phases do not have a significant environmental impact on the life cycle of a machine tool. Nevertheless, they represent areas, which the SMEs can directly influence and have an operational interest in.

For this reason, the detailed assessment offers the user the possibility to enter manufacturing process details as well as shipping specifications.

The environmental impact of the use phase is of central importance for machine tools. This can be seen in the case studies as well as the legislation. It is also reflected in the SME's request to make this a central feature of the tool. In the use phase the energy consumption is measured according to the energy measurement standard giving the energy consumption for all main components. The importance of the use scenario in the environmental evaluation has been incorporated in the tool by providing the option of creating several use scenarios within one assessment and showing the variation in the environmental impacts. Furthermore, the tool offers the option to account for other energy flows as well as operating resources. To enable the tool to suggest suitable improvement options, the assignment of the energy consumption in the different operating states to general machine functions is possible in this assessment step.

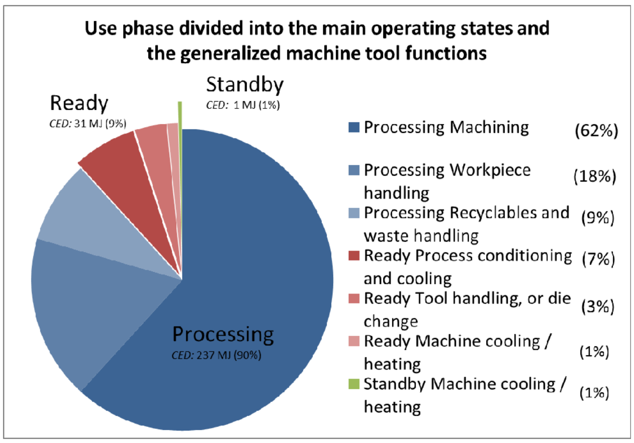

Figure 5: Detailed assessment of the use phase with the CED in the different operating states assigned to generalized machine functions.

For the End of Life phase the user can define the waste scenario for each material declared in the Materials phase, expanding the details of the disposal scenario.

Detailed outputs in this second step are given for each individual life cycle phases. The results for the entire life cycle from the detailed assessment are presented as shown in Figure 6 below. Depending on the depth of data input by the user, the impact of the different machine parts can be unbundled in the materials phase while in the use phase a distinction between the main operating states in all three scenarios is visible. The Data Quality Indicator gives an overview of the overall robustness of the result and improvements in data quality from the rough assessment can easily be identified.

3.5 Communication of an Energy Efficiency Index (EEI)

If the use phase is dominating an EEI will be calculated next to the CED. An EEI has the purpose to assess the energy efficiency of products and to show the efficiency performance in comparison to other products. The EEI is also very much favoured as business to business communication from the SMEs, as it provides clear and short information about energy consumption of a machine tool during the use phase. In comparison to other communication

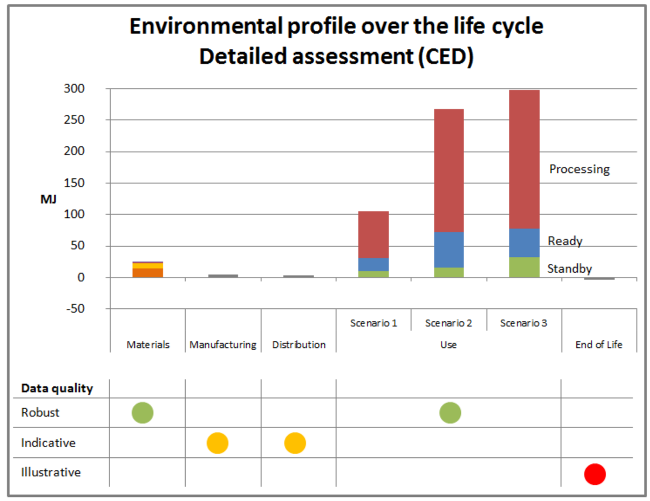

Figure 6: Result presentation of the detailed assessment containing information on the DQI after data refinement.

instruments like the product carbon footprint (PCF) the EEI methodology is easy to calculate and to understand. Moreover the value of the EEI is the same for a specific product in every country. Considering a PCF (calculated with CO2-equivalents) the value for one and the same product is different due to the different energy mixes.

The energy efficiency can be defined as the relation of the energy consumption to the production unit per hour. But in developing an EEI, the challenge is to get comparable results. This has to be secured by defining a suitable energy measurement standard. For example, NCG has proposed a standard where the machine has to run through a 15 min test cycle without producing a work piece. This leads to a method applicable for a broad range of machine tools, but on the other hand the productivity and the energy consumption during production are not included. Another approach to define specific test pieces like it is foreseen in the ISO/CD 14955-1 Part 3. This lead also to comparable results but a test piece for each product type needs to be defined.

4 OUTLOOK

In the next step a simplified operating method is generated including compiling environmental profiles and developing Product Category Rules (PCR). The challenges to get comparable results will be the definition of the use scenario and the energy measurement standard, which then can be used for calculating an EEI.

The details of the tool and the methodology will be defined further in collaboration with the later users, the SMEs.

5 ACKNOWLEDGEMENT

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6 REFERENCES

[1] Pamminger R., (2012) Deliverable 1.2: Methodology concepts for LCA support of SMEs, EU-FP7 Project, LCA2go Project, GA Nr. 265096

[2] Pamminger R., Wimmer W., Winkler R. (2009) Entwicklung von Kriterien zur Kommunikation der Energieeffizienz von Kunststoff verarbeitenden Maschinen. Berichte aus Energie und Umweltforschung 5/2010

[3] Schischke K., (2010) Energy-Using Product Group Analysis, Lot 5: Machine tools and related machinery, Executive Summary – Version 2

[4] ISO/CD 14955-1 (2011) Machine tools - Environmental evaluation of machine tools Part 1: Design methodology for energy-efficient machine tools

[5] CECIMO (2010) Concept Description for CECIMO's Regulatory Initiative (SRI) for Sector Specific Implementation of the Directive 2005/32/EC (EuP Directive), PE International GmbH

[6] Kaufeld M., (2011) Energieeffizienz – eine Kennziffer a' la NCG für den Anwender, NC transfer, Nr. 49

[7] PCR 44214 (2011) Product Category Rules CPC 44214: Machine-tools for drilling, boring or milling metal, open consultation version, 29.09.2011, EPD International System

[8] Coulon, R.; Camobreco, V.; Teulon, H.; Besnainou, J. (1997) *LCA Methodology – Data Quality and Uncertainty in LCI*. The International Journal of Life Cycle Assessment, September 1997, Volume 2, Issue 3, pp 178-182

[9] Bretz, R. (1998) SETAC LCA Workgroup: Data availability and data quality. The International Journal of Life Cycle Assessment, May 1998, Volume 3, Issue 3, pp 121-123

[10] Weidema, B.; Wesnaes, M. (1996) *Data quality management for life cycle inventories – an example of using data quality indicators*. Journal of Cleaner Production, 1996, Volume 4, Issues 3–4, Pages 167–174

[11] GHG Protocol (2011) *Product Life CycleAccounting and Reporting Standard* available at: http://www.ghgprotocol.org/standards/product-standard

[12] Goedkoop, M.; De Schryver, A.; Oele, M.; PRé Consultants (03.2006), *Introduction to LCA with SimaPro 7*

[13] IEA (2012) *Energy efficiency benchmarking report on residential laundry dryers* Version 2.1 April 2012 available at: http://mappingandbenchmarking.iea-4e.org/shared_files/220/download

Sustainability Assessment of Membrane System for Wastewater Treatment: A Review and Further Research

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Abstract

Membrane system for wastewater treatment process shows high demand industries that need attention in term of sustainability. In order to improve sustainability of membrane system, sustainability aspects such as environmental, economical and social aspect need to be considered. Traditionally, Life Cycle Assessment (LCA) is used as a tool to analyze environmental burden of product or service at every life cycle stages. This paper presents a review of researches on methodology for assessing sustainability for product development and suggests further research direction.

Keywords:

Sustainability Assessment; Membrane System; Wastewater Treatment

1 INTRODUCTION

It is generally acknowledge that sustainability results from a balance among the environment, economy and social aspects. Sustainability can be measured by a series of indicators or specific numerical parameters. Indicators for environmental, economical and social aspects can be serving as a framework to evaluate the sustainability of overall life cycle stages involved. The path to sustainability in product and process development must begin at the earliest stage so that the ideas are more flexible in term of recycling, reducing pollution and minimizing waste [1]. This paper will reviews the researches in the area of sustainability assessment and suggests further research direction.

Density of populations became bigger every year. The demand for fresh water is limited while the production of wastewater increased due to the rapidly growing industries. In addition, all type of industries consumed great amount of energy, raw materials, fossil fuel and natural resources in their processes. As for chemical industries, wastewater produced during each life cycle stages can cause harmful effects on human and aquatic life. Therefore, the treatment of wastewater is required to reduce the impact toward environment.

In order to achieve sustainable membrane system for wastewater treatment, system boundary and parameters involved need to be identified. The measurement of sustainability related to whole life cycle is needed. Hence, the methodology for assessing the sustainability can be developed to indicate the sustainability percentage or sustainability index in future. The methodology developed will consider minimizing necessities such as materials and energy during the design and development process of membrane system for wastewater treatment. Life Cycle Assessment (LCA) methodology will be used as a technique to evaluate the environmental aspects of a products or service through all these life cycle phase. It is important to assess the emission through life cycle, reduce the environmental impact, reduce cost and maintain the quality and safety of the membrane system.

2 LITERATURE REVIEW

2.1 Membrane Technology and Sustainability Issues

Lately, sustainability issues became high priority especially in wastewater treatment process. The use of membrane system showed high demand in industries. Membrane treatment process has been the method of choice in wastewater treatment industry due to it is potential to remove microorganism, synthetic organic chemicals and suspended and colloidal particles. The world's supply of fresh water is finite and threatened by pollution. Rising demands for water to supply agriculture, industry and cities are leading to competition over the allocation of limited fresh water resources [2]. By 2025, nearly one third of the world population will suffer from a water stress situation [3]. There is a need to improve the sustainability of the industrial practice by taking sustainability elements as important consideration. In practice, not all wastes can be easily prevented, treated, reused or recycled using the state-of-the-art of environment technology, and there may generally be some waste for final disposal.

That is why membrane system is playing an important role for treatment of wastewaters and is particularly drawing attention on water recycling schemes [4]. Compared to the traditional wastewater treatment, membrane treatment processes had smaller footprint, decrease sludge production, consistent effluent quality and lower sensitivity to contaminant peaks [5]. Without properly treatment, wastewater contained turbidity, Total Suspended Solid (TSS), Biochemical Oxygen Demand (BOD), ammonia (NH_3), heavy metals, oil and grease can cause water pollutions. In addition, pathogens and chemicals such as oxygen depleting organic matter and phosphorus should be filtrate before flow it back to nature.

This is in line with the Malaysia government's newly introduced National Green Technology as to provide direction and motivation for Malaysians to continuously enjoy good quality living and a healthy environment [6]. In addition, National Water Policy Malaysia narrowed the objective to ensure long term availability and sustainability of water supply including the conservation of water and to improve quality of life and environment through the effective and efficient management of water supply service [7].

In this new paradigm, it is important for developing countries such as Malaysia to set own wastewater management research and education. As a rapid growth country, water quality in Malaysia is seriously degrading due to industrial discharge and non-point source pollution, special strategies and models need to be developed [8]. One of the strategies proposed is using membrane treatment system for wastewater treatment for industries before flow it back to nature. It is not as easy to design membrane process and system that values education of the workforce, open space, and employment in the community. Optimizing sustainability elements associated with minimizing wastewater emission, while also minimizing costs, energy used, and maximizing treatment performance need to be considered.

2.2 System Boundary Analysis

In developing a methodology to measure sustainable membrane system, the boundary of analysis is needed to be considered. The system inputs and outputs such as energy, materials, waste and emission that cross the system boundary are determined to quantify all relevant indicators [9]. Figure 1 shows the inputs and outputs crossing the system boundary.

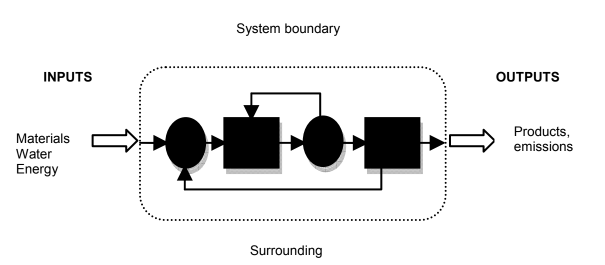

Figure 1: Inputs and outputs crossing the system boundary.

The selection of boundary analysis is depends on the objective, goal and scope of the analysis. The selected boundary either using *cradle to gate*, *cradle to grave*, *gate to grave* or *gate to gate* approaches. The *cradle to gate* boundary covers from raw material extraction, material processing, manufacturing and packaging. While for *cradle to grave* approach, the boundary is more widely compared to *cradle to gate* approach by extending until usage and end of life stages [10]. In *gate to grave* approach, it is includes the processes from usage and end of life phases. While for *gate to gate* approach, it is includes the processes from the single production phase only [11]. By considering the different life cycle boundary, the analysis of LCA result may be varies [12].

2.3 Life Cycle Assessment (LCA)

LCA methodology is a systematic way to evaluate the environmental impact of products or processes by following a *cradle-to-grave* approach. LCA is the process of evaluating the effects that a product has on the environment over the entire period of it is life cycle [13]. The environmental burden includes all types of impacts upon the environment including depletion of natural resources, energy consumption, and emission to land, water, and air. Sustainability of wastewater treatment system can be accessed through different assessment tools such as energy analysis, economic analysis and LCA [14].

LCA involves tracing out the major stages and processes involved over life cycle of a product, process and system covering raw materials extraction, manufacturing, product use, recycling and final disposal, identifying and quantifying relevant environmental impact at each stage [15]. LCA aims to facilitate membrane system for wastewater treatment view in product and process evaluation [16]. The implementation of LCA is standardized according to ISO 14040:2006, Environmental Management Life Cycle Assessment Principle and Framework [17]. The development of LCA consist four major stages as shown in Table 1.

2.4 Current Sustainability Evaluation Method

There are several tools for measuring sustainability levels such as LCA, Ten Golden Rule, Economy Indicator, Green Pro, Life Cycle Index and others as summarized in Table 2.

2.5 Current Framework Develop by Previous Researcher

The main objective of measuring membrane system sustainability is to indicate the performance of the design toward sustainability. Weak areas from whole life cycle can be identified and do the modification for existing life cycle. At a basic level the model will be required to quantify environmental impacts arising from changes in values of sustainability indexes for membrane system. The amounts to a sensitivity analysis on the LCA inventory data and will lead to decision, on whether new output condition comply with regulatory mechanism and whether a chosen waste minimization technique is appropriate [19].

Major challenge in the formulation of the model structure is to assemble elements or sub-models appropriate to cognate areas of the LCA study and which are capable of being interfaced with knowledge based on an expert software tool. Table 3 summarized the framework developed by previous researchers with tools and methodology used to assess sustainability in different case studies.

Stages	Requirements
Goal and scope definition	Purpose of this study is to estimate the environmental aspects and potential impacts associates to membrane system as a whole view of the technology less aggressive and harmful for the environment. A system boundary of this study begins from extraction materials, membrane fabrication, transportation, membrane usage and end of life.
Inventory analysis	Inventory analysis performing mass and energy balances to quantify all the material and energy inputs, wastes and emissions from the system, energy inputs and raw material inputs for hollow fibers membrane module is identified. Parameters involved will be obtained from primary and secondary data.
Impact assessment	From the whole process membrane system, environmental burdens categories will be quantified. The damages cause on various environmental impacts will be measured. To date, there are available numerous approaches towards the life cycle Impact assessment (LCIA) which can be used including with the help of software programs that enable users to develop, store, analysed and exchange vast amounts of data related to products, services, processes, and their respective impacts.
Interpretation	Environmental potential impacts associated with membrane system for wastewater treatment will be reduced by looking at the result from Impact Assessment.

Table 1: Four major stages consist in development of LCA.

Tools	Environmental	Economical	Societal	Remarks
Eco Indicator 95	√		√	A target level is set for a particular environmental effect. When the gap between the environmental impact and the target level are greater, a height weight will be given to the seriousness of the impact. Advantages; Generalized tools which can be used to evaluate any type of product, easy to be applied by a designer since it is easy to understand in environmental term. Limitation; Does not considering the economic factor such as cost, resource depletion and technology
Eco Indicator 99	√		√	Modification of Eco Indicator 95 which based on damage oriented method for LCA. It was developed based on the three main categories including human health, ecosystem and mineral resources. Advantages; Similarly to Eco Indicator 95, generalized tools which can be used to evaluate any type of product, accepted as international standard and well documented. Limitation; Does not include analysis of cost and technology.
Life Cycle Index (LInX)	√	√	√	An indexing system for evaluating process design. The environmental, economical and social aspects were considered. Advantages; Generalized tool that can be used for screening and evaluating any type of product and process design. Limitation; Boundary analysis is limited to the *cradle to gate* which does not cover the whole life cycle stages; usage and end of life.
Green Pro	√	√		Systematic methodology for process design that considers assessment and minimization of environmental impact. The analysis includes environmental, technology and economical factors at the design stage to determine a cost-effective solution. Advantages; Main elements of this tool is guidance for decision making is by applying Multi Criteria Decision Making. Limitation; Boundary analysis is limited to the *cradle to gate* which does not cover the whole life cycle stages; usage and end of life. In addition, this tool does not considering social aspects.
Green Pro 1	√	√		This tool is the extension and improvement of Green Pro mentioned before. The modification concerns on two areas which are broadening the boundary analysis to the *cradle to grave* and applying Fuzzy Multi Criteria Decision Making for better decision making analysis. Limitation; This tool does not considering social aspects.
Ten Golden Rules	√			Qualitative analysis method in providing common foundation which can be used as a basis and guidelines for the development of specific product design. The rules can be customized depending on the specific requirement of a product. Limitation; user must have background knowledge to be able to make sound use of these 10 rules. On the other hand, the analysis results may differ, depending on the user knowledge and experience. In addition, the tool only considering the environmental aspect.

Table 2: Summary of evaluation tools for measuring sustainability [18].

3 RESEARCH GAP

There are a lot of studies on the sustainable measurement indicators, but majority of them only focus on the usage stage and it is application. The researches do not cover the whole life cycle assessment; from cradle to grave that covered materials, fabrication process, transportation, usage and end of life. In addition, most of them only considering environmental aspect instead of three pillars of sustainability; environmental, economical and societal. They do not concerning the cost involved and community participant. Based

Researchers	Framework developed
[1]	This study developed sustainability indicator by using integrated fuzzy logic approach to assess product and process. This approach is able to evaluate both qualitative and quantitative data and capable of handling uncertainty in sustainability evaluation. The sustainability evaluated in three dimensional approaches; environmental, economical and societal.
[20]	This study developed a methodology to improve the design of product by selecting suitable material give less impact to environment. This study using LCA approach concept for material selection in product development. However, these study neglecting the transportation stages, and only focusing on material selection stages.
[21]	This study developed new index based method to assess the environmental impact of a water distribution system. The optimization approach combines the non-dominated sorting genetic algorithm with economic input-output (EIO-LCA) to minimize capital cost, energy used and environmental impact. This study is improvement of [20] and considering economical aspects.
[22]	This study developed methodology for evaluating of the environmental impact of water distribution systems developed according to a set of methodological criteria to assess the environmental effect of water network. Environmental measures are incorporated into the index-based method to account for nonrenewable resource consumption and emissions. This study does not considering economical and societal aspects in developing the methodology.
[23]	This study designed a system to determine end of life option in automotive engineering. The system developed help to evaluate the disassembly and disassemblability process of end of life. This study limited to automotive engineering and focusing at end of life stages.
[9]	This research presents the application of a new framework for sustainability metrics to general chemical process. Sustainability evaluated using a set of 3D indicators: economic, environmental and societal. This study focusing on general chemical process only.
[24]	This study developed a methodology of Design for End of Life Value in automotive engineering case studies. The methodology developed was conceptual approach for integrating recyclability concern at early product design phase. In developing the methodology, this study considering two aspects that is Recycling Function Deployment (RFD) and value analysis.
[19]	This research described general methodology for LCA of manufacturing process by taking into account the flexibility and expert system methodology. The objective is to reduce waste and associated sustainability characteristic in relation to environmental impact assessment and process improvement.

Table 3: Methodology developed by previous researcher.

on literature reviews, there are few studies concerns about whole cycle but the process is only limited to general chemical process. State to date, a few studies have investigated the environmental effect of direct and indirect exposure and no clear guidelines exist to quantify these effects [25].

According to the literature, every sustainability evaluation tools have their own advantages and limitation. The methodology will be develop should follow the ISO 14040 requirement in order to be accepted internationally. In addition, the methodology will be developed includes three pillar of sustainability elements and considering the whole life cycle analysis using *cradle to grave* approach.

4 RESEARCH DIRECTION

In membrane fabrication for wastewater treatment, varieties of process take place; producing dope solution, phase inversion process, rinsing and potting process. Therefore, it is necessary to analyze the whole life cycle of membrane system for wastewater treatment to assess the sustainability. Since the fabrication of membrane system for wastewater treatment involves varieties of polymers, solvents, additives, and chemicals for post treatment, so LCA is needed to access the environmental burdens. The aims of overall environmental effort in chemical area is to reduce environmental and health hazardous effect of chemical substances and to maintain an acceptable standard for the environment [26]. In addition, the methodology proposed to consider all sustainability elements; environmental, economical and social. The methodology proposed will be developed by using expert system for decision making process.

The purpose of the new methodology will be developed is to assess the sustainability of the membrane system for wastewater treatment. Hence, the membrane system sustainability can be improved in order to balance the sustainability elements for environmental, economical and social aspects at each level of stage. As for environmental aspect, membrane fabrication should not produce high impact towards global warming, ecotoxicity and euthrophication. While for economic aspect, the design should reduce the cost by optimizing the use of materials, energy and resources. Similarly, the aspect of human health must be considered by eliminating hazardous chemicals and improve the ergonomics factor.

Sustainability elements	Life Cycle Stages	Parameters
Environmental	Material	-Materials, chemicals, water
	Manufacturing	-Energy (electricity), chemicals waste, rejected membranes
	Transportation	-Fuel
	Usage	-Chemical usage for backwashing, nutrients, TSS, NH_3, phosphorus and pathogen removal -Potential negative environmental impact Euthrophication Global warming Spreading toxic to water and soil Acidification
	End of Life	-Chemical waste and solid waste
Economical	Material	-Material cost and water cost
	Manufacturing	-Energy cost, chemicals cost, production cost, operational and management cost
	Transportation	-Fuel cost
	Usage	-Energy cost, treatment cost, chemicals cost
	End of Life	-Product recovery cost, hazardous material treatment cost
Societal	Material	-Hazardous material
	Manufacturing	-Ergonomics, safety, hazardous and risk
	Transportation	-Emission (CO_2, NO_x)
	Usage	-Water and wastewater quality, acceptance, availability, Awareness/participation, competence/Information requirements, cultural acceptance
	End of Life	-Chemical hazard

Table 4: Sub-parameter of sustainability elements

5 CONCLUSION

This paper is aimed to propose the research direction for assessing the sustainability of membrane system as a whole. Only few studies have explored on measurement of sustainability while literature on membrane performance and purification is growing rapidly. Through LCA, parameters for this study will be identified. Parameters involved in sustainability elements; environmental, economical and social at each stage is important to indicate the sustainability of embrane system for wastewater treatment. Table 4 shows the sub parameter to be measured.

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7 REFERENCES

[1] Hemdi A. R., Saman M. Z. M. & Shariff S. (2011). Sustainability evaluation using fuzzy inference methods. International Journal of Sustainable Energy.2011,1-17.

[2] Anderson, J. (2003). The environmental benefits of water recycling and reuse. Water Science and Technology, 3(4), 1-10.

[3] Postel, S. L. & Wolf, A. T. (2001). Dehydrating conflict. Foreign Policy, Sept/Oct 2001, pp. 60-67.

[4] Parameshwaran, K., Fane, A.G., Cho, B.D., Kim, K.J. (2001) Analysis of Microfiltration Performance with Constant Flux Processing of Secondary Effluent. Water Research. 35, 4349-4358.

[5] Melin, T., Jefferson, B., Bixio, D., Thoeye, C., De Wilde, W., De Koning, J., et al. (2006). Membrane bioreactor technology for wastewater treatment and reuse. Desalination, 187(1–3), 271-282.

[6] KeTTHA (2009) National Green Technology Policy, Malaysia: Ministry of Energy, Green Technology and Water.

[7] Ujang Z. (2008). Water: Industry update, challenges and R&D direction. Institute of Chemical Engineers (IChemE), Sime Darby Convention Centre 12May 2008.

[8] Ujang, Z. and Buckley, C. (2002). Water and wastewater in developing countries: present reality and strategy for the future. Water Science and Technology, 46(9), 1-9.

[9] Martins, A. A., Mata, T. M., Costa, C. A. V., & Sikdar, S. K. (2006). Framework for Sustainability Metrics. Industrial & Engineering Chemistry Research, 46(10), 2962-2973.

[10] Sadiq,R. and Khan, F. I. (2006). An integrated approach for risk-based life cycle assessment and multi criteria decision making – Selection, Design and Evaluation of Cleaner and Greener Processes.Business Process Management Journal, Vol. 12, No. 6, pp. 770-792.

[11] PE International. (2011). GaBi paper clip tutorial, handbook for Life Cycle Assessment (LCA) using the GaBi Sotware.

[12] Gehin, A., Zwolinski, D. & Brissaud, D. (2008) A Tool to Implement Sustainable End-of-life Strategies in the Product Development Phase, Journal of Cleaner Production, 16: 566-576.

[13] Gallego, A., Hospido, A., Moreira, M. T., & Feijoo, G. (2008). Environmental performance of wastewater treatment plants for small populations. Resources, Conservation and Recycling, 52(6), 931-940.

[14] Muga, H. E., & Mihelcic, J. R. (2008). Sustainability of wastewater treatment technologies. Journal of Environmental Management, 88(3), 437-447.

[15] Joshi, S. (1999). Product Environmental Life-Cycle Assessment Using Input-Output Techniques. Journal of Industrial Ecology, 3(2-3), 95-120.

[16] Mahmood, S., Mat Saman, M. Z. & Yusof, N. M. (2013). Life Cycle Assessment of Membrane System for Wastewater Treatment: A Review and Further Research. Applied Mechanics and Materials, 315, 186-191.

[17] ISO 14040 (2006), Environmental Management-Life Cycle Assessment-Principle and Framework. International Standardization Organization.

[18] Hemdi A. R., Mat Saman M. Z. & Shariff S. (2009). Proposed decision making framework for sustainable product design evaluation. In: 10th Asia Pacific Industrial Engineering & Management System Conference (APIEMS 2009), 2009, Kitakyushu, Japan.

[19] Culaba A. B. & Purvis M.R.I. (1999). A methodology for the life cycle and sustainability analysis of manufacturing processes. Journal of Cleaner Production, 7(435-445).

[20] Yola M. (2011). A methodology of Life Cycle Assessment for material selection in product development. Unpublished master's thesis. Universiti Teknologi Malaysia.

[21] Herstein, L., & Filion, Y. (2010). Using Life-Cycle Assessment to Evaluate the Environmental Impacts of Water Network Design and Optimization, Providence, Rhode Island.

[22] Herstein, L. M., Filion, Y. R., & Hall, K. R. (2009). Evaluating Environmental Impact in Water Distribution System Design. Journal of Infrastructure Systems, 15(3), 241-250.

[23] Afrinaldi F.,Mat Saman M. Z., & Shaharoun A. M. (2010). EDAS: Software for End-of-Life Disassembly Analysis. International Journal of Sustainable Design, 1(13), 257-277.

[24] Mat Saman M. Z. (2005). Methodology of design for end of life value in automotive engineering. Doctor of Philosophy's thesis, Coventry University in collaboration with Jaguar Cars Limited & European Metal Recycling Limited.

[25] Colvin V. L. (2003). The potential environmental impact of engineered nanomaterial. Nature Publishing Group. 21(10),1166-1170.

[26] Olsen, S. I., Christensen, F. M., Hauschild, M., Pedersen, F., Larsen, H. F., & Tørsløv, J. (2001). Life cycle impact assessment and risk assessment of chemicals — a methodological comparison. Environmental Impact Assessment Review, 21(4), 385-404.

Combined Energy, Material and Building Simulation for Green Factory Planning

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Abstract

The paper describes a novel approach, Total Factory Simulation, for integration of energy and material flows in manufacturing as well as building simulation combined in a csolution to support planning and optimization of green factories. The first ready module of the approach based on PlantSimulation which explains the integration of energy flows based on programming and thermodynamic estimations within the application is in focus of this paper. A use case of the module in an Italian SME is presented for sequencing purposes taking into account environmental performances.

Keywords:

Energy efficiency; energy flow; material flow simulation; Plant Simulation

1 INTRODUCTION

1.1 General Preface

Nowadays the international economic scenario is characterized by several trends like the increase of the population, the higher competitive pressure, faster progress in research and innovation, climate change challenge or the rising attention of customers towards green products; these emerging trends have deeply changed the industrial perspective, enabling the existence of sustainability as a major topic and driver in research [1].

Manufacturing has an important role in determining sustainable solutions, because production processes determine consistent environmental consequences mainly due to material and energy consumption. This is testified by the fact that the industrial sector represents more than 33% of the global primary energy consumption and its energy related CO2 emissions [2]. Besides, most of the industrial processes consume at least 50% more energy than the theoretical minimum [3]. This data underlines the possibility to reduce energy use and the associated emissions by exploiting more efficient technologies and equipment.

In order to support the implementation and the deployment of energy efficiency policies, information systems have been developed to model economic and environmental aspects of the production system during the product lifecycle. Furthermore it is required from these information systems to be able to manage growing and more complex systems of materials and processes. These models have shown the ability to represent the reality and to present it in the best way under different perspectives: cost, time, availability of material and resource, environmental performances etc [4].

1.2 State of Research

Sustainability-oriented simulation and optimization advanced significantly in the last years being recognized as an appropriate tool for dealing with those challenges. Recently the focus of analysis has been enlarged from measuring not only productivity related performances but also sustainability driven criteria like energy consumption, emissions or environmental impact [5].

Discrete-event simulation (DES) has been identified as a viable source for conducting research in the way of combining material flow analysis with environmental and economic aspects. Several developments in this field can be highlighted starting basically from the same approach namely integrating energy flows into existing DES tools. Current approaches use common known commercial tools like Anylogic or PlantSimulation and enhance the material flow simulation with energy flows in different ways.

In this regard, for PlantSimulation most recent contributions come from Kulus, Wolff, Ungerland [6], Putz et al. [7], and Schulz and Jungnickel [8]. Kulus proposed a model implemented in the VDA Automotive model kit, which allows to model and manage system components at operational states level, calculating energy consumption for all levels from measured power data. On the other hand Putz provided a process-related enabling calculation of energy consumption according to the process step power profiles. Jungnickel proposes a model which is able to integrate both of these two, providing the calculation of energy consumption for each component of the model, considering both power levels of operational states and process profiles for the in-service mode.

Due to the fact that energy efficiency improvements are interacting and can be applied at machine level, at production system level or at technical building services makes the integration of energy and material flow in an holistic model necessary. Taking into consideration also media supporting the production, both the resource consumption directly related to the production and the one responsible for maintaining environment conditions needs to be represented in a Total Factory Simulation [9]. A seminal contribution in that direction is provided by Thiede, who developed an energy flow-oriented production system model which represents also the behavior of technical building services and their interdependencies with the production assets, using the Anylogic environment [10].

Mainly three directions and gaps can be found by investigating research contributions and commercial developments: although DES has been identified as a useful tool to approach energy efficiency in manufacturing, commercial tools still lack a standard integrating kit which allows users the conduction of environmental-oriented simulations without major programming work. In addition, propositions to merge DES with other techniques like Life Cycle Assessment (LCA) or Energy Value Stream Mapping (EVSM) exist, but have not reached maturity yet. The trend towards holistic simulations approaches taking into account production assets and technical building services is undeniable.

Today, factory planning is oriented for optimizing production facilities along the traditional competitive priorities cost, quality, lead time, and flexibility [11]. However, future developments require integrating the energy and resource perspective in this complex process to create a green factory planning, and to design tools which are enabled to serve different stakeholders and evaluate factories also from an energy point of view [12].

2 TOTAL FACOTRY SIMULATION

2.1 Motivation

To facilitate this vision of integrating green perspectives in the factory planning process and to make information available for experts from diverse domains, e.g. production planner, civil engineer and architect, the authors develop a multi-hierarchical simulation framework within the European research project 'EMC2-Factory' (www.emc2-factory.eu). The authors are working on a 'Total Factory Simulation' which interdisciplinary combines different modules of simulation in scalable level of detail. The aim is to develop an industrial solution which supports the different stakeholders in the factory planning process. This paper aims at describing briefly the main approach and focuses on the PlantSimulation module.

2.2 Integrated Approach

The Total Factory Simulation is compromised by five interconnected modules. These modules are applied along the factory planning cycle – rough planning, detailed planning, assessment – and provide information in different densities to the planners based on a common shared indicator framework. The overall approach is depicted in figure 1.

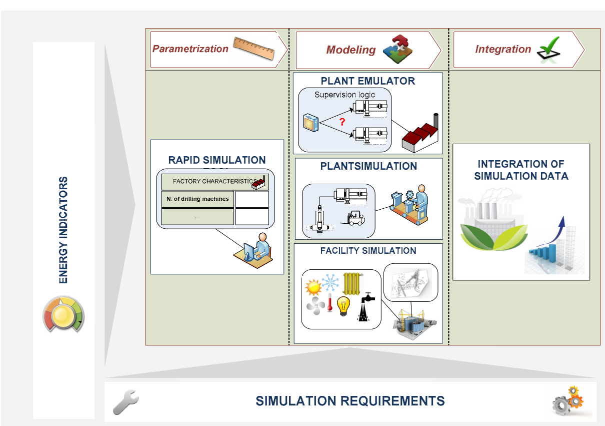

Figure 1: Total Factory Simulation.

The rapid simulation tool is a solely parametric-based java application which enables the user to perform quick estimations on the performance of the production system. The user can choose among certain entities of the production systems and attribute them specific values for e.g. energy consumption or production rate. The result is a fast calculation and estimation of energy demand in the production without any modeling expertise required. It is mainly meant to be applied in the rough estimation of factory planning.

The middle block of the modeling site is the heart of the Total Factory Simulation and combines three standalone applications together. Its main purpose is to provide very detailed information on the energetic but also productive behavior of the factory, taking into account not only the machines and other production assets, but also the building shell. PlantSimulation as a DES simulator builds the core part with the integration of energy calculation besides the material flow. Plant Emulator is a tool to emulate plant supervision algorithms for inter-machine connections, also algorithms which are tailored to energetic perspectives. Plant Emulator and Plant Simulation are dynamically connected, offering the user a great potential for production scheduling, planning and batching tasks. The third tool is a customized building and periphery system simulation based on the engine EnergyPlus. Results from the DES simulator can be read in the EnergyPlus simulation in order to create a link between the production system and building shell. The integration tool represents simulation results according to the user needs, e.g. as KPIs or as a graphical layer evaluation on the factory layout. This integration of simulation data tool supports the visualization of performance indicators in the green factory planning process [12].

Total Factory Simulation is able to provide dense information to different user groups while keeping the core database together and maintaining the interconnectivity of the five different applications. Thus, it can support green factory planning in an integrated manner. All applications are currently in design phase. This paper focuses on the developments in PlantSimulation which has by far the most mature status. First use cases in real factory environments to test the tool have been conducted. The following section describes the PlantSimulation module and its application in an Italian SME.

3 PLANTSIMULATION MODULE

3.1 Modeling Production Assets

Technical building services are divided into peripherical systems, the ones directly related to production and central technical building services related to the building shell and work environment. Production assets are the elements directly connected to the production processes. These assets, e.g. machines, pass through different states in their production activity. Each energetic state is characterized by different power requirements for the mix of energy carriers and could be constant or variable over time, according to the type of process and the product to be worked.

The behaviour of entities in PlantSimulation follows different productive states: off, starvation, set-up, failure, blocking and working. The productive states change continuously according to discrete events which affect the entities.

The productive states do not correspond one-to-one to the energetic states of entities. According to Cannata [14], the blocking production state can correspond to an off, stand-by or idle state from the energy point of view. In the same way a failure state from the production point of view can require the machine in the off in the stand-by or in the idle energy state. The same considerations can be drawn for the set-up state which can happen with the equipment in the off, stand-by, idle or set-up energy state.

The production assets modelled refer to four different types of kind: machine, conveyor, robot and buffer. For each machine, conveyor or robot a power profile needs to be associated. From this power profile the calculation of the energy consumption is done as follows: for each entity of the model the simulation provides the duration of the state intervals. Each state is then associated to a particular function, integral of the approximated power load profile. The time duration inserted in the integral of the power load profile allows the calculation of the energy consumption for the specific state.

The energy calculation for each specific production asset is done according to the following equation:

$$E = \int P \, dt \qquad (1)$$

where E [kWh] is the energy consumption, P [kW] the power load function and dt the time interval for a particular state. For each entity the energy consumption calculation is performed considering the electrical energy equivalent consumption for each of the different carrier feeding the equipment. For example if the machine receives electricity, compressed air and heat as input, the energy consumption calculation will be performed calculating the sum of the electrical energy consumption and the equivalent electrical energy consumption coming from compressed air and heat.

During the machine use phase, the electrical consumption represents the most significant impact factor from the environmental point of view. Furthermore, according to Cannata and Taisch [13], the electrical energy consumption is an indicator that can be measured and controlled in industry, it is simple to calculate and it represents a significant percentage of the total energy consumption in industry. In addition the electrical equivalent energy consumption allows summing the different contributions to the energy consumptions coming from different sources.

The model, for what concerns the production asset, does not differentiate the sources by which the power requirements satisfaction comes from. Considering the machine for example, it can require power in form of electrical power for some components and power coming from the compressed air for others. In order to calculate the energy consumption associated to the machine both the contribution are considered, even if in reality the power associated to the production of a specific amount of compressed air is consumed inside the periphery system and not inside the machine. Bringing also the power associated to the periphery system inside the machine allows the identification of the energy consumption deriving from the activity of that specific machine.

3.2 Modeling Periphery Systems

Periphery systems are not modelled as entities in PlantSimulation but in terms of requirements from the production assets, expressed by simple data for the consumption of a specific carrier. For example, the energy consumed by the compressed air system to produce the compressed air required for pneumatic components of the manufacturing system, is not equal to the energy consumption coming from the power requirement of the specific pneumatic component. This can be explained by the losses of the compressed air system and the specific efficiency of the system.

For what concerns the periphery systems, the energy consumption is not only deriving from the power required to feed the production assets. Considering a compressed air system, the energy consumption associated is not only represented by the energy due to the production of a specific amount of compressed air but also by the energy required to bring the system at operating level -a regime- and by the energy associated to the losses. All the energy computations are done in terms of electrical equivalent energy consumption. The figure below graphically shows this concept.

The two perspectives in the calculation of the energy consumption show an overlapping due to the fact that energy consumption associated to the on-site production of a specific amount of energy carrier is present in both perspectives. For the final computation this energy contribution is considered only once.

In the proposed approach, the behaviour of the production assets, characterised by the flow of the parts, is extended with the energy consumption consumed by the compressed air system in order to feed the production assets. This specific consumption represents the second component in the compressed air system energy consumption. For the other two components of this energy consumption, the calculations are done outside the simulation software and summed up to the results coming from the simulation running. Figure 4 underlines how the compressed air is activated when the equipment connected is in working or in set-up state. These are the states where compressed air is required usually, however it is dependent on the specific case. The connection happens in the following way for example: when the machine which is fed with compressed air is in working state, it calls the compressed air requirements, which are associated to a specific power required to generate the compressed air according to the assumption done above. From the amount of compressed air for the production asset the power required by the compressed air system can be reached to feed the production entities.

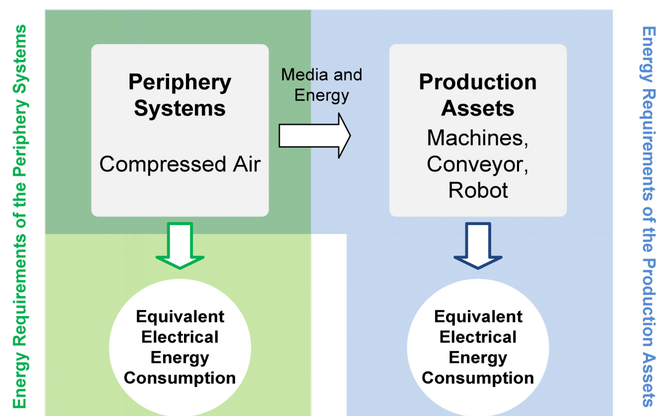

Figure 2: Energetic requirements of production assets and periphery systems.

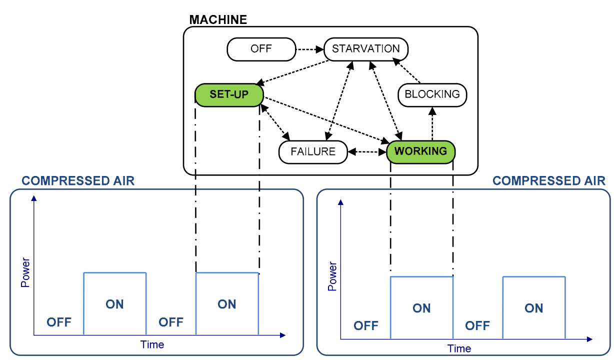

Figure 3: Power requirements of periphery systems in PlantSimulation.

The methodology adopted in this study to bring the power profiles inside the simulation model is mainly based on the Energy Blocks Methodology [15] even if the approach has been enriched with the consideration of the power peaks inside the power profiles. Furthermore the approach is used not only for the electrical energy required by the machine but also to the energy coming for the compressed air and assessed in terms of electrical energy required to produce a certain amount of compressed air.

4 USE CASE

4.1 Case Introduction

A first use case has been applied to test the Total Factory Simulation, especially the developed PlantSimulation Module. The case study which was conducted can be classified as an explanatory case study in which the energy performances of a manufacturing system are investigated. The case development has been conducted in collaboration with the Institute of Industrial Technologies and Automation in Milan (ITIA-CNR).

The production system of an Italian SME in the chemicals sector has been the object of investigation of the use case. The production system is represented by an automated line for filling sacks with powders. The automated manufacturing system actually is composed by two parallel lines, a line for the processing of the sacks and a line for the processing of pallets.

The line for the sacks is based on the following main components: a store of the sacks, a machine for the filling with powders, a conveyor, a machine for the flattening of the full sacks and another conveyor. The source outputs the sacks according to the three types of products the line produces: sacks of 5, 10 and 12 kg.

These sacks are then received by the filler machine, composed of seven different processes which are:

- Dosage: the sacks are filled with the powders by setting the dosage time according to the specific type of sack and powder used;
- Vibration: the powders are balanced insight the sack;
- Wearing out: the borders of the sack are prepared for the closure;
- Cutting and Incision: the line along which the folding will take place is marked;
- Folding: the upper edge of the sack is folded and pressed;
- Sticking: the edges are glued;
- Weight control: the weight of the sack is controlled;

Inside the first machine, the forward movements of the sacks are determined by the time intervals of the first operation. A conveyor then brings the sacks prepared to a machine which has the aim of flattening the sacks in order to make them more stable for being put on the pallet. After this phase the sacks are converged on the robot which takes and puts them on the pallet.

The parallel line to this one is represented by the pallet line for the preparation and the transport of the pallets where the sacks are then deposited. In detail, the line for the preparation of the pallet is composed by a store of the pallets where they are taken; by means of a conveyor they are transported to a station uncharged for the covering of the pallet with a nylon layer in order to prevent the possible damage of the sacks. Then another conveyor brings the pallet to another station where the nylon coating is stapled. Finally, a conveyor brings the pallet covered with nylon to the loading robot which receives the pallet and loads 10 sacks on it. The pallet source releases a new pallet only when a pallet full with 10 sacks exits the robot. After the loading robot, a final unmotorized conveyor brings the pallet to storage. The following figure provides the conceptual representation of the manufacturing system modelled.

The focus of the use case was on machine related energy data as well as data from the compressed air periphery system. The relevant energetic and production data from the production assets were made available by the company without any additional metering. On the other hand, data on the compressed air system were not available. Due to time and monetary constraints, it was decided to made reasonable estimations and calculations. These are briefly explained in the next section.

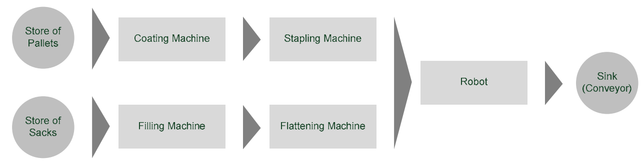

Figure 4: Schematic process system.

4.2 Data for Compressed Air

The compressed air system is composed by a compressor, two tanks and a network of pipes. The following table summarizes the data related to these components of the compressed air system.

Elements of Compressed Air System	*Number*	*Nominal Power*	*Type*
Compressor	1	30	rotary centrifugal
	Number	*Diameter [mm]*	*Height [mm]*
Tank	2	1000	2500
		Diameter [mm]	*Length [m]*
Pipes		25	500

Table 1: Data for compressed air system.

Considering an adiabatic transformation inside the compressor, it is possible to calculate the mechanical work associated to one litre of air that the compressor takes from the outside area and compresses into the pneumatic system:

$$Mm = \rho(air) * mass = \frac{1{,}17Kg}{m^3} * 1\, l \frac{m^3}{10^3 dm^3} * \frac{dm^3}{l} = 1{,}17\ 10^{-3}\ Kg$$

$$W = C_v * T * \left(1 - \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right) * Mm =$$

$$717{,}5\ \frac{J}{Kg\,K} * 298\ K * \left(1 - 8^{\frac{1{,}4-1}{1{,}4}}\right) * 1{,}17\ 10^{-3}\ Kg = 0{,}203\ kJ \quad (2)$$

the energy considered in the model is always assessed in terms of equivalent electrical energy consumption. Consequently in order to arrive to the value of the electrical energy consumed for producing the calculated mechanical work the efficiency of the compressor needs to be considered. The own efficiency of this specific compressor is about 0,75. Furthermore one of the components of the energy consumption related to the compressed air system, is represented by the leakages which are represented by 1% of the whole compressed air flow. This value, for simplicity, has been considered in the efficiency of the compressor in order to have this component of the compressed air system energy consumption already embodied in the calculations.

The total efficiency considered is then 0,74, including both the own efficiency of the compressor and the leakages in the whole pneumatic system. The associated electrical energy consumption for one litre of compressed air is:

$$E = \frac{W}{\eta} = \frac{0{,}203}{0{,}74} = 0{,}274\ kJ/l \quad (3)$$

This value represents the electrical energy consumed by the compressor to produce the calculated value of mechanical work *W*. Considering the maximum working point of the compressor that is characterized by a power value of 30 kW and by the air volume flow equal to 85l/s, it can be calculated the maximum work that the compressor could provide in 1 s. This value is:

$$W_{max} = E * l = 0{,}274 * 85 = 23{,}3\ kJ \quad (4)$$

It represents the maximum work the compressor would be able to do in one second, and relating it to the nominal power of the compressor, it is possible calculating the load at which the compressor works.

$$load = \frac{Pabsorbed}{Pnominal} = \frac{23{,}3\ kW}{30\ kW} = 0{,}788 \quad (5)$$

What is needed now are the requirements of compressed air of the machines in their working states. The liters of air required by each machine depend on the size and the number of cylinders located on each machine and by the number of cycles of each cylinder. The cylinders are all double-effect type which allows more effective control actions. Inside the cylinders the pressure and the temperature can be considered constant during the movement of the piston. Using adiabatic transformation by

$$V_1 = V_2 * \left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}} \quad (6)$$

by assuming the air pressure inside the cylinders equal to 6 bar, it is calculated the correspondent air volume at 1 bar pressure, so that compressed by the compressor, is needed to fill the cylinders. Multiplying these results for the value of the energy consumption associated to the compressor for providing one liter of air, it is possible obtaining the energy consumption in the compressor for feeding each single machine. In performing this attribution it has been assumed that the requested power by the compression inside the compressor, excluding leakages, is just equal to the power that the machine uses.

5 SIMULATION RESULTS

The objective of the simulation in the test case was to allow the assessment of different possible configurations and manufacturing policies taking into account the environmental perspective. Three different types of tests have been conducted. However this paper will focus on describing the first one which deals with assessing the different performances that different policies on the sequencing of the parts to be worked imply. Given a fixed number of parts to be worked, three different manufacturing sequencing strategies have been assessed considering the trade-off among productivity and energy performances. Different sequencing strategies – random, big batch, small batch – have been applied to one production cycle which consists of 90 parts or 9 pallets.

Strategy	*Part Type 1*	*Part Type 2*	*Part Type 3*
Random	17%	33%	50%
Big batches	15	30	45
Small batches	5	10	15

Table 2: Logic of parts releasing.

While the manufacturing performances like throughput, flow rate and makespan remain constant, the energy ones have been shown to change. The reason why even changing the sequence in which the parts are worked does not affect the productive performances can be traced to the fact that the set-up time, which is the main important affecting parameter when changing the order in which the product are worked, is always constant and it does not depend on the specific type of product.

For what concern the energy performances, it can be noticed how big batches represents the best solution in terms of total energy consumption. The following graph compares the three different scenarios from the point of view of the energy consumption.

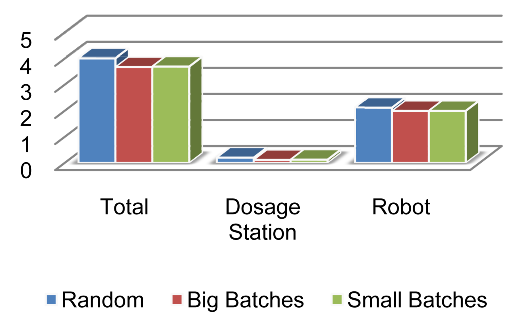

Figure 5: Energy consumption by total, dosage station and robot along sequencing strategies.

No significant changes have been recorded from the point of view of compressed air consumption and the energy associated to the production of compressed air.

Instead it is more interesting to look at the indicators eem (valuable energy by total energy), eec (energy consumption per entity by total energy consumption) and sec (state energy consumption by total equipment energy consumption). The eem, the indicator for the assessment of the energy efficiency of management, underlines if the resources are used efficiently. In this case it assesses if the changes in the sequencing of the parts affects the way in which the dosage station and the robot are used. Here again the second scenario, the one characterized by big batches represents the best solution.

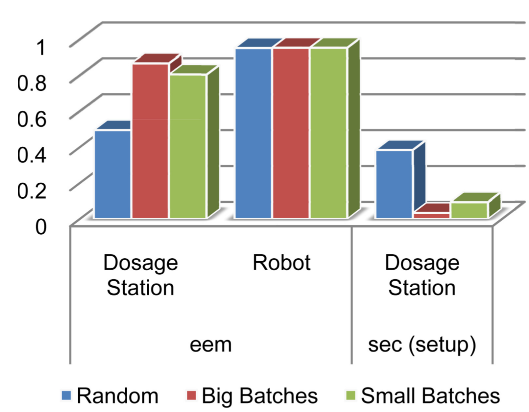

Figure 6: EEM and SEC results

Looking instead at the eec, assessing the impact of the single asset over the total energy consumption, it has been proved that both the batches solutions represent improvements in respect to the random one, in particular for what concerns the dosage station. The robot consumes significant more energy than the dosage station, as expected.

The sec indicator, evaluating the impact of energy consumption of a particular state over the total one, has been assessed only for the set-up state of the dosage station, because in this first test it represents the most significant state to assess. It testifies what can be easily imaged, that the less energetic impact of the set-up state is given by the big batches solution. The following figure reports the mentioned indicators.

6 SUMMARY AND OUTLOOK

A new approach for an integrated factory simulation framework has been introduced by this paper. The Total Factory Simulation, which is currently still under development, aims at combining material, energy and building simulation to provide interconnected planning mechanisms for detailed analysis and optimization. The PlantSimulation module and the model techniques have been introduced, showing a new approach by the integration of periphery system demands as thermodynamic assumptions. The case study has shown the validity of the approach.

Future developments will be concentrated on the other modules and their connection as well focus on the development of the evaluation tool for further integration into green factory planning purposes [12].

7 APPENDIX: THERMODYNAMIC ASSUMPTIONS FOR COMPRESSED AIR SYSTEM IN USE CASE

Thermodynamic parameter for periphery system calculations		
Entered Air	5,1 [m3/min]	85 [l/s]
Internal Pressure *p2*	6 [bar] (cylinder)	
	8 [bar] (tank and pipes)	
External Pressure *p1*	1 [bar]	
External Temperature *T*	25 [°C]	298 [°K]
Density *ρ*	1,17 [Kg/m3]	
Constant Pressure Heat Capacity *Cp*	1005 [J/KgK]	Cp=7/2 R*
Constant Volume Heat Capacity *Cv*	717,5 [J/KgK]	Cv=5/2 R*
Gas Constant Value *R*	8314 [J/KmolK]	
Molar Mass *Mm*	28,96 [Kg/Kmol]	
Number of mole *n*	n= M/Mm	
Specific Gas Constant Value *R**	287,05 [J/KgK]	R*=R/Mm
Heat capacity Ratio *γ*	1,4	γ = Cp/Cv

8 ACKNOWLEDGMENTS

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9 REFERENCES

[1] Garetti, M., Taisch, M. (2012): Sustainable Manufacturing: trends and research challenges, in: Production Planning & Control, Vol. 23, No. 2-3, pp. 83-104.

[2] International Energy Agency (2008): Worldwide trends in energy use and efficiency, key Insights from IEA indicator analysis, available at: www.iea.org/papers/2008/ indicators_2008.pdf.

[3] Worrel, E. et al (2009): Industrial energy efficiency and climate change mitigation, in: Energy Efficiency, Vol. 2, pp. 109-123.

[4] Bullinger, H., Steinacker, J.V., Weller, A. (1999): Concepts and methods for a production integrated environmental protection, in: International Journal of Production Economics, Vol. 61, pp. 35-42.

[5] Zhou, X., Kuhl, M.E. (2011): A sustainability toolkit for simulation: recent developments and future capabilitites, in: Winter Simulation Conference 2011, pp. 850-858.

[6] Kulus, D., Wolff, D., Ungerland, S. (2012): Simulating Energy Consumption in the Automotive Industry, Use Cases of Discrete Event Simulation, Springer Verlag, Berlin.

[7] Putz, M., Schlegel, A., Lorenz, S., Schulz, S., Franz, E. (2011): Gekoppelte Simulation von Material- und Energieflüssen in der Automobilfertigung, 14. Tage des Betriebs- und Systemingenieurs, Chemnitz, pp. 134-145.

[8] Schulz, S., Jungnickel, F. (2012): A General Approach to Simulating Energy Flow in Production Plants via Plant Simulation, in: Proceedings of the Global Conference of Sustainable Manufacturing 2012, pp. 724-729.

[9] Herrmann, C., Thiede, S. (2009): Process chain simulation to foster energy efficiency in manufacturing, in: CIRP Journal of Manufacturing Science and Technology, Vol.1, pp. 221-229.

[10] Thiede, S. (2012): Energy Efficiency in Manufacturing Systems, Springer Verlag, Berlin.

[11] Schuh, G., Kampker, A., Wesch-Potente, C. (2011): Condition based factory planning, in: Production Engineering, Vol. 5., pp. 89-94.

[12] Müller, F., Cannata, A., Okur, A., Herrmann, C., Thiede, S. (2012): Classification of factories from a green perspective: initial guidance and drivers for 'Green Factory Planning', in: Proceedings of the Global Conference of Sustainable Manufacturing 2012, pp. 765-771.

[13] Cannata, A., Taisch, M. (2010): Introducing Energy Performances in Production Management: Towards Energy Efficient Manufacturing, in: Advances in Production Management Systems, Springer Verlag, Boston, pp. 168-175.

[14] Cannata, A. (2011): A methodology to enhance energy efficiency at factory level: improvements for sustainable manufacturing, dissertation, Politecnico di Milano.

[15] Weinert, N., Chiotellis, S., Seliger, G. (2011): Methodology for planning and operating energy-efficient production systems, in: CIRP Annals – Manufacturing Technology, Vol. 60, pp. 41-44.

Discrete Event Simulation Inserted into Kaizen Event to Assess Energy Efficiency

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Abstract

A sustainable layout planning should provide a resource-efficient state. Companies face the facility layout problem not only when they create a new manufacturing system but also when they expand or modify existing systems. In these cases, a proper evaluation of manufacturing is a fundamental step to identify opportunities for improvement and to increase energy efficiency in production. This paper discusses a systematic approach for layout modification, which includes an assessment of energy efficiency, inserted into kaizen event. A case study was conducted, as a contribution towards this discussion.

Keywords:

Sustainability; energy efficiency; Discrete Event Simulation; Kaizen event.

1 INTRODUCTION

The industrial global economy already consumes more natural resources than ecologically bearable [1]. Energy becomes the bottle neck of sustainable manufacturing and to equalize the tradeoffs between economic growth and resource consumption is an essential challenge for the global community [2].

Approaches to increase the productivity benefits of resources for products from production technology have been in particular implemented on the product side. Researches up to now also focus on the product bounded material resources, in which the life cycle management and new possible use phases of products are improved through the development of processes and organizational structures [3] [4].

Layout planning often has a significant impact on the performance of a manufacturing or service industry system and is usually a multiple-objective problem. Designers face the facility layout problem not only when they create a new manufacturing system but also when they expand, consolidate, or modify existing systems. Even established manufacturing companies need to change the layout of departments every two or three years [2] [5].

The motivation for this work comes from the automotive industry, specifically from discrete manufacturing companies which traditionally uses kaizen events to achieve improvements in production systems. Some of these companies already use discrete event simulation for analysis of material flow and comparisons among different scenarios. However, the simulation tools not include so far standard functionalities to calculate energy consumption, although they seem like a promising approach.

The goal herein is to discuss a systematic approach for layout modification, which includes an assessment of energy efficiency, inserted into kaizen event.

This paper is organized as follows: Section 2 discusses related work; Section 3 presents a case study conducted to assess changes in layout considering the energy consumption in the processes of a manufacturing cell. Finally, Section 4 draws some conclusions and discusses future works.

2 RELATED WORK

2.1 Energy Efficiency in Manufacturing

Energy efficiency is used to compare energy consumption and product output. Under industrial manufacturing scope, it can be described as the maximum production output with the minimum consumption of energy [2].

The energy consumption of production related technical equipment is typically not constant over time but dynamic depending on the production process and the actual state of the machine [4].

Typically, different machine states can be distinguished in table 1 [4] [6] [7]:

State	description
Off	Main switch off, no energy consumption;
Start/ Rump-up	Energy demand peaks caused by switching on certain components, heating-up phases etc;
Idle	Relatively constant energy consumption after main supporting components completed ramp-up and machine is “ready for production”;
Processing	Actual value creating process takes place (e.g. removal of material).

Table1: Machine States.

This distinction between operating states of machine tools assists in predicting the energy consumption in production systems. Nevertheless, the influence of variation of power consumed during Processing State on the whole production line energy consumption is still a field of study in its early stages.

Newmann *et al*. [10] stated in their work that the energy consumption of machining processes can range significantly in at least 6% of the total energy consumption of the machine tool, at low loads, and is susceptible to increase by 40% at higher loads. As well as these authors, Balogun *et al*. [11] confirm that the energy consumption in machining processes can be used as a criterion for layout planning.

Schlosser *et al*. [8] show some technology requirements for data acquisition of electrical energy in machine tools, and display the composition of power demands, forming the overall process energy depending on the process times. According with this work, the energy consumption per part in manufacturing process can be calculated as the sum of the direct and indirect energy per part.

The direct manufacturing energy per part is the sum of the energies of the single manufacturing processes [8].

$$Epart, direct = \sum_{j=1}^{m} Epart, man_j \quad (1)$$

$E_{part,man}$: direct energy consumption per part in manufacturing process j.

The energy of a single manufacturing process consists of the real process energy, the energy consumed in the idling mode and a proportional part of the energy consumed in standby mode and while the machine tool is switched off [8].

$$E_{part,man_j} = E_{process_j} + E_{sb_j} + E_{idle_j} + E_{off_j} \quad (2)$$

$E_{process,j}$: process energy consumption
$E_{idle,j}$: energy consumption during idling
$E_{sb,j}$: energy consumption in standby mode
$E_{off,j}$: energy consumption while machine tool is switched off

It was previously shown by Diaz [12] that the energy consumed by a machine tool could be characterized with the following model:

$$E_{process} = \left(K * \frac{1}{MRR} + b\right) * V \quad (3)$$

Where K and b are the specific energy constants, MRR is the material removal rate and V the volume of material removed [12].

The energy consumed by CNC machine tools has an inverse relationship with the material removal rate (MRR) because these machine tools have a high tare power demand [12] [13] [14]. That is, even in standby mode when the machine tool is not processing parts the machine tool still demands a significant amount of power. Thus, the electrical energy consumption for any given machine tool is dominated by the time required to process the part when optimal cutting conditions are used as shown by Diaz, et al. [12] [14].

2.2 Process Planning with Energy Efficiency Consideration

A sustainable layout planning should not only save the space, optimize the process for manufacturing, but also provide a solution for improving energy efficiency. This means that an evaluation of the various alternative options for designing a layout according to its energy efficiency must take place [2].

Several models for energy and resource efficient process modeling, planning and scheduling have been presented in literature.

Seliger *et al*. [1] present the EnergyBlocks methodology to model process chains and support the planning process layout, focused on energy efficiency. The methodology is based on describing the energy consumption of production equipment e.g., machining centers or handling and transport systems according to their operating states, constitute the energy blocks. Each energy block describes the energy consumed during one operating state, independent of a specific production task.

Duflou *et al*. [16] presented a systematic overview of the state of the art in energy and resource efficiency increasing methods and techniques in the domain of discrete part manufacturing, with attention for the effectiveness of the available options.

Diaz & Dornfeld [12] used discrete event simulation to assist in decision making for machine tools selection in flexible manufacturing systems. The cost analysis considers the energy consumption during the manufacturing process.

Hermman *et al*. [4] presents a classification so called portfolio of energy consumption, where different parts of the corporation are classified according to energy consumption. It is also applied discrete event simulation for assessment of energy flows aiming factory planning with energy efficiency.

2.3 Kaizen Event and Simulation

The term "kaizen event" is used to indicate a limited time period where are realized identification and implementation of improvements [16]. In a typical Kaizen Blitz project, a cross-functional multi-level team of 6 to 12 members work intensely, 12 to 14 hours a day, to rapidly develop, test, and refine solutions to problems and leave a new process in place in just a few days. [17].

A discrete event simulation has been used in kaizen events to increase the level of knowledge about the stages of this process and improve the decision making modifications to factory layout. The method MAPS - *Melhoria Auxiliada por Simulacão* (Simulation Aided Improvement), presented in [18] has routines of a simulation process inserted in Kaizen activities.

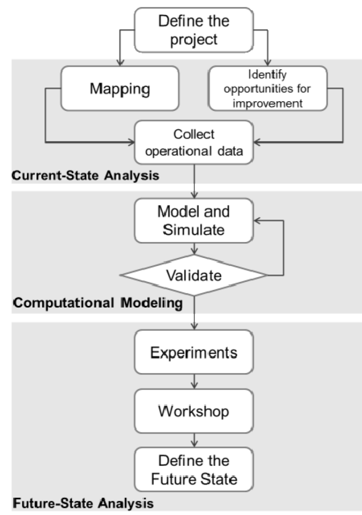

Figure 1: MAPS.

In the step called Define the project, the system is described and the goals of the simulation are defined. Moreover, the functions are defined for each member of the team kaizen, which can join two different teams work - team of model validation and measurement team.

In the next step - Current-State Analysis - the teams work going to the shop floor to map the process, identify waste during production and document all activities. This step guides the mapping of the Current State and provides the data for the conceptual modeling and for the computational model.

In the Future-state analysis step, the information gathered in the previous steps are used as starting point to develop alternatives and to compare these alternatives by means simulating experimental models. The best scenario is chosen according to established goals.

The use of simulation tools in MAPS method allows generating operational states for all model objects, such as states of processing and idling to the machines and operators. At the end of simulation run, time and utilization statistics provide information regarding the time share each object spends in the respective operating states.

3 CASE STUDY

3.1 Materials and Methods

The MAPS method is suggested to assess energy efficiency during the process of improving a manufacturing system because this approach involves the discrete event simulation in analyzing of several future state scenarios.

This paper considers only machine tools as consumers of electricity. Thus, the information of power consumption assigned to different states of the machine tools over a production process can be analyzed, in order to obtain a profile of energy consumption for each process or machine tool along the production chain.

The power demand data are entered in the phase "Collect operational data", during the step Current-State Analysis, as illustrated in figure 2. The results of energy consumption are analyzed after developing future-state scenarios, jointly with typical results of production.

The states of machine tools over simulation run time were analyzed, and the energy consumption of the current state was calculated by means of the equations (1) e (2). Subsequently, these results were compared with the energy consumption in the different scenarios simulated to future state.

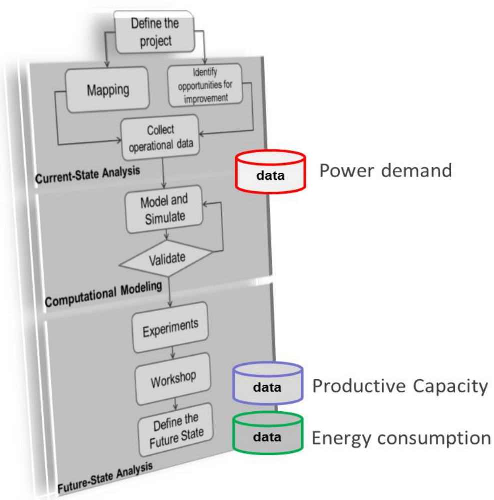

Figure 2: Power data into MAPS method.

The case study was conducted in a discrete manufacturing company from the automotive sector. This company seeks continuous improvement on the shop floor through kaizen events and, as a result of this approach, there is often the need to change the layout of manufacturing cells.

The operational data are from a manufacturing cell, which produces monthly 7152 auto parts, machined in pairs (right and left) by six machine tools and transported by five operators, with the help of conveyor belts (Figure 3).

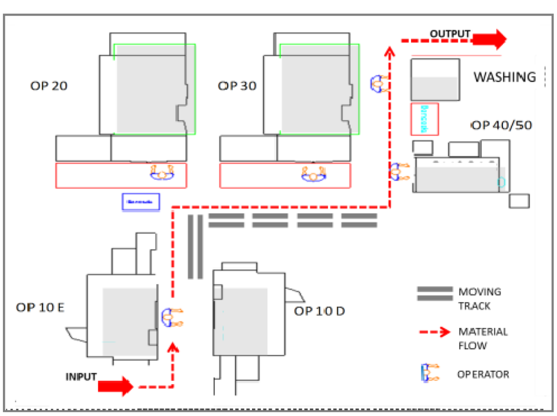

Figure 3: Current state layout.

There are three daily shifts of work, totaling 15 operators per day in nineteen hours a day. Figure 3 shows the flow of material, which starts with the operations OP10E and OP10D, and finishes at the washing process.

The sequence of activities performed during the kaizen was similar to the suggested MAPS method. Initially, the goals and objectives for the process of improvement were established. These were defined as:

- Provide manpower for other activities;
- Increase production capacity.

From the processes mapped and collected data, opportunities for improvement were identified and a computational model the current state was developed and validated by means of the software Plant Simulation [tm].

For reasons of confidentiality, the data of energy consumption of machine tools are shown in relative values (in relation to the values obtained for each process as reference) in this case study. Table 2 shows the power demand for each machine tool, for states process and idle. The states off and ramp-up were not considered in the analysis.

	Power Demand [kW]	
	Processing	Idle
OP10D	3,5	1,3
OP10E	3,5	1,3
OP20	6	1,5
OP30	6	1,5
OP40	5	1,2
OP50	5	1,2
Washing	1	0,2

Table 2: Power Demand.

3.2 Results and Discussions

The future state of the system chosen by the kaizen team has modifications of tools, cutting parameters and the following layout (Figure 4). The main layout changes are listed below:

- Material flow in the opposite direction;
- Reversed sequence of operations 20 and 30.

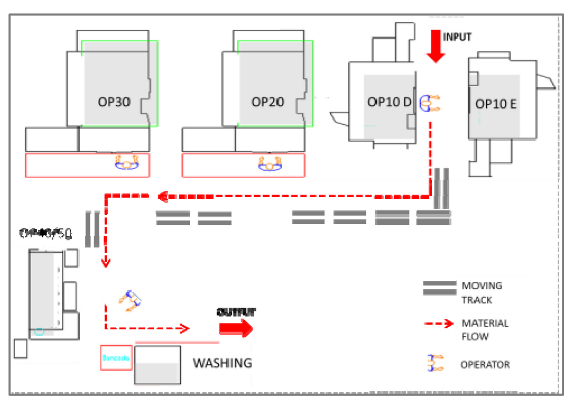

Figure 4: Future state layout.

Figures 5 and 6 show the simulation results for the behavior of operators in two different scenarios - current state layout and future state layout. Two states - working and waiting - are presented. The first corresponds to periods of movement or handling. The second is the period of waiting for tasks.

The possibility to use just four operators in the future state scenario was confirmed by the results of the simulation. As expected, there was an increase in the rate of working to the operator 4, which is accountable for operations 40/50 and washing. The expected rate among operators after modifications is still high and it was considered a target to future kaizen improvement.

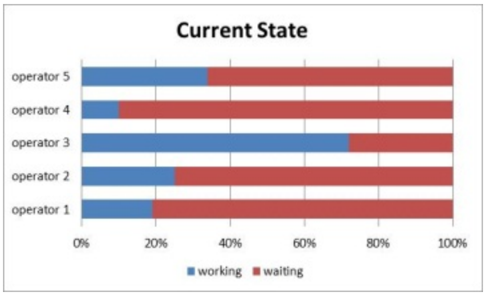

Figure 5: Operators' behavior – current state.

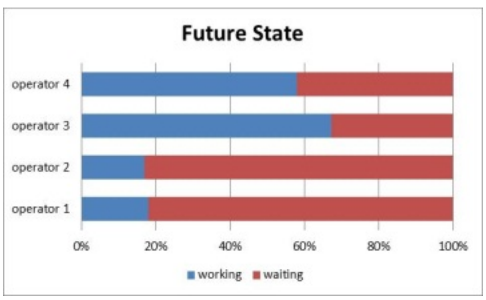

Figure 6: Operators' behavior – future state.

The results on the use of the machines in the current state and future state are presented in terms of rates of idle and processing states. Figures 7 and 8 show these results.

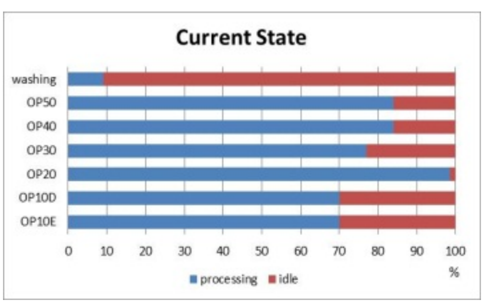

Figure 7: Machine states – current state.

There is a significant change in the rate of processing time allocated to OP20, when the results for the machine states are compared. Other operations showed variations less marked, as the decrease in the rate of the processing state in the OP50 and the increase in this rate for operations 10, 30 and 40.

These results indicate that the removal of an operator did not result in increased waits for machine tools, and also they portray that the modification of layout coupled with process improvements resulted in increased efficiency in the proportion between the number of parts produced per operator, as well as the relationship between the number of parts produced and the processing rates of machine tools.

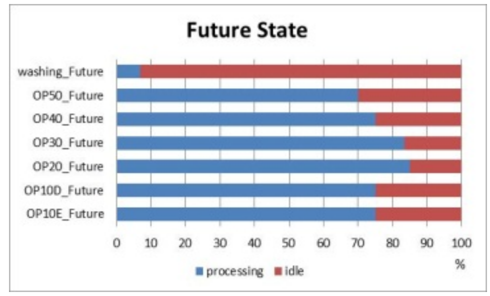

Figure 8: Operators' behavior – future state.

Towards the energy consumption, the power demands of machine tools for the processing and idle states were considered equal in both the current state and in the future state.

Figure 9 shows a comparison of the monthly energy consumption for each process step. There was a reduction in energy consumption in the operations 20, 40 and 50, however accompanied by an increased consumption of operations 10 and 30.

According to the table 2, operation 20 and operation 30 have a higher energy consume during processing and idle states, when compared to others. In the future state, the rates (processing and idle) have changed to these both operations. However, the power consumption to the proposed future state was lower than the current state, even with the increasing number of piece produced.

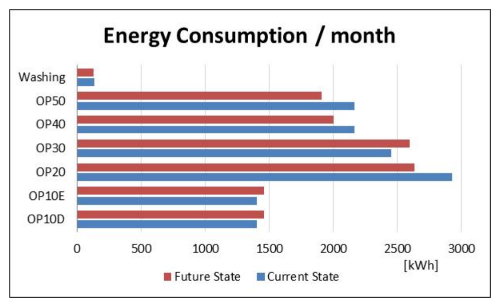

Figure 9: Monthly energy consumption.

Table 3 shows a comparison of the results of kaizen between the current state and future state.

	Current State	Future State
Produced output	7152	7182
Operators (O.)	15	12
Productive Capacity (parts/O. month)	476	598
Productive Capacity increase	-	25%
energy consumption (process chain) [kWh]	12675	12170
Spec. energy consumption [kWh / part]	1,77	1,70

Table 2: Simulation Results.

Although the number of parts produced in the future state (7182) is larger than the current state (7152), this increase does not occur sharply. However, there was a significant increase (25%) in the relationship between the numbers of parts produced by each operator.

With regard to energy consumption of the process, there was a small change (4%). It is important to emphasize that, from an optimistic viewpoint, the proposed changes for future state imply a 25% increase in production capacity, with a 4% reduction in energy consumption. But the corporation must wonder what this means in terms of energy efficiency.

This question can be answered in accordance with the definition described in Section 2.1, which relates the amount of parts manufactured with the energy consumed. And in this case, the simulation results indicate that the proposed improvements lead to an increase of just 0.4% in the number of manufactured parts, accompanied by a 4% reduction in energy consumption.

Therefore, the answer to the question is that, in terms of energy consumption, the improvements proposed for the future state have resulted in a similar system, when compared with the current state system. However, towards production capacity, the gain is clearly visible because with the removal of an operator the production system will provide a positive financial impact.

The data analyzed for this manufacturing system are stored for future interventions for improvement. In this case, the corporation may elect in the future to invest more resources into reducing energy consumption of machine tools.

4 CONCLUSIONS AND FUTURE WORK

The systematic approach used for the analysis of proposed improvements and for layout modification, which includes an assessment of energy efficiency inserted into kaizen event, proved to be feasible and applicable.

The simulation results allowed evaluating the behavior of production resources in both in terms of production capacity and compared to the energy consumption for different scenarios.

The results obtained in the case study showed that despite the kaizen ensue in significant increase in the productive efficiency, due to the withdrawal of an operator, there was not a significant gain in relation to increased energy efficiency. However, future interventions seeking continuous improvement in the production system can focus on energy efficiency.

Future research should focus on the influence of energy variation in machining performance applied to computational models to predict energy consumption in distinct scenarios.

5 REFERÊNCIAS

[1] Weinert, N.; Chiotellis, S.; Seliger, G. (2011): Methodology for planning and operating energy-efficient production systems, in CIRP Annals – Manufacturing Technology, pg41-44.

[2] Wang, C.; Seliger, G. (2011): Energy-oriented layout planning for production facilities, in: Proceedings of LCM – Towards Life Cycle Sustainability Management, Berlin.

[3] Seliger, G. (2007): Sustainability in Manufacturing. Springer, Berlin Heidelberg New York.

[4] Thiede, S.; Bogdanski, G.; Hermann, C. (2012): A systematic method for increasing the energy and resource efficiency in manufacturing companies, in: CIRP Global Web Conference: Interdisciplinary Research in Production Engineering.

[5] Tompkins, J. A. (2010): Facilities planning. 4th Edition, New Jersey: Wiley.

[6] Dietmair, A.; Verl, A. (2009): A generic energy consumption model for decision making and energy efficiency optimization in Manufacturing, in: International Journal of Sustainable Engineering, 2/2, pp. 123–133.

[7] Devoldere, T.; Dewulf, W.; Deprez, W.; Willems, B.; Duflou, J. R. (2007): Improvement Potential for Energy Consumption in Discrete Part Production Machines, In: Takata, S.; Umeda, Y. (Eds.): Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses - Proceedings of the 14th CIRP Conference on Life Cycle Engineering, Waseda University, Tokyo, Japan, London: Springer-Verlag, pp. 311–316.

[8] Schlosser R.; Klocke, F.; Döbbeler, B.; Riemer, B.; Hameyer, K.; Herold, T. (2011): Assessment of Energy and Resource Consumption of Processes and Process Chains within the Automotive Sector, in: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Braunschweig, Germany.

[9] Neugbauer, R.; Putz, M.; Schlegel, A.; Langer, T.; Franz, E.; Lorenz, S. (2012): Energy-sensitive Production Control in Mixed Model Manufacturing Processes. Proceedings of the 19th CIRP International Conference on Life Cycle Engineering, Berkeley, USA.

[10] Newman, S.T.; Nassehi, A.; Imani-Asrai, R.; Dhokia, V. (2012): Energy efficient process planning for CNC machining, in: CIRP Journal of Manufacturing Science and Technology, 127-136.

[11] Balogun, V. A.; Mativenga, P. T. (2012): Modeling of direct energy requirements in mechanical machining processes, in: Journal of Cleaner Production.

[12] Diaz, N.; Dornfeld, D. (2012): Cost and Energy Consumption Optmization of Product Manufacture in a Flexible Manufacturing System, in: Proceedings of the 19th CIRP International Conference on Life Cycle Engineering, Berkeley, USA.

[13] Niggeschmidt, S.; Helu, M.; Diaz, N.; Behmann, B.; Lanza, G.; Dornfeld, D. (2010): Integrating Green and Sustainability Aspects into Life Cycle Performance Evaluation, in: Proceedings of the 17th CIRP International Conference on Life Cycle Engineering (LCE 2010), pp. 366-371, Hefei, China.

[14] Diaz, N.; Redelsheimer, E.; Dornfeld, D. (2011): Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Use, in: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering (LCE2011), pp. 263-267, Braunschweig, Germany.

[15] Duflou, J. R.; Sutherland, J. W.; Dornfeld, D.; Herrmann, C.; Jeswiet, J.; Kara, S.; Hauschild, M.; Kellens, K. (2012): Towards energy and resource efficient manufacturing: A processes and systems approach, in: CIRP Annals - Manufacturing Technology 61 (2012) 587–609.

[16] Sánchez, A. M., Pérez, M. (2001): "Lean indicators and manufacturing strategies", in: International Journal of Operations & Production Management, Vol. 21 Iss: 11, pp.1433 – 1452.

[17] Mika, G.L. (2002): *Kaizen Event Implementation Manual*, in: Kaizen Sensei, Wake Forest, NC.

[18] Gomes, V.E.O. (2010): Proposta de um método de simulação em processo de melhoria contínua em uma empresa de manufatura discreta. Dissertation for Master´s degree in ITA (Instituto Tecnológico de Aeronáutica), São José dos Campos, Brazil, in: http://www.bd.bibl.ita.br/

Developing a Parametric Carbon Footprinting Tool: A Case Study of Wafer Fabrication in the Semiconductor Industry

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Abstract

This study aims to establish a parametric-based tool capable of identifying key factors of the complicated manufacturing processes in the semiconductor industry to simplify the calculation of carbon footprint of products (CFP). Development of this methodology for wafer fabrication has been completed. An inventory of carbon emissions from a total of 7,114 samples was conducted, down to each step of process, including all 6-, 8-, and 12-in wafers with six different functions. Several regression models for CFP, which include key parameters, were developed. The results indicate that these regression models can effectively predict the CFP of the wafer fabrication.

Keywords:

Parametric Carbon Footprinting; Wafer Fabrication; Regression Analysis

1 INTRODUCTION

Climate change has become a topical issue following scientific studies, most notably by the Intergovernmental Panel on Climate Change (IPCC). Climate change greatly affects earth and human systems, including ecosystems, water resources, food security, and human health [1]. Rising global temperatures have been accompanied by changes in weather and climate. Therefore, for solving global warming and reducing greenhouse gas emissions (GHGs), international society began a joint effort to create low-carbon products. However, almost all the electronics products need ICs (Integrated Circuit) as their essential components. Besides, for specific electronics products, carbon footprint of ICs could comprises up to 1/3 of total carbon footprint of product (CFP). The semi-conductor associations of the European Union (EU), Japan and other states have committed to lower emissions from perfluorinated compounds (PFCs), which are used in the in the semiconductor manufacturing process [2] [3]. Most PFC emissions from semiconductor manufacturing have been subject to voluntary reduction goals established by members of the World Semiconductor Council (WSC). A specific reduction goal was established for all WSC members: to limit PFCs emissions to 10% below a base-year level of emissions by 2010. Thus, the reduction of GHG emissions and the exploration of feasible strategies for semiconductor industries are important challenges for the future.

A growing need has arisen for carbon footprint of product assessment. Based on the ISO 14064-65 series and PAS2050 carbon footprint standard [4] [5], direct emission must be measured. However, that measurement is often unavailable because the consumption of significant time and labor for data inventory are the main obstacles to performing CFP. The great amount of data and the lack of specific system boundaries have resulted in increasingly difficult assessment for the designer to conduct, especially for electronics with short lifecycles and complicated manufacturing processes.

This study is part of a larger EU (European Union) project—Boosting Life Cycle Assessment Use in SMEs: Development of Sectoral Methods and Tools (LCA to go)—funded under the Seventh Research Framework Program (FP7), and aims to simplify the calculation of CFP by establishing a parametric-based tool capable of identifying the key factors of the complicated manufacturing processes in the semiconductor industry. Development of this methodology for wafer fabrication has been completed. Six regression models for CFP, including key parameters, were developed. The results indicate that these regression models can effectively predict CFP of the wafer fabrication. Those regression models apply to six different functions of wafer (CIS, eHV, eNVM, Logic/MM, PMIC, and other functions) by inputting the quantity of key parameters such as mask layer, technology node, and metal layer. To strengthen the application, the carbon emission factor of electricity, overall wafer effectiveness (OWE) and capacity utilization in different enterprises were considered in this methodology.

2 LITERATURE REVIEW

2.1 Life Cycle Assessment

The Life Cycle Assessment (LCA) methodology enables the calculation of environmental burdens in a systematic and scientific way by considering all in-puts and outputs of a system [6]. LCA is mainly used for assessing systems and identifying options for improvement. In some cases, it is also used for developing sustainability indicators [7]. It is a systematic tool used in analyzing and assessing environmental impact and energy use over the entire life cycle of a product, which generally includes raw material extraction, manufacture, product use, recycling, and final disposal [8] [9] [10]. It is regarded as the most comprehensive method for assessing and comparing materials, products and services from an environmental point of view [11] and provides a basis for assessing the ‘hidden’ indirect environmental burdens. LCA evaluates the overall impact of a product or service under review and is truly holistic since it handles a range of different environmental impact categories [12].However, as climate change is the focus here, which has direct links to the consumption of material and energy with associated GHG emissions. Although the application of such a single impact indicator can be criticized, as this ignores other environmental burdens associated with the lifecycle, it is nevertheless deemed to be valid for usage in the context of this study as it is simple, climate change problem-oriented and easy-to-understand for non-professionals [13].

2.2 Carbon Footprint

The concept of the carbon footprint came from the ecological footprint assessment created by Wackernagel [14], which considers humanity's energy and resource throughput, converting these data into area units. Over the past few years, the carbon footprint has become one of the most important environmental protection indicators [15] [16] [17]. Carbon footprint usually stands for the amount of CO_2 and other GHGs, emitted over the full life cycle of a process or product [5] [18]. The carbon footprint is quantified using such indicators as the GWP (Global Warming Potential) [19], which represents the quantities of GHGs that contribute to global warming and climate change. The carbon footprints currently available do not satisfy all of the highlighted requirements, particularly in the scope and assessment methods used to find the carbon footprint. If these limitations could be overcome, a simple and practical methodology would become much easier to develop [20]. Details of the limitations are shown in Table 1.

Limitation	Requirement
No spare time for data collection or assessment	Simple tool without complicated data requirements
Little money to spare on consultants or carbon management employees	Possible to be assessed and understood by non-specialists
Do not recognize the need to reduce environmental impact	Informative about environmental effects
Cannot afford to take risks based on faulty information	Accurate enough to make informed policy decisions

Table 1: The limitations and requirement of performing carbon footprint.

2.3 Wafer Fabrication

Semiconductor manufacturing process comprises four phases: wafer fabrication, wafer probe, assembly, and final testing [21], while wafer fabrication is the most complicated, expensive and time consuming part. In the wafer fabrication, there are hundreds of machines working together under various constraints, and following numerous processing steps, to build multiple layers of chemical patterns on a silicon wafer [22] [23]. The initial layers after releasing are basic operations for all kinds of wafers, and several layers, including poly and metal operations, can be identified distinctly according to product specification, generation and product type [24]. Every layer needs to be processed in a similar manner, so wafers have to visit a certain machine for several times, each time for a layer of circuitry, and this is known as re-entrant product flow [25]. Besides, wafer fabrication is also characterized by hybrid machine types. Several types of equipment work simultaneously in the wafer fabrication [26]. Due to these features, these complicated manufacturing processes are the main obstacles for the semiconductor industry to performing CFP.

3 RESEARCH METHOD

3.1 Research Procedure

There are three steps in developing a parametric carbon footprinting tool as follow:

Step 1: Identify Key Parameters

All possible parameters were selected based on the customer order factors and critical manufacturing processes of wafer. They were based on internal study of factory, including physical meaning of each parameter and factors that concerned by customer. And this study applied process analysis and correlation analysis to identify the key parameters by investigating the relation between parameters and CO_2 emission.

Step 2: Develop the Parametric Tool

Analyze the relationship between carbon emissions and selected parameters during the processes of wafer fabrication by regression analysis. In statistics, regression analysis helps one understand the changes in a typical value of the dependent variable when any one of the independent variables is varied; the other independent variables are fixed. In the study, regression analysis is applied to investigate the relationship between carbon emissions and selected parameters.

Step 3: Calibrate This Parametric Tool

Considering the data consistency in geographical coverage, the carbon emission factor of electricity, OWE and capacity utilization in different enterprises were considered in this tool.

3.2 System Boundary and Scope

In terms of the IC product's life cycle, the system boundary of this study has been set to include only the front-end processes-wafer and does not cover the entire life cycle. Stages excluded in the analysis are the use and disposal of electronic equipment and facilities. The method used for the simplified semiconductor CFP approach follows IC Product Category Rules (PCR) by EPD [27] (Figure 1) and focuses on global warming (kg CO_2 equivalent) as the environmental impact expression.

3.3 Functional Unit

The functional unit for wafer is defined as per wafer (such as 150 mm (6-inch), 200 mm (8-inch) or 300 mm (12-inch) wafer). All energy and materials are calculated into the system by each step of process; the consumption of each equipment move of process was considered in this study.

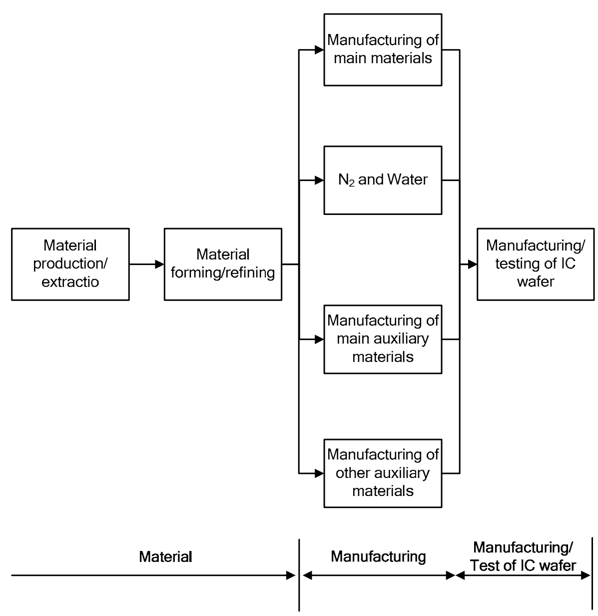

Figure 1: System boundary and scope of IC front-end processes-wafer.

Function	General purpose
CIS (CMOS Image Sensor)	CIS is primarily used in digital cameras, camera modules and other imaging devices.
eHV (extra High Voltage)	eHV is used in electrical power distribution in cathode ray tubes, to generate X-rays and particle beams, to demonstrate arcing, for ignition in photomultiplier tubes, in high power amplifier vacuum tubes, and other industrial and scientific applications.
eNVM (embedded Non-Volatile Memories)	eNVM can be used for trimming, redundancy, data encryption, ID, coding and programming.
Logic/MM	Logic/MM focuses on logical correctness, maximizing circuit density, and placing circuits so that clock and timing signals are routed efficiently.
PMIC (Power Management ICs)	PMICs are often included in battery-operated devices such as mobile phones and portable media players.
Others	Other functions, excluding CIS, eHV, eNVM, Logic/MM, and PMIC.

Table 2: The general purposes of function.

3.4 Data Collection and Assumptions

The inventory data of carbon emissions for various products (Wafers) were collected from eight semiconductor factories which include 6-, 8- and 12-in wafer processes with six functions in Taiwan. The general purpose of the six functions is shown in Table 2 [28]. All inventory data were collected from 2010 to 2011 in accordance with the rules of ISO 14067, PAS 2050 and PCR [4] [5] [27]. For investigating the relation between parameters and CO_2 emission with different product characteristics, UMC developed a method for calculating CFP of varies product characteristics [29]. It was based on PCR to inventory whole factory carbon footprint, then downscale data into each different product. Some assumptions were made based on interviews with engineers of IC plants: Numbers of major equipments were used as benchmark to allocate the consumption of total electricity and other fuels and for some chemicals like photo-resistive liquids, slurries, developers etc., this study used the information from Material Safety Data Sheets (MSDS) to calculate the mass and weight proportion by mass balance from chemical equations.

4 RESULT AND DISCUSSION

4.1 Sample Description

A total of 7,114 samples of CFP with product characteristics, including generation, function, technology node, mask layer, metal layer and poly layer, were conducted.

4.2 Identify Key Parameters

To identify the key parameters of CFP in wafer fabrication, all possible parameters from design and processes condition for wafer were selected. And we try to find the actual meaning of parameters in manufacture processes by process and correlation analysis. Then, we found the technology node, mask layer and metal layer are more important for predicting CFP. Details of the assumptions of these parameters are shown in Table 3.

Parameters	Process analysis	Correlation analysis with CFP	Assumption
Generation	The generations of wafer are limited by technology node. As generation increases and the consumption of energy and material also increases.	High positive	To integrate three different generations of wafer and simplify the calculation of CFP for the semiconductor industry, the functional unit is defined as per mm^2 of wafer.
Technology node	This is defined as the ground rules of a process governed by the smallest feature printed in a repetitive array. As this decreases, the difficulty in process increases, and the consumption of energy and material also increases.	High negative	The technology node on wafer affects CFP.
Mask Layer	All semiconductor devices are manufactured as a series of mask layers on some substrate material and each layer is created from a different mask and materials.	High positive	The quantity of mask layer on wafer affects CFP.
Metal Layer	Capacitors can be created by stacking different metal layers. Most PFC emissions are from the process of metal layer.	High positive	The quantity of metal layer on wafer affects CFP.
Poly Layer	Although poly layer is essential for semiconductor process, the rage of poly layer is narrow.	Low positive	The quantity of poly layer on wafer does not affect CFP.

Table 3: The assumptions of parameters select.

4.3 Develop the Parametric Tool

Next step, we rearranged the data to apply regression analysis for investigating the relationship between the three key parameters and CFP. Details of the inventory data rearranged are shown in Table 4.

Product	Product characteristics				CFP
NO.	Function	Technology Node (μm)	Mask Layer	Metal Layer	$KgCO_2e$ /mm^2
1	CIS	20	20	1	xxx
2	CIS	30	25	2	xxx
3	eNVM	30	25	3	xxx
4	PMIC	35	30	5	xxx
≀	≀	≀	≀	≀	≀
7114	eHV	40	40	7	xxx

Table 4: Example of sample for wafer fabrication rearranged.

Several regression models for CFP, which include key parameters, were developed. The simplified CFP equation for the wafer fabrication of semiconductor industry is proposed as:

CFP of mm^2 of Wafer with A_i Function =

a_1 + a_2*Technology Node + a_3*Mask Layers + a_4*Metal Layers (1)

A_i: Six type of function

a_j: Constants, depending on the selection of function.

The results indicate that these regression models can effectively predict the CFP of the wafer fabrication. Those regression models can apply to six different functions of wafer: CIS, eHV, eNVM, Logic/MM, PMIC, and other functions. The three parameters affected CFP because they were significant at $p < 0.001$. Technology node, mask layer, and metal layer are the key parameters in the wafer fabrication for CFP. In future, more samples should be collected for improvement of results. Details of these regression models are shown in Table 5.

4.4 Calibrate This Parametric Tool

For obtaining the best prediction results, the carbon emission factor of electricity, OWE and capacity utilization in different enterprises were considered in this tool, they are as follows:

Carbon Emission Factor of Electricity

The usage of electricity in Taiwan was also inventoried by LCA based on the Taiwan Power Company (TPC), and the carbon emission factors of electricity in this study is 0.827 ($KgCO_2$ e/kWh). Besides, the average carbon emission of electricity accounted for 60% of CFP in this study. However, the carbon emission factors of electricity could be adjusted in this tool.

Overall Wafer Effectiveness (OWE)

The OWE is referred the fraction of good die area to total wafer area and is expressed as follows [30]:

$$\textbf{OWE} = \frac{\text{Good die area}}{\text{Total wafer area}} *100\% \quad (2)$$

Where total wafer area means that whole area of raw wafer which is determined by used wafer size. Good die area is the area of produced dice that are passed wafer probe test.

Function	Standardized Coefficients (β)			R^2
	Tech	Mask	Metal	
CIS	0.26***	0.82***	0.42***	0.79
eHV	0.17***	0.72***	0.10***	0.50
eNVM	0.05***	0.69***	0.30***	0.85
Logic/MM	0.06***	0.56***	0.27***	0.58
PMIC	0.03***	0.68***	0.29***	0.89
Others	0.23***	0.90***	-	0.74

*** $p < 0.001$.

Table 5: Details of the regression models.

Capacity Utilization

Capacity utilization measures the extent to which a business is using its production potential, and it is often used as a measure of productive efficiency. Capacity utilization can be defined as the percentage of total capacity that is actually being achieved in a given period and is expressed as follows:

$$\textbf{Capacity utilization} = \frac{\text{Actual output of wafer}}{\text{Maximum output of wafer}} *100\% \quad (3)$$

We assumed that the capacity utilization is 100% in this study. Thus, the approach would be different if the capacity utilization was changed.

5 CONCLUSION

A parametric carbon footprinting tool for wafer fabrication in the semiconductor industry was developed in this paper. The R^2 of all regression models with different functions are from 0.50 to 0.89. It can effectively predict the CFP of the wafer fabrication. This methodology reduces the requirements of time, cost, and information of the product for traditional LCA. It also provides criteria for green design by adjusting the quantity of key parameters. For the semiconductor enterprises which have the ability to perform CFP, they can cite the key parameters we found to investigate the relationship to carbon emissions with process of wafer fabrication, so that they can establish own regression models for raising the prediction results. For the semiconductor enterprises which do not have the ability to perform CFP, they can use our regression models and get a referable value of CFP. Besides, the calibration factors (carbon emission factor of electricity and OWE) we considered could be adjusted in this parametric carbon footprinting tool for strengthening the application.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] Intergovernmental Panel on Climate Change, IPCC (2007): Climate Change 2007: Synthesis Report, Geneva, Switzerland.

[2] Chen, L.; Hu, A. (2012): Voluntary GHG Reduction of Industrial Sectors in Taiwan, Chemosphere. (Accepted and online DOI: 10.1016/j.chemosphere.2012.04.049)

[3] Lo, S. (2010): Global warming action of Taiwan's semiconductor/TFT-LCD industries: How does voluntary agreement work in the IT industry, Technology in Society, Vol. 32, pp. 249-254.

[4] International Organization for Standardization, ISO (2006): ISO 14064-1:2006. Greenhouse gases - Part 1: Specification with Guidance at the Organization Level for Quantification and Reporting of Greenhouse Gas Emissions and Removals. ISO, Geneva, Switzerland.

[5] British Standard Institute, BSI (2008): Guide to PAS 2050. How to Assess the Carbon Footprint of Goods and Services. British Standards, London, UK.

[6] Klopffer, W. (1997): Life Cycle Assessment-from the Beginning to the Current State, Environmental Science and Pollution Research, Vol.4, pp. 223-228.

[7] Mahgoub, M. E. M.; van der Steen, N. P.; Abu-Zeid, K.; Vairavamoorthy, K. (2010): Towards Sustainability in Urban Water : a Life Cycle Analysis of the Urban Water System of Alexandria City, Egypt, Journal of Cleaner Production, Vol.18, pp. 1100-1106.

[8] MacLean, H.; Lave, L. B. (2003): Evaluating Automobile Fuel/propulsion System Technologies, Progress in Energy and Combustion Science, Vol. 29, pp. 1-69.

[9] Maurice, B.; Frischknecht, R.; Coelho-Schwirtz, V.; Hungerbühler, K. (2000): Uncertainty Analysis in Life Cycle Inventory: Application to the Production of Electricity with French Coal Power Plants, Journal of Cleaner Production, Vol.8, pp. 95-108.

[10] Ortiz, O.; Castells, F.; Sonnemann, G. (2009): Sustainability in the Construction Industry: a Review of Recent Developments Based on LCA, Construction and Building Materials, Vol. 23, pp. 28-39.

[11] Arena, A. P.; de Rosa, C. (2003): Life Cycle Assessment of Energy and Environmental Implications of the Implementation of Conservation Technologies in School Buildings in Mendoza, Argentina, Building and Environment, Vol. 38, pp. 359-368.

[12] Menzies, G. F.; Turan, S.; Banfill, P. F. G. (2007): Life-cycle Assessment and Embodied Energy: a Review. Proceedings of the Institution of Civil Engineers Construction Materials, Vol. 160, pp. 135-143.

[13] Filimonau, V.; Dickinson, J.; Robbins, D.; Huijbregts, M. A. J. (2011): Reviewing the Carbon Footprint Analysis of Hotels: Life Cycle Energy Analysis (LCEA) as a Holistic Method for Carbon Impact Appraisal of Tourist Accommodation, Journal of Cleaner Production, Vol. 19, pp. 1917-1930.

[14] Wackernagel, M.; Rees, W. E. (1996): Our Ecological Footprint - Reducing Human Impact on the Earth, New Society Publishers Gabriola Island, B.C., Canada.

[15] Wiedmann, T.; Minx, J. (2008): A Definition of 'Carbon Footprint', in: C. C. Pertsova, Ecological Economics Research Trends: Chapter 1, pp. 1-11, Nova Science Publishers, Hauppauge NY, USA.

[16] Lam, H. L.; Varbanov, P. S.; Klemes, J. J. (2010): Minimising Carbon Footprint of Regional Biomass Supply Chains, Resources, Conservation and Recycling, Vol. 54, pp. 303-309.

[17] Galli, A.; Wiedmann, T.; Ercin, E.; Knoblauch, D.; Ewing, B.; Giljum, S. (2012): Integrating Ecological, Carbon and Water Footprint into a "Footprint Family" of Indicators: Definition and Role in Tracking Human Pressure on the Planet, Ecological Indicators, Vol. 16, pp. 100-112.

[18] Parliamentary Office of Science and Technology, POST (2006): Carbon Footprint of Electricity Generation, No. 268, UK.

[19] European Commission, EC, (2007): Carbon Footprint e What It Is and How to Measure It.

[20] Moss, J.; Lambert, C. G.; Rennie, A. E. W. (2008): SME Application of LCA-based Carbon Footprints, International Journal of Sustainable Engineering, Vol. 1, pp. 132-141.

[21] Uzsoy, R.; Church, L. K.; Ovacik, I. M.; Hinchman, J. (1992): Dispatching Rules for Semiconductor Testing Operations: A Computational Study, in: Proceedings of the 13th IEEE/ CHMT international electronics manufacturing technology symposium, pp. 272-276, Baltimore, MD.

[22] Kumar, P. R. (1994): Scheduling Semiconductor Manufacturing Plants. IEEE Control Systems Magazine, Vol. 14, pp. 33-40.

[23] Mason, S. J.; Fowler, J. W.; Carlyle, W. M. (2002): A Modified Shifting Bottleneck Heuristic for Minimizing Total Weighted Tardiness in Complex Job Shops, Journal of Scheduling, Vol. 5, pp. 247-262.

[24] Chung, S.; Lee, A.; Huang, C.; Chuang, C. (2008): Capacity Pricing Mechanism for Wafer Fabrication, Computers and Industrial Engineering, Vol. 55, pp. 647-662.

[25] Toktay, L. B.; Uzsoy, R. (1998): A Capacity Allocation Problem with Integer Side Constraints, European Journal of Production Research, Vol. 109, pp. 170-182.

[26] Guo, C.; Zhibin, J.; Zhang, H.; Li, N. (2012): Decomposition-based Classified Ant Colony Optimization Algorithm for Scheduling Semiconductor Wafer Fabrication System, Computers and Industrial Engineering, Vol. 62, pp. 141-151.

[27] Taiwan Semiconductor Manufacturing Company, TSMC.; Advanced Semiconductor Engineering, ASE.; Industrial Technology Research Institute, ITRI (2009): Product-Category Rules (PCR) for Preparing an Environmental Product Declaration (EPD) for Integrated Circuits, version 1.0.

[28] Hu, A.; Huang, C.; Yin, J.; Lin, P. (2012): Development of a Simplified Carbon Footprinting Methodology for the Semiconductor Industry, in: Proceedings of the Electronics Goes Green 2012+, pp. 117, Berlin, Germany.

[29] Yin, J.; Wang, H.; Wang, T.; Hu, A.; Huang, C. (2013): A Process-based and Simplified Carbon Footprint Model for Customized Semiconductor Products, The SESHA 35th Annual International High Technology ESH Symposium and Exhibition, CA , USA. (Accepted)

[30] Chien, C.; Hsu, C.; Chang, K. (2011): Overall Wafer Effectiveness (OWE): A Novel Industry Standard for Semiconductor Ecosystem as a Whole, Computers and Industrial Engineering, pp. 1-11.

Material Information Model across Product Lifecycle for Sustainability Assessment

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Abstract

Material Information Model (MIM) is central to evaluating the impact of material properties on sustainability in the product life cycle. It is almost imperative that we need standardized distributed material information models to address the needs from different perspectives in the product life cycle (manufacturing, quality and testing perspectives etc.). This paper is an attempt to understand the complexity of material information model, the requirements for defining a high level material information model and explore the possibility of formalizing “a language” for defining material information model that can capture this information across different life cycle stages. It is possible that MIM may be both structured and unstructured (heterogeneous as well as unstructured which is common in web data). Therefore, it is necessary to go beyond the existing relational database formalisms to build real-time MIM information models. This paper develops conceptual ideas to address the above with recommendations for a distributed cloud-based architecture.

Keywords:

Sustainability; material information

1 INTRODUCTION

To capture design knowledge, focus has historically been on form, function and fit. CAD/PDM/PLM tools focus on form for defining product information in terms of geometry and a collection of geometric entities (part features). Information for fit comes mostly from product assembly models and the bill-of-material (BOM). The language for this form and fit information is generally assembled in graph and tree structure. In comparison, function-based modeling, while sometimes addressed in specialized modeling packages, is still not widely available in most CAD/PDM/PLM tools.

More recently, interest in designing products and manufacturing processes with major consideration given to the resources used and waste produced over the entirety of the product/process life cycle, viz. sustainable manufacturing has increased. Unlike design and manufacturing process development activities that generally have access to a wealth of material information, sustainability assessment activities are generally made difficult by lack of a centralized source of information for sustainability metrics pertaining to engineering materials.

Some examples of material-related sustainability metrics that are necessary for accurate life cycle sustainability analyses of engineering products include, but are not limited to, energy expended in extracting/producing raw material forms (embodied energy), carbon footprint, hazardous byproducts, volume of waste produced and recyclability efficiency of waste forms [1-5]. To facilitate sustainability assessment, these metrics/indicators should be available to the design community in the same manner as other material information such as structure, properties, performance, safety and product application. The centralized availability of this life cycle of material information will be an important resource to be used in the development and assessment of sustainable products and processes.

Of particular interest to product designers and manufacturing engineers is the ability to rapidly and reliably quantify sustainability characteristics and other elements of product design, specification and quality for a specific portion of the life-cycle: the *gate-to-gate* sequence of activities used in manufacturing (Fig. 1). A manufacturing-focused view of sustainability can be useful for designing environmentally-friendly production sequences and also assessment of the environmental impact of new manufacturing technologies, without having to conduct far more expansive life cycle assessments from a cradle-to-grave perspective. Further, ability to assess sustainability at the design stage will enable better integration of assessments of form, function, fit and sustainability. Detailed material information is at the heart of these coupled assessments as the underlying computational models ultimately would rely on information tied directly to thermo-physical properties.

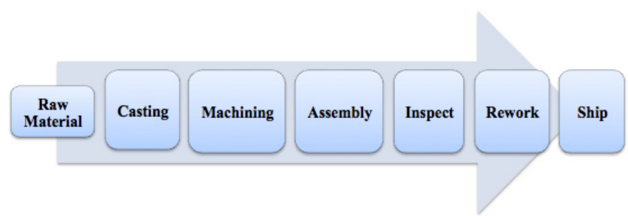

Figure 1: View of gate-to-gate sequence of activities used in manufacturing of discrete products.

We addresses the complexity of material information needed to support a gate-to-gate assessment of sustainability, requirements for defining a high-level material information model (MIM) and also the possibility of formalizing a language for defining a conceptual model that can capture this information across different life cycle stages. Further, we discuss an MIM structure that addresses needs of different perspectives in the gate-to-gate framework.

2 MATERIAL DATABASES

Material information necessary for coupled form, function, fit and sustainability assessments has long been available in a multitude of databases that aggregate material test data. Some material information is already available across several databases, including Chemicals Abstracts Service (CAS) Registry, NIST Materials Properties Database, National Institute for Materials Science (NIMS) MatNavi database, MatWeb, Metals Abstracts Alloys Index (METADEX), International Material Data System (IMDS), Material

Safety Data Sheets (MSDS), among others [6]. A wider set of material information is also available from patents, archival publications, conference reports, technical reports, books, dissertations and abstracts.

Practical implementation of centralized assessment methodologies requires a systematic approach to draw out material information in the format needed, given the format in which it is stored in these databases. Several primary challenges must be overcome in this regard, including variable data complexity, naming conventions, measurement units, levels of abstraction and data sparseness [7]. Material information necessary for form, function and fit assessments are typically related to material thermo-physical characteristics. These include thermal, mechanical and atomic/ microstructure measures that generally are available across the databases listed above.

In comparison, availability of material information for sustainability assessments, particularly in the gate-to-gate framework, is far more limited [7]. This information (e.g., energy expenditure, material usage) is somewhat different from thermo-physical material information as the it is strongly dependent on the type of processing used in manufacturing a product while the latter is mostly static and generally independent of the processing used. Unavailability of material-level sustainability related data is partially driven by the lack of centralized models for determining sustainability of unit manufacturing processes. Unit process models to establish functional relationships between fundamental material properties, process parameters/configurations and sustainability metrics (energy expenditure, waste and material usage). With the development of standard unit process models, material sustainability information can be represented and archived in similar databases as those listed above.

3 STAKEHOLDERS

The manner in which material information is used is tied directly to user-specific interest. From a form, fit and function perspective, thermo-physical information is of primary importance. For example, materials designers are primarily interested in structure (e.g., chemical composition, microstructure) and property data (e.g. yield strength, conductivity, and transformation temperatures). Product designers may be interested in the same parameters, but may also be interested in functional performance data (e.g. fatigue characteristics, creep resistance). Manufacturing engineers generally are interested in accessing process-related data that describes effective parameters for materials processing. Sustainability-related data, which has long been of primary importance to regulatory agencies and consumer interest groups, now also is an important resource sought by product designers and manufacturing engineers.

To better understand what information is required, a necessary first step is to define the range of users of material information and the information elements important to each. In the context of the gate-to-gate sequence of processes needed to manufacture a part, primary stakeholders include, but are not limited to, materials suppliers, manufacturing engineers, product design engineers, standards & test organizations, waste management groups, and environmental oversight agencies. A centralized material information model must be able to incorporate a dynamic view of material information, wherein each of these stakeholders will be interested in specific information elements (Fig. 2). However, it must be noted that such a centralized information model may have access to distributed databases.

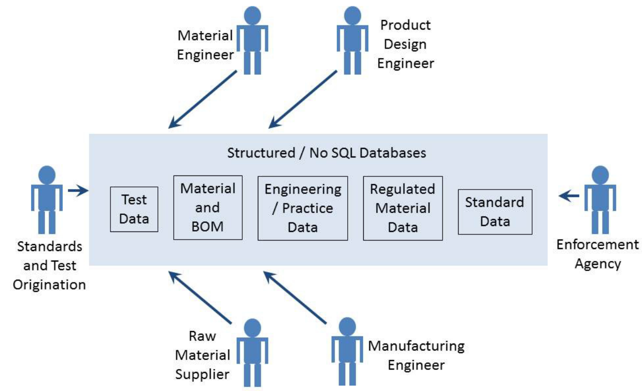

Figure 2: Material information and access from various stakeholders.

With regard to material-related sustainability data, the information itself may be interpreted in a multitude of ways. For example, a manufacturing engineer may be primarily interested in a sustainability metric, e.g. embodied energy, for the production activities that occur solely within his/her facility. This can be compared with a regulatory agency whose interest is in sustainability of the entire production sequence, including the intermediate manufacturing operations that are outsourced. The material information needed to determine the sustainability performance in either scenario is strongly dependent on the perspective being applied. Thus, information models developed to aggregate material information for coupled assessments of form, function, fit and sustainability must also provide mechanisms for dynamic assessment of data by a multitude of stakeholders.

4 PROPOSED MIM

We propose here a standard material information model that is able to address the informational requirements of coupled assessments of form, function, fit and sustainability. Fundamental to this effective material information model is a flexible data structure that can provide data elements required for coupled assessments in the various stages of the manufacturing life cycle by various stakeholders, as discussed above. Some fundamental views that we must consider here are the following: material development and test, engineering analysis in product design, manufacturing planning, manufacturing execution and monitoring and reporting and recycling.

Theoretically, the same materials that constitute the product are present across all or at least a multitude of the above views. However, the manner in which each of the above users views the material and corresponding material information can be very different. For example, the manufacturing planner will consider the flow stress of a candidate material in designing geometric elements of tool and die equipment for a deformation process. Alternatively, the product design engineer uses flow stress information to facilitate finite element analyses to simulate in-service stresses and strains for products. Similarly, the manufacturing and product engineers may also analyze sustainability-related material information differently. For example, the manufacturing engineer may be much more concerned with waste material generation in the manufacture of a product when compared with the perspective of the design engineer.

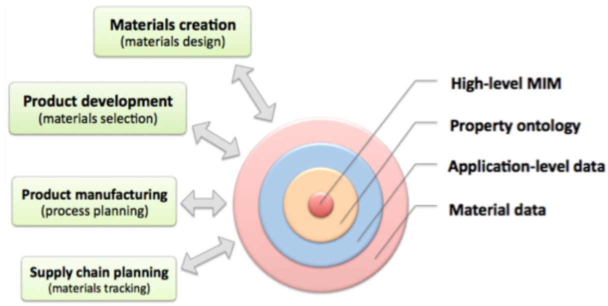

Figure 3: Potential high-level material information model (MIM) structure and two- way interaction with various life cycle activities.

As discussed above, sustainability-related information often is tied directly to characteristics of the gate-to-gate processing sequence selected and, as such, may be derived from the base-level data elements that pertain to material information. In this regard, a high-level material information model at its core includes representation of fundamental material data (e.g., thermo-physical properties) as well as application or process-level data that are derived from the fundamental material data through process models (e.g. Fig. 3). Various activities (e.g., users) will interact with this data through a high-level information model that arranges this base-level material data and application-specific information through a property ontology that can accurately describe the information as it pertains to that particular user.

From a logical perspective, this is equivalent to metaphor identification and representation. That is, the same material when viewed from different perspectives is found to convey different information. Each of the participants (or users) in the product life cycle: materials engineers, product design engineers, standard and test organizations, raw material suppliers, enforcement agencies and manufacturing engineers, will have a different view of the same material. That the same material property can be viewed differently by different participants underscores the need to build information architecture to represent these information characteristics.

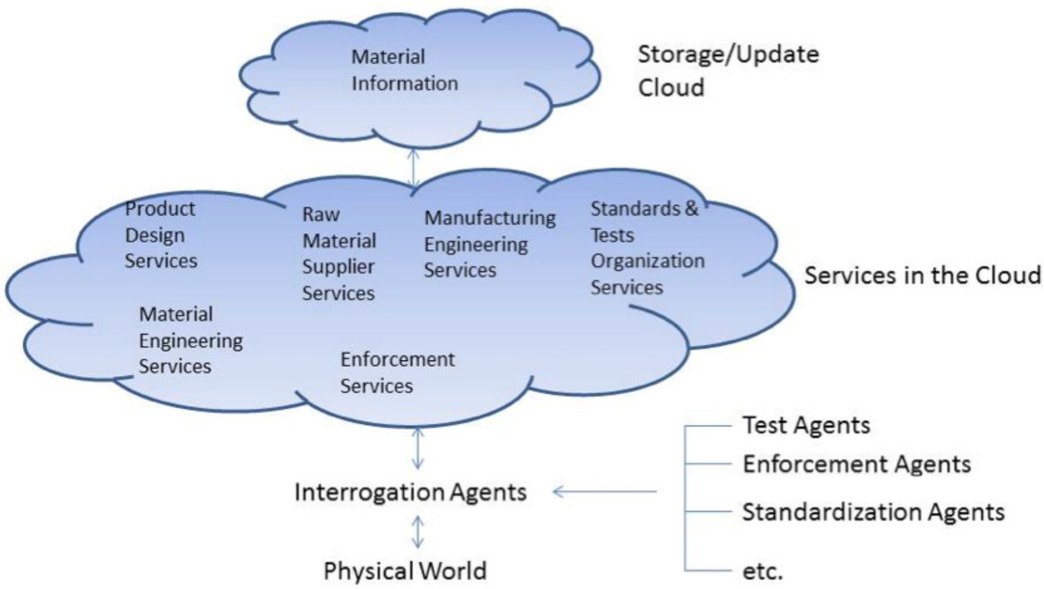

Figure 4: Cloud-based material information model.

In principle, one can build the relationship between material properties, stage in the life cycle and the relevant participant (user). Each of the users brings in a perspective to sustainability. These views of these material information models can be modeled as web services (Fig. 4). In a cloud-based computing architecture, these web services reside in the cloud and interact with information models and databases that also reside in the cloud, as well as with the physical world (e.g., manufacturing scenario). In the physical world, given a particular material, one may have to obtain necessary testing/inspection methods, tools for testing and inspection, information to be collected and computations that need to be performed. These mechanisms can be facilitated in an agent-based framework.

An agent-based cloud material information modeling language can facilitate the interaction between the physical world, cloud-based material services (users) and material information models. The physical world can interact with the manufacturing agent to communicate that specific manufacturing tasks need to be done and also to provide the necessary details. The manufacturing agent(s) will communicate this information to the manufacturing services. The manufacturing web service may need data from the material information models, and may need to invoke computations from the unit process models. Autonomy of each of the services, as well as ease of adding new services, can be established through agent formalism. In addition, there may be several instances of querying which may need multiple services to collaborate.

A complex element of material and process data is the proprietary nature of such information. Material information often may be proprietary and organizations / suppliers may not want to share specific material information openly. Therefore, when these services need this information, they through the query language, will send a request to the organization for the particular information. The only requirement we impose is that all organizations must be registered in the web services.

The development of a high-level information model and an agent-based approach to integrate the MIM with associated unit process models and a range of stakeholders affords unique capabilities for facilitating coupled assessments of form, function, fit and sustainability.

5 DISCUSSION

Given the above, the development of a Material Information Model must cater to different views of gate-to-gate manufacturing and should consider the following items.

1) How a conceptual model can capture the different granularities of material information that act as the core model and enable information flow across the product lifecycle.
2) How the MIM can help integrate material information from different material databases.
3) How the MIM can capture information generated by all stake holders, including: material scientists, product designers, manufacturing engineers, remanufacturers, quality engineers, recyclers, environmental engineers and others.
4) What the standards, technologies and languages that are needed to achieve this.

The information system described in our proposal in this paper is the first major step towards addressing these four questions.

6 CONCLUSIONS

Ability to assess gate-to-gate sustainability at the design stage will enable better integration of assessments of form, function, fit and sustainability. At the heart of any coupled assessment of form, function, fit and sustainability are detailed material information elements, underlying computational models and various stake-holders that have interest in particular information elements. The web-based information system proposed here provides a feasible framework for accomplishing these objectives. This type of system can be realized with the development of mechanisms to retrieve material information from existing database information and the development of standard unit process models. Ultimately, the coupled assessment that will be made possible will facilitate the design of new products and the improvement of manufacturing methods from a sustainability point of view.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

[1] S. Rachuri, R. D. Sriram and P. Sarkar, "Metrics, Standards and Industry Best Practices for Sustainable Manufacturing Systems," in 5th Annual IEEE Conference on Automation Science and Engineering, Bangalore, India, August 22-25, 2009.

[2] M. Schmidt, "Resource efficiency – what are critical metals and how scarce are they?" Electronic Displays Conference, 2012.

[3] T. E. Graedel, United Nations Environment Programme, "Recycling rates of metals", 978-92-807-3161-3, 2011.

[4] X. Du and T. E. Graedel, "Uncovering the Global Life Cycles of the Rare Earth Elements," Nature Scientific Reports, 1, 2011.

[5] C. J. Rydh and M. Sun, "Life cycle inventory data for materials grouped according to environmental and material properties," Journal of Cleaner Production, 13, 1258- 1268, 2005.

[6] P. S. Ramalhete, A. M. R. Senos, C. Aguiar, "Digital tools for material selection in product design," Materials and Design, 31, 2275-2287, 2010.

[7] P. Sargent, . E. Subrahmanian, . M. Downs,, R. Greene and . D. Rishel, "Materials' Information and Conceptual Data Modelling," Computerization and Networking of Materials Databases: Third Volume, ASTM, Philadelphia, 1992.

Comparative Life Cycle Assessment of Servo Press and Flywheel Press

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Abstract
Heavy duty machines consume a tremendous amount of energy during their life cycle. Then designing an energy efficient machine is of great importance. This paper presents a method for comparative life cycle assessment (LCA) of two different type of press: servo press and flywheel press to understand quantitatively the environmental emissions during their life cycles. To make a fair comparison of the two machines, the same amount of production is used as the basis for comparison. The results of the study can be used for decision making during the product purchase, planning and design process.

Keywords:
Life Cycle Assessment; Servo Press; Flywheel Press

1 INTRODUCTION

With the industrial revolution and the rapid development of economy, industrialization inevitably brings negative effects on environment. As the pillar industry of national economy in China, energy consumption of manufacturing and its product accounts for 63% of the primary energy consumption, and it is also an important source of carbon dioxide emissions. Because of the restriction of metal forming technology, press usually has features like strong installed power and large amount of material consumption. Flywheel press is driven by common alternate electrical asynchronous motor. It accomplishes pressing work relying on flywheel to store energy and provide a big short-term impact torque. The motion of slider cannot be controlled and adjusted. So the biggest disadvantage of flywheel press is the high energy consumption and the low efficiency. In comparison, servo press adopts ac servo drive technology and turns rigid drive to flexible drive. Therefore the power can be controlled and the parameter can be adjusted, showing superiority in the aspect of saving energy. In addition, servo press also calls off some energy consumption units like clutch and brake to shorten the drive link, which can not only save a lot of energy, but also improve the reliability of work and reduce the equipment volume [1].

Life cycle assessment (LCA) is an analytical tool for measuring the potential environment impact caused by a product. Taking various methods to collect related data, it can examine all life cycle stages of a product and provide a quantitative assessment of the total environment impact. For this paper, the life cycle of press consists of manufacturing phase, usage phase and end-of-life treatment. A comparative LCA analyzing multiple products offers an objective means of comparing different products. It can explain which product is more favorable for environment, and provide some basis for deciding which is better synthetically.

Recently with the increase of attention on environment, comparative LCA has been applied in many fields of industry as an effective tool. Gert Van Hoof, Diederik Schowanek and Tom CJ Feijtel applied this method to laundry detergent formulation, and chose the most favorable one by analyzing five solutions [2]. Domnita Fratila investigated several aspects of the machining process from an ecological perspective, and performed the comparative life cycle of near-dry machining and flood machining referring to the gear milling. SimaPro7.1.5 software and the ecoinvent1.5 database were used in the case [3]. Minjung Kwaka and Louis Kima presented a method for comparative LCA and demonstrated how to compare the environment impact performance of two machines. The impact generated by the same amount of production was used as the basis for comparison [4]. However, due to the complexity of the structure, few studies have been carried on as to press. So this paper refers to studies in other fields and conducts a comparative LCA for servo press and flywheel press.

This paper uses LCA for analyzing servo press and flywheel press respectively. The rest of the paper is organized as followed. Section 2 presents the goal and scope, as well as the functional unit of this LCA study. Section 3 describes the data collected for the two types of press. By modeling product life cycle with the help of SimaPro7.3 software, inventory of life cycle is obtained and analyzed. Section 4 summarizes the study along with suggestions for future work.

2 GOAL AND SCOPE

2.1 Objective of the Study

Energy consumption and pollutant emissions of servo press and flywheel press are analyzed, evaluated and compared. Among them resources and environmental problems about manufacturing are focused on and discussed the most. By comparing the results, the key links can be found and will be the target for improving in the next stage. The results of the study can be used for decision making during the product purchase, planning and design process.

2.2 System Boundary

The life cycle includes three parts: manufacturing phase, usage phase and end-of-life treatment. In order to make the results valid and significant, it is especially important to determine the system boundary, which must include the main process of life cycle. As to the links that have smaller impact on environment and use less resource, it is permissible to ignore them, so we can improve the work efficiency without changing the results. According to standard ISO14041, figure 1 gives an overview of the system boundary.

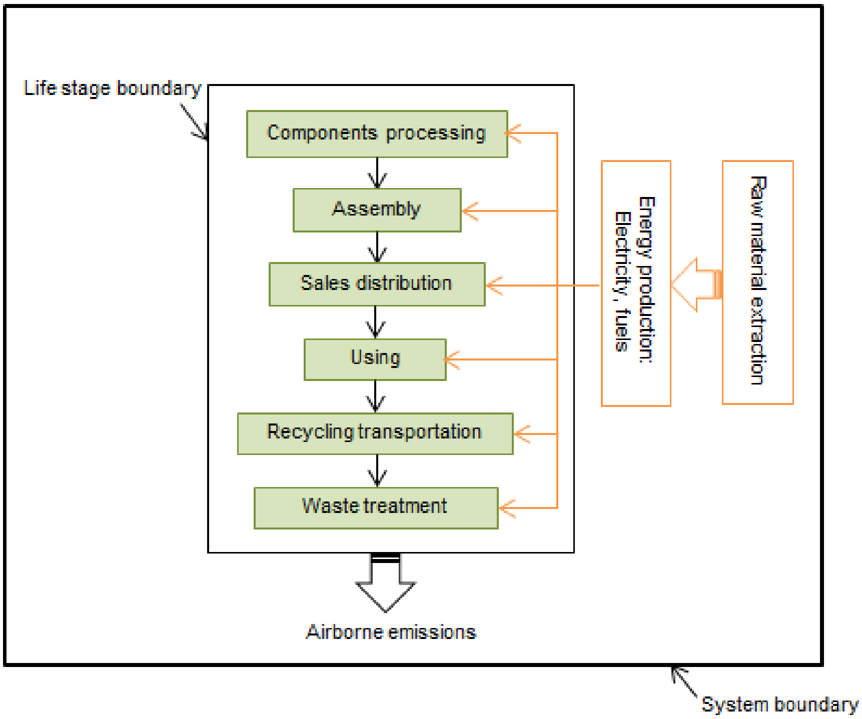

Figure 1: System boundary.

2.3 Function Units

The functional units in this study are a set of servo press and a set of flywheel press. To make a fair comparison, the study set functional units to accomplish the same amount of total production. Therefore, some parameters like nominal pressure, physical dimension and the maximum loading height should be equal and have little to do with this paper. Table 1 shows some specific parameters for two types of press.

Parameters	Servo press	Flywheel press
Mass	200tons	206.7tons
Rated power	45kw×2	45kw×2
Service life	365*30 days	365*30 days
Efficiency	33%	20%

Table 1: Basic parameters.

3 INVENTORY

3.1 Manufacturing

For the manufacturing of press, at first we need to analyze the production process of every component. By comparison, there are some similarities and differences in the structure of servo press and flywheel press.

System	Servo press	Flywheel press
Working	Crank shaft, rod shaft	Crank shaft, rod shaft
Transmission	Gear or belt drive	Gear or belt drive
Operating	PLC, servo drive	Brake, clutch
Energy	Ac servo motor, capacitor	Motor and flywheel
Support	Press frame	Press frame

Table 2: Structure of two presses.

As table 2 shows, the working, transmission and support systems are almost the same. However, for energy system, servo press uses permanent magnet ac servo motor instead of traditional ac asynchronous motor and adds storage capacitor as electronic flywheel. For operating system, servo press uses IMS-M2 ac servo driver instead of brake and clutch. In conclusion, there are mainly six types of components in servo press: crank shaft, spindle, rod shaft, slide block, rail and press frame. Three types of components such as flywheel, brake and clutch are added in flywheel press based on the differences in operating and energy system between them.

Then assembly the components which are produced before, this stage also requires a small amount of power consumption. According to empirical equation of size and consult density of the material, the weight of every component can be calculated [5]. Table 3 shows parts, materials and qualities of servo press and flywheel press. The total weights of two types are obtained, 200 tons for servo press and 206.7 tons for flywheel press.

Type	Material	Quality	Servo/flywheel
Crank shaft	45 steel	19.6t	Servo and flywheel
Spindle	45 steel	4.8t	Servo and flywheel
Rod shaft	ZG35 cast steel	24.4t	Servo and flywheel
Slide block	HT20-40 cast iron	32.7t	Servo and flywheel
Rail	HT20-40 cast iron	5.4t	Servo and flywheel
Press frame	Q235A	113.1t	Servo and flywheel
Flywheel	HT20-40 cast iron	5.3t	Flywheel
Brake	08AL steel	0.9t	Flywheel
Clutch	Powder metallurgy	0.5t	Flywheel

Table 3: Component classification.

The raw materials are divided into several kinds such as 45 steel, ZG35 cast steel, HT20-40 cast iron and Q235A. This part of data can be got from the database IDEMAT 2001 in the software. Manufacturing processes in this phase include forging, machining, turning, milling, scrub, heat treatment, casting, surface treatment (electroplating, phosphate), press frame wielding.

Take crank shaft as an example, the process route is identified as follows: 1.Cast blank in casting factory and normalize. 2. Be sent to the storage department. 3. Rough machining in the medium speed factory. 4. Normalized in the heat treatment plant and eliminate stress. 5. Fine machining in the medium speed factory. 6. Nitrogen treatment in the heat treatment plant. 7. Finishing cut in the medium speed factory and finally be sent to self-made parts storage. Some data can be obtained through database in the software such as forging and machining. Some can be obtained through referring to the relevant papers and project report, such as heat treatment [6], casting [7]. The rest can be found in Ecoinvent database (www.ecoinvent.org).

Table 4 quantifies energy consumption and airborne emissions during the manufacturing process of crank shaft. The first horizontal shows some forms of energy, the third horizon represents some types of emissions: carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), methane (CH_4), particulate matters (PM), sulfur dioxide (SO_2), sulfur monoxide (SO) and hydrocarbons (HC).

Energy consumption	Coal	Oil	Natural gas	Hydro power	Uranium	Potential	Other
	628.5GJ	141.1GJ	67.5GJ	6.49GJ	4.41GJ	3.68GJ	4.74GJ
Airborne emissions	CO_2	CO	NO_x	CH_4	PM	SO_2	SO
	55.1t	691.9kg	178.8kg	103.9kg	59.9kg	268.5kg	22.3kg

Table 4: Manufacturing inventory of crank shaft.

After all the components have been modeled in the software SimaPro7.3, we put them together to establish the assembly. By the use of the software, energy consumption and pollutant emissions inventory can be obtained for both servo press and flywheel press. Table 5 quantifies energy consumption in manufacturing phase. The first horizontal represents some types of energy, the rest two horizontals show the detailed amount of energy on behalf of servo and flywheel press respectively. Energy consumption of servo press is 6553.7GJ, while the one of flywheel press is 6595.2GJ, 4.10% larger than the former. The main reason is that servo press calls off some components like flywheel, brake and clutch. Energy from coal is the main factor of all kinds of energy, and the percentage of it is about 68%. This is decided by the energy structure in China.

Table 6 quantifies airborne emissions in manufacturing phase. The largest amount of emissions is CO_2, 403.7 tons for servo press and 420.5 tons for flywheel press, the latter is 3.14% larger than the former. There is a gap in order of magnitude between CO_2 and other emissions. As another greenhouse gas, the discharge values of CH_4 are 520.6 kilograms and 563.2 kilograms. Therefore, the key to control airborne emissions is how to reduce CO_2 emission.

	Coal	Oil	Natural gas	Hydro power	Uranium	Potential	Other
Servo press	4279.5GJ	1280.6GJ	642.9GJ	38.0GJ	22.1GJ	34.7GJ	37.9GJ
Flywheel press	4468.2GJ	1323.3GJ	666.2GJ	39.3GJ	22.9GJ	36.6GJ	38.7GJ

Table 5: Energy consumption inventory of manufacturing.

	CO_2	CO	NO_x	CH_4	PM	SO_2	SO
servo press	403.7t	6.14t	769.7kg	1.26t	850.8kg	1.44t	316.6kg
flywheel press	420.5t	6.23t	815.5kg	1.30t	910.4kg	1.48t	337.3kg

Table 6: Airborne emissions inventory of manufacturing.

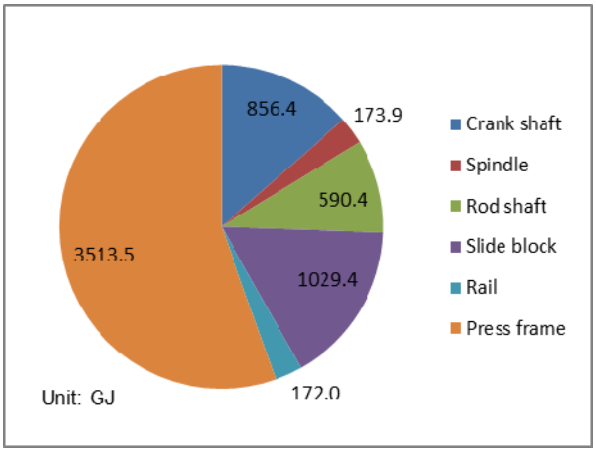

Figure 2: Energy consumption of servo press components.

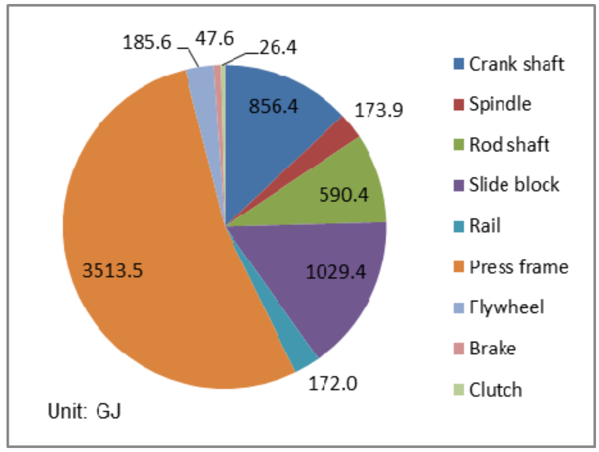

Figure 3: Energy consumption of flywheel press components.

Figure 2 and figure 3 show energy consumption of each component in servo press and flywheel press, as well as the proportion. Press frame is the basic and the most important part. Its structure is complex and its weight is big, so large amount of finish is needed to produce press frame. Take servo press for example, it accounts for 55.5% through calculation. Put the rest from larger to smaller, 16.2% is for connecting rod shaft, 13.5% is for crank shaft, 9.3% is for slide block, 2.8% is for spindle and 2.7% is for rail. How to design press frame reasonably becomes the direction in the following research. Under the conditions that meet stiffness requirement, reducing the quality can help not only reduce manufacturing time and energy consumption, but also be beneficial to the environment. Press frame can be divided into two kinds based on the structure. Casting structure performs well in shock absorption and the materials are convenient to supply. However, it has heavier weight and poorer rigidity, more suitable for batch production. To the contrary, welding structure has lower weight and better stiffness, and the appearance is more beautiful. But the property of weakening vibration is poor, more suitable for unit production. This paper has chosen the wielding structure to manufacture press frame.

3.2 Usage

The electric energy consumption in usage phase is quite large, and it is the main factor of environmental impact. Through drawing procedure and simulation experiment, servo press can economize energy by 40% compared with flywheel press [8]. According to the related information on energy consumption, it is supposed that the servo motor rated power is 45 kilowatt and the servo press is driven by two motors. Assume that the press can serve for 30 years and work 10 hours a day. The total power consumption in usage phase: 45*30*10*365=9.85*10^6kwh=3.55*10^13J. While the efficiency of flywheel press is lower but the energy consumption is higher. Under the same amount of production, the total power of flywheel press is: 3.55*10^13J*140%=4.97*10^13J.

According to the energy structure of China, the primary energy production composition proportion is as follows: energy from coal occupies 76.70%, energy from oil occupies 10.44%, energy from natural gas occupies 3.89%, and hydro power, uranium and potential power occupy the rest 8.97%. This section of data is referred to the database ETH-ESU in the software.

	Coal	Oil	Natural gas	Uranium	Potential
Servo press	279.9GJ	7944.9GJ	132.0GJ	5111.3GJ	1359.0GJ
Flywheel press	390.8GJ	10926.9GJ	176.7GJ	7154.3GJ	1902.3GJ

Table 7: Energy consumption inventory of usage.

	CO_2	CO	NO	CH_4	PM	HC	SO
Servo press	3174.0t	687.2kg	3678.1kg	883.6kg	600.1kg	22.6kg	7142.2kg
Flywheel press	4428.4t	878.8kg	4860.1kg	1218.5kg	833.8kg	31.5kg	9975.1kg

Table 8: Airborne emissions inventory of usage.

Table 7 quantifies energy consumption in usage phase. The values are 14262.8 GJ and 20551.0 GJ respectively, and the latter is 38.60% larger than the former. Table 8 quantifies airborne emissions in usage phase. The amount of CO2 emissions is 3174.0 tons for servo press and 4428.4 tons for flywheel press, 39.52% larger than the former.

3.3 End-of-Life Treatment

The materials of components in both servo press and flywheel press are mostly steel and iron. As the main raw material, waste iron and steel is the useful resource that can be recycled. In order to reduce product and improve the efficiency of making steel, the waste need to be processed, which includes selection, disintegration and collection. Then harmful impurities should be wiped off as far as possible. 70% of the rest is used for steelmaking, 8% is used for auxiliary steel and casting [9]. The data is obtained through the database BUWAL250 which is developed by Swiss packaging research institute. As to 1000 kilograms waste iron, 900 kilograms steel sheets will be got by recycling and smelting. Although a certain amount of energy need to be put in, the steel sheets serve as raw materials for production, which will save more energy as a circle.

Table 9 tells that 2652.4G and 2741.3GJ energy can be saved respectively in this phase. In addition to economizing a great deal of energy, some valuable and recycling materials are produced in the meantime. Therefore, many negative values appear in table 9 and table 10. From the aspect of airborne emissions, 298 tons CO_2 and 1540 kilograms CH_4 are reduced in the end-of-life treatment of servo press, which is of great help to relieve the global greenhouse effect.

	Coal	Oil	Natural gas	Uranium	Potential
Servo press	-1454.0GJ	-233.0GJ	33.2GJ	319.3GJ	8.4GJ
Flywheel press	-1502.7GJ	-240.8GJ	34.3GJ	330.0GJ	8.55GJ

Table 9: Energy consumption inventory of end-of-life treatment.

	CO_2	CO	NO	CH_4	PM	HC	SO
Servo press	-149t	-1210kg	-142.0kg	-770kg	9.9kg	263.0g	-270.0kg
Flywheel press	-154.0t	-1250.6kg	-146.8kg	-795.8kg	10.3kg	271.8g	-279.1kg

Table 10: Airborne emissions inventory of end-of-life treatment.

3.4 Total Life Cycle

On the basis of analyzing the inventory of three phases, we add the results together to get the whole life cycle inventory for both servo press and flywheel press.

According to table 11 and table 12, energy consumption in the whole life cycle of servo press is 19836.7GJ, while that of flywheel press is 25775.6GJ. The amount of CO_2 emissions are 3428.7 tons and 4694.9 tons. The amounts of CH_4 emissions are 634.2 kilograms and 985.9 kilograms. Because the unit kilogram greenhouse effect of CH_4 is far more than that of CO_2.By consulting related references, the carbon dioxide equivalent is 25, which means that the amount of CH_4 produced in the life cycle of servo press equals to 15.9 tons of CO_2. So we cannot ignore its emissions.

Figure 4 and figure 5 compare two types of press about energy consumption and CO_2 emissions in three stages and the whole life cycle. Energy consumption in usage phase accounts for the most, the percentages are 80.1% and 84.2% respectively. So do CO_2 emissions in this phase, the percentages are 92.6% and 94.3%. It is because that the service life is quite long, the machines need a lot of power to meet the demands of work, resulting in energy consumption and environmental impact. It is obvious to find that almost all values of flywheel press are bigger than servo press. Due to its rigid driving mode, flywheel press has low efficiency but high energy consumption.

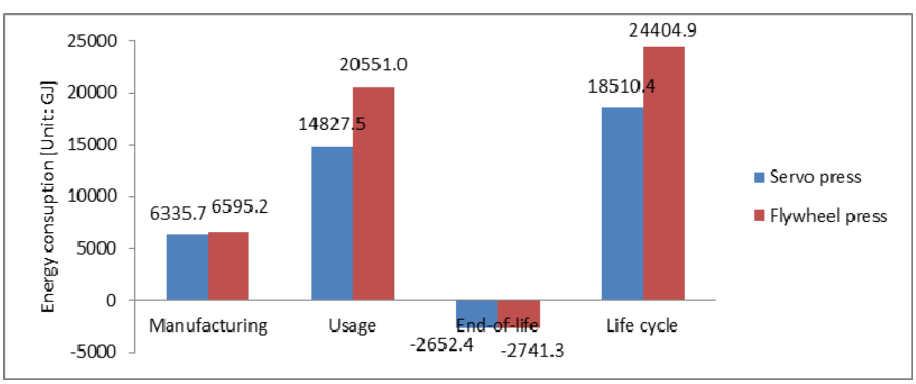

Figure 4: Comparative energy consumption of two presses.

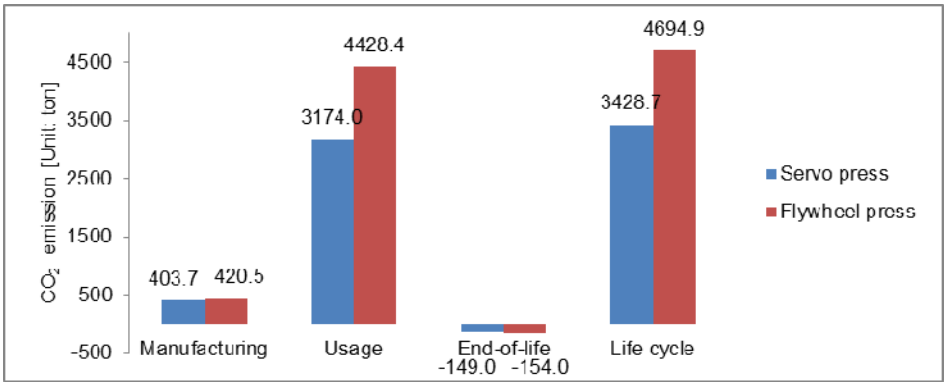

Figure 5: Comparative CO2 emission of two presses.

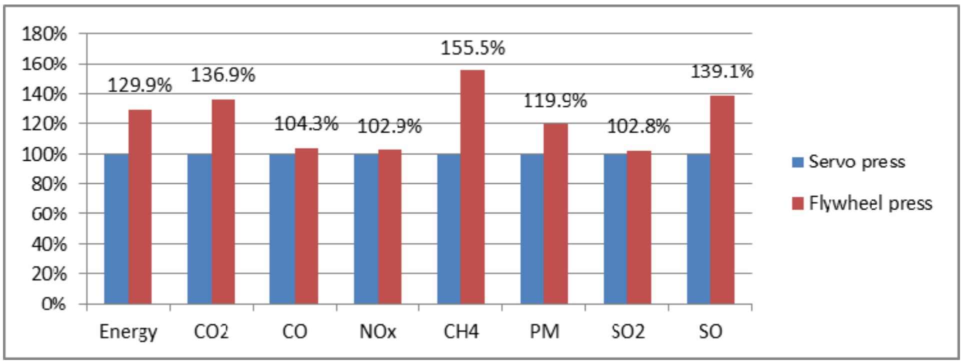

Figure 6: Comparative relative value of two presses.

	Coal	Oil	Natural gas	Hydro power	Uranium	Potential	Other
Servo press	3105.4GJ	8992.5GJ	808.1GJ	38.0GJ	5452.7GJ	1402.1GJ	37.9GJ
Flywheel press	3356.3GJ	12009.4GJ	877.2GJ	39.3GJ	7507.2GJ	1947.5GJ	38.7GJ

Table 11: Energy consumption inventory of total life cycle.

	CO_2	CO	NO_x	CH_4	PM	SO_2	SO
Servo press	3428.7t	5.62t	5.05t	634.2kg	1.46t	1.44t	7.19t
Flywheel press	4694.9t	5.86t	6.26t	985.9kg	1.75t	1.48t	10.0t

Table 12: Airborne emissions inventory of total life cycle.

Figure 6 presents the relative value of energy consumption and airborne emissions. Set every index of servo press to 100%, the amounts of corresponding index of flywheel press are expressed in the form of percentage. It is easy to find that emissions of flywheel press are larger more or less than the servo press.

The reason why flywheel press consumes 29.9% more energy than servo press in life cycle is discussed in two aspects. On one hand, more complicated structure of flywheel press will affect the manufacturing stage. On the other hand, the rigid driving mode of flywheel leads to lower efficiency and higher consumption. For airborne emissions, the index of servo press is also better than that of flywheel press. Such as CO_2 emission, the latter is 36.9% more than the former. Therefore, servo press has many advantages like energy conservation and environmental protection. But the cost of servo press is higher, because the development level for high power servo motor is still low in China, which hinders the research and development of servo press. There is a relatively large gap in the key technology compared with advanced countries. So comprehensive consideration should be taken when make decisions during the product purchase, planning and design process.

4 CONCLUSIONS AND FUTURE WORK

This paper presents a comparative LCA study conducted for servo press and flywheel press. The study demonstrates how LCA can be applied to the comparison of two different machines. As the premise, we should ensure that two types of press accomplish the same amount of work. The results show that the usage phase dominates in the whole life cycle with regard to both energy consumption and environmental impact. We need to note that CO_2 emissions produced by coal power in this stage may greatly aggravate the greenhouse effect.

In detail, 19836.7GJ energy is needed for the whole life cycle of servo press, and the amount of energy for flywheel press is 25775.6GJ, 29.9% larger than the former. With regard to air emissions, the largest one is CO_2, 3428.7 tons for servo press and 4694.9 tons for flywheel press. In compare with CO_2, the quantities of other airborne emissions are negligible, such as CO 5.62t and 5.86t, CH_4 634.2kg and 985,9kg, NO_x 5.05t and 6,26t respectively.

Future work will focus on how to collect more accurate data and improve manufacturing processes of components to make the results more practical.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

[1] Xiao, Y. (2009): Dynamic analysis and experimental research on 1100kN servo crank press. Master's thesis, Guangdong University of Technology.

[2] Hoof, G.-L., Schowanek, D. (2003): Comparative Life-Cycle Assessment of Laundry Detergent Formulations in the UK, in: Tender Surf, Vol. 40, pp. 266-275.

[3] Fratila, D. (2010): Macro-level environmental comparison of near-dry machining and flood machining, in: Journal of cleaner production, Vol. 18, pp.1031-1039.

[4] Kwaka, M., Kima, L. (2012): Comparative life cycle assessment of complex heavy-duty off-road equipment, in: Proceedings of the ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.

[5] Yuan, J. G. (2009): Finite element analysis of the servo press machining and structure optimization of the fuselage. Master's thesis, Huazhong University of Science and Technology.

[6] Yue, L. L .(2008): Environmental protection of bearing parts in heat treatment production, in: Bearing, Vol. 5, pp.44-47,53.

[7] Zhang, B. M. (2006): Energy consumption in foundry production, in: Modern cast iron, Vol. 26, No.3, 58-60.

[8] Fang, Y, Sun, Y. S. (2010): Analysis on energy consumption and energy-saving approaches for crank press, Vol. 35, No.1, pp. 110-113.

[9] Sun, M. H. (2009): Logistics system construction research on recycling of waste iron and steel. Master's thesis, Beijing Jiaotong University.

Three Dimensional Sustainability Assessment: A Case of Combustion Motor Industry in China

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Abstract

Industrial sustainability assessment becomes a new issue along with the depletion of natural resource and environmental degradation. As fundamental tools to quantitative assessment and management of sustainable development, indicator construction and evaluation methods have been a research focus. This paper intends to develop an innovative approach to evaluate corporate sustainability performance. Combined with specific situations of the combustion motor industry in China, a 3D sustainability assessment model is constructed by using Principal Component Analysis (PCA) and other multivariate statistics methods. Results of a case study based on 15 companies in the combustion motor industry demonstrated that the presented methodology is theoretically sound and easy to aggregate different indicators along all the three pillars of sustainability.

Keywords:

Sustainability; indicator construction; combustion motor industries; Principal Component Analysis (PCA); multivariate statistics method

1 INTRODUCTION

Today, as the sustainable development awareness increases, 'corporate sustainability,' which is a need for measuring the overall sustainability performance of a company, has become a hot issue. Manufacturing companies have found it advantageous to embrace responsibility for the impact of their activities on the environment, consumers, employees, communities, stakeholders and all other members of the public sphere. Moreover, consumers are increasingly interested in the environmental impact of the products they buy; investors want to judge how much reasonable governance should be made for environmental compliance, furthermore, governments and communities are gradually emphasizing corporate social responsibility.

Corporate sustainability is a measure of a company's performance in conducting a responsible and ethical business. There exist many different kinds of corporate sustainability definitions and most of them are analogous, which always include environment, society, economy, voluntariness and stakeholders [1]. The European Union has promulgated relative legislations to promote research on corporate sustainability and strengthen their social responsibilities, such as RoHS (The Restrictions of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment), WEEE (The Waste Electrical and Electronic Equipment directive) and Sustainability Reporting Guidelines formulated by Global Reporting Initiative.

Along with the appearance of national strategy of sustainable development, energy conservation and emission reduction, and green environmental protection policy in recent years, corporate sustainability has been transferred to comprehensive evaluation of economy, environment and society from economy alone. Sustainability reporting has received serious attention, and it has been accepted rapidly by corporations. A complete set of evaluation indexes and methods are major challenges in enterprise sustainability assessment and management. They are also the foundation of extracting and quantifying the information from sustainability reports in order to present a definite result to the stakeholders.

This paper intends to construct a complete, scientific, and operable evaluation indicator system and propose an effective and quantitative evaluation method for corporate sustainability assessment. The objectives are (1) to enrich sustainability theory research, (2) to provide a strong basis for compiling sustainability report, (3) to help corporations find the right direction for improvement, and (4) to promote the internal combustion engine industry to move towards a more environmental friendly and scientifically sound direction.

2 METHODOLOGY

The assessment methodology is to aggregate the sustainability indicators into a composite sustainability index (CSI) using multivariate statistical methods. CSI can be used to measure reliability and compare the sustainability of the companies and, at the same time, it is easy to understand by the stakeholders (policy-makers, consumers, etc.) [2]. Corporate sustainability can be divided into longitudinal and transversal evaluation based on the objectives of comparison. Transversal evaluation aims at evaluating sustainability of the same enterprise from different periods of time, while longitudinal methods evaluate the sustainability of different corporations in the same period. It can also be divided into single index evaluation and comprehensive index evaluation according to index property. Currently sustainability assessment methods are mainly focused on analytic hierarchy process (AHP), principal component analysis (PCA), neural networks, as well as some comprehensive methods such as fuzzy comprehensive evaluation method combined with AHP, correlate diagram analysis combined with dynamic graph analysis, and data envelopment analysis combined with AHP. The aforementioned methods above are not generally accepted because most of them are either subjective, or one-sided or difficult to operate. PCA is a variable reduction technique that can be used when variables are highly correlated; it can reduce the number of observed variables to a smaller number of principal components that account for most of the variation of the observed variables [3]. With PCA we can get not only the composite sustainability index but also the objective weights of each sustainability indicators without personal subjectivity. This paper uses the PCA method to assess the industrial sustainability by aggregating single index of individual indicators (environmental, economic and social). In order to make sure that the final index can represent the industry sustainability performance authentically, a set of indicators which can characterize the three-dimensional industry sustainability of environmental, economic and social aspects are formulated carefully with the method of validity and reliability analysis.

2.1 Principal Components Analysis

PCA was invented in 1901 by Karl Pearson [4]. Now it has become one of the most popular methods among multivariate techniques to construct sustainable development index. The central idea of PCA is to reduce the dimensionality of a data set which consists of a large number of interrelated variables, while retaining the variation that can reflect the information of the data set as much as possible. This is achieved by a mathematical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called Principal Components (PCs), which are linear combinations of original variables. The first principal component has the largest possible variance (that is, accounts for as much of the variability in the data as possible), and each succeeding component in turn has the highest variance possible under the constraint that it should be orthogonal to (i.e., uncorrelated with) the preceding components. The number of principal components is less than or equal to the number of original variables.

PCA is the simplest of the true eigenvector-based multivariate analyses which can be done by eigenvalue decomposition of a data covariance (or correlation) matrix or singular value decomposition of a data matrix, usually after standardizing the attribute data [5]. The results of a PCA are usually discussed in terms of component scores, sometimes called factor scores (the transformed variable values corresponding to a particular data point), and loadings (the weight by which each standardized original variable should be multiplied to get the component score) [6]. Specifically, PCA mainly consists of seven steps. Take the environmental indicators as an example, these steps are:

Step 1: construct a data matrix of n company/year × p indicators variables. Before developing the PCA, all the variables should be signed as positive or negative in order to make them unidirectional [7] to facilitate the possibility of pillar aggregation and to derive the total sustainable indicator for each company.

Step 2: Standardize the variables. The data are then normalized to zero mean and unit variance.

Step 3: Work out the correlation matrix.

Step 4: Calculate the eigenvalues and eigenvectors of correlation matrix and loadings of the variables.

Step 5: Select the number of principal components (PCs) which is determined by the accumulative amount of variance reaching up to 85%.

Step 6: Aggregate the data into a single environmental sustainability index (or environmental sustainability score) of each company by the following formula:

$$PCA_{env}(i) = \frac{\sum_{k=1}^{j} F_{ki}\sqrt{\lambda_k}}{\sum_{k=1}^{j}\sqrt{\lambda_k}}, i = 1,2...n \quad (1)$$

Where, F_{ki} is the coordinate of the company i in the component k (and j is the number of the retained components, $j \le p$) and λ_k is the eigenvalue of the component k.

Step seven: interpret the results. The single index from step 6 can give the information about the relative value of environmental sustainability of the companies. The higher the index, the better is the environmental sustainability of the company [8].

It should be pointed out that there are some essential conditions when conducting PCA. Firstly, the selected indicators should be able to characterize the industrial sustainability performance of the environmental, economic and social perspectives. Secondly, the environmental, economic and social sustainability indicators should be constructed separately using PCA, and then combined together to form a composite sustainability index for overall sustainability performance analysis [8]. Thirdly, the data of the sustainability indicators should be quantitative, available and reliable, because the PCA is a quantitative analysis method. In the case study section we collected the data of indicators from the combustion motor industry in China. Lastly, the variance contribution of the first PC must reach up to 50% or 4~5 times higher than the second PC in order to ensure the validity of the method.

2.2 Reliability and Validity Analysis

In order to ensure that the composite sustainability index could characterize the enterprise's sustainability, reliability and validity analysis are conducted with the available and reliable data.

Reliability analysis is an effective method which can measure the stability and reliability of a certain comprehensive evaluation system. Reliability addresses whether repeated measurements or assessments provide a consistent result given the same initial circumstances. This paper conducted reliability analysis using α coefficient method (Cronbach's α factor) with the formula:

$$\alpha = \frac{n}{n-1}\left(1 - \frac{\sum_{i=1}^{n} S_i^2}{S_x^2}\right) \quad (2)$$

Where, n is the number of the indicators, S_i^2 is the sample variance of indicator i, and S_x^2 is the total sample variance of all indicator variables.

Validity entails the question, 'does your measurement process, assessment, or project actually measure what you intend it to measure?' In other words, it detects the measurement accuracy and authenticity. Validity analysis can be generally divided into content validity, criterion validity and construct validity analysis. Content validity and construct validity analysis are conducted in this paper.

Content validity is used to examine whether the selected items could represent the content under measurement. In this paper, content validity analysis is measured by the correlation coefficient between the single indicator and the initial sustainability index. Structure validity is analyzed through ensuring that the variance contribution ratio of the first PC is over 50% when using PCA method to calculate the sustainability, or 4 to 5 times bigger than the second PC.

The results of reliability and validity analysis are the basis for the trade-off of indicators. The following conditions should be satisfied in order to ensure that the method used in enterprise sustainability measurement is effective and reliable:

(1) Coefficient α is greater than 0.6;

(2) In content validity analysis, the correlation coefficient between a certain indicator and the sustainability index is greater than 0.5;

(3) In the structure validity analysis, the loadings between correlated indicators and the first PC is greater than 0.5;

(4) A retained indicator could improve the reliability coefficient α;

3 CASE STUDY AND RESULTS ANALYSIS

In order to illustrate the validity and practicability of the evaluation method, a total of 15 Chinese combustion motor manufacturing companies are investigated to assess their sustainability in the year 2010 from economy, environment and social aspects. In order to eliminate the influence of different size of the companies and keep their comparability, a necessary 'Functional Unit' is needed for some relative indicators. In this paper the 'Functional Unit' is defined as 'unit industrial added value', and in order to keep the confidentiality of the industry data, the companies under investigation are represented by company 1 to15.

3.1 Construction of Initial Sustainability Indicators

Sustainable development indicators (SDIs) are used to collect, process and use information with the goal of making better decisions, directing smarter policy choices, measuring progress and monitoring feed-back mechanisms in all of the sustainability pillars [9][10]. A comprehensive, valid and measurable sustainability indicators framework is the base for conducting PCA. Therefore the construction of the indicators framework is very important.

The initial indicators framework can be constructed based on the basic criteria and impact assessment guidelines, and specifically reflects the needs of the combustion motor industry in China. Policy relevance and representativeness, analytical soundness, readily available and reliable data have been chosen as the criteria in measuring corporate sustainability [8] as well as specialized criteria for each environmental, economic and social dimension [1]. Global Reporting Initiative (GRI) is also a good source of reference assessment guideline. Besides, the indicators could also be selected from relative published literatures and corporate sustainable development report. The sustainability indicators of environmental, economic and social aspects selected in this paper are as follows.

Environmental Indicators	EN1	Energy consumption
	EN2	CO_2 emissions by weight
	EN3	SO_2 emissions by weight
	EN4	NO_x emissions by weight
	EN5	Total water consumption
	EN6	Total waste water volume
	EN7	Percent of recycled / reused water
	EN8	Total solid waste
	EN9	Percent of reused solid waste
	EN10	Chemical oxygen demand (COD) emissions
	EN11	Ammonia nitrogen in the waste water emissions
	EN12	Investments in environmental protection
Economic Indicators	EC1	Total assets
	EC2	Total sales
	EC3	Sales growth rate
	EC4	Total profit
	EC5	Asset-liability ratio
	EC6	Profit rate to net worth
	EC7	Current assets turnover
	EC8	Operating net cash flow
	EC9	Investing activities net cash flow
	EC10	All-personnel labor productivity
Social Indicators	S1	Technical engineering and R & D personnel number
	S2	Employee training ratio
	S3	Employee turnover rate
	S4	R&D Expenditure
	S5	Customer satisfaction
	S6	Community spending and charitable contributions
	S7	Female percentage in management levels

Table 1: The initial sustainability indicators framework.

3.2 Assessment Operation (Take Economy Aspect as Example in Certain Processes)

(1)Construction of the original data matrix

The original data matrix of economic indicator is constructed with 15 companies and 12 environmental indicators, 10 economic indicators, and 7 social indicators. The original data in this study are mainly from 《2011 year book of China auto industry》, sustainable development annual report 2010 and companies annual economic report. The data are converted into the 'unit industrial added value' and have been unidirectional processed.

(2)Reliability analysis

Reliability analysis of the indicators is conducted to ensure the value of α reaching up to 0.6, In the economic aspect, indicators EC2, EC3, EC5, EC7 are removed; in the social aspect, indicators S1, S2, S3 are removed, while in the environment aspect, the indicators are all retained for the initial value of α is 0.946 which satisfies the predetermined condition.

(3)Construct validity analysis

PCA is used to analyze the construct validity of the retained indicators. Loadings of correlated indicators with the PCs are calculated. The result showed that the loadings between the correlated indicators and the first PC of economic and social aspects are all greater than 0.5. In the environment aspect, indicators EN2, EN6, EN7, EN9 are removed after construct validity analysis.

(4)Calculate the initial sustainability

PCA is conducted to calculate the initial sustainability of each company with the retained sustainable indicators after reliability and construct validity analysis.

(5)Content validity analysis

In content validity analysis, the correlation coefficient between the retained indicators and the initial sustainability are calculated separately. According to the conditions of content validity analysis, economic indicator EC6, social indicator S5 are removed because the correlation coefficient are less than 0.5, and the environmental indicators are all retained. The final indicator system for sustainability assessment after reliability analysis, validity analysis is as follows:

	Economy		**Environment**		**Society**	
Reliability Analysis	Reliability Statistics		Reliability Statistics		Reliability Statistics	
	Cronbach's Alpha	N of Items	Cronbach's Alpha	N of Items	Cronbach's Alpha	N of Items
	0.792	6	0.946	8	0.709	4
	Indicators	Cronbach's Alpha if Item Deleted	Indicators	Cronbach's Alpha if Item Deleted	Indicators	Cronbach's Alpha if Item Deleted
	EC1	0.692	EN1	0.926	S4	0.566
	EC4	0.795	EN3	0.931	S5	0.766
	EC6	0.788	EN4	0.928	S6	0.621
	EC8	0.785	EN5	0.955	S7	0.601
	EC9	0.792	EN8	0.957		
	EC10	0.683	EN10	0.926		
			EN11	0.926		
			EN12	0.951		

	Economy				**Environment**			**Society**		
Construct validity analysis	PCs	PC1	PC2	PC3	PCs	PC1	PC2	PCs	PC1	PC2
	Eigenvalues	3.0617	1.4467	0.8458	Eigenvalues	6.0084	0.7911	Eigenvalues	2.1897	2.1156
	Variance absorption	0.51	0.241	0.141	Variance absorption	0.751	0.099	Variance absorption	0.547	0.279
		0.51	0.751	0.892		0.751	0.85		0.547	0.826
	Correlated indicators (loading)				Correlated indicators (loading)			Correlated indicators (loading)		
	EC1	0.89	0.274	0.226	EN1	0.991		S4	0.879	-0.397
	EC4	0.571	0.672	0.325	EN3	0.955		S5	0.458	0.794
	EC6	0.618	-0.672	-0.239	EN4	0.980		S6	0.799	-0.403
	EC8	0.619	-0.455	0.500	EN5	0.622		S7	0.755	0.406
	EC9	0.584	0.461	-0.572	EN8	0.589				
	EC10	0.915	-0.219	-0.235	EN10	0.995				
					EN11	0.991				
					EN12	0.669				

	Economy		**Environment**		**Society**	
Content validity analysis	Indicators	Correlation Coefficient with Initial sustainability	Indicators	Correlation Coefficient with Initial sustainability	Indicators	Correlation Coefficient with Initial sustainability
	EC1	0.931	EN1	0.987	S4	0.961
	EC4	0.786	EN3	0.949	S5	0.159
	EC6	0.284	EN4	0.973	S6	0.888
	EC8	0.493	EN5	0.604	S7	0.571
	EC9	0.601	EN8	0.621		
	EC10	0.753	EN10	0.990		
			EN11	0.987		
			EN12	0.685		

Table 2: Results of sustainability indicators.

1) Economic indicators: EC1, EC4, EC8, EC9, EC10

2) Environmental indicators: EN1, EN3, EN4, EN5, EN8, EN10, EN11, EN12

3) Social indicators: S4, S6, S7

(6)Calculate the final sustainability

PCA is used to calculate the final economic, environment and social sustainability score of each company based on the indicators retained after content validity analysis.

The assessment processes are conducted using SPSS software and Table 2 shows the analyzed results including reliability statistics, eigenvalues, variance absorption, loadings of correlated indicators and correlation coefficient between the retained indicators and initial sustainability.

Table 3 shows the results of the initial and the final sustainability as well as the rankings of each company associated with the final economic, social and environmental sustainability score separately.

Companies	***Initial Sustainability Scores***			***Finial Sustainability Scores***							
	Economy	Environment	Society	Economy	Ranking	Environment	Ranking	Society	Ranking	Overall	Ranking
Company1	2.299	0.012	-0.701	1.799	2	0.012	4	-0.567	11	1.244	4
Company2	-1.077	7.435	-0.190	-1.320	14	7.435	1	-0.724	12	5.391	1
Company3	0.158	0.772	-0.419	-0.700	10	0.772	2	-0.211	8	-0.139	6
Company4	1.300	-1.544	-0.673	0.985	4	-1.544	15	-0.846	13	-1.404	10
Company5	1.583	-0.741	-0.167	2.327	1	-0.741	9	0.200	5	1.786	3
Company6	0.931	-0.518	-0.391	1.463	3	-0.518	7	0.139	6	1.083	5
Company7	0.178	-1.003	-0.666	0.376	6	-1.003	11	-1.382	15	-2.010	14
Company8	0.184	-1.382	-0.336	0.389	5	-1.382	14	-0.496	10	-1.490	11
Company9	-0.234	-0.753	-0.271	-0.197	7	-0.753	10	-0.307	9	-1.257	9
Company10	-0.825	-0.572	0.768	-0.888	13	-0.572	8	1.266	2	-0.194	7
Company11	-0.526	-1.081	-0.370	-0.517	9	-1.081	12	-0.148	7	-1.745	13
Company12	-0.445	-1.121	-0.453	-0.434	8	-1.121	13	-0.877	14	-2.432	15
Company13	-1.179	-0.175	-0.039	-1.757	15	-0.175	6	0.226	4	-1.706	12
Company14	-0.802	-0.032	0.419	-0.822	12	-0.032	5	0.644	3	-0.210	8
Company15	-0.785	0.703	3.489	-0.704	11	0.703	3	3.082	1	3.081	2

Table 3: Results of the initial and the final sustainability.

In order to demonstrate the comprehensive sustainability of each company, an overall sustainability is defined as the sum of economic, social and environment sustainability score.

3.3 Results Analysis

Table 2 shows that 16 indicators are selected as the final set of sustainability indicators by reliability analysis, construct validity analysis and content validity analysis. The composite sustainability index and sustainability scores of individual dimensions are shown in Table 3. The higher the final sustainability score, the better the company's sustainability for we have set each indicator as positive sign before conducting the PCA. For most corporations sustainability of economy and society is better than environment in general which indicates that further improvement should be made on environment sustainability. There are 5 companies obtain positive value in the composite sustainability index, while other 10 companies obtain negative total score. Company 2, Company 15 and Company 5 show the best sustainability performance, while Company 12, Company 7, Company 11 obtain the lowest scores along with their sustainability performance measurement. With this assessment model, the strengths and weaknesses of each company's sustainability performance could be distinguished and the improvement opportunities can be obtained by analyzing the correlation matrix and loadings of variables. As for Company 8, it has weak sustainability performance from Table 3 because its environmental sustainability score is very low. Table 2 shows that the first component (PC1) is highly correlated with EN3, EN10, EN1, and EN11. So Company 8 should take some measures in these four aspects to improve its environmental sustainability performance.

4 CONCLUSIONS

This paper presents a 3D sustainability assessment model to select the sustainability indicator framework and evaluate the sustainability performance of companies based on PCA and other multivariate statistics method. A case study is conducted to demonstrate that the method is theoretically sound and practically applicable. Using this methodology, the company's sustainability level can be obtained by the composite index-sustainability score. The main factors which influence the company's sustainability most can also be find out from the loadings of variables, and then specific measures could be taken to improve the company's sustainability performance. It should be pointed out that some effort has to be taken in order to put this model into practical use. For instance, the sustainability indicators framework should be made more comprehensive and the validity of the indicators data should be guaranteed.

5 ACKNOWLEDGMENTS

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6 REFERENCES

[1] Carin, L., Alan, C. B., Ron, P. G. (2005): Assessing the Sustainability Performances of Industries, in: Journal of Cleaner Production, Vol. 13, pp. 373-385.

[2] Soler-Rovira, J., Soler-Rovira, P. (2008): Assessment of Aggregated Indicators of Sustainability Using PCA: The Case of Apple Trade in Spain, in: Proc.of the 6th Int. Conf. on LCA in the Agri-Food Sector, Zurich, pp. 133-143

[3] Jolliffe, I. T. (2002): Principal Component Analysis, Springer, New York.

[4] Pearson, K. (1901): On Lines and Planes of Closest Fit to Systems of Points in Space, in: Philosophical Magazine, Vol. 11, No. 2, pp. 559-572.

[5] Abdi, H., Williams, L. J. (2010): Principal Component Analysis, in: Wiley Interdisciplinary Reviews: Computational Statistics, Vol. 2, pp. 433-459.

[6] Shaw, P. J. A. (2003): Multivariate Statistics for the Environmental Sciences, Hodder-Arnold, ISBN 0-340-80763-6.

[7] Jha, R., Murthy, K. (2003): An Inverse Global Environmental Kuznets Curve, in: J Comp Econ, Vol. 31, No. 2, pp. 352-368.

[8] Tao, L., Hongchao, Z., Chris, Y., Zhichao, L., Chengcheng, F. (2012): A PCA-based Method for Construction of Composite Sustainability Indicators, in: The International Journal of Life Cycle Assessment, Vol. 17, No. 5, pp. 593-603.

[9] Hossein, M. H., Shinji, K. (2011): Dynamic Sustainability Assessment of Countries at the Macro Level: A Principal Component Analysis, in: Ecological Indicators , No. 11, pp. 811-823.

[10] Rametsteiner, E., Pülzl, H., Alkan-Olsson, J., Frederiksen, P. (2011): Sustainability Indicator Development- Science or Political Negotiation?, in: Ecol. Indic, No. 11, pp. 61-70

Life Cycle Assessment of Urea Formaldehyde Resin: Comparison by CML (2001), EDIP (1997) and USEtox (2008) Methods for Toxicological Impact Categories

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Abstract

This paper presents a Life Cycle Assessment comparison using CML (2001), EDIP (1997) and USETox (2008) methods for the impact assessment of urea formaldehyde resin (UF) used in the production of wood panels in Brazil. The impact results were focused just on toxicological categories like human toxicity and ecotoxicity. The main hotspots of UF resin were free formaldehyde air emissions to aquatic and terrestrial ecotoxicity and for human toxicity category, the results showed that emissions to air of nitrogen oxides from urea (raw material) are also very important and not just free formaldehyde air emissions like previously checked in literature.

Keywords:

Life cycle impact assessment; Toxicological impacts; Urea formaldehyde resin

1 INTRODUCTION

Wood based panels are used on construction and furniture sectors. In the furniture segment, stands out panels made from wood particles/fibers and synthetic adhesive like: particleboard/Medium Density Particleboard (MDP), Medium Density Fiberboard (MDF) and Hard Density Fiberboard (HDF) [1] and [2].

The MPD is current produced and consumed worldwide and is internationally traded [3], and Brazil is the 6th major producer [4]. MDP is a composite material consisting of agglutinated and compact particles mainly from reforested wood, produced in three layers, which the two surface layers consist of particles with smaller dimensions, and the inner layer, comprised of larger particles [5].

About the adhesives, urea formaldehyde (UF) resin is the most common applied on wooden panels [6], [7], that is a polymeric and thermoset resin prepared via condensation process. However, in literature, there are environmental concerns about its impacts mainly because air emissions of free formaldehyde from healing process at wooden based panel production [8], [9] and [10].

Free formaldehyde air emissions might cause cancer in humans [10], and in concentrations above 0.1 ppm can cause effects on human health such as watery eyes, nausea and eyes, nose and throat irritation [8]. In this sense, environmental impacts from UF resin seems to be specially related to human toxicity.

Despite highlighting free formaldehyde emissions, it is necessary to include the whole life cycle perspective [11] to identify and measure the environmental hotspots from UF resin. For this, the current paper aims to identify such hotspots from resource extraction to use phase of the UF resin applied to produce MDP based panel for the Brazilian context, with focus on toxicological impact categories. For the life cycle impact assessment (LCIA) phase, it was selected three different methods.

2 METHODOLOGY

We applied the technique of Life Cycle Assessment (LCA) in accordance with ISO 14040 and 14044 standards, considering the life cycle of UF resin produced in Brazil. For this, we selected three different midpoint methods: CML (2001), EDIP (1997) and USEtox (2008), considering just toxicological impact categories.

2.1 Scope Definition

Functional unit

UF resin is used as a binder, agglutinating wooden particles during panel manufacturing. Thereby, the functional unit was the production of 1m³ of MDP (or 630 kg), without coating, with 15 mm of thickness and 8% of moisture content.

For each 1 m³ of MDP is necessary to consume 71.65 kg of UF resin, with 67.0% of solids content and molar ratio formaldehyde/urea of 1.35.

System boundaries

For the life cycle inventory phase, all dataset of inputs and outputs were extracted from [5], who studied the LCA of MDP production in Brazil, in a cradle to gate perspective, including forestry production (for *Eucalyptus* species), UF resin production, industrial MDP manufacturing and others complementary subsystems. However, this paper focuses in studying the toxicological life cycle impacts from UF resin, according to the system boundaries in Figure 1. In this case, we analyzed UF resin production divided in three steps: extraction of resources, UF resin manufacturing and UF resin using.

- **Resource extraction:** we considered consumption of electricity, diesel (transportation of inputs), water, urea, methanol, formic acid and sodium hydroxide. These are the main inputs applied to produce UF resin, and according to [5], many of the input chemicals begin with natural gas or some other fossil fuel or feedstock for the life cycle inventory.
- **Manufacturing of UF resin:** the process begin with the conversion of methanol by catalytic oxidation in a reactor vessel to obtain an aqueous form of formaldehyde. After, the formaldehyde is cooled and sent to the absorber with water to produce an aqueous solution. Then the formaldehyde is sent to a batch reactor, where it mixed with urea. The reaction process is managed by parameters as pH, temperature, ratio of

formaldehyde/urea, and rate of charging until desired degree of polymerization is achieved. Others inputs are also employed during the process like catalysts and additives in small quantities as sodium hydroxide and formic acid.

- **UF resin using:** the resin is applied into MDP based panel production (see Figure 1). The industrial production of MDP involves UF resin application during the blending process. This is a process in which UF resin and others additives are distributed in the form of droplets onto the wood particles in quantities of 10-15% based on dried weight of particles [2]. After, blended particles form mats that are conveyed into large hot presses. The hot pressing process lasts at sufficient temperature, pressure and duration to cure the resin, and it results on air emissions of hazardous air pollutants mainly represented by free formaldehyde. So, in this step it was assumed just emissions of free formaldehyde.

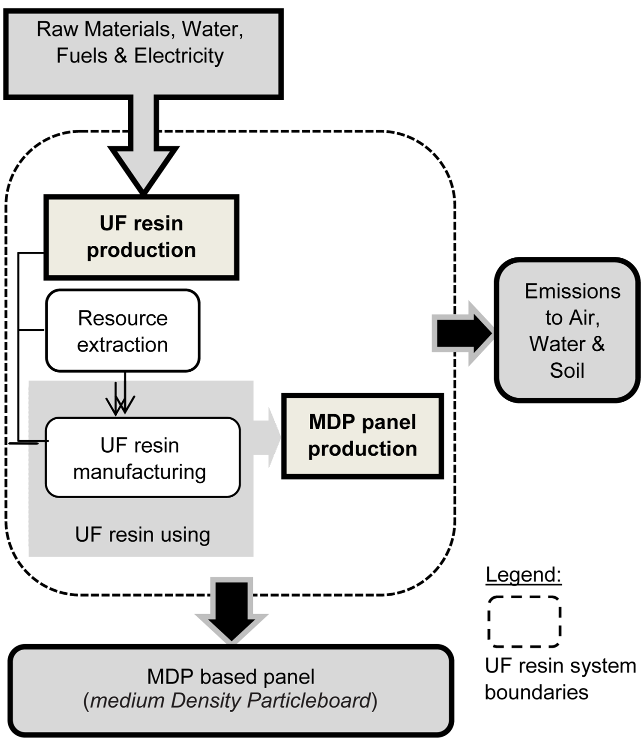

Figure 1: UF resin system boundaries.

This LCA study was conducted using the computational tool GaBi 4.4 Software-Systems and Databases, educational version. With this software the life cycle of UF resin was modeled.

2.2 The Selected LCIA Methods

The main LCIA methods were analyzed according to the following parameters:

- Evaluation level (midpoint / endpoint);
- Scope of application;
- Impact categories addressed by each method.

Among methods we have selected only those which comprise midpoint evaluation level. This choice is justified because the complexity and inherent uncertainties of midpoint modeling are smaller than for endpoint modeling [12]. Regarding the scope of application, it is understood that only methods classified as global are applicable in countries such as in Brazil. In this sense, CML (2001), EDIP (1997) and USEtox (2008) methods were selected because they are indicated for LCA anywhere in the world [13]. The toxicity of a substance varies according to the substance itself and the way it is exposed, and the impact categories that each method considers are different and with diverse units as shown below:

- **CML (2001):** Freshwater Aquatic Ecotoxicity [kg DCB-Equiv.]; Marine Aquatic Ecotoxicity [kg DCB-Equiv.]; Terrestric Ecotoxicity [kg DCB-Equiv.]; Human Toxicity [kg DCB-Equiv.];
- **EDIP (1997):** Ecotoxicity soil chronic [m³ soil]; Ecotoxicity water acute [m³ water]; Ecotoxicity water chronic [m³ water]; Human toxicity air [m³ air]; Human toxicity soil [m³ soil]; Human toxicity water [m³ water];
- **USEtox (2008):** Ecotoxicity [PAF m³.day]; Human toxicity [cases].

We choose just toxicological impact categories, which allowed a better understanding about the toxicological impacts mainly related to UF resin - checking if free formaldehyde emissions are really the major hotspot.

For CML (2001) and EDIP (1997) methods, the results analysis about ecotoxicity categories were performed by compartment (water and soil), since they have models with characterization factors that assess aquatic and terrestrial ecotoxicity subcategory separately.

For aquatic ecotoxicity, the EDIP (1997) method distinguishes between acute and chronic ecotoxicity, i.e. between short-term and long-term toxic effects, while CML (2001) method only considers chronic effects in the ecotoxicity category [14]. CML (2001) method evaluates aquatic ecotoxicity from the following subcategories: freshwater ecotoxicity and marine water ecotoxicity [13], while the EDIP (1997) method does not have this distinction.

The USEtox (2008) method presents its characterization model aimed at assessing the impacts related to freshwater ecotoxicity, without impacts related to soil [13], [15].

About toxicity related to humans, the CML (2001) method expresses the human toxicity impact in one total score, while EDIP (1997) gives a human toxicity score for each compartment (air, water, soil) [14]. The characterization modelling peformed in these methods are based on the same elements: fate and exposure analysis and effect analysis [14]. The USEtox (2008) method express the characterization factors for human toxicity in units of toxic comparative [16], providing the estimation of increased morbidity in the total human population per unit mass of chemical substance emitted (cases/kg emitted) [16], considering factors for cancerous, non-cancerous and totals impacts. The impact category of all methods covers the impacts on human of toxic substances present in the environment.

3 RESULTS AND DISCUSSION

3.1 Comparison of Toxicological and Non-toxicological Impact Results

Based on results from LCIA phase, the environmental impacts are summarized in Table 1. The impacts are aggregated for the three steps: resource extraction, UF resin manufacturing and UF resin using defined for the functional unit established.

LCIA METHOD	IMPACT CATEGORY	TOTAL
CML (2001)	Freshwater Aquatic Ecotoxicity [kg DCB-Equiv.]	2.70E+00
	Marine Aquatic Ecotoxicity [kg DCB-Equiv.]	2.99E+02
	Terrestric Ecotoxicity [kg DCB-Equiv.]	1.46E-01
	Human Toxicity [kg DCB-Equiv.]	6.35E-01
EDIP (1997)	Ecotoxicity soil chronic [m³ soil]	2.95E+04
	Ecotoxicity water acute [m³ water]	6.36E+02
	Ecotoxicity water chronic [m³ water]	4.21E+03
	Human toxicity air [m³ air]	1.82E+09
	Human toxicity soil [m³ soil]	1.89E+00
	Human toxicity water [m³ water]	2.79E+00
USEtox (2008)	Ecotoxicity [PAF m³.day]	8.92E-01
	Human toxicity [cases]	6.48E-07

Table 1: Overall environmental impacts of UF resin for the three LICA methods studied.

Considering Table1 results, a first relevant question could be: are these impacts the more important for the UF resin life cycle including also non-toxicological categories? Thus, Figure 2 shows the relative importance of toxicological impacts compared to the non-toxicological environmental results by CML (2001) and EDIP (1997). In terms of relative impacts (%), toxicological results are aggregated based on Table 1, and the non-toxicological impacts are aggregated considering the following others categories: abiotic depletion, acidification, eutrophication, global warming, photochemical ozone creation and ozone layer depletion.

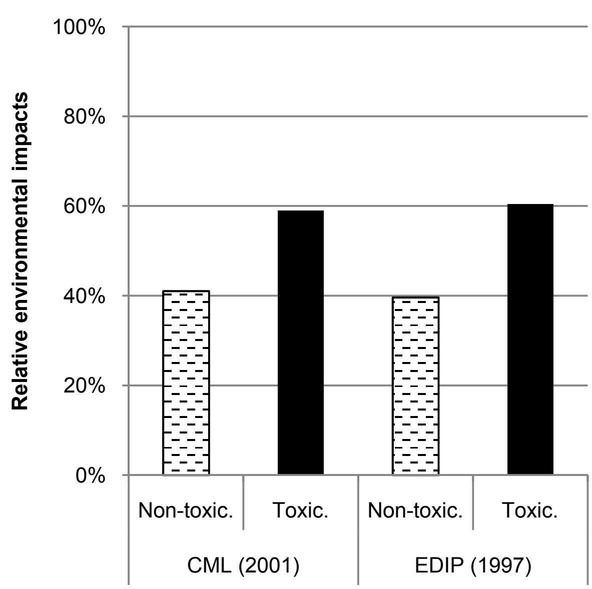

Figure 2: Non-toxicological and toxicological relative impacts (%) of UF resin by CML (2001) and EDIP (1997).

Figure 2 evidences that toxicological results were relatively more effective for environmental impacts of UF resin. For CML (2001) method, the toxicological impacts showed 30.36% higher, and for EDIP (1997) the results were 34.35% higher than those for non-toxicological impacts. Most part of non-toxicological impacts are from resource extraction step and toxicological impacts are predominantly from UF resin manufacturing and UF resin using steps as exposed in Figure 3.

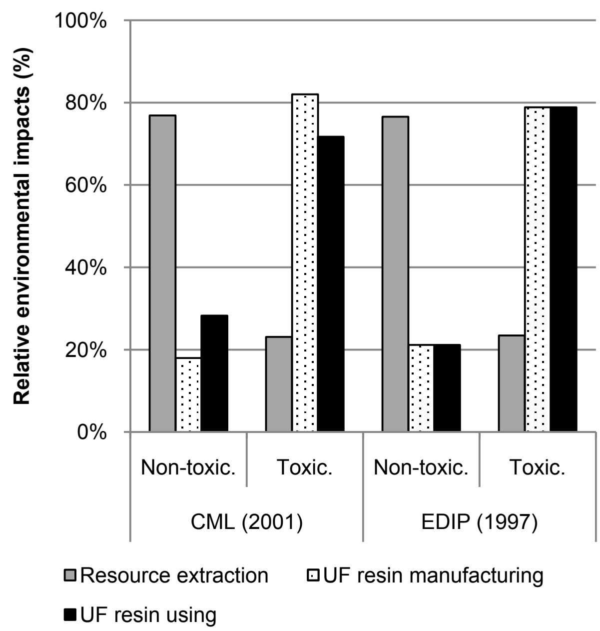

Figure 3: Non-toxicological and toxicological relative impacts (%) per step of UF resin life cycle.

According to Figure 3, the impacts varied of each method for all steps. For non-toxicological impacts, the results were more different for UF resin using step, with 25.18% of deviation between CML (2001) and EDIP (1997). For toxicological impacts all results varied less than 9%. For non-toxicological categories of both methods, [5] highlighted that main differences happen for photochemical ozone creation, because EDIP (1997) presents database about 39% longer than CML (2001), with characterization factors of more substances. EDIP (1997) includes characterization factors of NMVOCs groups and CML (2001) considers summer smog with SO_2 as main contributor [14], and also unsaturated organic compounds are commonly higher in terms of characterization factors than EDIP (1997). CML (2001) also includes abiotic depletion impact category and EDIP (1997) does not include it. So, in this paper the deviation results for non-toxicological categories were related especially due to these different approaches.

3.2 Details about Toxicological Impact Results

In view of a better understanding about toxicological impacts from UF resin life cycle, Figure 4 and Figure 5 present comparison results of ecotoxicological impacts (related to water and soil) for EDIP (1997), CML (2001) and USEtox (2008). After, Figure 6 shows toxicological results related to humans.

In Figure 4, taking into account the ecotoxicological impact categories related to water, the impacts results showed no tendency to converge impacts to a single UF resin life cycle step. By CML (2001), the impacts are more related to UF resin manufacturing and using steps to freshwater aquatic ecotoxicity potential (FAEP) category, and more related to resource extraction step to marine aquatic ecotoxicity potential (MAEP). By EDIP (1997), it should be highlighted that impacts of UF resin manufacturing and using steps are more expressive, and by USEtox (2008), impacts of resource extraction and UF resin manufacturing steps are more expressive.

The main hotspots occurred due to air emissions of free formaldehyde by EDIP (1997); inorganic air emissions of metals to MAEP and free formaldehyde to FAEP by CML (2001); and emissions of cyanide from urea production (raw material); and free formaldehyde emissions by USEtox (2008). Thus, emissions to air of free formaldehyde appeared predominantly in all methods studied, and its impacts varied from 42% by USEtox (2008) to 98% to FAEP by CML (2001) of all impacts.

In Figure 5, about ecotoxicological impacts related to soil, it is clear that most part of impacts is from UF resin using step. In this case, they happen due to free formaldehyde air emissions, with 90-99% of all impacts, respectively by CML (2001) and EDIP (1997).

As previously introduced, in literature environmental impacts from UF resin seems to be primarily related to human toxicity from air emissions of free formaldehyde. However, here we identified relevant impacts of free formaldehyde also to aquatic and terrestrial ecotoxicity for all LCIA methods investigated.

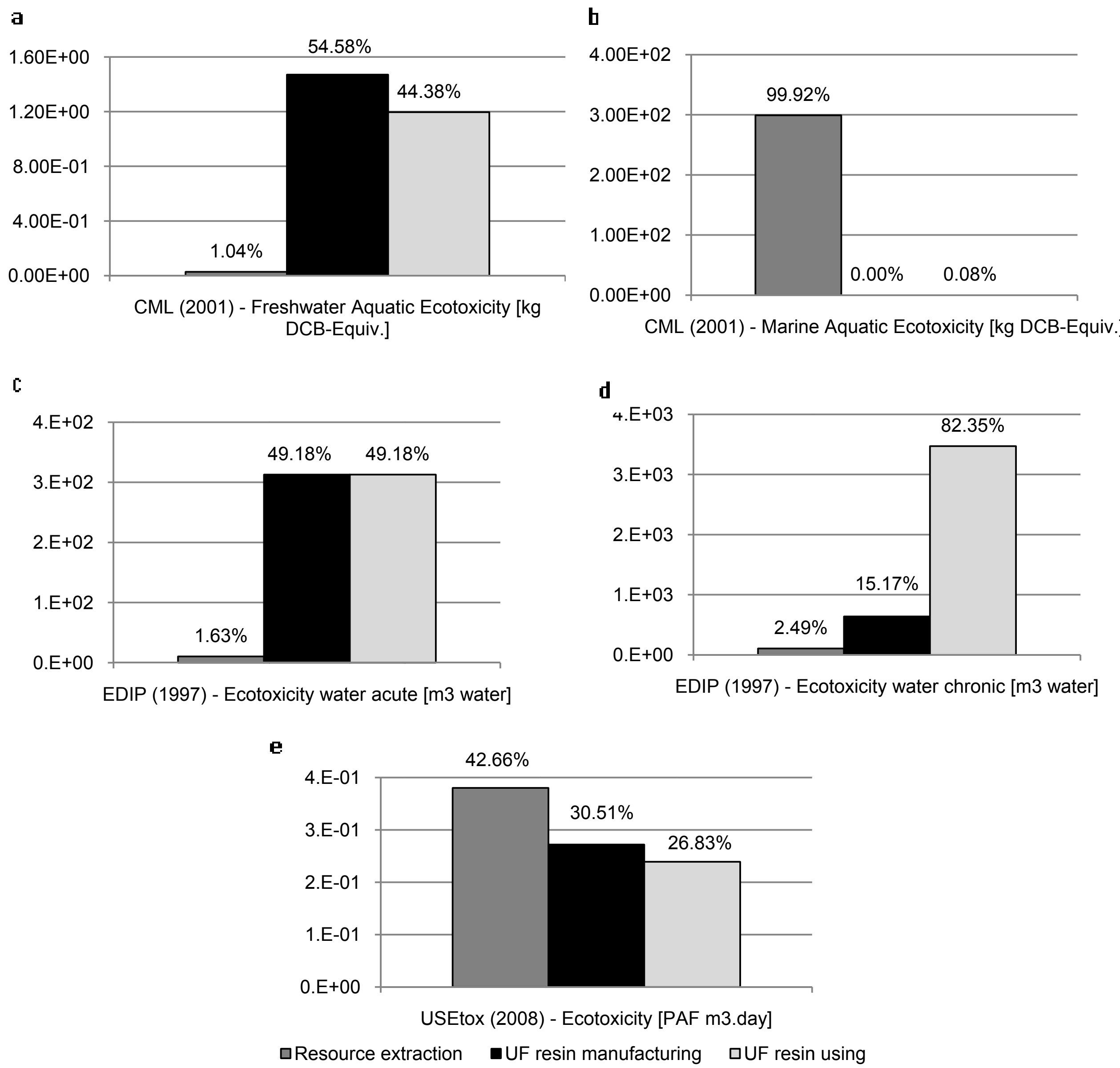

Figure 4: Ecotoxicological impact categories, related to water.

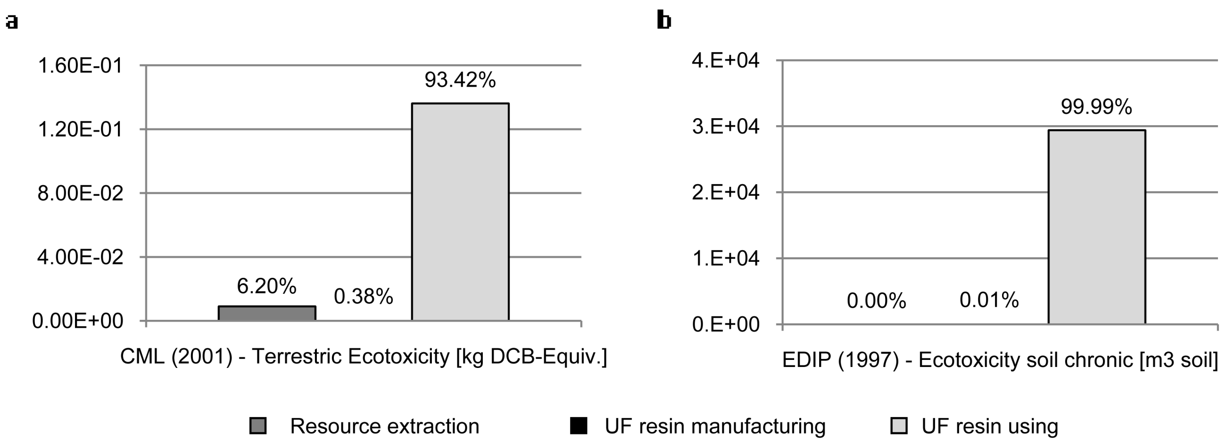

Figure 5: Ecotoxicological impact categories, related to soil.

In Figure 6, for toxicological impacts related to humans, the impacts showed again no tendency to converge to a single UF resin life cycle step. By CML (2001), 80.90% of impacts are from resource extraction due to nitrogen oxides air emissions from urea. By USEtox (2008), UF resin using step is responsible for 99.65% of impacts due to free formaldehyde emissions. Finally, by EDIP (1997), most part of impacts of resource extraction are from human toxicity water (HTW) and human toxicity soil (HTS), mainly due to nitrogen oxides air emissions from urea production; UF resin using step was relevant to human toxicity air (HTA) and HTS categories, both due to free formaldehyde air emissions. UF resin manufacturing step was not relevant in terms of relative impacts compared to other steps evaluated for all LCIA methods.

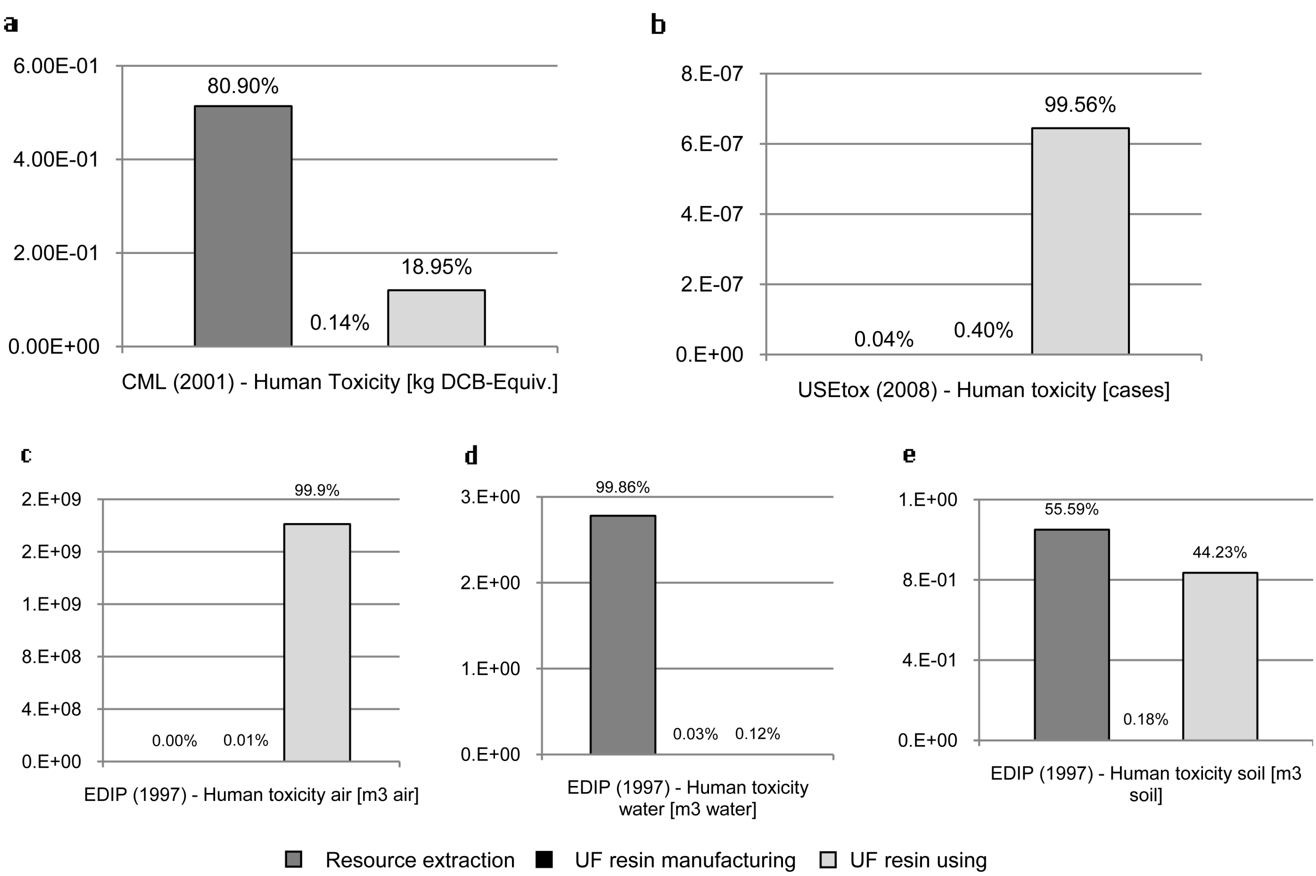

Figure 6: Toxicolgical impact categories, related to humans.

Given results about toxicological impacts for humans, emissions to air of nitrogen oxides and free formaldehyde were the main hotspots to UF resin life cycle. This is an interesting finding considering that UF resin human toxicity impacts are commonly attributed just to free formaldehyde.

4 ACKNOWLEDGMENTS

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5 CONCLUSIONS

This study aimed to identify and quantify the environmental toxicological impacts of the UF resin applied at wood-based panel industry, considering the MDP based panel case in Brazil, in order to check if free formaldehyde air emission is really a relevant hotspot. It was selected EDIP (1997), CML (2001) and USEtox (2008) LCIA methods and all results were compared.

It was verified that toxicological impact results were more effective than non-toxicological results by EDIP (1997) and CML (2001). Toxicological impacts were more than 30% superior in comparison to non-toxicological impacts.

The toxicological impacts results were evaluated in two categories: ecotoxicity and human toxicity; and also in three UF resin life cycle steps: resource extraction, UF resin manufacturing and UF resin using. All steps were relevant for the two impact categories studied and it is not possible to define a single step as the major contributor for the toxicological impacts. However, UF resin using step were predominant for terrestrial ecotoxicity category than others steps for all LCIA methods.

In literature most part of environmental impacts from UF resin seems to be more related to air emissions of free formaldehyde to human toxicity. However, we found relevant impacts of free formaldehyde also to aquatic and terrestrial ecotoxicity for all LCIA methods. Additionally, for human toxicity category, the results showed that emissions to air of nitrogen oxides are also very important and not just free formaldehyde air emissions, being both of them the main hotspots to UF resin life cycle in this category.

We suggest the development of more researches involving others LCIA methods to continue evaluating UF resin life cycle impacts focused on toxicological categories due to its theme’s relevance. It could also be addressed environmental comparisons of the current resin with other ones that can be applied as adhesive to produce wood based panels like: melamine-urea-formaldehyde, phenol-formaldehyde, isocyanate, tannin-urea-formaldehyde, etc.

6 REFERENCES

[1] Thoemen, H.; Irle, M.; Sernek, M. (2010): Wood-based panels - an introduction for specialists, Brunel University Press, London.

[2] Iwakiri, S. (2005): Painéis de madeira reconstituída, FUPEF, Curitiba.

[3] BIS Shrapnel. (2010): Particleboard in the Pacific Rim and Europe 2009 – 2013, BIS Sharpnel, Sydney.

[4] Biazus, A.; Hora, A. B.; Leite, B, G. P. (2010): Panorama de mercado: painéis de madeira, in BNDS Setorial, Vol. 32, pp.49–90.

[5] Silva, D. A. L. (2012): Avaliação do ciclo de vida da produção do painel de madeira MDP no Brasil, Master Thesis, University of São Paulo, São Paulo, Brazil.

[6] Maloney, T. M. (1993): Modern particleboard and dry-process fiberboard manufacturing, Miller Freeman, San Francisco.

[7] Wilson, J. B. (2009): Resins: a life-cycle inventory of manufacturing resins used in the wood composites industry, Oregon State University, Corvallis.

[8] Athanassiadou, E. (2000): Formaldehyde free aminoplastic bonded composites, in: Proceedings of 5th International Conference Environmental Pollution, p 15, Thessaloniki, Greece.

[9] Kinga, J. D.; Petrovici, V.; Zeleniuc, O.; Badescu, A. L.; Urdea, S. N. S.; Sangeorzan, L. (1996): Distribution of formaldehyde emission in particleboards, in: Proceedings of the 8th WSEAS International Conference on System Science and Simulation in Engineering. pp 153–159, Genova, Italy.

[10] European Panel Federation. (2004): Reclassification of formaldehyde by the International Agency for Research on Cancer (IARC) - a statement by the wood panels industry concerning workplace exposure, EPF Report, Brussels, Belgium.

[11] United Nations Environment Programme. (2007): Life Cycle Management. A Business Guide to Sustainability. Avaiable from:http://www.uneptie.org/shared/publications/pdf/DTIx0889xPA-lifeCycleManagement.pdf. (accessed 30.10.12).

[12] Hauschild, M Z; Goedkoop, M; Guinée, J; Heijungs, R; Huijbregts, M; Jolliet, O; Margni, M; De Schryver, A; Humbert, S; Laurent, A; Sala, S; Pant, R. (2012): Identifying best existing practice for characterization modeling in life cycle impact assessment. International Journal of Life Cycle Assessessment. DOI 10.1007/s11367-012-0489-5.

[13] EC-JRC, (2010): Analysis of existing environmental impact assessment methodologies for use in life cycle assessment - background document. ILCD Handbook - International Reference Life Cycle Data System, European Union. Avaiable from: http://lct.jrc.ec.europa.eu/assessment/assessment/projects#consultation_impact. (accessed 15.11.12).

[14] Dreyer, L. C.; Niemann, A. L.; Hauschild, M. Z. (2003): Comparison of Three Different LCIA Methods: EDIP97, CML2001 and Eco-indicator 99. International Journal of Life Cycle Assessment, Vol. 8, No 4, pp. 191-200.

[15] Pizzol, M.; Christensen, P.; Schmidt, J.; Thomsen, M. (2011): Eco-toxicological impact of “metals” on the aquatic and terrestrial ecosystem: A comparison between eight different methodologies for Life Cycle Impact Assessment (LCIA). Journal of Cleaner Production, Vol. 19, No, 6-7, pp.687-698.

[16] Rosenbaum, R. K.; Bachmann, T. M.; Gold, L. S.; Huijbregts, M. A. J.; Jolliet, O.; Juraske, R.; Koehler, A.; Larsen, H. F.; MacLeod, M.; Margni, M.; McKone, T. E.; Payet, J.; Schuhmacher, M.; van de Meent, D.; Hauschild, M. Z. (2008): USEtox—the UNEP-SETAC toxicity model: recommended characterization factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. International Journal of Life Cycle Assessment Vol. 13, No. 7, pp.532–546.

Life Cycle Assessment of Solar Chimneys

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Abstract

Climate change is increasingly becoming a significant issue globally and the use of solar thermal technology is one approach in managing the world's environment. There is now greater use of renewable energy sources in order to minimize the depletion of energy resources while providing an environmentally-friendly energy source that has minimal impact on the environment. It is thus important to be able to assess the environmental impact of different types of solar thermal technologies in order to have an understanding of the actual impact of solar thermal on the environment. Most solar thermal technologies need to use water in the production process to produce electricity. The most viable place to produce solar energy is in extremely hot climates like deserts where there is not much water to choose from. Most of the time water comes from sources that are far away and becomes expensive to transport the water to the solar plant sites. There is one solar thermal technology that does not require water to produce electricity. It is called Solar Chimney or Solar updraft tower. This paper will assess the environmental impact of Solar Chimneys across its life cycle using the Life Cycle Assessment approach (LCA). The contribution of this paper is providing further understanding of the environmental impact of solar chimneys across its life cycle particularly as new technologies in solar technology continue to be developed.

Keywords:

Solar Chimney; Solar upward draft tower; Hybrid power plant; Life Cycle; Solar Technology

1 INTRODUCTION

In most parts of the world, there is a growing awareness from companies, organizations and even political movements know that some alternative energy sources could have an important role to play in the reduction of global warming and green house gas emissions.

Recent studies have shown that Solar and Wind technologies are the most feasible green energy that can be produced over a long period of time. The most feasible areas to produce solar energy are in extremely hot areas like deserts in Africa and the Middle East which has low water reserves in those feasible areas. The need for water in these technologies has become critically important to obtain it cheaply and effectively [1]

Electricity generation in solar power plants require and consume water. Photovoltaic (PV) consumes water only for cleaning mirrors and surfaces and solar chimneys does not have a water demand to generate electricity. The amount of water used per megawatt hour (MWh) of electricity produced is called water intensity. The water intensity of electricity from a concentrating solar power (CSP) plant with wet cooling generally is higher than that of fossil fuel facilities with wet cooling. Although concentrated solar power (CSP) cooling technologies are generally the same as those used in traditional thermoelectric facilities, the CSP uses the least amount of water as shown below in Table 1. There are a few options that are available that don't use water in the production process.[6]

Estimate for Ivanpah based on calculations from public data; other data from U.S. Department of Energy. Accessed 7/26/10.

We have learned in the past to make use of three green technologies to do certain tasks, we use solar energy to heat water and to make greenhouses to grow food, we also have made use of chimney suction ventilation systems to cool buildings and windmills to ground grains and pump water. There is one green energy technology that uses a hybrid approach and does not require water to produce electricity; it is called a solar chimney also known as solar updraft tower. It is a hybrid plant which combines three of the above proven green technologies chimney effect, greenhouse effect and wind turbines. Air is heated by sunshine and contained in a very large greenhouse-like structure around the base of a tall tower; the resulting convection causes air to rise up the updraft tower. This airflow drives turbines, which produce electricity.

Technology	MWh
Estimate for Ivanpah solar-thermal (air cooled)	16
Solar photovoltaic (with panel washing)	30
Solar parabolic trough (air cooled)	78
Combined Cycle Gas (evaporated)	200
Coal (evaporative)	500
Solar power tower (evaporative)	600
Solar parabolic trough (evaporative)	800

Table 1: Water Consumption by Power Generation from solar power Status Report on Solar Thermal Power Plants (2006).

2 METHODOLOGY

Life cycle analysis (LCA) accounts for all impacts that a particular product might have from the extraction and supply of the raw materials through production and usage to when it is finally disposed of as waste (ISO14041/1998). Hybrid-Approach completes the generally used Process Chain Analysis by a model based on economic Input-Output-Tables(Marheinekeet al. 1999). Methodology allows a quick and easy estimation of the elementary flows of up- and downstream processes and commodity flows which are neglected and not included in the Process Chain Analysis.

3 DESIGN

Solar Chimney is a hybrid green technology that uses two of the main alternative energies wind a solar to generate electricity. It combines three elements; glass roof collector, chimney, and wind turbine which each element has been used for centuries to create energy. This combination of elements to generate electricity was already described (Gunther 1931) [15].

Figure 1: **Solar power chimney** - Prototype in Manzanares-Spain from concentrating solar power now (2008).

The power out is dependent on 2 main factors the collector area and chimney height. A larger area collects and warms a greater volume of air to flow up the chimney; collector areas as large as 7 kilometres (4.3 mi) in diameter have been discussed. A larger chimney height increases the pressure difference via the stack effect; chimneys as tall as 1,000 metres (3,281 ft) have been discussed.

With technology improving, the technology on the chimney has improved by installing telescopic collapsible features which enable adjustments of the chimneys height in order to prevent storm damage. Heat is stored inside the collector area. A saltwater thermal sink in the collector could 'flatten' the diurnal variation in energy output, while airflow humidification in the collector and condensation in the updraft could increase the energy flux of the system. Turbines can be installed in a ring around the base of the tower, with a horizontal axis. Carbon dioxide is emitted only negligibly as part of operations. Manufacturing and construction require substantial power, particularly to produce cement. Net energy payback is estimated to be 2–3 years [16].

These Solar Chimneys take up a large amount of area, deserts and other low usage sites are more likely to be used. A small tower may be a better option for remote regions and developing countries. With the low-tech approach would allow local resources and labour to be used for construction and maintenance

The EnviroMission design consists of a giant, round greenhouse like structure, under which air becomes trapped and gets very hot around 160 degrees Fahrenheit [17]. The hot air naturally rises, and would rush toward the tall tower in the centre, passing through 32 turbines, whose turning blades would run generators and create electricity. Heat can also be stored inside the collector area greenhouse or inside tubes filled with water to be used to warm the air later and increase energy storage as needed. Turbines can be installed in a ring around the base of solar updraft towers, with a horizontal axis, as planned for the Arizona project, or—as in the prototype in Spain—a single vertical axis turbine can be installed inside the chimney [17].

Typically carbon dioxide is emitted only negligibly while operating, but is emitted more significantly during manufacture of its construction materials, particularly cement. Net energy payback is estimated to be 2–3 years. A solar updraft tower power station would consume a significant area of land if it were designed to generate as much electricity as is produced by modern power stations using conventional technology. Construction is optimized in hot regions with large amounts of very low-value land, such as deserts, or otherwise degraded land. A small-scale solar updraft tower may be an attractive option for remote regions in developing countries. The relatively low-tech approach could allow local resources and labour to be used for its construction and maintenance [17].

Hybrid

Solar updraft towers can be combined with other technologies to increase output. Solar thermal collectors or photovoltaic can be arranged inside the collector greenhouse. This could further be combined with agriculture

4 FUNCTIONING

The solar chimney functioning principle is shown in the above figure 2. Solar radiation hits the glass roof collector which heats up the air and the ground below which forms a solar air collector. In the middle of the roof is a vertical tower with large air inlets at its base. At the base and the solar air collectors is airtight. As the air under the solar air collectors gets hotter it rises above the cold air and pushes in to the inlets and rises up the tower. Suction is created by the tower vacuuming in more hot air into to the tower from the solar air collectors, and cold air gets sucked in from the outer parameter which creates enough force to get the wind turbines to move in the tower which is converted in to electricity by using conventional generators. A 24/7 operation can be achieved by placing tight water-filled tubes or bags under the roof. The water heats up during day-time and releases its heat at night. These tubes are filled only once, no further water is needed. This result in solar radiation causes a constant updraft in the tower [17].

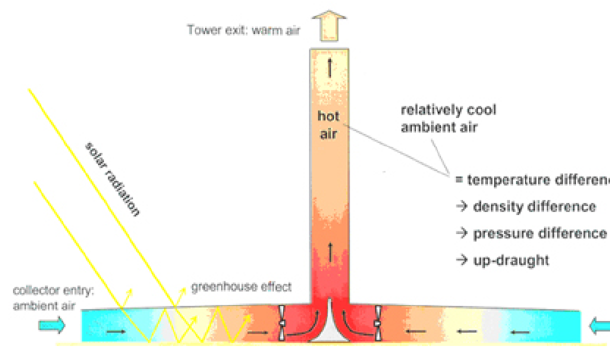

Figure 2: **Solar Chimney Functioning** Up-Draught solar tower and Down-Draught Energy Tower – A Comparison 2001.

5 TECHNOLOGY

5.1 The Collector

In a simple air collector the hot air is produced by the green house effect. The area is covered with glass or plastic filming about two to six meters collector increases with the height of the chimney base, so the air can be pushed vertically to reduce the friction loss. The covering helps to store short and long wave radiation from the ground. The ground under the roof heats up and transfers the heats the air flowing from outside the surrounding area to the chimney (10).

5.2 The Energy Storage

Black tubes are filled up with water only once in the entire life cycle of the plant and are laid side by side on the soil under the roof collector. Which means no evaporation takes place. The volume of water in the tubes corresponds to the power output that is desired (5cm to 20cm of water per tube) (17).

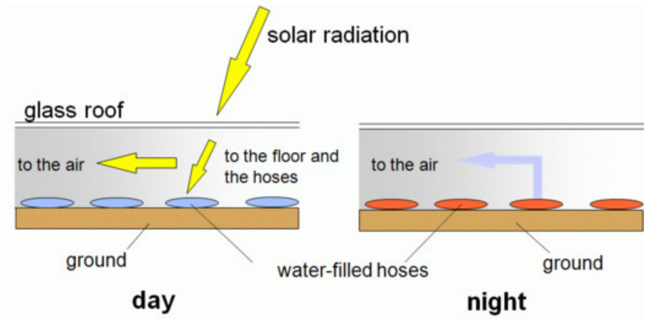

Figure 3: **Day and night energy storage** from Solar Chimney Simulation (2000).

The heat transfer between the black tubes and the water is greater than the ground surface and the deeper soils even at low water speed in the tubes, and heat capacity of water (4.2 kJ/kg) is much higher than that of soil (0.75 - 0.85 kJ/kg) the water inside the tubes stores a part of the solar heat and releases it during the night, when the air in the collector cools down therefore creating a 24 hour production period.

5.3 The Chimney

The chimney is the 'heart' of the plant. It is the plants thermal engine. It is a tube that creates pressure with low friction loss because of its smooth surface. The updraft of heated air in the collector is proportional to the air temperature rise in the DTcoll in the collector and the volume of the chimney. In a large solar chimney the collector raises the temperature by about 35k. This causes an updraft velocity in the chimney of about 15m/s. It is now possible for an operating solar chimney plant. A 1000 meter chimney can be built with no hassles. Solar chimneys are easy to construct. [19]

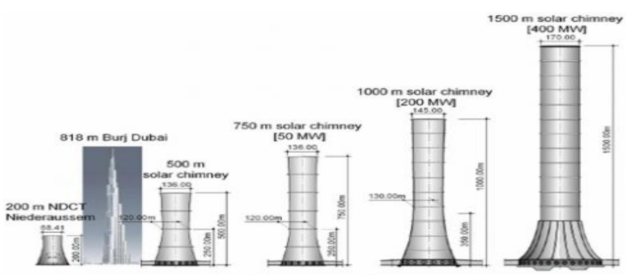

Figure 4: Heights of Solar Chimneys' and power outputs.

As can be seen from Figure 4 and Table 2 the solar Chimneys will be the biggest tower type structures to exist to man. Also the bigger you make the chimney the more power output would exist. For a 1,000 metre high chimney will produce 200 mega watts of power and 1,500m could produce 400 mega watts of power [19].

Capacity MW	5	30	100	200
tower height m	550	750	1000	1000
tower diameter m	45	70	110	120
collector diameter m	1250	2900	4300	7000
electricity output A GWh/a	14	99	320	680

Table 2: **Typical dimensions and electricity output Capacity MW 5 30 100 200** from the solar power tower 2003.

Chimneys are not difficult to build 1,000 metres high. There are already plans to build 2,000 metre skyscrapers [20]. A large diameter hollow cylinder, not slender and are subject to a few demands. There are a few ways to build the chimneys. The best are free standing in reinforced concrete. The guyed tubes, their skin is made of corrugated metal sheets, as well as cable-net design with cladding are also possible. All the structural designs already exist and do not need any new technology in order to construct them

5.4 The Turbines

The turbines use mechanical output in the form of rotational energy in the form of rotational energy which is powered by the air currently in the chimney. Turbines in a solar chimney do not work on staged velocity. Like a free running wind energy converter. It works like using cased pressure staged wind generator. This takes static pressure and converts it into rotational energy using a cased turbine. The power output of a cased pressure turbine is about eight times greater than that of a speed stepped open air turbine. The air speeds before and after the turbine is about the same. The output is achieved by the product of the volume and the fall in pressure at the turbine. By achieving this output the maximum energy yield the aim of the turbine regulation system is to maximize this product under all operating conditions. The blade speed is adjusted during operation to regulate power output according the changing airspeed and airflow. The blades need to be parallel to the airflow and allow air to flow through undisturbed and no drop in air pressure in order to produce electricity. These are the optimum blade settings. The electricity produced is maximised if the pressure drops at the turbine is about two thirds of the total pressure is available.

Figure 5: **Turbine** from Solar Chimney Simulation (2000).

6 LIFE CYCLE ASSESSMENT

Life Cycle Assessment (LCA) is a useful tool to assess the environmental impact of a product, process or service and together can be very useful to the comparison of similar products. Life Cycle Assessment can be very helpful to engineers and researchers. The application of the LCA methodology, can lead to techniques that minimize the magnitude of pollution, conserve fuels and ecological systems, develop and utilize cleaner technologies and maximize recycling Although LCA is a relatively new method it has been accepted by industries worldwide. LCA methodology is applied in the products eco-design, development of new techniques to improve products, as the global trend is towards to the environmental issues. The Life Cycle assessment can be used in all sorts of industries.

Environmental life cycle assessment is a method for the analysis of environmental effects of economic products. It covers a wide range of environmental themes and takes the total production chain 'from cradle to grave' into account. Life Cycle Assessment is to provide a holistic picture of the environmental impacts of a given system, while being relevant both at a global scale, i.e., for global impact categories such as climate change, and at a smaller scale, i.e., for regional impact categories. Among those, the LCA approach, which considers the whole product life cycle, is recommended by the European Union and UNEP. The EU communication on Integrated Product Policy states that "All products cause environmental degradation in some way, whether from their manufacturing, use or disposal. Integrated Product Policy (IPP) seeks to minimise these impacts by looking at all phases of a product's life cycle and taking action where it is most effective".

The stages of Solar Tower Power Plant's LCA from construction to recycling of its parts are the ones presented below:

- Raw materials excavation
- Materials processing
- Construction of the parts of Solar Power Tower Plant
- Transportation and assembly of the parts
- Operation of the Solar Tower Power Plant
- Decommissioning-Recycling
- Products disposal

The main operation of the system of Solar Power Tower is the exploitation of solar radiation and its conversion, firstly in thermal and continuously to electrical energy. In all the life cycle stages there are inputs and outputs. The inputs are energy, water and materials, while in outputs there are air and liquid emissions, solid wastes and the product, in this case electric power. In the operational stage the energy input is direct solar radiation that prostrates systems' sun-tracking mirrors. The functional unit of the analysis is set to be 1MWel and the operational life of the system is 30 years. The construction period is 3 years.

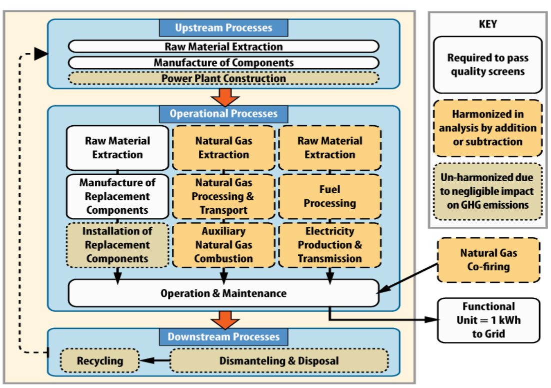

Figure 6: Life Cycle Stages.

In the analysis done, there are several assumptions made. For instance, during the operation period no replacement of any element of the Solar Tower Power Plant is taking place (Figure 1). Additionally, no hazardous gaseous or liquid emissions are released during operation of the solar power tower plant. In present study plant under study, there is no heat storage, thus no salt usage. In the case where there was heat storage no additional emissions occur; if a salt spill occurs, the salt will freeze before significant contamination of the soil occurs. Salt is picked up with a shovel and can be recycled if necessary [05].

The Solar Tower Power Plant has a nominal capacity of 1 MW and covers land and area of 4.07x10[6] m[2], of which 7000 m[2] [14] is the area covered by the heliostats.

The required materials for the construction of the plant are listed in table 1 and Figure 7[15].

Materials	Tons
Aluminum (0.29%)	32
Concrete (16.9%)	1850
Copper (64.34%)	7050
Chromium (12.5%)	1375
Glass (0.62%)	68
Plastic (0.1%)	11.5
Steel (5%)	545
Insulation (0.25%)	27.5
Total	**10959**

Table 3: Construction Materials.

Coal (MJ/Ton)	
Aluminium	1980
Concrete	360
Copper	13914
Chromium	51480
Glass	-
Plastic	7596
Steel	33840
Insulation	5464.14
Crude Oil (MJ/Ton)	
Aluminium	1.84884
Concrete	0.266676
Copper	27.9456
Glass	67.6
Plastic	45.582
Steel	23.3874
Insulation	39930
Natural Gases	
Aluminium	9205
Concrete	633.145
Copper	20265
Chromium	42700
Glass	154.4
Plastic	2660
Steel	11760
Insulation	72480
Total	
Aluminium	**11186.84884**
Concrete	**993.411676**
Copper	**34206.9456**
Chromium	**94246.456**
Glass	**222**
Plastic	**10301.582**
Steel	**45623.3874**
Insulation	**117874.14**

Table 4: **Energy usage for material production** from Life Cycle Assessment of a Solar Thermal Concentrating System (2008).

The energy used in the production of 1 ton of each material and its distribution is presented in Table 3. It is assumed that the materials are being transported from a region 100Km far from the plants' location with 200, 40tns diesel trucks. The diesel usage and the emissions from the trucks for 1Km distance are presented in table 3.

Input	Output		Distance
Diesel fuel 0.348 Kg	CH4	.0000197 Kg	1 tKm
	CO	0.00114 Kg	
	CO2	1.1 Kg	
	NOx	0.00992 Kg	
	SO2	0.000209 Kg	

Table 5: **Diesel oil use and emissions of a 40 ton truck** from Energy Technology Characterizations Handbook, Environmental Pollution and Control Factors (1983).

It is observed that the 1 ton of insulation has the highest energy requirements for its production (Table 4). On the other hand insulation has a small share of the construction materials. The total energy consumption for the production of the total amount of materials used in the plant is presented in Table 4 and Figure 8. Figure 9 presents the share of the coal, crude oil and natural gas. The diesel oil contribution to the development of the power plant is minimum compare to other fossils.

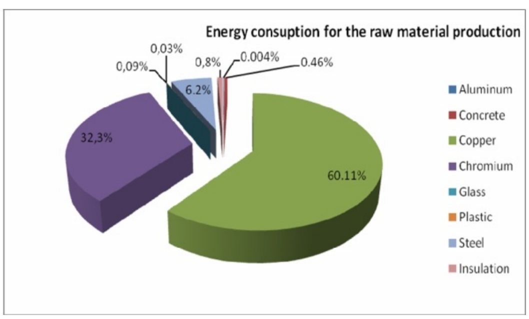

Figure 7: **Total energy use for the material production of the Power Plant** from Energy Technology Characterizations Handbook, Environmental Pollution and Control Factors,1983.

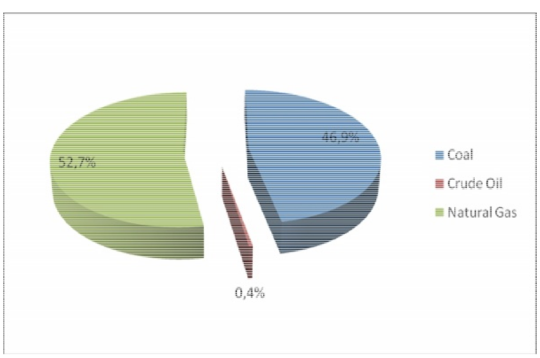

Figure 8: Total Energy Distribution.

Impact Assessment

Impact Categories Selection and Determination

In the present study are assessed the impacts that contribute to the following:

- Greenhouse Effect
- Stratospheric Ozone Depletion
- Acidification
- Eutrophication
- Carcinogenesis
- Winter Smog
- Summer Smog
- Heavy Metals

Classification

In the classification process emissions are associated with impacts categories. In this study emissions are proportioned to all impacts categories. Emissions are considered that they contribute 100% to all impacts categories.

Characterization

In the characterization process emissions are quantified. Each emission is converted to equivalent units for each impact using Eco-Indicator's characterization factor. The equivalent quantities for every impact category are presented in Table 6.

Eutrophication(air)	1.86E+02
Eutrophication(water)	1.51E-01
Stratospheric	3.18E+00
Ozone Depletion	
Carcinogenesis	5.11E+01
Winter Smog	4.47E+01
Summer Smog	2.31E+00
Solid Waste	0.00E+00
Heavy Metals(air)	5.12E+01

Equivalent Quantities (Kg)	
Greenhouse Effect (CO_2)	6.82E+06
Acidification (SO_2)	8.51E+03
Eutrophication(air) (PO_4)	1.42E+03
Eutrophication(water) (PO_4)	1.154034552
Stratospheric	2.57E-02
Ozone Depletion (CFC-11)	
Carcinogenesis (B(a)P)	4.82E-02
Winter Smog (SPM)	8.43E+02
Summer Smog (C_2H_4)	1.82E+01
Solid Waste	1.07E+02
Heavy Metals(air) (Pb)	5.76E-01

Table 6: Equivalent Quantities of Impact Categories from Solar Chimney Simulation (2000).

Normalization

Normalization follows characterization, and is the process which associates each impact with the region the normalization Values of the analysis are.

Normalization Values	
Greenhouse Effect	5.06E+02
Acidification	7.55E+01
Eutrophication(air)	3.73E+01
Eutrophication(water	3.02E-02
Stratospheric	3.18E-02
Ozone Depletion	
Carcinogenesis	5.11E+00
Winter Smog	8.94E+00
Summer Smog	9.25E-01
Solid Waste	0.00E+00
Heavy Metals(air)	1.02E+01
Heavy Metals(water)	1.89E+00

Table 7: Normalization Values of the Analysis from Solar Chimney Simulation (2000).

Evaluation

Evaluation is the final step of this L.C.A. study, where all impacts are associated between them and the significance of each impact category is assessed.

Impact Valuation Values	
Greenhouse Effect	1.27E+03
Acidification	7.55E+02
Eutrophication(air)	1.86E+02
Eutrophication(water)	1.51E-01
Stratospheric	3.18E+00
Ozone Depletion	
Carcinogenesis	5.11E+01
Winter Smog	4.47E+01
Summer Smog	2.31E+00
Solid Waste	0.00E+00
Heavy Metals(air)	5.12E+01

Table 8: Evaluation Values of the Analysis Analysis from Solar Chimney Simulation (2000).

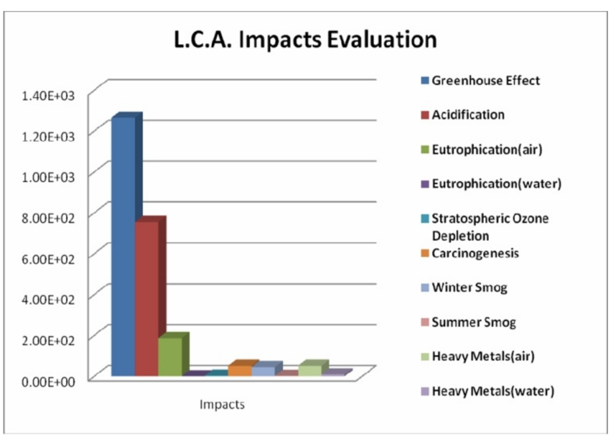

Figure 9: L.C.A Impact Evaluation.

7 ADVANTAGES AND DISADVANTAGES

7.1 Advantages

- Solar chimney power stations are particularly suitable for generating electricity in deserts and sun-rich wasteland.
- It provides electricity 24 hour a day from solar energy alone
- No fuel is needed. It needs no cooling water and is suitable in extreme drying regions
- It is particularly reliable and a little trouble-prone compared with other power plants
- The materials concrete, glass and steel necessary for the building of solar chimney power stations are everywhere in sufficient quantities.
- No ecological harm and no consumption of resources

7.2 Disadvantages

- Some estimates say that the cost of generating electricity from a solar chimney is five times more than from a gas turbine. Although fuel is not required, solar chimneys have a very high capital cost [2].
- The structure itself is massive and requires a lot of engineering expertise and materials to construct [2].

8 SUMMARY AND CONCLUSION

Conclusions

The dominant impact category in the construction and operation of a Power Tower plant is the Greenhouse effect, followed by the acidification and air eutrophication. The dominant air emission that affects the GH effect is CO_2, while in Acidification is the NO_x [14]. Thus, in order to design a more sustainable and environmental friendly power plant, there must be interfering in that life cycle process that has the maximum contribution to the generation of these emissions. Copper and Chromium are the dominant materials used in the construction of the power tower plant. Additionally, the coal consumption represents the 46,9% of the overall energy consumption. The 54,6% of the energy used in the chromium production came from the coal combustion, while the total amount of copper required for the power plant requires the highest consumption of energy and almost 40% of it came from coal combustion. Among the utilized solids fuels in the production of the materials coal produces the majority of CO_2 and NO_x emissions.

According the above coal usage minimization is the first and achievable in short terms, step in the minimization of the environmental impact. The energy gap that will rise from the coal minimization can easily be replaced by natural gas. Natural gas, compare to coal has significant less CO_2 and NO_x emissions. Another route is the usage of Nuclear power, although from the perspective of LCA it is not a sustainable solution, if we consider the nuclear waste production and their final disposal impact. Last but not least renewable energy can be utilized in the production of these materials, renewable for renewable. This is the best scenario, although it is not directly implemented.

Compare to other electricity production methods, GSP plants are the most sustainable of all, taking into consideration their whole life cycle (fig. 5). On the other hand they can be further “evolved”. Besides the research in the field of operational stage, there must be a research in the material usage. The minimization or replacement of copper for instance, with another less pollutant material.

9 REFERENCES

[1] http://www.eia.doe.gov/cneaf/solar.renewables/page/rea_data/rea_sum.html

[2] Subcontractor report, “Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts”, October 2003, NREL/SR-550-34440

[3] Hans Muller – Steinhagen, Franz Trieb, “Concentrating solar power - A review of the technology”, Quarterly of the Royal Academy of Engineering Ingenia 18, February/March 2004

[4] Energy Efficiency and Renewable Energy, “Concentrating Solar Power: Energy from Mirrors” DOE/GO-102001-1147 FS 128, March 2001

[5] EPRI Project Manager, E.A. DeMeo, “Renewable Energy Technology Characterizations”, TR- 109496, Final Report, December 1997

[6] Status Report on Solar Thermal Power Plants, Pilkington Solar International: 1996. Report ISBN 3-9804901-0-6.

[7] SOLAR DISH ENGINE (www.solarpaces.org)

[8] Washom, B., “Parabolic Dish Stirling Module Development and Test Results”, Paper No. 849516, Proceedings of the IECEC, San Francisco, CA (1984).

[9] Parabolic Trough Solar Collector Systems Made More Energy Efficient, http://www.sciencedaily.com/releases/2007/05/070515174832.htm

[10] Concentrating Solar Power Program, Office of Solar Energy Technologies Power Towers, “Proving the technical feasibility and cost potential of generating large-scale electric power from the sun when it is needed, day or night”, National Renewable Energy Laboratory a DOE national laboratory, DOE/GO-10098-468, September 1998, revised August 2000

[11] Scott Jones, “Concentrating Solar Power: The ‘Other ‘Solar…A Systems Perspective”, Sandia National Laboratories, October 19, 2004

[12] Concentrating Solar Power Now, Deutsches Zentrum für Luft und Raumfahrt e.V., German Aerospace Center.

[13] http://www.unep.org/

[14] U.S. Department of Energy, “Energy Technology Characterizations Handbook, Environmental Pollution and Control Factors”, March 1983, Third Edition, DOE/EP – 0093, Dist. Category UC - 11

[15] Günther, H. (1931). „In hundert Jahren – Die künftige Energieversorgung der Welt” Kosmos, Gesellschaft derNaturfreunde, Franckh'sche Verlagshandlung, Stuttgart

[16] Dos Santos Bernardes M.A., Voß A., Weinrebe G. (2003). “Thermal and technical analyses of solar chimneys” Solar Energy, 75, 511-524.

[17] Weinrebe, G. and Schiel, W (2001). “Up-Draught solar tower and Down-Draught Energy Tower – A Comparison”. *Proceedings of the ISES Solar World Congress 2001*, Adelaide,Australia.

[18] Weinrebe, G. (2000). “Solar Chimney Simulation”. *Proceedings of the IEA SolarPACES Task III Simulation of Solar Thermal Power Systems Workshop*, 28th and 29th Sept

[19] Jörg Schlaich, Rudolf Bergermann, Wolfgang Schiel, Gerhard Weinrebe (2004). Design of Commercial Solar Updraft Tower Systems – Utilization of Solar Induced Convective Flows for Power Generation

[20] SOLAR POWER TOWER (www.solarpaces.org)

[21] CHRISTOPHER J. KORONEOS, SOCRATES A. PIPERIDIS, CHRISTOS A. TATATZIKIDIS, DIMITRIOS C. ROVAS (2008). Life Cycle Assessment of a Solar Thermal Concentrating System

Impact of Mandatory Rates on the Recycling of Lithium-Ion Batteries from Electric Vehicles in Germany

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Abstract

We analyse the impact of mandatory recycling rates on the recycling of lithium-ion batteries from electric vehicles in Germany. For that, economically efficient network structures, determined by an optimisation model, are compared with and without mandatory recycling rates. The model determines number, technology, and capacities of recycling facilities to be deployed and volume and mix of batteries to be recycled. Different scenarios depict possible developments of the vehicle market, the battery technology, the material and energy prices, and the capital investment for the technologies. We show that a mandatory recycling rate of 50 % results only in minor advancements in the achieved recycling rates, but in higher risk and lower financial attractiveness for investors.

1 INTRODUCTION

Based on the plans of the German government to reach the number of one million battery and plug-in hybrid electric vehicles on German roads in 2020 [1], 590,000 spent lithium-ion batteries with a weight of 123,000 metric tons could accumulate between 2013 and 2025 [2]. The recycling of these batteries could be economically interesting due to the high value of materials, e. g. lithium and cobalt compounds, contained in them. If all materials from these batteries were recovered and sold at today's market prices, about 467 million USD could be realised in Germany alone [2]. The recycled materials could then serve as a secondary feedstock for the production of new batteries.

To realise this potential an efficient recycling process and network consisting of collection and treatment facilities has to be established. The actors in this network, e. g. battery and vehicle producers, network operators, logistics service providers, and metal recyclers, will perform the collection and treatment of batteries to recover the valuable materials [3]. A strategic planning task in setting up such a network is related to its logistical design, since this limits the profitability of recycling to a great extent [4]. Decisions with respect to this design include the selection of locations for facilities, their capacities, and the recycling technologies to be deployed over the time.

Some degrees of freedom in planning are restricted by legal regulation. The related directive, 2006/66/EC, and German laws derived from it, aim to minimise the ecological impact from spent batteries [5]. Consequently, battery and vehicle producers have to takeback spent batteries from retailers and end-of-life-vehicle treatment facilities without charge. Furthermore, they have to ensure that every collected battery is treated and recycled using state-of-the-art technology, when economically reasonable and technically feasible. In addition, minimum recycling rates have to be achieved annually. These rates are specified by ordinances, and thus can be adjusted by the responsible authorities over time. These regulations will influence the decisions on network design, as a very early deployment of the required collection systems and recycling technologies is required to guarantee their compliance.

Against this background, we analyse the impact of mandatory recycling rates on the recycling of lithium-ion batteries from electric vehicles in Germany. For that, we compare economically efficient recycling network structures with and without pre-set minimum recycling rates. The comparison is done with respect to the investments made in anticipation of impending legislation, the changes in the expected financial results, the increase in achieved recycling rates, and the differences in materials disposed of. For the determination of efficient network structures, a mathematic optimisation model is used.

We begin with a description of the LithoRec recycling process in Section 2, which is the basis for our analysis. In Section 3, we present our approach for the evaluation of the impact of legal recycling rates on the deployment of this process. Required data and computational results are presented in Section 4. We conclude with recommendations to industrial and political decision makers and a discussion of our approach in Section 5.

2 RECYCLING OF LITHIUM-ION BATTERIES FROM ELECTRIC VEHICLES

Within the last few years, lithium-ion battery recycling gained a lot in attention in research. Recycling processes and technologies in particular have been focused on. A review of some processes is given in [6]. However, most processes are developed for small batteries from consumer devices, e. g laptops or mobile phones, and these only involve small segments of the chain engaged in the collection of car batteries to the synthesis of new materials.

A promising and holistic recycling process for lithium-ion batteries from electric vehicles has been developed in the research project LithoRec [7,8,9]. The LithoRec project considers economically viable and ecologically compatible recycling of lithium-ion batteries from electric vehicles. In contrast to other research efforts [6], LithoRec particularly focusses on the recovery of lithium compounds, which are lost in traditional smelting processes.

The LithoRec process begins with the collection of batteries at vehicle service stations, where spent batteries are exchanged, and end-of-life vehicle treatment facilities, where batteries are separated from old cars. After that, the batteries have to be inspected regarding to their viability for reuse or recycling, sorted and stored. Subsequently, lithium-ion batteries go through three different recycling stages: disassembly, mechanical conditioning, and hydrometallurgical conditioning. In disassembly, the battery is first discharged and then disassembled to the cell level. In addition to the cells, reusable or recyclable components like electronics or electric conductors are separated. Next, the cells are shredded in the mechanical conditioning process, resulting in aluminium and copper fractions and cathode coating, which contain the lithium compounds.

Volatile liquids (electrolyte with conductive salts) are separated by evaporation and disposed of. In the final hydrometallurgical conditioning process, the cathode coating is treated to recover lithium-hydroxide as a powder, and a solution which may include nickel, cobalt, and manganese. These high quality-grade materials can be used directly for the production of new cells.

The development of the LithoRec process has been accompanied by a full life-cycle assessment according to ISO 14040, attesting to its ecological benefit compared to the primary production of the materials [10]. It promises to be economical since a large amount of materials is recovered, including battery components and all transition metals, and the process is suitable for large-scale recycling [7]. However, LithoRec is yet to be tested under actual conditions in a follow-up project, LithoRec II.

3 APPROACH FOR THE EVALUATION OF THE IMPACT OF MANDATORY RECYCLING RATES

To evaluate the impact of mandatory recycling rates on the recycling of lithium-ion batteries from electric vehicles, we consider the viewpoint of a central (ideal) decision maker, referred to as the potential investor. The investor is willing to invest in the deployment of a recycling network for lithium-ion batteries, regarding the deployment of the LithoRec process. The allocation of operational tasks in the network, potential competitors, and price setting questions are neglected for now. Therefore, we assume a perfectly coordinated (reverse) supply-chain.

The aim of the potential investor is to maximise his/her profits. To this end, the investor decides about the number of, capacities of, and technologies involved in the recycling facilities to be deployed, the volume and mix of spent batteries and their components that will be collected and treated in the facilities, the purchase of supplies required for the treatment, and the sale of recyclables or the disposal of waste materials that are output of the treatment. Thus, profits are determined by the cash-flows resulting from expenses for the collection of batteries, the initial investment and fixed operating expenses of the deployed facilities, the liquidation revenues that accrue from the ultimate retirement of these facilities, variable operational treatment expenses (e.g. wages), the revenues from selling recyclables, and the expenses from purchasing supplies and disposing of waste. The profit orientation of the potential investor and the long-term characteristic of the planning problem are considered by the net-present-value method, discounting the expected cash-flows that accrue from the investments.

The decisions of the potential investor are particularly influenced by the volume and mix of batteries that will be available for recycling, their economic value, and the financial key figures of the recycling technologies. The number of spent batteries returning over time is a function of the number of electric vehicles sold and their lifetime. One must also consider that batteries are subject to aging processes and may possibly be replaced within vehicle lifetime. Therefore, the volume of batteries returned also depends on the lifetime of the batteries. Additionally, it can be assumed that a certain proportion of batteries may be used further in stationary applications for a certain time, so their final availability for recycling may be delayed. The economic value then is a product of the number of spent batteries collected, the efficiency of material recovery, and prevailing material prices. This value is reduced by the capital investment and other financial key figures of the recycling technologies required.

In deciding about the capacities and technologies to be installed, the potential investor will contrast the revenues of recycling batteries and components with the expenses for erecting and operating the required facilities. He will choose that combination of options that

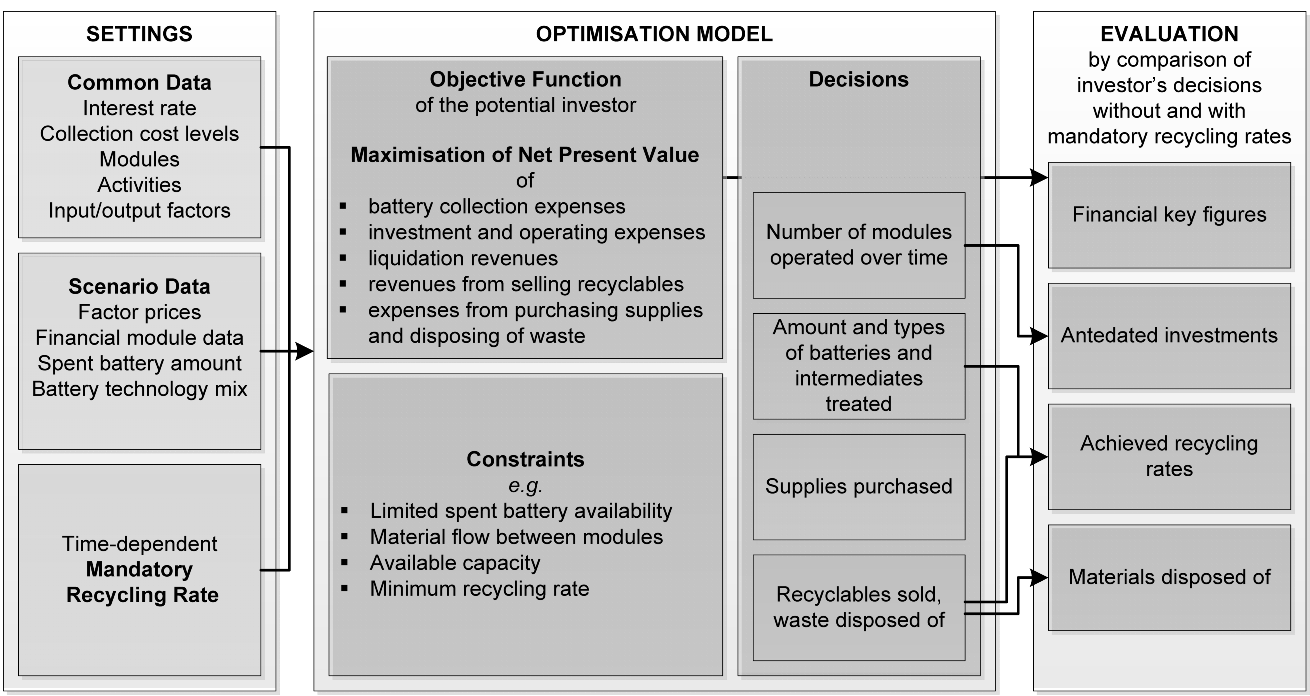

Figure 1: Approach for the evaluation of the impact of mandatory recycling rates.

will maximise the expected net present value. A particular challenge to the potential investor's decisions is that the principal factors – lifetime of batteries, suitability for further use, contained materials – vary with different vehicle and battery types, and the developments regarding the market for electric vehicles or the battery technology are very dynamic and uncertain. In addition, the required capital investments and other financial key figures of the recycling technologies that influence the decisions can only be estimated at this early stage of development. Mandatory recycling rates do complicate the decisions further. In contrast to a planning situation without mandatory recycling, the investor cannot just react on, but has to anticipate the volume and mix of batteries that return to ensure that the rates can be achieved annually. Beyond that, mandatory recycling rates may require an earlier installation of recycling technologies, and some types of batteries or components may have to be recycled even though this might be economically inefficient.

Against this background our approach is going to answer how the potential investor will react to a mandatory recycling rate in detail. For that, we compare the investor's decisions that result with and without pre-setting a 50 % recycling rate. The comparisons are separated into four categories. First, differences in investment decisions are analysed, measured in **antedated investments** and computed by the difference in time of installation of facilities of a certain capacity and technology as compared with the unconstrained optimal. Antedated investments influence financial figures: Facilities operate over a longer period in time, resulting in higher total expenses over the planning horizon; investment expenses are deferred in earlier periods, where lower discount rates apply, having a greater contribution to the sum of the discounted cash-flows. This reduces the net present value and raises the investor's risk. Hence, the second impact category is the change in the **financial key figures** (net present value and internal rate of return). Third, the **recycling rates that are actually achieved** are compared. Fourth and last, the differences in the mass and type of **materials disposed of** are analysed.

To depict the decision behaviour of our potential investor, we use a mathematic optimisation model. Its underlying structure is summarised in Figure 1. The model determines the number of recycling facilities of a certain technology and capacity to be operated in each period of the planning horizon, the amount and type of batteries that are treated in these modules, the purchased supplies, and the recyclables sold as well as the waste disposed of. Combinations of technologies and capacities are depicted as modules that can be engaged optionally in any number. Each module is connected with specific investment expenses, fixed operational expenses, and liquidation revenues, which allows for the depiction of economies of scale related to financial key figures. Further, decentralisation effects in the collection are considered by making the collection costs conditional on the number of disassembly facilities engaged, so that a higher number of facilities leads to lower collection costs per battery. The material transformation in the modules is depicted on the basis of linear activity analysis [11, 12]. For each module and each battery type, or intermediate product, these activities describe the input and output flows of materials and energy as vectors. Each execution of one activity is connected with variable expenses and capacity coefficients that are specific to the modules. Mathematical constraints ensure the compliance of technical and logical coherences, e. g. capacity restrictions, material flow between modules, and achievement of mandatory recycling rates. The resulting mathematic formulation of the optimisation model can be described as a mixed-integer linear network flow problem that can be solved with common mixed-integer-programming solvers.

To account for the prevailing uncertainties of the planning situation, the scenario technique is used. For that, scenarios are developed regarding the development of particularly uncertain parameters. The impacts of recycling rates are then measured by applying the optimisation to each scenario with and without the recycling-rate constraint and comparing the gained optimal solutions.

4 COMPUTATIONAL RESULTS

4.1 Experimental Data

The planning horizon of our analysis begins in 2015 on the assumption that a significant amount of spent batteries will be available for recycling at that time, and ends in 2030. The data required for our analysis are classified into three sets, based on the degree of their uncertainty. Unless noted otherwise, data have been acquired in collaboration with industrial partners in the project LithoRec [7].

The factors in the first set are "common data" and are the basis for all our deliberations. We consider six different battery types that result from three different vehicle types – hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and battery electric vehicles (BEV) – and two battery technologies, Nickel-Manganese-Cobalt (NMC) and Lithium-Iron-Phosphate (LFP). Besides the six battery types, factors embrace 4 intermediates and 12 materials accruing from them as well as 5 supplies required by the technologies, e. g. electricity and steam. The three subsequent co-production technologies of the LithoRec process, disassembly, mechanical conditioning, and hydrometallurgical conditioning, are considered in each two capacity classes, ending up with the consideration of six modules. Modules have to be renewed or liquidated after 20 years. The interest rate used for the calculation of the net present value is set to 8 %. Collection costs have been estimated with help of an existing facility location model, and range from 187 EUR per BEV battery with one collection location, and rapidly decrease to 97 EUR for 5 locations, converging to 61 EUR with 25 locations involved.

The second data category includes all factors that are highly uncertain: the spent batteries available for recycling, the prevailing battery technology, the financial key figures of the technologies, and the market prices of factors. For the analysis, different scenarios were generated, each describing a certain development of these factors.

Capacity Class / **Technology**	**Small** Capacity Investment Fixed Expenses	**Large** Capacity Investment Fixed Expense
Disassembly	6,000 BEV-eq/a* 560,000 EUR 227,000 EUR/a	60,000 BEV-eq/a* 3,100,000 EUR 1,020,000 EUR/a
Mechanical Conditioning	1,500 t cells/a 2,100,000 EUR 120,000 EUR/a	15,000 t cells/a 5,240,000 EUR 255,000 EUR/a
Hydrometallurgical Conditioning	3,300 t coating/a 10,000,000 EUR 1,350,000 EUR/a	33,000 t coating/a 40,000,000 EUR 5,380,000 EUR/a

**) BEV-battery equivalent. PHEV and HEV batteries correspond to 0.5 and 0.1 BEV-equivalents, respectively.*

Table 1: Capacities and original estimates of the modules.

In the *Basic scenario*, we presume a rather moderate spent battery return. To estimate this return, a simulation model developed in [2] is used. The underlying assumptions have been motivated in [7]. Further, we assume that 80 % of the spent batteries are of the NMC technology type, and the residual 20 % are LFP. The financial key figures of the technologies originate from order-of-magnitude estimates for the capital investment of the LithoRec technologies (see Table 1). Real data was available for only the small hydrometallurgical module. For the particularly uncertain market prices of factors, e. g. cobalt, copper, and energy, we assume that prices of most factors will increase linearly on the basis of today's prices by 5 % to 10 % each year.

We further regard three scenarios that are derived from the *Basic* scenario. In *Higher Investments* we suppose that that our original estimates are wrong and that the real investments are higher, namely +20 % for the disassembly modules, +30 % for the mechanical conditioning modules, and +10 % for the large hydrometallurgical conditioning module. In the *Low Economic Potential* scenario we regard the case that both the battery technology mix and the market prices lead to an economically unattractive situation for the recycling: NMC will be substituted increasingly by the less-valued LFP, again starting at a share of 20 % but reaching 80 % of the spent batteries by 2030. At the same time, the market prices of the recyclables are assumed to stagnate. Finally, in the *High Returns* scenario, we consider the case of a battery returns accrue from a fast growing electric vehicle market that leads to the circulation of one million electric vehicles in Germany by 2020.

The third data category is concerned with the mandatory recycling rates that are to be fulfilled in each period of the planning horizon. Since a method for the calculation of the recycling rate has not yet been prescribed, we define the achieved recycling rate as the sum of the weight of the recycled materials divided by the sum of the collected batteries of a specific period. Currently, the mandatory recycling rate for Germany is set to 50 % by weight [13]. Thus, the mandatory recycling rate values are set to 0.5 for each year. If the rate of 50 % is not feasible in a specific year due to a high share of LFP batteries, the highest feasible rate is prescribed. By setting all of the values to zero, we analyse a decision situation without mandatory recycling.

4.2 Impact Analysis

The impact of the mandatory recycling rate of 50 % compared with the situation without mandatory recycling on the four impact categories and all scenarios is reported in Table 2. In the discussion that follows, these impacts are analysed in detail.

Antedated Investments

Across all scenarios, the installation of the whole LithoRec process is necessary to achieve recycling rates higher than 50 %. Consequently, with a mandatory recycling rate of 50 %, all technologies have to be installed right from the start of the planning horizon. Deployed capacities of all modules are used only marginally in these periods. Moreover, in all scenarios but the *High Returns* scenario, a small mechanical conditioning facility is sufficient initially instead of a large one.

The lowest impact with respect to antedated investments is noted in the *High Returns* scenario. As both a large mechanical and a small hydrometallurgical conditioning module are installed in 2017 even without the mandatory recycling rate, these investments are antedated by only 2 years. The highest impact can be seen in the *Low Economic Potential* scenario. Without a mandatory recycling rate, mechanical conditioning and hydrometallurgical conditioning would be installed in 2021 and 2025, respectively. Thus, the mandatory recycling rate requires these technologies to be installed 6 and 10 years prior to when they would be optimally feasible.

Financial Key Figures

As a consequence, the financial impacts are most pronounced in the low economic potential scenario. Here, even without the mandatory recycling rate, the net present value is only 0.8 million EUR. The antedated investments provoked by the mandatory recycling rate result in a negative value of −10.7 million EUR (−107.8 %) and therefore in a non-economic investment plan.

The impact of the mandatory recycling rate is also high in both the *Basic* (−5.6 %) and the *High Investments* (−6.0 %) scenario. In *High Returns*, the impact is rather low (−0.7 %). Recycling remains highly economical in these scenarios with profits of 142.2 (*Basic*), 138.0 (*High Investments*), and 529.2 (*High Returns*) million EUR, although the internal rates of return are reduced by up to 21.4 percentage points.

Impact category	Description	Unit	Scenarios			
			Basic	High Investments	Low Economic Potential	High Returns
Antedated investments	Antedated mechanical conditioning module	[a]	4	5	6	2
	First hydrometallurgical conditioning module	[a]	6	6	10	2
Financial key figures	Deviation of the net present value	[M EUR]	−8.5	−8.9	−11.5	−3.8
		[%]	−5.6	−6.0	−107.8	−0.7
	Deviation of the internal rate of return	[%-points]	−21.4	−20.4	−6.7	−19.0
Achieved recycling rate	Deviation of the achieved recycling rate	[%-points]	+0.6	+0.6	+1.4	<0.1
Materials disposed of	Total	[%]	−0.8	−0.9	−1.5	−0.1
	Hazardous waste	[%]	−7.2	−9.5	−7.8	−0.8
	Thermally utilisable	[%]	+0.5	+0.9	+1.5	+0.1

Table 2: Impact of a 50 % mandatory recycling rate depending on the scenarios.

Achieved Recycling Rates

The impact of the mandatory recycling rate can be measured regarding the *annual* and the *total* recycling rate that are actually achieved. The recycling rates that are annually achieved in scenarios *Basic* and *Low Economic Potential* are compared in Figure 2 and Figure 3. These are reported only for the years from 2015 to 2022 since they are identical after 2023. Obviously, the impact of the mandatory recycling rate on the annual recycling rates is very high in both cases, especially in the *Low Economic Potential* scenario. Nevertheless, between 2015 and 2020, where the differences are highest, the amount of spent battery return is much lower than in the following years (3.900 t against 93.300 t, or 4 % of the total mass). Consequently, the differences have very low impact on the total recycling rates achieved. Regarding these, the mandatory recycling rate only results in a minor increase across all scenarios. Again, the highest impact can be seen in the *Low Economic Potential Scenario*. The total recycling rate achieved in the planning period increases by 1.4 percentage points to 46.3 %. In all other scenarios, the increase in the recycling rates is not worth mentioning.

Materials Disposed Of

The mandatory recycling rate reduces materials disposed of from −0.1 % in *High Returns* to −1.5 in *Low Economic Potential*. The materials disposed of can be categorised into thermally utilisable (plastics, graphite, and remnants) and hazardous waste (NMC and LFP cells, NMC and LFP coating, and other remnants). Looking at the latter, the impact is much more important: Hazardous waste is reduced by up to −9.5 % in the *Higher Investments* scenario.

In Figure 4, the masses of cells and coating that are disposed of are compared without and with the mandatory recycling rate. Clearly, both cells and coating are disposed of across all scenarios without the mandatory rate, because the corresponding recycling technologies are missing in the first years. Consequently, the mass of fractions disposed of is low (2,500 t) in the *High Returns* scenario because the required technologies are installed early and high (6,400 t) in the *Low Economic Potential* scenario because they are installed later.

With the mandatory recycling rate, almost all cells are treated and all NMC coating is recycled. Only LFP coating is still disposed of to a large degree across all scenarios. This happens when its mass exceeds the installed capacity of hydrometallurgical conditioning so slightly that capacity expansion would not be economic. In these cases, NMC coating is preferred due to its higher value.

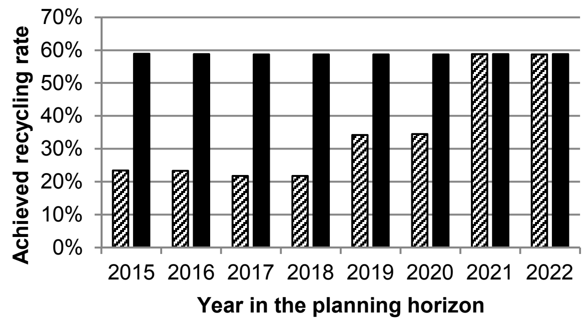

Figure 2: Impact of the mandatory recycling rate on recycling rates achieved in the Basic scenario.

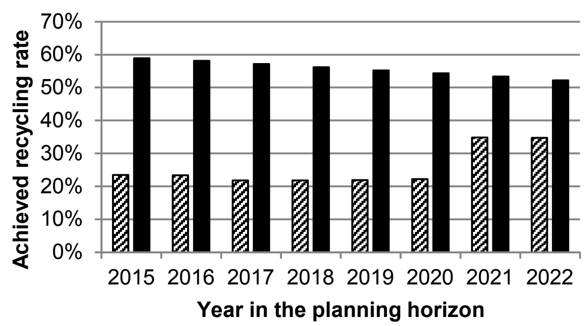

Figure 3: Impact of the mandatory recycling rate on recycling rates achieved in the Low Economic Potential scenario.

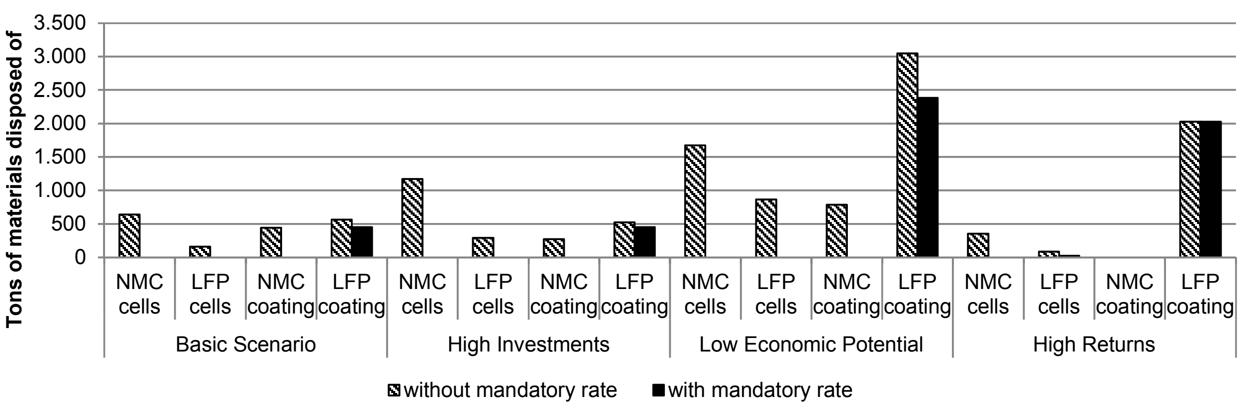

Figure 4: Impact of the mandatory recycling rate on the masses of cells and coating that are disposed of.

5 DISCUSSION

The contribution of this paper is the analysis of the impact of mandatory recycling rates on the recycling of lithium-ion batteries from electric vehicles in Germany. For the analysis, we consider the viewpoint of a potential investor who is willing to deploy the LithoRec process. The economically efficient decisions about technologies and capacities installed as well as the volumes and mix of batteries and components recycled between 2015 and 2030 are compared with and without the mandatory recycling rate of 50 %. The impact is measured with respect to four categories. To depict the decisions of the investor, a mathematical optimisation model is used that accounts for decentralisation effects, economies of scale, and the material flows in the network. Four different scenarios are created that account for prevailing uncertainties in the development of the vehicle market, the battery technology, the material and energy prices, and the capital investment for the technologies.

The analysis shows that on one hand the mandatory recycling rate of 50 % results in minor advancements of between 0.1 and 1.4 percentage points in the recycling rates that are achieved without this mandate. In some cases, the amount of hazardous waste is decreased considerably. On the other hand, the necessary technologies have to be installed up to ten years earlier, resulting in higher expenses and, thus, higher risk and lower financial attractiveness for the potential investor. It becomes obvious that the impact of the mandatory recycling rate especially depends on the volume and mix of the batteries returned: the impact of the mandatory recycling rate is low when the initial volume of battery returns is high and it is high if LFP battery technology prevails. The highest risk and consequently lowest financial attractiveness, as well as lowest recycling rates, would result if the return stream is dominated by LFP batteries and material prices stagnate. If the mandatory recycling rate forces an early deployment of the LithoRec process, it cannot be operated economically.

Different recommendations to both political decision makers as well as potential investors can be derived from the results. Political decision makers should allow for the temporal storage of intermediates, e. g. cells and cathode coating, and alter the associated calculation method of the recycling rate in a way that recycling deficits from early years could be compensated in later years when substantial battery return flows are reached. A good value for the threshold would be 1,500 t of batteries. This battery return is reached between 2017 (*High Returns Scenario*) and 2020 (*Basic Scenario*). Potential investors should continue research on additional recycling technologies to comply with mandatory recycling rates even if LFP prevails, which could lead to additional profits. If, for example, 90 % of the electrolyte could be recovered, the material cash-flow would increase by 43 % or 311 million EUR at current market rates, and the recycling rate would increase by 8 percentage points to 67 %.

There are several limitations to our approach. First, even though we have considered four different scenarios, the number of possible outcomes is countless, especially with regard to the volume of batteries available for recycling. Nevertheless, the scenarios used represent a wide spectrum of these developments and are suitable for an initial estimate of the impact of mandatory recycling rates. As the electric vehicle market advances, other scenarios can easily be considered using this approach. Second, a range of real options of the investors were excluded in our study, e. g. acquiring batteries from outside Germany to utilise the installed capacities, or using other recycling possibilities, e. g. a pyrometallurgical treatment of batteries or cells, which may change the achieved recycling rates and the cash-flows. Third, only six types of batteries and their precise compositions have been considered. Nevertheless, their composition was found in LithoRec as being representative for a wide spectrum of technical possibilities. Moreover, alternative technologies and battery variants can easily be included in the analysis using this approach. Future work will be on the extension of the modules to take additional capacity classes and electrolyte recycling into account, as well as the modelling of cell and coating storage. Also, sensitivity analysis will be applied to quantify the influence of other battery types and their compositions on the economics of recycling.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] Deutsche Bundesregierung (2009): German Federal Government's National Electromobility Development Plan.

[2] Hoyer C, Kieckhäfer K, Spengler T S (2011): Strategische Planung des Recyclings von Lithium-Ionen-Traktionsbatterien. In: Sucky E, Asdecker B, Dobhan A. et al. (eds) Logistikmanagement, vol 2. University of Bamberg Press, Bamberg, 399–419.

[3] Hoyer C, Kieckhäfer K, Spengler T S (2011): A Strategic Framework for the Design of Recycling Networks for Lithium-ion Batteries From Electric Vehicles. In: Hesselbach J, Herrmann C. (eds): Glocalized Solutions For Sustainability In Manufacturing. Springer, Heidelberg, 79–84.

[4] Fleischmann M, Bloemhof-Ruwaard J M, Beullens P et al. (2004): Reverse Logistics Network Design. In: Dekker R, Fleischmann M, Inderfurth K et al. (eds) Reverse Logistics. Quantitative Models for Closed-Loop Supply Chains. Springer, Berlin, 65–94.

[5] Deutscher Bundestag (2009): Batteriegesetz.

[6] Xu J, Thomas H, Francis R et al. (2008): A review of processes and technologies for the recycling of lithium-ion secondary batteries. Journal of Power Sources 177(2), 512–527.

[7] Kwade A, Bärwaldt G (2012): LithoRec. Recycling von Lithium-Ionen-Batterien. 1st ed., Cuvillier, Göttingen.

[8] Hanisch C, Haselrieder W, Kwade A (2011): Recovery of Active Materials from Spent Lithium-Ion Electrodes and Electrode Production Rejects. In: Hesselbach J, Herrmann C (eds): Glocalized Solutions For Sustainability In Manufacturing. Springer, Heidelberg, 85–89.

[9] Herrmann C, Raatz A, Mennenga M et al. (2012): Assessment of Automation Potentials for the Disassembly of Automotive Lithium Ion Battery Systems. In: Dornfeld D A, Linke, B S. (eds): Leveraging Technology for a Sustainable World. Springer, Heidelberg, 149–154.

[10] Buchert M, Jenseit W, Merz C et al. (2011): Ökobilanz zum „Recycling von Lithium-Ionen-Batterien“ (LithoRec), Darmstadt.

[11] Koopmans T C (1951): Analysis of Production as an Efficient Combination of Activities. In: Koopmanns T C (ed.): Activity Analysis of Production and Allocation. Cowles Commission for Research in Economics, vol. 13. Wiley, New York, 33–97.

[12] Debreu G (1959): Theory of Value. An Axiomatic Analysis of Economic Equilibrium. Wiley, New Haven and London.

[13] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (2009): Verordnung zur Durchführung des Batteriegesetzes (BattGDV).

Eco Reach Essencial Johnson&Johnson® Toothbrush: An LCA Study Case Application to Analyze Different Materials in Handle Design

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Abstract

Products which address environmental issues during the product development process bring opportunities for cost reduction, better brand's image and other strategic benefits. In this sense, Eco Reach Essencial Johnson&Johnson® toothbrush was developed in Brazil when a top-down opportunity merged with a bottom-up idea to design a product with lower environmental impacts, incorporating a pre consumption plastic waste into the toothbrush handle. In order to compare different alternatives from environmental point of view, a comparative LCA was conducted using primary data, secondary data from GaBi software and EDIP Method. The results show that potential environmental impacts were reduced, revealing in this new product concept a strategic opportunity to develop a more eco friendly product and to enhance the brand's image.

Keywords:

Comparative LCA; product development; study case; toothbrush

1 INTRODUCTION

Product development is considered a business process increasingly critical to business competitiveness [1]. New products are demanded and developed to attend specific market segments, incorporate new technologies, adapt to new uses and comply with regulatory requirements. The product development process is in the interface between the company and the market and it is responsible for identifying the market needs and offer solutions. This process is strategically important, since an effective product development process assures a competitive advantage [1].

The idea generation occurs in the initial stage of the product development process and is critical to determine the product's success. One prerequisite to effective idea generation is having a new product strategy for the business. This strategy defines the focus and makes the quest for great new product ideas much more directed. Idea generation can be both top-down, as well as bottom-up [2].

A bottom-up idea occurs when professionals who works directly with the product or process (e.g. scientist, salesman and manufacturing people) identify a new product opportunity, submit their ideas and, if approved, a new project starts. Top-down is usually more directed and may occur when a strategic exercise reveals an opportunity for a particular market segment. After some definitions, a new product is proposed to attend the identified need [2].

There is also an increasing awareness about the importance of environmental protection and the potential impacts associated to products in all life cycle phases, as manufacturing and use phases [3]. This fact has led companies to implement treatment actions, cleaner technologies and product modifications in order to reduce their environmental impact and to achieve other businesses opportunities [4]. Moreover, companies have included in their strategy planning the development of new products with lower environmental impacts.

This paper presents a study case to show how products which address environmental issues during the product development process bring such opportunities as cost reduction, better brand's image and other strategic benefits. Eco Reach Essencial Johnson&Johnson® toothbrush was developed in Brazil when a top-down opportunity merged with a bottom-up idea to design a product with lower environmental impacts, incorporating a pre consumption plastic waste into the toothbrush handle. In order to compare different alternatives from environmental point of view, a comparative LCA was conducted using primary data, secondary data from GaBi software and EDIP 97 Method.

2 ECODESIGN

The embedding of environmental issues in the product development is called by Ecodesign. Ecodesign and Design for Environment (DfE) are referred as a product development process when environmental concerns are considered in the design phase [5]. [6] defines that Ecodesign pursues not only environmental impacts reduction during the whole lifecycle, but also other essential characteristics for products, as cost and performance.

The integration of environmental considerations must find its place among the many other priorities considered in the development of a new product. Even from an environmental point of view, the weight given to the environmental performance of the product should not be higher than that which gives the strongest competitive edge to the product. If the product does not perform well in the marketplace and supersedes other less environmentally sound products, no reduction in the load on environment is obtained. Often, however, environmental improvement can easily be attained without impairing other important performance parameters of the product [7].

The life of a product starts with the initial design concept. This stage has been identified as determining its environmental impact over its lifecycle [8]. As design proceeds from the idea stage over conceptual and detailed design towards production, the knowledge about the product, and hence also about its environmental properties, increases strongly. Simultaneously, as more and more properties are fixed by the choices made in the course of the development process, the possibility to influence the environmental performance of the product is reduced. It is thus largest at the early stages of the product development process where the knowledge about the product is least [7].

To help designers to integrate environmental issues in the product development, a several number of Ecodesign methods, tools, guidelines, matrices and even more complex and wide techniques, such as Life Cycle Assessment (LCA), have been proposed in the literature [9].

According to ISO 14040 [10], LCA is a technique that identifies which lifecycle stage of a product represents greater potential environmental impact. Knowing these potential impacts, the design team can make the right decisions about the environmental directions the product should have, focusing on the development of a product which will bring benefits for society and the company, this last through cost reduction, innovation and creativity, new opportunities for product development (using recycling materials, for example), enhancing organization and brand's image, risk reduction and client loyalty [11].

Although the known Ecodesign benefits, there is little evidence of its practice [12]. The environmental design behavior of companies reflects a complex balance of designers' understanding of environmental issues and the extent of the design space, influenced by legal requirements, economic and supply chain constraints. Large companies are significantly more likely than others to design for energy consumption in production, waste/pollution and hazardous materials. Since these issues are tied to the environmental performance of the manufacturer, when these companies address their production management, the environmental management of their products is also addressed, even partially [13].

According to [14], there are 2 forms to incorporate sustainability in the product development: by product diversification or promoting changes in the product development process of the company. In the first form, the company develops a product or a product line with reduced environmental impacts, which are offered with the conventional products and directed to consumers with greater environmental awareness. In the second form, the company promotes generalized changes in the product development process so that all new product developed become ecoefficient. Although the authors present these forms as exclusive, they may be complementary. The company can start diversifying its products and, after this Ecodesign experience, it may incorporate this concept into the product development process of all portfolio of the business.

3 HOW ECO REACH ESSENCIAL JOHNSON&JOHNSON® TOOTHBRUSH WAS DEVELOPED

A structured design process usually includes: 1) identification and selection of opportunities; 2) concepts generation; 3) concept evaluation; 4) product development and 5) product launch [15]. It starts with a 'design brief', from where the designers, in consultation with the client/customer for the product, derive the functional requirement. In this way, the Eco Reach Essencial Johnson&Johnson® toothbrush development started with a strategic market definition: offer to the low cost market segment a product with more benefits than the products that were available in the market

The subsequent step in the design process is the idea generation, where the concepts are originated to meet the functional requirement. In this sense, a Design to Cost process was implemented in order to reach the best solution. The manufacturing process was redesigned to optimize resources use. At the end, the product design team delivered a toothbrush with less material and with more benefits, such as: ergonomic angled handle, tongue scraper and bristles on 2 levels.

However, the solutions were not sufficient to attend the target cost. In parallel, another product design team worked in a bottom-up idea to incorporate 40% of pre consumption material into the toothbrush handle. This material is originated as a waste of other plastic products manufactured in the same site.

The team challenge was to develop a process to enable the incorporation of this recycled material into the handle, without compromising its physical properties and without presenting any safety risk. Therefore, an additional process was developed to enable the appropriate waste incorporation into the handle of Eco Reach Essencial Johnson&Johnson® toothbrush. With this initiative, the waste generated in the manufacturing site was reduced, as observed in Figures 1 and 2. Therefore, the main potential benefits of using the recycled material were cost and environmental burden reductions.

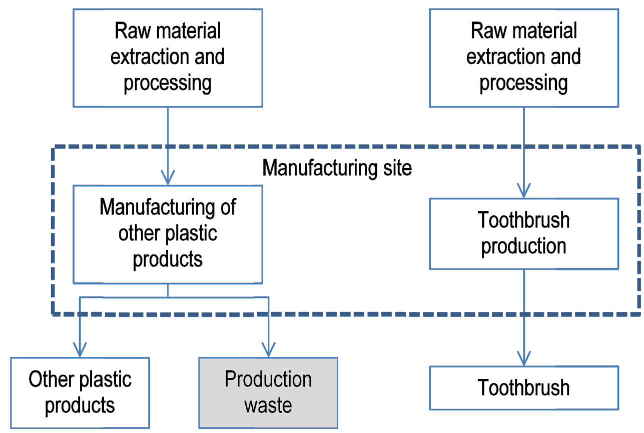

Figure 1: Toothbrush production process without waste incorporation.

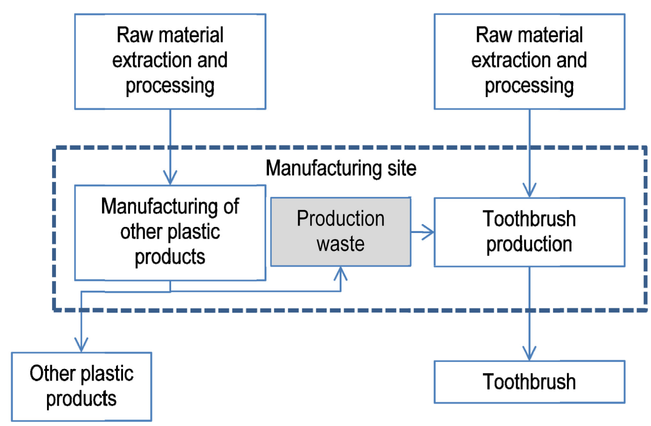

Figure 2: Toothbrush production process with waste incorporation.

When this bottom-up initiative merged to the strategic necessity, the Eco Reach Essencial Johnson&Johnson® toothbrush became feasible. In addition to the benefits delivered previously, a new and important benefit emerged: a product with less environmental burden. This reduction, which was analyzed by a LCA, is possible by the combination of less material per toothbrush, less use of non renewable resources and reduction of solid waste.

4 COMPARATIVE LCA

Life Cycle Assessment (LCA) is an analytical tool that allows evaluating the environmental impact associated to a product or activity during its life cycle. It also allows identify which life cycle stages present greater contribution for the environmental impact of the process or product in study. With LCA, it is possible to evaluate if the improvement in products, processes and services are effective [7].

For a product to perform its function, it must be designed, manufactured, distributed and maintained by the consumer during use. The product manufacturing requires many processes. Resources must be extracted and converted into materials or components. Infrastructure must provide its function to the plant and its employees. When the product no longer serves its purpose, it must be refitted, recycled or disposed. Transportation links physically all related processes and all these activities consume resources and cause environmental impact. The analysis must focus on the product system or the life cycle of the product in order to have information about the total environmental impacts caused by the product or service [7].

In order to compare the environmental impacts of Eco Reach Essencial Johnson&Johnson® (with 40% of pre consumption recycled plastic material) to Reach Essencial Johnson&Johnson® (with 100% of virgin plastic material), the LCA was conducted according to ISO 14040/14044 standards and EDIP method [16]. The objective of this study was to verify the environmental benefit of using recycled material in toothbrushes.

The function of the systems was oral hygiene by using toothbrush three times a day for three months and the functional unit for this study is “to promote oral hygiene of 250 persons for 1 year through tooth brushing”. Thereby, the reference flow for both systems was 1000 toothbrushes. The life cycle phases included were: Raw Materials, Transportation, Toothbrush Manufacture (handle production and bristling) and end-of-life. Since this was a comparative study, the identical phases for both systems (some production and transportation processes, packaging and use) were not considered.

Primary data on formulations, material compositions, primary suppliers and their locations, and toothbrush production are used to the maximum extent possible. According to the cut-off criteria established, the environmental impacts of inputs that represented less than 5% in mass of the product system were not considered. Secondary data was used based on GaBi 4 database for polyethylene and polypropylene life cycle inventories, literature data regarding equipment energy consumption and publication with data that reflects Brazilian condition for diesel and hydroelectric energy life cycle inventories [17].

All potential impact categories listed in EDIP were considered: global warming, stratospheric ozone depletion, photochemical ozone formation, acidification, nutrient enrichment, ecotoxicity, human toxicity, renewable and non-renewable resources consumption.

As observed in Figure 3, the energy consumption related to Eco Reach Essencial Johnson&Johnson® toothbrush is higher than the related to Reach Essencial Johnson&Johnson® toothbrush. An additional process is necessary to enable the appropriate waste incorporation into the handle of Eco Reach Essencial Johnson&Johnson® toothbrush. This process is essential to assure quality of the final product. The impact of this additional process is observed through the higher energy consumption.

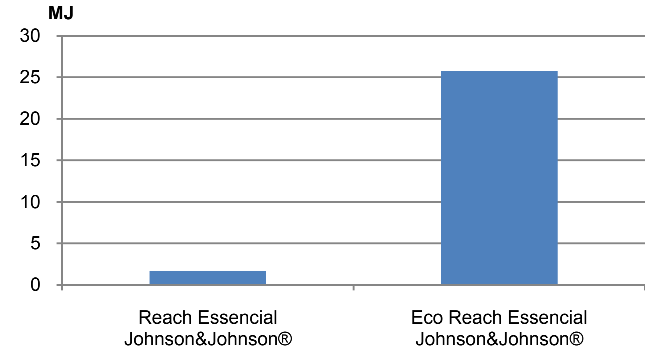

Figure 3: Energy consumption impact related to the product systems.

For all other categories, the Eco Reach Essencial Johnson&Johnson® toothbrush showed lower impact. Figure 4 illustrates the Global Warming potential impact related to each product system. The toothbrush with recycled material showed 34% less global warming potential impact when compared to the toothbrush without recycled material. Similar results were observed in other categories.

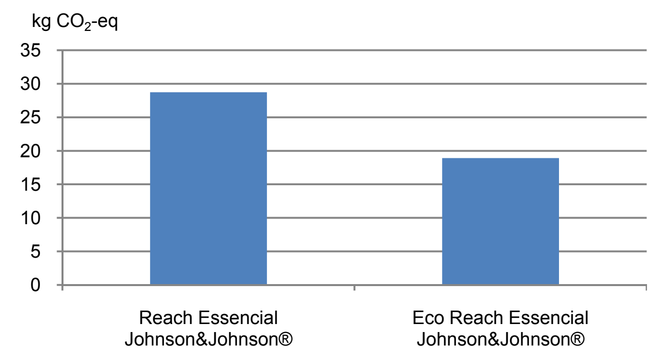

Figure 4: Global Warming potential impact related to the product systems.

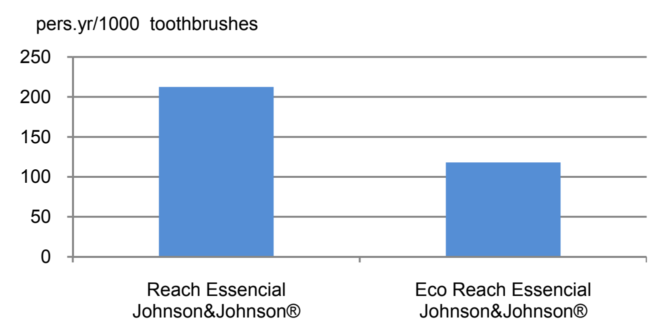

Figure 5: Normalized data for Reach Essencial Johnson&Johnson® toothbrush vs. Eco Reach Essencial Johnson&Johnson® toothbrush.

To evaluate the relevance of the potential environmental impacts, the contribution of each potential impact was normalized to annual consumption using EDIP 97, since the 2003 version does not consider impacts on a worldwide scale. Figure 5 shows the environmental impacts comparison according to normalized data. The toothbrush with recycled material showed 44% less environmental impact then the toothbrush with 100% of virgin material. It is assumed for many LCA's that a 10% difference between the test case and the baseline case qualifies as significant [18]. Therefore, it is verified an environmental benefit of the Eco Reach Essencial Johnson&Johnson® toothbrush when compared to a toothbrush without recycled material.

5 CONCLUSIONS

When a product is designed considering its environmental impact in the beginning of the development process, the chance of a new product with lower environmental impact is increasingly higher. This study showed how a new product was developed focusing in the reduction of its environmental impact. It also shows the importance of LCA application to verify the potential environmental reduction in new products. LCA is a powerful tool to verify the environmental improvement of the products and should be used increasingly early in the development process.

Although the environmental issues were considered in the initial design stages, they were not included in the first strategy plan. Incorporating environmental issues in the strategy definition phase is an important factor to enhance the Ecodesign success probability [6]. However, this study case is just a starting point. It helped to incorporate environmental issues into the product development process. The results show that potential environmental impacts were reduced, revealing in this new product concept a strategic opportunity to develop a more eco friendly product and to enhance the brand's image. This will certainly open doors to develop a more structured Ecodesign process in order to cover all portfolio, because designing more effective products is one of the most impactful manners that a corporation can achieve sustainable product development.

6 REFERENCES

[1] Rozenfeld, H et al (2006) Gestão de desenvolvimento de produto: uma referência para a melhoria do processo. São Paulo, Brazil: Saraiva.

[2] Cooper, R. G. (2001) Winning at New Products: Accelerating the Process from Idea to Launch. 3rd ed. New York, US: Basic Books.

[3] UNITED NATIONS ENVIRONMENT PROGRAMME (2007). Life Cycle Management: A business guide to sustainability.

[4] Porter, M.; Linde, C. (1995). Green and competitive: ending the stalemate, in: Harvard Business Review, Vol 73, No 5, p 120-134.

[5] Manzini, E., Vezzoli, C. O. (2002). Desenvolvimento de Produtos Sustentáveis - Os requisitos ambientais dos produtos industriais. São Paulo: Edusp, 367 p.

[6] Johansson, G. (2002). Success factors for integration of Ecodesign in product development: A review of state of the art, in: Environmental Management and Health, Vol 13, No 1, p 98–107.

[7] Hauschild, M., Jeswiet, J., Alting, L. (2005). From life cycle assessment to sustainable production: Status and perspectives, in: CIRP Annals - Manufacturing Technology 54 (2), p 535-555

[8] Baumann, H., Boons, F., Bragd, A. (2002). Mapping the green product development field: engineering, policy and business perspectives, in: Journal of Cleaner Production, Vol 10, p 409-425.

[9] Bovea, M.D., Wang, B. (2007). Redesign Methodology for Developing Environmentally Conscious Products. International Journal of Production Research, Vol 45, p 4057–4072.

[10] International Organisation for Standardisation (1997). ISO 14040: Environmental management – Life cycle assessment – Principles and framework. Geneva, Switzerland.

[11] International Organisation for Standardisation (2002). ISO 14062: Environmental management - Integrating environmental aspects into product design and development. Geneva, Switzerland.

[12] Tukker, A., Eder, P., Charter, M., Haag, E., Vercalsteren, A., Wiedmann, T. (2001). Ecodesign: the state of implementation in Europe Conclusions of a State of the art study for IPTS, in: The Journal of Sustainable Product Design Vol 1, p 147-161.

[13] Deutz, P., McGuire, M., Neighbour, G. (2013). Eco-design practice in the context of a structured design process: an interdisciplinary empirical study of UK manufacturers, in: Journal of Cleaner Production, Vol 39, p 117-128.

[14] Tingström, J; Karlsson, R. (2006). The Relationship between environmental analyses and the dialogue process in product development, in: Journal of Cleaner Production, Vol 14, No 15/16, p 1409-1419.

[15] Crawford, M.; Benedetto, A. (2006) New products management. 8th ed. New York, US: McGraw-Hill/Irwin.

[16] Wenzel, H.; Hauschild, M.; Alting, L. (1997): Environmental Assessment of Products. Volume 1: Methodology, tools and case studies in product development. Kluwer Academic Publishers.

[17] Monteiro, M. F. (2008). Avaliação do Ciclo de Vida do Fertilizante Superfosfato Simples. Dissertation. Escola Politécnica da Universidade Federal da Bahia, p 172 – 177, Bahia, Brazil.

[18] Weisbrod, A. V.; Hoof, G. V. (2011). LCA-measured environmental improvements in Pampers® diapers, in: International Journal Life Cycle Assessment, Vol 17, No 2, p 145-153.

Use Phase Parameter Variation and Uncertainty in LCA: Automobile Case Study

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Abstract

Product life cycle engineering studies typically rely on average use-phase parameter values to estimate impact, such as average usage intensity, and operational efficiency. In reality, these parameters can vary temporally, and depend on user behaviour as well as the context in which the product is being used. Insights on these are especially important for durable goods with long service lives. In this study, we examine the variation in user experiences in an automotive Life Cycle Assessment (LCA) case study, which is found to have a substantial influence on the life-cycle impact results. This underscores the importance of considering uncertainty in LCA studies.

Keywords:

Life cycle assessment, parametric uncertainty; vehicles; Monte Carlo simulation

1 INTRODUCTION

Many life cycle engineering studies of products focus on life cycle phases other than the product's use phase – materials processing, sustainable manufacturing and responsible end-of-life treatment. For durable products with long service lifetimes, such as automobiles and refrigerators, their use phase tends to dominate their life cycle environmental impact, and is the subject of this study.

Life Cycle Assessment (LCA) results of durable products are sensitive to use-related input parameters like usage intensity, operational efficiency, and product lifetime. These parameters can vary temporally, spatially, and widely across different users. Addressing this variation is important, but also complicates the accurate representation of LCA results. In this paper, we address the uncertainty due to variation in use-phase parameters for durable products, as applied to an automotive LCA.

We choose to examine an automobile because their life cycle impact has fairly been well documented, although the parametric variation and uncertainty less so. The key questions to be addressed are: How do a car's use-phase parameters vary, and what impact does this have on the LCA results?

2 PARAMETRIC UNCERTAINTY IN LCA

LCA studies are inherently subjected to many sources of uncertainty, and addressing them should form part of any assessment, although this is not always carried out. A few studies have reviewed, studied and proposed methods to address uncertainties in LCA. [1][2] In general, parametric uncertainty can arise from:

- Measurement error, or inaccurate data;
- Methods used to estimate/approximate/interpret missing or poor-quality data; and
- Contextual (e.g. geographical or temporal) variability in parameter data.

LCA studies can therefore be limited by the lack of good-quality, use-specific data in the inventory, and/or the aggregation of data over different geographical and temporal scales.

Methods to address these include deterministic scenarios or statistical approaches to estimate the data, such as stochastic or probabilistic modelling. In this study, we will first seek to understand the range of input use-phase parameter values, and then explore the impact of this on LCA results by running a Monte Carlo simulation. Monte Carlo simulation is a numerical approach to help us understand the propagation of uncertainty in the inputs. By capturing random samples of the input variables to explore thousands of possible combinations, the full range of possible outcomes is better understood.

3 FUEL USE AND EMISSIONS IN AUTOS

Let us first examine the use-phase of an automobile more carefully. The energy used, and hence fuel consumed and emissions generated, while driving an automobile depends on the loads it has to overcome (gross weight, aerodynamic drag, rolling resistance, etc.), and how efficiently its powertrain is able to convert chemical energy in the fuel into motive forces. For a conventional gasoline car with an internal combustion engine, only 14 to 26% of the total energy in the fuel is delivered to the wheels, the actual amount depending on the drive cycle, or speed-time trace. [3] The remaining energy is lost primarily due to inefficiencies in the engine, as well as to the transmission, idling, and to power accessories. The energy flows in a typical gasoline car is shown in Figure 1.

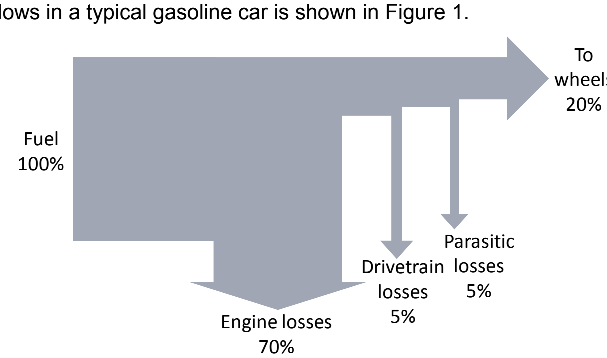

Figure 1: Energy flows in a typical car.

As part of compiling an automobile's life cycle inventory, the total amount of fuel used over its life span is needed. Collecting precise fuel use inventory data over its 10 to 15-year lifetime, however, is burdensome and not practical to carry out. Most LCA studies would instead use an estimate of the automobile's average fuel consumption rate[1], measured in liters of gasoline consumed per 100 km (L/100 km) to represent its fuel efficiency. This would be multiplied by the total lifetime distance travelled (km) to assess the total amount of fuel used (L). Let us examine these two parameters in turn.

[1] Or inversely, its fuel economy, measured in miles per gallon or MPG.

3.1 Operational Efficiency: Fuel Consumption

How does one determine an automobile's average fuel consumption? One commonplace approach is to use the fuel consumption rating based on standardized drive cycles created for the purpose of emissions testing and regulatory compliance. Example drive cycles used in the U.S. include the Environmental Protection Agency's (EPA) Federal Test Procedure to represent urban driving, and the Highway Fuel Economy Test to represent highway driving. Using a composite measure that attempts to capture both urban and highway driving, the range of the rated fuel consumption reported by EPA to label different car types sold in U.S. are shown in Figure 2. Depending on the size of the car and its powertrain, the average fuel consumption would vary. In model year (MY) 2011 alone, this ranges from 4.7 to 18.1 L/100 km across all car types.

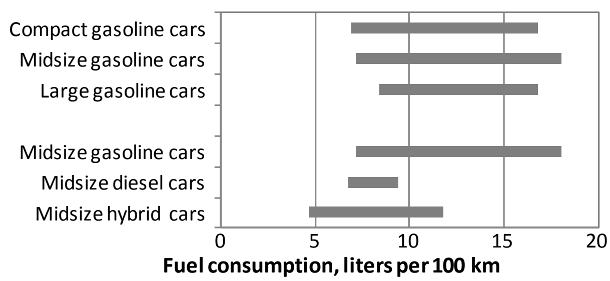

Figure 2: Range of rated fuel consumption for different car types offered in the U.S. in MY2011 (data: [3]).

Looking at a specific vehicle class, say midsize gasoline cars, the rated fuel consumption is known to vary historically, as shown in Figure 3. Average fuel consumption dropped significantly in the late 1970s, and remained level at around 11 L/100 km for two decades, before decreasing slightly again in recent years. So the average fuel consumption also varies over time.

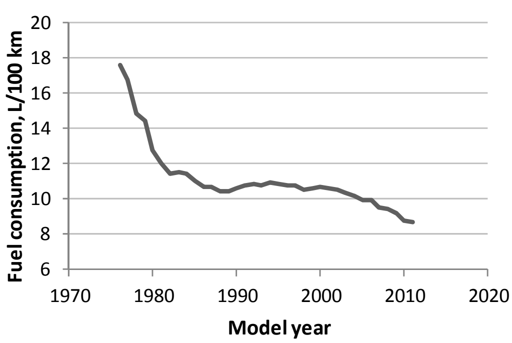

Figure 3. Historical sales-weighted average rated fuel consumption of midsize cars in the U.S. (data: [4]).

If one were to constrain the LCA study to a specific automobile make and model in a specific year, the "real-world" fuel consumption experienced by different drivers will also vary around the its rated fuel consumption. This is because standardized test drive cycles do not always reflect real-world driving conditions. Several factors can impact how and where the automobiles are driven, and in turn influence their actual on-road fuel consumption:

- User factors – trip profiles (routes, travel times), driving behaviour, use of accessories, additional loads;
- Product factors – maintenance and condition of the vehicle;
- Fuel factors – nature/quality of the fuel; and
- Contextual factors – road, weather, and traffic conditions.

3.2 Usage Intensity and Lifetime: Lifetime Distance Travelled

The second critical use-phase parameter is the lifetime distance travelled by an automobile, or vehicle kilometres travelled (VKT, or VMT for miles travelled). Estimates of VKT can be made from various sources, including traffic counts, surveys and odometer readings. VKT is known to vary by automobile age, by country, and over time. In the U.S., based on household travel surveys, annual distance travelled per automobile is observed to decrease with its age. [5] In a review of travel trends in eight industrialized countries, Millard-Ball and Schipper [6] found that VKT per capita varies by country, from as low as around 4,000 km per year in Japan to 13,000 km per year in the U.S. VKT per capita is observed to increase with GDP per capita in all countries studied, which is an indication of vehicle use intensity. Finally, the average annual distance driven per vehicle in the U.S. also varies historically, as shown in Figure 4 from 1969-2009.

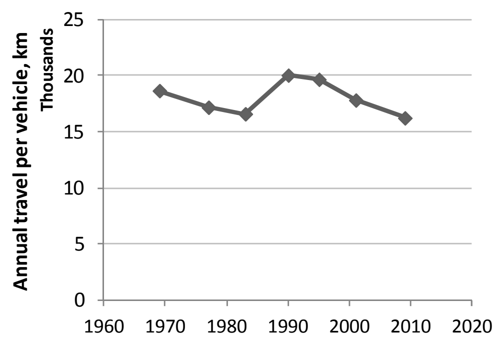

Figure 4: Historical average annual kilometres per vehicle in U.S. (data: [5]).

One can also expect VKT to depend on specific user-, as well as local contextual factors, including:

- Individual factors – need for activities which drive travel demand, preference for private car travel;
- Socio-geographical factors – land use patterns, availability of alternative transport modes;
- Socio-economic factors – personal income, fuel prices; and
- Legislation – early vehicle scrappage policies, congestion pricing, road tax, and other policies that discourages driving.

4 AVAILABILITY OF DATA ON USE-PHASE PARAMETERS

Understanding now that use-phase parameters can vary widely, we now review data that can reveal their underlying distributions. Several studies have been carried out to better understand naturalistic driving patterns in automobiles. In Michigan, LeBlanc et al [7] tracked 117 identical cars driven by different drivers, and observed that fuel consumption varied substantially even in such a small sample. The fuel consumption ranged from 8 to 13 L/100km, averaging 10 L/100 km. A few driver community websites have collected real-world data from users in larger numbers. Based on a survey of more than 28,000 drivers in Germany, the real-world fuel consumption experienced in conventional vehicles were consistently and on average 21% higher than the value based on the New European Driving Cycle (NEDC) standardized test cycle performed in a laboratory setting. [8] In the U.S., a similar survey of more than

31,000 sample drivers indicates a spread for all vehicle powertrain types, including diesel, gasoline and hybrid cars. As shown in Figure 5, the EPA rating both under- and over-estimates the real-world fuel economy (in miles per gallon, or MPG) for different drivers.

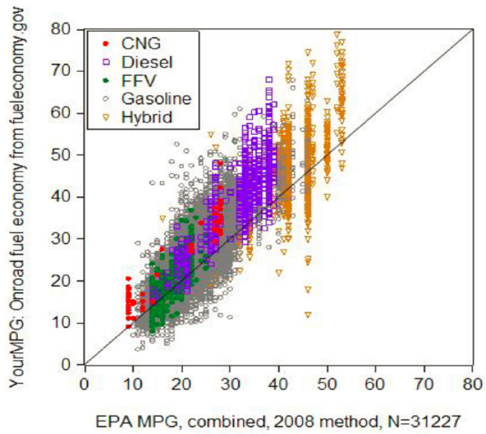

Figure 5: User-reported vs. EPA-rated fuel economy for different vehicle types [9].

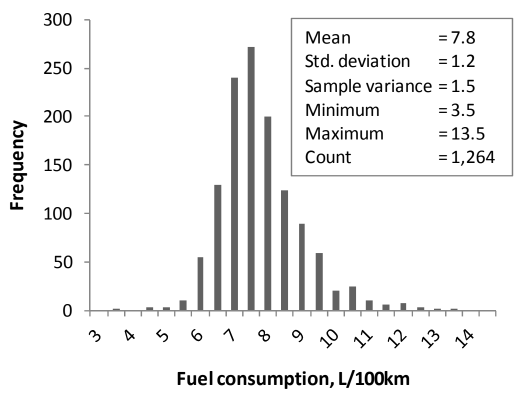

Figure 6: Histogram of self-reported fuel consumption from Toyota Corolla drivers.

For this assessment, we will necessarily limit the scope of the study to a single compact gasoline car model: the world's best-selling car, a Toyota Corolla. The study will only therefore examine the variance due to user and contextual factors, and not due to differences across different vehicle types. The latest Corolla is rated at 8.1 L/100km based on U.S. EPA test drive cycles. On a driver community website called fuelly.com [10], more than 1,200 Toyota Corolla drivers have reported their real-world fuel consumption. These drivers are mostly from North America. The values range widely from 3.5 to 13.5 L/100km, with a mean of 7.8 L/100km. This distribution of the average real-world fuel consumption experienced is charted in a histogram, together with the descriptive statistics, in Figure 6.

The observations of real-world fuel consumption were self-reported, so they could be biased, are susceptible to measurement errors, and are difficult to validate. More recently, GPS and on-board diagnostic devices can be embedded in automobiles to log data on fuel consumption, trip distances and other trip parameters in real-time. This allows one to characterize the probability distribution of different user experiences better. For example, Transport Canada has collected data from more than 1,000 vehicles in a Canadian Vehicle Use Study using on-board devices since 2010. Such data is more detailed and accurate, and presents an opportunity to better understand the way cars are being driven under specific contexts. Pending acquisition and availability of reliable, high-quality user data, however, this initial study will use the self-reported fuel consumption data as an indication of the inherent variation.

Data on actual lifetime distance travelled (VKT) across the automobile population is not as readily available. Assumptions used in past automotive LCA studies range widely from 100,000 to 300,000 km. [11][12][13][14][15] In the U.S., the National Highway Traffic Safety Administration (NHTSA) uses household travel survey data to estimate the lifetime VKT of passenger cars to be around 245,000 km. [16] While the distribution of this input parameter is not available, NHTSA also uses vehicle census data to estimate the survivability of cars by age. Cars typically last 10 to 15 years, and can remain in service for up to 25 years. Combining the survivability schedule with annual VKT, the histogram of a car's lifetime VKT used in this analysis is indicated in Figure 7.

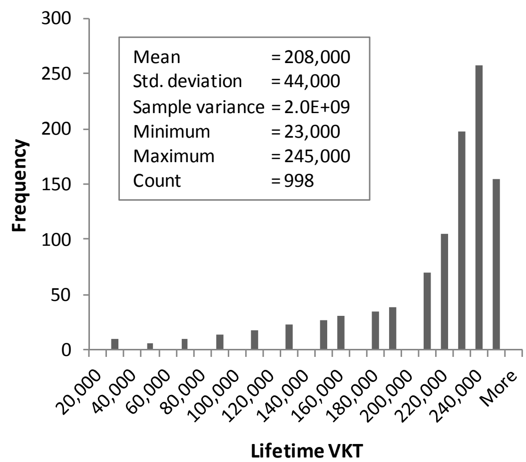

Figure 7: Histogram of lifetime vehicle distance travelled.

5 ANALYSIS

We will now look at a compact car's life cycle greenhouse gas (GHG) emissions impact using average use-phase parameters, as in a typical automotive LCA. The scope encompasses the car's complete life cycle, including the "well-to-tank" or fuel (gasoline) production impacts, and the results are shown in Figure 8. Base on the Toyota Corolla's specifications, the following key assumptions were made to derive these results, and more details of this LCA are available in [17]:

- The car's curb weight, or weight without passengers or cargo, is 1,270 kg;
- It has an average fuel consumption of 8.1 L/100km, or 29 MPG;
- Lifetime distance travelled over its service life is 245,000 km;
- Life cycle GHG emissions inventory data is obtained primarily from the GREET LCI database developed by Argonne National Laboratory [15]; and
- The GHG emissions factor for gasoline is 72.9 gCO_2-equivalent/MJ, which has a lower heating value of 31.9 MJ/L.

With these inputs, the car is estimated to emit 69 metric tons of CO_2-eq over its lifespan. As expected, combustion of fuel during the use-phase accounts for the greatest share of emissions, and dominates (70%) its life cycle impact. The next most dominant stage is fuel production and distribution, or well-to-tank stage, at 20%.

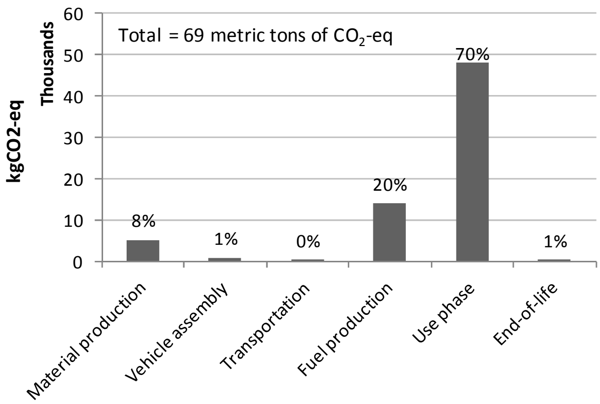

Figure 8: Greenhouse gas emissions from an average Toyota Corolla (8.1 L/100km, 245,000 km), by life-cycle phase.

Let us now compare these results from that accounting for uncertainty in the use-phase parameters with a Monte Carlo simulation. For the simulation, the distributions of the two input parameters – average fuel consumption and lifetime distance travelled – have been described in the preceding section. The emissions generated over other life cycle phases are fixed as a constant. The output of interest is the total life cycle GHG emissions for a current Toyota Corolla. Running the simulation over 2,000 observations, we find that the mean of the total emissions is 56 metric tons of CO_2-eq, with a standard deviation of 13 tons. This mean is lower than the earlier result using the average values for the input parameters. Figure 9 shows the histogram and cumulative probability of the results. In fact, around 90% of all possible input combinations turn out to be lower than the earlier estimate of 69 tons of CO_2-eq. Using single, average values for the use-phase input parameters therefore tends to overestimate the car's total life cycle emissions.

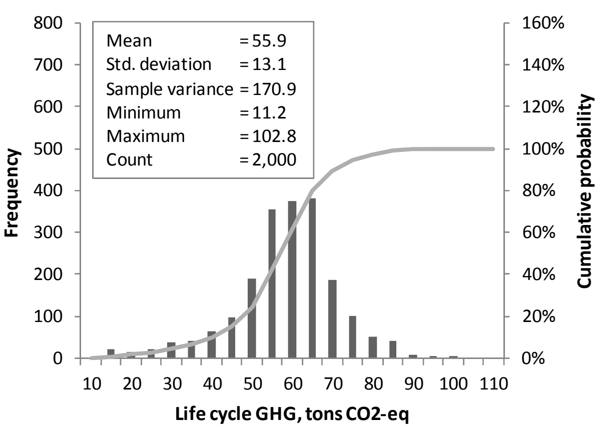

Figure 9: Results: Histogram of a Toyota Corolla's total life cycle GHG emissions.

6 DISCUSSION

This paper explores how LCA results vary depending on a product's use intensity in the functional description of a durable product, in this case, an automobile. Several findings have been made:

- The use-phase energy and emissions impact of a durable product, like a conventional automobile, varies by type, temporally, and is user-specific. Assessing the life cycle impact of durable goods is therefore complicated by the diversity of user experiences. Ascertaining and using average values for the input parameters is not straightforward to begin with, and may not be the most appropriate approach.
- Especially for durable products with long service lifetimes, life cycle studies should consider uncertainty in LCI data, which is influenced by the context and the way the product will likely be utilized.
- User data is gradually becoming available, presenting further opportunity for LCA practitioners to better characterize use-phase parametric uncertainty and variation, and also validate study results.
- From the case study, significant variance in LCA impact of conventional automobiles has been shown. The life cycle greenhouse gas emissions for a compact gasoline car is estimated at 56 ± 13 tons of CO_2-eq. For automobiles using alternative powertrains, like electric vehicles, parametric uncertainties or variation becomes more apparent when computing their life cycle impact. Factors like the characteristics of the regional electricity grid (fuel mix, temporal emissions), charging profile would matter, and is the subject of another manuscript in preparation. [18]

Future work planned will examine the probability distribution of the input parameters more carefully, and explore ways to better represent the uncertainty and sensitivity in LCA results. We will also examine case studies of other durable goods like home appliances and consumer electronics.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

[1] Huijbregts, M. (1998): Application of Uncertainty and Variability in LCA, Int. J. LCA 3 (6) 343-351.

[2] Lloyd, S., R. Ries (2007): Characterizing, Propagating, and Analyzing Uncertainty in Life-Cycle Assessment: A Survey of Quantitative Approaches, J. Industrial Ecology 11 (1) 161-179.

[3] United States Department of Energy (DOE) (2012): Fuel economy information, retrieved December 5, 2012 from www.fueleconomy.gov.

[4] United States Environmental Protection Agency (EPA) (2012): Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2011, Transportation and Climate Division, Office of Transportation and Air Quality, EPA-420-R-12-001a.

[5] Santos, A., N. McGuckin, H. Nakamoto, D. Gray, S. Liss (2011): Summary of Travel Trends: 2009 National Household Travel Survey, Report No. FHWA-PL-11-02, Federal Highway Administration, U.S. Department of Transportation.

[6] Millard-Ball, A., L. Schipper (2011): Are we reaching peak travel? Trends in passenger transport in eight industrialized countries, Transport Reviews: A Transnational Transdisciplinary Journal, 31:3, 357-378.

[7] LeBlanc, D., M. Sivak, S. Bogard (2010): Using Naturalistic Driving Data to Assess Variations in Fuel Efficiency among Individual Drivers, Transportation Research Institute, University of Michigan, Report UMTRI-2010-34.

[8] Mock, P., J. German, A. Bandivadekar, I. Riemersma (2012): Discrepancies between type-approval and "real-world" fuel consumption and CO_2 values: Assessment for 2001-2011 European passenger cars, International Council for Clean Transportation, Working paper 2012-2.

[9] Lin, Z., D. Greene (2011): Predicting Individual Fuel Economy, SAE 2011-01-0618, SAE International.

[10] Social Knowledge, LLC (2012): User-reported gas mileage, retrieved December 5, 2012 from www.fuelly.com.

[11] Sullivan, J., M. Costic, W. Han (1998): Automotive Life Cycle Assessment: Overview, Metrics and Examples, SAE International Congress and Exposition, February 23-26, 1998, Detroit, Michigan, SAE 980467, SAE International.

[12] Weiss, M., J. Heywood, E. Drake, A. Schafer, F. AuYeung (2000): On the Road in 2020: A life-cycle analysis of new automobile technologies, MIT Laboratory for Energy and the Environment, Cambridge, Massachusetts.

[13] Lave, L., H. MacLean, C. Hendrickson, R. Lankey (2000): Life-Cycle Analysis of Alternative Automobile Fuel/Propulsion Technologies, Environ. Sci. Technol., 34 (17), 3598-3605.

[14] Hayashi, T., M. Kumata, K. Aoki (2001): Reduction of Life Cycle CO_2 Emissions – The Example of Honda Insight, SAE 2001-01-3722, SAE International.

[15] Burnham, A., M. Wang, Y. Wu (2006): Development and Applications of GREET 2.7 – The Transportation Vehicle-Cycle Model, ANL/ESD/06-5, Argonne National Laboratory, Argonne, Illinois.

[16] United States National Highway Traffic Safety Administration (NHTSA) (2006): Vehicle Survivability and Travel Mileage Schedules, Technical Report, DOT HS 809 952.

[17] Cheah, L (2013): Automotive Environmental Life Cycle Assessment, chapter manuscript submitted for publication in the Encyclopedia for Automotive Engineering, John Wiley & Sons, West Sussex, United Kingdom.

[18] Noshadravan, A., L. Cheah, R. Roth, F. Freire, L. Dias, J. Gregory (2013), Stochastic comparative assessment of environmental life cycle for conventional and electric vehicles, manuscript in preparation.

Lessons Learned from Conducting a Company-level, Downstream MFA

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Abstract

Material Flow Analysis (MFA) has been widely used to assess national and regional material flows. The use of MFA at the organizational level is less established. This paper presents research that uses MFA to examine the end-of-use (EoU) product management for an international steel component manufacturer and offers lessons learned from the process. It is found that MFA is useful for mapping product flows and material losses. Also, dividing the initial product flow into sub-flows helps indicate feasibility of improved company-level EoU product management. Finally, results indicate that some material losses can be delayed while others can be avoided altogether.

Keywords:

Material flow analysis; company-level; product end-of-use management

1 INTRODUCTION

A leading international manufacturer of steel based components wants to understand the fate of its products, determine the limits to its control over the end-of-use (EoU) product, and reconsider product EoU management. This exercise is especially challenging for a component manufacturer, which doesn't always have direct contact with the user and whose products are often just one of many pieces making up a larger end-product.

The project is conducted under the umbrella of life cycle management (LCM) and involves first assessing physical flows and later identifying and evaluating opportunities to improve product EoU management. This paper reports on the first phase of the project, the mapping of the physical flows.

Material Flow Analysis (MFA) was identified as a tool that could be used in the first step of the investigation, understanding the manufacturer's physical downstream flows. Since the MFA is driven by interests in improving a company's EoU management, the study is focused on not only traditional MFA questions like, *What is the material of interest?* and *Where and how do material losses occur?* but also *What products make up what portion of the flow?* and *To what customers and end products do the products flow and to what geographical areas?* It is thought that answering these questions can help the company assess feasibility of and plan improved end-of-use management. Looking at physical flows in regards to product type, business segment and customer is hoped to offer insights not usually gained by other forms of MFA. The purpose of this paper is to explore the benefits of using MFA in this situation and to present preliminary findings, which demonstrate examples of what kind of results can be achieved.

2 RESEARCH BACKGROUND

Material Flow Analysis (MFA) has been widely used as a tool to assess national flows and material flows of industrial sectors. For example, Davis et. al. (2007) looks at flows of iron and steel in the UK [1]. Also, Nakajima et. al. (2008) presents a substance flow analysis of Manganese (Mn) through iron and steel in Japan [2]. Despite this more common use, MFA at other levels is also acknowledged to be valuable. Two types are noted by Bringezu (2006) as related to products or firms – Type 1c (Life Cycle Assessment, LCA) and Type 2a (metabolic performance of firm or sector) [3].

In addition, some studies do address "product flow analysis" such as Oguchi et. al. 2008, which quantifies the flow of 94 consumer durables in Japan [4]. A review by Tukker and Jansen (2006) reveal that some studies related to the Environmental Impacts of Products (EIPRO) project have similar foci, albeit, again, over sectors and regions [5]. Also, Mathieux and Brissaud (2010) addresses end-of-life product-specific material flow analysis and acknowledges the use of MFA for economy-wide systems and identifies the need for a product-specific approach [6]. However, these studies take either an economy or product-perspective and not a company perspective. Given the research gap in this area as well as increased focus on resource efficiency and critical materials, it is considered relevant to attempt use of MFA for a company-level analysis and to assess its value as a tool at that level.

3 METHOD AND DATA SOURCES

The primary method for this study was MFA. Basic guidelines for conducting an MFA from Brunner and Rechberger (2004) were used [7]. Materials and substances related to the products of interest were mapped from the manufacturer's production to the user to final material sorting and recycling or disposal. Substances of special interest in this study that are also noted by the European Commission as being of high relative economic importance are Iron (Fe) and alloys, Nickel (Ni), Molybdenum (Mo), Manganese (Mn), and Chromium (Cr) [8].

A simple model was created to represent the system and throughput in the product cycle. The conceptual diagram (Figure 1) depicts the system analyzed. Viewed from top to bottom, the diagram reflects decreasing material form and function. The *EoU System* (green box) includes *Use* and EoU material processing, to include remanufacturing (*Reman*). Processes of interest are shown as boxes. Material flows are shown as arrows (not to scale) between processes or entering or exiting the *EoU System*. Flows that reach the system boundaries are shown in gray. *Preparation for Use* (blue box) includes two *Manufacturing Realms*. Flows enter the system from the *Component Manufacturer* as product (*a)* and replacement flows *(z).* Flows exit the system as losses (*f, n*), recycled steel (*i, l*), or slag for use (*m*). Flows to and from *Reman* include: used product for remanufacturing (*b)*, remanufactured product (*c*) to *Use*, replacement material (*z*) from the remanufacturer, and scrapped product (*e)* to *Material Handling*. Material from *Use* also goes to *Material Handling* in flow *(d).* From *Material Handling,* the flow is separated into *carbon steel production* (*g*) and to *alloyed steel production* (*h*). This separation was made based on the consideration that the function of alloys is lost when they are diluted in carbon steel. This consideration is consistent with other works such as Johnson et. al. (2006) and Daigo et. al. (2010) that refer to the recycling of alloys in "downgraded scrap" [9][10]. In addition, Amini et. al (2007) notes the importance of quality loss in understanding metal flows and recycling [11].

Waste fractions from Scrap Steel Production, namely *Carbon (j) and Alloyed Steel Production (k)*, are sent to *slag handling.* This process includes preparing materials for *Disposal,* or *Preparation for Use* in such applications as in road construction material.

Transfer coefficients were determined for each process with assistance from the manufacturer, customers, subject matter experts from respective fields, and publically available studies. With these values and the initial flow data, throughput for each process and the system was estimated.

The data collection included gaining data about 1) product composition and sales, 2) user activities, 3) product remanufacturing, 4) material (scrap) handling, 5) scrap steel production, and 6) resulting secondary material use. From the collected data, transfer coefficients were determined to determine flows between processes and losses.

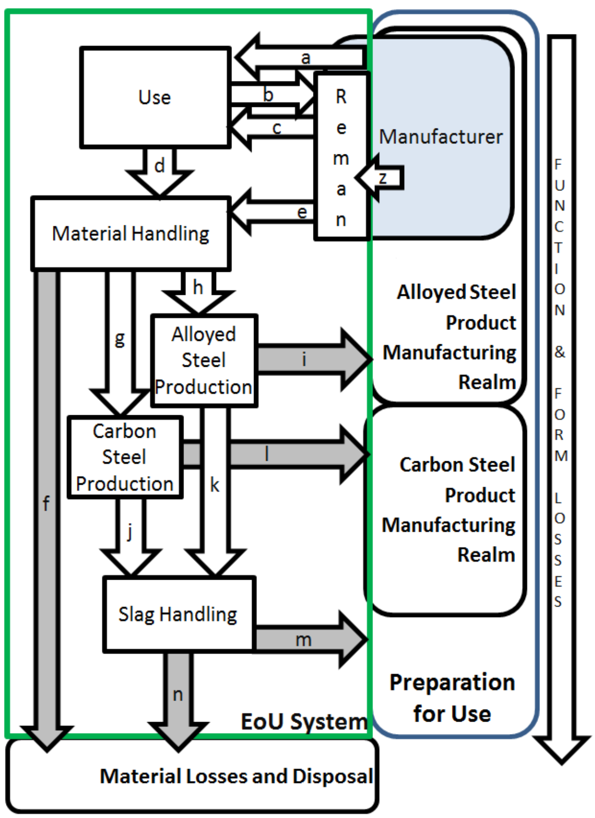

Figure 1: Conceptual diagram of system of interest. Flows *a* and *z* represents inflow from the manufacturer. Materials are followed and processes documented until they reach a system exit, such as with flows *f, i, l, m,* and *n.*

For this pilot study, two business segments were chosen to test the methodology. The flows from respective business segments were analyzed with respect to customer, geographical region, product types, product size (weight) and value.

3.1 Establishing Initial Material Flow

The initial material flow leaving the manufacturer (flow *a*) was determined using product sales and composition data, which were received from the manufacturer. Sales data were coupled with product information on product weight and composition. Composition data were given by percent substance present in the products and related materials (see Table 1 for example % composition of substances of interest). They were used to translate sales data into mass flow and to establish the foundational material (and substance) flow for the MFA.

For product sales, two business segments were chosen based on suggestions by manufacturer representatives. For each business segment, spreadsheets were obtained displaying all sales line items for an entire year. A line item is an individual sale to a customer and includes data for the sales such as product types, volumes, and prices. Product weights were added to each line item specifically for use in this study. Only direct sales were included in the study and indirect sales, such as those via distribution channels, were disregarded.

3.2 Establishing Use Activity Transfer Coefficients

In the process of establishing the initial material flows, suggested contacts within the business segments were approached and potential customer contacts were identified. A questionnaire was devised with six questions focused on the circumstances of product EoU. The question list included such questions as, *"In what circumstances are products deemed obsolete?"*, and *"How are products handled upon being removed from use?"* Customers were then approached with help of the questionnaire. Follow-up communications allowed for clarification of obtained information.

Quantitative data obtained by means of the questionnaires were used to define transfer coefficients for the MFA model. Customer estimates of the amount of product scrapped (*d*) or sent for remanufacturing (*b*), were used in the model.

3.3 Establishing Remanufacturing Transfer Coefficients

Remanufacturing, which for this study includes everything from product inspection and polishing to replacement of product components, is one option for product EoU management. For this study, the remanufacturing process was considered to be inside the EoU system, and thus flows to and from this process are not considered as system inputs or outputs. Customer questionnaires provided some estimates as to how often customers send products for remanufacturing (*b*). However, once products reach the remanufacturing facility, some of them are deemed to be unfit for remanufacturing and are scrapped (*e)* and some additional material *(z)* is added. Based on discussions with the manufacturer's remanufacturing operations, it was estimated that 75% of (*b*) materials received are remanufactured and returned to the customer. The remaining 25% was assumed to be scrapped (flow *e)*. In addition, material added (z) is estimated to be approximately 10% of *b.* Remanufactured products (*c*) were assumed to be used only one time, and not sent again to remanufacturing.

3.4 Establishing Material Handling Transfer Coefficients

When products are scrapped, it is often material handlers (scrap brokers) who process the scrap to make it sellable on the material market. It is known that some obsolete material from society never makes it to material handling [12]. However, it was assumed, based on customer questionnaires and follow-up discussions, that the products of interest for this study are fully captured by material handlers.

However, once the scrap metal has arrived at the material handler, there may be losses. Scrap handling loss estimates were obtained from representatives of a Swedish material broker for three possible processing options – direct transfer (0% loss), metal cutting (1% loss), and fragmentation (3% loss) (Torring, M., Sturesson, B., 2012, personal communication, Sep.- Nov.). Direct transfer is used when material is in a form that is sellable without processing. Cutting is used most often when pieces are too large and have to be made smaller. Fragmentation is utilized often with large materially heterogeneous products (made up of various materials), such as automobiles, or with heterogeneous or unknown scrap fractions that have to be segregated to attain or ensure of the right quality [12]. For this initial study, each of these three treatment options was assumed to be equally likely and to represent one third of the total flow to scrap steel sorting. As seen in Table 1, this results in an estimated loss of 1.3%. As an exception, a few users reported having established cooperation with steel producers and in these cases, direct transfer (0% loss) was used. Once processed, the material is sold to a steel producer. The proportion at which scrap is sold to carbon steel producers versus alloyed steel producers varies based on local factors and market conditions and was estimated for each case.

3.5 Establishing Scrap Steel Production Transfer Coefficients

The processed scrap is sold by the material broker to a scrap steel producer (either alloyed or carbon steel producers). Scrap steel producers melt scrap steel in an Electric Arc Furnace (EAF) and add ferro-alloys to create desired steel grades. During this process, substances are distributed among three phases – melt (liquid steel), slag (oxides), and gas [13]. The fate of each substance was considered to be of extra importance, since scrap steel production is the only process in which substances can be lost in proportions that differ from those in the product. It is known that the exchanges of material in scrap steel metallurgy are complicated and vary widely depending on many factors. For this study, simplifications were made to estimate losses to waste fractions (slag, dust, refractories). Transfer coefficients (losses) for Cr, Ni, and Mo were taken from sources of quantitative and qualitative nature. According to Hutchinson and Nylén (2003), 5% of Cr ends up in slag [14]. Ni and Mo are known to reside minimally in slag and mostly in the liquid steel [14][15]. Thus, a 0% loss was used for Ni and Mo.

Transfer coefficients for Fe and Mn, for which no better estimates were found, had to be determined. These estimates were made with assistance from the European IPCC Bureau's Best Available Technology (BAT) Reference Document for Iron and Steel [13]. Two main numbers were needed: (1) how much material ends up in waste fractions during the process and (2) the composition of waste fractions from the process.

During scrap steel production, substances end up in two types of slag, EAF and ladle, as well as to waste refractories, dust, and air emissions. EAF slag is reported to occur at amounts between 60 and 270 kg per tonne liquid steel (LS) compared to up to 80 kg/ tonne LS for ladle slag and up to 30 and 22.8 kg/ tonne LS for dust and waste refractories, respectively [13]. Based on these figures and an input-output analysis from the BAT document, three overall waste output levels were estimated, minimum (5%), moderate (10%), and maximum (25%) total waste per input. For this paper, only results reflecting 10% material losses are shown. Losses to gas are minimal in relation to losses to slag and are not considered further in this study [13].

Regarding waste fraction composition, the typical composition of EAF slag reported in the BAT document is assumed to be representative of the composition of all waste fractions. In regards to the substances of interest, Fe in the form of iron oxide (FeO) represents 32% of the typical composition. Mn appears in slag at a typical MnO concentration of 5% [13].

Product		Material Handling	Steel Production (Carbon or Alloyed)		
substance	example % in product	% loss	% oxide in slag	% element in slag	% loss (to waste fraction)
Mn	0.45%	1.3%	5.0%	3.9%	56%
Cr	1.60%	1.3%	1.8%	1.2%	5%
Ni	0.25%	1.3%	0%	0%	0%
Mo	0.10%	1.3%	0%	0%	0%
Fe	95.73%	1.3%	32.0%	24.9%	2.6%

Table 1: Substances of interest in product composition, substance presence in slag [13], and % substance loss for *Material Handling* and *Scrap Steel Production.*

With these slag composition estimates and by using product composition % as the scrap-input composition for the process, it was possible to estimate the percentage loss for Fe and Mn. Table 1 displays the estimated percentages of each oxide of interest in the slag and resulting % of loss for each substance. Mn, for example, is present in the product at 0.45%, and in typical slag at 3.9%. This means that approximately 55% of the Mn ends up in the waste fraction. As noted earlier, estimated Cr, Ni, and Mo losses were not determined for this study but were taken from other sources.

Transfer coefficients used for this study appear to be in agreement with the general trends suggested by the commonly-used Ellingham diagram and tables provided by two other sources [14] [15]. It should be noted, however, that these sources yield only a general indication of substance fate for steel production.

3.6 Establishing Slag Use Possibilities

After slag is removed from steel production it is typically reused, treated for reuse or disposed. For this study, slag use data provided by the BAT document for "Total EAF slags" were used to indicate occurrences of different fates including on-site recycling (4.7%), external use (23.1%), sold (10.4%) and landfilled and stored (61.4%) [13]. Material that is landfilled and stored was considered to be lost, whereas the others (*m*) were regarded as going to *Preparation for Use.*

3.7 Characterizing Secondary Use

Secondary use is considered to be any use of the material after the product EoU. Four main divisions of secondary use were considered as used to group possibilities: (1) product reuse allowed via remanufacturing (*c*), in which product form and function is largely retained; (2) material recycling to alloyed steel (*i*); (3) material recycling to carbon steel (*l*); and (4) material use in non-metal form (*m*), such as slag fractions used in roads. This hierarchical grouping of secondary use is consistent with common waste management hierarchies. It is also supported by LCA-related studies, such as Michaelis et. al. (1998), which looks at exergy in the life cycle of steel [16].

3.8 Compiling and Displaying Data

Product sales and composition data were compiled in a spreadsheet. Analysis of the initial flow was conducted, which primarily involved breaking the total flow into sub-flows.

Using initial flow data and determined transfer coefficients for processes, simple scenario-based analysis was used to generate MFA results and compare the outcome of varying flows from *Use*. The decision to use scenarios was made due to the lack of statistical relevance of the customer data gathered. For one business segment, only seven customers were represented and they displayed a large uncertainty and wide variation with what they do with EoU products. Scenarios were created based on customer responses. Results for scenarios were displayed in Sankey diagrams.

4 RESULTS

Results are presented in two major sections: analyzing the product flow and mapping the material flow.

4.1 Analyzing the Product Flow

There are many ways to cut and dice the product flow. For purposes of EoU management, the product sales, expressed in terms of weight, was divided by customer, product type, industry sub-segments, geographical region, product size, quantity, value and mass.

Some of the results are displayed in Figure 2. Figure 2a displays a breakdown of business segment A's customers. It demonstrates how seven customers (A-G) receive approximately 50% of the product flow. Figure 2b displays a breakdown of product sales (weight) by region. Geographical analysis can be important since regions are expected to have varying conditions for EoU management, such as different recycling markets and remanufacturing possibilities. A distinction was made between sales to Original Equipment Manufacturers (OEMs) and to Non-OEMs (Note: the ratio of OEM sales to Non-OEM sales is approximately 1:1). This was done because product flow to OEMs may end up being sold as a component as part of equipment to another region. Bearing this in mind, only the 53% of the Non-OEM product weight can be considered to positively reach EoU in Europe (*EU*). The final destination of the 81% of OEM product weight is less certain.

Figures 2c and 2d display product sales by weight and by monetary terms, respectively. Weight and sales breakdown show similar patterns, which demonstrate a strong correlation between sales

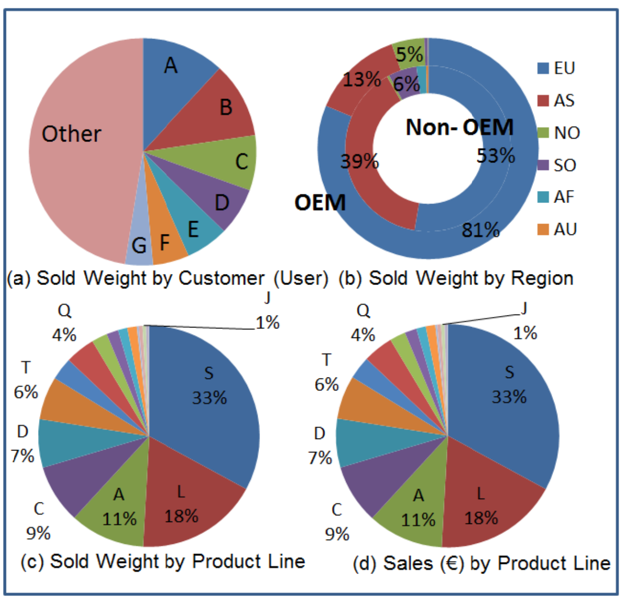

Figure 2: Business Segment A: Sales Broken down by Customer, Region, and Product Line (by weight and €). (a) shows that 7 customers receive over 50% of the flow. (b) displays to which region products are flowing for OEMs and Non-OEMs. (c) and (d) show a strong correlation between sales by weight and by monetary unit (€) for the business segment.

price and weight. It is also seen that product line S represents a significant part (33%) of the flow.

Weight, quantities (pieces), and sales prices can also be compared to give other perspectives. For example, cumulative weight can be displayed starting with the most expensive products first. This assumes that the least valuable product would be targeted last for remanufacturing or other improved EoU management. This analysis (Figure 3a, below) reveals that capturing only components worth at least €100 would reap over 70% of the weight. For Business Segment B, not pictured here, such products represent 87%.

In Figure 3b, products for Business Segment A are again segregated into two sales price categories, greater than or less than €100. By displaying the components in relation to pieces (quantity), sales value and mass, it is shown again that larger and more expensive components represent a small percentage of the quantity (pieces) flow, but a large percentage of the value and weight.

4.2 Mapping the Material Flow

Since the determination of transfer coefficients was largely revealed in earlier sections, the intent here is to present resulting throughput visually and note where losses occur. Results of two divergent scenarios (*Customer G* and *Customer 1*) are displayed in Sankey diagrams in Figure 4. Input, throughput and losses for each scenario are reflected in the diagram. *Customer G* is a real customer that displays EoU activities that are favorable to minimizing material and function losses. *Customer 1* is a hypothetical construction based on customer responses combined to form a less favorable scenario. *Customer G* sends most of its EoU product to remanufacturing, whereas *Customer 1* does not.

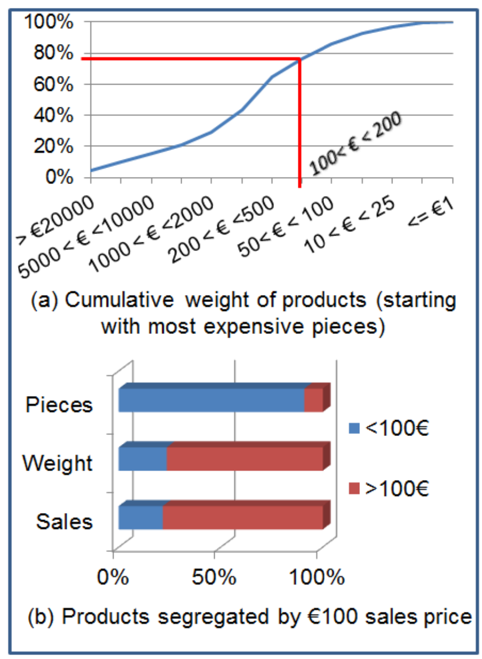

Figure 3: Business Segment A: Analysis of flows greater than and less than €100 sales price. (a) shows the results of accumulating the weight of products starting with the most expensive products first. Products sold for more than €100 represent 76% of the sold weight. (b) demonstrates that although products sold for greater than €100 represent little in quantity (pieces), they represent the majority in weight and sales (€).

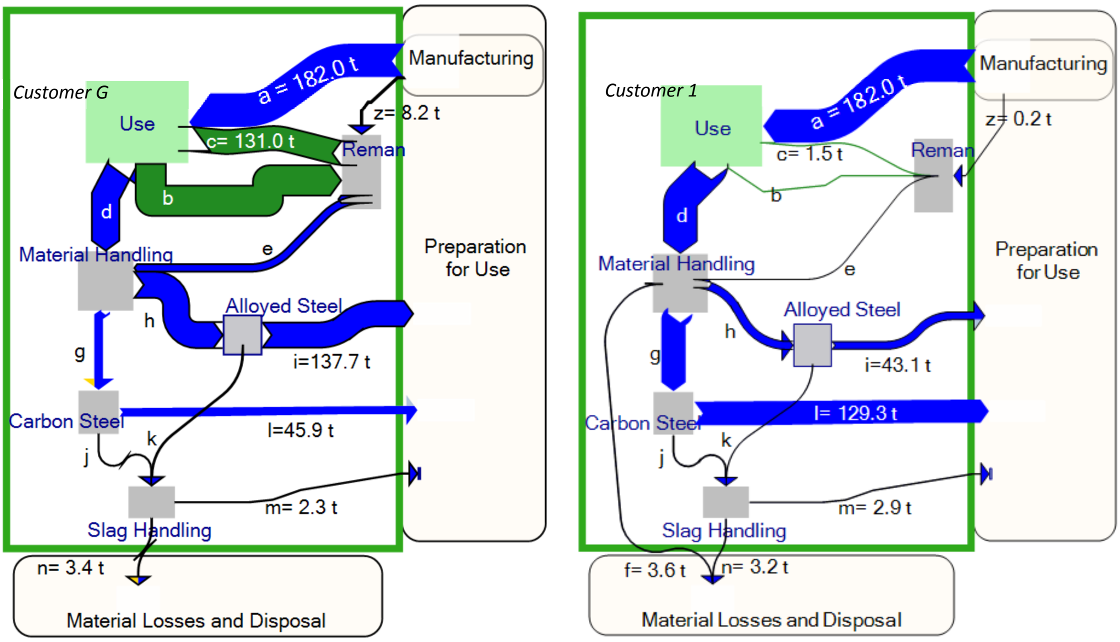

Figure 4: Sankey diagrams for *Customer G* and *Customer 1*. For *Customer G*, reuse flow (c) and flow (h) to alloyed steel production are high. Material handling losses (f) are avoided due to planned segregation. *Customer 1,* alternatively, sends minimal product to remanufacturing and does little scrap segregation, resulting in little reuse (c), material handling losses (f), and high flow (g) to carbon steel production. Thus, *Customer G* achieves more reuse, and less loss of material and material function. In addition, *Customer G* gets much more function out of the same amount of products.

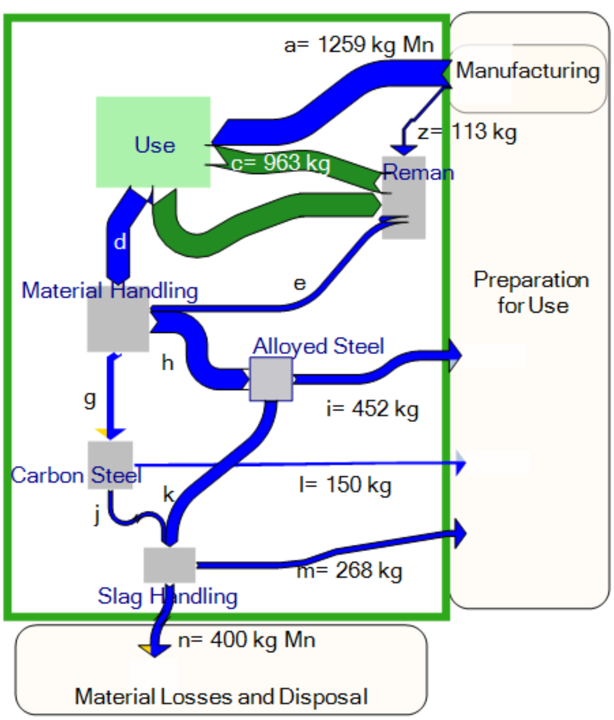

Figure 5: Sankey diagram of Mn flows related to *Customer G*

Furthermore, Customer G has an agreement with a nearby alloyed steel producer and segregates and sends obsolete material to that producer. *Customer 1* sends obsolete material to *Material Handling,* where 1.3% of material *(d)* is lost. Output from this process ends up primarily in *Carbon Steel Production*. In the end, *Customer G* achieves more reuse, and less loss of material and material function. In addition, *Customer G* gets much more function out of the same amount of products. However, it is observable that losses from steel production and slag handling are similar for the two scenarios. Losses from these processes are magnified when looking at certain substance flows. Figure 5 displays the flow of Mn related to *Customer G.* Even for this preferred scenario, almost one third of the Mn ends up in disposal.

5 DISCUSSION

Two MFA activities were noted as yielding information of interest for the manufacturer and for EoU management in general: 1) defining the material flow and 2) mapping the material flow. When defining the material flow in MFA, materials and substances and their fates are put under the microscope in a way that is not usually done in LCA. Materials are presented in their entirety instead of by functional unit. Instead of focusing on one or a few products or components in one or a few uses, one can look at many products in various industrial sectors, separately, or at the same time. Furthermore, breaking the flow into different categories allows for a relatively quick assessment of current material flows and could allow for prioritization of flows by a manufacturer. For instance, by looking at the analysis, the manufacturer could determine that by cooperating with *Customer A*, the manufacturer could recover (or better manage) a tangible percentage of the flow.

Also, cumulative flow curves, as displayed in this paper, can be helpful. By matching them with estimated break-even points, where sales price meets cost of the retrieval, it is possible to assess what additional EoU management could yield for different values. For example, if it were deemed that a €100 sales price is an indicator of when remanufacturing is financially feasible, it could be determined when looking at business segment A (Figure 3a), that 76% of products could be feasibly recovered. Because products sold to business segments A and B are large (and heavy) relative to other segments, it is projected that the cumulative weight curve looks much different for some other segments. This type of comparison could be used to prioritize EoU management efforts. Also, the analysis can be said to be particularly attuned to the business environment- it could be argued that it is favorable in this sense to other types of environmental analysis. In addition, the analysis revealed that there is a strong correlation between sales price and material weight hinting that this example study may be especially relevant for other manufacturers that make similarly composed products. This also indicates that price could be a substitute for material amount when weight information is not available.

In regards to the mapping of material flows, it is observed, maybe unsurprisingly, that what customers do after *Use* has a great impact on the outcome. Assuming that initial manufactured product mass is maintained, the amount of flow through the use phase greatly differs from one user to another. Remanufacturing operations thus greatly increase the flow of product through the use process. In other words, much more function is delivered by the same initial product flow. Also, preliminary findings indicate that segregation of EoU products may allow diversion of alloyed steel from unneeded *Material Handling* and from alloys ending up in carbon steel. Thus, the amount of material function realized can be greatly improved by remanufacturing and scrap segregation. However, if products are only remanufactured once, losses from scrap steel production and slag handling are essentially unavoidable. Finally, each of these conclusions can be assessed further by dividing material flows into substance flows. Displaying product-related substance flows offers a perspective that may be lost if one only looks at the material level.

Regarding the formation of the model and data used, as always, improvements could be made. Using mostly single sources to determine process transfer coefficients limits the model's ability to represent exact reality. However, the aim of the investigation was not to exactly replicate the system and inherent processes. It was to represent the system well enough to allow insights for the manufacturer and to generate lessons learned from the process itself. It should also be noted that there are two potential losses that are not assessed in the model: (1) loss during *Use* inside the system; and (2) losses during manufacturing that occur after steel production and outside the system boundaries.

Planned improvements to this MFA investigation include sensitivity analysis to improve an understanding of the effects of individual parameters. Other future work includes investigation into the qualitative aspects that determine flows and qualitative benefits of using MFA at the company-level.

6 CONCLUSIONS

When viewing the specific results of this study, it appears that the manufacturer is not as far removed from many of the material losses as initially perceived. Losses associated with material handling and scrap steel production can be delayed if not overcome to a large degree with modified user activities. Users, with which the company has varying levels of contact, essentially determine what will happen to materials at the point of product EoU. Increased remanufacturing and segregation of materials allows the delay or circumvention of much of the material and function losses.

Regarding general lessons learned, MFA appears to be a valuable tool for use at the company-level. Determining and mapping material flows and losses yields valuable insights towards better EoU product management. Defining the initial flow with product sales data allows one to determine the size and nature of a product-based material (and substance) flow. Assessing relationships between product sales quantity, size (mass) and sales price can give an indication of what additional EoU product accountability and management would entail. This analysis of the initial flow can be strongly correlated with business strategies, making this type of assessment potentially of benefit when conducting analyses and communicating results in a company setting.

7 REFERENCES

[1] Davis, J., Geyer, R., Ley, J., He, J., Clift, R., Kwan, A., Sansom, M., Jackson, T. (2007): Time-dependent material flow analysis of iron and steel in the UK. Part 2. Scrap generation and recycling, Resources, Conservation and Recycling, 51(1), pp. 118-140.

[2] Nakajima, K., Yokoyama, K., Nagasaka, T. (2008): Substance flow analysis of manganese associated with iron and steel flow in Japanese economy, ISIJ Int.2008, 48, pp. 549– 553.

[3] Bringezu, S., Moriguchi, Y. (2002): 8. Material flow analysis, in: A handbook of industrial ecology: pp. 79-90.

[4] Oguchi, M., Kameya, T, Yagi, S., Urano, K. (2008): Product flow analysis of various consumer durables in Japan. Resources, Conservation and Recycling, 52(3), pp.463-480.

[5] Tukker, A., Jansen, B. (2006): Environmental impacts of products: a detailed review of studies, J. Indust. Ecol., 10(3), pp. 159–182.

[6] Mathieux, F. & Brissaud, D. (2010): End-of-life product-specific material flow analysis. Application to aluminum coming from end-of-life commercial vehicles in Europe, Resources, Conservation and Recycling, 55(2), pp.92-105.

[7] Brunner, P.H., Rechberger, H., (2004). Practical Handbook of Material Flow Analysis, Lewis Publishers, Boca Raton.

[8] European Commission (EC) (2010): Critical raw materials for the EU, Report of the Ad-hoc Working Group on defining critical raw materials, Version of 30 July 2010.

[9] Johnson, J., Schewel, L., Graedel, T.E. (2006): The Contemporary Anthropogenic Chromium Cycle, Environ. Sci. Technol. 40, pp. 7060–7069.

[10] Daigo, I., Matsuno, Y., Adachi, Y. (2010): Substance flow analysis of chromium and nickel in the material flow of stainless steel in Japan, Resources, Conservation and Recycling, 54(11), pp. 851-863.

[11] Amini, S.H., Remmerswaal, J.A.M., Castro, M.B., Reuter, M.A. (2007): Quantifying the quality loss and resource efficiency of recycling by means of exergy analysis, Journal of Cleaner Production, 15(10), pp.907–913.

[12] Manouchehri, H. (2007): Looking at Shredding Plant Configuration and Its Performance for Developing Shredder Product Stream, Jernkontoret Report 88011, D 823.

[13] European Integrated Pollution Prevention and Control (IPCC) Bureau (2012): Best Available Techniques (BAT) Reference Document for Iron and Steel Production, under Industrial Emissions Directive 2010/75/EU, Joint Research Centre.

[14] Hutchinson, B., Nylén, M. (2003): Legeringar och Föroreningar i Stål- Statusrapport (in Swedish), Jernkontoret, Report 95003, D 795.

[15] Rod, O., Becker, C., Nylén, M. (2006): Opportunities and dangers of using residual elements in steels: a literature survey, Jernkontoret, Report 88042, D 819.

[16] Michaelis, P., Jackson, T., Clift, R. (1998): Exergy analysis of the life cycle of steel, Energy Int. J., 23(3), pp. 213-220.

Strategies and Ecosystem View for Industrial Sustainability

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Abstract

Industrial sustainability is a rapidly developing field of research. Numerous industrial examples show that it is possible to decouple economic performance and environmental degradation using the waste and energy hierarchies, but they are not applied systematically. This paper reviews approaches and strategies for industrial sustainability which has been synthesised by the authors into an improvement hierarchy (action framework). By adopting an ecosystem view (thinking framework), these strategies applied at various levels can provide guidance to create sustainable industrial systems. Resource flows within, in and out of a given system are represented using a conceptual ecosystem model. Because "less bad is not good enough", a novel industrial ecosystem model is proposed based on the principles of circular economy, i.e. industrial ecology and cradle-to-cradle, to promote positive environmental impact and natural capital regeneration as an ideal model for future industrial systems. The model change can be explained and guided by the improvement hierarchy applied at global level to connect the action and thinking frameworks, thereby contributing to lessen the barriers for practitioners to adopt and implement industrial ecology and cradle-to-cradle concepts.

Keywords:

Cradle-to-cradle; Ecosystem view; Industrial ecology; Industrial sustainability; Resource efficiency

1 INTRODUCTION

The way society currently operates clearly exceeds Earth's carrying capacity and, if not changed, will prevent the future generations to meet their needs [1]. Technological progress during the previous industrial revolutions has greatly advanced society but also had (and has) negative consequences on the planet such as increased resource scarcity, accumulation of waste and climate change [2]. A major shift in the way industry operates is needed, and soon. The challenges ahead are huge and complex. It involves a multitude of concepts and disciplines around sustainability, ranging from energy efficiency, product design to innovative business models.

A sustainable society can be defined as one in which economic prosperity, environmental preservation and social equity are achieved by taking into consideration the limitations in Earth's carrying capacity [3]. The approaches for sustainability need to be interdisciplinary to account for and built upon the complexity of industrial and societal systems. It is therefore crucial for industrial sustainability research to be highly collaborative with industrial companies and across academic boundaries.

This paper synthesises themes, strategies and approaches for industrial sustainability into an improvement hierarchy (action framework) and links it with concepts for industrial sustainability (thinking framework). An ecosystems view of industrial systems is adopted and includes the larger surrounding systems, i.e. the Earth's natural ecosystems (ecosphere and biosphere), society (humansphere) and man-made technological systems and built environment (technosphere). The paper also introduces a model based on industrial ecology model typology.

There is a necessity to combine the powerful concepts of industrial ecology and cradle-to-cradle as a thinking framework with the action framework of the well-established improvement strategies. Although practitioners apply the improvement hierarchies (e.g. waste and energy hierarchies), they do not use industrial ecology directly as it is not expressed in readily accessible language at the necessary level of detail. A direct connection between the two is currently absent; if the action framework can be clearly linked to the thinking framework, it can provide more clarity for practitioners to use industrial ecology as a guiding model for practice improvement.

2 INDUSTRIAL SUSTAINABILITY: A REVIEW

Various authors have proposed sets of strategies or principles for industrial sustainability by adopting different perspectives [4-7]. Major concepts and approaches for industrial sustainability can be mapped (Figure 1) to show these various perspectives to tackle sustainability issues in industry:

(1) "horizontal" perspectives: from local to global
  a. process view, e.g. technology and resource efficiency
  b. technosphere view, e.g. eco-parks and supply chain
  c. ecosphere view, e.g. natural resource flows and stocks

(2) "vertical" perspectives: from short- to long-term
  a. solution-oriented approaches focusing on processes and products to efficiently meet current demand, e.g. industrial engineering and product design
  b. problem-oriented approaches focusing on environmental and social issues and how to efficiently remedy these, e.g. integrated pollution prevention and control (IPPC), environmental policies, analysis of future scenarios
  c. opportunity-oriented approaches focusing on innovation and how to meet human needs effectively, e.g. cradle-to-cradle, biomimicry, product service systems (PSS)

(3) type of progress or development: from incremental to radical changes to develop industrial systems
  a. incremental changes to improve existing systems and mitigate negative impact, e.g. efficiency improvements, reduce-ruse-recycle approach
  b. radical change to develop new systems with innovative design and achieve positive impact, e.g. renewables, biomimicry and cradle-to-cradle

Most concepts and approaches for industrial sustainability are using more than one of the perspectives listed above and correspond to a range rather than a discrete point on a scale from short-term local solutions to long-term global solutions (Figure 2). The next sections review perspectives for industrial sustainability.

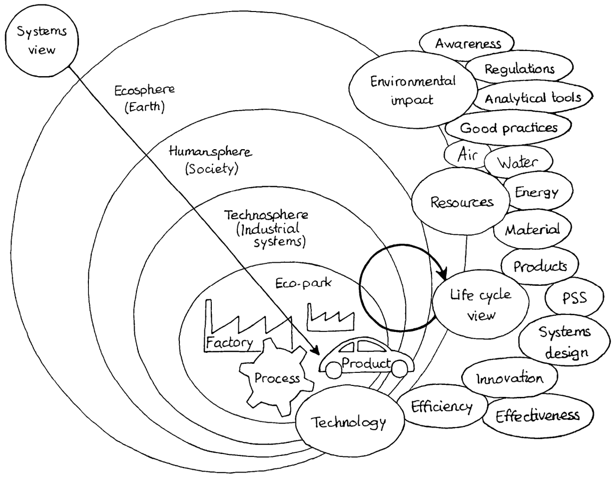

Figure 1: Perspectives for industrial sustainability and examples of themes, concepts and approaches.

2.1 "Horizontal" Perspectives: Scale and Scope

Different perspectives can bring different directions for improvement; it depends on the scope of the problem considered, the objectives and priorities.

Process Viewpoint

Strategies at process level typical focuses on local optimisation, e.g. [8; 9]. Although these strategies are imperative to achieve efficiency in individual phases or processes in a given system, similarly to the solution-oriented approaches discussed in the previous subsection, they are highly reductionist: manufacturing engineers work on process optimisation, facility manager utility network maintenance, product designers on fulfilling customer requirements, etc. Each expert works in his discipline in isolation resulting in missed opportunities for more optimal design and processes. Therefore the process-level strategies must take into account the implications for the larger surrounding system and be adjusted to contribute to wider improvements.

Factory Viewpoint

A whole factory perspective on improvements has been adopted by many groups of researchers and showed that an integrated analysis of resource flows through the factory. By crossing the discipline boundaries between building services, manufacturing operations and facilities brings new opportunities in the way manufacturing systems can be improved [10-12]. Powerful IT tools have been developed to tackle the complexity of manufacturing systems through modelling and simulation [13; 14], and improve the resource flows through a factory in a systematic way [15].

Technosphere Viewpoint

This perspective is anthropocentric and focuses on product strategies for the design, manufacture, distribution and use of products and services to minimise their environmental impact. It pays particular attention to material selection, dematerialisation, and recycling [16]. Tools and approaches such as life cycle assessment, eco-design and eco-efficiency [17] can support the assessment and improvement of production systems and to deliver sustainable value for the humansphere. Other approaches adopting this perspective include green supply chain management, product life management, reverse logistics and industrial eco-parks.

Ecosphere Viewpoint

This perspective is ecocentric and addresses global issues. The concepts of ecological rucksack and material input per service unit look at how much resource is needed to produce one unit of useful material, product or service [18]. Ecological footprinting and material flow analysis, among other tools, can also be used to analyse resource flows and stocks in a given system and their impact on the environment. Such tools help to better understand the current situation and develop scenarios to manage our impact on the ecosphere, e.g. climate change and resource scarcity.

2.2 "Vertical" Perspectives: Themes and Strategies

When analysing the literature, common themes in research are reoccurring in various forms. Some of the key themes and concepts for sustainability are listed in Table 1. They range from more traditional solution-oriented approaches focused on technology, to problem-oriented approaches such as environmental impact assessment and pollution prevention. More recently, opportunity-oriented approaches have emerged as innovative business models and technologies are being developed. This section discusses those three approaches to sustainability.

Reference	Examples of concepts and approaches
Themes for design and manufacture [19]	• Design for environment • Environmental management • Energy and waste management • Supply chain management • Product end-of-life management
Processes in product life cycle [20]	• Engineering: technical function analysis • Manufacturing: process optimization • Use: technical behaviour and utilization rates
Sub-systems strategies [21]	• Environmental engineering and technology • Integrated pollution prevention and control • Industrial ecology • Pollution prevention • Environmental management strategies • Product service systems strategy

Table 1: Approaches for industrial sustainability in the literature.

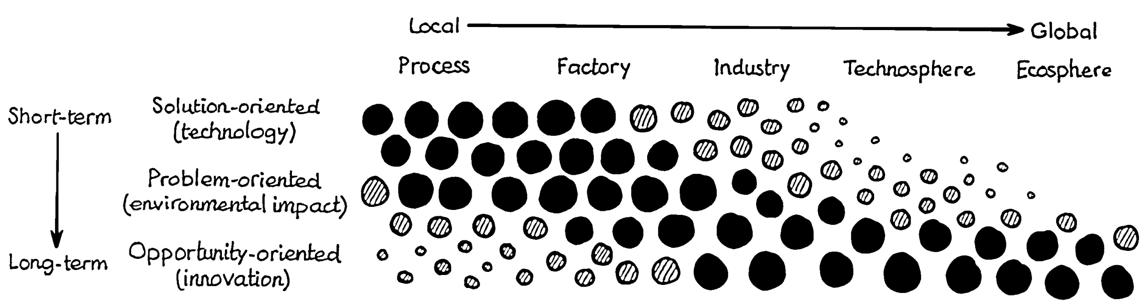

Figure 1: Horizontal and vertical perspectives on a temporal and geographical scale.

Reference	Improvement strategies
Options for sustainable manufacturing [30]	• Use less material and energy • Substitute input materials • Reduce unwanted outputs • Convert outputs to inputs • Changed structures of ownership and production
Key steps in making manufacturing more sustainable [31]	• Optimize use of fossil fuels • Eliminate waste • Reduce, eliminate pollution • Recycle • Recover energy • Save time
Elements of eco-efficiency [32]	• Reduce intensity • Reduce the energy intensity • Reduce toxic dispersion • Enhance material recyclability • Maximise sustainable use of renewables • Extend product durability • Increase the service intensity

Table 2: Strategies for industrial sustainability in the literature.

Solution-oriented: How to Meet Our Needs Efficiently?

Solution-oriented perspectives focus on technology and industrial engineering. Traditional engineering and technological approaches to progress aim at anticipating and controlling changes. Although they have been the main drivers of change during the industrial revolutions of the past century, they also had unforeseen consequences. They are also the remedy to the problems caused by those very changes [2]: it is now widely recognised that clean and efficient technology is part of the equation for sustainability.

Although they are not the panacea to all sustainability issues, technologies to reduce the impact of industry on the environment already exist. They are a key element to address the most pressing issues in the short-term and bridging the gap between currently available solutions and more sustainable long-term solutions [6]. Technological solutions are developed to achieve specific targets. Therefore they are mainly concerned with specialised, focused, local improvements, e.g. high efficiency and low carbon technology. Indeed, such solution-oriented approach allows shifting from toxic emissions control to cleaner and safer products and processes but it tends to be reductionist and thus sub-optimal. This perspective connects strongly with process viewpoint (“horizontal” perspective).

Problem-oriented: How to Address Sustainability Concerns?

Roome (1992) identified four attitudes to environmental problems: defensive, reactive, accommodative and proactive attitudes [22]. Defensive response is resisting change. Reactive response is driven by external forces: compliance with regulations and policies [23]. Accommodative response goes beyond compliance and is driven by market opportunity and internal factors such as management and employee involvement. Proactive response is driven by corporate vision; environmental capabilities are valuable to create competitiveness and leadership. For all attitudes, except defensive response, a problem-solving approach is often adopted.

Problem-solving approach is composed of four phases: identify the problem, analyse its causes, develop solutions, and apply them [24]. Industrial systems performance has typically been improved using such approach. For the first two phases (problem definition and analysis), environmental impact assessment and life cycle assessment are well-established tools to quantify the environmental impact of products and industrial systems [25]. They provide the basis on which informed decisions are made to select the most appropriate options for the second and third phase (develop solutions and apply them). The solutions developed aim at mitigating negative impacts, e.g. minimize emission of pollutants (soil, water and air emissions such as mercury, VOC or CO_2) and reduce the consumption of scarce resources (such as clean water or copper). Once the options are chosen, they are put into actions. These actions can be taken at three different levels:

- At the source with preventive measures such as IPPC and improved product and process design to reduce extraction of scarce resource from the ecosphere. This also includes closed-loop circulation of resource within the technosphere through reuse, repair remanufacturing and recycling (Rs strategies).
- During material processing, manufacturing and use phase in the technosphere with technical measures for efficiency.
- After pollutants are generated with the end-of-pipe measures such as filtering, emissions treatment and other pollution control solutions to mitigate the negative impact.

Preventive measures taken at the design stage have higher chances to impact on the overall performance of the system than measures taken later as “add-ons” to compensate for design faults (or unanticipated side effects).

Opportunity-oriented: Is there Another way to Achieve Our Goals?

The sustainability challenge facing society requires fundamental changes and a systems approach to the design of industrial systems. Although sustainability issues and goals are widely recognised by companies and government, the pace of change is still slow. Approaches developed in recent year such as design of resilient sustainable system try to take advantage of the complexity, diversity and adaptability of industrial systems to develop new ways to address the sustainability challenge [26]. For instance, manufacturing companies can convert waste into valuable by-products to allow reuse of this waste as a resource. This can only be achieved by adopting systems thinking and by crossing traditional discipline and function boundaries. Concepts such as industrial ecology [5] and cradle-to-cradle design [7] encourage industrial companies to consider the larger system in which they are embedded to find more optimal solutions.

New innovative business models such as PSS provide new ways to fulfil needs [27]. They dramatically increase resource productivity and decouple socio-economic benefits and environmental impact.

Models for the design of products, process and whole industrial systems are also increasingly inspired by nature. Biomimicry imitates the way nature solves problems to develop materials and technologies reaching new levels of performance and efficiency [28]. Industrial eco-parks [29] also imitate the way natural ecosystems optimally exploit available resources (renewable energy sources and locally abundant resources) and exchange waste as food so that resources circulate in a cyclic fashion.

2.3 Types of System Development: Incremental vs. Radical

The literature proposes sets of strategies and principles for industrial sustainability. Certain authors present improvement strategies which must all be followed to achieve sustainability (Table 2), while others are presenting options with a prioritisation order (i.e. hierarchies, Table 3). Despite this difference in approaches, both Table 2 and Table 3 show similar strategies.

The hierarchies in Table 3 help to prioritise improvement options by identifying at which stage an improvement should be implemented. The energy and waste hierarchies [4; 38] are well-established and are typically represented by a pyramid with Reduce-Reuse-Recycle (the so-called ‘Rs’ strategies sometimes including remanufacturing and recovery). These strategies and hierarchies from Table 2 and Table 3 can be used not only to incrementally improve existing systems (e.g. dematerialisation and eco-efficiency) but they can also

Reference	Improvement hierarchies
Green productivity [33]	• Waste reduction • Waste control • Waste avoidance • Waste prevention
Rs strategies [4]	• Reduce • Remanufacture • Recycle and Reuse

Table 3: Hierarchies for industrial sustainability in the literature.

be used as specifications to create new industrial systems (radical change through substitution and innovation). Table 4 provides examples of other sets of strategies which can be used as specifications for creating sustainable industrial systems.

The strategies reviewed in this section can be synthesised into the following improvement hierarchy (Figure 3) for resource efficiency [38] to formulate an action framework:

- Prevention: eliminate unnecessary activities to avoid usage;
- Waste reduction: good housekeeping, recovery and treatment to reduce waste and maintain (or increase) its value;
- Resource reduction: minimise demand and increase efficiency;
- Reuse: convert waste into resource to close the loop;
- Substitution: change the way human needs are met.

It is important to note that the lower levels of the waste and energy hierarchies are the least desirable options, e.g. waste incineration with energy recovery (but loss of all material value), landfill, conventional energy and carbon capture and sequestration. These solutions do not correspond to any strategies in the improvement hierarchy as they are not considered as improvements, but as business as usual. The improvement hierarchy can be seen as a loop or improvement cycle;

Reference	Specifications for sustainability
Sustainable industry features [34]	• Appropriate technologies • Safe and environmentally compatible materials • Products that meet basic social needs and some individual wants • Low- and no-waste production processes • Safe and skill-enhancing working conditions • Energy efficiency • Resource conservation to meet future needs
Strategic technology areas [35]	• Waste-free processes • New materials processes • Enterprise modelling and simulation • Improved design methodologies • Education and training
Natural capitalism [36]	• Dramatically increase resource productivity • Shift to biologically inspired production models • Move to a solutions-based business model • Reinvest in natural capital
Objectives to address the four system conditions of the natural step [37]	• Eliminate our contribution to systematic increases in concentrations of substances from the Earth's crust • Eliminate our contribution to systematic increases in concentrations of substances produced by society • Eliminate our contribution to the systematic physical degradation of nature • Contribute to the meeting of human needs

Table 4: Specifications for industrial sustainability in the literature.

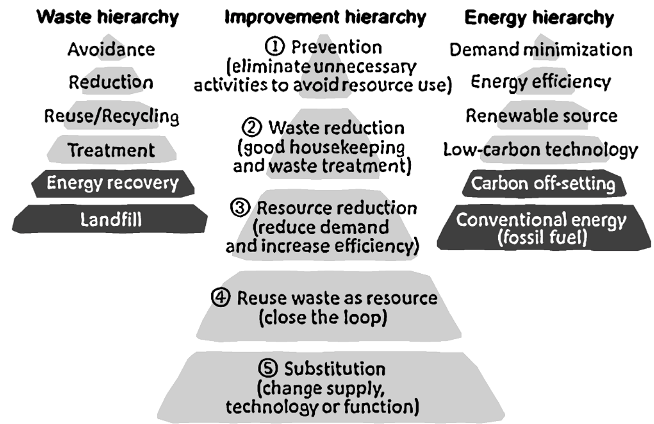

Figure 3: Improvement hierarchy (adapted from [38]).

when arriving at improvement "saturation" characterised by high efforts invested for little returns at a given level, one can move on to the next level in the hierarchy until improvements are exhausted at all level of the hierarchy; then a larger scale change (or "leap") can be done to reach a new level of performance and reset the loop to start the improvement cycle again. This leap corresponds to the "substitution" type of improvement and is the opportunity to move to a new technology, new model or new paradigm.

3 TOWARDS SUSTAINABLE INDUSTRIAL SYSTEM

The way we perceive the role of the ecosphere and natural resources has changed by applying strategies for more sustainable industrial systems at global scale.

3.1 Four Industrial (Eco)System Models

The visualisation of the four models is based on industrial ecology model typology [39]. The third and fourth models incorporate elements form cradle-to-cradle design [7]. Cradle-to-cradle introduced a new approach to design and production which focuses on positive consequences rather than reduction of the negative impact of industrial activities as proposed by more traditional approaches to sustainability such as IPPC and eco-efficiency.

The four models of industrial systems are represented by their respective flow types in Figure 4 and are used as a thinking framework to guide sustainable improvement of industrial systems:

1. Nature as an external system providing abundant resources and assimilating waste—this model assumes abundance (unlimited Earth's carrying capacity) and is represented by a linear flow;
2. Nature as a limiting factor (defining *maximum* capacity) due to resource scarcity and environmental degradation further limiting nature's ability to fulfil human demand—this model corresponds to a more responsible resource exploitation with reduced and closed-loop material flow, represented by a quasi-cyclic flow;
3. Nature as an ideal model (reaching *optimal* capacity) with perfectly cyclic flows, i.e. waste systematically becomes food for other system's components, no undesired outputs and no impact—this model is represented by a cyclic flow;
4. Finally, the authors are proposing an additional model based on cradle-to-cradle and net positive environmental impact—this model is represented by the inverted flow.

3.2 Strategies to Guide Model Shift

The strategies reviewed in the previous section are used rather locally, i.e. process and product perspectives. Here we propose to apply them at a larger scale to guide industrial systems to shift from one model to another. First, the prevention and reduction strategies are applied to the first model (linear flow) in order to reduce the intake of resources from and the waste released to the ecosphere. Then, the reuse strategy helps moving towards the second model (quasi-cyclic flow) where there is certain degree of cyclicity. This means that the flow within the system is larger than the total inputs and outputs of the system. In other words, the affluence can remain the same as with the linear flow but the intake of resources and the waste released to the ecosphere are reduced.

By pushing the reuse strategy at its maximum in addition to the substitution strategy to implement new technologies and new business models, the third model (cyclic flow) can be reached. It corresponds to an ideal ecosystem with closed-loop circulation of resources: technical nutrients are reused and recycled in technosphere while biological nutrients are food for the ecosphere.

As the third model (perfect cyclic flow) is not realistically achievable, the fourth model (inverted flow) compensates for the imperfection the system and the limits on realising the third model to achieve zero net environmental impact, or positive environmental impact. In this fourth model waste and pollutant become inputs to the industrial system and the output are sustainable products (technical nutrients) and sustainable waste (biological nutrients to regenerate resource capital) which both have a positive impact within their respective boundaries (technosphere and ecosphere). Thus the flows associated with environmental degradation are inverted compared to the first model. This approach has similar characteristics as pollution control in that it treats waste and pollutants after they have been generated but before they are released to the ecosphere (as opposed to IPPC which applies before they are generated). The main difference is that the emissions are already in the ecosphere and the aim is not only to clean up, but to create value from these waste and pollutants.

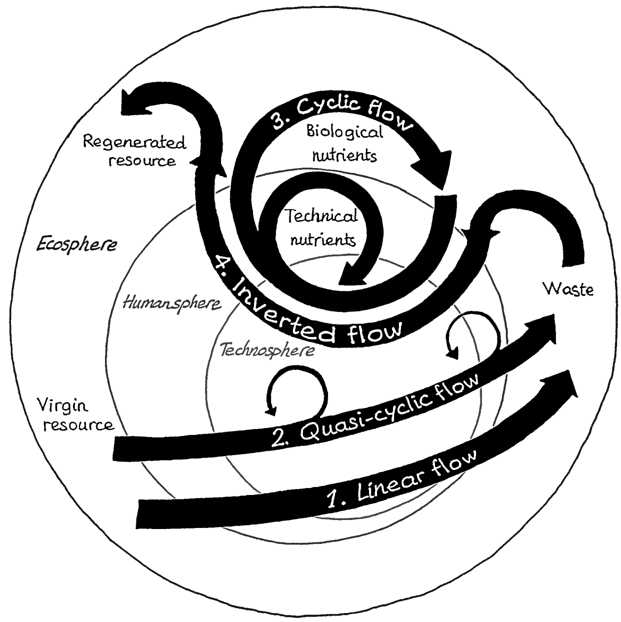

Figure 4: Industrial ecology and beyond: model types and flows.

The number of good practices is rapidly increasing and a good integration of the solutions implemented is absolutely key for their success. This means that research as well as industrial approaches be increasingly interdisciplinary to cross functional boundaries and ensure the compatibility of the various solutions needed if the sustainability challenges are to be addressed quickly, efficiently and if the sustainability challenges are to be addressed quickly, efficiently and effectively.

4 PRACTICAL IMPLICATIONS

Numerous application examples exist to show the practicality of the perspectives and strategies reviewed in this paper. On the technology side, there are countless solutions existing for improving the sustainability performance of products and processes. Many renewable and high-efficiency technologies are commercially available while others will require the strong policies to be deployed widely [6]. These solutions help to reduce our overexploitation of and dependency on virgin natural resources, thereby contributing in reducing the impact of the linear “take-make-waste” model.

But there are limits to efficiency improvements which this model can achieve. We must shift towards a circular economy. Among the most famous examples of quasi-cyclic and cyclic flow models are the Kalundborg eco-industrial park [29], Xerox remanufacturing initiative [4], cradle-to-cradle “House Like a Tree” with the cherry tree analogy [7]. Such innovative business models and opportunity-oriented approaches to design have already proven the applicability of the closed-loop resource circulation concepts.

Finally, to illustrate the proposed inverted flow model, examples can be found in biomimicry case studies. For instance buildings can clean air in cities by using cement capable of absorbing and photocatalytically decomposing various pollutants from the air [40]. The technology has a double function: it generates clean air while provide regular building function. A second example of solution inspired by nature is the algal turf scrubbers (ATS) which are used as wastewater treatment systems [41]. They can extract excess nutrients from water polluted by agricultural, domestic, and some industrial runoff. They use sunlight as their principal source of energy and simultaneously restore oxygen levels. In addition to this cleaning function, the ATS produce high-value waste which can be used as fertilizer and for conversion to biofuel.

5 CONCLUDING REMARKS

This paper has examined strategies and concepts for industrial sustainability. In particular the concepts of cradle-to-cradle and industrial ecology as well as the strategies containing improvement hierarchies have been reviewed.

All perspectives and themes reviewed in the first part of this paper are playing a role in moving society towards sustainability; one is not necessarily better than another in particular contexts. But the work needs to be framed and contextualised within the wider systems they belong to or collaborate with so that the solutions developed fit it in the bigger picture. This first part proposes an improvement hierarchy to synthesise well-established strategies for industrial sustainability. The second part of the paper shows how to connect two proven and well-established frameworks: a thinking framework based on industrial ecology and cradle-to-cradle design and an action framework in the form of an improvement hierarchy.

The first contribution of this paper resides in aligning the thinking framework and action framework by clarifying the connection between the two and thus making industrial ecology and cradle-to-cradle more accessible to practitioners. In turn, it enables actions for industrial sustainability to be taken more systematically and more broadly. The paper has also contributed to the field of industrial sustainability by proposing a novel model of industrial systems which goes beyond industrial ecology concept. It differs according to how resources enter and possibly leave the technosphere to enable net positive environmental impact. Examples are used to illustrate this ‘inverted flow’ model, but more research is required to specify the details which can further enable the application of this model.

6 REFERENCES

[1] Club of Rome and Meadows, D. H. (1972), *The limits to growth,* Earth Island Ltd, London.

[2] Gray, P. E. (1989), "The Paradox of Technological Development", in Ausubel, J. H. and Sladovich, H. E. (eds.) *Technology and Environment,* National Academy of Sciences, Washington, D.C., pp. 192-204.

[3] Daily, G. C. and Ehrlich, P. R. (1996), "Socioeconomic equity, sustain ability, and earth's carrying capacity", *Ecological Applications,* vol. 6, no. 4, pp. 991-1001.

[4] Sarkis, J. and Rasheed, A. (1995), "Greening the Manufacturing Function", *Business Horizons,* vol. 38, no. 5, pp. 17-27.

[5] Lifset, R. J. and Graedel, T. E. (2002), "Industrial ecology: goals and definitions", in Ayres, R. U. and Ayres, L. W. (eds.) *A Handbook of Industrial Ecology,* Edward Elgar Publishing, Northampton, MA, pp. 3-15.

[6] Sandén, B. A. and Azar, C. (2005), "Near-term technology policies for long-term climate targets - Economy wide versus technology specific approaches", *Energy Policy,* vol. 33, no. 12, pp. 1557-1576.

[7] Braungart, M., McDonough, W. and Bollinger, A. (2007), "Cradle-to-cradle design: creating healthy emissions – a strategy for eco-effective product and system design", *J. Clean. Prod.,* vol. 15, no. 13-14, pp. 1337-1348.

[8] Clelland, I. J., Dean, T. J. and Douglas, T. J. (2000), "Stepping towards sustainable business ", *Interfaces,* vol. 30, no. 3, pp. 107-124.

[9] Pusavec, F., Krajnik, P. and Kopac, J. (2010), "Transitioning to sustainable production – Part I: application on machining technologies", *J. Clean. Prod.,* vol. 18, no. 2, pp. 174-184.

[10] Hesselbach, J., Herrman, C., Detzer, R., Martin, L., Thiede, S. and Lüdemann, B. (2008), "Energy efficiency through optimized coordination of production and technical building services", *Proc. 15th CIRP Int. Conf. LCE 2008,* 17–19 March 2008, Sydney (Australia), pp. 624.

[11] Herrmann, C. and Thiede, S. (2009), "Process chain simulation to foster energy efficiency in manufacturing", *CIRP J. Manuf. Sc. & Technol.,* vol. 1, no. 4, pp. 221-229.

[12] Ball, P. D., Evans, S., Levers, A. and Ellison, D. (2009), "Zero carbon manufacturing facility – towards integrating material, energy, and waste process flows", *Proc. IMechE, Part B: JEM,* vol. 223, no. 9, pp. 1085-1096.

[13] Heilala, J., Vatanen, S., Tonteri, H., Montonen, J., Lind, S., Johansson, B. and Stahre, J. (2008), "Simulation-based sustainable manufacturing system design", *WSC'08,* 7–10 Dec. 2008, Miami, FL, pp. 1922.

[14] Michaloski, J. L., Shao, G., Arinez, J., Lyons, K., Leong, S. and Riddick, F. (2011), "Analysis of Sustainable Manufacturing Using Simulation for Integration of Production and Building Service", *SimAUD 2011,* 4–6 April 2011, Boston, MA, pp. 1.

[15] THERM Project (2011), *THrough-life Energy and Resource Modelling (THERM)*, available at: http://www.therm-project.org/ (accessed 15 July 2011).

[16] Ljungberg, L. Y. (2007), "Materials selection and design for development of sustainable products", *Materials and Design,* vol. 28, no. 2, pp. 466-479.

[17] Hauschild, M., Jeswiet, J. and Alting, L. (2005), "From life cycle assessment to sustainable production: Status and perspectives", *CIRP Annals - Manufacturing Technology,* vol. 54, no. 2, pp. 535-555.

[18] Hertwich, E. G., Pease, W. S. and Koshland, C. P. (1997), "Evaluating the environmental impact of products and production processes: A comparison of six methods", *Science of the Total Environment,* vol. 196, no. 1, pp. 13-29.

[19] Rahimifard, S. and Clegg, A. J. (2007), "Aspects of sustainable design and manufacture", *Int. J. Production Research,* vol. 45, no. 18-19, pp. 4013-4019.

[20] Westkämper, E., Alting, L. and Arndt, G. (2001), "Life cycle management and assessment: Approaches and visions towards sustainable manufacturing", *Proc. IMechE, Part B: JEM,* vol. 215, no. 5, pp. 599-626.

[21] Glavič, P. and Lukman, R. (2007), "Review of sustainability terms and their definitions", *J. Clean. Prod.,* vol. 15, no. 18, pp. 1875-1885.

[22] Roome, N. (1992), "Developing environmental management strategies", *Bus. Strat. Env.,* vol. 1, no. 1, pp. 11-24.

[23] Sterner, T. (2001), *Policy instruments for environmental and natural resource management,* Resources for the Future, World Bank and SIDA, Washington, D.C.

[24] Fisher, R. and Ury, W. (1981), *Getting to Yes: Negotiating Agreement Without Giving in*, Houghton Mifflin, Boston.

[25] Finnveden, G. and Moberg, A. (2005), "Environmental systems analysis tools - An overview", *J. Clean. Prod.,* vol. 13, no. 12, pp. 1165-1173.

[26] Fiksel, J. (2003), "Designing Resilient, Sustainable Systems", *Environmental Science and Technology,* vol. 37, no. 23, pp. 5330-5339.

[27] Mont, O. K. (2002), "Clarifying the concept of product-service system", *J. Clean. Prod.,* vol. 10, no. 3, pp. 237-245.

[28] Benyus, J. M. (2002), *Biomimicry: Innovation Inspired by Nature,* Harper Perennial, New York.

[29] Chertow, M. R. (2000), "Industrial symbiosis: Literature and taxonomy", *Annual Review of Energy and the Environment,* vol. 25, pp. 313-337.

[30] Allwood, J. M. (2005), "What is Sustainable Manufacturing?", *Sustainable Manufacturing Seminar Series,* 16th February 2005, Cambridge University, pp. 1-32.

[31] Hibbard, S. (2009), "Six key factors for achieving: Sustainable Manufacturing", *Foundry Management & Technology,* vol. 137, no. 2, pp. 40.

[32] World Business Council for Sustainable Development (1996), *Eco-efficient leadership for improved economic and environmental performance,* Conches, Geneva.

[33] Mohanty, R. P. and Deshmukh, S. G. (1998), "Managing green productivity: Some strategic directions", *Production Planning and Control,* vol. 9, no. 7, pp. 624-633.

[34] Geiser, K. (1991), "The greening of industry: making the transition to a sustainable economy", *Technology review,* vol. 94, no. 6, pp. 64-72.

[35] Jawahir, I. S., Wanigarathne, P. C. and Wang, X. (2005), "Chapter 12: Product Design and Manufacturing Processes for Sustainability", in Myer, K. (ed.) *Mech. Eng. Handbook,* 3rd ed, John Wiley & Sons, Hoboken, NJ, pp. 414-443.

[36] Lovins, A. B., Lovins, L. H. and Hawken, P. (1999), "A road map for natural capitalism", *HBR,* vol. 77, no. 3, pp. 145-158.

[37] Robèrt, K. H., et al. (2002), "Strategic sustainable development - Selection, design and synergies of applied tools", *J. Clean. Prod.,* vol. 10, no. 3, pp. 197-214.

[38] Despeisse, M., Ball, P. D., Evans, S. and Levers, A. (2012), "Industrial ecology at factory level – a conceptual model", *J. Clean. Prod.,* vol. 31, no. 3-4, pp. 30-39.

[39] Jelinski, L. W., Graedel, T. E., Laudise, R. A., McCall, D. W. and Patel, C. K. N. (1992), "Industrial ecology: Concepts and approaches", *Proc. National Academy of Sciences USA,* vol. 89, no. 3, pp. 793-797.

[40] AskNature (2012), *TX Active® cement* available at: http://www.asknature.org/product/779b5dbf9739d925b8caca665ea374bc (accessed 04/12/2012).

[41] AskNature (2011), *Algal turf scrubber*, available at: http://www.asknature.org/product/e37ad98658974d79f8b34b1da2574b49 (accessed 04/12/2012).

Sustainability through Lifecycle Synthesis of Material Information

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Abstract

The synthesis of material information across lifecycle stages will lay the foundation for a material information model to support sustainable decision making. This paper explores how material information is represented in select standards that address product and process information at different lifecycle stages. We discuss some of the challenges in synthesizing information between these standards, and explore the use of ontologies as a means to create and manage material information across a lifecycle. We discuss the potential benefits of fully synthesizing material information across the lifecycle, and the potential applications of a material information model that possesses this capability.

Keywords:

Material Information Model; PLM standards; information modeling; ontologies; sustainable manufacturing

1 INTRODUCTION

Historically, the development of products has been optimized based on three primary drivers: quality, cost, and time to market (throughput). Today a new driver has emerged: sustainability [1]. Sustainability has become a principal business driver brought about by customer demand for products to be more “green” and “friendly.” The perception of what makes a product “sustainable” can be difficult to pinpoint. This is especially true when focusing on the manufacturing of products, where decisions are not always as simple as “using recyclable materials.” Despite the industry-wide push to make advancements in sustainable manufacturing, the science for measuring sustainability performance metrics (i.e., energy and material efficiency) remains immature.

Manufacturing for sustainability requires an integrated systems approach that spans the product lifecycle. Metrics from each stage of a lifecycle can be optimized to better support a sustainable system; however, focusing on any single stage in the product lifecycle in isolation could result in suboptimal solutions and unintended consequences. Evaluation not only within, but also *across* lifecycle activities is critical to the fundamental understanding of sustainable manufacturing. Material selection plays an important part in determining total lifecycle impact. For example, creating products out of lower impact materials may result in less energy and material use in the production of a single product but may end up jeopardizing the longevity of the product and result in the production of more goods to meet the same need—incurring a greater impact on society.

We believe that available technologies can be augmented to provide new insight into the sustainability implications of decisions across the lifecycle of a product. Industry realized years ago the need to collect and manage information across lifecycle stages. To interoperate with the software used at different stages of a product’s lifecycle, Product Lifecycle Management (PLM) systems provide a means for information exchange, often in a standardized way. While the information managed by different tools is often specific to a lifecycle stage, there is also “common” information that passes between stages. In this paper, we discuss how sustainability assessment can be integrated with traditional product management techniques through standards, materials, and material properties.

This paper reviews several standards that are available at different lifecycle stages to describe an approach for building a sustainability-focused integration infrastructure. Section 2 highlights materials and their role in lifecycle synthesis and sustainability. Section 3 surveys the types of standards used across the lifecycle, and how material information is used. Section 4 discusses the technical challenges of synthesizing material information across the lifecycle; both in terms of integrating engineering information at the semantic level and in terms of the necessary information technology to support such integration. This section also demonstrates a general approach to integration. Section 5 identifies ways our material synthesis approach can move forward and the potential impact.

2 SUSTAINABILITY THROUGH SYNTHESIS OF MATERIAL INFORMATION

As noted, sustainability considerations are becoming increasingly important during the manufacturing stages of product development. Currently, however, sustainability assessment is typically performed after much of the early design and process plan has already been decided.

The current state of the art for sustainability assessment, Lifecycle Assessment (LCA), relies on knowledge about how a product will be sourced, manufactured, used, and disposed. LCAs are often complex and calculation intensive. We propose that by making material information more transparent we can expand the quality of the material information available during early design stages. We believe this new transparency can supplement methods currently used by LCA tools while also providing new design-time insight into sustainability implications.

At the highest level of abstraction the one physical characteristic that all manufactured products have in common is that they are composed of materials. Materials can provide the connection between the virtual world of design and the physical world of manufacture, as a primary function of manufacturing is the manipulation of materials. Materials provide a common thread to connect all stages of the product lifecycle. As such, materials can also serve as a basis for sustainability measurement.

Lifecycle impacts can be more efficiently assessed when incorporating metrics associated with materials. When focusing on the manufacturing stages, these metrics include actual measures of energy and material usage during manufacturing. As other stages of the lifecycle are incorporated, the impacts begin to vary. As Allwood et al note, "the environmental impacts of materials production and processing, particularly those related to energy, are rapidly becoming critical [2]." To better understand the impact of material choice during design and manufacturing, the impacts from all lifecycle stages need to be made more transparent. This transparency can be achieved through the lifecycle synthesis of material information.

The first step to incorporating material considerations from across the lifecycle into design time evaluation is to understand the use of material information at different stages of the product lifecycle. Material information is inherently interconnected between lifecycle stages, and any impact assessed, regardless of stage, should reflect contributions from other stages. However, due to many different viewpoints (Figure 1), the necessary integration and synthesis can be a challenge. To address this challenge, we turn to PLM systems and standards.

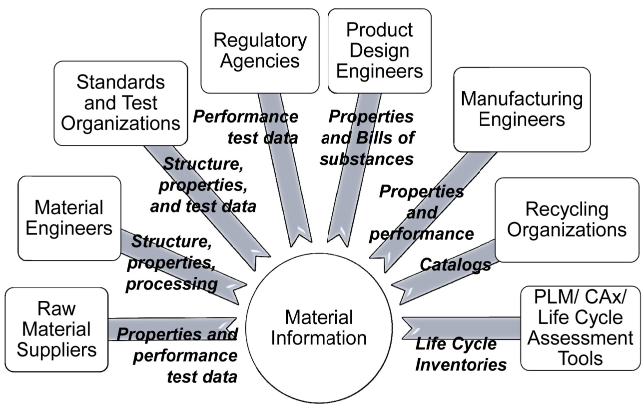

Figure 1: Different views and uses of material information.

3 MATERIAL INFORMATION IN THE PRODUCT LIFECYCLE

New capabilities in PLM tools are trending them away from a file exchange platform towards a more integrated knowledge management system [3]. Industry is embracing this shift, as it allows more granular information exchange across domains, platforms, and regions, providing a new level of support to both distributed and concurrent product development. These advancements mean material information can, and is being, integrated across those stages of the product lifecycle captured within the system. PLM developers have been successful in using material properties to provide point assessments at different lifecycle stages. Though PLM systems have continued to advance lifecycle analysis capabilities, they come with several caveats because they are proprietary. Namely, users may be forced to conform to a specific PLM platform and partner applications, and they are restricted to the lifecycle stages supported by the specific PLM system. However, to accommodate increasing information requirements, PLM tools are supporting information exchange to and from different systems[4, 5], and these exchanges often involve standards.

Standards deployed within a product's lifecycle may provide information representations at distinct stages of the product's life, as well as across stages of the lifecycle. As product information becomes increasingly granular, information standards increase in both numbers and detail. Much of this increase is a result of stage-specific and stakeholder-specific needs. Depending on the need, the differences in how material is represented in the different lifecycle stages can be great, and the overlap, if any, is not always simple to identify. This creates difficulties when trying to synthesize material information across a lifecycle.

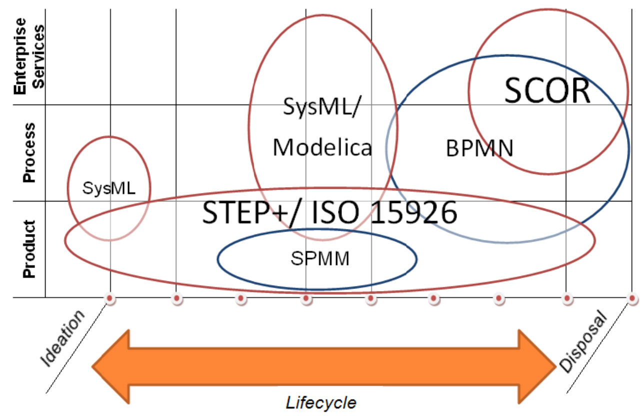

Figure 2: Sample of standard coverage across lifecycle. Derived from [6].

The type of information associated with a material, and how this information is represented, depends on the information requirements of the different lifecycle stages. As shown in Figure 2, common product information representations can differ not only across the product lifecycle, but also within a stage. Representations can depend on the viewpoint of the stakeholder. For instance, representations may vary depending on whether the information is engineering specific, or related to the product via process or enterprise information [6, 7].

The result of the many different representation needs is a conglomerate of material information that does not often synthesize well. The material information may vary by factors such as material property type, granularity of material information, expression of material information (function vs. value), unit of material information (unit vs. mass), and even the basic representation structure of the material information. Here we review several different standards that are used to represent product, process, and enterprise information across a product's lifecycle. We specifically look at the intent of the standard, who may adopt it, and how material information is represented. We then review examples of how standards have been previously leveraged to achieve some form of lifecycle synthesis for materials.

3.1 Design and Planning Stages

At the early stages of the lifecycle, information requirements focus mostly on design details. These may be the most critical stages, as the earliest stages of the product lifecycle determine about 70% of the overall product costs [8-10]. This cost translates into a significant resource commitment in early design, and therefore plays an integral part in determining the sustainability impact of a product. It is important to make as much sustainability-related information as possible available during the early stages of a product's development.

Material information at the earliest stages of the product lifecycle traditionally focuses on metrics needed to meet performance, quality, and cost requirements. The information is often used to make predictions such as how a product will perform under specific loading conditions, how durable a product is under cyclic conditions, or cost implications. The information necessary to predict such implications varies greatly depending on the nature of the product.

Material representation at the design stage varies in detail depending on the application. Work at the National Institute of Standards and Technology (NIST) on the Core Product Model (CPM) [11] and later the Semantic Product Meta Model (SPMM) [12] focused on developing core representations of product information, providing placeholders for material without defining many specifics.

Standards such as ISO 10303 (commonly known as STEP)[13] and ISO 13584[14] have been developed to support product requirements, but also offer additional material detail. Part 45 of STEP contains generic structures for material information. These structures are specialized for different purposes in the Application Protocols (AP) of this standard. For example, AP 235, the application protocol for "Materials information for the design and verification of products," is specially developed for modeling information related to the mechanical design of products.

Aside from component design, in product development processes the supply chain can also complicate material information management. Supply chain considerations require accessing information from different viewpoints. In addition, companies with similar viewpoints may still use different standard representations. Standards used in the supply chain will be discussed further in Section 3.3.

3.2 Manufacturing Stages and Systems

Manufacturing stage standards focus on the processing and production aspect of products. Material information may include details on process materials, (i.e., coolant or lubricant), tooling materials, or the raw material being processed (i.e., material inventory or material storage requirements). In general, the material information represented at these stages supports the manufacturing of a product within a system.

The standards used during manufacturing may depend on the type of manufacturing (discrete, batch, continuous). For instance, ISA88 [15] is a standard for batch control that is applied to production processes. ISA88 has been adopted mainly by manufacturing companies and focuses on batch manufacturing, while also addressing some supply chain of products/processes.

Other standards, such as ISA95 [16] or IEC 62264 [17], integrate production processes with the supply chain at the enterprise level. For instance, ISA88 and ISA95 complement each other as ISA88 focuses on automating the control of machines and devices while ISA95 (standard for integration of enterprise and control systems) meshes the information between manufacturing systems and resource planning.

Some standards used during the manufacturing stages are not specific to manufacturing, but to systems in general. Standards such as the Systems Modeling Language (SysML) [18] or Modelica [19] provide a means for connecting enterprise, process, and product points of view. For instance, SysML supports the specification, analysis, design, verification and validation of a broad range of systems and systems-of-systems - including hardware, software, information, processes, personnel, and facilities.

As mentioned, it is important to make as much information as possible available during the earlier stages of product development. Information from manufacturing stages is important to understand how the processing and assembly of different components will affect a product's sustainability impact. This information can also be used to assess the material and energy efficiency of processes used in product creation.

3.3 Use to End-of-life Stages

The later stages of the lifecycle often fall under the enterprise perspective. From the enterprise perspective, stakeholders are concerned with operations information. These stages will focus on information related to business decisions, such as logistics (including supply chain), product life span, product support, and product disposal. Information standards such as the Supply Chain Operations Reference (SCOR) model [20] or the Business Process Model and Notation (BPMN) [21] are often employed in these stages. For instance, SCOR helps companies to examine supply chain configuration and processes. It is used to identify, define, and measure metrics across the entire supply chain.

In regards to the type of material information found in enterprise representations, the material information may include details such as quantity and cost of materials. Details specific to the end-of-life product representations may include metrics such as recyclability or amount of material recoverable. End-of-life material information plays an important role when determining the sustainability impact of a product.

3.4 PLM Standards and Synthesis Approach

Until now, we have discussed how standards may be used to represent material information at different stages of the product lifecycle. Now we will look at how product information standards have been used in broader lifecycle applications.

In the past decade, the Department of Defense has extensively investigated lifecycle interoperability through different product representations [6] [22] [23]. One such effort came in the development of GEIA-927[22]. Primarily based on ISO/TS 18876[24] and ISO 15926-2[25], GEIA-927 also builds on and integrates several existing standards for product information. A similar effort, the Adaptive Modeling Language [23], provides the ability to integrate and automate product configuration, visualization, design, analysis, manufacturing, production planning, inspection and cost estimation through standards. These efforts demonstrate the synthesis of different standards across the lifecycle, and the opportunities such a synthesis can provide.

The approach discussed in this paper is very similar to the integration approach used in the development of GEIA-927, where instead of replacing information models we explore their synthesis to "facilitate the exchange of data concepts…by harmonizing disparate standards into a single object model [26]." Here we place a focus on *material* synthesis, and the impacts this synthesis may have on making more sustainable decisions.

Towards this end, we discuss some of the challenges faced when synthesizing diverse material information and then discuss how some of these challenges may be overcome. A material model can be developed to synthesize material information regardless of lifecycle stage, stakeholder, or representation.

4 TOWARDS SYNTHESIS OF MATERIAL INFORMATION

Synthesis of material information across the lifecycle requires the development of an information structure that is able to meet representation challenges at each stage while ensuring that the integrity of the material information is preserved across stages. We will call this information structure a "material information model." The challenges encountered in creating the material information model come in two varieties: the challenges of conceptual integration of material information and the challenges of integrating different representational formats.

4.1 Challenges of Materials Information Synthesis

The need to address requirements of multiple stakeholders is the root of many synthesis challenges. Each stakeholder in different product lifecycle stages has different views for material information; however, this does not mean the associated information is independent. The material representations in the proposed material model need to capture the core properties of material usage in product development, and make this information accessible at different lifecycle stages. Often times, such as when addressing the supply chain, changes to material information at one lifecycle stage will propagate to other stages. This means that not only should the material information model be able to provide stakeholder-specific information at different stages of the lifecycle, it should also provide traceability across the lifecycle. These two requirements create many information representation and management challenges.

The material information model needs explicit relationships between product requirements, functions, behaviors, geometry, tolerance, and manufacturing process information so as to provide engineers with enough information to select the best material for their product design and manufacturing. Three types of concerns that such a material information model must address are [27]:

1. Capturing relationships between items of data from divergent perspectives
2. Addressing challenges in measurement and detail
3. Supporting the consistent and correct exchange of material information across systems

A material information model must have the ability to represent a wide range of material properties across a wide variety of materials. As new types of engineering materials are constantly being developed, material information must be treated as an open-world problem. The material information model must be able to support the inclusion of new types of materials and new material properties. The material information model must be able to capture variability in property types in a concise and reusable way. For instance, some material properties may be variables, depending on factors such as ambient temperature or pressure.

Because material information is used across a wide range of domains, our material model must support wide ranges of detail and granularity. Material information may exist as generic concepts at the bulk level such as density, or very detailed properties at the micro-structure level. In general, it is impractical for a single system to be able to handle properties at such a wide range of abstraction levels. However, for our use of material information, it is important to properly separate these concerns, and maintain traceability across these degrees of detail. It must be possible to generalize or specialize the material information model as necessary.

Finally, the material information model must address a variety of data interchange issues between different representations. The model should support data presentation and interchange schemes that make it easy for human readability and machine processing.

4.2 Challenges of Representation Formats

In standards used throughout the product lifecycle, material information exists in many different languages and formats, both across the lifecycle and between stakeholders. Various information representation formats may be applied to represent material information, and each has its own advantages and disadvantages. While each format is often very specific, most can be grouped, each group with its own pros and cons. Here, we review some of the most common formats used in product lifecycle and material information, and some of the challenges they may present when pursuing material synthesis.

Tabular representation systems, such as relational databases, are relatively easy to design, fairly customizable, and are well supported by a wide range of tools. However, these systems are not very powerful in conceptual modeling, and offer limited support for expressing associativity of concepts[28]. They cannot support a complex and associative material information model, one that can represent the same information at multiple levels of detail.

Markup languages, such as the Extensible Markup Language (XML), allow the identification of concepts and properties, and support a tree like organization scheme. While XML supports the representation of properties, it does not enforce constraints on relationships or provide enough semantics to directly support any form of verification.

Object-oriented modeling paradigms, such as the Unified Modeling Language (UML) and SysML, are excellent for conceptual modeling when the concepts are fairly well understood high level concepts. However, they face problems of scalability and expressivity when encountered with very detailed information[29].

An increasingly popular type of format, known as ontologies, has emerged as a means for information representation, a format with the ability to represent relationships and constraints based on formal semantics. Several ontology-based languages have emerged in the past decade, the most popular of which is the Web Ontology Language (OWL). OWL is a representation language for ontologies and offers many of the same advantages of XML while also providing further capabilities. OWL supports the organization of concepts and relationships that allows for easy expandability, and also supports verification through inferencing. Information from different sources may be synthesized in an OWL ontology by using various mechanisms, such as assertions or equivalencies. In the following subsections, we describe an initial effort on synthesizing material information across product representations using an OWL ontology.

4.3 Synthesis Through OWL

The previous section discussed various obstacles faced in the development of our material information model. These obstacles can be overcome with the development of a material information model that meets two primary needs: the necessity to be able to synthesize many types of information at many levels of detail, and the necessity to be able to integrate languages possessing different representation formats. With these needs as our main drivers, our initial efforts have focused on ontologies and the role they can play in material synthesis.

Other researchers have recognized the same benefits and opportunities offered by ontologies, and as a result various efforts have led to different standards being translated into OWL. Several of these works were selected to demonstrate the synthesis of material information between lifecycle representations.

Proof-of-Concept OWL Synthesis

To demonstrate the synthesis of material information we obtained OWL representations of the following formats: SPMM [12], ISO15926[30], ISA95[31], and SCOR[32]. These four were selected as they covered most lifecycle stages, as well as many of the stakeholder viewpoints described. With a focus on materials, a new ontology was created.

The information related to materials was mapped between ontologies (See Figure 3). The level of abstraction of material differed significantly between these standards, creating challenges when synthesizing the information. Although the "path" to a material definition differed greatly depending on the standard, common groupings were created and the information was synthesized through the OWL ontology.

Figure 3 is a very basic example, which demonstrates how differences in granularity and usage of material information can be overcome in the development of a single representation. By adding additional structure to the ontology in Figure 3, a more direct synthesis could have been achieved. The next two sections will discuss how OWL was used to overcome the two main challenges highlighted in Section 4.1 and 4.2.

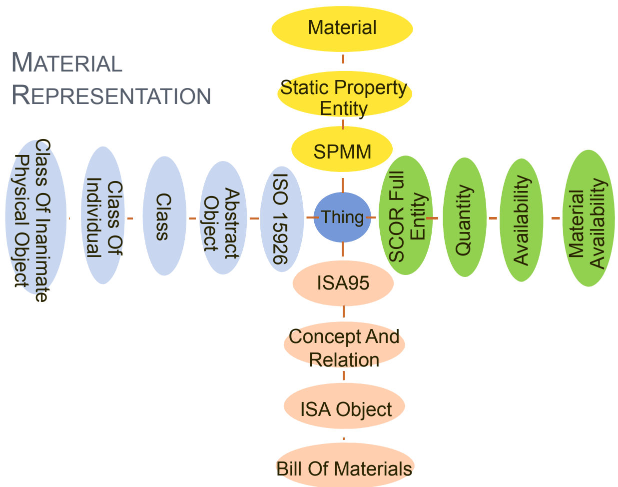

Figure 3: Concept of synthesizing material information.

Addressing Material Complexities

The abilities of OWL to group similar classes and to specify equivalence were key in this proof-of-concept. The hierarchical nature of ontologies provides an intuitive way to address the material information complexities. Specializations can be used to address not only material information at different levels of abstraction (i.e., quantity vs. mass), but also at different levels of granularity (i.e., additional information at same level of abstraction). New classes can be continuously added to specialize existing ones, providing a grouping mechanism for associating similar classes as well as equivalent classes with added detail and closer associations. OWL semantics also allow for classes to be declared "equivalent," essentially creating a single concept from two and simplifying material traceability. Through inferencing, OWL also allows for the automatic association of information based on defined semantics [33].

Addressing Representation Format Challenges

The variety of expressiveness offered by different representation formats often make it difficult to maintain the integrity of mapped information. When synthesizing information, OWL can be used to address the challenges presented by representation formats in much the same way it did with material complexities. While some formats can be translated directly into OWL, such as XML, others can usually be translated with minimal guidance and support. The grouping and equivalence mechanisms discussed earlier are also supportive of representational challenges.

Because of the appeal of OWL's capabilities, many of the challenges faced in the synthesis of these standards have already been addressed by various research communities, including translating many of the standards discussed in Section 3 into OWL as well as the standards identified in this section. Further work involving the continued development of our proof-of-concept synthesis will be discussed in Section 6.

5 SUSTAINABLE DECISION MAKING THROUGH MATERIALS

This section discusses how improved access to materials and material properties can lead to better decisions regarding sustainability impact. Table 1 lists some of the notable benefits achievable with a completed material information model. This section will discuss several of these benefits in further detail.

Material information use-case	Material information requirements
Allow material selection based on customer performance requirements (Indexing)	Different abstraction levels, property representations
Bring Gate-to-Gate process information (relative to material and energy efficiency) into design	Integrated process and product metrics
Account for effect of material/process choice through product lifespan (durability, aesthetics)	Associate product and process information
Allow material selection based on recycling/remanufacturing ratio	Sustainability information of materials
Provide material metrics to processes in Gate-to-Gate operations to predict efficiency	Material test data information
Account for material information in different phases (material phase change) during manufacturing processes to predict efficiency	Material information in different phases
Provide material sample information after processing (outputs of processes)	Material output information
Provide supply chain traceability for sustainability metrics	Material synthesis and verification

Table 1: Role of Material Information Model.

Manufacturing process parameters influence productivity and efficiency of manufacturing process. In addition to a material's physical properties, other factors such as material availability, price, delivery time, lot size, geometry, and quality test information are necessary inputs for manufacturing processes. The material information model can play a significant role in determining parameters for sustainable manufacturing process planning. A successful material information model will not only be able to provide this information as input to applicable stages, but also pull from and incorporate available information from other stages. By further incorporating indexing mechanisms into the material model, insight can be provided into the potential impact of changes in the magnitudes of values at different lifecycle stages.

A successful material model will not only provide information for assessing sustainability, but also simplify the information management aspects of material information. A successful material information model will support multiple representations of a single material property. As noted earlier, different stakeholders may refer to the same material property in different ways. For example, in one stage, a property may be represented per unit, while in another stage it may be represented for a bulk or composite material. One stakeholder may represent a varying material property as an equation, while another stakeholder may represent the same property as a table. Another example is when a property such as "work" is measured in Joules at one case, and "man-hours" in another. The material information model will have the ability to represent different levels of granularity of material information. By supporting varied representations of essentially the same concept, the material mode can facilitate the integration of processes from varied domains.

Another area where the material model can improve sustainability assessments is through better material tracking in product development, including the supply chain. The transparency of material information across the supply chain can be enhanced by synthesizing standards and representations that are implemented at different stages of the product lifecycle. On the macro scale, material tracking can be used to calculate how much and what types of material are being used, thereby facilitating planning for reductions and substitutions. The tracking of what materials are used, where and when, also supports the implementation of efficient recycling and reclamation programs.

Finally, the material model will provide the ability to map between material information in design and material sample information in manufacturing process planning. Material selection in the design stage should propagate through complex relationships in order to predict impacts on 1) product performance, 2) product life-span, 3) manufacturing process efficiency, 4) development cost, and 5) environments. A well-developed material information model should enable engineers to select materials in the design stage by considering their impacts in later stages. This is essential for ensuring that the sustainability-related design decisions are followed through into production, allowing fine-grained control over parameters to achieve improved sustainability. To successfully address some of challenges presented by product and process integration, more detailed and specific material information representations must be incorporated. This will be discussed in future work.

6 DISCUSSION AND FUTURE WORK

In this paper we discussed the potential impact of improved material management in sustainability assessments. We reviewed common information representations used throughout a product's lifecycle and demonstrated the synthesis of their material-related information. Each representation offers a unique perspective on material information, and a synthesized model from these representations can offer many advantages. However, when fine-grained control is needed, more material-centric information representations must be considered. Future work will look into how more material-centric information representations, such as MatML [34], can be leveraged to address specific material information needs.

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8 REFERENCES

[1] (2009): The business of sustainability, in: MIT Sloan Management Review Special Report.

[2] Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E.,(2011): Material efficiency: A white paper, Resources, Conservation and Recycling, 55 362-381.

[3] Pardo, N., (2012): 5 Trends in Next-Generation PLM, in: Product Lifecycle Stories: Insight on Products, Manufacturing, and Service, PTC.

[4] Siemens, (2012): PLM Components: Support tools for CAD, CAM, CAE and PLM software development and interoperability, in: Siemens (Ed.), pp. 1-19.

[5] Prostep, (2012): OpenPDM: PLM System Integration, in: Prostep (Ed.), pp. 1-8.

[6] Sudarsan Rachuri, S.F., Sharon Kemmerer, (2006): Analysis of Standards for Lifecycle Management of Systems for US Army --- a preliminary investigation, in.

[7] Ameta, G., Sarkar, P.,(2010): Comparison of Electronics Products Standards for Sustainability, International Jounal for Product Design, 1.

[8] Bedworth, D.D., Henderson, M.R., Wolfe, P.M., (1991): Computer-integrated design and manufacturing, McGraw-Hill, Inc.

[9] Ferreirinha, P., Hubka, V., Eder, W.E.,(1993): Early cost calculation: Reliable calculation, not just estimation, ASME Design for Manufacturability, DE, 52 97-104.

[10] Ou-Yang, C., Lin, T.,(1997): Developing an integrated framework for feature-based early manufacturing cost estimation, The International Journal of Advanced Manufacturing Technology, 13 618-629.

[11] Fenves, S.J., Foufou, S., Bock, C., Rachuri, S., Bouillon, N., Sriram, R.D., (2005): CPM 2: A revised core product model for representing design information, in, National Institute of Standards and Technology (NIST), Gaithersburg.

[12] Lee, J.H., Fenves, S.J., Bock, C., Hyo-Won, S., Rachuri, S., Fiorentini, X., Sriram, R.D.,(2012): A Semantic Product Modeling Framework and Its Application to Behavior Evaluation, Automation Science and Engineering, IEEE Transactions on, 9 110-123.

[13] Pratt, M.J.,(2001): Introduction to ISO 10303—the STEP standard for product data exchange, J. Comput. Info. Sci. Eng., 1 102-103.

[14] ISO, (2010): ISO 13584- Industrial automation systems and integration -- Parts library, in.

[15] ISA, (2010): ISA88-Batch Control, in.

[16] ISA, (2010): ISA95-Enterprise-Control System Integration, in.

[17] IEC, (2004): IEC 62264 -Enterprise-control system integration, in.

[18] OMG, (2012): OMG Systems Modeling Language, in.

[19] Association, M., (2012): Modelica Lanugage Specification 3.3, in.

[20] Supply Chain Council, I., (2011): SCOR Frameworks, in.

[21] OMG, (2011): Business Process Model and Notation (BPMN), in.

[22] TechAmerica, (2007): GEIA-HB-927 Implementation Guide for Common Data Schema for Complex Standards, in, pp. 136.

[23] TechnoSoft, (2012): Adaptive Modeling Language, in.

[24] ISO, (2003): ISO/TS 18876: Industrial automation systems and integration -- Integration of industrial data for exchange, access and sharing in.

[25] ISO, (2003): ISO 15926-2: Industrial automation systems and integration -- Integration of life-cycle data for process plants including oil and gas production facilities -- Part 2: Data model, in.

[26] Colson, J., (19 Sep 07): GEIA-927, Common Data Schema for Complex Systems ,GEIA-STD-0007, Logistics Product Data, in.

[27] Sargent, P., (1991): Materials information for CAD/CAM, Butterworth-Heinemann.

[28] da Silva, A.S., Laender, A.H.F., Casanova, M.A.,(2000): On the relational representation of complex specialization structures, Information Systems, 25 399-415.

[29] Johnson, T., Kerzhner, A., Paredis, C.J.J., Burkhart, R.,(2012): Integrating Models and Simulations of Continuous Dynamics Into SysML, Journal of Computing and Information Science in Engineering, 12 011002.

[30] Batres, R., West, M., Leal, D., Price, D., Masaki, K., Shimada, Y., Fuchino, T., Naka, Y.,(2007): An upper ontology based on ISO 15926, Computers & Chemical Engineering, 31 519-534.

[31] Diep, D., Alexakos, C., Wagner, T., (2007): An ontology-based interoperability framework for distributed manufacturing control, in: Emerging Technologies and Factory Automation, 2007. ETFA. IEEE Conference on, pp. 855-862.

[32] Zdravković, M., Panetto, H., Trajanović, M., Aubry, A.,(2011): An approach for formalising the supply chain operations, Enterprise Information Systems, 5 401-421.

[33] D'Alessio, A., Witherell, P., Rachuri, S., (2012): Modeling Gaps and Overlaps of Sustainability Standards, in: D.A. Dornfeld, B.S. Linke (Eds.) Leveraging Technology for a Sustainable World, Springer Berlin Heidelberg, pp. 443-448.

[34] Sturrock, C., Begley, E., Kaufman, J.G., (2001): MatML, Materials Markup Language Workshop Report.

Green Cycles Economy and Factory

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Abstract

Climate change calls for answers beyond pure optimization of resources and energy consumption in production. Our presented green vision looks long-term at CO2 as raw material for new synthetic raw materials and products as well as markets, referred to as green cycle economy. Green cycles are defined as CO2 sinks, empowered by renewable energy used for synthesizing fuels and materials from carbon sources. Green factories are defined by applying the concepts of green cycles to manufacturing industries. The transformation of existing into green factories is achieved in an evolutionary way, successively applying the technology levels defined for green cycle economies.

Keywords:

Green cycles economy; carbon-based production vision

1 INTRODUCTION

The green cycles economy and factory vision presented looks at carbon (C) as a raw material for new materials, products, and synthetic raw materials. CO_2 as one of the principal agents of climate change [1] is an interesting source for carbon. The vision can open up new business models and new markets that use carbon to provide an answer to the world's hunger for materials [2]. We define "green" as a CO_2 sink, i.e. consuming CO_2 to provide green energy sources and green materials that can be used in a CO_2 based cycling production and businesses. The prerequisites will be CO_2 neutral forms of renewable energy and chemistry as well as petro-chemistry technologies. The applications available today have already been put to work cost-effectively in the fields of green fuels and the production of intermediate products for plastics. One motivation for the green cycles economy and factory vision is that the advancing climate change calls for answers that go beyond the currently ongoing optimizations of our use of energy and resources.

The Siemens AG sustainability goals are to establish a substantial equilibrium between the planet and the people. This equilibrium is to be achieved with a profit orientation from the business point of view (see Figure 1). The Siemens AG Sustainability Board defines and guides business activities for this purpose [3].

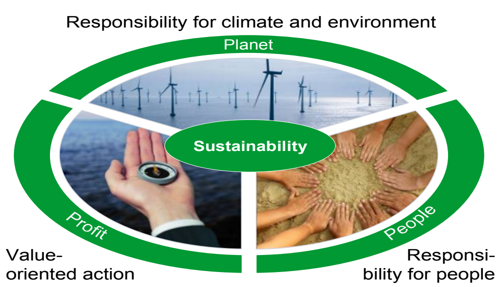

Figure 1: The Siemens AG sustainability definition.

2 REASONS TO "GO GREEN"

We face a worldwide energy dilemma (see Figure 2):

- The world's total energy demand will double by 2050. Demand for electrical energy will double as early as 2030. [4]
- The goal, in the sense of bringing global climate change to a halt, is to reduce CO_2 emissions by at least half within the same period. [5]

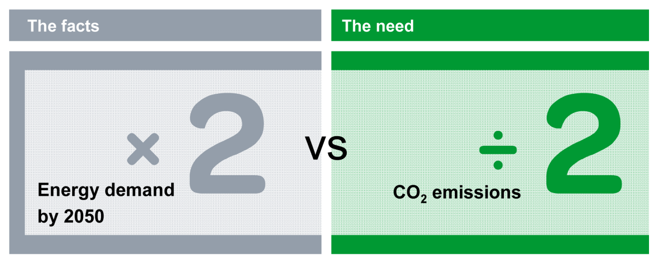

Figure 2: The energy dilemma. Source: [5],[4] (compared to 1990).

We address the energy dilemma in two dimensions: from the economical necessities of industry and production as well as from a climate change perspective.

The current global energy mix, which relies primarily on fossil fuels, cannot meet these challenges assuming that the necessary reduction in CO_2 emissions is to be achieved in the same time [5],[6].

The worldwide increase in prosperity, especially in newly industrializing nations like China and India, will steadily increase CO_2 emissions [7],[8] unless extensive countermeasures are taken, and at the same time will increase demand for materials, for products, and production (so called rebound-effect [9]).

At present, the challenge of achieving a secure energy supply – a central factor for industrialized nations - in combination with a secure supply of materials [10],[11], while at the same time reducing greenhouse gases has been met only in very isolated cases, for example in parts of Iceland [12]. Both decentralized and large-scale industrial solutions must be considered.

In terms of the climate change perspective the current concentration of CO_2 in the atmosphere is about 392 ppm (parts per million) [13], and is increasing by about 2 ppm annually [14] (see Figure 3). The maximum 2ºC temperature increase currently targeted by the world community can be achieved with a 75% probability if the CO_2 concentration does not exceed 400 ppm (some sources assume as much as 450 ppm) [5],[15]. The 2°C increase has been chosen because this temperature represents the system limit for the climate models under which climate change appears to be manageable and major global climatic processes remain calculable [5],[15]. However, the current increase in concentration (the greatest in human history) will mean that this limit will be exceeded as early as 2020 [5],[6].

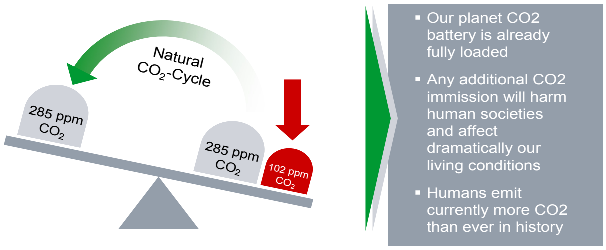

Figure 3: The CO_2 cycle and global climate change.

CO_2 has a crucial influence on the global warming, because it is responsible for about 64% of the effect, and unlike methane, it remains in the atmosphere for as long as 200 years [5],[16] (see Figure 4). Methane, at 20%, has considerably less influence on warming, and remains in the atmosphere for only 9 to 15 years.

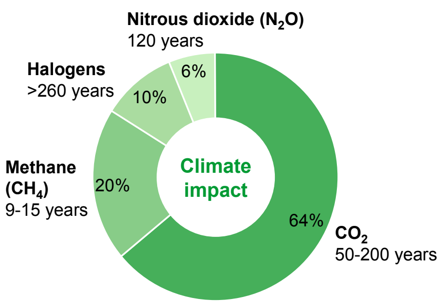

Figure 4: Residence time of climatic gases in the atmosphere. Source: IPCC 2007 [5],[16].

To achieve the 2°C goal according to [5], the worldwide CO_2 emission peak should be reached no later than 2020. In their words a 60% reduction of the energy-related CO_2 emissions should be accomplished in 2050, of the total CO_2 emissions 50% - 85% compared to the year 2000. By the year 2070 all CO_2 emissions must be reduced to zero. Moreover, after that point a negative CO_2 footprint must be achieved to "remove" the rising CO_2 concentration of the coming decades from the atmosphere.

2.1 Our Concept of Green

One answer to these climate challenges and the economical necessities of industry and production are newly introduced so called "green cycles": We conjecture that new technologies, which operate as CO_2 sinks, i.e. that have a negative carbon footprint, will come into use and that at the same time these new technologies will offer the necessary features for a positive economic performance. Green cycles actively consume CO_2, when considered in terms of a life cycle assessment. In other words, CO_2 is viewed as a raw material, which is often available cheaply for direct recycling, i.e. as an industrial waste product. Not every part of the economy will be able to achieve this goal. Therefore, primarily industrial production, which the Siemens AG serves, will have to provide a substantial overcompensation if the climate change perspectives are also considered. In case of the Siemens AG this is part of our sustainability definition [3] (see Figure 1).

As the term "green" is used in today's communication, "green" technologies are usually understood as environmental technologies. However, environmental technologies are primarily aimed at minimizing the impact on the environment. They provide usually solutions that represent improvements over conventional technologies in this regard and that aim to increase the solution's energy efficiency at reasonable costs. Ideally, CO_2 emissions will then be reduced zero (see Figure 5).

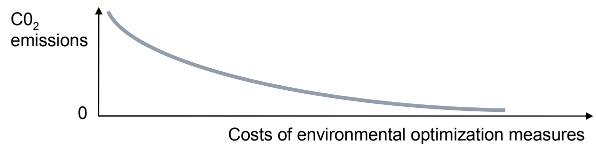

Figure 5: Environmental technologies cost perspective.

Here it is essential to take measurements using uniform criteria. But this is not assured, at least not in all cases. There is no unique definition of "green" in the current literature. However, the etymological derivation from the Indo-European term "gher" yield a definition starting point for "green" in terms of the meanings "to stick out", "grow" (like leaves), and "verdancy" [17] (see Figure 6).

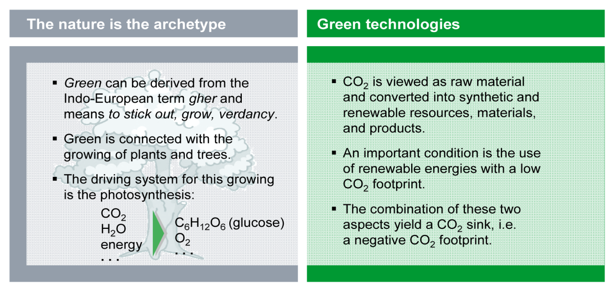

Figure 6: The two aspects of "green".

We define "green" in the sense of a "green cycle" analogously to the photosynthesis process in the vegetation, i.e. plants and trees (see Figure 6). Accordingly, any technology whose carbon footprint is negative over its life cycle is defined as a green technology. Green technologies in terms of green cycles include:

- Applying mechanisms to use and consume CO_2.
- Applying new methods to produce new raw and finished materials based on carbon (C) and CO_2.

Our understanding of "green", i.e. our proposal for an evolving Siemens AG vision can be grouped in a broader context as illustrated in Figure 7.

The first two items of the "green evolution", i.e. energy efficiency optimization and energy supply shift have already been partially attained and form the foundation of Siemens AG's environmental portfolio. The clean cycles cannot be achieved fully in any economically viable way with current environmental technologies. Today's products, which are increasingly produced from highly specialized materials and compounds are very expensive to process for material separation and recycling. In contrast, when combining environmental technologies (energy efficiency optimization and energy supply shift) with green technologies (meaning CO_2 sinks) the new green cycles offer the possibility of achieving economically viable solutions (including for clean cycles), because the materials for products and production are based on renewable hydrocarbon compounds.

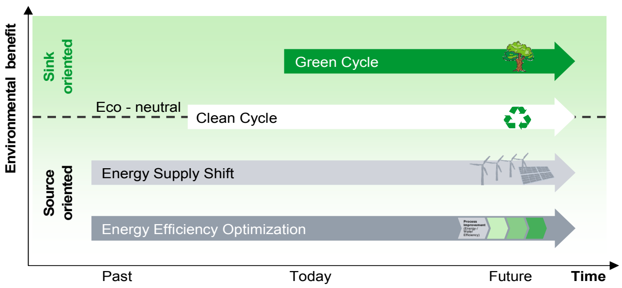

Figure 7: Grouping of green and environmental technologies and pointing out an evolutionary path to green cycles.

2.2 Green Cycle Economy

Green cycle solutions offer additional market potential, In other words, a complementary market to the existing energy efficiency optimization und supply shift markets that are drivers for current innovative products and production. Green cycles imitate natural processes from the biosphere by technical (synthetic) means. In nature, two cyclical processes are crucial: the water cycle, and the carbon cycle [18]. It is remarkable that in nature there are (almost) no heavy-metal cycles.

2.3 Green Cycle Definition

Our concept of green cycles with the chemical recycling of carbon (C) and CO_2 to synthetic hydrocarbons creates a new understanding of renewable energy usage to produce environmentally neutral carbon resources or raw materials. The hydrogen needed for the chemical processing of the carbon comes from water. The green cycle concept can utilize any form and any amount of renewable energy such as solar, wind, hydro, as well as geothermal sourced electrical energy.

It is increasingly necessary to find suitable new ways to capture, store, transport, and utilize renewable energy very cost efficient. Focusing on electric power generation clearly shows that in just a few years, renewable energy sources (primarily solar) will achieve price and grid parity with conventional energy sources like coal, oil, and nuclear [19].

The green cycle is shown in Figure 8. A considerable amount of electrical energy is needed to run the green cycle. The quantity of CO_2 fixed in a green cycle, i.e. converted from a gas to a liquid fuel can be demonstrated by an example: It takes about 8 MWh of electrical energy for water-electrolysis combined with a Methanol synthesis to fixate one metric ton of CO_2 in about 3/4 metric ton of synthetic raw material, e.g. fuels. This is equivalent to the annual power consumption of about 2000 three-person households, or the hourly production of two 4 MW wind turbines. This cycle approach generates all required aspects to shift to a 100% renewable energy economy. We call this the green energy cycle (see left part in Figure 9).

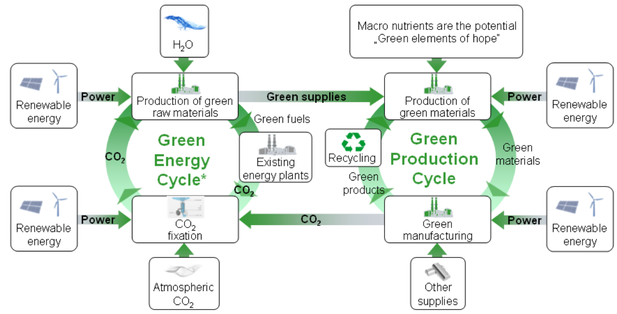

Figure 9: Green cycles.

In addition to the green energy cycle there is a green production cycle (see right part in Figure 9). The green production cycle takes hydrocarbons, oxygen, and hydrogen as well as so-called "green elements of hope" as input resources for the production of green materials and products, e.g. plastics. This green production cycle requires different ways of product design and production technologies that are focusing on molecular layers of the carbon materials and that need to be produced in these layers.

The growth of the world population and the associated consumption of natural resources yield increasingly the scarcity of materials [10],[20]. For instance the scarcity of specific metals is becoming one of the most urgent global problems, comparable with energy scarcity [10]. The peak oil situation is analogously transferable to certain mineral resources [21]. A particularly feasible approach is the substitution of scarce metal elements by most abundant elements [10]. This requires advanced engineering sciences as well as disciplines like agriculture and biosciences.

The green elements of hope are environmentally friendly and sustainable as they contain all macronutrients of life and lack heavy metals. We propose that carbon-based materials are a complementary source of interest for alternative green materials and alternative production processes.

2.4 Green Factories

A green factory is a plant that has no negative impact on the global or local environment, i.e. a production site or a network of productions that attempt to meet the triple bottom line of the sustainability definition of the Siemens AG [3]. Green factories focus on environmental and economical targets. In general, business is described as green if it matches the following four criteria:

1. It aims to supply environmentally friendly products or services that replace demand for non green products and/or services.
2. It uses high energy efficiency solutions in all of its business processes.

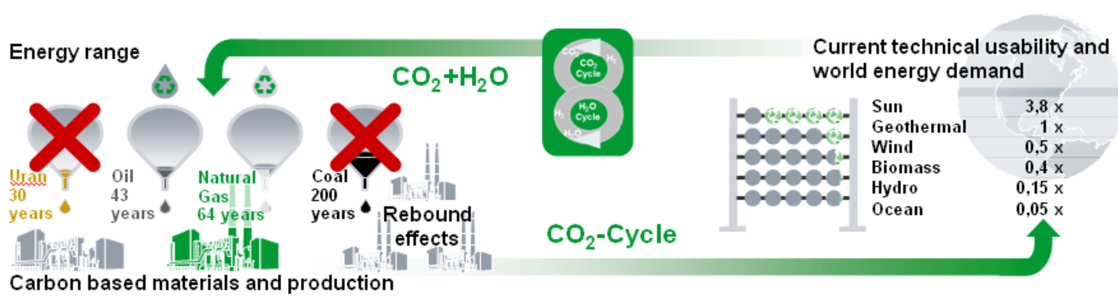

Figure 8: Green cycle economy.

3. It uses mainly renewable power and supplies based on renewable energy.
4. It emphasizes on the implementation of recycling of heat, water, and energy supplies of the factory.
5. Green factories use exhaust gases like CO_2 as a resource.

The green factory supports to meet the needs of the present world without compromising the ability of the future generations to address their own needs [3],[22]. It emphasizes the transformation process of achieving the design of products and production processes that use the advantages of carbon, hydrogen, oxygen, and additional green elements. The most important elements of a green factory are depicted in Figure 10. These are renewable, CO_2-neutral electrical energy sources, suitable production processes and facilities, and additional chemistry processes that enable the recycling.

2.5 The Evolution of Green Factories

The concept of “green factories” is to be achieved on an evolutionary path as illustrated in Figure 7. Tree fundamental stages of evolution can be described. Each stage is essential for the next stage in the overall concept.

The first stage is the energy efficiency optimization. This covers the current activities regarding production, logistics, buildings, etc. The main goal of energy efficiency optimization is to use the limited energy resources more effectively. Since efficiency optimization processes in general are a key driver for economic growth and improved competitiveness of companies operating in global markets, the existing methods form a basis for evolutionary extension of these processes, methods, and solutions for the new and additional aspect of energy. The methods and solutions aim at emitting less CO_2 than comparable predecessors while guaranteeing similar product and operation performance compared to the not energy optimized solutions. However, the goal of zero CO_2 emissions at reasonable costs cannot be reached by these approaches (recall Figures 5 and 11).

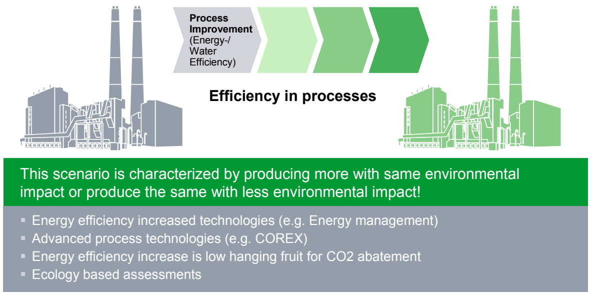

Figure 11: Energy efficiency optimization.

The second stage is the energy supply shift. Shifting to renewable energy means primarily to switch the factory electricity supply with the related purchasing processes from fossil thermal power plants to renewable power plants. The aim is a complete replacement of the energy input by renewable energy sources and adequate decentralized grid technologies (see Figure 11). All aspects of renewable energy production and stable supply of factories including the distribution, the storage, and the demand response issues need to be addressed here [23].

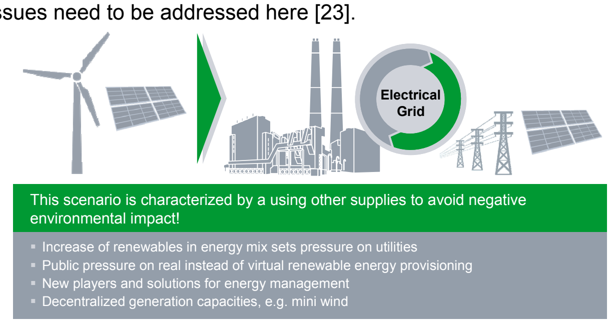

Figure 12: Supply shift.

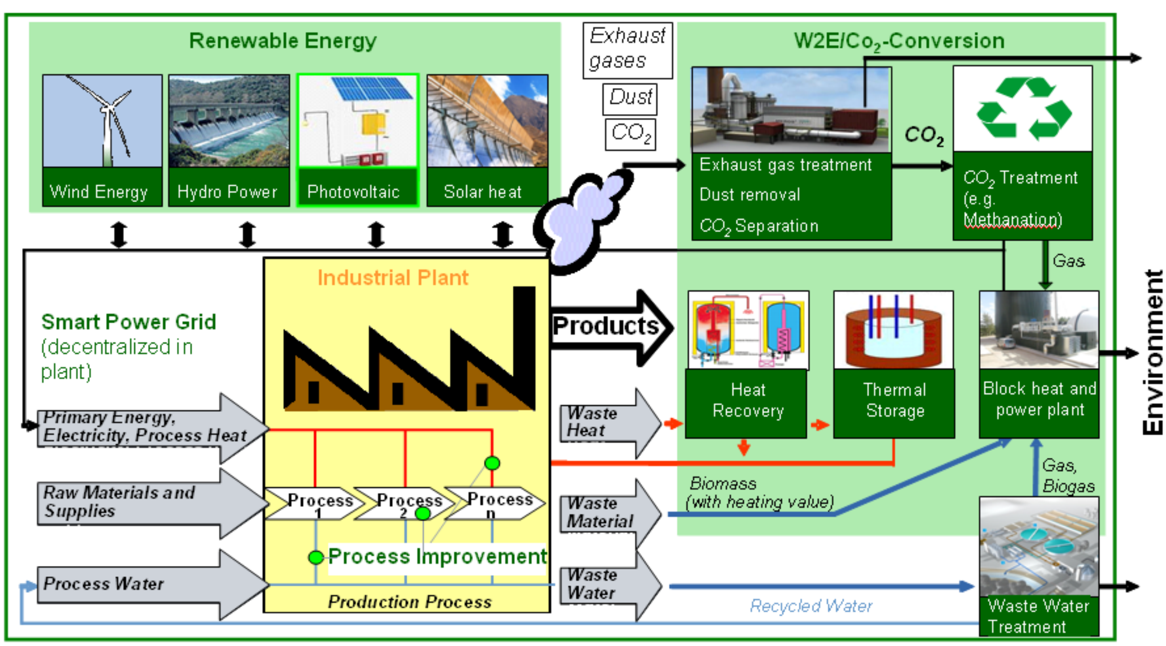

Figure 10: Green plant elements.

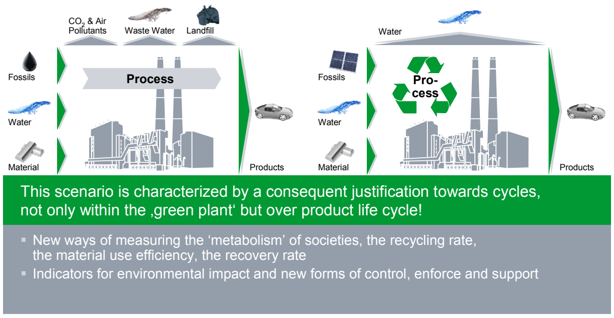

Figure 13: Clean cycle.

The third stage is the clean cycle (recycling processes). The goal is to generate few or no waste products outside the production processes (see Figure 12). In terms of today's limitations of the environmental technologies, productions, and products, clean cycles cannot be fully achieved in an economically feasible way, except for certain areas like the waste water treatment.

The fourth stage is the green cycle factory. It is based on synthetic imitation of natural processes from the biosphere, i.e. plants and trees. It combines technologies that provide a negative CO_2 footprint over their whole life cycle and thus form the technical core of a green cycle production.

Raw materials as well as energy carriers are synthesized from carbon (C) sources like CO_2, using renewable electricity. Synthesized energy carriers, such as artificial natural gas (methane), are used for storing and transporting energy until the production processes take place, transferring carbon based raw materials into products. Figure 14 illustrates how to create a green energy cycle. The following development path characterizes green cycle plants:

- The electrical energy to maintain the cycles comes entirely from renewable, CO_2-neutral energy sources.
- The water from the atmosphere (assuming certain purity) is split into hydrogen and pure oxygen.
- The resulting hydrogen is enriched with the CO_2 from industrial waste products, processes, or best of all in long-term directly from the atmosphere [24]. It is used to produce hydrocarbon compounds.
- The hydrocarbon compounds are used, among other possibilities, for the petrochemical industry, new carbon industries, e.g. to produce new materials like carbon-fiber composites, and to generate green fuels, like methane and methanol.

An example is given by the Island based company Carbon Recycling International, which shows that this can already be achieved cost-effectively today assuming specific energy and raw-material cost situations [12]. Another example is the "CO2rrect" project (CO_2 reaction using regenerative energies and catalytic technologies) from Bayer AG, Bayer MaterialScience AG, Siemens AG, and other partners. Yet another example is a Bayer AG pilot plant at the Leverkusen chemical park that uses CO_2 as a chemical intermediate product in the polyurethane production (an intermediate product for producing plastics).

Furthermore, hydrogen can be used in a large industrial scale, for steelmaking processes like COREX. However, this application is not part of a Green Cycle.

There will be also new possibilities for producing clean water, an important raw material for the entire Green Cycle.

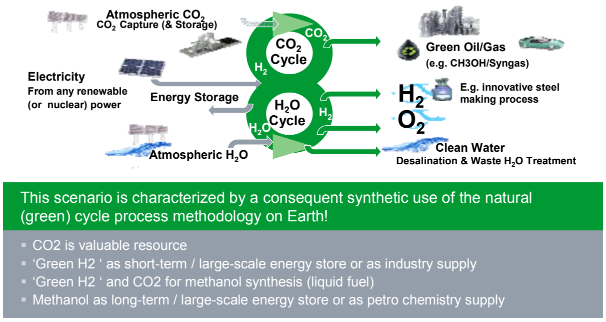

Figure 14: Green Cycle.

Not only raw materials, but also emissions and wastes become more expensive as the international Trading Scheme for emission and waste matures [2]. In the first phase green cycle factories will be in the position to derive revenues from the carbon credit and renewable fuel markets, e.g. since green methanol [12] has higher margins that fossil based methanol.

3 CONCLUSION AND OUTLOOK

A systematic approach to define green technologies and to point out an evolutionary path that structures environmental and green technologies related to production is presented.

The developed green vision offers economically attractive new areas of market potential that opens new opportunities for green products and green production under the assumption of renewable energy supply as the main supply for energy.

The existing plants and even fossil power generation plants can be well integrated in the novel concept in an evolutionary way so that existing infrastructure can still be utilized. The goal to achieve zero emission plants in an economical feasibly way requires a paradigm shift from primarily fossil and/or metal based products to carbon based products including the necessary new production processes. However, the existing product and production technologies and solutions play an important role during the green transition process so that only economical green technologies will be considered at each development stage. Green fuels are among the first products to be considered. CO_2 fixation is a goal that might not be economically feasible at the beginning of the green transition. Rather other carbon sources from existing plants and factories will be the first carbon suppliers. The increasing speed of renewable energy technologies and renewable supply supports the green transition process and sets the transition speed.

The authors recommend investigating the green areas further, in particular in terms of the consequences for the production.

4 REFERENCES

[1] Sekretariat der Klimakonventionen (Ed.) (1997): Das Protokoll von Kyoto zum Rahmenübereinkommen der Vereinten Nationen über Klimaänderungen, http://unfccc.int/resource/docs/convkp/kpger.pdf, accessed 11.12.2011.

[2] Müller, E.; Engelmann, J.; Löffler, T.; et. al. (2009): Energieeffiziente Fabriken planen und betreiben, Berlin Heidelberg: Springer.

[3] http://www.siemens.com/about/en/index/strategy.htm, accessed 11.11.2012

[4] International Energy Agency (2010): World Energy Outlook 2010, IEA Publications, 2010.

[5] IPCC (Ed.) (2007): Climate Change 2007: Synthesis Report, http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf, accessed 22.11.2012.

[6] European Commission (2007): World Energy Technology Outlook - 2050, Office for Official Publications of the European Communities.

[7] http://www.berlin-institut.org/online-handbuchdemografie/bevoelkerungsdynamik/auswirkungen/bevoelkerungsprojektionen.html, accessed 21.10.2011.

[8] GLOBAL 2000/SERI (Ed.) (2009): Ohne Mass und Ziel? Über unseren Umgang mit den natürlichen Ressourcen unserer Erde, in: http://old.seri.at/documentupload/SERI%20PR/ohne_mass_und_ziel--2009.pdf, accessed 16.10.2011.

[9] Binswanger, M. (2001): Technological progress and sustainable development: what about the rebound effect?, Ecological Economics, Vol. 36, p.119-132.

[10] Diederen, A. M. (2009): Metal mineral scarcity: A call for managed austerity and the elements of hope, in: http://www.tno.nl/downloads/Metal_minerals_scarcity.pdf, accessed 22.11.2012.

[11] McKinsey & Company Inc. (2007): Kosten und Potenziale der Vermeidung von Treibhausgasemissionen in Deutschland. Study by McKinsey & Company for BDI initiativ – Wirtschaft für Klimaschutz, Berlin.

[12] http://www.carbonrecycling.is, accessed 24.11.2012

[13] http://scrippsco2.ucsd.edu/data/atmospheric_co2.html, accessed 21.10.2011.

[14] Tans, P. (2010): Trends in Atmospheric Carbon Dioxide. www.esrl.noaa.gov/gmd/ccgg/trends, accessed 18.01.2010.

[15] Held, T. M.; Kriegler, E.; et al. (2008): Tipping elements in the Earth's climate system, Proceedings of National Academy of Science of the United States of America, Vol. 105, No. 6,

[16] http://www.grida.no/publications/other/ipcc_tar/?src=/climate/ipcc_tar/wg1/016.htm, accessed 18.12.2011.

[17] Pfeifer, W.; et al. (2004): Etymologisches Wörterbuch,dtv, Munich.

[18] Olah, G.; Goeppert, A.; Surya Prakash, G. K. (2009): Beyond Oil and Gas - The Methanol Economy, 2. Edition, Weinheim:Wiley-VCH.

[19] Nitsch, J.; Pregger, T.; Scholz, Y.; et al. (2010): Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung und Europa und global - „Leitstudie 2010"; http://www.bmu.de/files/pdfs/allgemein/application/pdf/leitstudie2010_bf.pdf, accessed 07.03.2012.

[20] http://www.berlin-institut.org/online-handbuchdemografie/bevoelkerungsdynamik/auswirkungen/bevoelkerungsprojektionen.html, accessed 21.10.2011.

[21] BP (2011): Energy Outlook 2030, in: http://www.deutschebp.de/liveassets/bp_internet/germany/STAGING/home_assets/assets/deutsche_bp/broschueren/broschuere_bp_energy_outlook_2030_dt.pdf, accessed 19.12.2011.

[22] Anderson, D. R. (2006).: The critical importance of sustainability risk management, Risk Management. Vol. 53, no. 4.

[23] Fischer, J.; Rohrmus, D.; Weinert, N. (2012):Investigation on adapting production strategies for a Smart Grid environment, Proceedings of the 10th Global Conference for Sustainable Manufacturing, Oct. 31st – Nov. 2nd, 2012, Istanbul, Turkey, p. 611-616.

[24] Lackner, K. L. (2009): Capture of carbon dioxide from ambient air, The European Physical Journal Special Topics, Vol. 176, p. 93 – 106

Defining Sustainability: Critical Factors in Sustainable Material Selection

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Abstract

The designer is faced often with questions of material selection. To answer these, functional requirements must always be met, and second the cost constraints of the project must not be exceeded, and preferably they are minimized. Sadly, once the functional requirements are met, and the costs minimized, the selection process usually ends. By taking a life cycle analysis approach, the environmental impacts of a particular material can be assessed properly. If this were the third criterion, one could expect that environmental impacts like carbon emissions, energy requirements, and toxic emissions would all be minimized. But will these efforts result in sustainable material use? In this article we postulate that the additional question of whether a material can be recycled repeatedly without degradation, or cycled at a sustainable rate through nature (for example, by composting), is the most significant question to ask when assessing the sustainability of a particular material. Because economic considerations are often held paramount, it is common to select non-recyclable materials that are eventually discarded. These non-recyclable materials must be acquired as primary resources, and all the technologies required to obtain, process, and use these materials must be developed. When finally scarcity renders it economically prohibitive to extract, the effort and energy put into developing its use will have been wasted. This paper considers the long term life cycle cost of non-recyclable and recyclable materials. The results suggest that future designers avoid the use of non-recyclable materials in order to minimize environmental and economic cost over the long term.

Keywords:

Life Cycle Analysis; Material Selection; Recycling; Sustainability

1 INTRODUCTION

Everyday designers are faced with questions of material selection. Some of these decisions seem predetermined simply because a particular material is traditionally used for a given application. In other instances it is the client or customer who requires a specific material. But when the decision is left to the designer, how do they choose?

The first thoughts are likely to be of the functional requirements. Does this material have the ability to be shaped as needed? Will it have the necessary strength and resilience to survive the environment in which it will be used? Is it light enough? When there is enough flexibility in the design it is often the case that several possibilities satisfy the functional requirements, and then costs begin to factor into the equation. Which materials are the least costly, both initially and also once the cost of manufacturing is included. Figure 1 illustrates these.

If the functional requirements are met and the costs of both the material and manufacturing are minimized, the process of material selection often ends. It is essential that the selection process not end here because ultimately material choices affect sustainability. And, it can be argued that the state of our current and future energy supplies suggest the need for a rapid transition to a sustainable existence. The materials we choose require energy to extract, process, and manufacture.

In 2010, approximately 12,717 million tonnes of oil equivalent, (Mtoe), or 148PWh of energy was produced by humans and used in the world. This figure is the total primary energy supply (TPES) as determined by the International Energy Agency (IEA). In the same year the total final consumption (TFC) was approximately 8,677 Mtoe. The difference between these two numbers is a result of the energy consumed in the production of fossil fuels. That is "backflows from the petrochemical industry are not included in final consumption." [1] And so only about 68% of the energy supply was consumed for the reason the energy was collected in the first place. In 1973 the TPES was 6,107 Mtoe, and the TFC was 4,672 Mtoe, which results in 76% of the energy arriving at its end use. Apparently, our energy supply is getting less efficient despite advances in technology, and this is due in no small part to the increased difficulty of extracting fossil fuels that require more refining, from locations that are more difficult to access. As of 2010, over 81% of our energy supply worldwide was fossil fuel based [1]. We are already using almost one third of our energy supply in an effort to provide energy. The strain will only be greater in the future.

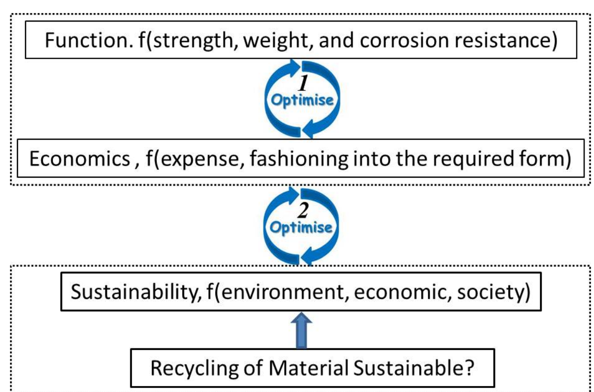

Figure 1: Product optimization process.

Similarly, materials like copper require greater efforts to extract when it can only be found at lower concentrations than in the past. Transitioning from a scarce material to one that is entirely recyclable, or in the case of copper simply ensuring we can recycle it instead of needing to extract it, will require effort and energy. According to some research it will be disruptive to make changes to material use if it requires more than about 3.5% of the global energy supply [2]. With the need to transition our energy supply to sources other than fossil fuels, and the need at some point to transition each and every material that cannot be sustainably used to those that can, those 3.5% of global energy supply will be quickly used. It is therefore vital that we make these changes as soon as possible.

If designers use materials that are sustainable, there will be greater need and demand for them. The infrastructure needed to provide larger quantities will be built and the technology surrounding these materials will be developed. Not only will environmental impacts be reduced in the short term, but paying the overall cost of the inevitable transition should be less disruptive because it occurs at a time when energy is available.

2 SUSTAINABILITY

In modern society, a primary concern of must be *sustainability*. The definition for sustainability is derived from the one published in the 1987 United Nations study headed by Brundtland [3], where the word *design* is substituted for *development*: "Design that meets the needs of the present without compromising the ability of future generations to meet their own needs". This includes the *three pillars of sustainability* and the interaction of Environment, Economics and Society. The three pillars are illustrated in figure 2.

2.1 Environment

The environmental pillar includes: maintaining diverse ecological systems, renewable energy, reducing fossil fuel consumption and emissions, sustainable agriculture and fishing, organic farming, tree planting and reducing deforestation, recycling, and better waste management.

2.2 Society

The pillar for a sustainable society is controversial and is discussed by Kates [4]. They find peace, freedom, development, and the environment to be prominent issues and aspirations. The foregoing now include: peace, social justice, reducing poverty, and ideals that promote social equity as listed in figure2.

Some companies [5] have taken this further by placing an emphasis upon the following:

- Decent/ Fair Wages Health & Safety
- Working Conditions
- Standard of Living
- Security and Stability
- Empowerment
- Community Cohesion
- Human Capital
- Diversity and Gender Equality
- Health & Well-Being
- Cultural Heritage

2.3 Economic

The basis of economics is consumption and collaboration; hence this pillar includes a managed, sustainable economic model that ensures fair distribution and efficient allocation of our resources for purposes of consumption. This pillar ensures that economic growth maintains a healthy balance with ecosystems. Can free enterprise operate sustainably? Yes it can with the proper ground rules in place, which take the foregoing two pillars into account.

2.4 Products

Products are not limited to engineered products as envisioned in CIRP [6]. The first notion of sustainability came from agriculture and biology with the book by Rachel Carson [7]. Products range from agricultural, to biological, to chemical, to mechanical, to electrical, etc. In fact, any product has some element of sustainability associated with it.

Buildings are also products and every building product has environmental, economic, and social impacts. These impacts occur at all life-cycle stages in multiple ways and on local, regional, and global scales. Building products now have their own ASTM standards [8], based upon ISO 14040: "Sustainable development is a scientific and technological endeavor that seeks to enhance the contribution of knowledge to environmentally sustainable human development". An example of materials is cement, which is an important building material and is recognized as a major carbon emitter in energy in production [9]. It accounts for around 5% of global carbon dioxide (CO_2) emissions [10] and is the second most consumed product globally, after water.

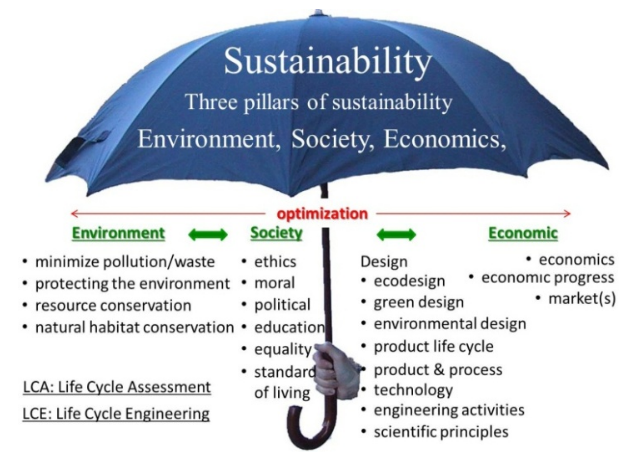

Figure 2: The Sustainability Umbrella, with the three pillars of sustainability.

Important product impacts include material use and energy consumption. Use is concerned with material scarcity, product EOL, recycling, energy and the three stressors: solids, fluids and gasses. The six main air pollutants (non-global warming effects), called "criteria pollutants" are: ozone, particulate matter, carbon monoxide, lead, nitrogen oxide and sulphur dioxide (affects lungs and is in acid rain). Effects are [10]: ozone (damage to lungs), particulate matter (PM affects heart and lungs), carbon monoxide (organs and brain), lead (nervous system, kidneys, immune system), nitrogen oxide (lungs and associated with PM and ozone) and sulphur dioxide (affects lungs and is in acid rain). Some of these are also contribute to global warming.

2.5 Defining Sustainability of Materials

The following definitions are needed for clarification. Many books [11, 12], reports and papers talk about product, the environment and impacts without giving a clear definition of the environment. Even SETAC in its definition of Life Cycle Assessment [13] talks about the environment without defining it. Documents such as the EU Directive 2011/92/EU on environmental impact assessment also do not have a definition.

A broad definition is: the natural environment, encompassing all living and nonliving things occurring naturally on earth. However, this is too general and because this paper deals with resources and a wide range of potential impacts, reference is made to a study which had a major impact upon development of a one million square kilometre area in 2004 [14].

Environment

We define the environment as follows: the components of the Earth including (a) land, water and air, including all layers of the atmosphere; (b) all organic and inorganic matter and living organisms; and (c) the interacting natural systems that include components referred to in paragraphs (a) and (b) [14].

Impact Upon the Environment

Any effect on land, water, air or any other component of the environment, as well as on wildlife harvesting, and includes any effect on the social and cultural environment or on heritage resources [14].

The following are areas of physical and chemical effects:

- Ground water.
- Surface water.
- Noise.
- Land.
- Nonrenewable natural resources; including resource depletion.
- Air/Climate/Atmosphere.
- Vegetation.
- Wildlife and Fish
- Habitat and communities
- Social and economic.
- Cultural and heritage.

Environmental Impact

Environmental impact is usually framed in terms of sustainability, which can have many interpretations. Even the EU Directive 2011/92/EU on environmental impact assessment does not have a definition of environmental impact. The business directory [15] gives the following definition: possible adverse effects caused by development, industrial or infrastructural projects or by release of a substance.

Environmental Impact Assessment [16] is the process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development prior to major decisions being taken and commitments made.

Irreversible Processes

Many materials are obtained via extraction of a resource from our environment. In the case of fossil fuels it involves extraction, refining into a form that we can use, and then burning of that fuel to use the energy contained within it. The last process is irreversible, and makes fossil fuels a non-sustainable source of energy. That is to say that at some point it will no longer be feasible to extract fossil fuels in order to supply energy.

Dispersion

Fertilizer use is a prime example of a mineral dispersion system deployed at the global scale. Phosphorus in particular is mined in a number of locations around the world where it occurs in concentrations that make mining economically feasible. It is then transported everywhere there is agriculture, and it is spread about to nourish crops. Unfortunately, the phosphorus is not recovered. It is instead dispersed in the soils, waterways, and surrounds. This process cannot continue as it will result in the eventual dispersion of all the available phosphorus deposits and we will no longer be able to collect and utilize what is an abundant mineral for modern agriculture.

These are the cases one would aim to avoid. Using materials in a manner that makes it impossible to recover them for future use either by chemically changing them or by dispersing them is not sustainable. Therefore sustainable material use is to utilize while ensuring it can be infinitely recycled without degradation or irrecoverable dispersion. This is the ideal. It may not be achievable in all circumstances, but especially for some metals it seems at least theoretically possible to have nearly 100% recycling rates. [17]

3 MATERIAL SELECTION METHODOLOGY

It is suggested that when selecting materials, three requirements are fulfilled and optimized. These are:

1. Function: strength, weight, food-safety, corrosion, etc;
2. Sustainability;
3. Cost Minimization.

The first and last items are nearly always considered. It is the second that we will observe.

3.1 Life Cycle Assessment

Life cycle assessment is commonly applied with a temporal scope, including only the life of the product. The environmental impacts of mining, manufacturing, transporting, using, and recycling/disposing of that product are calculated and reported. Whether the materials that comprise the product are recyclable or not, will impact the analysis, but it will not guarantee sustainability. It is proposed that sustainable material choices will yield the lowest environmental impact in the long run.

By extending the term of a life cycle analysis to include the impacts of choosing materials that will in the future have to be replaced, we can show that the environmental cost is greater than choosing a material that can be used in perpetuity.

Resource depletion is an obvious consequence. The depletion will occur faster without recycling. If there were 100% recycling then resource depletion would stop.

This is an obvious consequence of either action or inaction. However, there are unknowns, such as discovery of new deposits through geologic exploration. A case in point is the discovery of chromite in the “ring of fire” in Northern Ontario [18]. With this discovery, the supply of chromium changed. Overnight, Canada suddenly had an estimated 10% of the world’s chromium supply. Discoveries such as this one are obvious “game changers” in terms of raw material supply availability.

No mines have been started at the foregoing location, but questions posed earlier in this paper are raised. For instance, considerations include the three sustainability issues of environment, economics, and society: 1) first is the energy needed to extract these resources (transportation, equipment operation, road or rail); 2) economic (is it viable?); 3) environment (how destructive will it be, how widespread will it be and can the end result be a renewed landscape with negligible impact?); 4) Will there be an employment benefit to society? 5) will aboriginal peoples claims to land use and the associated opportunities be respected? (society); 6) can the mined chromium be recycled for future use?

3.2 Materials, Cost, Complexity, Consumption, Environment, Energy

The challenge in design is to connect, optimally, product complexity (no. of parts), materials, cost, consumption (product & energy), carbon emissions, manufacturing, and environment. It is an optimization process.

Product complexity is important and economists define it as: an assessment about the number of components in a product [19]. In this paper it is proposed that a more extensive definition includes: material, number of parts, shape, size and energy needed to produce a part or product.

Since the industrial revolution the number of parts in a product often increases dramatically with time, as can be seen in figure 1. Once introduced, and accepted by markets, product complexity increases, with the number of parts in a product increasing exponentially in most cases. This is one factor in product complexity; however other factors also play a role.

As a product becomes more complex, materials often change. This can mean increased energy needs where the shape and size will also contribute to the amount of energy expended. Additionally, as a product becomes more complex the value added will increase. If energy needs increase, costs will also increase. Design for assembly considerations also come into play, with a goal being optimization, including the reduction in the number of parts, thereby reducing costs and hopefully energy consumption and emissions [20,21]. Often the foregoing is all optimized with one goal, to maximize profitability.

Product complexity plays a major role in determining if a product is worth disassembling (recycling) [22], especially with respect to reuse of part or all of a product, including materials. Usually it is the financial worth of the material content that is attractive. Ultimately, the financial benefit in disassembling and reusing, and/or recycling all or part of a product and its materials, will determine the EOL strategy for that product.

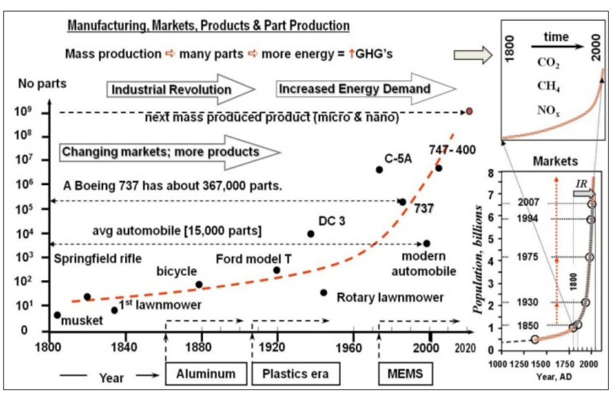

Figure 3: Increasing product complexity, as defined by the number of parts per product.

Products have become increasingly complex since the industrial revolution, as shown in figure 3. Energy supplies have changed, manufacturing is more complicated and automation has enabled mass production with increased efficiency and increasing energy needs and emissions. It is obvious that as a part is made, repeatedly, the energy consumption increases and the carbon emissions (carbon footprint) from manufacturing that part or product becomes an important factor. There will be increased carbon emissions, and water use which is also becoming a concern.

Economics is important in complexity: if it is not economical to produce a product because of complexity, it will not be manufactured. Hence marketing and customer requirements are important factors. Production cost will also have a major effect upon producing a product economically.

3.3 Examples of Products, Materials and Energy needs

The following looks at how products have material requirements where there is a potential to for materials to become scarce. In the following computer chip technology, Lithium batteries and photovoltaics (PV) are considered.

Computer Chip Technology

Computer chips are an example of new products coming to market. Figure 4 shows Moore's Law [23]. Silicon is the base material for computer chips, hence there is not a shortage in sight. Small amounts of gold are also used, but it too will be available in the foreseeable future, although expensive. The trend shown is linear.

The life cycle of Intel chips is shown in figure 5, indicating an increase in the production of units with time. So although material needs can be supplied, production energy is increasing.

Although there is not any concern with material supply, there is concern with energy needs for production and energy use [24][Low-tech, 2012]. As with any process, energy is required to produce pure silicon for computer chips. The energy used in producing nine or ten computers is enough to produce one automobile [22], which is 973 GJ per average sedan [25], or 97.3 GJ per computer, for which a major portion is for silicon production. 43% of the pure silicon crystal used in the process becomes part of the chip [22], hence approximately 41.8 GJ. If used for 12 hours per day, every day, for five years, a laptop using an average of 50W would require 1,095kWh or 4 GJ of energy over its lifetime. Corkish [26] shows the energy consumption to produce electronic grade silicon is in the range of 200 kWh/kg to 50 kWh/kg. It can be seen that although energy needs to produce electric grade silicon are decreasing, the production quantity is going up, increasing the total energy requirements.

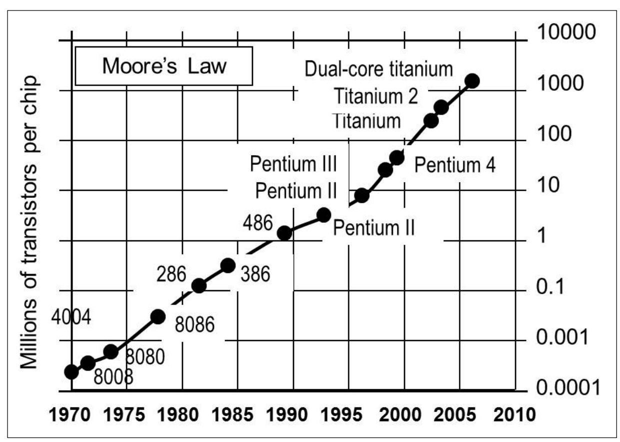

Figure 4: Moore's Law [23]

Waste in production goes to either PV cells or is recycled. As indicated in source [22] there are four stages to silicon chip manufacture: Raw Material Extraction; Material Production; Part Production; Assembly. 1) Raw Material Extraction: inputs, outputs and processes required to produce a supply of energy and silicon, including mining of materials. 2) Material Production: inputs, outputs and processes to produce crystalline silicon, including the crystallization of purified liquid silicon. 3) Part Production: inputs, outputs and processes to manufacture a chip, including etching circuits on a silicon wafer. 4) Assembly: inputs, outputs and processes to produce the final packaged chip, including the plastic or ceramic case with metal pins that encases the chip.

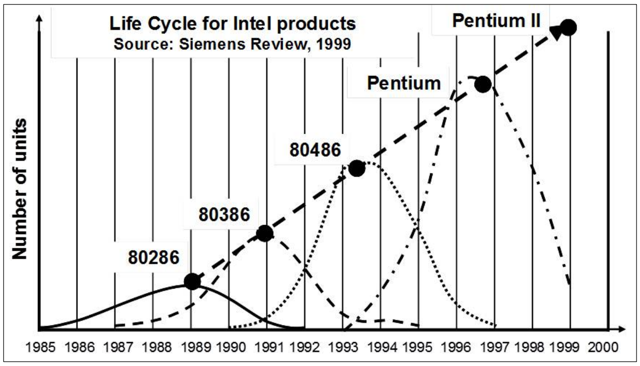

Figure 5: Life Cycle of Intel Processors [37].

Lithium Ion Batteries

Batteries have changed dramatically over time. The development of the modern battery coincides with the start of the industrial revolution, with the original batteries consisting of a galvanic cell made of zinc, copper and brine in the first iteration [27]. Over time, materials have changed, making them more efficient and smaller, ending up in 1949, with compact, portable alkaline batteries which are now ubiquitous. It is interesting to note the first solar cell in 1954, called a battery, is an offshoot of battery development [28]; this is discussed later. The materials used in batteries, up to that time, were commonplace and not thought of as scarce or strategic (materials critical to a supply chain). Material changes include: zinc-carbon, nickel-cadmium, nickel-metal hydride, iron-phospate, aluminum, cobalt oxide, etc [29].

Lithium carbonate reserves, 2008, million tonnes				Product ion
Lithium carbonate reserves, 2008, million tonnes				2010
Country	Brine	Mineral	Mixed	Tonnes
Argentina	1.86			2,200
Australia		1.17		4,400
Bolivia	28.7 4			
Brazil		4.84		
Canada		1.92		
Chile	15.9 7			7,400
China			5.86	2,300
Zimbabwe		0.14		

Table 1: Li Reserves, 2008 [38].

A change came about with the introduction of Lithium, because of its lightness and ability to deliver high current densities. Lithium is now an important battery material. Lithium alloys can store the greatest electrical energy per unit volume of any rechargeable battery technology [30]. They have long discharge-charge cycle lives, for longer times and give higher current densities when needed.

It is used in a variety of other products. It powers around 90% of laptop computers [30] and it is predicted that the demand for lithium will increase as shown in figure 6 [23].

In 1976 it was estimated there were 10.6 million tonnes of elemental lithium. Twelve years later, in 2008, estimates had changed to 28.4 million tonnes Li equivalent and to more than 150.0 million tonnes of lithium carbonate of which nearly 14.0 million tonnes lithium (about 74.0 million tonnes of carbonate) are at active or proposed operations [27]. Table 1 shows estimated Lithium reserves as of 2008. A third source, hectorite clays, has been identified but production methods have not been proven [31].

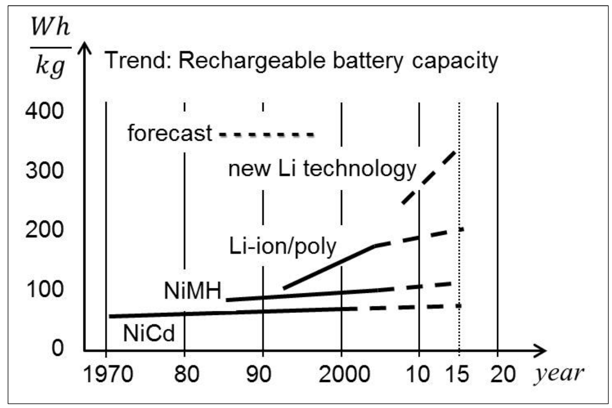

Figure 6: Predicted changes for lithium batteries [23].

Lithium has an embodied energy of 853 MJ/kg and carbon emissions of 5.3 kg CO2/GJ [32].The energy needed to mine Lithium depends upon whether it is brine or mineral. Because brine is like a combination of sand and liquid, it is easy to see that it is much simpler and more economical to use as a source [31]. The major energy component is in pumping the brine to solar pounds where evaporation yields Lithium carbonate and Lithium hydroxide. Note that up to 50% of the lithium in used batteries may be recycled in the future.

Photovoltaic Materials and Increasing Efficiency

There is competition to develop the most efficient PV solar cell, as shown in figure 7. Materials that play a role in the PV cells are:

- Silicon, Si, semiconductor;
- Gallium Arsenide, GaAs, semiconductor, gallium and arsenic;
- Cadmium Telluride, CdTe, thin film solar cells, 12% efficiency in 2012 [33]. Cd is a known toxic heavy metal [34];
- Ternary chalcopyrite, Cu(In, Ga)Se_2, thin film solar cells, 11.4% efficiency in 2011 [35]. CdTe systems have the smallest carbon footprint of any PV technology.

None of these materials is in danger of becoming scarce, however, there are other potential problems. Gases like nitrogen trifluoride, or NF3, is a greenhouse gas 17,000 times more potent than carbon dioxide. NF3 is commonly used in the manufacture of electronics and some solar panels [29]. In 2009 it was found NF3 levels were increasing at 11 percent each year, although the cause is unclear. Production of some other panels involves another gas called sulfur hexafluoride — the most potent greenhouse gas known to science.

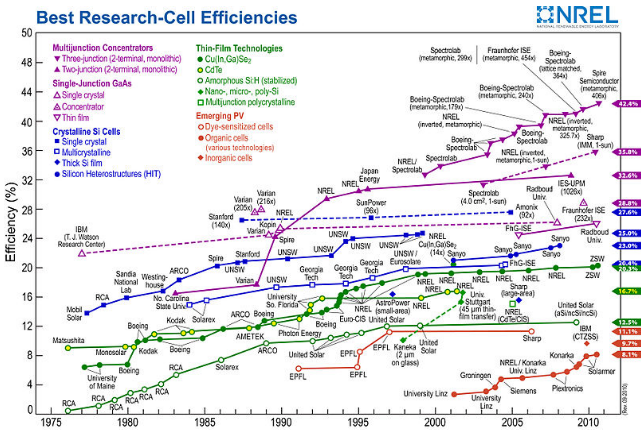

Figure 7: Changes in efficiency for PV cells [39].

3.4 Predicting Future Shortages

Predicting the future is risky at the best of times. Farmer and Trancik [36] conducted an extensive study in predicting trends for modern technology, using financial data. In the case of new technologies, where there is no historical data to extrapolate, forecasting the future is likely to be less certain, than technologies with track records of steady improvement, such as the Ford model T.

For the foregoing cases, one for PV cells and the other for Lithium use, trends indicate PV cells are likely to become more efficient, and in the case of batteries, Lithium use is likely to increase [23]. Hence, the materials necessary to manufacture PV cells, silicon and its doping materials, and Lithium to make batteries will become more necessary. In the one case, PV cells, there is not a potential shortage of material sources, but the process is toxic and requires considerable quantities of energy for manufacturing. Recycling may be a necessary alternative to keep energy needs lower.

However, Lithium is another case altogether. Energy needed to mine brine deposits and to produce commercial quantities is minimal. However, sources of Lithium brine are in finite supply, therefore a different approach is required. For reasons of potential scarcity it may be necessary to embark upon recycling Lithium.
So recycling is necessary for two different reasons, one to decrease energy use, and control toxic elements, the other for reasons of potential scarcity.

4 GENERAL DISCUSSION

Materials have generally been abundant since the industrial revolution. However, since the industrial revolution circumstances have changed considerably with much larger populations, increased complexity of products and more intensive use of resources, and with the advent of increased consumption there is a potential of depleting resources that contribute to environmental impacts and but are also important to decreasing environmental impacts. For instance, Lithium, whose alloys can store the greatest electrical energy per unit volume of any rechargeable battery technology [27] for longer times and give higher current densities.

Therefore choosing materials for a design has become much more complicated. To decrease the future impacts a designer must do a Risk Assessment and conduct a Due Diligence with respect to the goal of sustainability:"Design that meets the needs of the present without compromising the ability of future generations to meet their own needs". This includes choosing materials, the potential future scarcity of materials, toxicity in production and the energy expended in extracting those materials.

A list of concerns from Risk Assessment (RA) includes:

Scarcity

- Has resource consumption been optimized?
- Are closed loops being used?
- Is a material continuously recyclable?
- Is there a finite supply of a critical material such as Lithium? Potential scarcity requires an assessment of economic supply, and what will happen if economically attainable Lithium is depleted.
- Does the design include few, simple, recycled, unblended materials?
- Does the design include: recycling, and proper labelling; modules and breakpoints, and understandable and thoroughly explicit manuals?

Environment

- What is the trade-off between scarcity, pollution and toxicity?
- Is the material being considered a toxic substance as defined by the local legal jurisdiction? Although exposure to toxic materials is controlled locally, it becomes a moral/ethical question if requirements are less stringent in areas such as developing countries. Or if it concerns an area in a developed country where the remote possibility of jobs overrules local objections due to unemployment. This is a risk assessment problem. What is a population willing to risk to have full employment?
- Has material durability been designed into products which have significant environmental impacts, outside the use phase?
- Does the design include structural features and higher quality materials, to minimize weight, without interfering with the product: flexibility, impact strength or functional properties?
- Does the design use better materials, surface treatments or structural arrangements to protect products from dirt, corrosion and wear?
- What are energy requirements for recycling a material?

Non Material Specific Questions Include

- Does the design use the minimum joining elements possible, and use screws, adhesives, welding, snap fits, geometric locking, etc. according to DFMA guidelines.
- Is minimization of packaging implemented?
- Have social implications been considered?
- Has energy consumption been optimized in production and transportation?
- Have energy and resource consumption been minimized in the use phase; especially for products having significant environmental impacts in use?
- Have easy repair, maintenance and upgrading been implemented?

Scarcity and energy waste are the two factors discussed in this paper. It has been shown that trying to predict material scarcity and price are difficult to ascertain. Material price is subject to market forces which can only be observed.

In order to be informed about potential scarcity problems and the risks involved, access to an inexpensive database with a few very simple indicators is needed.

5 CONCLUSIONS

Choosing materials in the design phase, their potential scarcity, and the energy wasted in not recycling a material, in place of using virgin materials has been discussed.

Predicting which materials can potentially become scarce has become critical given the rate of consumption in our modern society. It is paramount to use potentially scarce materials judiciously and at the same time reduce emissions. How this is addressed needs to be determined.

Two cases concerning potential material scarcity, one for PV cells and the other Lithium batteries have been considered. Lithium brine deposits are scarce and their supply needs to be nursed until appropriate recycling technology is in place. This is because Lithium-ion cells are being viewed as a solution to storing energy from renewable sources. PV cells have adequate supplies of materials, but energy needs are high and toxic elements are present in manufacturing. Both energy and toxicity are important.

Although predicting the future in the case of new technologies is risky, it is an important endeavour in modern society where there is a potential for scarcity and increased emissions.

6 REFERENCES

[1] International Energy Agency, Key World Energy Statistics 2012, 9 Rue de la Federation, 75739 Paris Cedex 15. Accessed 27 August 2012 http://www.iea.org/publications/freepublications/publication/kwes.pdf

[2] Igor Lubomirsky and David Cahen (2012). Energy limitations on materials availability. MRS Bulletin,37, pp 412-416

[3] Brundtland, G. 1987. World Commission on Environment and Development (WCED), *Our Common Future* (New York: Oxford University Press, 1987).

[4] Kates, R.W., Parris, T.M, and Leiserowitz, A.A. “What is sustainable development? Goals, indicators, values and practice”. Environment: Science and Policy for Sustainable Development, 2005, Volume 47, Number 3, pages 8–21.

[5] Puma, 2012. http://about.puma.com/wpcontent/themes/aboutPUMA_theme/media/pdf/2011/en/PRESS_KIT_E_P&L.pdf; accessed 7 Feb 2012.

[6] CIRP. College International pour la Recherche en Productique (The International Academy for Production Engineering); http://www.cirp.net/. 2012.

[7] Carson, 1962. Rachel Carson. Silent Spring © 1962 Rachel Carson.

[8] ASTM E2432; ISO 14040.

[9] Rubenstein, M. Emissions from the Cement Industry. Accessed 1 September 2012. http://blogs.ei.columbia.edu/2012/05/09/emissions-from-the-cement-industry/.

[10] USEPA air quality website; accessed Sept 2012; http://www.airnow.gov/.

[11] Graedel, T.E. Streamlined Life-Cycle Assessment © 1998, Bell Laboratories, Lucent Technologies.

[12] Graedel, T.E. and Allenby, B.R. Industrial Ecology. © 2003 by AT&T, published by Prentice Hall, New Jersey.

[13] SETAC, Society of Environmental Toxicology and Chemistry; Pensacola, Florida, USA; http://www.setac.org/. 2012.

[14] MacKenzie, 2004. MacKenzie Valley Environmental Impact Review Board: Environmental Impact Assessment Guidelines March 2004; (accessed 1 september 2012; http://www.reviewboard.ca/upload/ref_library/MVE%20EIA%20Guidelines_1195078754.pdf.

[15] Business Directory, 2012. Business Directory.com. http://www.businessdictionary.com/definition/environmental-impact.html; accessed 1 Sept 2012.

[16] IEA, 2012. Institute of Environmental Assessment, Welton House, Limekiln Way, Lincoln, LINCS LN2 4US, UK. Accessed 1 September 2012. http://www.iaia.org/publicdocuments/special-publications/Principles%20of%20IA_web.pdf.

[17] Graedel, Erdmann T.E. Graedel and Lorenz Erdmann (2012). Will metal scarcity impede routine industrial use?. MRS Bulletin,37, pp 325-331.

[18] Gordon, J, Bhaswati, M. “Risk and Reward Beckon in Canada’s Ring of Fire”. Reuters May 24, 2012.

[19] Financial Terms, 2012.http://www.finance-lib.com/financial-term-product. complexity.html; 29 June 2012.

[20] Boothroyd, Dewhurst and Knight. Product Design for Manufacture and Assembly. © 1994 Marcel Dekker, NY.

[21] Boothroyd G. and Alting, L. Design for assembly and disassembly, Annals of CIRP, 41/2/1992; 625.

[22] ELC, 2008. Environmental Literacy Council, 2008. http://www.enviroliteracy.org/article.php/1275.html. 1 July 2012.

[23] The Economist 2008. Technology Quarterly: Case history. In search of the perfect battery. Mar 6th 2008.

[24] Low-tech, 2009. Low-tech Magazine The monster footprint of digital technology; http://www.low techmagazine.com/2009/06/embodied-energy-of-digital-technology.html; accessed July 2010.

[25] Sullivan, J.L., Williams, R.L., Yester, S., Cobas-Flores, E., Chubbs, S.T., Hentges, S.G., Pomper, S.D. “Life Cycle Inventory of a Generic US Family Sedan Overview of Results, USCAR AMP, 1998, SAE paper 982160.

[26] Corkish, R. “Can Solar Cells Ever Recapture the Energy Invested in their Manufacture?”. Solar Progress, vol. 18, No. 2, pp. 16-17 (1997).

[27] Evans, R.K. Lithium abundance – World lithium reserve. Accessed 1 September 2012. http://lithiumabundance.blogspot.ca/.

[28] Bellis, M. “History timeline of the Battery”. Accessed 1 September 2012. http://inventors.about.com/od/bstartinventions/a/History-Of-The-Battery.htm.

[29] Parkinson, J. Feb 16, 2009. Voice of San Diego. http://www.voiceofsandiego.org/science/article_37811382-9d69-5936-adeb-5db1395225e3.html; 1 June 2009.

[30] Dahn, J., Jiang, J., Moshurchak, L., Buhrmester, C., Wang, R.L. “The Drugstore Li-Ion Cell”. The Electrochemical Society Interface, Winter 2005, pp 27 – 31.

[31] Rodinia, 2012. Rodinia Lithium. http://rodinialithium.com/lithium/lithium_mining/; July1, 2012.

[32] Hammond, G.P. and Jones, C. Inventory of Carbon and Energy, ICE. Version 1.6 a. 2008. University of Bath.

[33] Bush, S. “Thin film CdTe solar cells to be 12% efficent in 2012 - First Solar”. 25 July 2008, Electronics Weekly.com. Accessed June 1, 2012.

[34] Johri, N., Jacquillet, G, Unwin, R. “Heavy metal poisoning: the effects of cadmium on the kidney”. Biometals, 2010 Oct;23(5):783-92.

[35] Gladyshev, P.P. “Thin film solar cells based on CdTe and Cu(In,Ga)Se_2 (CIGS) compounds.” J of Physics, Conference series, vol 291, no 1.

[36] Farmer, J.D, and Trancik, J. (2007). J. Dynamics of technological development in the energy sector. (http://tuvalu.santafe.edu/~jdf/papers/DynamTechDev.pdf).

[37] Siemens, 1999. Life Cycle of Intel chips; Siemens Review, 1999.

[38] Greeniacs.com.http://www.greeniacs.com/GreeniacsArticles/Energy/Lithium-Mining.html; 2 July 2012.

[39] NewEnergyNews, 2011. http://newenergynews.blogspot.com/2011/03/germans-push-pvs-efficiency-limit.html; accessed March 30, 2011.

A Framework for Synergy Evaluation and Development in Heavy Industries

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Abstract

Industrial ecology research has so far assessed the economic and environmental implications of existing synergies. However, it warrants investigations into unused by-products, which can potentially generate resource synergies between neighbouring industries and thus help to attain the zero wastes scenario. This paper presents a theoretical framework for sustainability assessment to aid new by-product synergies evaluation in the Kwinana Industrial Area of Western Australia. Accordingly, a generic symbiotic relation is suggested to link various industries together as a first step of the framework. Secondly, the principle of process engineering has been applied for the identification and development of resource synergies. Thirdly, the feasibility analysis of green processing is presented using a case study.

Keywords:

Industrial Symbiosis; Sustainability; Process Engineering

1 INTRODUCTION

The challenge for resource-based industries is not only to maximise profits, but also to minimise environmental impacts such as landscape changes, resource scarcity, greenhouse gases (GHG) emissions, and solid wastes [1,2]. In the climate change regime, where laws are applied to resource based industries for GHG reduction, industries have been required to come up with innovative end pipe solutions to meet the emission targets. However, the ever changing and stringent government legislation coupled with exorbitant end of pipe solutions requires process industries to rethink and redesign industrial processes from scratch.

Industrial ecology is the study on the material and energy flows between industrial systems and the resultant effects on the environment [3]. It aims at achieving zero waste through the application of green chemistry; e.g. reducing virgin resource use; increasing plant efficiency; and forming closed loop operations, therefore, providing a long term solution for maintaining a sustainable environment. Industrial symbiosis (synergy) is one of these industrial ecology methodologies and tools, involving the exchange of by-products between neighbouring industries. In order to be effective, industrial symbiosis is built up among those industries that are clustered together within a locality so that overall savings of transport and resource availability can be achievable [4]. Furthermore, with a varied group of industries clustered together, there is potential to attract new industry to join in, thereby enhancing further synergy developments. The closed loop synergies maintain material streams within the industrial system and interaction with the surrounding environments is greatly reduced [5].

Kwinana Industrial Area (KIA), in WA, has a strong industrial symbiotic relationship between industries. Despite this, there are so many unused by-products which can be potentially turned into resources to strengthen the symbiotic relationships further. Thus, this paper aims to investigate new synergy development opportunities for KIA through the development of a framework incorporating both process engineering and sustainability principles. To this effect, two by-products: Petroleum Coke and Phosphate rock digestion off gases, and two waste products: Nitrogen Oxides (NO_2) waste gases and Calcium Chloride ($CaCl_2$), have been identified to develop future resource synergies. Firstly, a generic symbiotic relationship is suggested to link various industries together and to aid in synergy evaluation process before the proposed framework is highlighted. The sustainability framework incorporates a substantial preliminary work in the application of process engineering principles to identify additional synergies in KIA, which provides a technical background for the following feasibility study from economic, social and environmental perspectives.

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2 BACKGROUND OF KWINANA INDUSTRIAL AREA

Kwinana Industrial Area (KIA) is by far the largest and most diverse industrial processing region (with supporting industries) in Western Australia. It consists of large inorganic mineral processing industries, chemical industries, an oil refinery, fertiliser manufacturer, and a number of other minor industries. This area has boasted of many synergies where materials and utilities are shared, and wastes from one company are inputs for another. The presence of various types of industries within Kwinana and the number of developed synergetic relations are the main reason for choosing KIA as a case study.

As with elsewhere in Australia and globally, the KIA is facing sustainability challenges on various fronts, including water and energy scarcity, climate change, an aging workforce, and growing community sustainability expectations. According to Curtin University's Sustainable Engineering Group investigation [6], four areas can be further focused on. These are the use of inorganic mineral wastes, enhancing by-product synergies, waste water utilisation and energy economy. A detailed analysis, from process engineering point of view, on the relevant industrial outputs (material streams) which are categorised as wastes or unwanted products was undertaken to investigate their potential reuse and recycle.

3 FRAMEWORK FOR EVALUATION AND IMPLEMENTATION OF NEW SYNERGIES

Industrial ecology research has experienced tremendous growth in recent years. However, most research has focussed on a particular industrial zone which is beneficial to that zone only. Previous studies in KIA were primarily focused on the application of sustainability principles to existing synergies [7,8]. These studies did not take into account life cycle approaches for critically assessing the environmental implication of synergies and to design green processes. The proposed framework is developed for new and unexplored by-product synergies. Nonetheless, there are a plethora of chemicals and products manufactured globally, the feed of which mostly stems from the primary/major mineral processing industries. To this effect, a preliminary generic symbiotic relation between these industries has been suggested as a first step in aiding synergy evaluation in the proposed framework.

3.1 Premises of the Framework

The preliminary outlay (Figure 1) classifies industries into several groups based on common manufacturing processes and product properties. Depending on the solvents/reducing agents used, different wastes are generated. The three most commonly used reducing agents are nitric, sulphuric and hydrochloric acids. Thus, many of the wastes or by-products will be in the form of nitrates, sulphates or chlorides. There are other major wastes and by-products depending on impurities and emissions.

In this generic outlay, the industries on the left side are identified to be major sources of wastes/ by-products. In the middle, there are core industries which generate most of the synergies because of their ability to utilise neighbouring industries wastes as inputs and to deliver useful by-products to the nearby industries. The right side of the outlay represents the industries that can form synergies mainly by utilising wastes from other industries.

The purpose of this generic outlay is to promote the implementation of industrial symbiosis from local to regional levels. Therefore, instead of focusing on a single industrial area, there can be a greater co-ordination between industries within a specific region. The challenges however, lie on geographical proximity, infrastructural constraints and their costs, such as pipelines between industries and market changes. Once these technical challenges can be tackled, greater industrial cooperation can be achieved, which will lead commercially viable synergies.

3.2 Proposed Framework

The highlights of the proposed framework shown in Figure 2 can be summarised as follows:

- *Synergy evaluation* – the initial focus of the framework will be to identify unused by-products which can generate potential resource synergies. Accordingly, process engineering applications including waste categorisation, post-processing requirements and industrial feedback/review of synergy implementation benefits and constraints will be carried out to assess technical feasibility of synergies.
- *Green process design and optimisation* – this involves the detailed life cycle assessment of processes for the four synergies to identify opportunities for applying green processes to achieve minimum waste. Once emission and energy intensive processes have been identified, the next stage will focus on the redesigning synergy applications utilising green engineering concepts. It also involves the application of social and economic indicators, including cleaner production principles, eco-efficiency, inter and intra-generational social equity.

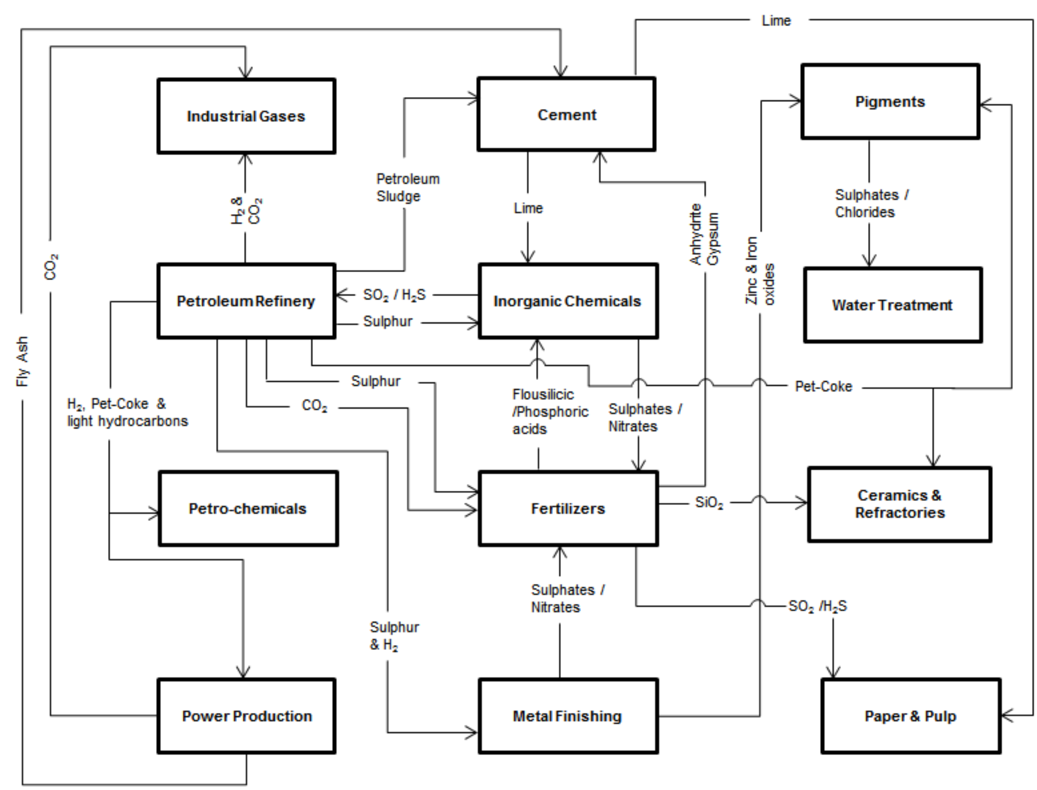

Figure 1: Generic industrial symbiotic relation.

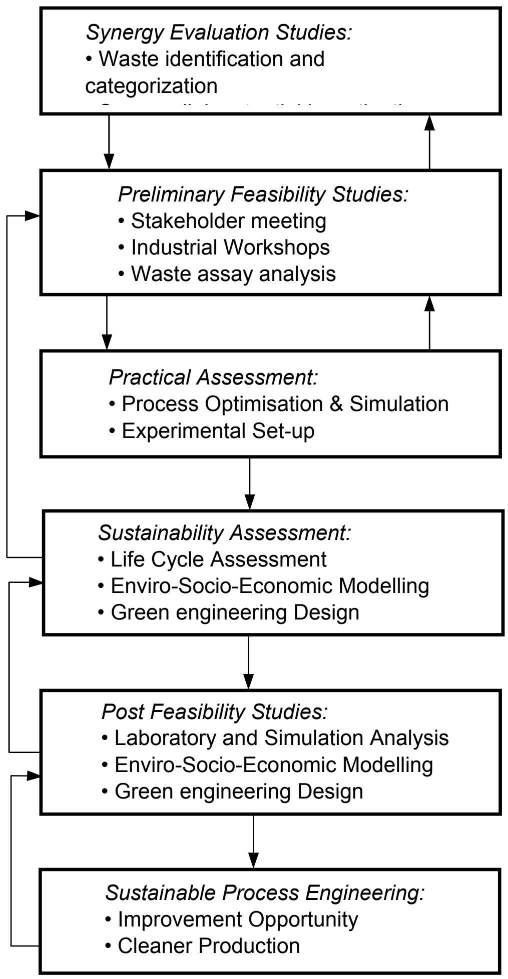

Figure 2: Framework for the evaluation and implementation of new synergies.

In order to complete the above tasks, the following steps will be conducted:

- *Technical data for green processing* – to complement the design and optimisation above, physical data and/or sample from industries will be sought through industrial collaboration to develop an experimental design for analysing waste streams. Analysis will be done on waste compositions, reaction paths to treat the waste to suitable forms and post-analysis of reaction paths for efficiency in processing.
- *Stakeholder meetings and workshops* – the laboratory results will be compared to simulated results and presented to industries for their understanding. Feedback from industry will be reviewed and simulation will be carried out until an acceptable synergy is attained. With further industrial interest, subsequent analysis will be performed for industrial application.

The practical application of the framework to a case study is proposed to take place at KIA. This paper only presents some results from the stages of synergy evaluation studies and pre-feasibility studies.

4 NEW SYNERGY OPPORTUNITIES AT KIA: EVALUATION STUDIES

Through process engineering analysis at KIA, four potential wastes that could be re-utilized within the area have been identified. Table 1 summarises the by-products, source companies, potential products, the receiving companies, and the processes involved. The preliminary feasibility analysis is briefed below.

Petroleum Coke

Petroleum coke, also referred to as pet-coke or green-coke, is one of the by-products of the oil refining process. It is produced from thermal cracking of residual oil fractions after distillation. The proposed potential uses of pet-coke are in titanium dioxide pigment production, Zircon production and silicon carbide manufacture. Using pet-coke instead of natural coke can reduce the demand for coke mining or its derivation from coal. In addition, its lower volatile organic compound and higher calorific content make it an environmentally better alternative, resulting in lower emissions and less effects on surrounding environment and communities.

Phosphate Rock Digestion Off-Gases

Flousilicic acid (H_2SiF_6) and silicon dioxide (SiO_2) produced as by-products of phosphate fertilizer production at a fertilizer manufacturer in Kwinana provide another two possible synergies. H_2SiF_6 acid could be used in the manufacture of aluminium fluoride, which is useful for the production of aluminium metal from alumina. The SiO_2 produced as an off gas can also be used as a raw material in ceramics manufacture. These uses can provide economic benefits from the by-products sale while the avoided release of SiO_2 can protect surrounding communities from its long term exposure that can be a health hazard.

Nitric Acid Production Tail Gases

Nitrogen oxides, the major emissions in nitric acid production, are dangerous greenhouse gas emissions whose effects are three hundred times that of CO_2 on an equivalent basis. Tail gases clean-up is necessary in these plants to reduce or eliminate the nitrogen oxide emissions. A suitable strategy is the use of sodium hydroxide in a series of counter current absorption process to produce sodium nitrate ($NaNO_2$). Sodium nitrate has various uses: manufacture of safety explosives with ammonium nitrate mixing; as an agricultural fertiliser; tempering of steel; and as a heat transfer medium. Thus, nitrogen oxides tail gas clean-up not only benefits environmental and social aspects from avoided emissions and acid rain but the products formed can bring increased economic benefits with it.

The major wastes produced during the production of TiO_2 pigment via the chloride route are iron oxide and calcium chloride. With industrial ecology, these wastes can be used as a feed material to other industries.

The promising areas at Kwinana where calcium chloride can be used are in water treatment, as a dust suppressant due its deliquescent nature (ability to absorb moisture) and a kiln additive in cement production. Though not an environmentally toxic material, its re-utilisation can form several synergies and bring economic value while bringing social benefits from people employed in its separation and purification from the TiO_2 wastes stream.

By-product	Source Company	Process for Removal	Potential Reuse Companies
Pet-coke	Oil refinery	Residual Oil Cracking	1. Titanium dioxide pigment plant 2. Silicon carbide manufacture 3. Zircon production
Phosphate rock digestion off-gas	Fertilizer company	Absorption of contaminated gas	1. Zircon production
Nitrogen oxides tail gases	Nitric acid production plant	Excess Nitrous oxide during water scrubbing of nitrogen oxides	1. Explosives manufacture 2. Glass and enamel industries 3. Fertilizer industry
Calcium chloride	Titanium dioxide pigment plant	Metal chlorides redox reaction with lime (CaO)	1. Water treatment plant 2. Cement industry 3. Drying applications in industry

Table 1: By-product source and use by potential industries.

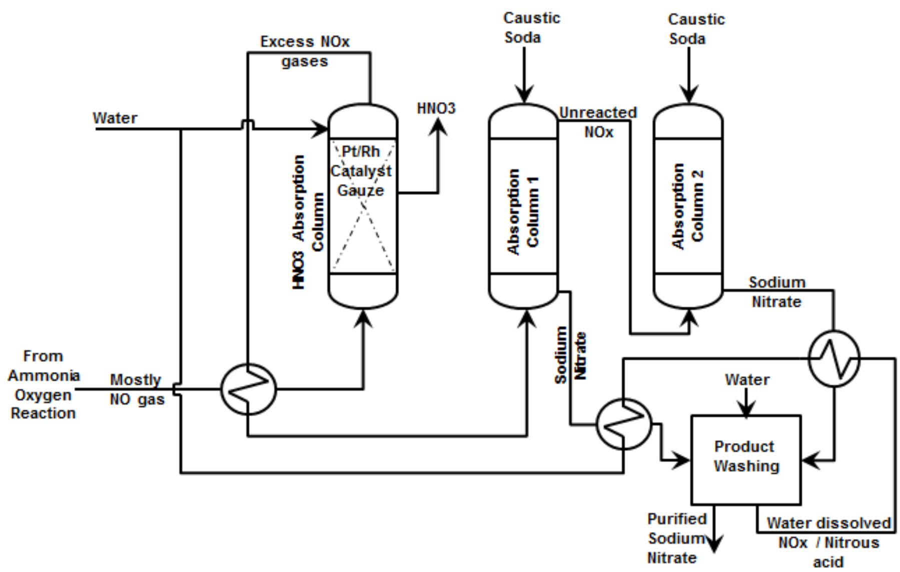

Figure 3: Schematic of nitrogen oxides absorption with caustic soda*Calcium Chloride from Titanium Dioxide Pigment Plant.*

5 NO_X –PRE FEASIBILITY STUDIES

Technologies to control nitrogen oxides (NO_x) emissions have been compared in order to find the best approach, which not only reducing emissions but offering opportunities that are economically beneficial through synergetic developments from the applications of the framework. There are three main methods that nitrogen oxides emissions can be controlled:

- Selective catalytic reduction (SCR)
- Selective non- catalytic reduction (SNCR)
- Direct reduction

The SCR method incorporates the use of special catalysts to breakdown the nitrogen oxides to nitrogen and oxygen gases. For tail gas such as nitrogen monoxide (NO), SCR is ideal with very high efficiencies. However, in the case of nitrogen dioxide (NO_2), higher temperatures of more than 400˚C are required to effectively reduce them. This is the major drawback of SCR, as higher tail gas temperatures mean higher energy costs which can make the process economically unviable. In addition, the capital cost of setting up the SCR technology and cost of catalysts and their regeneration are also highly expensive.

The SNCR method utilises reductants to react with the oxygen atoms in nitrogen oxides thereby reducing them to nitrogen gas, water and CO_2. Hydrocarbons, generally methane, are one of the most widely used reductants for SNCR methods. The use of hydrocarbons is equally effective at lower tail gas temperatures for NO_x reduction as the SCR methods. However, the use of hydrocarbons results in the production of CO_2, a green-house gas. Furthermore, hydrocarbon itself entails an additional expense. The use of urea and ammonia can replace the use of hydrocarbons to lower costs but urea is affected by temperature – lower temperatures affect efficiency, while ammonia has high capital costs for setup.

The direct reduction method entails the scrubbing of tail gases through a liquid medium to absorb the nitrogen oxides. Water and alkali/alkali earth oxides solutions are the main liquids employed for the absorption. With water usage, the conversion of N_2O into dinitrogen tetroxide (N_2O_4) is necessary for it to be absorbed by water to form nitrous and nitric acids. Nitrous acid decomposes to NO and oxygen and can be recycled for nitric acid production through water spraying. However, the NO and oxygen from nitrous acid recombine to form N_2O. This is the drawback of this method as N_2O_4 can easily change state to N_2O.

The use of alkali/alkali earth metal oxides (caustic solutions) for scrubbing the nitrogen oxides, as depicted in Figure 3, is a suitable alternative to the water scrubbing. The nitrogen oxides react with metal oxides to form water and metal nitrates. The capital cost of using caustic solutions is fairly reasonable and the metal nitrates produced can be sold as by-products, offsetting investment costs and adding income to the process. The efficiencies for NO_x removal are reasonably good though they are still much lower than the SCR and SNCR methods. Higher efficiencies would entail the use of multiple scrubbers which would add to the expensiveness of the use of this method.

The SCR and SNCR methods are process expensive in that the process conditions for effectively running them entails the use of higher utilities to maintain desired specifications for the effective reduction of NO_x emissions. The process conditions are also very sensitive and have to be carefully controlled as any significant drop in temperature will affect reduction efficiency. Impurities have to be also controlled so that they do not choke the catalysts in SCR methods, or, for SNCR, change the process dynamics to produce undesired CO_2. Both SCR and SNCR have high efficiency in reducing NO_x emissions for nitric acid plants, though, the expensive cost limits their applications.

The NO_x reduction methods using caustic solutions require lower process temperatures and the process conditions are not as sensitive as the other two methods. Thus, better control can be achieved during operation and operating cost is also lower. Capital costs for setting up such a process are also reasonable and the fairly good efficiency in reducing NO_x emissions make it more economically viable.

By-product		Nitrogen Oxides
Further use		Sodium nitrate production
Preliminary Sustainability Assessment	**Social**	Less acidic rain and adverse effects of nitrogen oxides to health from avoided release
	Economic	• Avoided fines resulting from emissions making savings to company. • Revenue from the sodium nitrate sale
	Environmental	• Less environmental burdens from avoided nitrogen oxides emissions. • Avoided virgin resource use through substitution or blending of ammonium nitrate with sodium nitrate in safety explosives

Table 2: Sustainability assessment of sodium hydroxide use for NO_x absorption.

A less subjective sustainability assessment to assess the benefits of using the reduction method was conducted using sodium hydroxide as the scrubbing solution. This would result in theproduction of sodium nitrate as a by-product which can be utilised or sold to other companies. The results of the assessment are summarised in Table 2 where the avoided emissions of NO_x gases are seen to bring improved environmental conditions that result in lower effects to the surrounded environment and communities. The by-product of sodium nitrate adds an extra economic incentive as a result of re-sale.

6 CONCLUSIONS

The Kwinana Industrial Area is a good example in practice where various bodies and industries have made a concerted effort to foster synergies and reduce wastes. In the aim of promoting further industrial synergies, a framework has been developed to evaluate and implement potential synergy opportunities to improve industrial relations. Four by-products, namely, pet-coke, Phosphate rock digestion off gases, nitrogen oxides waste gases and calcium chloride are identified for potential synergy development.

The benefits of industrial ecology are great as has been witnessed through the evaluation of further synergies at KIA. If fully captured, synergies may one day bridge the finite resources dilemma that faces many industries.

7 REFERENCES

[1] Azapagic, A. (2004): Developing a Framework for Sustainable Development Indicators for the Mining and Minerals Industry. *Journal of Cleaner Production*, Vol. 12, No. 6, pp. 639–662.

[2] Broadhurst, J. L., Petrie, J. G. (2010): Ranking and Scoring Potential Environmental Risks from Solid Mineral Wastes. *Minerals Engineering, V*ol. 23, No. 3, pp. 182–191.

[3] Urmila, D. (2005): Green Process Design, Industrial Ecology, and Sustainability: a Systems Analysis Perspective, *Resources, Conservation and Recycling,* Vol. 44, No. 3, pp. 215–235.

[4] Chertow, M. R. (2007): Uncovering Industrial Symbiosis. *Journal of Industrial Ecology*, Vol. 11, No. 1, pp. 11 – 30.

[5] Faria, D. C., Bagajewicz, M. J. (2011): Novel Bound Contraction Procedure for Global Optimization of Bilinear MINLP Problems with Applications to Water Management Problems. *Computers& Chemical Engineering*, Vol. 35, No. 3, pp. 446–455.

[6] Van Beers, D. (2008): Capturing Regional Synergies in the Kwinana Industrial Area – 2008 Status Report. Centre for Sustainable Resource Processing, Perth.

[7] Kurup, B., Altham, W., van Berkel, R. (2005): Triple Bottom Line Accounting Applied for Industrial Symbiosis, Proceedings of the 4th Australian Conference on Life Cycle Assessment, Australian Life Cycle Assessment Society, Sydney, Australia.

[8] Van Beers, D. (2009): Application of the Cleaner Production Framework to the Development of Regional Synergies in Heavy Industrial Areas: A Case Study of Kwinana (Western Australia).PhD diss., Curtin University, Perth, Australia.

Jointly Consider Acquisition Price, Trade in Rebate and Selling Price in Remanufacturing

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Abstract

In remanufacturing business of durable products, a special feature is the correlation between supply and demand. This is because customers who return their end-of-life products usually need to do replacement purchase. At the same time, pricing strategies have been widely adopted by remanufacturing companies to balance the supply and demand. In this study, we consider the pricing strategies with the presence of replacement purchase. We argue that despite the acquisition price for return products and the selling price to new customers, remanufacturing company should offer a trade in program to the replacement customer segment. We study the optimal pricing policies when return yield rate is uncertain. We also compare the profitability of different pricing schemes under different yield variations.

Keywords:

Remanufacturing; Return Acquisition; Yield Rate; Price Discrimination

1 INTRODUCTION

In recent years, there has been an increasing concern on the closed loop supply chains. Due to both economic incentives and legislation regulation, more and more companies are involved in product recovery business. Remanufacturing is one of the various product recovery options. By repairing or replacing old components, remanufacturing brings used products to same-as-new conditions. Compare with manufacturing, remanufacturing reduces the wastes produced and materials needed. Successful practices of remanufacturing can be found in industries like automotive, toner cartridges, electric equipment, office furniture, etc.

One of the unique characteristics in remanufacturing business is the uncertainty of return flows. This makes it difficult for the company to match supply and demand. Remanufacturing companies usually use pricing tools to control the return flow of used products. For example, Kodak gives a rebate to the photofinishing laboratory for each used camera they returned [1]. Cisco Systems, Inc. offers trade-in credits to their customers to promote end use returns [2]. Another special feature of remanufacturing is the correlation between supply and demand. This phenomenon reveals that there are a large proportion of replacement customers. As reported, many remanufactured products are used for replacement [3].

This study is motivated by these special characteristics of remanufacturing practices. We consider a remanufacturing system which incorporates the uncertainty of return flows and the existence of replacement customer segment. The remanufacturing company acquires used products from previous customers through buyback programs. The supply of return flow is price dependent. Demand comes from both replacement customer and first time buyer which also depend on the price. Replacement customer will return their old product and get a trade-in rebate for the purchase. The demand can be satisfied either by remanufacturing used products or manufacturing new ones. Our model represents the remanufacturing practice of many durable products. For highly saturated markets, a significant portion of purchase could be replacement. A typical example is the remanufacturing practice of Caterpillar, which is the world's largest manufacturer of construction and mining equipment, diesel and natural gas engines. Customers who return their end-of-life products will get cash back from Caterpillar. The company also offers trade-in rebates to those replacement customers.

The objective of this study is to investigate the optimal pricing policies of the firm under the existence of replacement customer and different yield rate conditions. We start with case when yield rate of return products is deterministic. We then focus on the situation when yield rate is random. The effect of different pricing schemes is also investigated. The rest of the study is organized as follows. We first review the relevant literature and point out the difference and contribution of our work. In Section 3, we provide a detailed description of the problem and present the optimal pricing policy. To get managerial insights, numerical study is provided in Section 4. Finally, we conclude our study and discuss future research directions in Section 5.

2 RELATED LITERATURE

This study is mainly related to three streams of research in operations research: consumers' replacement purchase, product acquisition in remanufacturing, and systems with random yield.

Most studies in remanufacturing assume supply and demand are independent. However, this assumption is only reasonable for new product manufacture and sales. In remanufacturing business, a notable feature is the correlation between returns and sales, especially for durable product markets like engines or transmissions, where customers need to do replacement after their original ones reach the end of service life. Remanufacturing companies usually provide trade-in rebates for this customer segment to stimulate reman product sales and to acquire cores for remanufacturing.

Consumers' replacement or repurchase behavior has been widely discussed in marketing research. Fully understand of replacement behavior helps marketers better target their promotions to potential customers. Some researchers argue that the time of replacement decision is a function of consumers' demographic characteristics, attitudes, perceptions, and search behavior [4]. Customers' valuation of their existing product is also influenced by seller's activities. Others show that marketers can affect the product-level discount rates by advertising and rapid product developments improvement [5]. It is also suggested that marketers can mitigate consumers' loss aversion by accept the old product as a trade in [6]. Unlike these studies which focus on descriptive and empirical analysis of consumer’s replacement behavior, in this work, we assume that companies can use trade in rebates as a pricing tool to differentiate replacement customers and first time buyers. We assume the demand is a function of price and study the optimal pricing strategies under a random yield environment.

Due to the increasing concern on closed-loop supply chains, there is an extensive literature on remanufacturing, reverse logistics and other related problems. There are several detailed reviews of quantitative models for reverse logistics [7] [8]. More recent reviews are also available [9], [10], [11]. In both practice and academia, product acquisition management has been widely discussed because of its importance for closed loop supply chains. Early investigations provide the frame work for product acquisition management [12]. Acquisition problem with multiple type of returns has also been considered [13]. Game theory model is used to investigate the efficiency of different reverse channel in a supply chain setting [14]. Recently, the optimal acquisition, pricing and inventory management problem is studied in a multiperiod setting [15]. Despite the extensive discussion of product acquisition management, only a few of studies have investigated the effect of replacement purchase on remanufacturing business. Some researchers consider repeated purchase in an infinite horizon model [16]. Joint pricing problem of new and remanufactured products under the existence of green segment customers is also studied [17]. In an empirical study, count regression models are used to forecast actual product returns based on return quantity signals [18]. Similar to our work, some researchers also believe that firms can influence replacement purchase decision by offering trade-in rebates to current users [19].

This work is also related to the extensive literature on systems with random yields. A comprehensive review of this problem can be found [20]. More recent work includes [21], [22], [23], [24], and [25]. In remanufacturing planning, there are several works consider the effect of uncertain yield. Some authors analyze a system in which the firm needs to make disassembly and procurement decisions when facing limited information on remanufacturing yields or a potentially long supplier lead time [26]. Some others study a remanufacturing system where return supply can come from two collection sites, both with uncertain yield rate [27]. It is shown that in some situations, it is optimal to collect from only one site. Models with random yield and product acquisition management are also developed [28]. Mukhopadhyay and Ma [29] study the joint procurement and production problem of a hybrid system where both used and new parts can be served as inputs for production, and both demand and return yield rate are random. Zhou et al. [30] study a multiperiod remanufacturing inventory system with multiple types of returns. In their model, returned items can be either remanufactured or disposed. The objective is to minimize the expected total discounted cost over a infinite planning horizon, by making the optimal manufacturing, remanufacturing and disposal strategy.

Our work differs from the existing studies in that we consider replacement customers as a different customer segment. Unlike those models which consider repeated purchase as an uncontrollable process, we model their demand as a price dependent function. To our knowledge, this is the first one that explicitly studies the effect of replacement demand under uncertain yield rate.

3 MODEL

3.1 Assumption

In this analysis, we consider a single period remanufacturing business model. A remanufacturing company acquires end-of-use products from existing users, and sells remanufactured products to both new and replacement customers. New customers are first time buyers. Their demand is modeled as a linear function in selling price p, $\omega(p) = a - bp$ where $a, b > 0$. Replacement customers are current users who need to replace their end-of-life products. The repurchasing decision also depends on price. Since end-of-life product can be used for remanufacturing, companies usually offer trade in rebates for those replacement purchase. We assume the demand of replacement customers is also linearly depends on repurchasing price f, $\theta(f) = \delta - \gamma f$ where $\delta, \gamma > 0$, and the difference between p and f is the trade-in rebates offered to replacement customers. The company acquires end-of-use products from existing users. The buyback return is deterministic, depends on acquisition price r, and can be modeled as $\eta(f) = \alpha + \beta f$, where $\alpha, \beta > 0$. After return products are acquired (both through trade-in and buyback), they are disassembled and inspected to check whether they can be remanufactured, disassemble and inspection cost is d. The percentage of remanufacturable returns is yield rate ρ. It is observed after inspection process. The remanufacturing quantity is $min\{\omega + \theta, \rho(\theta + \eta)\}$, with unit remanufacturing cost c_r Worn out returns and excess remanufacturable returns are disposed with zero disposition cost. When reusable returns are insufficient to satisfy demand, the company needs to manufacture new components at unit cost c, where $c > c_r$. Figure 1 shows the material flow of such a hybrid system.

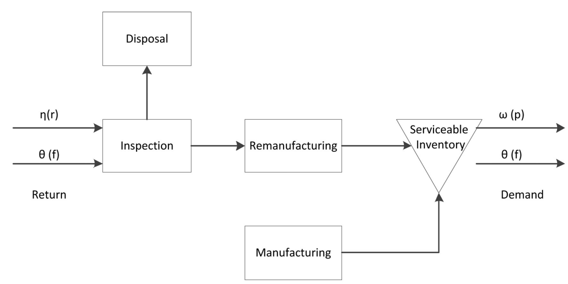


Figure 1: Problem environment.

3.2 Deterministic Yield Rate

Given the model described, we now formulate the pricing and production planning problems. We first consider the case when yield rate is deterministic, which means the percentage of remanufacturable cores is fixed and known. We also consider the case when the company decides not to offer a trade-in program. The optimal decisions are characterized for both cases.

3.3 Deterministic Case

In this subsection, we assume the firm recognizes that there exists replacement customer segment, but decide not to offer trade in programs. Customers who would like to replace their old products will sell the old ones to the firm at price r, and buy new products at price p. In this case, demand function of replacement customers can be characterized as $\theta(p-r) = \delta - \gamma(p-r)$. Consequently the company decides p and r simultaneously to maximize the profit. We call such a pricing strategy as uniform pricing. This pricing strategy represents the case when product sales and return collection are lack of coordination, for example, the reverse channel is outsourced to a third party collector. It is not the main focus of our study, but serves as a benchmark for the pricing strategy analyzed above. For more details of such a model, readers can refer to [19] and [14]. The pricing problem is as follows:

$$\begin{aligned}\max_{r,p} \Pi_U(r,p) &= \omega(p)p + \theta(p-r)(p-r-d) \\ &-\eta(r)(r+d) - c_r\rho(\eta(r)+\theta(p-r)) \\ &-c(\omega(p)+\theta(p-r)-\rho(\theta(p-r)+\eta(r))) \\ s.t.\quad & \rho(\eta(r)+\theta(p-r)) \le \theta(p-r)+\omega(p)\end{aligned}$$

The optimal pricing decision has two possible forms:

$$(r_U^*, p_U^*) = \begin{cases}(r_{U0}, p_{U0}) & when \quad I>0 \\ (r_{U1}, p_{U1}) & otherwise\end{cases}$$

where $I = a - bc - (c+d)\gamma + \delta) + (2\gamma(c-c_r) + d(\beta+\gamma) - \delta - \alpha)\rho - (c-c_r)(\beta+\gamma)\rho^2$; (r_{U0}, p_{U0}) solves the first order condition, and (r_{U1}, p_{U1}) is the optimal solution when constraint is binding.

When the company decides to offer trade-in to replacement customers, it will charge p to new customers, f to replacement customers and pay r for each buyback return. Depend on the company whether to manufacture or not, we obtain two different scenarios. First, if the company chooses to manufacture, remanufacturable return is then less than total demand, $\omega(p)+\theta(f) > \rho(\eta(r)+\theta(f))$, part of the total demand will be satisfied by manufacturing, the profit is revenue minus acquisition, inspection, remanufacturing and manufacturing cost. Second, when demand is only filled by remanufacturing, i.e. $\omega(p)+\theta(f) = \rho(\eta(r)+\theta(f))$, the profit is revenue minus acquisition, inspection and remanufacturing cost. Additionally, the company should assure $p - f \ge r$ to make the trade-in price attractive to replacement customers. The pricing problem in deterministic case can be formulated as follows:

$$\begin{aligned}\max_{r,f,p} \Pi(r,f,p) &= \omega(p)p + \theta(f)(f-d) - \eta(r)(r+d) - c_r\rho(\eta(r)+\theta(f)) \\ &-c(\omega(p)+\theta(f)-\rho(\theta(f)+\eta(r))) \\ s.t.\quad & \rho(\eta(r)+\theta(f)) \le \theta(f)+\omega(p) \\ & r+f \le p\end{aligned}$$

The first constraint denotes that the company should not acquire more remanufacturable returns than total demand. The second constraint means that trade-in rebates should be greater than or equal to the acquisition price. Otherwise, replacement customer would sell end-of-life product at price r and purchase new product at price p . When the second constraint is binding, the above problem reduces to the uniform pricing case. In the following part, we first solve the relaxation problem without considering the second constraint. After that, we identify when the optimal solution violates this constraint, and the company should choose uniform pricing strategy. Similar to the uniform pricing case, the optimal decision under deterministic yield rate can be characterized as follows:

Proposition 1. *The optimal pricing policy for deterministic return yield rate is*

$$(r^*, f^*, p^*) = \begin{cases}(r_0, f_0, p_0) & when \quad I>0 \\ (r_1, f_1, p_1) & otherwise\end{cases}$$

where I follows previous definition, (r_0, f_0, p_0) solves the first order condition, and (r_1, f_1, p_1) is the optimal solution when constraint is binding.

Corollary 1. *Price discrimination policy should be chosen when $\delta/\gamma - a/b - \alpha/\beta \le 0$.*

This corollary can be proved by checking the optimal solution in Proposition 1; we can find the condition when the second constraint is binding. It shows that price discrimination policy is not always implementable. An interesting question is that given the above condition, what the benefit of price discrimination is. Define value of price discrimination as $\Pi(r^*, f^*, p^*) - \Pi_U(r_U^*, p_U^*)$. The following corollary gives the result.

Corollary 2. *Given $\delta/\gamma - a/b - \alpha/\beta \le 0$, the value of price discrimination is $\frac{(b\alpha\gamma + a\beta\gamma - b\beta\delta)^2}{4b\beta\gamma(\beta\gamma + b(\beta+\gamma))}$*

Corollary 2 can be easily proved by substituting (r^*, f^*, p^*) and (r_U^*, p_U^*) into the profit functions. This corollary also shows that the value of price discrimination is independent of unit manufacturing cost, unit remanufacturing cost and yield rate. It is observed that the demand and return volume are the same for both pricing strategies. Therefore, the production cost is the same under both pricing strategies. On the other hand, unit remanufacturing cost, unit manufacturing cost and yield rate only affect the production cost. This explains why the profit difference is independent in c, c_r and ρ . This observation shows that, instead of the cost savings from production, the benefit of price discrimination is from better targeting at different customer segments.

3.3 Random Yield Rate

In practice, exact yield rate information is unlikely obtainable. Therefore, in this section, we consider the problem when yield rate is random. The expected profit function under uncertain yield rate is:

$$\begin{aligned}E[\Pi(r,f,p)] &= \omega p + \theta(f-d) - \eta(r+d) \qquad - c_r E[min\{\omega+\theta, \rho(\eta+\theta)\}] \\ &-cE[((\omega+\theta)-\rho(\eta+\theta))^+]\end{aligned}$$

We assume the random yield rate is distributed on $[A,B], (0 \le A < B \le 1)$, with CDF $G(\cdot)$, PDF $g(\cdot)$, and mean value μ . The company then has two pricing options to balance supply and sales:

Case 1: $(\theta+\eta)A \le \theta+\omega \le (\theta+\eta)B$

$$\begin{aligned}E[\Pi(r,f,p)] &= \omega p + \theta(f-d) - \eta(r+d) \\ &-(c-c_r)\int_A^{\frac{\theta+\omega}{\eta+\theta}} (\omega+\theta-\rho(\eta+\theta))g(\rho)d\rho - c_r(\omega+\theta)\end{aligned}$$

Case 2 : $(\theta+\eta)B \le \theta+\omega$

$$E[\Pi(r,f,p)] = \omega p + \theta f - \eta d - c(\omega+\theta) + (c\mu - c_r\mu - d)(\theta+\eta)$$

When $(\theta+\eta)A \ge \theta+\eta$, reusable returns will be always more than demand, and this pricing strategy is then obviously suboptimal.

For Case 2, reusable returns are always less than demand. Hence, manufacturing is needed anyway. The optimization problem is similar to the situation of deterministic yield rate. In this case, the optimal price only depends on the mean value of yield rate. For Case 1, the expected profit function is similar to that of a classical newsvendor problem with price dependent demand. However, there is a major difference between this model and newsvendor problem. Classic newsvendor model usually assume random demand and perfectly reliable supply. While in this remanufacturing problem, we assume a deterministic demand and uncertain yield rate. Because of this difference, the profit function in Case 1 shows a different property compared to that of a newsvendor model.

Proposition 2. *Given* $(\theta+\eta)A \le \theta+\omega \le (\theta+\eta)B$ *, the expected profit function is jointly concave in* r *,* f *and* p *.*

This proposition can be proved by applying Sylvester's criterion. Consequently, an optimal solution exists for the random yield rate problem. For the uniform pricing problem, it is equivalent to add a linear constrain $r+f=p$ to the above problem. Since we have proved the concavity of the profit function, the optimal (r_u^*, p_u^*) can be obtained similarly. By definition, it is indisputable that $E[\Pi(r^*, f^*, p^*)] \ge E[\Pi(r_u^*, p_u^*)]$. However, because of the complexity of the problem, a closed form solution is not obtainable. An interesting question is that whether Corollary 2 still holds for the random yield rate problem. We show the numerical results in Section 4.

4 NUMERICAL STUDY

In this section, we conduct computational experiments based on the model described above. The purpose of the numerical study is twofold. First, since it is difficult to attain a closed form solution for the optimal pricing decision, we need to use numerical results to investigate the advantages and limitations of our pricing policy. Secondly, we carry out sensitivity analyses to find how the optimal decisions change as the value of parameters change. This would help managers make decisions when facing different market conditions. For the numerical study, the following data sets are assigned as base value throughout this section:

$$a=150, b=3, \delta=100, \gamma=3,$$
$$\alpha=10, \beta=10, c_r=5, d=2, c=30\$.$$

In the following content, we analyze the effect of different yield rate condition on pricing decisions and profits.

In practice, complete information on the yield rate distribution is usually not obtainable. For the following numerical experiments, we assume the aggregate yield rate of buyback and replacement return follows uniform distribution. However, we are not claim that uniform distribution is more suitable to model the yield rate of return products. In literature, several distributions have been adopted for study, Weibull distribution is used by Lo et al. [31], and Wee et al. [32]. Bakal and Akcali [28] use normal distribution in their analysis. Uniform distribution has been used by Kazaz [33], Mukhopadhyay and Ma [29], and Tang et al. [25].

We first illustrate the sensitivity of optimal pricing decisions with respect to the expected yield rate of return products. We fix the standard deviation σ at 1/75, and vary the mean value of yield rate μ from 0.3 to 0.8. Figure 2 shows the results we have obtained. As we can see, the optimal acquisition price is firstly increasing with mean value μ , then after a threshold the relation becomes indefinite. On the contrary, the optimal replacement purchase is always decreasing in μ within the range of computational experiment. When yield rate is low the optimal selling price for new customers is independent of μ , but as μ further increases the optimal price decreases to attract more first time buyers. The result reveals that when μ is low, the firm would choose to acquire fewer cores $(\theta+\eta)B \le \theta+\omega$, and demand is satisfied by both manufacturing and remanufacturing. When return quality is high, the firm then can reduces the selling price to attract more new customers.

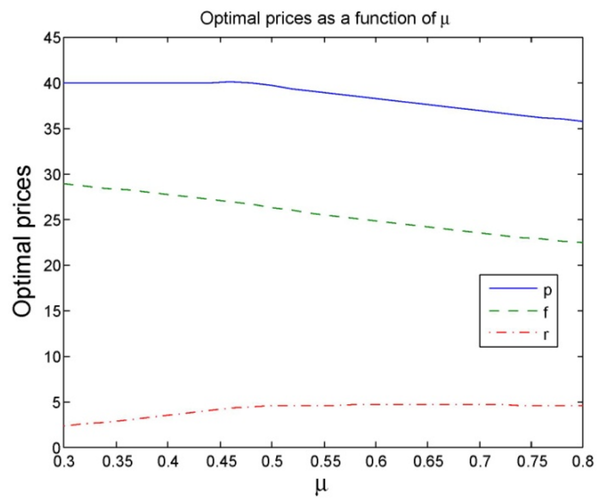
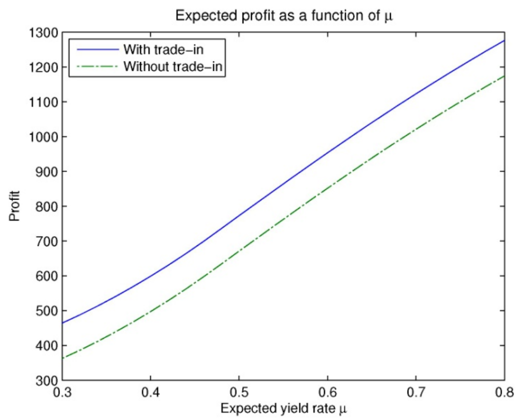


Figure 2: Effects of expected yield rate.

In Corollary 2, we find that, when yield rate is identical and deterministic, the value of price discrimination is independent of c, c_r and ρ . However, when yield rate is random, closed form expression of this value is not attainable. We now conduct computational experiments to verify whether this result still holds in random yield rate case. Firstly, we fix the variance σ^2 at 1/75 and study the effect of expected yield rate μ . Then we fix μ at 0.5 and vary σ to see how the standard deviation affects expected profit.

Figure 3 illustrates the profit difference of these two pricing schemes under different yield rate conditions. Under both pricing schemes the expected profit is increasing with μ and decreasing with σ . These two observations are consistent with intuitions as higher yield rate saves acquisition cost and lower randomness leads to higher profits. We can also find that to offer a trade-in program always makes the company better off. But it is especially favorable when the expected yield rate is low and the variance of yield rate is large, since in such cases the percentage profit improvement is high. On the other hand, managers should also take into account the related cost of such a market decision.

Another observation is that, under random yield rate, the profit difference between the two pricing strategies is stable with respect to both μ and σ . Moreover, although not shown here, numerical results also reveals that the profit difference is independent of C and c_r . This result is in consistent with the case of deterministic yield rate. We conjecture that, when the aggregate yield rate is a random variable, the value of price discrimination is independent of unit remanufacturing cost, unit manufacturing cost, and return yield rate.



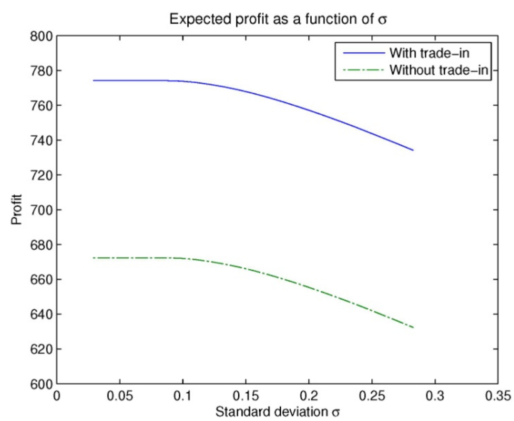


Figure 3: Value of price discrimination

5 CONCLUSION AND FUTURE RESEARCH

Matching supply and demand is the major concern of mangers who are dealing with remanufacturing business. Most studies in remanufacturing systems have assumed that supply and demand are independent. However, because of the correlation between returns and sales, this assumption is not reasonable for remanufacturing systems. In this study we investigate the pricing problem of a hybrid system with the presence of replacement customer segment. This is the first attempt to study the effect of correlation between supply and demand in remanufacturing business. We develop a single period model to evaluate the benefit of adopting a price discrimination policy for replacement customers.

When yield rate is uncertain, due to the complexity of the problem, a closed form solution is not attainable. We carry out computational experiments to compare the profits from different pricing schemes. Factors like distribution of yield rate and cost savings of remanufacturing are investigated. Our numerical results show that both factors are crucial for the firm. Also the price discrimination policy to replacement customer outperforms the uniform pricing policy in every case. Furthermore, price discrimination policy is significantly better off when the yield rate difference is large.

The present model has assumed deterministic demand function. However, the demand information is usually imperfect. Consequently, it is meaningful to incorporate random demand into the model. The company will then decide on both pricing strategy and production quantity. Such a model is similar to the newsvendor problem with endogenous demand, which has been extensively studied in inventory system researches. The existing results will facility our analysis with a remanufacturing problem setting.

There are several other possible extensions for this model. One is to relax the assumption of independence of new customer and replacement customer. In practice, replacement customers may choose to purchase a new product without returning their old one. We expect that the optimal pricing policy would be different, but the price discrimination policy should preserve its profitability. A limitation of this model is that we only consider yield rate as the fraction of reusable returns. In practice, return products are usually under different quality conditions and require different remanufacturing cost. Our model would be more realistic if we can incorporate multiple types of returns.

6 REFERENCES

[1] Toktay, L. B., Wein, L. M., and Zenios, S. A. Inventory management of remanufacturable products. Management Science, 46(11):1412-1426, 2000.

[2] Guide, Jr., V. D. R. and Li, J. The potential for cannibalization of new products sales by remanufactured products. Decision Sciences, 41(3):547-572, 2010.

[3] Lund, R. T. and Hauser, W. M. Remanufacturing - an american perspective. In Responsive Manufacturing - Green Manufacturing (ICRM 2010), 5th International Conference on, pages 1 -6, jan. 2010.

[4] Bayus, B. L. The consumer durable replacement buyer. Journal of Marketing, 55(1):pp.42-51, 1991.

[5] Winer, R. S. Discounting and its impact on durables buying decisions. Marketing Letters, 8:109-118, 1997.

[6] Novemsky, N. and Kahneman, D. The boundaries of loss aversion. Journal of Marketing Research, 42:119-128, 2005.

[7] Fleischmann, M., Bloemhof-Ruwaard, J. M., Dekker, R., van derLaan, E., vanNunen, J. A.,and Wassenhove, L. N. V. Quantitative models for reverse logistics: A review. European Journal of Operational Research, 103(1):1 - 17, 1997.

[8] Guide, V. D. R. and Van Wassenhove, L. N. Business Aspects of Closed-Loop Supply Chains. Carnegie Mellon University Press, Pittsburgh, 2003.

[9] Atasu, A., Guide, V. D. R., and Van Wassenhove, L. N. Product reuse economics in closed-loop supply chain research. Production and Operations Management, 17(5):483-496, 2008.

[10] Souza, G. C. Closed-loop supply chains with remanufacturing. INFORMS, Hanover, MD, 2008.

[11] Guide, V. D. R. and Van Wassenhove, L. N. Or forum-the evolution of closed-loop supply chain research. Operations Research, 57(1):10-18, 2009.

[12] Guide, V. D. R. and Jayaraman, V. Product acquisition management: Current industry practice and a proposed framework. International Journal of Production Research, 38(16):3779-3800, 2000.

[13] Guide, V. D. R., Teunter, R. H., and Van Wassenhove, L. N. Matching demand and supply to maximize products from remanufacturing. Manufacturing & Service Operations Management, 5(4):303-316, 2003.

[14] Savaskan, R. C., Bhattacharya, S., and Van Wassenhove, L. N. Closed-loop supply chain models with product remanufacturing. Management Science, 50(2):239-252, 2004.

[15] Zhou, S. X. and Yu, Y. Optimal product acquisition, pricing, and inventory management for systems with remanufacturing. Operations Research, 59:514-521, 2011.

[16] Debo, L. G., Toktay, L. B., and Wassenhove, L. N. V. Joint life-cycle dynamics of new and remanufactured products. Production and Operations Management, 15(4):498-513, 2006.

[17] Atasu, A., Sarvary, M., and Wassenhove, L. N. V. Remanufacturing as a marketing strategy. Management Science, 54:1731-1746, 2008.

[18] Li, K. J., Fong, D. K. H., and Xu, S. H. Managing trade-in programs based on product characteristics and customer heterogeneity in business-to-business markets. Manufacturing & Service Operations Management, 13(1):108-123, 2011.

[19] Ray, S., Boyaci, T., and Aras, N. Optimal prices and trade-in rebates for durable, remanufacturable products. Manufacturing & Service Operations Management, 7(3):208-228, 2005.

[20] Yano, C. A. and Lee, H. L. Lot sizing with random yields: A review. Operations Research, 43(2):311-334, 1995.

[21] Hsu, A. and Bassok, Y. Random yield and random demand in a production system with downward substitution. Operations Research, 47(2):277-290, 1999.

[22] Bollapragada, S. and Morton, T. E. Myopic heuristics for the random yield problem. Operations Research, 47(5):713-722, 1999.

[23] Li, Q. and Zheng, S. Joint inventory replenishment and pricing control for systems with uncertain yield and demand. Operations Research, 54(4):696-705, 2006.

[24] Inderfurth, K. and Transchel, S. Technical note - note on "myopic heuristics for the random yield problem". Operations Research, 55(6):1183-1186, 2007.

[25] Tang, O., Musa, S. N., and Li, J. Dynamic pricing in the newsvendor problem with yield risks. International Journal of Production Economics, 139(1):127 - 134, 2012.

[26] Ferrer, G. Yield information and supplier responsiveness in remanufacturing operations. European Journal of Operational Research, 149(3):540 - 556, 2003.

[27] Zikopoulos, C. and Tagaras, G. Impact of uncertainty in the quality of returns on the profitability of a single-period refurbishing operation. European Journal of Operational Research, 182(1):205 - 225, 2007.

[28] Bakal, I. S. and Akcali, E. Eects of random yield in remanufacturing with price sensitive supply and demand. Production and Operations Management, 15(3):407-420, 2006.

[29] Mukhopadhyay, S. K. and Ma, H. Joint procurement and production decisions in remanufacturing under quality and demand uncertainty. International Journal of Production Economics, 120(1):5 - 17, 2009.

[30] Zhou, S. X., Tao, Z., and Chao, X. Optimal control of inventory systems with multiple types of remanufacturable products. Manufacturing & Service Operations Management, 13(1):20-34, 2011.

[31] Lo, S.-T., Wee, H.-M., and Huang, W.-C. An integrated production-inventory model with imperfect production processes and weibull distribution deterioration under inflation. International Journal of Production Economics, 106(1):248 - 260, 2007.

[32] Wee, H., Yu, J., and Chen, M. Optimal inventory model for items with imperfect quality and shortage backordering. Omega, 35(1):7 - 11, 2007.

[33] Kazaz, B. Production planning under yield and demand uncertainty with yield-dependent cost and price. Manufacturing & Service Operations Management, 6(3):209-224, 2004.

Module Reconfiguration Management for Circular Factories without Discriminating between Virgin and Reused Products

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Abstract

In the face of worsening environmental problems, the manufacturing industry is required to reduce environmental loads and resource consumption over product life cycles while also responding to diverse user needs and not increasing costs. In this paper, we consider a circular factory in which remanufacturing is carried out not as an auxiliary means but as an alternative to conventional manufacturing. In the circular factory, products are reconfigured using reused modules extracted from returned products and newly produced modules without discriminating between virgin and reused products. We discuss the optimal method to reconfigure modules in order to reduce costs and environmental load while satisfying various user needs. The proposed reconfiguration method is applied to copy machines to demonstrate its effectiveness.

Keywords:

Reuse; Module reconfiguration; Remanufacturing; Circular factory

1 INTRODUCTION

As the seriousness of environmental problems increases, the manufacturing industry is required to plan product life cycles such that environmental load is minimized while maintaining profitability. Remanufacturing is an effective means to exhaust potential lives of products without detracting from their performances. However, only a few instances of reuse have been effectively implemented in the current business world, although it is one of the most effective ways to prolong the potential lives of products. The main reason for this is an imbalance between supply and demand in timing and performance. Regarding the former imbalance, the timing of product return is widely distributed after the sales period. Because of this, sufficient returned products often cannot be obtained when there is a certain amount of demand. On the other hand, demand decreases when the value of the returned products reaches its peak. With regard to the imbalance in product performance, many users expect returned products to have a higher performance than that of remanufactured products. Therefore, even when the volume of returned products is sufficient, they cannot effectively be put to use. To solve the latter problem, Sakai et al. proposed the module reconfiguration method [1]. They attempted to deliver remanufactured products by reconfiguring modules extracted from returned products of different generations, which have different levels of performance, rather than delivering remanufactured products with the same configuration as the original ones. With this method, products that meet the various requirements of different users can be remanufactured by using the modules extracted from returned products. However, their proposed reconfiguration planning algorithm only addresses modules that are extracted from returned products, because the authors only consider the market of remanufactured products, which is distinct from the newly produced product market. Moreover, they did not evaluate the consumption of the physical lives of the modules and assumed that modules could be reused only once.

In this paper, we propose a module reconfiguration method to remanufacture products without discriminating between virgin and reused modules. In addition, the consumption of physical lives is evaluated to enable reuse on multiple occasions. We verify the effectiveness of the proposed method by applying it to copy machines.

We can apply this method to products with modular structures. A significant number of studies examine modular design from the perspective of life cycle design. For example, Umeda et al. proposed a method for evaluating modular design based on product life cycle scenarios [2]. G. Seliger et al. developed a software tool to find a life-cycle-oriented modularization [3].

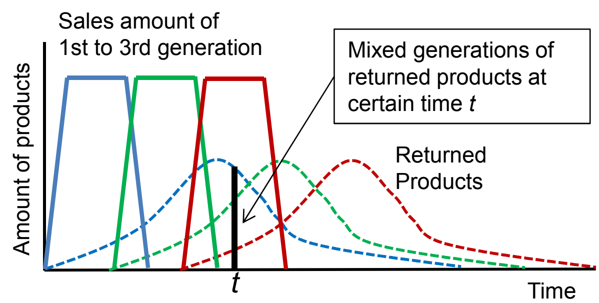

Figure 1: Change of sales and returned product volumes.

This paper is organized as follows. In section 2, we explain the concept of module reconfiguration in producing remanufactured (RM) products. We propose a reconfiguration method for RM products that uses modules extracted from returned products of different generations as well as newly produced modules in section 3. We then apply the method to copy machines to validate its effectiveness in section 4.

2 CONCEPT OF MODULE RECONFIGURATION METHOD

Considering the environmental impact and resource consumption of products, the role of manufacturing should not be to provide people with products but rather with the functions that are realized by products. In this sense, we should not discriminate between newly produced and reused products and should make use of returned products, modules, and parts as much as possible as long as they provide the required functionality. The factory of the future, which we call a circular factory, should be a kind of a pump that circulates resources. New resources are acquired only to replenish a deficiency. The circular factory performs both manufacturing and remanufacturing, but not separately, as is the current practice.

To realize effective circulation, we need to balance supply with demand. In other words, products that are remanufactured from returned products should satisfy the demands of customers in the market. However, returned products include products of multiple generations, as depicted in Figure 1, despite the differences in the sales period of each product generation, because the timing of buying new products and discarding them varies according to users. In addition, the performance of the returned products is inferior to that of products available in the current market because they are usually products from previous generations. Therefore, it is difficult to satisfy customers with products that are directly remanufactured from the returned products. To solve this problem, we propose module reconfiguration in remanufacturing.

Users evaluate the product according to several performance indices. In fact, not all users require high performance in every product performance index. The concept of module reconfiguration is based on differences in user needs. Let us consider PCs of two generations, for example. We assume that users evaluate PCs in terms of two types of performance: processing speed and storage capacity. We also assume that these types of performance correspond to the CPU and HDD functional levels. If two users have different requirements for each performance index and there are two returned products of the i-th generation and the $i-1$-th generation, as shown in Figure 2(b), we can provide the product for either user 1 or user 2, because both users are satisfied with i-th generation product only. However, if we produce RM products by reconfiguring modules in the i-th and $i-1$-th generation products, we could provide products for both users 1 and 2 as depicted in Figure 2(c). In this way, we can address various user requirements by reconfiguring modules obtained from returned products.

3 MODULE RECONFIGURATION METHOD

3.1 Reconfiguration Strategy

In this section, we explain the algorithms of module reconfiguration management. The reconfiguration plan is made at the beginning of each term. In the reconfiguration plan, we determine how to reconfigure the remanufactured products by using modules extracted from the products that were returned in the previous term as well as newly produced modules. The plan is optimized to minimize the cost and environmental load generated by each term, which we call expanded cost.

First, we select the performance indices for which each user may have different requirements and categorize users into user groups. We also identify the required performance levels of the user groups. We consider the increase of the needs of each user group for the performance of the product with the time. Secondly, we calculate realizable performance values of the RM products based on their module configuration. We assume that types of product performance are determined by the combination of the modules. Next, we identify reconfiguration patterns that can satisfy the required performance of each user group. We consider that each user group could accept the products that have equal or higher performance levels than required in every performance index. Finally, we calculate the optimal production volume of each reconfiguration pattern by using integer programming. We assume that the demand of each user group in each term is given at the beginning of the term.

3.2 Clustering Users into Groups

We represent user preferences for the types of performance of the product by the utilities obtained by conjoint analysis. We adopt pair-wise comparisons in the questionnaire. Respondents compare two products that differ in two selected performance indices. We calculate the utilities of the types of performance by applying a multi-regression analysis of the difference in utilities obtained in the questionnaire. We define these utilities as the required values of each user on each performance index. Then, we classify users through cluster analysis by categorizing users who have similar requirements in terms of the performance indices.

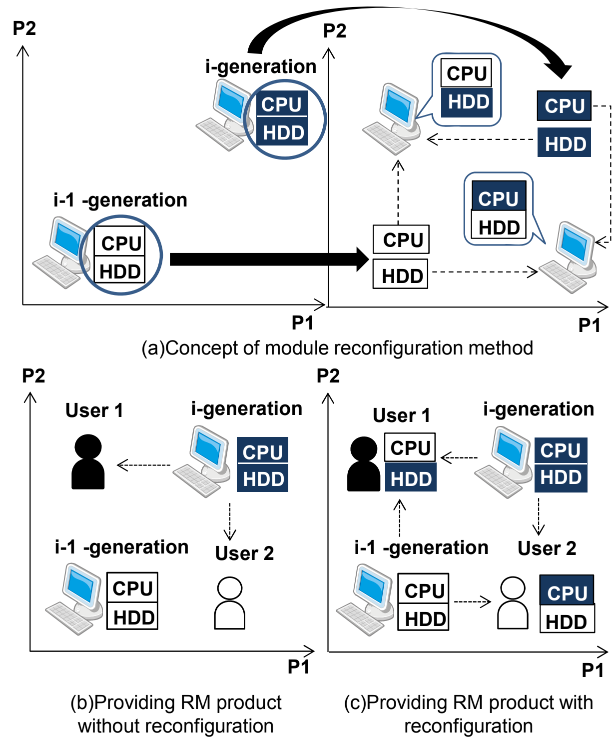

Figure 2: Concept of the reconfiguration method.

3.3 Calculation of the Realizable Performance Value of RM Products

The realizable performance values of the RM product depend on functional characteristics of its embedded modules. The functional characteristics of the modules are assumed to be represented in terms of functional values that are determined based on technical improvements when next generation products come to market. We assume that we can fully restore any physical deterioration of the modules. Usually, the relations between the functional values of modules and the realizable performance values of products are not one-to-one, unlike the case exemplified in section 2. Therefore, we use the contribution coefficient table to represent these relations. In Figure 3, for example, we assume that the product has two modules, M1 and M2, and that its performance is represented by two performance indices, P1 and P2. Each module composing the product is extracted from a product of two generations. When the product is reconfigured with the module reconfiguration pattern {M1(1st-generation), M2(2nd-generation)}, the realizable performance of the product is calculated by the sum of the product's functional values and the contribution coefficient. In the case of Figure 3, there are four patterns. The realizable performance values of each pattern are represented by Equation (1).

$$p_{jf} = \sum_i q_{ji} c_{if} \qquad (1)$$

In the equation, p_{jf}, q_{ji}, and c_{if} denote the f-th performance value of the RM product with the reconfiguration pattern j, a functional value of module i included in the reconfiguration pattern j, and the contribution coefficient between module i and performance f, respectively.

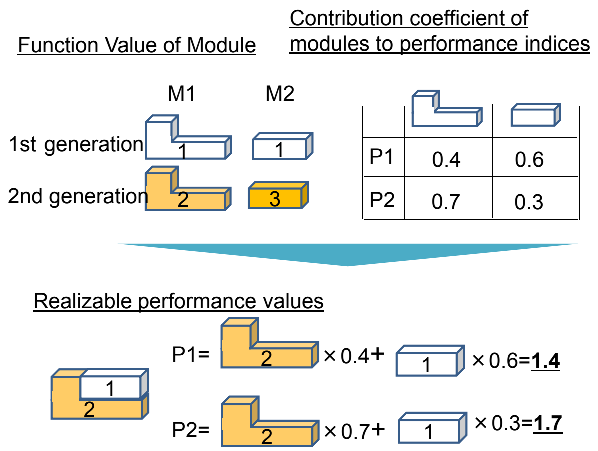

Figure 3: Example of calculation of realizable performance value.

3.4 Calculation of the Optimal Production Volume of RM Products with Each Reconfiguration Pattern

There are n^m reconfiguration patterns, where n denotes the number of product generations used for reconfiguration and m denotes the number of modules composing the product. Based on the requirements of the user groups and the realizable performance values of the reconfiguration patterns, we determine which reconfiguration pattern can satisfy the required performance of each user group. For this purpose, we relate the maximum and minimum values of required performance to those of realizable performance because these two values are calculated in different ways. In the case of the example shown in Figure 4, the realizable performance values P1 and P2 are related to the required performance values P1' and P2'. Through this procedure, we can identify the set of the reconfiguration patterns of the RM products, which can be provided to the user group g. We denote this set of reconfiguration patterns as V_g.

We try to calculate the optimal amount of RM products for each reconfiguration pattern. For this purpose, we define x_{gj} as the number of products with the reconfiguration pattern j, which can be provided to the user group g. Then, we calculate x_{gj} to minimize the expanded cost, that is the multiplication of cost and environmental load, through integer programming. The optimization is executed for each term. The expanded cost in each term are calculated by adding the expanded costs of the modules embedded in the remanufactured products with each reconfiguration pattern j, as shown in Equation (2). The module cost and environmental load are determined based on actual data.

In executing integer programming, there are two kinds of constraints. One is the limited amount of available reusable modules, which is expressed in Equation (3). The amount of reusable modules r_{oi} is determined by the number of returned products in the previous term. The other limitation is the demand of each user group, which is expressed in Equation (4). We assume that we must satisfy all user needs and that the distribution of demand of each user group is aligned with the ratio of the number of users in group g, determined by cluster analysis, d_g.

$$\min \; S = \sum_j C_j E_j \left(\sum_g x_{gj} \right) \tag{2}$$

Subject to

$$\sum_g \left(\sum_j M_{j(oi)} x_{gj} \right) \le r_{oi} \tag{3}$$

$$\sum_j x_{gj} = Q \times d_g \tag{4}$$

C_j : cost of pattern j

E_j : environmental load of pattern j

$x_{gj} \ge 0, \quad x_{gj} \in Z, \quad j \in V_g$

x_{gj} : sales amount for group g in pattern j

s_g : sales price for group g

m_{oi} : amount of module i of returned product o

$m_{oi} \in \{0,1\}$, $\sum_o m_{oi} = 1$

$M_{j(oi)}$: set of 0.1, which consist of module m_{oi} in pattern j

$M_{j(oi)} = \{m_{11} \cdots m_{oi} \cdots\}$

r_{oi} : amount of reusable module i of returned product o

r : total amount of reusable returned products in each term

Q : total amount of demand

d_g : ratio of the number of users in group g in a market

Z : integer set

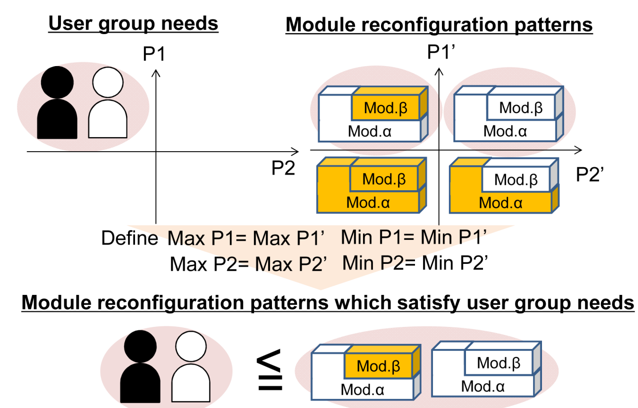

Figure 4: Groups of module reconfiguration patterns in which RM product can satisfy requirement performance of the user groups.

4 APPLICATION EXAMPLE

4.1 Case Study Scenario

We applied the proposed method to copy machines. Usually, new models of copy machines are released every two years. We considered that one platform can be shared by three consecutive models and that modules belonging to the same platform can be reconfigured. We also assumed that we can produce only the two latest consecutive models as newly produced modules, as shown in Figure 5. We set the sales amount of copy machines to 1500 units per month. The number of returned products was calculated based on the model proposed in [4]. We defined five performance indices: image quality, electricity consumption, usability, paper jam frequency, and waiting time. We identified 12 modules composing the copy machines: scanning module, image exposure module, photoconductor dram module, transfer module, fuser module, delivery module, paper-feeding module, driving module, electric equipment module, image-development module, document feeder, and frame. Based on these assumptions, we verified the effectiveness of the module reconfiguration method by using a life cycle simulation. We executed the simulation for 12 years, which correspond to the lives of two platforms, and evaluated the second 6 years of this period to exclude the transient state in the beginning of the simulation, as shown in Figure 5.

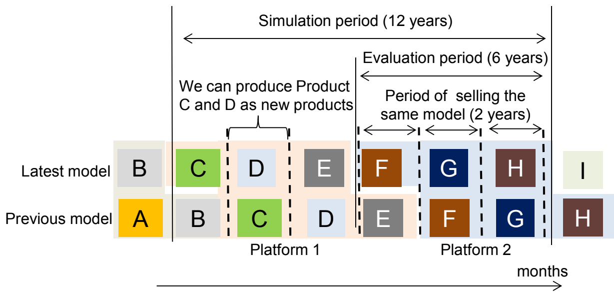

Figure 5: Assumptions for producing products.

4.2 Clustering Users into Groups

To determine the required performance levels, we used the results of the questionnaire described in [1]. In the questionnaire survey, the respondents were asked to compare two products and evaluate their preferences for these products according to five levels, as depicted in Figure 6. Conjoint analysis was applied to the results of the questionnaire survey, and the utilities of five performance indices were calculated. Based on the results, five user groups were identified through cluster analysis, as shown in Figure 7.

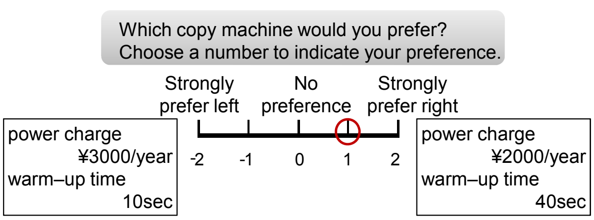

Figure 6: Example of a question.

To identify the types of performance required by the user groups, we administered a survey on the changes in the performance of mid-speed monochrome copy machines over the past six product generations. The results of the survey showed that levels of all performance indices did not always improve at the time of the change in the product generation. Therefore, we decided to divide image quality and power consumption into three levels, and the other performance indices into two levels. We adopted the upper and lower quartiles of the utility values as the thresholds to divide levels in the case of image quality and power consumption. In the case of usability and paper jam frequency, we used the lowest quartile. In the case of waiting time, we adopted the median. As a result, the ratio of the number of users in each group and the initial required levels of each performance index for each user group were determined as shown in Table 1. Here, we assumed that the product performance requirements of the user groups increase when new products go into market. If the user group's initial required level of a specific type of performance is 1, the increment of requirement is set to 0, because users are regarded to be unconcerned about the performance; if the initial level of required performance is 2, the initial required level increases by 0.5; finally, if the level of required performance is 3, the required level increases by 1 when a new product goes into the market.

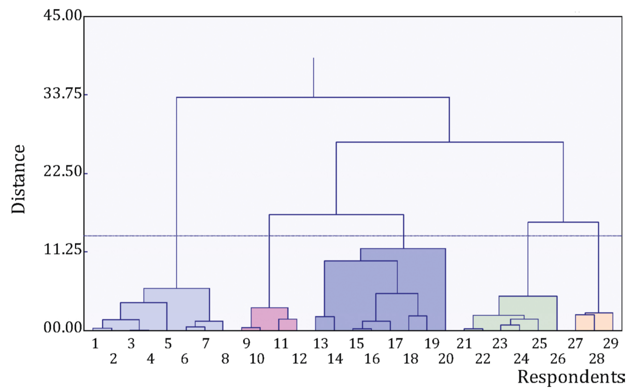

Figure 7: Result of cluster analysis.

4.3 Calculation of Realizable Performance Value of RM Products

In order to calculate the realizable performance of RM products, we estimated the functional values of modules q_{jf} and the contribution coefficient c_{jf} as follows. We investigated the improvement rate of each module by referring to the technical report of a copy machine's company and determined the functional values of the modules in each product generation.

With regard to the contribution coefficient, we adopted the one proposed by Watanabe and Takata [5], with modifications according to experts in copy machine manufacturing. The contribution coefficient table used in this study is shown in Table 2.

4.4 Setting to Optimize the Reconfiguration Plan

To relate the maximum and minimum realizable performance values to the required performance values, we compared the range of required performance values and the realizable performance values that could be obtained by reconfiguring the module extracted from products.

Next, we set the cost and environmental load of module manufacturing and remanufacturing. We assumed that every module has the same price because we could not obtain price data for each module. To reflect the differences of the functional values of the modules from the prices, however, the cost of the *i–k-th* generation modules were determined in proportion to the ratio of their functional values with the functional values of the modules of the *i-th* generation. With regard to the environmental load, we determined the *i-th* generation modules by the weight ratio of a module in a product. The cost and environmental load of the remanufactured module is determined by multiplying their fixed ratio by those of the newly produced module. Then, we determine whether returned modules can be reused by the remaining lifespan of the returned module. We also assumed that we can reuse the module regardless of the amount of times it has been reused if the physical life of the module exceeds the threshold. The physical lives of copy machines are estimated based on the frequency of printing, which is logged by the machine and sent to the maintenance center. The physical life of

Ratio of users	Image quality	Electricity consuming	Usability	Paper jam frequency	Waiting time
Group 1 (28%)	2	2	1	3	3
Group 2 (14%)	3	2	1	1	3
Group 3 (28%)	2	2	3	1	1
Group 4 (20%)	2	2	1	1	1
Group 5 (10%)	2	3	1	1	1

Table 1: Result of grouping.

Module	Image quality	Electricity consuming	Usability	Paper jam frequency	Waiting time
Scanning module	0.08	0.01	0.00	0.00	0.00
Image exposure module	0.08	0.06	0.00	0.00	0.00
Photoconductor dram	0.22	0.00	0.00	0.09	0.00
Transfer module	0.13	0.00	0.00	0.09	0.00
Image-development module	0.13	0.11	0.00	0.11	0.83
Delivery module	0.08	0.49	0.00	0.15	0.00
Fuser module	0.00	0.00	0.00	0.03	0.00
Paper-feeding module	0.00	0.08	0.00	0.10	0.00
Driving module	0.00	0.02	0.00	0.00	0.17
Electric equipment module	0.29	0.23	0.78	0.30	0.00
Document feeder	0.00	0.00	0.22	0.06	0.00
Frame	0.00	0.00	0.00	0.06	0.00

Table 2: Contribution coefficient.

Original Product	Image quality	Electricity consuming	Usability	Paper jam frequency	Waiting time
Product A	1	1	1	1	1
Product B	2	2	1	1	3
Product C	3	3	3	3	3
Product D	4	4	3	3	5
Product E	5	5	5	5	5
Product F	6	6	6	6	6
Product G	7	7	6	6	8
Product H	8	8	8	8	8

Table 3: Realizable performance level of products.

the modules and the distribution of users in terms of copy machine usage are determined on the basis of actual data.

We used Xpress to execute integer programming to calculate the optimal cost and environmental load.

4.5 Result and Discussion

The results of three cases are compared as follows: (case 1) satisfies demand using only newly produced products, (case 2) satisfies demand using reconditioned products without reconfiguration as well as newly produced products, and (case 3 - the proposed method) satisfies demand using products that have been reconfigured using returned products as well as newly produced modules. In cases 1 and 2, the realizable performance levels of the RM products without reconfiguration are shown in Table 3. We identified a 23% improvement in the accumulated values of the evaluation index in case 3 relative to case 2. This result comprises a 17% improvement in cost and a 10% improvement in environmental load during the evaluation period of 6 years in case 3 relative to case 2. Figure 8 shows the simulation results, in which the changes in the evaluation index, that is, the product's monthly cost and environmental load, are indicated for cases 1, 2, and 3. The stepwise reductions in the index values at the 96th and 120th months are caused by a reduction in the environmental load of the new models. We can see that there are few differences in the index values between cases 2 and 3 in the period from the 72nd to 96th month because, according to the required and realizable performance levels shown in Tables 1 and 3, the products with the 1st platform cannot satisfy users, except for those in group 4, in this term. Other user groups are satisfied only with product F, which uses the 2nd platform. Therefore, there is no room for module reconfiguration to provide RM products to the user groups, except for group 4. This is why module reconfiguration has little effect in the period from the 72nd to 96th month. However, the differences in the values of the evaluation index increase with time after the 96th month. This tendency is aligned with the increase in the ratio of the reused modules in the RM products, as shown in Figure 9. In case 2, some of the reused products are no longer able to satisfy users because their requirements increase with the release of new models. However, such situations could be avoided in case 3 because the proposed method allows for the reuse of modules that are extracted from previous models.

Figure 10 shows the changes in the ratio of the reused modules in the RM products with the 2nd platform, which are the modules extracted from Products F, G, and H. It shows that the 1st generation product (in this case, product F, depicted in Figure 5) significantly contributes to the amount of reused modules used in the RM products. Therefore, it is important to improve the functional values of the modules in the 1st generation products with each platform as much as possible to make efficient use of the reused modules.

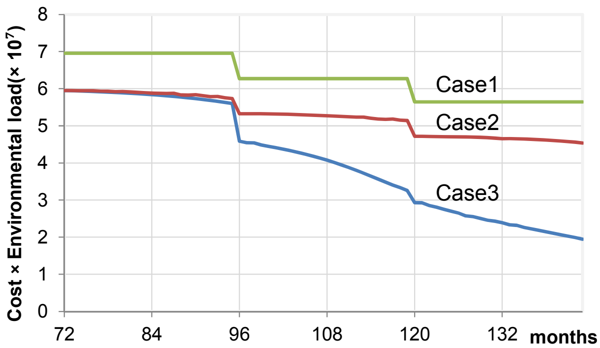

Figure 8: Result of lifecycle simulation.

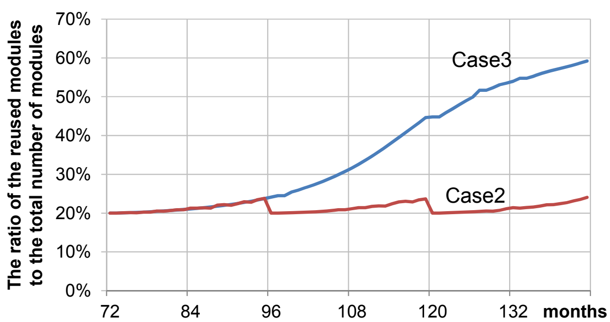

Figure 9: Ratio of reused modules to the total number of modules. (Calculated from the amount of products A to H).

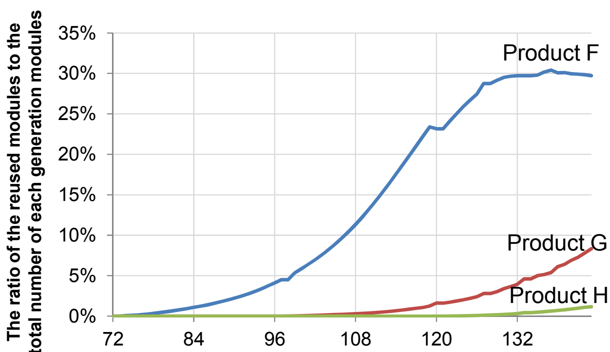

Figure 10: The ratio of reused modules to the total number of modules. (Products F, G and H).

We also simulated a case in which demand is met by the reconfigured products using only returned modules and newly produced products (case 4). Figure 11 shows the result of the simulation. The lines indicate the changes in the evaluation index and the bars represent the ratio of the reused modules to the total number of modules that are used in all products delivered to users in each month. We identified an 18% improvement in the accumulated values of the evaluation index in case 3 relative to case 4. This result comprises a 10% improvement in cost and an 8% improvement in environmental load. The figure shows that the value of the evaluation index increases in the 120th month in case 4. This is because the products that include some of the 1st generation modules become unable to satisfy user requirements due to the model change; subsequently, the ratio of the reused modules declines, as shown by the dotted lines in the bar chart. These results prove the effectiveness of the reconfiguration method without discriminating between virgin and reused products.

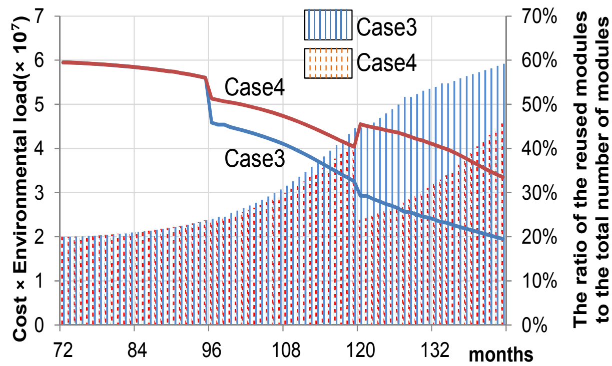

Figure 11: The result of lifecycle simulation and the ratio of the reused modules to the total number of modules.

5 CONCLUSION

In this study, we have proposed the concept of RM products that are reconfigured using reused modules extracted from returned products as well as newly produced modules. We also developed a method to generate a reconfiguration plan that minimizes the cost and environmental load of remanufacturing the products. The advantage of reconfiguration is derived from the fact that users have different requirements for individual types of performance, which can be addressed by RM products consisting of modules with various functional values. In our method, manufacturing and remanufacturing are not separated, as in previous studies. All demand is met by the products that are reconfigured using both reused and virgin modules. The optimal reconfiguration plan can be obtained through integer programming. We applied the method to copy machines, and the results showed that the method can improve both cost and environmental load.

6 REFERENCES

[1] T. Sakai, S. Takata, 2012, Reconfiguration Management of Remanufactured Products for Responding to Varied User Needs. CIRP Annals - Manufacturing Technology 61(1), 21–26.

[2] Y. Umeda, S. Fukushige, K. Tonoike, 2009, Evaluation of Scenario-based Modularization for Lifecycle Design. CIRP Annals - Manufacturing Technologies 58(1), 1–4.

[3] Seliger G, Zettl M, 2008, Modularization as an Enabler for Cycle Economy. CIRP Annals - Manufacturing Technology 57(1),133–136.

[4] S. Takata, M. Watanabe, Y. Ohbayashi, 2006, Collection Rate Estimation Model in Closed-Loop Manufacturing, in: Proc. of 13th CIRP-LCE, Vol. 2, pp. 601–605.

[5] Watanabe M, Takata S, 2005, Module-Based Model Change Planning in Consideration of Environmental Impact and Customer Satisfaction, Proc. of EcoDesign 1C-2-1F.

Production Planning and Inventory Control of a Two-Product Recovery System

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Abstract

Increasing attention has been paid to production and inventory management of the product recovery system where demand is satisfied through either manufacturing brand-new products or remanufacturing returns into new ones. In this work, we investigate a recovery system with two products and two respective return flows. A periodic review inventory problem is addressed on the two-product recovery system with stochastic demands and returns over a finite horizon and an approximate dynamic programming approach is proposed to obtain production and recovery decisions for both single-period and multi-period problem. The optimal solutions are represented by a multi-level threshold policy.

Keywords:

Two-product Recovery System; Threshold Policy; Approximate Dynamic Programming; Infinitesimal Perturbation Analysis

1 INTRODUCTION

In recent years, product recovery has emerged as an important field of reverse logistics and supply chain management with increasing attention on the management of return flows in parallel with conventional manufacturing process. Returns of used products complicate the product recovery systems compared with traditional inventory systems since there are two options to fulfill customer demands: manufacturing brand-new products by normal production, and remanufacturing returned items into new ones by recovery. Thus, production planning and inventory management become an issue to the manufacturers as they need to coordinate between these two options in order to optimize the performance of system. Besides, both returns and demands are usually uncertain in practice. Presence of uncertain returns introduces additional stochastic impact to the system. Furthermore, the situation is even more complicated when the number of product types increases since there will be more sources of uncertainty involved.

Our work draws on and contributes to the primary stream of literature that is the management of production and inventory of product recovery systems. Production planning and inventory control of product recovery systems has been attracting growing research efforts and many articles have been published to explore the structure of the optimal policy or propose well-designed heuristic approach to draw near-optimal solutions([1],[2]). Inderfurth et al.[3] presents a periodic review model for product recovery in a system with returns of a single product and multiple alternating reuse options. Kleber et al.[4] propose a continuous model of a recovery system with multiple recovery options, each of which corresponds to different demand classes. Huang et al.[5] model the setting as multi-period inventory system and derive the optimal base-stock ordering policy.

In this work we investigate a two-product recovery system in which two types of products are demanded and two return flows are involved. Returns can be remanufactured into new products and used to satisfy two respective demand flows in parallel with normal production over a finite horizon. Our proposed periodic review inventory model is to determine the production quantities of each manufacturing/remanufacturing channel and the inventory policy for the system under uncertainties of returns and demands. Existence of two return flows with respect to two products makes our problem much different from most of other production and inventory management problems since we now need to jointly determine how to choose the manufacturing/remanufacturing option and how many units of products to make by each option under the cost structure and demand information. It also complicates the problem as there are more than one demand flows. Priority of each flow needs to be set to help decide how to properly allocate production resources between them and achieve trade-off between production costs and holding costs.

A dynamic programming model with the aim to maximize the expected total profit is developed to obtain the optimal production and inventory decisions. Since the last period of multi-period problem actually forms a single period problem, it's natural to investigate the single-period problem first. We prove the concavity of the single-period model and obtain global optimum by solving Karush-Kuhn-Tucker(KKT) conditions. The optimal solution contains 21 cases totally which is further analyzed and represented by a multi-level threshold policy. Although this threshold policy is not necessarily optimal for the multi-period problem, it is instructive and easy to extend. An approximate dynamic programming approach is then proposed for multi-period problem and we show through approximation, the threshold levels of each period only depend on the gradients of the cost-to-go function at points of interest so as to free us from assuming any explicit form for the cost-to-go function. The gradients are estimated by an Infinitesimal Perturbation Analysis(IPA) based method and a backward induction approach is then conducted from the last second period to the first period to sequentially derive the threshold policy of each period.

2 A DYNAMIC PROGRAMMING MODEL

2.1 Problem Description

Two products, which belong to the same product family, are provided to customers by a manufacturer. In the meantime, the manufacturer is required to take responsibility of dealing with returned products. Returned products can be remanufactured into news ones, which are as good as those from normal production. A two-product recovery system is established, in which both recovery and normal production are used to make new products for two stochastic demand flows following independent stationary general distributions. As the two products belong to the same family, returns of each product can be recovered to either of the two products and one unit of returns is recovered to one unit of new product. Returns regardless of their types are then divided into two groups according to the recovery costs so that returns of the same group are remanufactured at the same recovery cost. In addition, normal production is more costly than recovery such that normal production is only used when returns for recovery are insufficient and the capacity for normal production is unlimited.

A simplified operation flow of a manufacturer over a finite horizon is described as follows. Returns arrive at the system at the beginning of each period. After observing on-hand inventory, the manufacturer makes recovery and production decisions. Inventory gets replenished instantly and is used to satisfy demand later in the same period. If demand cannot be fully satisfied, unsatisfied demand will be lost forever and penalty cost on the shortage is incurred. Otherwise, remaining inventory will be carried to subsequent periods and holding cost will be counted. At the end of each period, unused returns are disposed of and disposal cost is negligible. Revenue of the system is generated by selling new products and the total cost consists of production cost, recovery cost, holding cost and penalty cost. The manufacturer needs to make the optimal policy of production and recovery decisions at each period.

The two products are denoted as product 1 and product 2 respectively and returns of the two groups are denoted as group 1 and group 2. Without loss of generality, returns of group 2 are recovered at lower cost than those of group 1. We use the index $i \in \{1,2\}$ and $j \in \{1,2\}$ to distinguish between two groups of returns and two types of products respectively, and the index $t \in \{1, \dots, T\}$ to distinguish among T planning periods. Parameters and decision variables are specified in Table 1. Demands are uncertain and denoted as $D_1$and D_2 respectively. No stocking of returns is allowed and the unused ones will be disposed of.

Parameters:
I_{jt}: initial inventory of product j at period t;
s_j: selling price of product j;
rc_{ij}: recovery cost of one unit of returns in group i to produce j;
pc_j: production cost for one unit of product j;
h_j: holding cost for one unit of product j;
v_j: penalty cost of one unit of shortage on product j;
R_{it}: return of group i at period t;
$\{R_{it}\}$: set of returned items in group i at period t;
D_{jt}: demand for product j at period t;
μ_{jt}: the mean of demand for product j at period t;
$f_{it}(.)$,$F_{it}(.)$: pdf and cdf of the distribution of D_{jt};
$F_{it}^{-1}(.)$: reverse function of $F_{it}(.)$;
Decision variables:
p_{jt}: production amount of product j at period t;
r_{ijt}: amount of returns in $\{R_{it}\}$ recovered to product j at period t.

Table 1: Parameters and decision variables.

In addition, some restrictions on cost parameters are imposed to ensure the economic meaningfulness of our study. First, for each product, selling price is higher than production cost, and penalty cost is higher than the profit from normal production: $s_1 > pc_1, s_2 > pc_2, v_1 > s_1 - pc_1, v_2 > s_2 - pc_2$; Production cost is higher than recovery cost, otherwise recovery is unnecessary: $pc_1 > rc_{11}, pc_1 > rc_{21}, pc_2 > rc_{12}, pc_2 > rc_{22}$. Besides, without loss of generality, the recovery using returns of R_2 is assumed to be cheaper than using returns of R_1 : $rc_{21} < rc_{11}, rc_{22} < rc_{12}$. Therefore, to fulfill the demand, group 2 always has the highest priority to be selected to make products. Group 1 takes the second place and normal production is used only when returns in group 1 and 2 are used up.

2.2 Model Formulation

A dynamic programming model of the two-product recovery system is developed with the aim to maximize the expected profit over the finite horizon. In practice, once production and recovery decisions have been made, inventory of products gets replenished instantly and is used to satisfy the realization of stochastic demands later in the same period. We define I'_{1t} and I'_{2t} as the inventory level after replenishment at period t and thus we have: $I'_{1t} = I_{1t} + p_{1t} + r_{11t} + r_{21t}$, $I'_{2t} = I_{2t} + p_{2t} + r_{12t} + r_{22t}$. Therefore, the expected revenue of period t(denoted asER_t) is formulated as follows:

$$ER_t = s_1\mu_{1t} + s_2\mu_{2t} - s_1\int_{I'_{1t}}^{+\infty}(D_{1t} - I'_{1t})f_{1t}(.)dD_{1t} - s_2\int_{I'_{2t}}^{+\infty}(D_{2t} - I'_{2t})f_{2t}(.)dD_{2t}$$

The total cost includes production cost, recovery cost, holding cost and penalty cost of shortage. Therefore, the expected total cost of period t is formulated as follows:

$$EC_t = pc_1p_{1t} + pc_2p_{2t} + rc_{11}r_{11t} + rc_{12}r_{12t} + rc_{21}r_{21t} + rc_{22}r_{22t} + h_1\int_0^{I'_{1t}}(I'_{1t} - D_{1t})f_{1t}(.)dD_{1t} + v_1\int_{I'_{1t}}^{+\infty}(D_{1t} - I'_{1t})f_{1t}(.)dD_{1t} + h_2\int_0^{I'_{2t}}(I'_{2t} - D_{2t})f_{2t}(.)dD_{2t} + v_2\int_{I'_{2t}}^{+\infty}(D_{2t} - I'_{2t})f_{2t}(.)dD_{2t}$$

We define EP_t as the expected profit of period t. It can be expressed as follows:

$$EP_t = ER_t - EC_t. \tag{1}$$

The optimal cost-to-go function from period t till final period is denoted as $Q_t(I_{1t}, I_{2t})$. For the multi-period problem, the Bellman's equation of dynamic programming model can be written as:

$$Q_t(I_{1t}, I_{2t}) = \max EP_t + E[Q_{t+1}(I_{1,t+1}, I_{2,t+1})]$$

Consumption of the returns of the two groups is no more than availability. So, $r_{11t} + r_{12t} \le R_{1t}, r_{21t} + r_{22t} \le R_{2t}$.

It is intractable to solve dynamic programming problem involving more than two states due to the curse of dimensionality. In the following, we will first investigate the single period problem as a starting point and then apply the properties found to solve the multi-period dynamic programming model.

3 RECOVERY SYSTEM IN A SINGLE PERIOD

3.1 Solving the Single Period Problem

By dropping the t in (1), the model formulation for the single period problem can be obtained. Plus, by taking the second-order partial derivative of objective function, we can easily show the objective function of the model is jointly concave on all the decision variables for the single-period two-product recovery system disregarding salvage value of the unused returned products. The method of Lagrange Multipliers is then applied to find the maximum of the model. The Lagrangian function (denoted as L) is expressed:

$$\begin{aligned} L(p_1, p_2, r_{11}, r_{12}, r_{21}, r_{22}, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \lambda_7, \lambda_8) &= EP + \lambda_1(r_{11} + r_{12} - R_1) + \lambda_2(r_{21} + r_{22} - R_2) \\ &\quad - \lambda_3 p_1 - \lambda_4 p_2 - \lambda_5 r_{11} - \lambda_6 r_{12} - \lambda_7 r_{21} - \lambda_8 \lambda_{22} \end{aligned}$$

In order to obtain the optimal solution, we need to consider the KKT conditions. Since the objective function and constraints are concave, the solution to KKT conditions is also the global maximum of the model.

The values of decision variables are dependent on the availability of each resource, initial inventory position and cost structure. Under a certain cost structure, optimal solution of the model usually contains a number of cases given different inventories and returns. After analyzing the cases of optimal solution, we realize they can be represented by an optimal multi-level threshold policy which is characterized by a set of threshold levels. Therefore, we can employ these threshold levels to help make optimal decisions once they are determined. In the following, we will explain how to determine the multi-level threshold policy and make optimal decisions with its help.

3.2 Multi-level Threshold Policy

There exist three channels to make a product, i.e. normal production, recovery from returns of R_1 or R_2. To fulfill the demand and maximize the expected profit, we need to decide when to choose each channel and how many units of each product to make by each channel. In other words, recovery from returns provides alternative options to make products in product recovery system. Resource of each channel needs to be sequentially allocated between two products according to the cost structure.

As different cost structures usually result in different forms of production and recovery decisions, we choose one structure for example to illustrate. For other cost structures, the process of modeling and solving can easily refer to it. Note that, we have already made assumptions in Chapter 2 which indicate among the three channels, the sequence of being selected for replenishment is recovery from R_2 , recovery from R_1 and normal production. Besides, to simplify the illustration, we further impose some restrictions:

$$pc_1 - rc_{11} > pc_2 - rc_{12}, pc_1 - rc_{21} > pc_2 - rc_{22},$$
$$rc_{11} - rc_{21} > rc_{12} - rc_{22}$$

For instance, the first inequality above indicates replenishment for one unit of product 1 from R_1 instead of normal production brings more cost saving than replenishment for one unit of product 2 from R_1 instead of normal production. Therefore, the three inequalities tell us if returns of R_2 or R_1 are not enough, the manufacturer will allocate them to product 1 first rather than product 2.

At the beginning of the period, information about initial inventories and the availability of each channel is known. Each resource is then sequentially allocated between two products until corresponding resource is used up or the amount of the product reaches a certain threshold level, beyond which any further replenishment is not economically worthwhile any longer(i.e. order-up-to level) or replenishment for the other product becomes more profitable(i.e. switching level) so that the replenishment should switch. These threshold levels are employed to control the process of resource allocation. Under the given cost structure, optimal solution has 21 cases in total based on the different combinations of initial inventories and amount of returns.

Among these threshold levels, there are three order-up-to levels for each product corresponding to three different resources. The order-up-to level is the highest inventory level when the product is replenished by a certain resource. It means any further replenishment after the order-up-to level is not profitable and the replenishment should stop. These order-up-to levels can be obtained by solving the related KKT conditions as follows

- Order-up-to level by production

For each product, the order-up-to level by production is defined as the maximum inventory level by the channel of normal production. At this order-up-to level, the marginal profit of further replenishment is equal to zero. Let AL_0 and BL_0 denote the order-up-to levels by production for product 1 and 2 respectively. We have:

$$\frac{\partial EP}{\partial p_1^*}|_{I'^*_1=AL_0} - \lambda_3 = 0, \lambda_3 p_1^* = 0, p_1^* > 0 \Rightarrow AL_0 = F_1^{-1}(\frac{s_1 + v_1 - pc_1}{s_1 + v_1 + h_1})$$

Similarly, for product 2, the order-up-to level by production can be determined as: $BL_0 = F_2^{-1}(\frac{s_2+v_2-pc_2}{s_2+v_2+h_2})$.

- Order-up-to level by group 1

For each product, the order-up-to level by group 1 is defined as the maximum inventory level by replenishment using returns of R_1. If they are enough for the recovery of two products, their inventories will be replenished until the order-up-to levels(AL_1 and BL_1), at which the marginal profits of further replenishment are equal to zero. Order-up-to levels of the two products can be determined as:

$$\frac{\partial EP}{\partial r_{11}^*}|_{I'^*_1=AL_1} = \frac{\partial EP}{\partial r_{12}^*}|_{I'^*_2=BL_1} = 0$$
$$\Rightarrow AL_1 = F_1^{-1}\left(\frac{s_1 + v_1 - rc_{11}}{s_1 + v_1 + h_1}\right), BL_1 = F_2^{-1}\left(\frac{s_2 + v_2 - rc_{12}}{s_2 + v_2 + h_2}\right)$$

- Order-up-to level by group 2

Similarly, Order-up-to levels of the two products by group 2(AL_2 and BL_2) can be determined as:

$$\frac{\partial EP}{\partial r_{11}^*}|_{I'^*_1=AL_1} = \frac{\partial EP}{\partial r_{12}^*}|_{I'^*_2=BL_1} = 0$$
$$\Rightarrow AL_2 = F_1^{-1}\left(\frac{s_1 + v_1 - rc_{21}}{s_1 + v_1 + h_1}\right), BL_2 = F_2^{-1}\left(\frac{s_2 + v_2 - rc_{22}}{s_2 + v_2 + h_2}\right)$$

If there is only one resource available, the above order-up-to level is the highest level which the resource can replenish the inventory of a product to. Since R_2 is the cheapest resource, R_1 is the second and normal production is more expensive than recovery, we have: $AL_2 > AL_1 > AL_0, BL_2 > BL_1 > BL_0$.

The replenishment procedure first chooses R_2 to make products. If the returns of R_2 are enough to replenish product 1 and 2 to more than AL_1 and BL_1, recovery from R_1 and normal production will be unnecessary because replenishment by these two channels is not profitable. If the inventory levels of the products by recovery from R_2 are between AL_0 (BL_0) and AL_1 (BL_1) after R_2 is used up, R_1 will be used since the inventory levels haven't reached its order-up-to levels and normal production is avoided. If the inventory levels are still lower than AL_0 and BL_0 after R_2 and R_1 is used up, normal production will be needed to replenish the inventories.

Since two products are considered, if a certain channel is not able to replenish the inventories of both two products to their order-up-to levels, they will compete for the resource. Therefore, besides order-up-to levels, three switching levels, denoted as SW_1, SW_2 and RP, are used to control the allocation of possibly limited resource between the two products. Allocation of a limited resource involves the comparison of marginal profits with respect to each channel. Returns of R_2 or R_1 will be assigned to the product with higher marginal profit which means replenishment for this product is more profitable than the other under current situation. Thus, the inventory of the product with higher marginal profit increases and its marginal profit is decreasing at the same time. On the other hand, the inventory of the other product remains unchanged. Process continues until the two products have equal marginal profits. This is when the recovery process switches from one product to the other since the marginal profit of the product is not higher than the other any more. After this, recovery process allocates the resource between two products simultaneously and maintains the equality of two marginal profits until the resource is used up or the inventories reach their corresponding order-up-to levels. Such kind of allocation policy is defined as fair allocation rule, which aims to balance the marginal profits of the two products while being replenished by a recovery channel. The introduction of the switching levels helps determine at which point recovery switches from one product to the other and process of fair allocation begins.

In the following, we will illustrate how to determine the switching levels in detail by using the 'replacement' concept. Suppose initial inventories of product 1 and 2 are below AL_0 and BL_0 and normal production is the only channel. Due to unlimited production capacity, product 1 and 2 can be replenished to AL_0 and BL_0. When the two recovery resources become available, they will be sequentially used to replace the products which are originally made by normal production. Since the recovery cost of R_2 is lower than R_1, R_2 will be used first. Details of these switching levels are further explained as follows (We advice you to read the SW_2 part first):

- Switching level SW_1

The switching level SW_1 is the inventory level of product 1 which corresponds to the inventory level BL_0 of product 2. It denotes the inventory level of product 1, at which recovery process from group 1 switches from product 1 to product 2.

When recovery resources are available and R_2 is not able to replenish the inventory level of product 1 to a certain level, i.e. SW_1, R_1 will be used. If there are still new items of product 1 by normal production left, R_1 will be used to replace them first. During this replacement process, the recovery amount of product 1 from R_1, i.e. r_{11} is increasing and the amount by normal production, i.e. p_1 decreases. In other words, a portion of the new items originally completed by normal production is now made by R_1 instead. Before the new items by normal production are all replaced, its inventory, i.e. I_1' remains unchanged. Therefore, the marginal profit with respect to r_{11} does not change and we have: $\frac{\partial EP}{\partial r_{11}}|_{I_1'=AL_0} = pc_1 - rc_{11}$. On the other hand, the inventory of product 2 stays unchanged too and the marginal profit with respect to rc_{12} at BL_0 is equal to $pc_2 - rc_{12}$. We have: $\frac{\partial EP}{\partial r_{11}}|_{I_1'=AL_0} > \frac{\partial EP}{\partial r_{12}}|_{I_2'=BL_0}$. Therefore, if R_1 is enough to replace all new items of product 1, replenishment process will continue to make product 1. r_{11} and I_1' increase at the same time. $\frac{\partial EP}{\partial r_{11}}|_{I_1'}$ decreases and the process continues until I_1' reaches SW_1, at which $\frac{\partial EP}{\partial r_{11}}|_{I_1'=SW_1}$ is equal to $\frac{\partial EP}{\partial r_{12}}|_{I_2'=BL_0}$. After that, the process will switch to replenish product 2 to replace the new items originally made by normal production. During this process, r_{12} is increasing and p_2 decreases. I_2' remains unchanged and $\frac{\partial EP}{\partial r_{12}}|_{I_2'}$ does not change. If there are still items of R_1 left after all new items of product 2 by normal production are replaced, the remaining R_1 will be allocated between two products simultaneously following the fair allocation rule.

Therefore, when the inventory levels of product 1 and 2 are at SW_1 and BL_0 respectively, the two products have equal marginal profits with respect to the recovery amount from R_1. Thus, we have:

$$\frac{\partial EP}{\partial r_{11}^*}|_{I'^*_1=SW_1} = \frac{\partial EP}{\partial r_{12}^*}|_{I'^*_2=BL_0} = pc_2 - rc_{12}$$
$$\Rightarrow SW_1 = F_1^{-1}\left(\frac{s_1 + v_1 + rc_{12} - rc_{11} - pc_2}{s_1 + v_1 + h_1}\right)$$

- Switching level SW_2

The switching level SW_2 is the inventory level of product 1 which corresponds to the inventory level BL_0 of product 2. It denotes the inventory level of product 1, at which recovery process from group 2 switches from product 1 to product 2.

When recovery resources are available, R_2 will be used to replace the new items of product 1 by normal production first. During this replacement process, the recovery amount of product 1 from R_2, i.e. r_{21} is increasing and the amount by normal production, i.e. p_1 decreases. In other words, a portion of the new items originally completed by normal production is now made by R_2 instead. Before the new items by normal production are all replaced, its inventory i.e. I_1' remains unchanged. Therefore, the marginal profit with respect to r_{21} does not change and we have: $\frac{\partial EP}{\partial r_{21}}|_{I_1'=AL_0} = pc_1 - rc_{21}$. On the other hand, the inventory of product 2, i.e. I_2' stays unchanged too and the marginal profit with respect to r_{22} at BL_0 is $pc_2 - rc_{22}$. We have: $\frac{\partial EP}{\partial r_{21}}|_{I_1'=AL_0} > \frac{\partial EP}{\partial r_{22}}|_{I_2'=BL_0}$. Therefore, if R_2 is enough to replace all new items of product 1, replenishment process will continue to make product 1. r_{21} and I_1' will increase at the same time. $\frac{\partial EP}{\partial r_{21}}|_{I_1'}$ decreases and the process continues until I_1' reaches certain level, i.e. SW_2, at which $\frac{\partial EP}{\partial r_{21}}|_{I_1'=SW_2}$ is equal to $\frac{\partial EP}{\partial r_{22}}|_{I_2'=BL_0}$. After that, the process will switch to replenish product 2 to replace the new items originally made by normal production. During this replacement process, r_{22} is increasing and p_2 decreases. I_2' remains unchanged and $\frac{\partial EP}{\partial r_{22}}|_{I_2'}$ does not change. If there are still items of R_2 left after all new items of product 2 by normal production have been replaced, the remaining R_2 will be allocated between two products simultaneously following the fair allocation rule.

Therefore, when the inventory levels of product 1 and 2 are at SW_2 and BL_0 respectively, the two products have equal marginal profits with respect to the recovery amount from R_2. Thus, we have:

$$\frac{\partial EP}{\partial r_{21}^*}|_{I'^*_1=SW_2} = \frac{\partial EP}{\partial r_{22}^*}|_{I'^*_2=BL_0} = pc_2 - rc_{22}$$
$$\Rightarrow SW_2 = F_1^{-1}\left(\frac{s_1 + v_1 + rc_{22} - rc_{21} - pc_2}{s_1 + v_1 + h_1}\right)$$

- Switching level RP

The switching level RP is the inventory level of product 1 which corresponds to the inventory level BL_1 of product 2. It denotes the inventory level of product 1, at which recovery process from group 1 switches from product 1 to product 2.

If we have excessR_1, the inventories of product 1 and 2 will be replenished to AL_1 and BL_1 respectively. When R_2 is available, it will be used to replace the new items of product 1 from R_1 first. During this replacement process, the recovery amount of product 1 from R_2, i.e. r_{21} is increasing and the amount from R_1, i.e. r_{11} decreases. In other words, a portion of the new items originally completed by recovery from R_1 is now made by R_2 instead. Before the new items from R_1 are all replaced, its inventory, i.e. I_1' remains unchanged. Therefore, the marginal profit with respect to r_{21} does not change and we have: $\frac{\partial EP}{\partial r_{21}}|_{I_1'=AL_1} = rc_{11} - rc_{21}$. On the other hand, the inventory of product 2, i.e. I_2' stays unchanged too and the marginal profit with respect to r_{22} at BL_1 is $rc_{12} - rc_{22}$. We have: $\frac{\partial EP}{\partial r_{21}}|_{I_1'=AL_1} > \frac{\partial EP}{\partial r_{22}}|_{I_2'=BL_1}$. Therefore, if R_2 is enough to replace all new items of product 1 from R_1, replenishment process will continue to make product 1. r_{21} and I_1' will increase at the same time. $\frac{\partial EP}{\partial r_{21}}|_{I_1'}$ decreases and the process continues until I_1' reaches a certain level, i.e. RP, at which $\frac{\partial EP}{\partial r_{21}}|_{I_1'=RP}$ is equal to $\frac{\partial EP}{\partial r_{22}}|_{I_2'=BL_1}$. After that, the process will switch to replenish product 2 to replace the new items originally made from R_1. During this replacement process, r_{22} is increasing and r_{12} decreases. I_2' remains unchanged and $\frac{\partial EP}{\partial r_{22}}|_{I_2'}$ does not change. If there are still items of R_2 left after all new items of product 2 from R_2 are replaced, the remaining R_2 will be allocated between two products simultaneously by the fair allocation rule.

Therefore, when the inventory levels of product 1 and 2 are at RP and BL_1, the two products will have equal marginal profits from recovering the returns of R_2. Thus, we have:

$$\frac{\partial EP}{\partial r_{21}^*}|_{I'^*_1=RP} = \frac{\partial EP}{\partial r_{22}^*}|_{I'^*_2=BL_1} = rc_{12} - rc_{22}$$

$$\Rightarrow RP = F_1^{-1}\left(\frac{s_1 + v_1 + rc_{22} - rc_{21} - rc_{12}}{s_1 + v_1 + h_1}\right)$$

4 RECOVERY SYSTEM OVER A FINITE HORIZON

Through solving the single period problem, an optimal multi-level threshold policy has been obtained. We assume this threshold policy is also applicable to the multi-period problem. Since the last period of the multi-period problem is actually a single period problem, we can start from the last period and take advantage of the threshold levels obtained previously.

4.1 An Approximate Dynamic Programming Approach

In the multi-period two-product recovery problem, returns arrive at the beginning of each period. Production and recovery decisions are made and the inventories of products get replenished instantly. If the demands are not fully met, penalty cost of the shortages will be incurred. Otherwise, remaining inventories will be carried to future periods and holding cost will be counted. Unused returns are disposed of and disposal costs are negligible.

Recall that the Bellman's equation of dynamic programming is:

$$\boldsymbol{Q_t(I_{1t}, I_{2t}) = \max EP_t + E[Q_{t+1}(I_{1,t+1}, I_{2,t+1})]}$$

We cannot expect to solve the above cost-to-go function to optimality. However, we assume the multi-level threshold policy can also be obtained here and 9 threshold levels can be determined to help make decisions for the multi-period problem.

We take first-order partial derivative of it with respect to each decision variable. For example, to decide $\boldsymbol{p_{1t}}$, its first-order partial derivative is expressed as:

$$\frac{\boldsymbol{EP_t + E[Q_{t+1}(I_{1,t+1}, I_{2,t+1})}}{\boldsymbol{\partial p_{1t}}} = \frac{\boldsymbol{\partial EP_t}}{\boldsymbol{\partial p_{1t}}} + \frac{\boldsymbol{\partial E[Q_{t+1}(I_{1,t+1}, I_{2,t+1})}}{\boldsymbol{\partial p_{1t}}}$$

The first term can be calculated as:

$$\frac{\boldsymbol{\partial EP_t}}{\boldsymbol{\partial p_{1t}}} = \boldsymbol{-pc_1 + s_1 + v_1 - (s_1 + v_1 + h_1)F_{1t}(I'_{1t})}$$

Since there is no closed-form to explicitly express the second term, we approximate it as the gradient of inventory level at period $\boldsymbol{t}$: $\boldsymbol{u_{1t}(I'_{1t}, I'_{2t})}$. Let the approximation of partial derivative be equal to 0:

$$\frac{\boldsymbol{\partial EP_t}}{\boldsymbol{\partial p_{1t}}} + \boldsymbol{u_{1t}(I'_{1t}, I'_{2t}) = 0}$$

$$\Rightarrow \boldsymbol{s_1 + v_1 - pc_1 - (s_1 + v_1 + h_1)F_{1t}(I'_{1t}) + u_{1t}(I'_{1t}, I'_{2t})} \qquad (2)$$

By solving (2), we can obtain the inventory level of product 1 when normal production is involved. This inventory level is called order-up-to level. Denote $\boldsymbol{AL_{0t}}$ as the order-up-to level of product 1 by normal production at period $\boldsymbol{t}$, we have:

$$\boldsymbol{AL_{0t} = F_{1t}^{-1}\left(\frac{u_{1t}(I'_{1t}, I'_{2t})|_{I'_{1t}=AL_{0t}} + s_1 + v_1 - pc_1}{s_1 + v_1 + h_1}\right)}$$

Similarly, other threshold levels of period $\boldsymbol{t}$(i.e. $\boldsymbol{AL_{1t}, AL_{2t}, BL_{0t}, BL_{1t}, BL_{2t}, SW_{1t}, SW_{2t}, RP}$ can be determined in the same way.

It can be seen the threshold levels of the multi-period problem are only dependent on the gradients of the cost-to-go function at the corresponding threshold levels after approximation. Therefore, unlike usual approaches which represent the cost-to-go function by a single function (or piecewise function) across the whole state space, we only need to estimate the gradients at the points of interest. Hence, performance of the solution is not affected by the function we assume which could be a challenge for most of the approximate dynamic programming approaches.

If the cost-to-go function is separable with the inventory levels of two products, the gradient $\boldsymbol{u_{1t}}$ is independent of $\boldsymbol{I'_{2t}}$. However, it might not actually be separable. We have done some numerical experiments on a number of samples and the result shows the position of $\boldsymbol{I'_{2t}}$ does not have much impact on $\boldsymbol{u_{1t}}$. Therefore, we use the average of the gradients at the three order-up-to levels as the approximation of $\boldsymbol{u_{1t}}$ at $\boldsymbol{AL_{0t}}$. Thus, $\boldsymbol{u_{1t}}$ is estimated:

$$\boldsymbol{u_{1t}(I'_{1t}, I'_{2t})|_{I'_{1t}=AL_{0t}} \approx \frac{1}{3}\sum_{l=0}^{2} u_{1t}(I'_{1t}, I'_{2t})|_{I'_{1t}=AL_{0t}, I'_{2t}=BL_{lt}}}$$

In addition, to determine a threshold level, say $\boldsymbol{AL_{0t}}$, the gradient at $\boldsymbol{AL_{0t}}$ needs to be obtained first. However, the gradient at $\boldsymbol{AL_{0t}}$ can be computed only after $\boldsymbol{AL_{0t}}$ is decided. Therefore, an iterative algorithm is employed to search for the threshold levels, which starts with the pre-determined threshold levels of period $\boldsymbol{t+1}$.

In the beginning, $\boldsymbol{u_{1t}}$ is obtained by taking pre-determined threshold levels of period $\boldsymbol{t+1}$ as initial values, i.e. $|_{I'_{1t}=AL_{0,t+1}, I'_{2t}=BL_{l,t+1}}$. $\boldsymbol{u_{1t}}$ is then smoothed with previous value to get a weighted average gradient, which is used to calculate the corresponding threshold level. After that, the newest threshold level is also smoothed by certain rule to obtain a weighted average. The procedure is repeated until it converges. Due to the time consuming computation, the algorithm generally stops if total absolute change of the threshold level over a certain number of iterations is small. For example, if $\boldsymbol{\sum_{i=m-L+1, m>L}^{m} \left||AL_{0t}^{i} - AL_{0t}^{i-1}|\right| < \delta}$ ($\boldsymbol{L}$: the number of consecutive results used for calculating the absolute change; $\boldsymbol{d}$: a small number), algorithm will be halted.

4.2 Determination of Gradients in Multi-period Context

For the two-product recovery system over a finite horizon, the problem of determining the threshold levels for the last period, i.e. period T can be regarded as a single period problem. Therefore, we can start from period T and then take advantage of a backward induction approach to determine the threshold levels of each period from the second last period, i.e. period $T-1$ till period 1. Since the threshold levels of each period, expect period T, are actually dependent on their corresponding gradients, they can be obtained by determining the gradients at points of interest through the backward induction approach from period $T-1$ to period 1.

The threshold levels of period T are obtained by solving a single-period problem. Then, for period $T-1$, the threshold levels can be determined after the gradients of the optimal cost-to-go function, i.e. the gradients of the maximum expected profit of period T, have been estimated. Suppose we are now at period t. Up to now, the threshold levels from period $t+1$ till period T have been decided and replenishment decisions have been made. In order to determine its threshold levels, we need to estimate the gradients of the optimal cost-to-go function, i.e. the gradients of maximum expected total profit earned from period $t+1$ till period T. After that, replenishment decisions are made under the optimal policy and the approach goes to period $t-1$.

The gradients u_{jt} are estimated by Monte Carlo simulation. N sets of random realization of stochastic returns and demands in each period from t till T are generated. The value of optimal cost-to-go function of sample k is obtained by summing the profit of the realization from period $t+1$ till period $T-1$ after applying the optimal policy for these periods and the expected profit of period T. Let p_τ^{k*} be the maximum profit of period τ of sample k, which is($[X]^+ = max\{X, 0\}$):

$$P_\tau^{k*} = s_1 I'^*_{1\tau} + I'^*_{2\tau} - (h_1 + s_1)[I'^*_{1\tau} - D^k_{1\tau}]^+ - v_1[D^k_{1\tau} - I'^*_{1\tau}]^+$$
$$-(h_2 + s_2)[I'^*_{2\tau} - D^k_{2\tau}]^+ - v_2[D^k_{2\tau} - I'^*_{2\tau}]^+$$
$$-(pc_1 p^*_{1\tau} + pc_1 p^*_{1\tau} + rc_{11} r^*_{11\tau} + rc_{12} r^*_{12\tau} + rc_{21} r^*_{21\tau} + rc_{22} r^*_{22\tau})$$

where $I'^*_{1\tau} = I_{1\tau} + p^*_{1\tau} + r^*_{11\tau} + r^*_{21\tau}, I'^*_{2\tau} = I_{2\tau} + p^*_{2\tau} + r^*_{12\tau} + r^*_{22\tau}$.

Let EP_T^{k*} be the maximum expected profit of period T of sample k. Therefore, the gradient with respect to p_{1t} of sample k is:

$$grad_{1t}^k(I'_{1t}, I'_{2t}) = \sum_{j=1}^{2} \frac{\partial(\sum_{\tau=t+1}^{T-1} P_\tau^{k*} + EP_T^{k*})}{\partial I'_{jt}} \frac{\partial I'_{jt}}{\partial p_{1t}}$$

$$= \sum_{j=1}^{2} (\frac{P_{t+1}^{k*}}{\partial I'_{jt}} + \frac{\partial(\sum_{\tau=t+2}^{T-1} P_\tau^{k*} + EP_T^{k*})}{\partial I'_{jt}}) \frac{\partial I'_{jt}}{\partial p_{1t}}$$

$$= \sum_{j=1}^{2} (\frac{P_{t+1}^{k*}}{\partial I'_{jt}} + \frac{\partial I'^{*}_{1,t+1}}{\partial I'_{jt}} grad_{1,t+1}^k + \frac{\partial I'^{*}_{1,t+1}}{\partial I'_{jt}} grad_{1,t+1}^k) \frac{\partial I'_{jt}}{\partial p_{1t}}$$

Since the sample gradients $grad_{1,t+1}^k(I'_{1,t+1}, I'_{2,t+1})$ and $grad_{2,t+1}^k(I'_{1,t+1}, I'_{2,t+1})$ have been computed during the process of determining the sample gradients of period $t+1$, $grad_{1t}^k(I'_{1t}, I'_{2t})$ can be easily calculated. Through this backward induction approaches, the sample gradients at order-up-to levels of each period are obtained period by period in reverse order from period $T-1$ to period 1. The gradient u_{jt} is approximated by sample average of the gradients over all the N realizations.

As I'_{1t} and I'_{2t} are assumed to be independent of each other, the perturbation of I'_{jt} is only propagated to $I_{j,t+1}$ if there is no shortage of product j at period t. Therefore, $if\ I'_{jt} < D_{jt}^k$, we have $grad_{1t}^k(I'_{1t}, I'_{2t}) = 0$.

Partial derivatives of the optimal replenishment decisions with respect to initial inventory are involved in the calculation of $grad_{1t}^k(I'_{1t}, I'_{2t})$. Therefore, Infinite Perturbation Analysis is applied to compute the derivatives. The perturbation of the initial inventory of product j of period $t+1$ is propagated to the final inventory of product i in the same period:

$$\frac{\partial I'^{*}_{i,t+1}}{\partial I_{j,t+1}} = \frac{\partial I_{i,t+1}}{\partial I_{j,t+1}} + \frac{\partial p^{*}_{i,t+1}}{\partial I_{j,t+1}} + \frac{\partial r^{*}_{1i,t+1}}{\partial I_{j,t+1}} + \frac{\partial r^{*}_{2i,t+1}}{\partial I_{j,t+1}}$$

Suppose current condition at period $t+1$ matches one of the 21 cases we have obtained in Section 3, which is:

$$R_{2,t+1}^k + I_{1,t+1} < SW_{1,t+1}, R_{1,t+1}^k + R_{2,t+1}^k + I_{1,t+1} > SW_{1,t+1}$$

$$R_{1,t+1}^k + R_{2,t+1}^k + I_{1,t+1} + I_{2,t+1} \le SW_{1,t+1} + BL_{0,t+1}$$

Then, the optimal replenishment decisions for sample k are as follows:

$$p^{*}_{1,t+1} = 0, r^{*}_{11,t+1} = SW_{1,t+1} - R_{2,t+1}^k - I_{1,t+1}, r^{*}_{21,t+1} = R_{2,t+1}^k$$

$$p^{*}_{2,t+1} = SW_{1,t+1} + BL_{0,t+1} - R_{1,t+1}^k - R_{2,t+1}^k - I_{1,t+1} - I_{2,t+1}$$

$$r^{*}_{12,t+1} = R_{1,t+1}^k + R_{2,t+1}^k + I_{1,t+1} - SW_{1,t+1}, r^{*}_{22,t+1} = 0,$$

$$and, I'^{*}_{1t+1} = SW_{1,t+1}, I'^{*}_{2,t+1} = BL_{0,t+1}$$

We can tell that the inventory levels of the two products after replenishment have reached the threshold levels $SW_{1,t+1}$ and $BL_{0,t+1}$ respectively. Therefore, the perturbation on the initial inventory of the two products is not propagated to the order-up-to levels of the two products, i.e.

$$\frac{\partial I'^{*}_{1,t+1}}{\partial I_{1,t+1}} = \frac{\partial I'^{*}_{2,t+1}}{\partial I_{1,t+1}} = \frac{\partial I'^{*}_{1,t+1}}{\partial I_{2,t+1}} = \frac{\partial I'^{*}_{2,t+1}}{\partial I_{2,t+1}} = 0$$

However, the perturbation affects the related replenishment decisions and the impact can be determined as: $\frac{\partial p'^{*}_{2,t+1}}{\partial I_{1,t+1}} = -1$, $\frac{\partial r'^{*}_{12,t+1}}{\partial I_{1,t+1}} = 1$. Thus, we conclude if the initial inventory of product 1 is increased by a small amount Δ, the same amount of normal production for product 2 will be saved and the recovery amount from R_1 for product 2 will be increased by the same amount Δ. Despite the impact on related replenishment decisions, the order-up-to levels of each product remain unaffected.

5 CONCLUSION

In this study, we consider a two-product recovery system over a finite horizon. Based on the multi-level threshold policy derived from solving single period problem, an approximate dynamic programming approach is proposed to solve the multi-period problem, which only needs to estimate the gradients of the cost-to-go function at points of interest and frees us from assuming the cost-to-go function as any concrete form. Compared with existing researches on the related areas, we would like to summarize the contributions of this paper as follows:

(1) Our paper considers production planning and inventory control of a recovery system with two products and two respective return flows which as far as we know, is the first study on recovery system involving multiple products and multiple returns;

(2) A single period two-product recovery problem is solved to optimality and a multi-level threshold policy is derived to help make production and inventory decisions. This threshold policy serves as a good starting point for solving multi-period problem;

(3) An approximate dynamic programming approach is used to address the multi-period two-product recovery problem. We have shown the threshold levels of each period only depend on the gradients of cost-to-go function at points of interest through a simple approximation. Therefore, we do not need to assume any explicit form of the cost-to-go function which could be a challenge for most of approximate dynamic programming approaches;

(4) To solve the multi-period problem, we have proven by formula derivation the gradients of each period can be sequentially calculated period by period through a backward induction approach which starts from the last period and then go backwards to the first period.

REFERENCES

[1] Fleischmann, M.; Bloemhof-Ruwaard, J. M.; Dekker, R.; Van der Laan, E.; Van Nunen, J. A. E. E.; Van Wassenhove, L. N. (1997): Quantitative models for reverse logistics: A review, European Journal of Operational Research, Vol. 103, pp. 1–17.

[2] Ilgin, M. A.; Gupta, S. M. (2010): Environmentally conscious manufacturing and product recovery (ecmpro): A review of the state of the art, Journal of Environmental Management, Vol. 91, pp. 563–591.

[3] Inderfurth, K.; De Kok, A. G.; Flapper, S. D. P. (2001): Product recovery in stochastic remanufacturing systems with multiple reuse options, European Journal of Operational Research, Vol. 133, pp. 130–152.

[4] Kleber, R.; Minner, S.; Kiesmller, G. P. (2002): A continuous time inventory model for a product recovery system with multiple options, International Journal of Production Economics, Vol. 79, pp. 121–141.

[5] Huang, W.; Kulkarni, V.; Swaminathan, J. M. (2008): Managing the inventory of an item with a replacement warranty, Management Science, Vol. 54, No. 8, pp. 1441–1452.

Active Remanufacturing Timing Determination Based on Failure State Assessment

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Abstract

Nowadays, since the resources of remanufacturing are the “cores”, the uncertainty in quantity and quality of the “cores” is an important issue in remanufacturing engineering. To meet with this issue, the concept of active remanufacturing is discussed and presented in this paper. It is elaborated from the aspects of product performance degradation and the failure state of key components, based on which the active remanufacturing timing determination mechanism is put forward. Finally, to validate the mechanism, the active remanufacturing timing of engines is determined by analyzing the crankshaft.

Keywords:

Active Remanufacturing; Performance Degradation; Failure State; Remanufacturing Critical Point

1 INTRODUCTION

Remanufacturing engineering is the general name of a series of technical measures or engineering activities made to repair and refurbish the retired electromechanical products[1]. Because of the uncertainty in quantity and quality of the “cores”, the detection process is a very important part of remanufacturing engineering, which consists of Ultrasonic Testing, Magnetic Memory Testing, X-Ray Testing and so on. However, it is very difficult to be used on a large scale because of the low detection efficiency.

To meet with this issue, a lot of scholars and experts have done some research. Considering that whether remanufacturing engineering can be conducted or not is largely dependent on the rationality of initial design stage[2], the theory that products can be suitable for remanufacturing by design is put forward. For example, Winifred L Ijomah et al. did some research about the relationship between products’ property and remanufacturability and analyzed how different factors influenced the remanufacturing process[3]; Erik Sundin described how to achieve a successful remanufacturing process with an efficient take-back system and good product designs[4]; Tony Amezquita et al. identified design characteristics which facilitate remanufacturing by addressing the principal driving factors for remanufacturing[5]; Niu Tongxun proposed an optimized mathematical model for remanufacturing tolerance design by deep analysis on tolerance design characteristics and tolerance distribution principles of remanufacturing[6]; Ke Xing et al. proposed a mathematical model of product upgradeability to provide a holistic measure at the design stage for a product’s potential to serve an extended use life and accommodate incremental changes/ improvements of its functionality in the context of remanufacture[7].

Theoretically, products can be designed in some ways to be suitable for remanufacturing. However, the design scheme of engineering machinery is comparatively constant and difficult to modify. In order to solve the two problems above, in this paper, the concept of active remanufacturing is discussed and presented. By analyzing the product life cycle based on a large number of data statistics of the same batch, the active remanufacturing timing, when to remanufacture, is determined, using scientific decision-making methods. And a determination mechanism is proposed to explain how to determine the active remanufacturing timing based on product performance and physical dimension.

2 ACTIVE REMANUFACTURING TIMING DETERMINATION MECHANISM

Since the product is composed of multiple components, among which there are some key components with a high value and wearing parts that would mostly be replaced in the process of remanufacturing. Active remanufacturing is product-oriented, not component-oriented. And the remanufacturability of key components must be considered. When the performance parameters reach the threshold, the product failure occurs. But by this time residual strength of the key components with high remanufacturing value is far from the failure critical point. In order to avoid damage to the key components when the product fails, remanufacturing should be conducted before timing. Therefore the active remanufacturing timing is determined from the aspects of product performance and key components, which is shown in Figure 1.

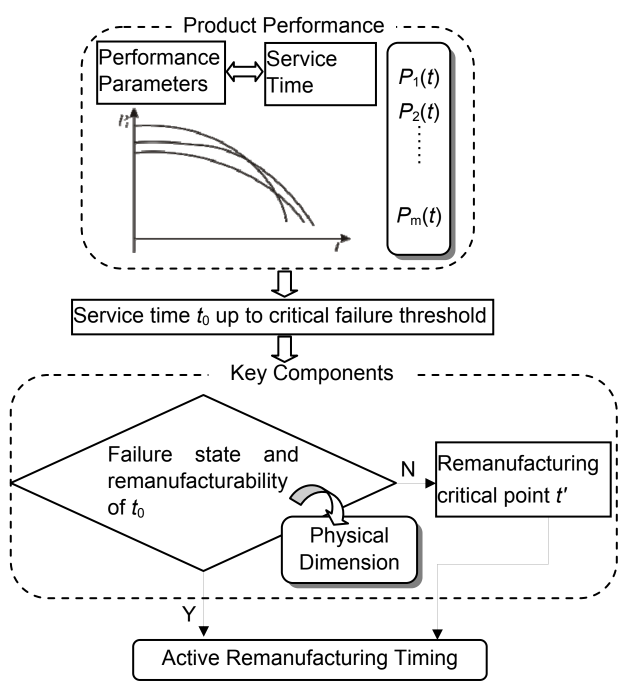

Figure 1: Active remanufacturing timing determination mechanism.

The first step of the determination mechanism is to establish the mapping model $P_1(t)$, $P_2(t)$,……, $P_m(t)$ between the main performance parameters (P_1, P_2,……, P_m) of the product and service time t. Then figure out the critical service time t_0 according to the performance failure threshold. By analyzing the physical dimension of the key components of t_0, the failure state and remanufacturability can be concluded. If the key components are valuable being remanufactured, then t_0 is the active remanufacturing timing; Otherwise, the remanufacturing critical point t' of key components C should be figured out. Because $t' \leq t_0$, the key components are valuable being remanufactured and the product performance hasn′t reached failure threshold, then t' is the active remanufacturing timing.

The product performance is described with m parameters $P_1, P_2, \ldots\ldots, P_m$, like Output Power, Output Torque and so on. The performance gradually reduces with the increase of service time t. And the relationship between performance parameters and service time can be concluded according to statistical data. For each of the performance parameters, a failure threshold is usually predetermined. And the service time of each performance parameters reach the failure threshold are, respectively, t_1, t_2,……, t_m. As long as one of the parameters reaches the failure threshold, it will be regarded as product failure. The service time at the moment will be the product critical service time t_0, mathematically, $t_0=\min(t_1,t_2,\ldots\ldots,t_m)$.

The product performance failure time t_0, as a reference of timing determination, is an initial estimate of active remanufacturing timing. It is advantageous, but not necessary, to obtain t_0 by accurate function relationship. The time when the product performance declined sharply obtained by practical experience can also be helpful.

3 FAILURE STATE ASSESSMENT AND REMANUFACTURING CRITICAL POINT

To determine the active remanufacturing timing of the product, firstly, the failure state of key components of t_0 should be assessed. Then figure out whether it is reasonable if t_0 is regarded as active remanufacturing timing, and should more work be done to identify the remanufacturing critical point.

3.1 Failure State Assessment

The failure state of components after service time t_0 is mainly reflected in the changes of physical dimension. As the basis of failure state assessment, n physical dimensional parameters are pre-set. For example, as to engine crankshaft, the diameter of journals, tortuosity, parallelism, cylindricity, circular run-out and so on, which is shown in Figure 2. The remanufacturing value of components will lose if out of tolerance dimensionally.

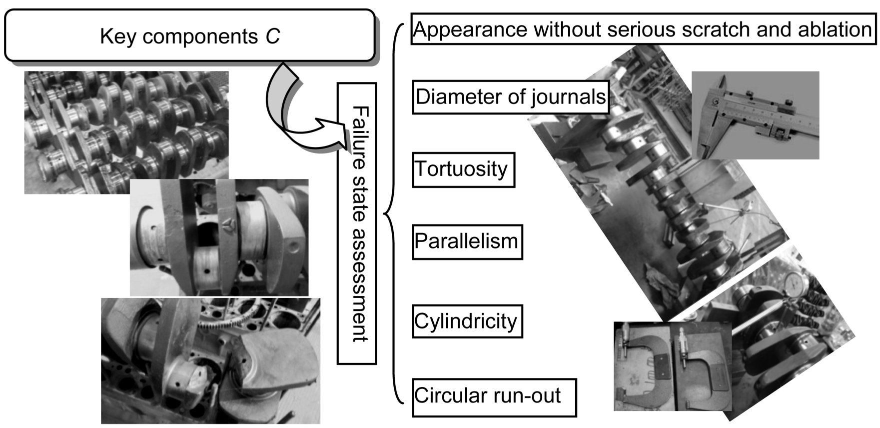

Figure 2: Failure state assessment of crankshaft.

The physical dimension of components C will change in varying degrees after service time t_0. Assumed that the initial design dimension is X_0 and the measurement is X_M, the deviation is defined by

$$\Delta X = \left| X_M - X_0 \right| \geq 0 \tag{1}$$

At t_0, the distribution of components′ dimension can be concluded based on a mass of data statistics. It is regulated that the components can be remanufactured if the physical dimension of more than 95% of components hasn′t reached the remanufacturing critical threshold, that is, $P(\Delta X \leq \Delta X') \geq 95\%$. Otherwise, the components will not be worth being remanufactured.

It is supposed that if the component is worth being remanufactured under the current failure state, then Fs=1; Otherwise, Fs=0, i.e

$$Fs = \begin{cases} 1 & P(\Delta x \leq \Delta x') \geq 95\% \\ 0 & P(\Delta x < \Delta x') < 95\% \end{cases} \tag{2}$$

If the probability density function of the dimensional deviation is $f(x)$, then

$$P(\Delta x \leq \Delta x') = \int_0^{\Delta x'} f(x)dx \tag{3}$$

If the distribution of dimensional deviation is normal distribution, which is $N(\mu, \sigma)$.

$$P(\Delta x \leq \Delta x') = \int_0^{\Delta x'} f(x)dx = \int_0^{\Delta x'} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} dx \tag{4}$$

After simplification and standardization, the probability will be

$$P(\Delta x \leq \Delta x') = \int_{-\frac{\mu}{\sigma}}^{\frac{\Delta x'-\mu}{\sigma}} \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}} dz = \phi(\frac{\Delta x'-\mu}{\sigma}) - \phi(-\frac{\mu}{\sigma}) \tag{5}$$

where

$$z = \frac{x - \mu}{\sigma}$$

By referring to the standard normal distribution table, the probability of components that are not out-of-tolerance can be obtained, based on which the remanufacturability of the batch of components of t_0 can be concluded. For other distributions, such as logarithmic normal distribution, Weibull distribution and so on, the probability can also be figured out in the same way.

The remanufacturing critical threshold should be determined according to the repairing levels based on the current remanufacturing techniques. For example, there are four repairing levels for main journals and rod journals of the crankshaft, each of which is 0.25mm. Therefore, the remanufacturing critical threshold is $\Delta X_1'=\Delta X_2'=0.75$mm. Similarly, other thresholds are: tortuosity $\Delta X_3'=0.15$, cylindricity $\Delta X_4'=0.005$, circular run-out $\Delta X_5'=0.04$, parallelism between the main journals and rod journals $\Delta X_6'=0.01$.

For different components, the physical dimensional parameters selected are also different, which should be determined according to actual experience. For each parameter, the dimensional distribution of components can be obtained based on sample statistics. By calculating the probability of components that hasn′t reached the remanufacturing critical threshold, the whole failure state can be assessed. That is, decide the remanufacturability from the aspect of physical dimension by figuring out whether more than 95% components are within the threshold. Since the probability is an important criterion for remanufacturability determination, it is necessary to get the statistics data from remanufacturing enterprises or sample simulation experiment. The failure state of components of t_0 is assessed, then whether t_0 is the active remanufacturing timing should be discussed.

3.2 Active Remanufacturing Timing Determination

To assess the failure state of a component, n physical dimensional parameters are determined. Being equally important, the parameters should not be divided into different weights. $\Delta X'$ refers to the remanufacturing critical threshold. For one of the parameters, once there are less than 95% of components that haven′t reached $\Delta X'$, the kind of component of t_0 cannot be remanufactured. All of the parameters should reach the standard, respectively, which is equivalent to series connection.

Since there are n physical dimensional parameters, correspondingly there are n sub-failure-states Fs_j (j=1,2,……,n). The failure state of the whole component can be described by

$$Fs = \prod_{j=1}^{n} Fs_j \tag{6}$$

Apparently, as long as one of the parameters can′t reach the standard, i.e, $Fs_k=0$, the failure state of the whole component will be $Fs=0$; Only when all the parameters reach the standard will the failure of the whole component be $Fs=1$.

If $Fs=1$, which means more than 95% of the components of t_0 are not out-of-tolerance dimensionally, then t_0 can be regarded as active remanufacturing timing;

If $Fs=0$, then because the critical components are not worth being remanufactured at this time, t_0 can′t be regarded as active remanufacturing timing. The remanufacturing point should be determined additionally.

The dimensional deviation ΔX changes with the increase of service time t, which can be divided into three periods: firstly, run-in period; secondly, steady running period; thirdly, wear-out period.

By data fitting, the periods can be described by

$$\Delta x(t) = F(t) = \begin{cases} f_1(t) & [0, t_1] \\ f_2(t) & (t_1, t_2] \\ f_3(t) & (t_2, +\infty) \end{cases} \tag{7}$$

In the third period, the components will experience sharp wear, which will decline the remanufacturability. Thus, t' should be in the steady running period. The fitting function $f_2(t)$ can be obtained by measuring the parameters of some timing points. In this period, the dimensional deviation changes steadily, which can be described with a line, approximately. By measuring the dimensional change $\Delta y=\Delta x(t_a)-\Delta x(t_b)$ of an arbitrary time section Δt, the slope will be obtained: $k=\Delta y/\Delta t$. In addition, by failure state assessment, (t_0, $\Delta x(t_0)$) can be figured out. Then the line will be

$$f_2(t) \approx \frac{\Delta y}{\Delta t} t + \Delta x(t_0) - \frac{\Delta y}{\Delta t} t_0 \tag{8}$$

When $f_2(t)=\Delta x'$,

$$t' = \frac{\Delta x' \Delta t - \Delta x(t_0)\Delta t + \Delta y t_0}{\Delta y}$$

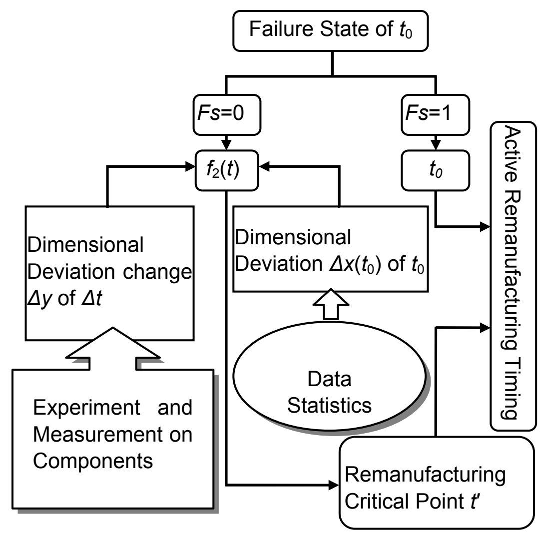

Figure 3: Active remanufacturing determination.

According to the function $f_2(t)$ and $\Delta X'$, the remanufacturing critical point t′ of the key component C is figured out.

If there are more than one key component that should be taken into account, the minimum t' will be taken for the remanufacturing critical point. In summary, the process of determining the active remanufacturing timing is shown in Figure 3.

The failure state of t_0 is the basis of active remanufacturing timing, which describes the relationship between product performance failure and key components failure. Also whether the remanufacturing critical point t' should be analyzed is judged by the failure state.

4 CASE STUDY

The engines that are used in mines are selected as the research object. According to actual experience, the product performance will decline sharply before overhaul, so this moment will be regarded as the performance failure threshold point t_0. The overhaul time of this kind of engines is 2~3 years, about 300,000 kilometers. Crankshaft is the key part with a high value of engines, therefore, its failure state will be assessed by analyzing its physical dimension when the engine is to overhaul. The structure of the crankshaft is shown in Figure 4, in which *Rj* (*j*=1,2,……,6) for the *j*th rod journal and *Mi* (*i*=1,2,……,7) for the *i*th main journal.

Based on a large number of data statistics of the retired engines from a remanufacturing enterprise, the physical dimension of crankshafts is obtained. There are seven main journals and six rod journals. The average, standard deviation (SD) and probability that hasn't reached the threshold of the main journals and rod journals of t_0 are shown in Table 1 and Table 2.

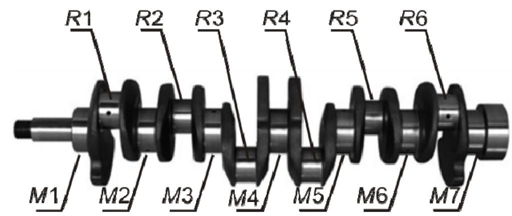

Figure 4: Main journals and rod journals of crankshaft.

Main Journals	*M*1	*M* 2	*M*3	*M* 4	*M* 5	*M* 6	*M* 7
Average *μ*	0.5158	0.5177	0.5102	0.5070	0.5112	0.5187	0.5084
SD *σ*	0.1276	0.1339	0.1235	0.1251	0.1264	0.1337	0.1338
P	96.70%	95.81%	97.38%	97.38%	97.06%	95.81%	96.47%

Table 1: The deviation of main journals.

Rod Journals	*R*1	*R* 2	*R* 3	*R* 4	*R* 5	*R* 6
Average *μ*	0.5153	0.5133	0.5146	0.5085	0.5140	0.5027
SD *σ*	0.1326	0.1309	0.1322	0.1279	0.1349	0.1244
P	96.16%	96.48%	96.25%	97.06%	95.98%	97.68%

Table 2: The deviation of rod journals.

By calculating and analyzing, it can be concluded that both the main journals and rod journals of more than 95% of components hasn't reached the remanufacturing critical threshold. Therefore $Fs_1=Fs_2=1$.

Similarly, by data statistics, the failure state of other parameters can also be obtained: tortuosity $Fs_3=1$, cylindricity $Fs_4=1$, circular run-out $Fs_5=1$, parallelism $Fs_6=1$.

Then the failure state of the whole component will be:

$$Fs = \prod_{j=1}^{6} Fs_j = 1$$

It can be identified that more than 95% of crankshafts hasn't reached the remanufacturing critical threshold, thus, t_0 can be regarded as the active remanufacturing timing.

In this case, the failure state of t_0 is good enough that the key component is worth being remanufactured. However, maybe in other cases t_0 cannot be regarded as the active remanufacturing timing, then the remanufacturing critical point of key components should be calculated additionally. Then the remanufacturing critical point t' will be regarded as the active remanufacturing timing.

5 SUMMARY

Active remanufacturing reduces the uncertainty of "cores", by which the quality is restricted to a certain range, and provides a foundation for industrialization of remanufacturing.

(1) By analyzing the product performance degradation and failure state of key components, an active remanufacturing timing determination mechanism is established. And the failure state is assessed from the aspect of physical dimension. Then the mechanism is used to analyze the engines. It turned out that the mechanism is an effective and practical method for active remanufacturing timing determination.

(2) The mechanism is based on data statistics, which is a disadvantage. However, for the same kind of product, as long as the active remanufacturing timing is determined, it will be helpful for the realization of remanufacturing industrialization. The mechanism puts an emphasis on physical dimension, which is far from enough. The internal damage should also be taken into consideration. And with intensive study, the mechanism will be gradually improved to be more complete and easier to implement.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] XU Binshi. (2005): Foundations and Application of Remanufacturing Engineering, Harbin Institute of Technology Press, Reading, Harbin, China.

[2] Yang Jirong, Duan Guanghong, Xiang Dong. (2006): The Research on the Method of the Green Modular Design for Remanufacture Engineering, in: China Surface Engineering, No. 5, pp. 67-70.

[3] Winifred L Ijomah, Christopher A McMahon, Geoffrey P Hammond, et al. (2007):Development of design for remanufacturing guidelines to support sustainable manufacturing, in: Robotics and Computer-Integrated Manufacturing, Vol. 23, No. 6, pp. 712-719.

[4] E Sundin, M Lindahl. (2008): Rethinking product design for remanufacturing to facilitate integrated product service offerings, in: 2008 IEEE International Symposium on Electronics and the Environment, pp.263-268, San Francisco, USA.

[5] Tony Amezquita, Rick Hammond, Marc Salazar, etc. (1995): Characterizing the remanufacturability of engineering systems, in: Proceedings 1995 ASME Advances in Design Automation Conference, pp. 271-278, Boston, USA.

[6] Niu Tongxun. (2011): Optimal model for remanufacturing tolerance design and its application, in: Computer Integrated Manufacturing Systems, Vol. 17, No.2, pp. 232-238.

[7] Ke Xing, Martin Belusko, Lee Luong, Kazem Abhary. (2007): An evaluation model of product upgradeability for remanufacture, in: Int J Adv Manuf Technol, Vol. 35, pp. 1-14

The Use of Product Life-Cycle Information in a Value Chain Including Remanufacturing

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Abstract
Product life-cycle information is used to improve a product's performance over its life-cycle. The objective of this paper is to describe how information from the product life-cycle phases of design, manufacturing, use, service and end-of-life are used and handled in a value chain comprised of an international original equipment manufacturer with its suppliers and contracted remanufacturers. A case study of a value chain was conducted. The paper concludes that the information flows within the value chain studied are well-functioning; however the organizational structure seems to be a hindrance for full information exchange within the value chain.

Keywords:
Product life-cycle; Product life-cycle information; Remanufacturing; Product-Service System

1 INTRODUCTION

There is a limited amount of virgin materials, and as humans keep impoverishing the resources of the earth, the value of maintaining the materials embodied in products increases. Combined with the trends of mass consumption and price deflation, which cause manufacturers to produce products the cheapest way possible, waste of materials is one of the global challenges that needs to be tackled in order to achieve sustainable societies.

One way of addressing this problem is to engage in remanufacturing and take-back the product after the use phase. Thus, the product's end-of-life is potentially postponed and the product incorporated into a cyclic flow. Remanufacturing is an industrial process whereby used/broken-down products (or components) – referred to as *cores* – are restored to useful life [1]. According to several studies, remanufacturing is more environmentally sound than manufacturing of new products [2]. Further, efficient remanufacturing, where the products can be remanufactured more than once, reduces energy consumption over the product life-cycle [3].

Even so, companies that engage in remanufacturing face different challenges, mainly characterized by uncertainties and complexity, including prediction of when incoming goods are due and what condition they are in [4]. Moreover, a product's design is rarely adapted to the remanufacturing process [5]. In order to address these issues, decisions about product take-back options should preferably be considered early in the product design process.

The design process is a complex, yet creative task that involves extensive information sharing and communication [6]. There are many opportunities for feedback on how the product performs during its life-cycle. Information about the product in use can provide a basis for improved design of products that are more reliable and easier to service [7]. Further, complex products require instructions on how to use, service, and remanufacture the same, thus requesting information about the product design.

2 OBJECTIVE

The objective of this paper is to describe how information from the product life-cycle phases of design, manufacturing, use, service and end-of-life is used and handled in a value chain comprised of an international original equipment manufacturer (OEM) with its suppliers and contracted remanufacturers (CR).

3 RESEARCH METHODOLOGY

The method approach used in this paper was mainly a descriptive case study. A literature study was performed, and the collection of empirical data was made by semi-structured interviews. Managers of product development, service and remanufacturing departments were interviewed.

4 REMANUFACTURING

Remanufacturing is defined here as: *an industrial process whereby products referred to as cores are restored to useful life. During this process the cores pass through a number of remanufacturing steps, e.g. inspection, disassembly, part replacement/refurbishment, cleaning, reassembly, and testing to ensure they meet the desired standards* [8].

The remanufacturing process is characterised by logistical distribution of the cores. The cores are collected, remanufactured and redistributed to the customers (Figure 1). Thus, remanufacturing poses different challenges than ordinary manufacturing. The general challenge that all remanufacturers face is the acquisition of cores and the uncertainties that it involves, both in terms of timing and quality [4].

Moreover, challenges depend on who the remanufacturer is. An OEM that remanufacturers can protect their product design. A CR provides the OEM with the service of remanufacturing its cores, while independent remanufacturers usually have no partnership with the OEM [10].

These organisational structures further affect how the remanufacturers are able to access and administer information from the design and manufacturing phases [9]. According to Ramani et al. [11], a remanufacturing OEM is in control of both the product design and the product recovery; while a CR that remanufactures can supply the OEM with feedback from the product design and are able to receive information from the OEM, the independent remanufacturers are often competitors and need to purchase parts they cannot retrive for the recovery process.

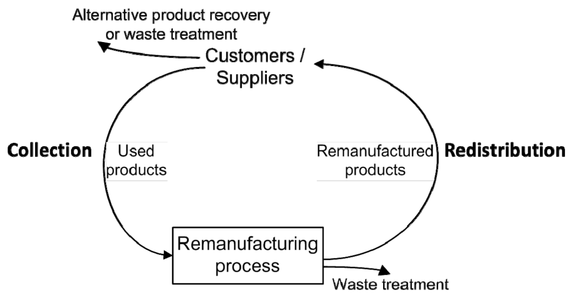

Figure 1: A generic remanufacturing process, adapted from Östlin [9].

Consequently, independent remanufacturers will not receive any information from the OEM, nor have the opportunity to impact the design of the cores via information feedback. On the contrary, most OEMs regard the independent remanufacturer as a competitor and rather design the product to make remanufacturing difficult [12]. The result is that most independent remanufacturers do not have the same possibilities to succed with their businesses as remanufacturing OEMs and CRs [13].

To facilitate remanufacturing, the product design should for instance allow for easy disassembly, enabled by design for remanufacturing (DfRem). Efficient remanufacturing demands product design that allows for easy disassemble and potential upgrading [14].

However, there is little DfRem carried out in companies at present [5]. In order for that to change, the business models of companies wanting to engage in DfRem need to be adjusted accordingly [13]. In fact, manufacturers need to consider the entire product life-cycle in order to increase efficiency throughout it [15]. Inefficient remanufacturing processes are an unnecessary cost. One strategy to apply when opting to cut costs in the remanufacturing process is to capture the value of life-cycle information [16].

5 PRODUCT LIFE -CYCLE INFORMATION

Ultimately, the product should be adapted as to suit all product life-cycle phases such as manufacture, use, service and end-of-life [17]. Previous research has identified the following sources of information from the product life-cycle: manufacturing process and personnel data, conditioning monitoring data, customer data, service process and personnel data, remanufacturing process and personnel data, and wear on components [18]. Preferably, the entire life-cycle of a product (Figure 2) is considered in the design phase. Whilst product design is vital for the performance of the product over its life span, the designers cannot be omniscient about the product's performance in each phase of the product life-cycle. Thus, it is necessary for the product designer to have access to information feedback from all stages of the product life-cycle. On the other hand, the designers may have information to provide to the product life-cycle stages. It is important, therefore, to establish communication throughout the product life-cycle. However, the functional divisions within companies often hinder information and knowledge sharing across divisions [7].

The incentive to handle and use information to and from the product life-cycle is that it promotes efficient design and increases value creation, making the product more competitive on the market as it is better adapted to the different aspects of the product life-cycle. Thus, companies not only gain environmental benefits but also have opportunities to increase their revenue [13].

The retrieved information should be collected in a coordinated way and structured so that collating and analysis of the information can be facilitated [19]. Information management requires not only tools and methods to capture and use the data and information in order to acquire knowledge, but also organizational strategies and processes [7]. The retrieved information can be objective data related to actual product performance, or subjective data based on customers, technicians, and company staffs' opinions [18].

5.1 Product-Service Systems

One of the global sustainability goals is to maximize use with a minimum of resources. This is compatible with the aim of Product-Service Systems (PSS) to provide reliable products and reliable services [20]. The longer a product functions without problems, the better for the PSS provider as it lowers the company’s costs. Products that are unreliable and hard to service, maintain and remanufacture are a cost issue that the producing company will feel the full impact of if they are PSS providers. Thus, there is a strong incentive for the producing company to develop robust products that are easy to service.

Design for PSS is described in Sundin et al. [21] and the importance of regarding the entire product life-cycle when developing products for PSS is highlighted. Moreover, since service could extend a product’s useful life through maintenance and, for instance, education directed at users on how to best use the product, there are potential benefits for the environment to be gained [22].

Consequently, with carefully planned product design and by providing different services during the use phase as part of a PSS, the producing company has opportunities for revenues throughout the use phase.

Applying the PSS business model facilitates the opportunities for manufacturers to access information from the product life-cycle [23]. Thus, the manufacturer has the opportunity to become more knowledgeable about the product in use [24].

5.2 Condition Monitoring

Condition monitoring is typically used to analyse the performance of machines in manufacturing [25]. The goal is to increase the machine uptime by monitoring the performance and make diagnoses for the future performance of the machine. When proactive maintenance can be done instead of reactive, the cost is reduced five times [26]. However, as service selling has become a more important part of producing companies’ revenues, condition monitoring of machines in use at the customer’s site increases. Further, the use of condition monitoring could be used to verify components’ useful life and used to evaluate the remanufacturing process.

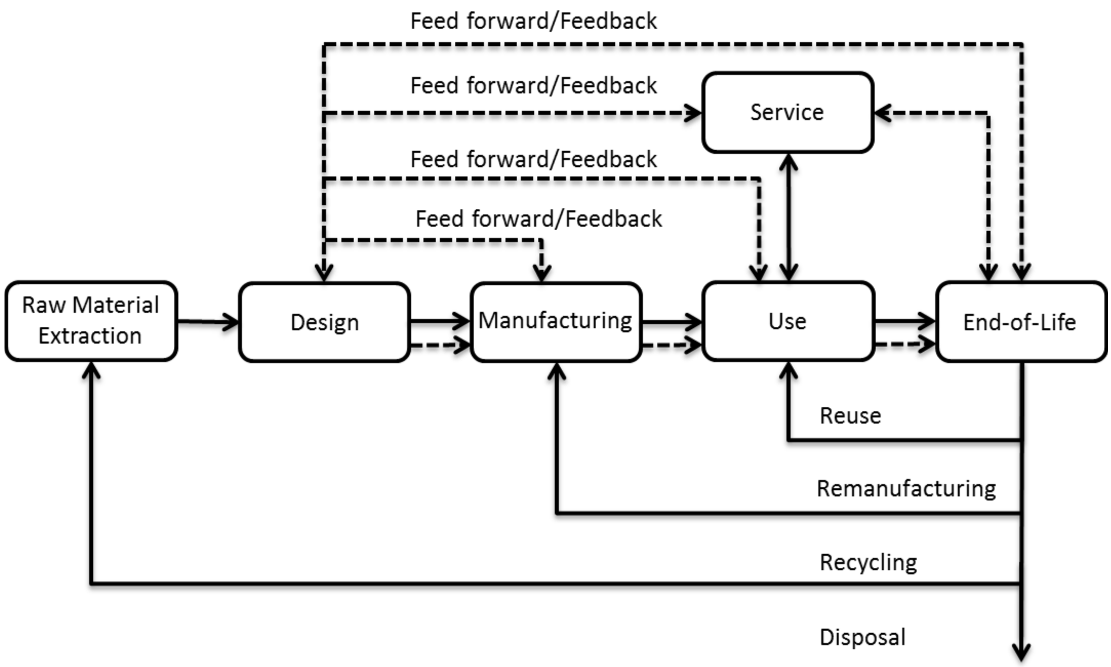

Figure 2: Product life-cycle information flows of a generic product life-cycle. The solid arrows represent material flow, whilst the dashed arrows represent information flows.

6 CASE STUDY OF A VALUE CHAIN

The following paragraphs presented in this section are based on interviews with managers in the case company's value chain. The case company is a large multinational company and its product is a mechanical product used worldwide. The product value chain is comprised of an OEM with subcontracted manufacturers, sales companies, and CRs .

The CRs are strategically situated globally. The organization itself is comprised of a design, service, and marketing department, the latter of which is responsible for the customer contacts. The manufacturing is outsourced and coordinated via a supply chain, while the remanufacturing is performed by CRs. The number of remanufactured machines is quite low compared to newly manufactured machines, but increasing.

The OEM has a manufacturing sequence with suppliers and a forward supply chain. In addition, they have a reverse supply chain that works according to Figure 3. The remanufacturing process at the CR is controlled by the OEM. When a customer orders a remanufactured machine, the OEM sales company locates suitable cores and ships them to the remanufacturer. The remanufacturer orders parts if necessary from the manufacturers and updates the machines. Additional features that the customer might desire and appropriate modifications are done before the remanufactured machine is delivered to the customer.

6.1 Information Flows

The information flows in the value chain studied are illustrated in Figure 4. Databases are important carriers of information in the global organization. However, each unit does not have more information than necessary as the information is filtered and selectively distributed.

6.2 Information Feed Forward

There is no direct contact between the manufacturers and the design and service departments; the communication is instead handled by the supply chain as an intermediary. The communication between the design department and the contracted remanufacturers has recently improved, as the database containing information about

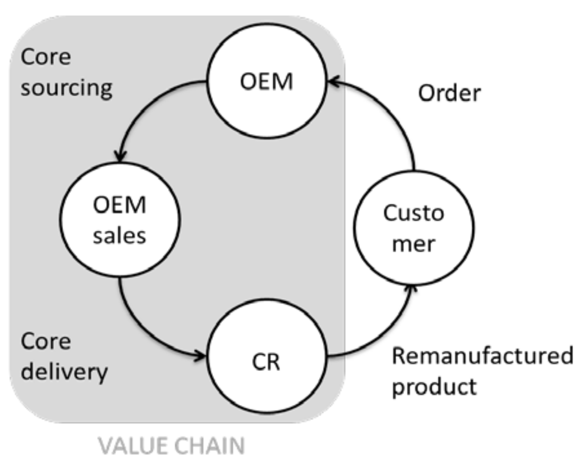

Figure 3: A schematic picture of the remanufacturing system at the value chain studied (OEM = Original Equipment Manufacturer, CR = Contracted Remanufacturer).

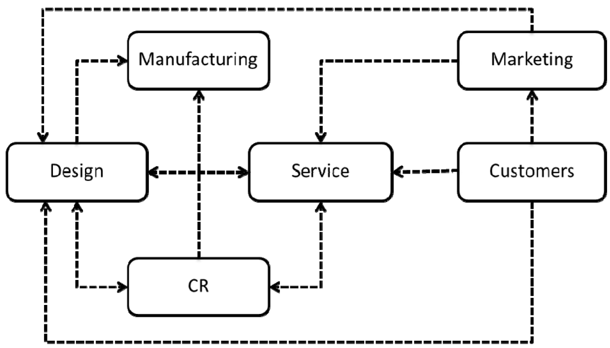

Figure 4: A schematic picture of the information flows in the value chain studied (CR = Contracted Remanufacturer).

the drawings and all updates has been made available to the CRs. Thus, the design, service and remanufacturing departments all have access to the database where the drawings and manuals are stored, and they all receive instant information about updates to the documents.

At the service department, the maintenance is developed and instruction manuals are provided to the service technicians with the exact information on how service should be performed. The manuals are continually updated via the database. The service technicians, in turn, educate the remanufacturing personnel on how to remanufacture new machines. However, the instructions on how to disassemble the machines are provided from the service development department. The physical training is only used when new machines are introduced to the CRs, in order to avoid misunderstandings.

6.3 Information Feedback

The case company prioritises service engineers' feedback. The service engineers are required to write reports after each completed assignment and send them to the service department. There, the information is clustered and prioritised and forwarded to the design department. Since the service engineers are out in the field at the customer's sites and in direct contact with the machines, their feedback is considered a rich resource. The service technicians are able to inspect the machines first hand and supply the designers with information about the current state, but also provide insights and suggestions for improvements. This is made possible since the service department is an integrated part of the company and not performed by an external actor.

Further, the customers' opinions are naturally a valuable source of information for the design department. Their opinions are gathered by the marketing department, analysed and forwarded to the design department. The marketing department also provides the service development department with customer's feedback on the maintenance performed.

The CRs provide feedback on how the service manuals are written and suggestions for improvement, however not routinely. Occasionally, the remanufacturing personnel provide feedback for the design department on how the design could be further improved, but such information is not routinely or systematically gathered. There is some contact between the CRs and the manufacturing units. However, problems arise when obsolete parts are needed in the remanufacturing process. The supplier may have stopped making the parts, or might no longer be a supplier to the OEM. Hence, the CR has to spend time finding another supplier which may cause delays in the remanufacturing process.

6.4 Condition Monitoring

The condition monitoring data is used both as information to be fed forward to the CRs and as feedback to the design and service departments. The OEM has started to implement conditioning monitoring as a source of objective data. They are currently building up a database with conditioning monitoring data in order to compare components' calculated lifetime with the actual outcome. Further, the CRs are able to perform momentary conditioning monitoring. As the goods are received, certain critical parts are monitored momentarily and their performance is documented. The result is later compared to the parts' performance in the final testing procedures, and thus the impact of the remanufacturing process on the particular part can be clarified. In addition, the profile of the machine retrieved at the final test stage can also be verified when the machine is installed at the customer to ensure that the equipment has not been damaged during shipment and instalment at the customer site. The OEM is considering expanding its continuous conditioning monitoring by including smart functions in their new machine. Current information from the conditioning monitoring is only sparsely used. A new data system is required in order to manage all the incoming data. With that in place, statistics over components' performance, uptime, maintenance intervals and end-of–life could be closely monitored and followed up on.

7 DISCUSSION

The studied OEM highly values feedback from the product life-cycle, especially input from service technicians and customers. The design department regards the information feedback from the service technicians as a valuable resource. Their reports documenting the maintenance carried out in the field at the customer's site provide valuable input for the designers. However, the OEM could potentially benefit from regarding more input from remanufacturing and manufacturing. In particular, the manufacturing units are not involved in the information flows to a satisfying extent. The organisation of the value chain can be part of the explanation, since the machine is not manufactured at one subcontractor but several. The OEMs machines are designed in modules, which facilitates upgrading. Pure DfRem is however not carried out, since more focus is put on manufacturing and Design for Manufacture (DfM). However, in order to save costs and avoid late design changes designers should consider these kinds of issues as early as possible. This is also known as the design paradox [27], where design decisions have to take place early in the product development process at a time when knowledge of the product is low.

The case OEM's partnerships with CRs does secure information sharing channels, as desicribed by Östlin et al. [10]. The information feed forward has recently improved as the CRs now have access to the databases with continuous updates on drawings and manuals. However, efficient remanufacturing not only requires a well-functioning remanufacturing process, but foremost a product design that allows for efficient disassembly [see e.g. 5, 8, 13-15]. Altough data is collected from condition monitoring in the remanufacturing process, further information feedback is overlooked at the studied case company. According to Lindkvist and Sundin [18], sources of feedback from the remanufqacturing phase include data from the remanufacturing process evaluating how well the product is adapted to efficient remanufacturing (e.g. how easy it is to disassemble), as well as suggestions of improvements from the remanufacturing personell are important. Feedback from the remanufacturing department to the design department concerns the remanufacturing manuals and aspects of the product design. However, in contrast to feedback from service, feedback from the CRs is not routinely gathered. Further, the organisational structure may aslo cause problems in locating cores. For instance, change of suppliers that are currently producing the core the CRs need. This problem might be avoided if the OEM was organised differently or had information about what parts the CRs might need in the future. Furthermore, condition monitoring offers opportunities for more thorough information gathering in order to save costs on service and remanufacturing processes.

Much information is retrieved and stored, but the information must also be available to the right people at the right time in order to achieve an efficient remanufacturing process. Further, there is a need to balance the information streaming from manufacturing and users, but also from service and end-of-life process, for instance remanufacturing. The purpose of gathering information is to adapt the product to the entire product life-cycle, and not only the use phase. As circular product flows are a must for sustainable societies, products should be adapted to be able to go through multiple life-cycles [2, 24, 28].

8 CONCLUSIONS AND FURTHER RESEARCH

In the value chain studied, information fed forward is foremost used to improve the service and remanufacturing processes. The CRs have recently been involved in the internal information flows that the design and service departments utilize. However, the OEMs subcontracted manufacturers are still excluded.

Information feedback from the product life-cycle phases of manufacturing, use, service and end-of-life is used in the design phase to improve the product and service manual designs. While information from the service and use phases are routinely gathered, that is not true for information from the end-of-life and manufacturing phases.

In conclusion, the information flows within the value chain studied are well-functioning; however, the organizational structure seems to be a hindrance for full information exchange within the value chain.

Future research will focus on how product life-cycle information could be used and handled in order to increase efficiency and flow throughout the product life-cycle. In addition, the benefits of product life-cycle information for sustainable development should be further investigated.

9 ACKNOWLEDGMENTS

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10 REFERENCES

1 Östlin J., Sundin E. and Björkman M. (2009) Product Life-cycle Implications for Remanufacturing Strategies, Journal of Cleaner Production, Vol. 17, Issue 11, pp 999-1009.

2. Sundin E., Lee H.M., (2011), In What Ways is Remanufacturing Good for the Environment?, Proceedings of EcoDesign 2011 International Symposium, pp. 551.

3. Sutherland, J.W., Adler, D.P., Haapala, K.R. and Kumar, V., (2008). A comparison of manufacturing and remanufacturing energy intensities with application to diesel engine production. CIRP Annals - Manufacturing Technology, 57(1), pp. 5-8.

4. Lundmark P, Sundin E, Bjorkman M, (2009). Industrial challenges within the remanufacturing system. Proceedings of Swedish Production Symposium. Stockholm 2009, pp.132-139

5. . Hatcher, G. D., W. L. Ijomah, and J. F. C. Windmill. (2011). Design for remanufacture: A literature review and future research needs. Journal of Cleaner Production 19, (17-18): 2004-14.

6. Brandt, S. C., Morbach, J., Miatidis, M.,Theiβen, M., Jarke, M., and Marquardt, W. (2008). An ontology-based approach to knowledge management in design processes. Computers & Chemical Engineering 32, (1–2) (1): 320-42.

7. Goh, Y. M., and McMahon, C. (2009). Improving reuse of in-service information capture and feedback. Journal of Manufacturing Technology Management 20, (5): 626-39

8. Sundin, E. (2004), Product and process design for successful remanufacturing Linköping Studies in Science and Technology, Dissertation No 906 Linköping University, Linköping

9. Östlin, J. (2008), On Remanufacturing Systems, Analyzing and Managing Material Flows and Remanufacturing Processes. Linköping Studies in Science and Technology, Dissertation No 1192 Linköping University, Linköping

10. Östlin J., Sundin E., and Björman M., (2008), Importance of Closed-Loop Supply Chain Relationship for Product Remanufacturing, International Journal of Production Economics, pp.336-348

11. Ramani, K., Ramanujan, D., Bernstein, W. Z., Zhao, F., Sutherland, J., Handwerker, C., Ghoi, J-K., Harrisson, K., and Thurston, D., (2010) Integrated sustainable life cycle design: a review. Journal of Mechanical Design vol. 132

12. Sundin E. and Östlin J. (2005), Case Study of Three Toner Cartridge Remanufacturers, Proceedings of EcoDesign-05, Tokyo, Japan, December 12-14.

13. Hatcher G. D., Ijomah W., and Windmill J., (2011), Design for Remanufacture in an OEM-Remanufacturer Organization, Proceedings of the 1st International Conference on Remanufacturing, pp. 286-292.

14. Sundin, E. and Lindahl, M. (2008), Rethinking product design for remanufacturing to facilitate integrated product service offerings, IEEE International Symposium on Electronics and the Environment

15. Pigosso, D.C.A., Zanette, E.T., Filho, A.G., Ometto, A.R. and Rozenfeld, H. (2010), Ecodesign methods focused on remanufacturing, Journal of Cleaner Production, vol. 18, no. 1, pp. 21-31.

16. Ferrer, G. and Swaminathan, J.M., (2010), Managing new and differentiated remanufactured products. European Journal of Operational Research, 203(2), pp. 370-379.

17. Maxwell, D. and van der Vorst, R., (2003), Developing sustainable products and services. Journal of Cleaner Production, 11(8), pp. 883-895.

18. Lindkvist, L., and Sundin, E. (2012), Life-Cycle Information Feedback to Product Design. Proceedings of the Swedish Production Symposium 2012 pp. 99-105
19. Roberts, N., and D. Clarke. (1989), Organizational information concepts and information management. International Journal of Information Management 9, (1) (3): 25-34.
20. Meier, H., R. Roy, and G. Seliger. (2010), Industrial product-service systems-IPS 2. CIRP Annals - Manufacturing Technology 59, (2): 607-27.
21. Sundin, E., M. Lindahl, and W. Ijomah. (2009), Product design for product/service systems: Design experiences from swedish industry. Journal of Manufacturing Technology Management 20, (5): 723-53.
22. Tukker, A. (2004), "Eight types of product-service system: Eight ways to sustainability? Experiences from suspronet", Business Strategy
23. Seliger, G., Gegusch, R., Abramovici, M. and Neubach,M., (2010), Knowledge-based feedback of IPS2 use information, 2010 IEEE International Conference on Information Reuse and Integration, IRI 2010 2010, pp. 292-297
24. Sundin, E. and Bras, B., (2005), Making functional sales environmentally and economically beneficial through product remanufacturing. Journal of Cleaner Production, 13(9), pp. 913-925.
25. Williams, J.H., Davies, A., and Drake, P.R. (1994), Condition-based maintenance and machine diagnostics. Chapman Hall, London
26. Gondal, I., Yaqub, M. F., and Hua, X. (2012), Smart phone based ma chine condition monitoring system.2012.
27. Lindahl, M. (2000), Environmental Effect Analysis - an approach to design for environment, Licentiate Thesis, Royal Institute of Technology, Stockholm, Sweden.
28. Kerr, W. and Ryan, C., (2001), Eco-efficiency gains from remanufacturing: A case study of photocopier remanufacturing at Fuji Xerox Australia. Journal of Cleaner Production, 9(1), pp. 75-81.

Application of Electro-Magnetic Heat Effect on Crack Arrest in Remanufacturing Blank

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Abstract

Remanufacturing is the only way of sustainable development of equipment manufacturing industry. In order to have a prolonged service life of a remanufactured blank with crack, it is vital to prevent propagation of the crack. This also ensures the effectiveness of the manufacturing processes to follow. In this paper, the theory of crack arrest through the heat effect of electromagnetic field is presented. And the effect of the crack arrest is analyzed from three aspects: stress concentration, residual stress, and work of crack formation. Through a calculation example, the distribution of temperature field in the specimen is provided.

Keywords:

Remanufacturing; Crack Arrest; Joule Heating

1 INTRODUCTION

Remanufacturing is a concept of a series of technical measures or engineering activities – like instructions of whole life cycle theory of a product, criteria for high quality, high efficiency, energy saving, material saving, or environmental protection, with the means of advanced technology and industrialization – to repair and alter the waste equipments or products[1]. Remanufacturing engineering is an important technical means to realize the development mode of recycle economy, which can constantly improve the technology of mechanical and electrical products, reduce cost of the rest of life cycle, extend product life, save material, reduce pollution and create more profit.

2 RESEARCH STATUS OF CRACK ARREST IN REMANUFACTURING

Remanufacturing process of the retired products includes disassembly, sorting, cleaning, machining process, assembly, running in test, painting, etc., as shown in figure 1. To the parts which still possess residual life, advanced surface technology is adopted to recover the surface size and make the remanufacturing parts superior to the original ones. Or the advance manufacturing technique is adopted to process the parts to satisfy the assembly requirements. During processing of the remanufacturing blanks with crack, it is vital to arrest propagation of the cracks, so as to guarantee the effectiveness of the repair processes to follow and achieve the purpose of extending the life of the products.

At present, the technology of crack arrest in remanufacturing has the following processing possibilities:

- Drilling the crack-cutting hole at the crack tip or in the direction of the crack propagation;
- Digging the material with the crack and ambient part with the boring machine or carbon arc air gouging;
- Applying a layered material, which is same or similar to the parent metal, by the principle of fusion welding using heat produced by current through a resistor;
- Coating a layer of same or similar material on the parent metal by utilizing vapor deposition technique with the aid of high energy laser beam. The process yields a compact coating, which is metallurgically bonded to the parent material.

Drilling crack-cutting hole can only stop the expansion of the crack along the length direction and also it is difficult to drill hole on hard materials. It also increases the workload of the subsequent repair. It is possible to repair surface cracks with welding or laser cladding, but the two methods are not suitable for the length and depth cracks.

With the formation and development of the magnetic elasticity and thermal –magnetoelasticity theory, the heating effect of electromagnetic field can be used to arrest crack propagation. This method has gradually become a very promising non-equilibrium processing technology for practical solutions.

When pulse current flows through the conductive metal containing a crack, the current flow and heat concentration effect becomes very obvious, due to existence of the crack. The small range of structure around the crack tip heated intensely and the temperature becomes high enough to initiate melting. As the temperature increased, the curvature radius of the crack tip is increased by 2 to 3 times in magnitude and welded junction is formed due to local fusion and eruption. So the mechanical stress concentration can be reduced or even eliminated, and a large hot pressure stress area would be generated around the crack tip. This causes prevention of the crack propagation and at the same time inhibits the potential energy of formation of the main crack and, thus, the purpose of arresting the crack propagation is achieved effectively[2].

Compared to the currently used methods, the obvious advantages of arresting crack through the heating effect of electromagnetic field are as follows:

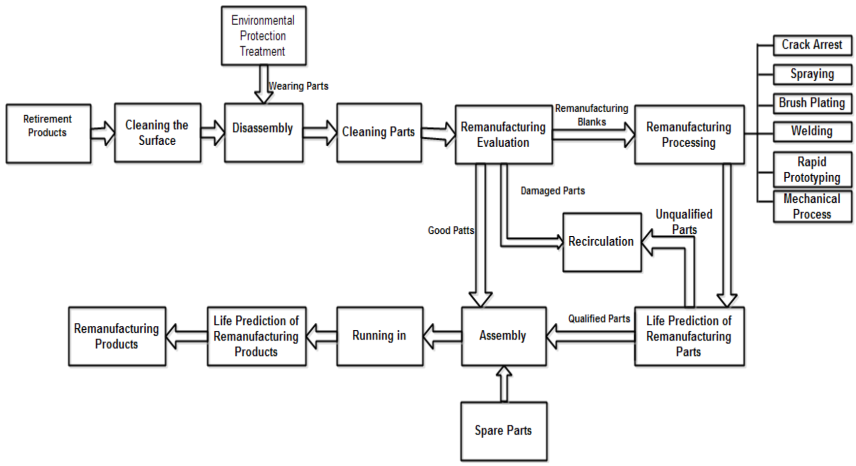

Figure 1: A General Flow Chart of a Remanufacturing Process.

- This method does not damage the other portions of the remanufacturing blank. The instantaneous concentration of the current around the crack tip is used to arrest the crack propagation. In its simple operation, the curvature radius of the crack tip is increased by 2 to 3 times in magnitude, causing the elimination in stress concentration around the crack tip, thus, preventing the extension of the crack.
- From mechanics perspective, pressure stress is produced by electromagnetic field and phase transformation stress is caused by process of rapid cooling. They are seen as a benefit to arrest a crack. The important factors affecting crack arrest are: crystal structure of the melted range around the crack tip and changes in pressure stress.

3 THEORETICAL ANALYSIS OF USING THE HEATING EFFECT OF ELECTROMAGNETIC FIELD TO ARREST CRACK PROPAGATION TEXT AREA

3.1 Distribution of Current Density around Crack Tip

In reference [3], a relationship between singularity around the crack tip in the sheet metal containing current flow and the intensity factor of mode III crack problem is set up. The disturbance effect of the current distribution due to existence of the crack is investigated by the existing knowledge and analytical method in the facture mechanics.

Make a contrast between current density distribution in a conducting sheet metal [4] and anti-plane shear problem without being affected by physical force [5]. The analogy relationship is: the potential function of electric current W to the inverse function of out-of – plane displacement component $-\Phi$, electric conductivity μ to shear modulus γ, the components of current density j_x and j_y to the components of anti-plane shear stress σ_{xz} and σ_{yz}, the analogy relationships are given as:

$$W \sim -\Phi, \quad \mu \sim \gamma, \quad \sigma_{xz} \sim j_x, \quad \sigma_{yz} \sim j_y$$

Hence from mathematics perspective, distribution of current density in a plane is absolutely equivalent to components of shear stress in an anti-plane problem.

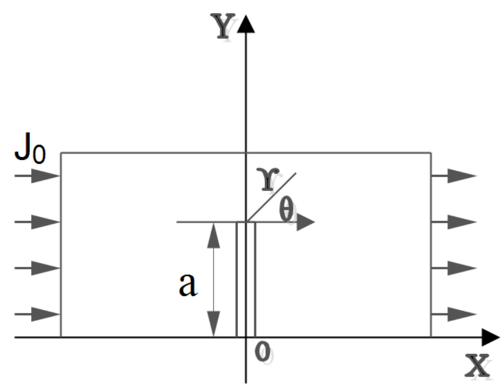

Figure 2: The conducting sheet containing a unilateral crack.

Move the origin of coordinate to the crack tip, using polar form shown in figure 2. The current density factor can be defined according to the expression of stress field at crack tip in mode III crack problem, as described in reference [5]. Refer to aforementioned analogy relationship.

$$K_J = J_0\sqrt{\pi a} \tag{1}$$

$$\begin{cases} J_x = -\dfrac{K_J}{\sqrt{2\pi r}}\sin\dfrac{\theta}{2} \\ J_y = \dfrac{K_J}{\sqrt{2\pi r}}\cos\dfrac{\theta}{2} \end{cases} \tag{2}$$

Where, K_J is the current density factor; j_x and j_y are the components of current density in direction X and Y; J_0 is current density varying with time, applied on both sides of specimen; a is length of crack.

According to the expression of heat source power density [6]: $Q(x,y) = \int_{-h}^{h} \frac{1}{\sigma_t}\left(j_x^2 + j_y^2\right)dz$, equivalent heat source can be obtained:

$$Q(x,y)=\int_0^h \frac{1}{\mu}(j_x{}^2+j_y{}^2)dz=J_0{}^2\frac{ha}{\mu r} \tag{3}$$

Where, h is thickness of the conductive sheet metal; μ is electric conductivity.

3.2 Determination of the Temperature Field around the Crack Tip

Discharge moment is equivalent to placing a heat source at the crack tip. Assume there is a straight line crack which is adiabatic, place an equivalent heat source with power Q and initial temperature T_0 at the crack tip $(0,a)$.

The temperature field can be written in the following form[7]:

$$T(x,y)=T_0(x,y)+T_*(x,y) \tag{4}$$

Where $T_0(x,y)$ is temperature field on a continuous plane; $T_*(x,y)$ is disturbance value of temperature field at the existence of crack. The parameter is the function of local characteristics.

The temperature field around the crack tip can be written as:

$$T_0(x,y)=2\mathrm{Re}F_0(a,z) \tag{5}$$

Where $F_0(a,z)=-\frac{Q}{4\pi\lambda}\ln(a-z)$; λ is thermal conductivity.

Hence

$$T_0(x,y)=-\frac{Q}{4\pi\lambda}\ln\left[x^2+(a-y)^2\right] \tag{6}$$

Boundary condition at both sides of the crack is adiabatic: $\lambda\left(\frac{\partial T}{\partial n}\right)=0, \tau\in L$ （L is the border of crack）.

From Eqs. (4), we can get

$$\lambda\left(\frac{\partial T_*}{\partial n}\right)=-\lambda\left(\frac{\partial T_0}{\partial n}\right), \tau\in L \tag{7}$$

Hence $T_*(x,y)$ can be written as:

$$T_*(x,y)=2\mathrm{Re}F_*(z) \tag{8}$$

Where, $F_*(z)=\frac{C}{2}+\frac{1}{2\pi i}\int_L\frac{\phi(\tau)}{\tau-z}d\tau,(\tau\in L)$; C is a constant and its value is 2 times of the initial temperature; $\phi(\tau)$ is real function definite on the boundary. On the boundary:

$$\left[\frac{\partial T_*}{\partial n}\right]^{\pm}=\pm ie^{ia_0}\phi(\tau_0)-\frac{e^{ia_0}}{\pi}\int_L\phi(\tau)K(\tau,\tau_0)d\tau \tag{9}$$

Where $\pm$ is right and left sides of the crack, $K(\tau,\tau_0)=\frac{1}{2}\left[\frac{\chi'(\tau)}{\overline{\tau}-\overline{\tau_0}}-\frac{1}{\tau-\tau_0}\right]$, $\chi'(\tau)=\frac{d\overline{\tau}}{d\tau}=-e^{-2ia}$, a_0 is the included angle between X axis and boundary of the crack at point $\pm\tau_0$. In this paper, $a_0=\frac{\pi}{2}$, thus, we can get

$$\begin{aligned}&\left[\frac{\partial T_*}{\partial n}\right]^{\pm}=\mp\phi(\tau_0)\\&\left[\frac{\partial T_0}{\partial n_0}\right]=\left[\frac{\partial T_0}{\partial x}\right]=-\frac{Q}{2\pi\lambda}\cdot\frac{x}{x^2+(a-y)^2}\end{aligned} \tag{10}$$

From Eqs.(7),we can get

$$\left[\frac{\partial T_*}{\partial n_0}\right]^{\pm}=-\left[\frac{\partial T_0}{\partial n_0}\right]^{\pm} \tag{11}$$

$$\phi(\tau_0)=\mp\frac{Q}{2\pi\lambda}\cdot\frac{b}{b^2+(a-y)^2} \tag{12}$$

Where $2b$ is width of the crack. We set initial temperature of specimen as 0 ℃, that is $C=0$. Hence we can get

$$\begin{aligned}F_*(Z)&=\frac{1}{2\pi i}\int_L\frac{\phi(\tau)}{\tau-Z}d\tau=\pm\frac{1}{2\pi i}\int_L\left[\frac{Q\cdot b}{2\pi\lambda}\cdot\frac{1}{b^2+(a-y)^2}\right]\frac{dy}{y-Z}\\&=\pm\frac{Q\cdot b}{4\pi^2\lambda i}\cdot\frac{1}{(Z-a)^2+b^2}\left[\frac{1}{2}\ln\left|\frac{a^2+b^2}{b^2}\right|-\frac{Z-a}{b}\arctan\left(\frac{a}{b}\right)-\ln\left|\frac{Z}{Z-a}\right|\right]\end{aligned} \tag{13}$$

Hence

$$\begin{aligned}T_*(x,y)&=2\,\mathrm{Re}\,F_*(x,y)=2\,\mathrm{Re}\,F_*(Z)\\&=\frac{Q\cdot b}{2\pi^2\lambda}\cdot\frac{1}{\left[(y-a)^2-x^2+b^2\right]+4x^2(y-a)^2}\cdot\\&\left\{-x(y-a)\ln\left|\frac{a^2+b^2}{b^2}\right|+\frac{x}{b}\left[(y-a)^2+x^2-b^2\right]\arctan\frac{a}{b}\right\}\end{aligned} \tag{14}$$

From Eqs.(4), Eqs.(6) and Eqs.(14),we can get

$$\begin{aligned}T(x,y)&=T_0(x,y)+T_*(x,y)\\&=\frac{Q}{4\pi\lambda}\left\{-\ln\left[x^2+(a-y)^2\right]+\frac{2b}{\pi}\cdot\frac{1}{\left[(x-a)^2-y^2+b^2\right]+4y^2(x-a)^2}\cdot\right.\\&\left.\left\{-y(x-a)\ln\left|\frac{a^2+b^2}{b^2}\right|+\frac{y}{b}\left[(x-a)^2+y^2-b^2\right]\arctan\frac{a}{b}\right\}\right\}\end{aligned} \tag{15}$$

When $b\to 0$, the result is

$$T(x,y)=T_0(x,y)=-\frac{Q}{4\pi\lambda}\ln\left[x^2+(a-y)^2\right] \tag{16}$$

4 CALCULATION EXAMPLE

From eqs.(16) the temperature in the vicinity of the crack tip is connected with the thickness of the specimen h and the length of the crack a. Because of the restriction of the discharge capacity of the experimental facility, the sheet specimen is chosen in this paper. The object of study is an impeller blade of a compressor; its material is high strength stainless steel $FV520B$. The dimensions of the specimen are $60\mathrm{mm}\times 30\mathrm{mm}\times 1\mathrm{mm}$, length of unilateral crack is $a = 20mm$, electric conductivity is $\sigma_t = 5.5\times10^6(\Omega\cdot m)^{-1}$, thermal conductivity is $\lambda = 25.5W\cdot(m\cdot{}^\circ C)^{-1}$, modulus of elasticity is $E = 210GP$, coefficient of thermal expansion is $\alpha = 11.3\times10^{-6} m/(m\cdot{}^\circ C)$, and melting point is 1530℃. The current density loaded on both sides of the specimen is $J_0 = 2.1\times10^8 A/m^2$.

4.1 Numerical Calculation

The temperature field distribution is calculated in the numerical calculation software MATLAB, as shown in figure 3. The highest temperature is 2070℃, which is found to be at the crack tip and is more than the melting point of the material. The temperature is very high only in local region and the range of temperature is not significantly high in the other regions. This implies that the material structure would not be changed in the other regions. Therefore, it can only repair the damaged area through the heat effect of electromagnetic field to arrest the crack propagation. Furthermore, it would not affect the overall performance of the remanufactured part.

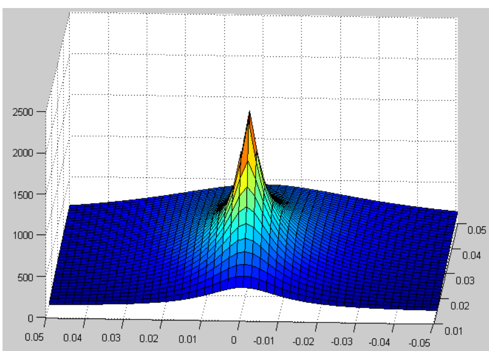

Figure 3:the Distribution of Temperature Field in Specimen.

4.2 Finite Element Simulation of Temperature Field

Thermoelectric coupling is the weak coupling. The calculation can be achieved through alternate solving temperature field in each incremental step. First, the heat generation by current in transient process is solved in each incremental step. And then heat due to the current concentration is considered as internal heat source. Through solving the problem of heat conduction, the distribution of temperature field can be obtained and the temperature-dependent resistivity can be calculated. And the results are regarded as the analysis conduction of the problem of heat generated by current. At last, the calculation results reach certain accuracy [8].

By analyzing the problem of thermoelectric couple, electrical conduction equation can be express as:

$$\mu(\boldsymbol{T})\boldsymbol{V} = \boldsymbol{I}.. \qquad (17)$$

Where **μ(T)** is temperature-dependent matrix of coefficient of electrical conduction; $\boldsymbol{I}$ is vector of node current ; $\boldsymbol{V}$ is vector of node voltage.

Matrix equation of heat conduction:

$$\boldsymbol{C}(\boldsymbol{T})\dot{\boldsymbol{T}} + \boldsymbol{K}(\boldsymbol{T})\boldsymbol{T} = \boldsymbol{Q} = \boldsymbol{Q}^E \qquad (18)$$

Where $\boldsymbol{C}(\boldsymbol{T})$ is temperature-dependent matrix of thermal equivalent; $\boldsymbol{K}(\boldsymbol{T})$ is thermal-dependent matrix of heat conduction; $\dot{\boldsymbol{T}}$ is derivative of temperature vector to time; $\boldsymbol{T}$ is vector of temperature on node; $\boldsymbol{Q}$ is vector of heat flux; $\boldsymbol{Q}^E$ is vector of internal heat source due to current flows. Coupling between heat generated by current and heat conduction is achieved through substituting $\mu(\boldsymbol{T})$ in eqs.(17) and $\boldsymbol{Q}^E$ in eqs.(18).

Backward difference and discretization of time variable in eq.(18), leads to

$$\left\{\frac{1}{\Delta t}\left[\boldsymbol{C}(\boldsymbol{T})\right] + \boldsymbol{K}(\boldsymbol{T})\right\}\boldsymbol{T}_n = \boldsymbol{Q}_n + \boldsymbol{Q}^E + \frac{1}{\Delta t}\boldsymbol{C}(\boldsymbol{T})\boldsymbol{T}_{n-1} \qquad (19)$$

Node temperature in every time step Δt can be calculated from eqs.(19).

The vector of internal heat source can be obtained from the following equation.

$$\boldsymbol{Q}^E = \int_V \boldsymbol{B}^T \boldsymbol{q}^E dV \qquad (20)$$
$$\boldsymbol{q}^E = \boldsymbol{i}^2\boldsymbol{R}$$

The process of discharge is simulated in a "finite element analysis" software ANSYS. The distribution of temperature field of specimen containing unilateral crack is shown in figure 4. The highest temperature is the one that appears at the crack tip, which is 2137℃. The result is very close to the one obtained by the theoretical model, which proves the validity of theoretical model.

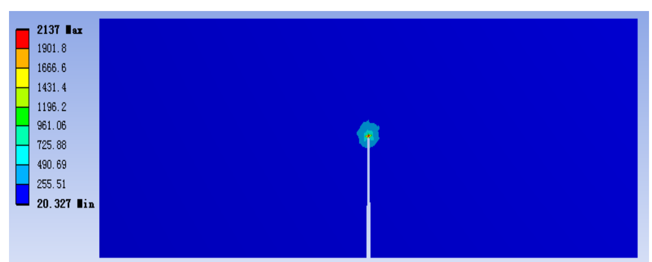

Figure 4: the distribution of temperature field.

5 ANALYSIS OF THE EFFECT OF CRACK ARREST

When the current flows through a specimen, it concentrates at the crack tip due to existence of the crack. The temperature rise exceeds even the melting point in a very short time, which causes evaporation and eruption, leading to a series of physical, chemical, and metallurgical changes. After discharge, molten crack tip is chilled by means of conduction through the metal around. Due to the pressure stress that is generated when discharging still exists, the diffusion of atoms is prevented. The metal around the crack tip is refined in the process of crystallization .The interface of the grain boundary at front of the crack tip is increased by the refined metal structure. It also increases the interface resistance of the crack extension and work of the crack extension, so as to prevent the propagation of crack [9].

5.1 Stress Concentration around the Crack Tip

Because of melting, the stress at the crack tip is released and stress concentration is greatly reduced. After discharge, the curvature radius of the crack tip is amplified, as shown in figure 5. The factor of stress concentration is [10]:

$$\beta = 2\sqrt{\frac{d}{\rho}} + 1 \tag{21}$$

Where β is factor of stress concentration; d is curvature radius of ellipse; and ρ is curvature radius of crack tip.

Figure 5: Contrast macro morphology before and after the crack arrest.

Before charge, the stress concentration factor is high. After the crack is arrested by discharge, an approximate circular hole is generated at the crack tip, that is $d \approx \rho$, so the factor of stress concentration becomes close to 3. The condition of stress concentration is similar to crack-cutting hole. The stress concentration is eliminated and generation of a secondary crack is effectively prevented and avoided.

5.2 Residual Stress around Crack Tip

When pulse current flows through the specimen with unilateral crack, the volume expansion nearby the crack tip is generated by joule heating and phase transformation. While the ring and radial pressure stress is caused by the unmelted metal around the crack tip, it offsets the tensile stress caused by instant cooling. So that the pressure stress field is always maintained at front of the crack tip and it is benefited to inhibit the propagation of crack.

According to the analysis in reference [9], a plastic strain ε remains around the crack tip after discharge, that is:

$$\varepsilon = -\alpha \Delta T \tag{22}$$

Where α is coefficient of thermal expansion; ΔT is temperature difference between the highest temperature (melting temperature) and the initial temperature. In this paper the initial temperature is 0 ℃. We get: $\Delta T = T$.

The residual stress can be obtained by:

$$\begin{aligned}\sigma &= E\varepsilon = -E\alpha\Delta T \\ &= -E\alpha\frac{Q}{4\pi\lambda}\left\{-\ln\left[x^2+(a-y)^2\right]+\frac{2b}{\pi}\cdot\frac{1}{\left[(x-a)^2-y^2+b^2\right]+4y^2(x-a)^2}\cdot\right. \\ &\left.\left\{-y(x-a)\ln\left|\frac{a^2+b^2}{b^2}\right|+\frac{y}{b}\left[(x-a)^2+y^2-b^2\right]\arctan\frac{a}{b}\right\}\right\}\end{aligned} \tag{23}$$

5.3 Work of Crack Formation

According to the theory of crack formation in fracture mechanics [5], critical shear stress and normal stress of crack formation are presented, respectively, as:

$$T_{cr^-} - T_i = K_2\sqrt{Er_s}\,d^{-\frac{1}{2}} \qquad \sigma_c = \left(2\mu r_m K_y\right)d^{-\frac{1}{2}} \tag{24}$$

Where T_{cr^-} is critical shear stress; T_i is shear stress of friction; K_2 and K_y are constants; E is modulus of elasticity; r_s is surface energy; d is grain size; σ_c is critical stress; μ is shear modulus; and r_m is energy of expansion in the grain.

Theoretical analysis shows that the finer the grain size is, the larger the critical shear stress and normal stress of crack formation and the higher the work of crack formation are. Therefore, the crack germination is more difficult and the secondary crack is hard to produce at crack tip.

6 SUMMARY

- It is a kind of high efficiency and simple repair method through the heat effect of electromagnetic field to arrest the crack of the remanufacturing blank. In the repair process, it affects only the area of crack, so that the other parts of the blank remain unaffected. Therefore, this method is especially suitable for large-sized remanufacturing blanks.
- For surface crack, the technology can combine with brush plating technology for arresting large depth and length open cracks. It can also combine with laser cladding and welding technology and would be more effective to repair the remanufacturing blank containing cracks.
- How to produce powerful pulse current is a key problem in the crack arrest by electromagnetic heat effect. A series of problems need to be explored and perfected: the relationship between the discharge parameters and the effect of crack arrest, how to import the current into the workpiece, how to improvement the unit volume of stored energy of the discharge equipment and so on.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] Tian, X.L. (2010): Convergence of Remanufacturing & Advanced Manufacturing and Relative Technology, National Defense Industry Press, Reading, Beijing.

[2] Bai, X.Z.; Tian, Z.G.; Zheng, J. (2009): The Electric Heating Effect in Fracture Mechanics National Defense Industry Press, Reading, Beijing.

[3] Jin, X.Q.;Li,H. (2006): On the Analogy Between the Current Density Distribution in a Thin Conductive Plane and the Anti-plane Shear Problem, in MECH in ENG, Vol.28, No.6, pp. 23-27.

[4] Bi, D.X (1985): The Theory of Electromagnetic Field, Electronic Industry Press, Reading, Beijing.

[5] Ding, S.D (1997): Fracture Mechanics, .Mechanical Industry Press,Reading, Beijing.

[6] Ma, X.K. (2002): The Theory and Application of Electromagnetic Field, Xian Jiaotong University Press, Reading, Xi'an.

[7] Kandt,G.S.;Krivtsum,M.G. (1983): Two-dimensional Problems of Themo-elastic for the Bodies with the Cracks, Naukova Dumka, Reading, Kiev(in Russian).

[8] Ramaswaymy,B.; Liu,T.J.C. (1992): Some Recent Trends and Developments in Finite Element Analysis for Incompressible Thermal Flows, in Int.J.Numer.Methods Eng, Vol.35, No.4,pp. 671-707.

[9] Wang,C.J.;Lai, X.S (2006): Research and Analysis on Pulse Discharge Crack Arrest in Welding Junction, in MECH ENG, Vol.73,pp. 73-74.

[10] Masataka, T.S (Japan); Li,A.Z.(transl) (1986): Stress Concentration, Mechanical Industry Press, Reading, Beijing.

Current State and Development of the Research on Solid Particle Erosion and Repair of Turbomachine Blades

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Abstract

Centrifugal compressors, steam turbines and aircraft engines are the three typical high-speed turbomachines. Solid particle erosion is one of the main reasons causing the blades wear failure. In this paper, failure conditions and failure modes of erosion are summarized. The development and status of the theories on the solid particle erosion are reviewed, the primary influencing factors on erosion such as the particle characteristics, environmental condition and materials characteristics are analyzed. The researches on the repair of worn blades are introduced.

Keywords:

Turbomachine Blade; Solid Particle Erosion; Remanufacturing

1 INTRODUCTION

Centrifugal compressors, steam turbines, aircraft engines are typical high-speed turbomachines using gas as the working medium. They are the important mechanical equipments which play important roles in civil production and national defense construction. The blades are the key parts of the turbomachines playing a decisive role in the whole performance of the turbomachines. However, the working conditions of the blades in the centrifugal compressors, steam turbines and aircraft engines are extremely harsh. The blades rotate in high speed under high temperature and high pressure. As a result, even tiny particles will cause solid particle erosion (SPE, Solid Particle Erosion) to the blades. Solid particle erosion refers to a phenomenon or process that a large number of solid particles whose size is less than 1000 μm impact on the material surface with a certain speed and angle carried by high-speed gas, which causes the loss of material [20]. Solid particle erosion will lead to the defect of blade profile line, decrease of efficiency, and will destruct the continuity and mechanical properties of the surface and the near-surface material, and it even brings about micro-cracks near the wounded pits which always account for the blade fracture or major accident.

The impellers of centrifugal compressors, steam turbines and aircraft engines are expensive. In fact, to reduce production costs, many enterprises repair the failure impellers relying on welding, laser cladding and spraying for reuse. As early as 1990s, the United States had made researches on the repair of turbine engine impellers [38].

In this paper, to study the mechanism of the blade erosion and re-manufacturability, the working conditions of the blades in the three machines are analyzed. Failure conditions and failure modes of erosion are summarized. The development and status of the theories on the solid particle erosion are reviewed, the primary influencing factors on erosion such as the particle characteristics, environmental condition, and materials characteristics are analyzed.

2 FAILURE CONDITIONS AND FAILURE MODES OF EROSION

2 Solid Particle Erosion of Centrifugal Compressors

The operating speed range of centrifugal compressor is from 2000 r/min to 80000 r/min, even up to 100000 r/min. The operating temperature is usually from room temperature to 300 °C. The internal pressure of multistage compressor is from 0.1 MPa to 20 MPa. Thus, the impellers work under the typical high-speed, high temperature and high pressure condition.

Solid particles which lead to compressor blade erosion come from two sources: the one is the industrial dust, ground dust, coal smoke and second particulates of the atmosphere in the industrial regions. Centrifugal compressors usually operate in the industrial areas with high concentration of particulate matter in the atmosphere. For example, the mass concentration of TSP (particle size less than 100 μm) is up to 0.6810 mg/m^3 in the Jilin developed area - Hadawan, during the winter heating period. By the research, for air compressor, although the inhaled air is filtered, the particles with diameter near 5 μm can also enter the compressor. And when the filter fault occurs, a large number of solid impurities will enter into the compressor, which will impact the blades driven by high speed airflow and cause solid particle erosion.

Another source is the small metal particles generated in the channel of the compressor. Some scholars have found that due to the unreasonable design of interstage cooler, particles falling off from the aluminum fins scour the high-speed blades constantly, as a result, the trailing edge of the blade becomes thinning seriously, and fatigue cracks appear in the 30 mm distance from the blade trailing edge [5].

Due to the flow field, the inlet, pressure face and the outlet of the first stage impeller are more susceptible to erosion. Slight erosion causes the blade surface roughness to increase, and then pits and furrows appear with the development of erosion. Serious erosion leads to the thinning, jagged edges and fall-block [2-6]. The macroscopic morphology of erosion is shown in Figure 1 and the thinning and fall-block failure are shown in Figure 2 and Figure 3.

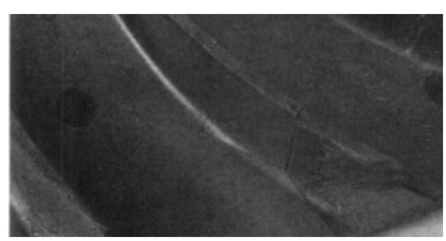

Figure 1: The macroscopic morphology of the worn blades.

Figure 2: The thinning failure of erosive wear blades.

Figure 3: Solid particle erosion of the worn steam turbine blades.

2.2 Solid Particle Erosion of Steam Turbines

The working condition of the modern large turbine blades, especially the rotating blades are extremely harsh. The temperature of the steam around the blades is up to 1700 K. The high-speed rotating blades also bear great centrifugal force, steam pressure and steam force. And there are a number of solid impurities brought by the boiler impact the blades at high speed which leads to solid particle erosion [8].

The high-temperature oxide flaking from the boiler tubes and steam pipe walls accounts for the turbine blades erosion. The main compositions of these oxide particles are α-Fe_2O_3, Fe_3O_4, and some of the alloying elements (Ni, Cr, etc.). Scholars did research on the hydrophobic samples from the boiler and the superheater, and indicated that most of the size of the particles was less than 100 μm. Other scholars also found that there were many small irregular solid particles attached to the medial belt of the damaged impeller, and the large ones had the size from 3 mm to 5 mm, while the small ones had the size less than 1 mm [11-14].

Steam turbines erosion occurs mainly in the regulating stage, high and medium pressure cylinders. The entrance side and ventral side of stationary blades, the dorsal side of the rotating blades and the back side near the outlet of the stationary blades are the area where worse serious erosion occurs.

Especially for the dorsal side of the rotating blades, due to the high speed rotation of the rotating blades, the impact velocity can be up to 120-200 m/s. Under high speed erosion, the rotating blades often become thinning and defect [15].

2.3 Solid Particle Erosion of Aircraft Engines

The aircraft engine blades mainly refer to the rotating blades and guide blades of the compressor and turbine.

Located in the front of the engine, the compressor blades are directly exposed to particulate matter (such as sand, dust, etc.) in the atmosphere. Under the high-speed erosion, the surface integrity of the blade is damaged and even severe deformation or fracture occurs on the blade.

The data shows that the aircraft engines performing tasks in the desert area are easy to endure erosion, for example during the Gulf War, U.S. "Black Hawk" helicopters flying in the desert areas had been faced with serious solid particle erosion owing to the sand that were inhaled into the engines. Erosion causes the destruction of blade profile line, and decreases the efficiency of the engine power.

Turbine blades are located in the combustion chamber, they are the key components that use the high temperature gas to work directly, and also their work condition is extremely harsh.

The carbon particles, carbon black, organic particles, and the particulate matter from the atmospheric, impact the blades in high speed carried by the high temperature gas in the combustion chamber [19]. The high temperature erosion destructs the high temperature coating of the blades and results in pits, trenches and even thinning. Erosion can cause great damage to aircraft engine blades: a low-carbon steel blade with 2 to 3 mm thickness can be worn out in only 2 months [20].

3 MECHANISM AND BEHAVIORS OF SOLID PARTICLE EROSION

The studies show that: the solid particle erosion can be categorized into plastic erosion and brittle erosion. Since 1958 when I. Finnie proposed the micro-cutting theory for erosion, many scholars have proposed different theoretical models for erosion, but up to now, there is still no mode that can fully reveal the mechanism of material erosion. In this paper, several profound erosion theories are introduced.

3.1 Erosion Theory for Plastic Materials

Micro-cutting Theory

I. Finnie was the first one to come up with the micro-cutting theory for plastic metal erosion with rigid particles. This is the first full theory with quantitative description. And the volume erosion rate V changing with the impact angle α can be expressed as follow.

$$V = K\frac{mv^n}{p}f(\alpha) \qquad n = 2.2 \sim 2.4 \tag{1}$$

$$f(\alpha) = \begin{cases} \sin 2\alpha - 3\sin^2\alpha & \alpha \le 18.5^\circ \\ \cos^2\alpha / 3 & 18.5^\circ \le \alpha \le 90^\circ \end{cases} \tag{2}$$

Where m is the mass of the particle, v is the particle velocity, p is the elastic flow pressure between the particles and the target, n is the velocity index.

Experiments have proved that this model successfully explains the erosion behavior of plastic materials with polygonal rigid particles at low impact angle, but has large errors when used to explain the erosion behaviors of brittle materials and plastic materials with spherical particles and high impact angle. Budinskif divided single particle erosion with polygonal particles into four categories: pitting, plowing, shoveling and chipping [29].

Deformation and Wear Theory

In 1963, Bitter [34] proposed that erosion can be divided into deformation wear and cutting wear, and the erosion with 90º impact angle is related to deformation of the target. When the impact stress is less than the yield strength of the material, only elastic deformation occurs; but when the impact stress is greater than the yield strength of the material, the target will undergo elastic and plastic deformation. Based on the energy balance theory, he deduced the equations of deformation wear and cutting wear, and considered the total amount of wear to be the sum of the two. This theory has been verified by the single-particle erosion test. It explains the phenomenon of plastic material erosion reasonably, but lacks the physical model support.

Platelet Theory

Levy et al [35] did research on plastic materials erosion with high impact angle. They analyzed the dynamic process of erosion via the step experiments and single particle tracing method and proposed the platelet theory. Due to the impact of the particle, pits and lips appear on the surface of the target. And then the particles forge the lips constantly. Having experienced serious plastic deformation, the material flakes from the surface.

3.2 Erosion Theory for Brittle Materials

The erosion process of the brittle materials can be divided into two processes.

1. Elastic-plastic deformation occurs near the erosion pit.
2. The surface crack nucleates, expands and fractures.

In 1979, Evans et al provided the elastic-plastic indentation fracture theory. In this theory, they believed that the elastic deformation region is formed in the indentation region. Under load, the intermediate cracks extend downward from the elastic region, and become radial cracks, meanwhile the residual stress causes the lateral cracks to grow if the primary force exceeds the threshold value of the intermediate cracks [27]. And the volume erosion amount formula was deduced as follows:

$$V \propto v_0^{3.2} r^{3.7} \rho^{1.58} K_c^{-1.3} H^{-0.26} \tag{3}$$

Where V is the volume of erosion amount, r is the radius of the particle, v_0 is the velocity of the particle, ρ is the material density, H is the material hardness, K_c is the intensity factor of critical stress. Additionally, the critical speed to cause fracture can be determined by the following formula.

$$V_c \propto K_c^2 H^{-1.5} \tag{4}$$

3.3 Secondary Erosion Theory

Tilly [36] studied the relationship between the fragmentation of the particles and the plastic material erosion using the high-speed camera technique, sieving and scanning electron microscope. He pointed out that the fragmentation of the particles is related to their size, speed and impact angle. The cataclastic particles would cause secondary erosion. This model divided the erosion process into two stages: the first erosion (cutting, chiselling, plowing, squeezing) and secondary erosion caused by the broken particles. And the total erosion rate is the sum of the two. This model can well explain erosion behaviors of brittle materials at high impact angle.

3.4 Influencing Factors on Erosion Behavior

The primary influencing factors on erosion are environmental conditions, particle characteristics and material properties.

Environmental Conditions

(1) The impact angle

The impact angle refers to the angle between the target surface and the incident trajectory of particle, also known as the incident angle or attack angle.

Impact angle has different influences on the erosion rate of the plastic materials and the brittle materials.

For plastic materials there is a peak on the erosion rate with impact angle curve. As the impact angle increases, the erosion rate rises gradually and reduces over the peak. The maximun erosion rate of typical plastic materials (such as pure metals and alloys) appears when the impact angle ranges from 20° to 30°.

But the erosion rate of brittle materials (ceramic and glass) rises as impact angle increases, and reaches a maximum at an impact angle of 90°. The angle for maximum erosion of the other materials is usually between that of plastic and brittle materials.

The relationship between the impact angle and the erosion rate can be expressed as the following equation.

$$\varepsilon = A' \cos^2 \alpha \cdot \sin(n\alpha) + B' \sin^2 \alpha \tag{5}$$

Where ε is the erosion rate, α is the impact angle, n, A', B' are constants. For brittle materials A'= 0, plastic materials B' = 0. And $n = \pi/2\alpha$.

(2) Impact velocity

There is a lower limit for impact velocity when the erosion occurs, which is called the impact velocity threshold. When the impact velocity is below this threshold, only elastic collision occurs without erosion. And this value depends on the particle and material properties. Above this speed, no matter for the plastic materials or the brittle materials, the erosion rate increases as impact velocity rises. A large number of erosion tests show that there is a relationship between the erosion rate and impact velocity as follows.

$$\varepsilon = Kv^n \tag{6}$$

Where v is the impact velocity, K and N are constants. The value of n is related to the properties of the materials. For metal materials erosion with low impact angle, the value of n ranges from 2.2 to 2.4, while that of ceramic materials is about 3 [27]. Numerous studies show that, the angle for maximum erosion is unrelated to the impact velocity, which shows that the impact velocity has no effect on the erosion mechanism.

(3) Erosion Temperature

The variation of temperature causes thermo-physical properties, mechanical properties of the materials to change accordingly, thus affects the erosion behavior. The influence of the environmental temperature on the erosion rate is complicated. For some materials, the erosion rate increases, as temperature rises, but for other materials, the erosion rate decreases with the increasing temperature. The former is easier to be accepted, because the material yield limit declines at high temperature, and the energy used to remove the same volume of material decreases.

There are two kinds of explanations for the latter one. One of the viewpoints is that, at high temperatures, oxide film is formed on the surface of the material, which improves the performance of anti-erosion of the material. But the other point holds that the material plasticity increases with the increasing of temperature, as a result, erosion resistance rises [28].

Particle Characteristics

(1)The particle size

The erosion rate of plastic material grows as particle size increases in a certain range, but when the particle size reaches a critical value (D_c), the erosion rate is almost constant, this phenomenon is known as "particle size effect", and the value of D_c varies from different materials and erosion conditions. There are many explanations to the particle size effect, such as influence of strain rate, influence of deformation zone, the size of surface grain and the influence of the oxide layer. Misra and Finnie [32] has summarized different views, and found the relatively reasonable explanation which holds that there is a rigid thin layer near the surface of materials, small particles can only have an impact on the hard layer. When the particle size is greater than the value of *Dc*, the impact force can penetrate the hard layer and act directly on the base material, the influence of the hard layer disappears, thereby the erosion rate reaches a stable high value. However, this interpretation is not perfect, and lacks supporting data.

The influence of particle size on brittle materials erosion behavior is significantly different from that of plastic materials. The erosion rate rises constantly as particle size increase, and there is no critical value.

(2) Particle shape

The studies of Levy and Ballout showed that for no matter plastic materials or brittle materials, the weightlessness of erosion caused by the sharp corner particles is much heavier than that caused by the spherical particles. Generally believed, sharp corners particles can cause more cutting or plowing. There are two norms to describe the sharp corner particles: the ratio of width to length (W/L) and the ratio of the square of the circumference to area (P^2/A). Bahadur and Badruddini studied the influence of polygonal SiC particles on the erosion behavior of 18Ni martensitic steel, and found that the erosion rate is inversely proportional to the W/L, but proportional to P^2/A.

(3) Particle hardness

The surface hardness ratio between the particles and the material (H_p/H_t) has a major impact on the material erosion behavior. Tabor pointed out that when the value of H_p/H_t is greater than 1.2, the erosion rate of the plastic material is large, and tends to be saturated. When the value of H_p/H_t is less than 1.2, the erosion rate declines as the value of H_p/H_t decreases. Zhang Lei, Mao Zhiyuan et al studied the erosion behaviors of several mold steels with the impact of Al_2O_3 particles and glass sands, and considered that when the particle hardness is higher than or close to the hardness of the material, the erosion is caused by micro cutting and plowing but when the particle hardness is less than the hardness of the material, the impact of particle will cause small pieces to fall off the material.

Material Characteristics

(1) The hardness and strength of the material

From the formula of the elastic-plastic indentation fracture theory we can find that the hardness of brittle materials has a certain influence on the erosion rate, and the increasing of hardness will help improve the erosion resistance of materials when the other parameters remain unchanged. Sundararajan and Manish Roy summarized the researches of recent decades on the influence of strengthening methods to the erosion rate for single-phase metals, alloys and the multiphase alloys at room temperature. They found that, the hardness of pure metal in annealed condition shows a good linear relationship with the erosion rate. But cold working, fine grain strengthening, solid solution strengthening cannot improve the erosion resistance for the single-phase metals. The methods of martensitic hardening, precipitation hardening and dispersion strengthening have unregularly effect on the erosion rate for the multiphase alloys. Most researchers believe that the influence of hardness to erosion is relative for brittle materials. Shipway and Hutchings thought that the elastic-plastic indentation fraction theory has an imperfect estimation for the influence of hardness to erosion considering the impact of H_p/H_t.

Viewing from the existing research results, there are only pure metals and cast iron whose erosion resistance rises with the increasing of hardness (strength). For given erosion situation, it is necessary to study the influence of particle hardness combining with the ratio of H_p to H_t and resort to the experiments.

(2)Plasticity and toughness of materials

For plastic materials, weightlessness of erosion will decrease with the rising of plasticity according to Foley and Levy's research, which is also true for Cu, Cu-Al, Cu-Zn and cast iron. However, other studies have different results, for example, stainless steel with medium plasticity shows the best performance of anti-erosion.

For brittle materials, fracture toughness is a major factor affecting erosive behavior of materials. From the theoretical formula of elastic-plastic indentation and fracture, it can be concluded that fracture toughness has a greater influence on erosion than hardness. And it has also been proved that brittle materials with good toughness, even with relatively low hardness, still show high performance of anti-erosion within a certain range.

(3)Microstructure of materials

Balan's studies on erosion behaviors of grey cast iron, malleable cast iron and ductile iron showed that the performance of resistance to forward-erosion from high to low was in the following order: ductile iron > malleable cast iron > grey cast iron, and the performance of resistance to erosion related to microstructure was in the following order: spherical flake > graphite flake, tempered martensite > lamellar pearlite. For the influence of second hard phase to the erosion behaviors of double-phase alloys or multiple-phase alloys, different researchers have different views. The dominating belief is that the carbide factors such as size, shape, location have a certain influence on the erosion rate, but the influence of carbide factors is less obvious than mechanical properties' influence such as hardness, plasticity. According to Levy's systematic studies about the influence of carbide content to plastic materials' erosion resistance, the performance of material's anti-erosion decreases with the rising of carbide content, and when the carbide content achieves around 80%, materials show the opposite trend because of the formation of continuous carbide-framework.

For brittle materials, it is generally considered that it can improve the material's ability to resist erosion to have low porosity and fine grain, because the presence of defects such as pores tends to lead to the nucleation and growth of cracks in these parts and more pores lead to the wastage of materials easily. The presence of fine grain leads to the increase of grain boundary, consequently limits the extension of the crack.

4 THE REPAIR OF WORN BLADES

The manufacturing process of the three kinds of turbomachines impellers is complex and expensive. The price of each stage impeller in whether centrifugal compressors or aircraft engines is up to hundreds of thousands or even millions Yuan. Replacing impellers in case of discovering wear will squander the resource and increase the productive cost. But if we repair and remanufacture the worn portion of impellers by adopting the advanced repair technology, and restore their original performance, it will improve the using life of machines and their economy. For a long time, the repair technologies of aircraft turbine blades have been actively studied in the United States, Britain, Germany and the Netherlands. Generally considered, when the expenses of repairing blades is less than the 70% of the cost to replace the blade, the repair work is totally worth it [39]. Many scholars and enterprises have made experimental exploration in this area. Arc welding, argon-arc welding, plasma welding, cold welding and laser cladding were proposed to repair worn blades.

Li-burdi Company has used argon tungsten arc welding surfacing technology to repair the blades of aircraft turbine in 1990s. GE

Company used plasma welding to repair turbine blades tip with Rene142 alloy. Panzhihua Iron and Oxygen Plant used multi-channel arc welding surfacing technology with austenitic stainless steel electrodes to repair the worn blades of DH-80 centrifugal air compressor and the maximum size of the repaired defects was 10 mm [41].

The heat-affected zone of the conventional welding is great, and it is easy to cause blades deformation. Usually the parts need to be preheated before welding and treated by aging treatment after welding. Cold welding surfacing technology utilizes the discharge of high-frequency sparks to make the electrode and the work-piece melt partially, and become alloying and cladding solidification. Cold welding surfacing has an extremely short discharge time (several microseconds to several milliseconds) but a high current density. It begans to be noticed and adopted because of its excellent features such as small thermal effect area, high bonding strength and low repair costs.

Li Zhongwei [42] repaired the large steam turbine impellers with surface abrasion and corrosion, using cold weld surfacing technology. The impeller has been operating normally, until it retired in 2007. It proved that cold welding surfacing technology can be fully qualified for the repair of steam turbine impellers. Wu Zhixing repaired the worn blades of VK50-3 air compressor with cold welding surfacing technology. After restoration, it had been installed and tested successfully, and had run steadily for nearly a year without deterioration trend.

Laser cladding technology makes use of the high-power laser to gather high energy. And micro area on the surface of work-piece will be melted, the micro-melted layer is thin, at the same time, the alloyed powder prepositioned on the surface is completely melted, as a result, a dense cladding layer combined with the matrix by metallurgical bonding is obtained. Laser cladding guarantees dense tissue, small heat affected zone, well combined and no defect. Also it is easy to realize automated control and widely adopted in the impeller repair.

Huang Wei [43] repaired a serious worn blade damaged by solid particle erosion of centrifugal compressor in Nanjing Meishan Steel Company. After buffing treatment, laser cladding, machining and testing, the impeller almost met all the requirements of the new rotor. It was tested successfully after installation and run well so far.

Zhang Wei [45] made a research on laser cladding repair and alloy strengthening of a worn turbine blade, and sampled blade after experiment. He analyzed the microstructure, hardness, erosion resistance of the blade. The results showed that the laser cladding layer and the matrix material was combined tightly, the average hardness of repair layer was 350HV0.2 and the average hardness of alloy strengthening layer was 800HV0.2, the erosion resistance of repair layer and alloy strengthening layer were increased above 1 times and 3 times compared to base material of the blade. The performance of repaired and strengthened blade was better than the new ones. It could improve the service life of the blade greatly.

Wang Dingjiang [39] studied the laser cladding process of the worn aircraft engines blades with Ni-based powders, and inspected the qualities of the repaired blades. Room temperature and high temperature tensile tests showed that the strength properties of the repair site had reached or exceeded the matrix material. Observed at the electron micro-scope, the repair tissue was fine and dense and most of the grains were columnar crystals. The actual test showed that the blade could work steadily for a long time and satisfy the service requirements.

In addition, because of the harsh working conditions, coating technology is applied on the aircraft engines and steam turbine blades to improve their performance to resist antioxidation, corrosion and erosion. For these blades, after repaired, the coatings also need be repaired. The types of the coatings applied in aircraft engines blades include anti-oxidation coatings, corrosion-resistant coatings, thermal barrier coatings and wear-resistant coatings. While anti-oxidation coatings and anti-erosion coatings are applied in steam turbine blades. The coating preparation process includes diffusion metallizing, thermal spraying, physical deposition and chemical deposition.

5 SUMMARY

- The impellers of centrifugal compressors, steam turbines and aircraft engines work under the typical high-speed, high temperature, high pressure conditions. Due to the existence of industrial dust, oxide particles and sand dust in the working medium, solid particle erosion of the blades becomes inevitable. Slight erosion causes the blade surface roughness to increase, and then pits and furrows appear with the development of erosion. Serious erosion leads to the blade thinning, jagged edges and fall-block.
- There are several theories to explain the mechanism of solid particle erosion including: micro-cutting, deformation and wear, platelet, elastic-plastic indentation fracture and secondary erosion. But up to now, there is still no mode that can fully reveal the mechanism of material erosion. The impact angle, impact velocity, erosion temperature, particle size, particle shape, particle hardness, the hardness, plasticity and microstructure of the materials are the main factors influencing the erosion behavior.
- The impellers of centrifugal compressors, steam turbines and aircraft engines have complicated manufacturing processes and high price. The repair and re-manufacturing of the worn impellers is an inevitable trend. Many restoration researches of scholars and enterprises show that arc welding, argon-arc welding surfacing, cold welding surfacing, laser cladding technology can be used to repair the worn impeller.

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7 REFERENCES

[1] Zhang, Z. Y.; Lu, J. H. (2010): Research Status and Development of Turbomachinery Blades Erosion in Theory and Experiment, in: Shahai University of Engineering Science Journal, Vol. 24, No. 4, pp. 305-309.

[2] Qu, X. B.; Chen, J. M.; Zhou, H. D.; Ye, Y. P. (1999): Current State and Development Trend of the Research on Material Wear Failure and Failure Prevention, in: Tribology, Vol. 19, No. 2, pp. 187-192.

[3] Xu, Y. T. (2007): Theory and Prevention of Solid Particle Erosion in Critical (Supercritical) Unit, in: Power System Engineering, Vol. 23, No. 5, pp.1-4.

[4] Lan, H. F. (2010): Failure Analysis of Centrifugal Compressor Operation, in: Applied Science and Technology, Vol. 6, No. 1, pp. 23-25.

[5] Ma, X. M.; Hu, L. X. (2011): Failure Analysis on Fracture of Impeller Blades of High-speed Centrifugal Aircompressor, in: Testing, Vol. 47, No. 8, pp. 527-533.

[6] Sheng, Q.; Wang, S. T.; Hu, L. (2005): Analysis of Centrifugal Air Compressor Running Failure, in: Wind Turbine Technology, Vol. 5, pp. 51-53, 57.

[7] Wang, Z. M.; Shang, E. F; Xue, S. H.; Wang, Y. Q. (2009): Fracture Failure Analysis on Primary Impeller Blades of Vertical Air Compressor, in: Testing, Vol. 45, pp. 224-227.

[8] Wu, Y. K.; Shang, J. E. (1995): Common Failure Mode of Steam Turbine Blades and the Research Status, in: Steam Turbine Technology, Vol. 37, No. 6, pp. 362-367.

[9] Robert,P.; Dewey, F. (1985): Survey of Blade Failure in Turbine Genarator Units, in: EPRI cs-4001, Vol. 121, pp. 475-479.

[10] Jin, W. L. (2000): Study on Quality Cheeking Methods of Steam Turbine Blades with Failure Analysis and Remedies, in: Journal of Power Generation Equipment, Vol. 1, pp. 5-7,36.

[11] Zhu, B. T. (2003): Reducing Solid Particle Erosion Damage in Flow Passage of Steam Turbine, in: Journal of China Electric Power, Vol. 38, No. 5, pp. 27-30.

[12] McCloskey T.; Bellanca C. (1989): Minimizing Solid Particle Erosion in Power Turbines, in: Power Engineering, Vol. 93, No. 8, pp. 35-38.

[13] Han, Y.; Zhang, J. L. (2005): The Solid Particle Erosion Analysis of 362 MW Steam Turbine Flow Passage, in: Journal of Hunan Electric Power, Vol. 5, No. 1, pp. 50-52.

[14] Pan, W. J.; Zhang, C. M. (2010): Wear Analysis of the 250MW Steam Turbine Blades, in: Journals of Heilongjiang Science and Technology Information, Vol. 2, pp. 2.

[15] Wang, S. Z. (1995): SPE Wear and Preventive Measures of Super (Sub) Critical Steam Turbine, in: Journal of North China Electric Power Technology, Vol. 4, pp.56-59.

[16] Feng, W. Z. (2007): Comprehensive Prevention of Steam Oxidation and Solid Particle Erosion for the Ultra—Supercritical Unit, in: Electric Power, Vol. 40, No. 1, pp.69-73.

[17] Shi, J. Y.; Yang, Y.(2003): Research on Solid Particle Erosion of Ultra—Supercritical Steam Turbines, in: Journal of Power Engineering, Vol. 4, pp.2487-2489,2597.

[18] Fu, G. R.; Yu, Z. M.; Wang, H. W. (2006): Main Farlure Attributes and Rule of Compressor-blades in Aero-engines, in: Failure Analysis and Prevention, Vol. 1, No. 1, pp. 18-24.

[19] Xu, X. Y.; Zuo, T. Y.; Liu, S. S. (2000): The Surface Failure and Protective Coatings Technology of Gas Turbine Engies, in: Aviation Engineering and Repair, Vol. 6, pp. 21-23.

[20] Sun, J. S. (1992): Wear of Metals, Metallurgical Industry Press, Bei Jing.

[21] Jilbert, G. H; Field, J. E. (2000): Synergistic Effects of Rain and Sand Erosion, in: Wear, Vol. 243, pp.6-17.

[22] Lv, F. J.; Fu, G. R.; Chen, R.; Li, Q. (2001): Fracture Analysis of Second-stage Aero-engine Compressor Blade, in: Journal of Aerospace Power, Vol. 16, No. 4, pp. 327-330.

[23] Morini, M.; Pinelli, M.; Spina, P. R. (2010): Influence of Blade Deterioration on Compressor and Turbine Performance, in: Journal of Engineering For Gas Turbines Power, Vol. 132, No. 3, pp. 032401-032411.

[24] Hamed, A; Tabakoff, W.; Rivir, R. B. (2005): Turbine Blade Surface Deterioration by Erosion, in: Journal of Turbomach, Vol. 127, No. 7, pp. 445-452.

[25] Liu, J. J.(1993): Principles of Material Wear and Its Wear Resistance, Tsinghua University Press translation, Beijing.

[26] Shao, H. S.; Qu, X. J. (1992): Friction and Wear, Coal Industry Press, Beijing.

[27] Dong, G.; Zhang, J. Y. (2003): Developments of Reserch on the Solid Particle Erosion of Materials, in: Journal of Materials Science & Engineering, Vol. 21, No. 2, pp. 307-312.

[28] Ma, Y.; Ren, J.; Li, Y. D. (2005): Development of Research on Erosion of Materials, in: Journal of Lanzhou University of Technology, Vol. 31, No. 1, pp. 21-25.

[29] Mu, J.; Li, J.; Guo, S. Y. (1994): Development of Research on Erosion of Metallic and Ceramic Materials, in: Materials Science & Engineering, Vol. 12, No. 2, pp. 9-15.

[30] Hutchings, I. M. (1981): A Model for the Erosion of Metals by Spherical Particles at Normal Incidence, in: Wear, Vol.70, pp. 269-281.

[31] Bahadur, S.; Badruddin, R. (1990): Erosion Particle Characterization and the Effect of Particle Size and Shape on Erosion, in: Wear, Vol.138, pp. 189-208.

[32] Misra, A.; Finnie, I. (1981): On the Size Effect in Abrasive and Erosion Wear, in: Wear, Vol.65, pp. 359-373.

[33] Huss, A. I.; Kubarsepp, J.; Pirso, J. (2001): Mechanical Properties and Features of Erosion of Cermets, in: Wear, Vol. 250, pp. 818-825.

[34] Bitter, J. G. (1963): A Study of Erosion Phenomena, in: Wear, Vol. 6, pp. 5-21.

[35] Levy, A. V. (1988): The Erosion of Structure Alloys, Cerametș and Insitu-oxide Scales on Steels, in: Wear, Vol. 127, pp. 31-52.

[36] Tilly, G. P. (1973): A Two Stage Mechanism of Ductile Erosion, in: Wear, Vol. 23, pp. 87-96.

[37] Finnie, I. (1995): Some Reflections on the Past and Future of Erosion, in: Wear, Vol.186-187, pp. 1-10.

[38] Liu, J.; Wang. J. (1994): Discussion on Welding and Repair Techniques for Aero-engine Turbine Blade Tip, in: Aircraft Engine, Vol. 2, pp. 46-50.

[39] Wang, D. J.; Xia, C. B.; Wang, D. F. (2010): A New Repaire Process of Aero Engine Turbine Lamina Crack Based on Laser Cladding Technology, in: New Technology and New Process, Vol. 8, pp. 72-74.

[40] Sun, H. G.; Huo, W. J. (2001): Repair Technologies for Blades of Aero-engine Turbine, in: Aviation Maintenance, Vol. 6, pp.12-14.

[41] Wang, Z. Y.; Yin, K. L. (1999): Reparation of Blade Wheels Corroded by Impingement of DH-80 Turbine Air Compressor, in: Metallurical Power, No. 2, pp. 50-51.

[42] Li, Z. Y.; Fan, J. C. (2007): The Crack Analysis and Repair Measures for Centrifugal Compressor Impeller, in: Blower Technology, Vol.5, pp.34-38.

[43] Huang, W. (2011): Laser Cladding Technology in Air Compressor Impeller Repairation, in: Chemical Machinery, Vol. 38, No. 3, pp. 62-63.

[44] Li, Z. W.; Zheng, X. F. (2008): Application of Electro Spark Deposition on Damaged Bearing Section of Turbine Rotor, in: North China Electric Power, No.7, pp. 38-40.

[45] Zhang, W.; Yao, J. H.; Dong, C. H.; Tang, X. D.; (2008): Repairing and Strengthening of Eroded Turbine Blades by Laser Technology, in: Journal of Power Engineering, Vol. 28, No. 6, pp. 967-971.

Thermodynamic Research on $SCCO_2$ Cleaning Process of Remanufacturing

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Abstract

In cleaning system, the difference between free energy of supercritical fluid CO_2 and solid phase is just the driving force to conduct the cleaning processes. The entropy, thermal capacity and enthalpy of every component under supercritical state are calculated by using Benedict Webb Rubin (BWR) equation. The cleaning powers of $SCCO_2$ system in the different condition are calculated. The ideal ranges of pressures and temperatures of a $SCCO_2$ cleaning system are discussed at which maximum cleaning efficiency can be received with minimum operational costs. The research results contribute to speed $SCCO_2$ cleaning from laboratory or pilot-scale testing to industry implementation.

Keywords:

Remanufacturing; Cleaning; Supercritical carbon-dioxide ($SCCO_2$); Free energy; Cleaning efficiency

1 INTRODUCTION

Remanufacturing is a process of bringing broken assemblies to a "like-new" functional state by rebuilding and replacing their component parts. Cleaning is an important remanufacturing process to remove the contaminants from the parts. There are lots of cleaning methods such as Ultrasonic cleaning, Abrasive blasting, Spray washing, Supercritical carbon-dioxide ($SCCO_2$) cleaning, etc. Among them, $SCCO_2$ cleaning gets more and more attentions, since CO_2 is non-flammable, virtually inert, and is not an ozone-depleting compound [1, 2].

However, $SCCO_2$ cleaning theory has not been completely explored yet [3]. At certain temperature, pressure and reactants, the thermodynamic theory is powerful tool to analyze and quantify the energy value of a system [4]. In order to design optimized supercritical processes, Kurnik and Reid [5], Goldman et al. [6] developed thermodynamic models based on the cubic equations of state. The Patel–Teja (PT) different equations of state (EoS) was first used by Sheng et al. [7] with modified Huron–Vidal mixing rule to estimate the solubilities of aromatic compounds in supercritical carbon dioxide. Huang et al. [8] applied mixing rules with the UNIFAC activity coefficient model to calculate the solid solubilities of aromatic, fatty acid and heavy alcohol compounds in supercritical CO_2. Gutowski et al. made early contributions in developing enthalpy based models for manufacturing. Such as, calculating the minimum exergy requirements for the preparation of single walled carbon NT (HiPco process) based on standard chemical exergy model [9]; developing Specific energy calculation method for machine tool based on entropy, enthalpy and exergy[10].

This paper explains the phenomenon of $SCCO_2$ cleaning from thermodynamics point of view. The cleaning abilities of $SCCO_2$ system in the different condition are calculated. The ideal ranges of pressures and temperatures for operating a $SCCO_2$ cleaning system are discussed. Maximum and minimum cleaning efficiency and optimal experiment conditions have been obtained from analysis.

2 BASIC THEORY

2.1 Cleaning Character of $SCCO_2$

$SCCO_2$ is a fluid state of carbon dioxide where it is held at or above its critical temperature and critical pressure[11]. It has the unique ability to diffuse through solids like a gas, and dissolve materials like a liquid. Carbon dioxide usually behaves as a gas in air at standard temperature and pressure (STP), or as a solid called dry ice when frozen. If the temperature and pressure are both increased from STP to be at or above the critical point for carbon dioxide, it can adopt properties midway between a gas and a liquid. More specifically, it behaves as a supercritical fluid above its critical temperature (304.25K / 31.25ºC) and critical pressure (7.38MPa /72.9atm), expanding to fill its container like a gas but with a density like that of a liquid. This kind of character makes $SCCO_2$ becoming an important commercial and industrial solvent due to its role in chemical extraction and dissolution in addition to its low toxicity and environmental impact.

2.2 Cleaning Force

In different cleaning process, the cleaning force is different. There are six kinds of cleaning forces: dissolving force, surface active force, chemical reaction force, adsorption force, physical force and enzyme force. Among them, dissolving force refers cleaning liquid solvents dissolve contaminants and steady dispersion contaminants into the cleaning liquid. Dissolving process contains complicated physical and chemical change, the law of dissolved theory has not yet gotten a perfect research. The most practical experience rule is similar miscibility. The similar usually refers to the chemical composition similar, including solvent and solute molecules elements similar, molecular structure, molecular polarity similarity etc.

The $SCCO_2$ cleaning technology is applied the principle of dissolving solution, but comparing to the existing remanufacturing cleaning technology, it not only realizes the separation of the contaminants and cleaner, but also avoids the pollution of the environment. The importance of cleaning process is overcoming the surface adhesion force and achieving of contaminants and cleaning object and achieving the purpose of the removal of contaminants. In $SCCO_2$ cleaning, it is difficult to ensure the value of dissolving force, and there are no accepted scientific methods to calculate the degree of cleaning.

2.3 Second Law of Thermodynamics

Second law of thermodynamics indicates that heat always flows from a substance of higher temperature to a substance of lower temperature, and any spontaneous process results in an increase of entropy [12]. Material system always changes from the state of higher energy to lower state spontaneously at the condition of isothermal-isobaric. As to the system of $SCCO_2$ cleaning, the difference between the supercritical carbon-dioxide and contaminants is the key of cleaning process. If the free energy of contaminants is higher than that of $SCCO_2$, the contaminants will change to the low-energy state and will remove spontaneous. The difference of free energies between $SCCO_2$ and contaminants is the driving force which promotes cleaning happening.

3 CLEANING MECHANISM OF $SCCO_2$

3.1 Calculation of Free Energy Difference

In thermodynamics, the free energy is a thermodynamic potential that measures the "usefulness" or process-initiating work obtainable from a thermodynamic system at a constant temperature and pressure. Free energy was originally defined graphically [13]. Three coordinates of the entropy, volume and energy to represent the state of the body, defined on three figures [14-15].

Thermodynamics indicates that physical condition is different, and the free energy is also different. The free energy of material system can be expressed as follows,

$$G = H - TS \tag{1}$$

where *H* is enthalpy, *T* is thermodynamic temperature, *S* is entropy. *H=U+pV,* where *U is* thermodynamics energy, also named Internal Energy which is the all energy inside the system. *p* is the pressure of the system, *V* is the volume of the system.

No matter what kind of state the substance in, the free energy will change while the temperature and pressure changes. Another equation can be derived from Equation (1),

$$dG = Vdp - SdT \tag{2}$$

Since supercritical cleaning process is usually under the isobaric state, *p* can be defined as a invariant, *dp=0*, Equation (2) can be abbreviated as another equation,

$$dG = -SdT \tag{3}$$

Entropy is a parameter of physical significance which represents the degree of the atomic-arrangement randomness of a material. Atomic activity capacity enhances when the temperature rises, and the confusion degree of the atomic-arrangement increases. The free energy also reduces immediately with the temperature rising. Figure 1 shows the curve of two phase free energy changing with the change of temperature.

As for cleaning system, the randomness of $SCCO_2$ atomic arrangement is more closely than that of solid contaminants. $S_S < Sco_2$. It illustrates that the free energy curve of $SCCO_2$ slopes faster than that of solid phase. When $G_S = Gco_2$, two phase will coexist in thermodynamic equilibrium state, and the temperature is theoretical minimum cleaning temperature, called T_m.

3.2 The Calculation of Entropy, Thermal Capacity and Enthalpy

The equations used to calculate the entropy, thermal capacity and enthalpy of $SCCO_2$ system have been obtained by professor Xue who uses the program Gaussian98 [16]. Equations are as follows:

$$S = S_0 + \left[\int_{T_0}^{T} C_P \frac{dT}{T}\right]_{P_0} + \left[\int_{V_A}^{V_B}\left(\frac{\partial P}{\partial T}\right)_V dV\right]_T \tag{4}$$

$$C_P = C_V - T\frac{\left(\frac{\partial P}{\partial T}\right)_V^2}{\left(\frac{\partial P}{\partial V}\right)_T} \tag{5}$$

$$H_{f,B} = H_{f,0} + \left[\int_{T_B}^{T_A} C_P dT\right]_{P_0} - \left\{\int_{V_A}^{V_B}\left[P - T\left(\frac{\partial P}{\partial T}\right)_V\right]dV\right\}_T + PV_B - P_0V_A \tag{6}$$

where S_0, T_0 and P_0 are the values of the standard state. V_A, V_B are the volumes under the temperature of T_0 and T, respectively. $H_{f,B}$ is the standard enthalpy of formation, C_v is the thermal capacity under the condition of 101.3 Kpa, 400K.

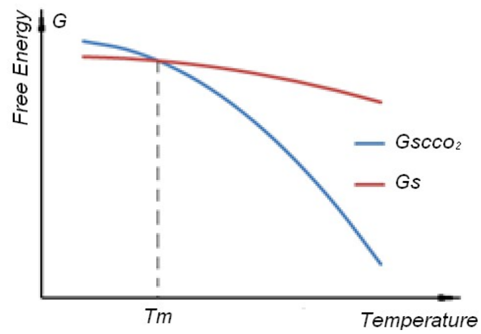

Figure 1: The schematic diagram of two phase free energy changing with temperature in cleaning system.

3.3 The Calculation of $SCCO_2$ Free Energy

In the calculation of the thermodynamic properties of pure substance, P-V-T state function acts an important role. The fitting degree of the model directly affects the calculation accuracy of the thermodynamic properties. Benedict Webb Rubin (BWR) equation [17] is a widely used fluid state equation based on measured data,

$$p = \frac{RT}{v} + \left(B_0RT - A_0 - \frac{C_0}{T^2}\right)\frac{1}{v^2} + (bRT - a)\frac{1}{v^3} + \frac{a\alpha}{v^6} + \frac{c(1+\gamma/v^2)}{T^2v^3}e^{-\gamma/v^2} \tag{7}$$

Where *p is* the pressure, *T* is the temperature, *v* is the mole volume, A_0, B_0, C_0, *a*, *b*, *c*,*α* and γ are experience parameters.

The entropy, thermal capacity and enthalpy of every component under supercritical state are calculated. According to experimental data [18, 19], the free energy of $SCCO_2$ under different P-T condition can be gained by using equation (1) to (6). The Free energy of solid contaminants can obtain from the related thermodynamic manual or use Thermo Calc, Factsage or HSC calculation. Relevant data are showed in Table 1.

4 ANALYSIS OF $SCCO_2$ CLEANING ABILITY TO CA_3SIO_5

In order to analysis the cleaning ability of $SCCO_2$, we select Ca_3SiO_5 as the research object and compare the free energy of two materials under the condition of 80bar and 300bar, temperature from 310 K to 600K, shown in Figure 2.

T/K	P/bar	Cp/J·K^{-1}mol^{-1}	S/J·mol^{-1}K^{-1}	H/J·mol^{-1}	G/J·mol^{-1}
310	80	55	144	384.3	339660
320	80	85	148	385.3	337940
330	80	126	151	386.4	336570
340	80	187	154	387.5	335140
350	80	504	157	388.8	333850
360	80	801	161	389.8	331840
370	80	1187	163	391.1	330790

Table 1: The free energy of $SCCO_2$ under different P-T condition.

As can be seen from the graph, the difference of free energy between the $SCCO_2$ and Ca_3SiO_5 is so obviously. The transition of solid contaminants from higher free energy state to lower happens easily for the great energy gradient between the two materials. Solid contaminants will break away from the base and the purpose of cleaning can be achieved.

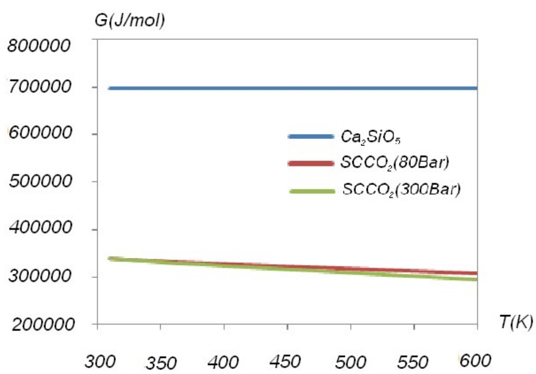

Figure 2: The free energy of $SCCO_2$ and Ca_2SiO_5 under the condition of 80Bar and 300bar, temperature from 310 K to 600K.

From Figure 2, we can see the change of free energy is not obviously with the raise of temperature of Ca_3SiO_5. This is because the atomic arrangement of solid contaminants is so close that atomic activity ability is restricted, and does not easily fluctuation with temperature changing. There is 1700J/mol decrease of free energy of Ca_3SiO_5 from temperature 310K to 600K. In comparison, free energy changing of $SCCO_2$ is larger. With the increase of the pressure, this kind of change is more obvious. This is because the activity ability of $SCCO_2$ particles increase drastically as the temperature increases. Meanwhile both the confusion degree of atomic arrangement and the value of entropy increase evidently. With the increase of the pressure, the internal energy of $SCCO_2$ reduces gradually and the increase rate of enthalpy value drop down accordingly. The decreasing amplitude of free energy in the high pressure is much larger than that in the low pressure. There is a decrease about 42427J/mol from temperature 310K to 600K under the condition of 300bar and about 33204J/ mol under the condition of 80bar.

The second phenomenon can be seen from Figure 3, the free energy values of $SCCO_2$ under two kinds of pressure conditions are similar. The difference of free energy is only 620J/mol under the condition of 310K. It shows that the influence of adjusting the pressure is not significant to the cleaning system in the normal temperature. As the temperature increases, the difference of free energy between the $SCCO_2$ and solid pollutions increase, and the cleaning effect will be more obvious.

Through the data analysis, the third phenomenon can be concluded that at the same temperature the different between the free energies of $SCCO_2$ of different pressure is very little. The maximum value is near to 10943J/mol under the different pressure, which is much less than that of different temperatures at the same pressure condition. This shows that it is a better way by adjusting the pressure to enhance cleaning effect in the cleaning system than adjusting the temperature.

Another phenomenon can be seen from Figure 3, the difference of gradient among three curves is not obvious, and it is hard to obtain T_m which is the minimum cleaning temperature in theory. We can draw the conclusion that the $SCCO_2$ cleaning is available to the solid contaminants of Ca_3SiO_5 in the current work conditions.

It can be predicted that the best cleaning condition to $SCCO_2$ and Ca_3SiO_5 is 80Bar and 310K from the aspects such as economy, cleaning effect, etc.

5 SUMMARY

The work condition of the Supercritical carbon-dioxide ($SCCO_2$) system at 310~600 K and 80~300 bar is chosen to analyze the thermodynamics problems of cleaning process. In the constant temperature and constant press process, physical system always changes from the status of higher free energy to the status of lower. Energy gradients of each component in the system will be obtained and the thermodynamics mechanism of $SCCO_2$ cleaning the deposit sediments will be explained. The research results are as follows:

(1) Through establishing the free energy function of the physical, free energies of two kinds of material are analyzed and calculated. By comparing the difference of two free energies, whether cleaning process will conduct can be judgment, and cleaning efficiency can also get an initial judgment. (For materials with similar chemical, physical properties)

(2) With the temperature increasing, free energy of supercritical carbon dioxide gradually reduces. In temperature range 310~600 K, the free energy of supercritical carbon dioxide decreases 42427 J/mol at 300 bar, and the free energy of supercritical carbon dioxide free decreases only 33204 J/mol at 80 bar.

(3) In the condition of normal temperature, the pressure adjusting shows small significant on cleaning efficiency. In the cleaning process, pressure adjusting gets much lower effect then temperature adjusting to enhance cleaning ability.

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7 REFERENCES

[1] Hale S. J. (1993) Supercritical fluid carbon dioxide cleaning of plutonium parts. LA-UR-93-3103.

[2] Crag M. V.; Tayor L. S.;Rubin J. B. (1997) Supercritical fluid carbon dioxide cleaning of nuclear weapon components. LA-UR-97-4420.

[3] Russdick E. M.; Poulter G A.; Adkins L J.; et al. (1994) Corrosive effects of supercritical carbon dioxide and cosolvents on metals. DE94–012921.

[4] Torres-Huerta A. M.; Vargas-Garcia J. R.; Dominguez-Crespo M. A.; Romero-Serrano J. A. (2009) Thermodynamic study of CVD-ZrO2 phase diagrams, J. Alloy. Compd. Vol.483, pp. 394–398.

[5] Kurnik R.T.; Reid R.C. (1982) Solubility of solid mixtures in supercritical fluids, Fluid Phase Equilibria, Vol. 8, pp. 93–105.

[6] Goldman S.; Gray C.G.; Li W.; Tomberli B.; Joslin C.G. (1996) Predicting solubilities in supercritical fluids, J. Physical Chemistry, Vol.100, pp. 7246–7249.

[7] Sheng Y.J.; Chen P.C.; Chen Y.P.; Wong D.S.H. (1992) Calculations of solubilities of aromatic compounds in supercritical carbon dioxide, Industrial & Engineering Chemistry Research, Vol.31, pp. 967–973.

[8] Huang C.; Tang M.; Tao W.; Chen Y. (2001) Calculation of the solid solubilities in supercritical carbon dioxide using a modified mixing model, Fluid Phase Equilibria, Vol.179, pp. 67–84.

[9] Gutowski T.; Liow, J. L.; Sekulic, D. P. (2010) Minimum Exergy Requirements for the Manufacturing of Carbon Nanotubes, presented at the IEEE International Symposium on Sustainable Systems and Technology, Washington D.C.

[10] Gutowski T. (2007) The Carbon and Energy Intensity of Manufacturing. 40th CIRP International Manufacturing Systems Seminar at Liverpool University, May 30-June 1.

[11] Takao I.; Yoshio O.; Hiroshi I. (2004) Performance of air filters cleaned by supercritical carbon dioxide, Separation and Purification Technology, Vol. 40, pp. 41–46

[12] Bejan A. (2006). Advanced Engineering Thermodynamics, Wiley. ISBN 0-471-67763-9

[13] Gibbs J. W. (1873) Graphical Methods in the Thermodynamics of Fluids, Transactions of the Connecticut Academy of Arts and Sciences.

[14] Gibbs J. W. (1873) A Method of Geometrical Representation of the Thermodynamic Properties of Substances by Means of Surfaces, Transactions of the Connecticut Academy of Arts and Sciences 2, Dec. 1873, pp. 382–404

[15] Maxwell J. C., Garber E., Brush S. G.; et al (1995), Maxwell on heat and statistical mechanics: on "avoiding all personal enquiries" of molecules, Lehigh University Press, p. 248.

[16] Xue W. D.; Zhu Z. H.; Zou L. X.; et al. (2002) Theoretic calculation on thermodynamic character for carbon dioxide. Chinese Journal of Atxmfic and Molecular PhyNcs, Vol. 19, No. 1, pp. 24–26.

[17] Benedlct M.; Webb G B.; Rubin L. C. (1940) An empirical equation for thermodynamics properties of light hydrocarbons and their mixtures. Chem. Phys., Vol. 8, pp.334–345.

[18] AnguS S.; Armstrong B.; Reuck K. M. de. (1976) International thermodynamic tables of the fluid state carbon dioxide. Pergamon, pp.108–156.

[19] Xue W.D.; Zhu Z. H.; Zou L. X.; Zhang G. F. (2004) Theoretic calculation on thermodynamic character for SCF CO_2, Journal of Atomic and Molecular Physics. Vol. 21, No. 2, pp. 295–26.

Study on Remanufacturing Cleaning Technology in Mechanical Equipment Remanufacturing Process

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Abstract

The cleaning technology plays an important role in product quality during the remanufacturing processing. The availability, quality, remanufacturing cost and the remaining life of the remanufactured product will be directly influenced by various cleaning methods and the corresponding cleaning quality. In the meantime, the introduction of cleaning also brings contamination to the remanufacturing processing, which restricts its engineering application. Therefore, with the study of cleaning methods those are suitable for remanufacturing process, the fundamental concepts of remanufacturing cleaning technology were introduced in this paper, and the major cleaning technologies for each stage in the remanufacturing stage were described, which is beneficial to find out the optimize cleaning method in actual production and realize the real green remanufacturing.

Keywords:

Remanufacturing; Fouling; Cleaning Technology; Green Cleaning

1 INTRODUCTION

Green manufacture, environmental protection, sustainable development and recycling have been drawing the world's attention in recent years. In this context, remanufacturing as a specific type of recycling makes the fact that the used durable goods can be repaired to be like-new realized [1]. Therefore, remanufacture engineering has become the tendency and played a significant role in the development of the advanced manufacturing technology. Remanufacturing is such an industry that it concerns the high-tech restoration and transformation of discarded mechanical and electrical products, of which the scrapped parts will be redesigned and remanufactured on the basis of performance failure analysis and life assessment analysis so as to achieve or exceed the qualities of new products. For this reason, remanufacturing is environmentally friendly because it maintains the raw material, saves the energy, reduces environmental pollution and preserves the land from the disposal of waste materials. On the other hand, remanufacturing contributes greatly to the social sustainable development by creating new productive jobs. Consequently, remanufacturing has become a key strategy for sustainable development [2].

The technological process of remanufacturing is shown in Figure.1. It can be found that the core (the used/worn-out/broken products that enter the remanufacturing process are referred to as 'core' [3].) passes through a number of remanufacturing steps such as disassembly, cleaning, inspection & sorting, reconditioning, testing, reassembly and painting & packing. As can be seen from Figure.1, cleaning is among the most demanding steps and is a particularly essential process in remanufacturing because the quality of core surface cleanliness directly determines the parts surface analysis and the following process as surface inspection, reconditioning, reassembly and painting processing. In the meantime, remanufacturing cleaning is often the main source of pollution in the remanufacturing process. And that is, the cost, quality and environmental performance of remanufactured products are closely related to the remanufacturing cleaning process. Therefore, remanufacturing cleaning is a crucial step but is often neglected during remanufacturing process optimization at present.

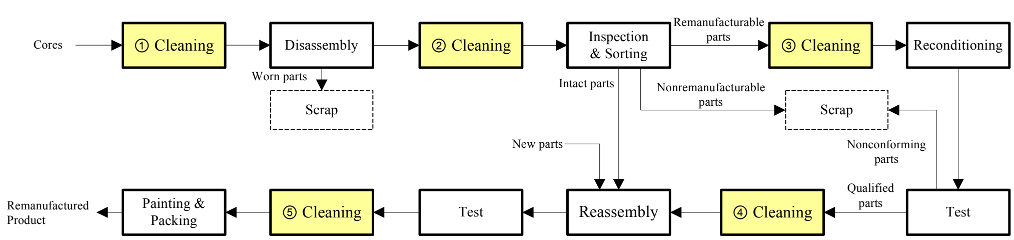

Figure 1: Common technological process of remanufacturing.

Cleaning in remanufacturing is an industrial process for the reduction of the quantity of contaminations present in or on a component until the specified cleanliness level has been reached in remanufacturing process. The objectives of remanufacturing cleaning in each stage of the remanufacturing process are different. Firstly, the purpose of core pre-cleaning before disassembly is mainly to reduce the quantity of contaminations outside the products. Secondly, by removing the grease, scale deposit, rust, carbon deposition and the paintcoat attached on the surface, and the cleaning after disassembly is convenient for detecting the surface abrasion, micro crack or other failure situations in order to make sure if remanufacture can be applied and what kind of method can be employed. Thirdly, the cleaning processes in other stages, such as the cleaning processes before reconditioning, reassembly and painting, are performed to remove surface contaminants (oils, greases, inorganic residues, particulates, etc.) and to prepare surfaces for additional treatment prior to subsequent steps. Many cleaning operations are critical to the ultimate performance of remanufactured product. Inadequate or inappropriate cleaning leads to unacceptable production yields or, even worse, to product failure during use.

Remanufacturing cleaning is distinct from cleaning in maintenance or cleaning in new production. Cleaning in maintenance concentrates on the position of damage before repairing while cleaning in remanufacturing is done for the whole mechanical parts in order to make them meet the quality requirement after remanufactured. Cleaning in new production is another case. Firstly, the cleaning objects in new production process are changeless in work piece size and material, and the contaminations are mainly the residual metal cutting fluid, lubricating oil, antirust oil, polishing paste and so on. By contrast, cleaning in remanufacturing is not so easy that the objects are of great many types with different sizes and materials and complex and long-termed surface fouling. Secondly, cleaning in new production is performed at a high level. Due to high standards of OEMs (Original Equipment Manufacturers), suppliers have made great efforts to optimize cleaning processes. Also, the ISO Standard 16232 on technical cleanliness gives recommendations for cleaning in new production steps. However, at present, in strong contrast to the well-defined cleaning in new production processes, cleaning in remanufacturing is mostly performed based on the experience of the operator instead of knowledge based and therefore often results in a lack of efficient solutions. So, cleaning in remanufacturing has a great potential for optimizations and innovations.

As can be seen from the above analysis, cleaning is an essential step in the remanufacturing process, which lacks systematic understanding yet. Therefore, the main purpose of this paper is to establish a foundation for further study on remanufacturing cleaning, about the establishment of knowledge base, process optimization, innovations and related standardization.

The remainder of this paper is organized as follows. The fundamental concepts and the basic elements of remanufacturing cleaning technology are introduced in section 2. Section 3 gives a brief introduction about the commonly used cleaning technologies that are suitable for remanufacturing process and outlines the development tendency of remanufacturing cleaning technology. The principle of the selection of the cleaning methods at each stage in the remanufacturing is described in section 4, and the final conclusions are given in section 5.

2 BASIC ELEMENTS OF REMANUFACTURING CLEANING

By mechanical, physical, chemical or electrochemical means, remanufacturing cleaning removes the grease, scale deposit, rust, carbon deposition and the paintcoat attached on the core surface so that the specified cleanliness level requirements can be reached. Four basic elements are included for core remanufacturing cleaning: cleaning object, core contamination, cleaning force and cleaning medium. A synopsis to elaborate the four elements is given as follows.

Contaminant		Position	Components	Characteristics
External deposits		Outside surface of parts.	Dust, oil sludge, etc.	Easy to be removed, but difficult to clean thoroughly.
Residual lubrication oil		The surface contacted by parts and with lubricating medium.	Aged viscous oil, water, salt, product of corrosion and deterioration on parts surface.	Complex components, furring, which determines corresponding cleaning methods.
Carbonized Sediment	Carbon deposition	Combustor surface, air valve, piston head, piston ring, spark plug.	Carboid and carbides, lubricating oil and tar, a handful of oxygen acid, ash content, etc.	Most of the components are insoluble, which are difficult to be removed.
	Film like painting	Piston skirt, connecting rod.	Carbon.	Low strength, easy to be removed.
	Other types of sediment	Shell wall, crankshaft journal, oil pump, filters, lubricating oil passage.	Lubricating oil, tar, a handful of carboid, carbides and ash content, etc..	Most of the components are insoluble, which are difficult to be removed.
Scale deposit		Cooling system.	Calcium salt and magnesium salt, etc.	Soluble in acid.
Rust		The surfaces of part.	Iron oxide, alumina, etc.	Insoluble in water and alkali, and soluble in acid.
Detection residues		The whole part surface.	Metal debris, perspiration, and fingerprint, etc.	Adhesive force is small, and easy to be removed.
Residues of machining		The whole part surface.	Metal debris, polishing paste, abrasive paste, lubricating liquid, coolant liquid, etc.	Adhesive force is not large, but need to clean thoroughly.

Table 1: Contaminants of automotive products during remanufacturing process.

1. **Cleaning object,** the one which needs to be cleaned in a remanufacturing process. For example, all sorts of machinery parts, electronic components, etc. These parts and electronic components are mainly made of metal, ceramic (containing silicon compounds), plastic and etc. Different cleaning methods should be employed, according to different cleaning objects (different materials, shapes, and geometric dimension).
2. **Core contaminant**, a kind of "unpopular" deposits which are deposited on the core surface because of the long-termed effects of physical, chemical or biological during the core's service time (i.e., before remanufacturing process), or a kind of fouling (such as residual metal cutting fluid, lubricating oil, antirust oil, polishing paste, etc.) which is introduced during remanufacturing process. Remanufacturing cleaning is therefore a process of contamination removal from the core surface to achieve the required cleanliness.

Taking automobile remanufacturing cores as examples, there are varieties of core contaminant, which can be mainly divided into the following categories as seen in Table 1.

3. **Cleaning force,** the force among cleaning objects, contaminants and cleaning medium, which disperses steadily in the cleaning medium during the cleaning processes to remove the contaminants away from the part surface. The contaminant molecules are combined by electrostatic or molecular attraction forces so that they can be removed by overcoming those forces in the cleaning process. Generally, the cleaning forces can be classified into five categories, that is, 1) solvency force and dispersion force, 2) surface active force, 3) enzyme force, 4) chemical reaction force and 5) physical force, as described in Table 2.

Type		Interaction Way
Solvency force and dispersion force		Contaminants can be dissolved in water or organic solvent and then steadily dispersed into cleaning medium.
Surface active force		Comprehensive effects of wetting, permeating, emulsifying, scattering and solubilizing on the contaminants will be produced by lowering the interfacial tension between surfactants and contaminations.
Enzyme force		Organic contaminants (i.e., grease) can be resolved by hydrolysis reaction accelerated by the enzyme (a kind of biological molecule), which then disperse into cleaning medium.
Chemical reaction force		Contaminants can be dispersed by the chemical reaction between chemical agent and contaminants, which then disperse into cleaning medium.
Physical force	Thermal effect	Contaminants will change their physical properties or decompose by thermal effect, which promotes the cleaning process.
	Pressure	Cleaning force generated by high pressure, medium pressure, negative pressure or vacuum.
	Friction	The contaminants on the surface can be removed by rushing to scraping.
	Abrasive force	The contaminants on the surface can be removed by mechanical force.
	Ultrasound effect	The contaminants on the surface can be removed by the function of cavitations of ultrasonic wave in cleaning medium.
	Electrolytic force	The contaminants on the surface can be removed by electrolytic action
	Ultraviolet ray	The atoms of organic contamination molecule absorb certain wavelength of ultraviolet light and the priming effect causes the decomposition of contaminants molecules.

Table 2: Categories of cleaning force.

Cleaning medium	Decontamination force	Major ingredient	Applicable contaminants
Solvent	Dissolving force and dispersion force.	Organic solvent.	Oil and grease.
Aqueous based cleaning fluid	Adsorption, wetting, permeating, emulsifying, scattering and solubilizing, etc.	Surfactant, detergent, additive agent, etc.	Various contaminants adsorbed on core surface.
Chemical solvent	Chemical reaction force.	Acid solution, alkali solution, oxidizing and reducing agents, etc.	Rust, saponified grease, etc.
Solid particle	Abrasive force, impact force.	Various solid particles.	Rust, paintcoat, etc.

Table 3: Common cleaning medium.

4. **Cleaning medium,** through which the cleaning environment is offered and directly contacted with surfaces to be cleaned during cleaning process. Cleaning medium plays a significant role in the cleaning process, which is reflected in transmitting the cleaning force and preventing re-adsorption of the contaminants which have been detached. The common cleaning mediums, with great varieties, are listed in table 3.

3 REMANUFACTURING CLEANING TECHNOLOGY AND DEVELOPMENT TENDENCY

3.1 Current Situation of Remanufacturing Cleaning Technology

Continuous development and improvement are required for remanufacturing cleaning technology, cleaning methods as well as cleaning equipments, which have few ideas to borrow from new product manufacturing process. Different techniques and methods depend on different purposes at different stages. Sometimes a variety of methods are used simultaneously or successively. The cleaning technologies which are under consideration for remanufacturing cleaning are briefly introduced as follows.

1. **Organic solvent cleaning technology.** By means of soaking the core in organic solvent or spraying organic solvent to the object, the contaminations can be removed from the core surface because of dissolution and chemical reaction [4]. However, there are some issues with this cleaning technology such as waste liquid, which must be treated in a lifecycle in manufacturing cleaning when environmental factor is taken into account.
2. **Jet cleaning technology.** According to the mediums, this technology includes classified as high-pressure water jet cleaning [5], abrasive blasting cleaning [6] and dry ice blast cleaning [7], etc. The grease, rust and other contaminations can be removed from the core surface due to the physical interaction of the accelerated mediums by compressed air or high pressure water. However, there are some issues with such approach, such as waste liquor treatment during the high-pressure water jet cleaning, high cost of the dry ice blast cleaning and dust pollution also in the abrasive blasting cleaning.
3. **Thermal cleaning technology.** By use of high temperature or hot stream, oil or grease on the core surface will be evaporated during the cleaning process. Therefore, this cleaning method is suitable for hydrocarbon which does not contain chlorine and fluorine, but not applicable for low melting point or flammable metal parts. Even though, for this time-consuming and energy-consuming process, a lot of improvements are still needed.
4. **The Ultrasonic cleaning technology.** Ultrasonic cleaning uses high frequency (usually from 20-400 kHz) sound waves to generate agitation in a liquid [8]. Cavitation bubbles induced by the agitation will act on contaminants adhering to substrates like metals, plastics, glass, rubber, and ceramics and cause the final contaminant detachment. However, it is difficult to choose proper cleaning parameters for different contaminants process because to some extent surface corrosion will be produced once the cleaning parameters are set improperly. Meanwhile, waste liquor treatment is needed for environmental account. Therefore, researches about high power, series and high reliability ultrasonic power are required to optimize the cleaning process.
5. **Electrolytic cleaning technology.** Electrolytic cleaning is derived from the release of bubbles [9] and it is not suitable for non-ferrous metals such as copper, bronze, brass, pewter, tin or aluminum. Moreover, great amount of energy will be spent during electrolytic cleaning process.

Definitely, there are still other ways to remove contaminants away from core surface, such as ultraviolet radiation cleaning [10], plasma cleaning [11], ion beam cleaning [12], laser cleaning [13], supercritical fluid cleaning [14], biological enzyme cleaning [15], etc.

Current imperfection of remanufacturing cleaning is reflected as follows in remanufacturing industry. 1) Contamination degree and type are not classified before the cleaning process. 2) Necessary cleanliness specifications are not set in advance before processing the parts. 3) The utilization of cleaning machinery generally bases on experience rather than systematic knowledge. 4) Various technologies (e.g. shot basting, wet cleaning) are not tailored to the needs of remanufacturing and cost drivers. 5) Cleanliness measuring systems, methods or equipment is unknown while the need of remanufactured parts is tightening. 6) Remanufacturing cleaning is a bottleneck in the material flow. Dirty parts are gathered to a large size in order to achieve a high operating ratio of the machine. This, however, works against the trend of decreasing batch sizes. High intermediate storages with correspondingly long lead-times and high cost of inventory are consequences. 7) Cleaning is the most environmentally unfriendly process in remanufacturing as many hazardous cleaning agents are used during the process.

3.2 Development Tendency of Remanufacturing Cleaning Technology

Cleaning is one of vital process for remanufacturing of mechanical equipment parts. It should follow the principle of high efficiency, low-cost, energy efficiency, low-emissions of pollutants (including waste gas, waste liquor and solid wastes). Presently, cleaning agents like ozone depleting substance (ODS) and chlorofluorocarbon (CFC) are widely used in cleaning industry, both of which have been phased out under the Montreal Protocol because of their negative environmental effect. Thus, the study of non-ODS cleaning solvents is a development tendency of remanufacturing cleaning technology. The selection principle of non-ODS cleaning solvents is listed as follows: excellent cleaning abilities, appropriate cost performance ratio, non-toxic and environmentally friendly. Consequently, conventional chemical cleaning methods which use hazardous or banned cleaning agents become unsuitable for remanufacturing cleaning because of the environmental contamination. By contrast, physical cleaning methods and the cleaning methods which use environmentally friendly cleaning agents are widely used in virtue of their unique advantage of less influence on environment.

In addition, with increasing demands of large-scale and efficient mechanical equipment remanufacturing, the demand of low-cost cleaning system in remanufacturing is also increasing. That greatly accelerates the application of the latest semi-automatic and full automatic cleaning equipments, such as cleaning production line and cleaning robots, etc. Another development tendency of remanufacturing cleaning technology is the study of composite cleaning technology or hybrid cleaning system which is higher level of automation, less cost and less environmental pollution.

Moreover, to find the best balance between environmental and economical requirements is a major issue for remanufacturing cleaning because cleaning process is one of the main pollution sources in remanufacturing. In recent years, the biological engineering as a kind of environmental friendly technology has become a new trend in cleaning industry. The enzyme cleaning technology, one of the most common biological engineering in cleaning, might be used for a wide range of remanufacturing cleaning applications.

Apart from the cleaning technologies mentioned above which need to be improved or innovated, cleanliness detection and analysis technologies for remanufacturing cores are going to require improvement and innovation. This includes the reorganization of contaminant degree and type before cleaning process, specification definitions for technical component cleanliness, and measurement of the technical component cleanliness and etc.

4 PRINCIPLES OF SELECTION

In remanufacturing cleaning process, several factors such as maximum cleanliness, quality, time, cost and environmentally friendly requirements should be taken into consideration when cleaning methods and technological parameters are determined. Generally, for optimizations in practice, the principles of remanufacturing cleaning methods selection at each stage are described as follow.

1) Identify cleaning purposes and technical cleanliness requirements. Table 4 represents five cleaning steps in each phase of remanufacturing with different purposes for the subsequent process as detection, machining or assemble. It can be seen that the remanufacturing cleaning changes in each stage of the remanufacturing process for different objectives.

2) Recognize the core contaminant type and its attachment manner, and then choose the appropriate cleaning method and cleaning agent.

3) According to the material, quantity, geometric dimensions of the cores to be cleaned, choose the appropriate cleaning method and cleaning agent. Meanwhile, make the comprehensive evaluation of the cleaning agent damages to the part surface as well as cleaning efficiency and cost.

4) According to the environmental requirements, make an evaluation of energy consumption, discharge of wastes (including waste gas, wastewater, waste oil and solid wastes) and make sure to decrease resource consumption and degrade environment pollution.

No.	Cleaning Process	Contaminants	Cleaning purse	Requirements
①	Pre-cleaning before disassembly	Deposits on the outside of equipments, such as dust, silt, grease, etc.	Convenient for components and parts disassemble and preventing taking the contaminant into the workshop.	Roughly clean.
②	Cleaning for components and parts after disassembly	Grease, rust, Carbon sediment, residues of lubrication, scale deposit, paintings and etc.	Convenient for detection of remanufacturing properties.	Surfaces of the components and parts can be seen clearly.
③	Cleaning before reconditioning	Residues produced during detection.	Guarantee the machining quality of the remanufactured parts.	Rather clean.
④	Cleaning before remanufactured parts assemble	Machining residues such as rust, cuttings abrasive material, grease, antirust oil and dust on standard components and parts.	Guarantee the assemble quality of the manufactured parts.	Very clean.
⑤	Cleaning before remanufactured parts painting	Grease and slag inclusions on remanufactured part surface.	Guarantee the painting protection of the manufactured parts and Nice appearance.	Very clean.

Table 4: The cleaning process and requirements of automobile in each stage of remanufacturing process.

5 SUMMARY

Mechanical equipment products experience a fast development in recent years. As an important process in remanufacturing, remanufacturing cleaning has great effects on the quality of remanufactured products as well as environmental benefits and remanufacture cost. Actually, the pre-cleaning before disassembly, the cleaning for cores after disassembly, the cleaning before reconditioning, the cleaning before assemble and the cleaning before painting are mainly included in remanufacturing cleaning. Therefore, varieties of remanufacturing cleaning technologies, like organic solvent cleaning technology, jetting cleaning technology, high temperature cleaning technology, ultrasonic cleaning technology, electrolytic cleaning technology, and so on can be applied to achieve different cleaning purpose. In spite of the simplification and effectiveness of present remanufacturing cleaning process, unified standards for cleanliness judgment and the knowledge base of remanufacturing cleaning are insufficient. Furthermore, problems such as secondary pollution, energy waste, and low cleaning efficiency due to low levels of automation also arise. Even so, the concentrated research of cleaning technologies and cleaning equipments unquestionably leads remanufacturing cleaning to be more effective, automated and environmental, which also accelerates the establishment of relevant standards such as enterprise standard, national standard or international standard.

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7 REFERENCES

[1] Bernard, S. (2011): Remanufacturing, in: Journal of Environmental Economics and Management, Vol.62, No.3, pp: 337-351.

[2] Ijomah, W. L. (2009): Addressing decision making for remanufacturing operations and design-for-remanufacture, in: International Journal of Sustainable Engineering, Vol.2, No.2, pp: 91-102.

[3] Nnorom, I. C., Osibanjo, O. (2010): Overview of prospects in adopting remanufacturing of end-of-life electronic products in the developing countries, in: International Journal of Innovation, Management and Technology, Vol.1, No.3, pp: 328-338.

[4] Kikuchi, E., Kikuchi, Y., Hirao, M. (2011): Analysis of risk trade-off relationships between organic solvents and aqueous agents: case study of metal cleaning processes, in: Journal of Cleaner Production, Vol.19, No.5, pp: 414-423.

[5] Guha, A., Barron, R. M., Balachandar, R. (2011): An experimental and numerical study of water jet cleaning process, in: Journal of Materials Processing Technology, Vol.11, No.4, pp: 610-618.

[6] Kambham, K., Sangameswaran, S., Datar, S. R., Kura, B. (2007): Copper slag: optimization of productivity and consumption for cleaner production in dry abrasive blasting, in: Journal of Cleaner Production, Vol.15, No.5, pp: 465-473.

[7] Yang, S. C., Huang, K. S., Lin, Y. C. (2007): Optimization of a pulsed carbon dioxide snow jet for cleaning CMOS image sensors by using the Taguchi method, in: Sensors and Actuators A: Physical, Vol. 139, No.1-2,pp: 265-271.

[8] Niemczewski, B. (2007): Observations of water cavitation intensity under practical ultrasonic cleaning conditions, in: Ultrasonics Sonochemistry, Vol.14, No.1, pp: 13-18.

[9] Cuthberston J.W. (1995): Electrolytic cleaning and polishing, in: Journal of the Institution of Electrical Engineers, Vol.1, No.9, pp: 601-602.

[10] Takahagi, T., Nagai, I., Ishitani, A., Kuroda, H., Nagasawa, Y. (1988): The formation of hydrogen passivated silicon single-crystal surfaces using ultraviolet cleaning and HF etching, in: Journal of Applied Physics, Vol.64, No.7, pp: 3516-3521.

[11] Kegel, B., Schmid, H. (1999): Low-pressure plasma cleaning of metallic surfaces on industrial scale, in: Surface and Coatings Technology, Vol.112, No.1-3, pp: 63-66.

[12] Razek, N., Schindler, A., Rauschenbach, B. (2007): Ultra-high vacuum direct bonding of a p–n junction GaAs wafer using low-energy hydrogen ion beam surface cleaning, in: Vacuum, Vol.81, No.8, pp: 974-978.

[13] Ye, Y. Y., Yuan, X. D., Xiang, X., Cheng, X. F., Miao, X. X. (2012): Laser cleaning of particle and grease contaminations on the surface of optics, in: Optik - International Journal for Light and Electron Optics, Vol.123, No.12, pp: 1056-1060.

[14] Della, P. G., Volpe, M. C., Reverchon, E. (2006): Supercritical cleaning of rollers for printing and packaging industry, in: The Journal of Supercritical Fluids, Vol.37, No.3, pp: 409-416.

[15] Basketter, D., Berg, N., Broekhuizen, C., Fieldsend, M., Kirkwood, S., Kluin, C., Mathieu, S., Rodriguez, C. (2012): Enzymes in cleaning products: An overview of toxicological properties and risk assessment/management, in: Regulatory Toxicology and Pharmacology, Vol.64, No.1, pp: 117-123.

Energy Consumption Assessment of Remanufacturing Processes

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Abstract

In order to analyze the energy consumption of the remanufacturing processes, the energy consumptions of electrical, fuel oil and auxiliary materials in remanufacturing process are conducted by considering as embodied energies. Energy assessment methods of typical processes of laser cladding and turning are established based on the thermodynamic theories and metal-cutting theories. For uncertainty of failure degree and processes, energy consumption methods about one remanufacturing process sequence are presented by using probability theory. The upper and the lower values of energy consumption are given, which can be used as a basic theory for developing energy assessment standards of remanufacturing technology.

Keywords:

Remanufacturing; Energy; Evaluation; Uncertainty; Probability

1 INTRODUCTION

Remanufacturing is an industrial process of bringing a used product to a condition as good as new one [1]. A series of industrial processes are used in remanufacturing process, such as high temperature cleaning, shot blasting, sandblasting, ultrasonic testing, magnetic particle testing, laser cladding, plasma cladding, Nano electric-brush plating, turning, grinding, etc. The benefits of remanufacturing relative to manufacturing have been examined [2, 3]. Since material characteristics and damage degrees in use of every core are different, there are highly uncertainties in energy consumption of re-manufacturing process. The difficulty of energy assessment of re-manufacturing processes resides in the variable nature of the remanufacturing process. There are no standards yet to measure or evaluate energy consumption and material utilization of each process.

A number of modeling approaches have been used to investigate the energy consumption within a manufacturing facility [4-7]. These modelings can be viewed under three generic perspectives of “plant”, “process” and “equipment” levels [8]. In “equipment” levels, Gutowski et al. [9] took a step further to develop generalised ‘equipment-level’ energy models, using average energy intensities of different manufacturing processes to evaluate the efficiency of processing lines. Seow et al. [8] modeled energy flows within a manufacturing system from the viewpoints of “product” based on the data of “plant” and “process”levels.

The energy consumption is one of the main considerations within a life cycle assessment (LCA) study [10], however, due to the information intensive nature of LCA and the lack of accurate data related to energy demand across a product life cycle (in particular during the manufacturing phase), significant assumptions and simplifications are often made. This has motivated numerous research programmes to investigate energy consumption within a manufacturing facility so as to gain a better understanding of the energy use and breakdown. For Example, CO_2PE are cooperative effort on modeling process emissions in manufacturing [11]. Two approaches, the screening approach and the in-depth approach, are proposed by CO_2PE!-UPLCI Workshop, and both approaches have already provided useful results in some initial case studies.

Embodied energy (EE) was widely used in energy analysis of the buildings [12]. Primary embodied energy determination methods are statistical analysis, process-based analysis, economic input/output based analysis and hybrid analysis [13]. Most embodied energy calculations performed as a part of LCA by past research studies followed LCA ISO standards [14]. Previous studies of embodied energy analysis and computation exhibit considerable variation in embodied energy results owing to numerous factors. The problems of embodied energy research are lacking of standard methodology for embodied energy calculation and missing a robust database of embodied energy. Some Research Teams (For example, Sustainable Energy Research Team of the University of Bath) have published the figures of embodied energy based on a ‘Cradle-to-Gate’ analysis, which can be used for embodied energy analysis for a product or a process.

The research objective of this paper is to assess energy consumption of remanufacturing process based on the conception of embodied energy. The research based on “equipment” and “process” levels viewpoint which is not only capable of quantifying the total energy inputted into a remanufacturing process sequence but also providing a method to solve the energy assessment uncertainties in remanufacturing processes by using the probability theory.

2 EMBODIED ENERGY AND REMANUFACTURING PROCESSES

2.1 Embodied Energy

The difference between the energy material and the non-energy material is that the energy material is the resource producing energy, while the non-energy material is the resoure consuming energy. The energy material and the non-energy material are all called energy carrier. For example, primary energy, second energy, and material, intermediate product, product, etc. are all energy carriers. That is, the energy material includes “live” energy, while the non-energy includes “embodied” energy.

Embodied energy (EE) refers to the sum of all the energy required to produce goods, since the energy was 'embodied' in the product itself. Typical units of embodied energy is MJ/kg (megajoules of energy needed to make a kilogram of product). For example, the energy embodied in an automobile includes the energy consumed directly in the manufacturing plus all the energy consumed to produce the other inputs of automobile manufacturing, such as glass, steel, labor, and capital.

Embodied energy is an accounting method which aims to find the sum total of the energy necessary for a product or material. Embodied energy calculation of a product or material throughout its entire lifecycle including raw materials extraction, transport, manufacture, assembly, installation, use and waste management, etc. It is valuable to set up a boundary for process analysis and data collection on energy consumption. There are four factors that affect the embodied energy of the materials. These include: (1) weight of the raw materials; (2) energy used to extract and process the raw materials; (3) distance to transport raw materials from the source to the manufacturer; and (4) transportation method used to transport the raw material from the source to the manufacturer.

2.2 Energy Consumption Description of Remanufacturing Processes

In order to simplify the energy analysis, the energy consumption in remanufacturing process is classified as [8]: (1) direct energy (*DE*) refers to the energy direct consumed in one process step (e.g. coal, electricity, gasoline and diesel etc, which can be converted into the mass of standard coal); and (2) indirect energy (*IE*) refers to the energy embodied in raw materials and other non-energy materials consumed by the process. By calculating *EE*, *IE* of a process can be easily calculated as,

$$IE_i = \sum_{j=1}^{m} EE_{ij} \times g_{ij} \tag{1}$$

Where, IE_i is indirect energy of process i; m is the number of non-energy materials; EE_{ij} is the EE of non-energy material j; g_{ij} is the mass of non-energy material.

For most parts, theirs remanufacturing processes encompass disassembly, cleaning, inspection, repairing, reassembly process steps, etc. The total energy consumption of a remanufacturing processes sequence is,

$$E_{total} = E_1 + E_2 + \cdots + E_i + \cdots + E_n \tag{2}$$

where E_i is energy consumption of processing step i,

$$E_i = DE_i + IE_i \tag{3}$$

So the total energy consumption of a remanufacturing process sequence in Equation (1) can be expressed as,

$$E_{total} = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} (DE_i + IE_i) \tag{4}$$

In order to calculate the total energy of a process, all energies and raw materials interacting with the process sequence should be traced back to raw materials as found in nature. Energy consumption E_{total} of a remanufacturing process sequence is,

$$E_{total} = \sum_{i=1}^{n} (DE_i + \sum_{j=1}^{m} EE_{ij} \times g_{ij}) \tag{5}$$

But since there is a high level of uncertainty associated with the condition of the end-usage of the product to be remanufactured. The energy consumption in each remanufacturing process will be also different due to the uncertainty of individual usage condition of the product. So E_{total} of a product to remanufacture is a random function. The energy consumption values can be estimated in a certain range. It can be deduced that the value of E_{total} has an upper and a lower bound and the energy consumption E_{total} of most cases (99.7%) in remanufacturing lie in the range in industrial practice.

3 ENERGY ASSESSMENT OF TYPICAL PROCESSES

In this section, two energy assessment methods of typical processes, laser cladding and turning are established based on the thermodynamic and metal-cutting theories. Through the energy calculation equations, it is can be seen that the energy consumption and energy efficiency is variable which changes with matieral properties and process conditions, such as basis matierals, auxiliary materials, technological parameter, etc.

3.1 Energy Assessment of Laser Cladding

(1) Total Energy Consumption analysis

Laser cladding process is emerging as a strategic technique for repairing damaged components and improving surface protection properties for better wear or corrosion resistance. Laser cladding process is a complex process, with various energies converted to one another.

Because of the complexity of the laser cladding process, energy assessment measurement of energies conversion is deducted in ideal operations. Based on the first law of thermodynamics, energy-balance equation of Laser cladding process is:

$$E_{laser} = E_{coating} + E_{basis} + E_{radiation} + E_{reflect} + E_{mechanicalloss}$$

where E_{laser} is the total energy of laser beam contained, $E_{coating}$ is the energy absorbed by coating, E_{basis} is the energy absorbed by basis material, $E_{radiation}$ and $E_{reflect}$ is the energy radiated and reflected by the melt pool and basis material, $E_{mechanical\ loss}$ is the loss energy caused by cladding material splashing.

(2) Useful energy consumption

Based on spectroscopy, Metal crystal theory and heat transfer theory, each part of energy consumption above can be calculated. Among them, E_{basis} and $E_{coating}$ are the useful energy to cause melting of cladding material and basis material to occur and to form clad layer.

$$E_{cladding\text{-useful}} = E_{basis} + E_{coating} \tag{6}$$

The energy absorbed by basis material E_{basis} [15]:

$$E_{basis} = C_1M_1(T_m - T_0) + C_1M_1(T - T_m) + M_1\Delta H_{f1}$$
$$= M_1(C_1\Delta T + \Delta H_{f1})$$

where C_1 is the heat capacity of basis material, M_1 is the mass of basis material melting per unit length cladding track, which is a variable depending on the density, T_0 is the room temperature, T_m is the melting point of cladding material, T is the temperature needing by metallurgical bonding, ΔH_{f1} is the latent heat of fusion of basis material. Similarly, the energy absorbed by coating $E_{coating}$[15]:

$$E_{coating} = C_2M_2(T_m - T_0) + C_2M_2(T - T_m) + M_2\Delta H_{f2}$$
$$= M_2(C_2\Delta T + \Delta H_{f2})$$

From the equations above, we can see energy consumption of laser cladding process has a linear relation with cladding material. Suppose the mass of cladding material has linear relation with the wear degree of part surface, and then energy consumption of laser cladding is linear to the degree of the wear of the part surface.

(3) Energy efficiency

DE of Laser cladding process is the electric energy, If the rated power of the Laser cladding equipment is P_1, the cladding time is t_1, then $DE_{cladding} = k_1P_1t_1$, where k_1 is the load factor.

Then Energy efficiency of laser cladding is:

$$\eta = \frac{E_{coating} + E_{basis}}{DE_{cladding}} \tag{7}$$

3.2 Energy Assessment of Turning Cutting

(1) Calculation of Cutting Forces

In turning cutting process, main cutting force can be divided into three mutually vertical component, feed force F_f, back force F_p and cutting force F_c [16]:

$$F_f = C_1 a_p^{x1} f^{y1} v^{z1}$$

$$F_p = C_2 a_p^{x2} f^{y2} v^{z2}$$

$$F_c = C_3 a_p^{x3} f^{y3} v^{z3}$$

Where C_1, C_2, C_3 are the coefficients decided by cutting metal and condition; x_1, y_1, z_1, x_2, y_2, z_2, x_3, y_3, z_3 are the exponents of the cutting depth a_p, feed rate f, and cutting speed v.

For common material, the coefficients and exponents C_1, C_2, C_3, x_1, y_1, z_1, x_2, y_2, z_2, x_3, y_3, z_3 can be gotten from the handbook. For special material, such as nickel base alloy used for laser cladding, through experiments, the coefficients and exponents can be determined. Refer to [17] for details on variales and units in the formulas.

Material removal rate is:

$$MRR = a_p v f$$

The turning cutting power is:

$$P_c = F_c v + \frac{F_f n f}{1000}$$

So the energy comsumed by cutting is:

$$E_{cutting\ useful} = \int_0^t P_c dt$$

(2) Specific Energy Consumption

Specific energy e_s is defined as the energy consumed by cutting unit volume material [18]. Common unit is J/kg. Specific energy can reflect the relationship between energy consumption and material rate and can describe the energy efficiency of equipment,

$$e_s = \frac{P_c}{MRR} = \frac{P_c}{a_p v f}$$

For common material, e_s can be gotten from the handbook. For special material, through experiments, e_s can be calculated by the expression above. Then Specific Energy Consumption,

$$E_{cutting\text{-useful}} = e_s V \tag{8}$$

where V is the total volume of the cut material.

(3) Energy efficiency

If the power of the whole equipment is P, the cutting time is t, then $E_{total}=Pt$. So energy efficiency of turning cutting is:

Suppose the rated power of the cutting machine is P_2, and the cutting time is t_2, then $DE_{cutting}=k_2P_2t_2$, where k_2 is the load factor.

$$\eta = \frac{E_{cut\text{-}useful}}{DE_{cutting}} \tag{9}$$

From analysis above, we can suppose that energy consumption has a linear relation with the volume of turning cutting, so it is also linear to the total material cutting edge of the turning process.

3.3 Energy Efficiency of Laser Cladding and Turning Cutting

Suppose there is only one type of auxiliary material, nickel-cadmium alloy wire, used as cladding material. Then the total embodied energy of the auxiliary material is:

$EE_{cladding}=EE_{nc}\times g_{nc\text{-}total}$

In order to obtain accurate part size after laser cladding, some clad layer should be cut off, so embodied energy of reserve material of nickel-cadmium alloy is:

$EE_{reserve}=EE_{nc}\times g_{nc\text{-}reserve}$

So the useful energy in laser cladding process is,

$E_{useful}=E_{basis}+E_{coating}+EE_{reserve}$

The useful energy in cutting process is,

$E_{cut\text{-}useful}=e_s(g_{nc\text{-}total}-g_{nc\text{-}reserve})/\rho$

where e_s *is the* specific energy of nickel-cadmium alloy, ρ is the density of the coating of nickel-cadmium alloy.

Then energy efficiency of laser cladding and cutting processes is:

$$\eta = \frac{E_{coating} + E_{basis} + EE_{reserve} + E_{cut-useful}}{k_1P_1t_1 + k_2P_2t_2 + EE_{cladding}} \tag{10}$$

4 ENERGY ASSESSMENT OF REMANUFACTURING BASED ON PROBABILITY THEORY

The uncertainties in remanufacturing process reflect in: (1) The greasy dirt degree of the waste parts; (2) The failure type and degree of the waste parts; and (3) The difference of the materials of the waste parts. These uncertaintes cause the uncertainty of the repairing technologies, the uncertainty of materials and energies consumption.

In order to simplify analysis, suppose the material of the waste parts are same and the failure type of the waste parts is wear failure. Two kinds of uncertainties are considered: (1) The greasy dirt degree of the waste parts; (2) The wear degree of the waste parts. The greasy dirt degree and wear degree of the waste parts follow the normal distribution. So the distribution function of greasy dirt degree is $X \sim N(\mu_1, \sigma_1^2)$, the distribution function of wear degree is $Y \sim N(\mu_2, \sigma_2^2)$, where μ_1, σ_1^2, μ_2, σ_2^2, can be de determined through the statistical method. Suppose the energy consumption function of cleaning is $E_1 = a_1X + b_1$, the energy consumption function of laser cladding is $E_2 = a_2X + b_2$, the energy consumption function of turing cutting is $E_3 = a_3X + b_3$, the energy consumption function of inspection is $E_4 = a_4X + b_4$,... where a_i, b_i are the coefficients having relationships with parts shape, cladding material density, equipment power, etc.

Then according to probability theory, the linear combination of finite number of normal random variables which are mutual independent still follows the normal distribution. So the energy consumption function of the total energy is:

$$\begin{aligned} E_{total} &= E_1 + E_2 + E_3 + E_4 \\ &\sim N(a_1\mu_1 + b_1 + (a_2 + a_3 + a_4)\mu_2 + b_2 + b_3 + b_4, \\ &\quad (a_1\sigma_1)^2 + ((a_2 + a_3 + a_4)\sigma_2)^2) \end{aligned}$$

Generally,

$$E_{total} \sim N(\mu_t, \sigma_t^2) \tag{11}$$

Where $\mu_t = a_1\mu_1 + b_1 + (a_2 + a_3 + a_4)\mu_2 + b_2 + b_3 + b_4$,

and $\sigma_t = \sqrt{(a_1\sigma_1)^2 + ((a_2 + a_3 + a_4)\sigma_2)^2}$

So the mean value of the total energy consumption is:

$$E_{mean} = \mu_t \tag{12}$$

According to the principle of 3σ, 99.7% of all possible energy consumptions of an uncertainty remanufacturing process lie in the numerical range of $\mu_t - 3\sigma_t < E_{total} < \mu_t + 3\sigma_t$.

The upper value of the total energy consumption of a remanufacutring process could be:

$$E_{upper} = \mu_t + 3\sigma_t \tag{13}$$

The lower value of the total energy consumption could be:

$$E_{lower} = \mu_t - 3\sigma_t \tag{14}$$

In engineering practice, the total energy consumption can be estimated as a value between E_{upper} and E_{lower}.

The analysis results indicate the total energy consumption follows the normal distribution, which gives a theoretical basis for the statistical analysis of energy consumption assessment of remanufacturing process sequence. It should be noted that it is very difficult to find out all coefficients μ_1, σ_1^2, μ_2, σ_2^2, a_1, b_1, a_2, b_2, etc. in practice, since there are so many influencing factors in a product remanufacturing process. However by a series of tests or data investigations, energy consumption of remanufacturing process sequence can be calculated, and coefficients μ_t, σ_t^2 can be determined through statistical data analysis.

5 CASE STUDY

SINOTRUK, Jinan Fuqiang power Co., LTD has a span of nearly 60 years of producing heavy trucks and components, which engaged in manufacturing and remanufacturing of diesel engine. The crankshaft of waste diesel engine WD615 is taken as a case study to analyze the energy consumption of the remanufacturing processes. The weight of the crankshaft is 103 kg; the shaft neck diameter for connector is 83 mm; the length of shaft neck is 46 mm. There are six shaft necks in the crankshaft. Figure 1 presents the flowchart of a typical remanufacturing process of the crankshafts.

Through the data analysis and modeling, two scenarios are identified and demonstrated on energy consumption estimate, specifically using the energy assessment method presented. In scenario 1, the greasy dirt degree of crankshaft and the degree of the wear of the crankshaft is light. In scenario 2, the greasy dirt degree of crankshaft and the degree of the wear of the crankshaft is heavy. The data about embodied energy of the materials come from the database of LCA software E-balance 4 and Gabi 4. The analysis result about energy, material consumptions are listed in Table 1.

	P_1: Kerosene Cleaning		P_2: High-temperature jet Cleaning		P_3: Laser Cladding		P_4: Inspection		P_5: Turning cutting		P_6: Final cleaning		Total energy(MJ)
Scenario 1	Kerosene	0.20kg	Energy consumption	2.01kw	Nickel-cadmium alloy wire	2.52kg	Energy consumption;	8.87kW	Energy consumption	2.33kW	Energy consumption	0.77kW	140.2
			Water consumption	3.12m^3	The thickness of clad layer	4mm	Ferroferric oxide (magnetic powder)	15g	Removal material(Removal 3.5mm thickness)	m=2.21kg	Water consumption	1.25m^3	
Scenario 2	Kerosene	0.30kg	Energy consumption	2.68kw	Nickel-cadmium alloy wire	3.78kg	Energy consumption;	13.30kW	Energy consumption	3.50kW	Energy consumption	0.77kW	187.34
			Water consumption	4.17m^3	The thickness of clad layer	6mm	Ferroferric oxide (magnetic powder)	20g	Removal material(Removal 4.5mm thickness)	m=2.88kg	Water consumption	1.25m^3	

Table 1: Energy and material consumptions of the crankshaft in the remanufacturing.

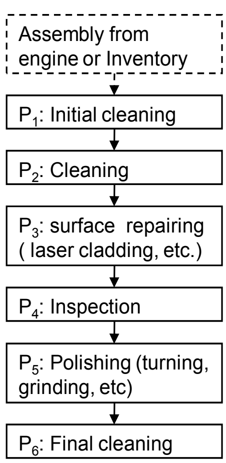

Figure 1: The remanufacturing processes of the crankshaft.

6 CONCLUDING REMARKS

To assess energy consumption of remanufacturing process, the concept of embodied energies is introduced to quantize the energy of electrical, fuel oil and auxiliary materials of remanufacturing processes. Two energy consumption models of typical processes, laser cladding and turning are established based on the thermodynamic and metal-cutting theories. Probability theory is used to describe and mitigate the uncertainties in energy consumption estimation of remanufacturing process. The distribution of the value of the total energy consumption is disscused. The concept of the upper and the lower bounds of energy consumption in remanufacturing are proposed, which can be used as a basic theory for developing energy consumption standards in remanufacturing engineering and systems.

A case study is conducted on the crankshaft of waste diesel engine to demonstrate the method of energy consumption estimation. The result shows different energy consumption values of different greasy dirt degree and wear degree of the waste crankshaft in remanufacturing process. For the method itself, how to determine coefficients μ_t, σ_t^2 and how to evaluate the energy efficiency of remanufacturing process will be the future study in the next research.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] Sutherland J. W.; Adler D. P.; Haapala Karl R. (2008) A Comparison of Manufacturing and Remanufacturing Energy Intensities with Application to Diesel Engine Production, CIRP Annals - Manufacturing Technology, Vol.57, pp. 5-8.

[2] Warsen J.; Laumer M.; Momberg W. (2011) Comparative Life Cycle Assessment of Remanufacturing and New Manufacturing of a Manual Transmission, Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Technische Universität Braunschweig, Braunschweig, Germany, May 2nd-4th, 2011.

[3] Ijomah W. L. (2010) The Application of Remanufacturing in Sustainable Manufacture, Proceedings of the Institution of Civil Engineers - Waste and Resource Management, 01 November 2010 ,Vol. 163, No. 4, pp.157-163.

[4] Boyd, G.; Dutrow, E.; Tunnessen, W., (2008) The Evolution of the ENERGY STAR1 Energy Performance Indicator for Benchmarking Industrial Plant Manufacturing Use, Journal of Cleaner Production, Vol. 16, pp. 709-715.

[5] Mills E.; Shamshoian G.; Blazek M.; Naughton P.; Seese R. S.; Tschudi W.; Sartor D. (2008) The Business Case for Energy Management in High-tech Industries, Energy Efficiency Journal, Vol. 1, pp. 5-20.

[6] Devoldere T.; Dewulf W.; Deprez W.; Willems B.; Duflou R. J. (2007) Improvement Potentials for Energy Consumptionin Discrete Part ProductionMachines, Proceedings of the 14th CIRP Conference on Life Cycle Engineering, Tokyo, Japan, pp. 311-316.

[7] Herrmann C.; Thiede S. (2009) Process Chain Simulation to Foster Energy Efficiency in Manufacturing, CIRP Journal of Manufacturing Science and Technology, Vol.1, pp. 221-229.

[8] Seow Y.; Rahimifard S. (2011) A Framework for Modelling Energy Consumption within Manufacturing Systems, CIRP Journal of Manufacturing Science and Technology, Vol. 4, pp. 258-264.

[9] Gutowski T.; Dahmus J.; et al. (2006) Electrical Energy Requirements for a Manufacturing Process, Proceedings of 13th CIRP International Conference on Life Cycle Engineering, Leuven, Belgium, pp. 623-627.

[10] Hauschild, M.; Jeswiet, J.; Alting, L. (2005) From Life Cycle Assessment to Sustainable Production: Status and Perspectives, CIRP Annals—ManufacturingTechnology, Vol. 54, No. 2, pp. 1-21.

[11] Dixit,M. K.; Fernández-Solís, J. L.; Lavy S.; et al. (2012) Need for an Embodied Energy Measurement Protocol for Buildings: A Review Paper, Renewable and Sustainable Energy Reviews, Vol. 16, No. 6, pp. 3730-3743.

[12] Dixit M. K.; Fernandez-Solis J. L.; Lavy S.; Culp C. H. (2010) Identification of Parameters for Embodied Energy Measurement: a Literature Review, Energy and Buildings, Vol. 44, No. 8, pp. 1238-1247.

[13] Treloar G. J. (1998) A Comprehensive Embodied Energy Analysis Framework. Doctor Dissertation. Deakin University.

[14] Kellens, K.; Dewulf, W.; Overcash, M.; Hauschild, M., Duflou, J.R. (2012), Methodology for Systematic Analysis and Improvement of Manufacturing Unit Process Life Cycle inventory (UPLCI), Int. Journal of Life Cycle Assessment, Vol. 17, No.1, pp. 69-78.

[15] Zhang Q. M.; Liu X. M.; Zhong M. L.; Liu W. J. (2003) Characterization Methods of the Laser Effective Energy Utilization in the Process of Powder Feeding Laser Cladding, Rare Metal Materials and Engineering, Vol. 32, No. 7, pp. 550-553 [In Chinese].

[16] Serope K.; Steven R. S. (2006) Manufacturing, Engineering & Technology (5th Edition), Prentice- Hall, 2006.

[17] Chen R. Z.(2008) theory of metal cutting. Beijing: China Machine Press, pp. 56-60 [In Chinese].

[18] Gutowski T. G.; Branham M. S.; Dahmus J. B.; et al. (2009) Thermodynamic Analysis of Resources Used in Manufacturing Processes, Environmental Science and Technology, Vol. 43, No. 5, pp. 1584-1590.

Design for Remanufacturing – A Fuzzy-QFD Approach

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Abstract

This paper proposes a methodology based on fuzzy sets theory and qualify function deployment (QFD) for integrating the various remanufacturing design factors into the initial product definition stage and providing a compromising solution for different or sometimes conflicting design requirements. In this methodology, weights will be assigned to design requirements based on a multi-objective decision hierarchy. Next, a QFD framework will be employed to map these requirements to engineering attributes that designers would need to focus on in order to improve product remanufacturability. A case study for the automobile remanufacturing industry is selected to illustrate the proposed methodology.

Keywords:

Remanufacturing; Quality Function Deployment; Fuzzy sets

1 INTRODUCTION

Forced by stringent environmental legislations and motivated by customer's growing awareness of environmental issues, many organizations and companies have adopted the practice of sustainable development. To achieve sustainability, a closed-loop material flow needs to be formed. Reusing, remanufacturing and recycling are currently the most commonly adopted end-of-life strategies in a closed-loop system. Among these strategies, remanufacturing is gaining popularity. Remanufacturing is the process of bringing products back to sound working status, through the process of disassembly, sorting, inspection, cleaning, reconditioning and reassembly [1]. Previous research studies have indicated that barriers to the remanufacturing process can be traced to the initial product design stage, and this has ignited the concept of 'design for remanufacturing' as a much pursued design activity [2-3]. However, integration of remanufacturability concerns into the product design process is not a simple issue. For instance, design for remanufacturing may conflict with other design-for-X factors. In addition, weak communication between remanufacturers and Original Equipment Manufacturer (OEM) designers may impede the successful integration of remanufacturing in the initial product design stage. To address this problem as well as to promote the successful integration of remanufacturing in the initial product design stage, the quality function deployment (QFD) method is proposed. QFD is a proven methodology for translating consumer demands into appropriate technical characteristics and specifications for product developments and production [4]. It is a widely adopted design tool used in many fields and industries, ranging from product developments, customer needs analysis, to teamwork and even management [5]. However, the vague linguistic terms involved in the judgmental process have resulted in the subjectivity and impreciseness of the traditional QFD method. Therefore, in this paper, fuzzy sets theory is proposed to address this issue in the QFD methodology to increase the reliability of the decision-making process.

This paper presents a fuzzy-QFD approach to address the integration of remanufacturing in the initial design stage and determine the important engineering attributes that the designers need to focus on to enhance the remanufacturability of products. A case study is presented to illustrate the proposed method.

2 LITERATURE REVIEW

2.1 Design for Remanufacturing

Remanufacturing is the process of returning the performance of a product to OEM performance specifications, sometimes even surpassing these specifications through upgrading the function to the latest technology [6]. The remanufacturing process could be described by following activities [7]:

Core collection: products are returned from the individual users to the remanufacturing factories.

Disassembly: products are disassembled to the single part level.

Sorting and inspection: parts are sorted and visually inspected; badly damaged elements will be discarded.

Cleaning: substances that are not intended to be present in the components will be removed.

Refurbishment/replacement: the cores will be returned to like-new condition through special techniques, sometimes even return to upgraded conditions or replaced with new parts.

Reassemble, test and dispatch: this process is quite similar to the new product manufacturing process, except that remanufacturing and reassembly are usually taking place in a comparably smaller batch assembly line.

The most effective way in promoting remanufacturability of products is during the design stage [8]. In order to produce the desired candidate for remanufacturing, every stage of the remanufacturing process needs to be addressed in the product definition stage. Shu and Flower [8] proposed that design should avoid protruding structures so as to facilitate stacking during transportation. Simon [9] stated that standardization of the fasteners and joints, easy accessibility to the inner parts, etc., are the key factors for successful disassembly. Using either identical or grossly dissimilar parts so as to reduce the effort expended on differentiating the subtly different, but not interchangeable parts, is suggested by Warnecke and Steinhipler [10]. Hundal [11] recommended surfaces to be cleaned should be wear resistant and smooth such that the cleaning cost could be reduced. Kutta [12] concluded that durable products with bulky over-design components are preferred over less material-intensive products, because there are more incentives to salvage an expensive part that is slightly worn than to salvage a cheap part that is mostly worn.

2.2 Quality Function Deployment

QFD, a powerful tool to improve the communication between customers and designers, was first developed by Akao in the late 1960s [13]. Among all the phases of QFD, the House of Quality (HOQ) is the most important phase that captures the customers' requirements and translates them into engineering characteristics that designers would need to focus on. HOQ consists of the following four basic steps [14].

1. Identification of the customers' requirements.
2. Identification of the engineering attributes which influence the customers' requirements.
3. Identification of the correlations between the customers' requirements and engineering attributes.
4. Determination of the important technical attributes to be further deployed.

2.3 Fuzzy Sets Theory

The fuzzy sets theory [15] has been applied to address the uncertainty and impreciseness of the judgments made during decision-making processes. The triangular fuzzy number, $\tilde{1}$ to $\tilde{9}$ are used to represent the subjective requirements of the customers as shown in Figure. 1. These numbers are special fuzzy sets, which can capture the vagueness of the judgment. Each triangular fuzzy number is denoted as $\tilde{M}$=(l,m,u), where l≤m≤n. An alpha-cut α is introduced to represent the interval of the confidence levels. The larger the deviation of the alpha value from 1, the lower will be the level of certainty or confidence of a decision maker. Therefore, the triangular fuzzy number can be further expressed as follows [16]:

$$M_\alpha=[l^\alpha,u^\alpha]=[(m-l)*\alpha+l,-(u-m)*\alpha+u],\forall\alpha\in[0,1] \quad (1)$$

The common arithmetic operators for positive fuzzy numbers described by the interval of confidence are listed below [17]:

$$\forall m_L, m_R, n_L, n_R \in R^+$$

$$\tilde{M}_\alpha = [m_L^\alpha, m_R^\alpha], \tilde{N}_\alpha = [n_L^\alpha, n_R^\alpha], \forall \alpha \in [0,1] \quad (2)$$

$$\tilde{M} \oplus \tilde{N} = [M_L^\alpha + N_L^\alpha, M_R^\alpha + N_R^\alpha] \quad (3)$$

$$\tilde{M} \Theta \tilde{N} = [M_L^\alpha - N_R^\alpha, M_R^\alpha - N_L^\alpha] \quad (4)$$

$$\tilde{M} \otimes \tilde{N} = [M_L^\alpha * N_L^\alpha, M_R^\alpha * N_R^\alpha] \quad (5)$$

$$\tilde{M} \phi \tilde{N} = [M_L^\alpha / N_R^\alpha, M_R^\alpha / N_L^\alpha] \quad (6)$$

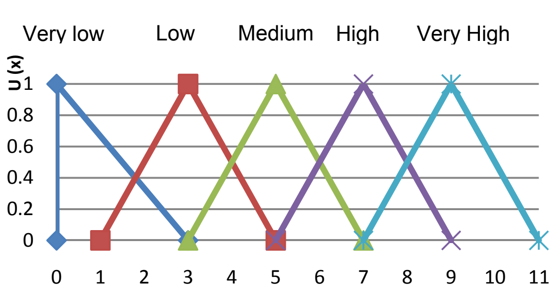

Figure 1: Triangular membership function for fuzzy sets.

The defuzzification is conducted by converting a fuzzy preference into a crisp judgment through the following equation:

$$X_{ij}^\alpha = \omega X_{iju}^\alpha + (1-\omega) X_{ijl}^\alpha, \omega \in [0,1] \quad (7)$$

ω is the index of optimism, which reflects the degree of optimism of decision makers towards their judgment [18]. When ω approaches 1, it reflects that the designers' attitude is inclined towards more extreme values, whereas when ω is approaching 0, it reflects that the designers' attitude is inclined towards more moderate values.

2.4 Fuzzy-QFD and Its Applications

QFD has been widely applied in manufacturing due to its effectiveness in identifying the conceptual requirements of the customers and translating them into engineering attributes that can enhance product design, reduce time-to-market and the production cost [4-5]. A major challenge of traditional QFD is the presence of incomplete and vague information. The fuzzy sets theory has been applied to handle the vague information involved in QFD, hence the fuzzy-QFD approach. Khoo and Ho [19] has applied the possibility theory and the fuzzy sets theory to address the vagueness involved in the correlation of the requirements and design attributes. Vinodh [20] has applied fuzzy QFD to identify the lean decision domains, lean attributes and lean enablers for an organization.

Fuzzy-QFD has been applied in remanufacturing, where the "customers" refer to the remanufacturers and the engineering attributes refer to the design paramenters that can improve the remanufacturability of the products [21]. Although many studies have been reported on the application of fuzzy-QFD in remanufacturing, there are some limitations. First, many studies only focus on the specific aspects of remanufacturing, e.g., remanufacturing processes, reverse supply chain, etc. There is a lack of decision tools that can consider the various "voices" associated with remanufacturing simultaneously, e.g., environmental factors, cost concerns, etc. Secondly, there is no clear framework to analyze the relationships between different aspects of requirements and assign proper weights to them. A fuzzy-QFD model that can consider the various vague opinions from groups of decision-makers is needed because evaluators with different expertise can have different judgments. Hence, to address these limitations, an integrative fuzzy-QFD approach to integrate the various 'voices' of remanufacturing into the initial design stage is proposed in this paper.

3 METHDOLOGY

The proposed model in this paper is based on three key modifications to the traditional QFD.

- The first modification is to expand the conventional scope of the 'customers' to include the remanufacturers, environment concerns, cost factors as well as product users. Weak communications between remanufacturers and OEM design engineers have impeded the successful integration of remanufacturing in the initial product design stage. Therefore, remanufacturers are considered as a "customer" in the proposed model so that the remanufacturing process requirements can be translated into product design attributes. In addition, by including environmental concerns and cost factors in the design requirements, a compromising result can be obtained between the various requirements. To address the market demands for the remanufacturing products, feedbacks from users are also investigated and included.
- The second modification is to develop a hierarchical structure of requirements and compute their weights. To do this, the

fundamental objectives are first identified along the direction of preferences, e.g. enhancing the product remanufacturability, minimizing the production cost, etc. Next, these fundamental objectives are further decomposed in a hierarchical fashion to sub-objectives until they can be comprehended easily and evaluated, e.g., easy access to the inner parts, reduce the cleaning cost, etc. Subsequently, the importance of the elements at each level of the decision hierarchy will be decided and synthesized to determine their global priorities.

- The third modification is to use the fuzzy sets theory to overcome the vagueness and impreciseness involved in the QFD decision-making process. For example, instead of using "7" to represent "important", this crisp value will be fuzzified into an interval representation [5+2α,9-2α], where α is used to address the certainty of the linguistic judgment.

The HOQ, which is the first and fundamental matrix of QFD, will be elaborated on in this paper. The other three QFD matrices are essentially the same and can be developed in the similar manner as HOQ. The following steps are proposed for developing the Fuzzy-HOQ for design for remanufacturing.

a) Determine the scope of the customers and the fundamental objectives O_i from the remanufacturers, environment concerns, cost factors and users aspects.
b) Using a hierarchy structure to determine the sub-level requirements R_i for each fundamental objective (WHATs). Affinity diagrams, tree diagrams and cluster analysis could be used for this purpose [16].
c) Determine and compute the weights of the fundamental and sub-level requirements of the customers.
d) Determine the relevant engineering attributes (HOWs).
e) Determine the relationship between HOWs and WHATs by using linguistic variables {Very low, Low, Medium, High, Very high}.
f) Translate the linguistic variables into fuzzy numbers with alpha cut values.
g) Determine the weights for each engineering characteristic using fuzzy sets theory. For HOQ with N WHATs and M HOWs, the weight of each engineering characteristic can be calculated using Equation (8).

$$\widetilde{M}_j = (\widetilde{C}_{1j} \times \widetilde{I}_1) + (\widetilde{C}_{2j} \times \widetilde{I}_1) + ... + (\widetilde{C}_{Nj} \times \widetilde{I}_N), \quad \forall j \in \{1,2,...M\} \tag{8}$$

h) Input the value of ω into Equation (7) to convert the fuzzy number into the crispy form so that the ranking of each HOW can be determined.

4 AN ILLUSTRATIVE EXAMPL0045

A case study for the automobile remanufacturing industry is selected as an example to illustrate the proposed methodology. Since the *End of Life Vehicle Directive* has been introduced in EU, in 2002, remanufacturers are required to achieve the goal of vehicles reusability and/or recyclability of at least 85% and reusability and/or recoverability of at least 95% by weights [22]. This has driven the manufacturers to develop new planning processes, and designing products for remanufacturing. The automobile industry has the longest tradition of remanufacturing and accounts for 2/3 of the global remanufacturing activities in terms of volume [23]. In this case study, the proposed methodology is used to determine the important engineering characteristics that designers need to focus on so as to facilitate remanufacturing. The detailed analysis of using proposed methodology is presented next.

Step 1: Determine the scope of the customers and the fundamental objective O_i.

The scope of 'customers' in this methodology includes:

- Automobile remanufacturing factory/sectors, who can provide feedback on the inefficiency and difficulty involved in the remanufacturing processes.
- Environmental regulators, who can identify the environment concerns and the respective legislations.
- Financial department, who aims to reduce the cost of the products.
- Marketing department which investigates the market demand and understands the users' preference.

Accordingly, the fundamental objectives are identified as: (1) maximize the remanufacturability of the products, (2) minimize the environmental impacts, (3) minimize the cost, and (4) maximize the customer satisfaction. These objectives represent a combination of the long term and short term development goals of companies, aligning with business strategy, sustainable development strategy as well as financial consideration.

Step 2: Determine the sub-level requirements R_{ij} for each fundamental objective

The fundamental objectives are decomposed into 14 sub-criteria R_{ij}. At the next lower level, 19 customers requirements R_{ijk} are considered significant in influencing the sub-criteria, as shown in Table 1. These factors are summarized from existing published literature on design for remanufacturing as well as survey results conducted for the automobile remanufacturing industry [24-26].

Step 3: Compute the weights of the customer requirements.

After the hierarchy of the customer requirements is constructed, many decision-makers are required to provide local weights (LW) for these requirements at different levels. The requirements will be compared at a given level to estimate their relative weights (RW) with respect to their immediate preceding requirement.

To obtain reliable data, the decision-makers should be chosen carefully. For example, the importance of the fundamental objectives should be determined by a high level management team since they are in the position to decide product development and the market strategy of the company. In the next level, the importance of the criteria will be determined by the corresponding departments. For instance, the weight of the various remanufacturing requirements will be determined by the engineers from the remanufacturing department.

After the relative weight of requirement R_{ijk} at the base level of the decision hierarchy has been calculated, the weight of the requirement R_{ijk} will be normalized separately with respect to their immediate preceding R_{ij} to obtain the normalized weight (NW) and adjusted with respect to remanufacturing, environmental impact, cost concern as well as customers' requirements to determine their global priorities. For example, the global weight of the second column R_{121} is calculated as $3 \approx 21 * 20\% * 60\%$.

Step 4: Determine the relevant engineering attributes

In this step, the set of measurable engineering attributes (HOWs) to realize the customer needs (WHATs) will be determined. The list of engineering attributes that influence the remanufacturing process is shown at the top of the HOQ in Table 2.

Step 5: Determine the relationship between HOWs and WHATs

The correlations between the customer requirements (WHATs) and the engineering attributes (HOWs) are determined by analyzing the extent of influence that the engineering attributes have on the requirements.

R_i	R_1																		
RW	60%																		
R_{ij}	R_{11}	R_{12}							R_{13}		R_{14}					R_{15}			R_{16}
LW	1	2							1		5					8			3
RW	5%	20%							5%		25%					40%			5%
R_{ijk}	R_{111}	R_{121}	R_{122}	R_{123}	R_{124}	R_{125}	R_{126}	R_{127}	R_{131}	R_{132}	R_{141}	R_{142}	R_{143}	R_{144}	R_{145}	R_{151}	R_{152}	R_{153}	R_{161}
LW	7	9	9	7	5	5	5	3	3	5	5	1	5	3	3	9	7	7	3
RW	100	21	21	16	12	12	12	7	38	63	29	6	29	18	18	39	30	30	100
NW	5	4	4	3	2	2	2	1	2	3	7	1	7	4	4	16	12	12	5
GW	3	3	3	2	1	1	1	1	1	2	4	1	4	3	3	9	7	7	3

Table 1: Weights of remanufacturing requirements.

The linguistic variables used to define the relationship $\tilde{C}_{ij}$ between HOWs and WHATs include {Very low, Low, Medium, High, Very high}. The data pertaining to remanufacturing design feedback were taken from the work reported by Yukesel [21], i.e., the relative weights and correlations. However, the scores have been adjusted and scaled because of the different evaluation schemes used, new design requirements and engineering attributes. The rest of the data pertaining to environmental aspects, cost requirements and user feedback are obtained from surveys in the automobile industry as well as the relevant literature [2-3, 24-26].

Step 6: Translate the Linguistic Evaluation into Fuzzy Numbers

After evaluating the correlations between the HOWs and WHATs, the evaluation results will be translated into fuzzy numbers with respect to an alpha cut value to address the vagueness of the decision-making process. The alpha value will be chosen between 0 to 1, and the farther the deviation of alpha value from 1, the lower is the level of confidence of a decision-maker. The linguistic values with their corresponding fuzzy numbers are given in the following equations:

Very low: $\tilde{1}^{\alpha} = [1, 3 - 2\alpha]$

Low: $\tilde{3}^{\alpha} = [1 + 2\alpha, 5 - 2\alpha]$

Medium: $\tilde{5}^{\alpha} = [3 + 2\alpha, 7 - 2\alpha]$

High: $\tilde{7}^{\alpha} = [5 + 2\alpha, 9 - 2\alpha]$

Very high: $\tilde{9}^{\alpha} = [7 + 2\alpha, 11 - 2\alpha]$

If the decision-makers have an average confidence of their judgment, the alpha value will be assigned as 0.5. Meanwhile the weights determined in Step 3 will also be translated into fuzzy numbers in a similar manner using equation (1) with α=0.5.

Step 7: Determine the weight for each engineering characteristic

By using equation (8), the resulting weight for each engineering characteristic can be calculated. The raw score for each engineering attribute is shown in the fuzzy form in Table 2.

Step 8: Computing the rank for each HOW

In this step, the value of ω will be chosen between 0 to 1 for defuzzification. A larger ω value reflects extreme judgments and a smaller ω value reflects moderate judgments. Equation (7) will be used to defuzzify each $\tilde{M}_j$. After defuzzification, the rank of each HOW can be determined. The results show that "durable material and structure design", "positions of parts and components" and "types of fasteners and joints" are the top three important engineering attributes that influence the remanufacturability of automobile components.

5 RESULT AND DISCUSSION

At the product design stage, two-thirds of the remanufacturability potential of products has been determined. With the proposed methodology, the remanufacturer feedback, environmental concerns, cost factors as well as user requirements are taken into consider-ation and translated into engineering attributes that designers need to focus on to improve the remanufacturability of the products. The results obtained from the case study show that the engineering attributes that have major influence on remanufacturing require-ments are *"durable material and structure design", "positions of parts and components" and "types of fasteners and joints"*. These results have been compared with findings by Yuksel [21], in which the engineering attributes of *"position of the parts", "types of the parts" and "types of fasteners and joints"* are determined to be the most important engineering attributes for automobile. This difference could be because only feedbacks of the remanufacturers are considered for customer requirement in Yuksel's work, whereas in this paper, environmental concerns, cost factors as well as user requirements are included as design requirements. The key factor to reducing the environmental impact and the cost of remanufacturing is the component reusability [27], and the key enabler of component reusability is to use durable materials and design durable structures such that the components could be used for multiple life cycles [1,12,28,29]. Meanwhile, durable design is critical for attaining higher reliability of the remanufactured products. Hence, durability is the most important remanufacturing attribute in the automobile industry, when environment impacts, cost factors and user's requirements have all been taken into considerations. In addition, in this paper, it is found that the "positions of parts and components"

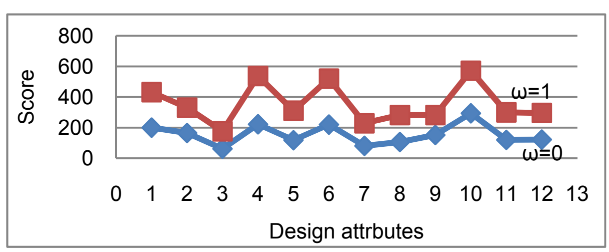

Figure 2: Attributes weight result from different ω value.

Requirements		Engineering characteristic	Importance	Types of materials	Standardization of parts	Number of the parts/components	Position of parts/components	Shape of parts	Types of fasteners /joints	Position of fasteners /joints	Standardization of fasteners /joints	Commonality of products	Durable material and structure design	Platform and modularity design	Indication of the condition
R1.Enhance Remanufacturability	R11.Easy transport	R111.Protection from damage	(2,4)	(4,6)	(0,0)	(0,0)	(0,0)	(8,10	(0,0)	(0,0)	(0,0)	(0,0)	(4,6)	(0,0)	(2,4)
	R12.Easy disassembly	R121.No damage to other parts	(2,4)	(0,0)	(0,0)	(0,0)	(4,6)	(1,2)	(2,4)	(1,2)	(2,4)	(0,0)	(0,0)	(4,6)	(0,0)
		R122.Easy disassemble joints /fasteners	(2,4)	(0,0)	(0,0)	(0,0)	(4,6)	(2,4)	(8,10	(6,8)	(8,10	(0,0)	(0,0)	(0,0)	(0,0)
		R123.Low number of tools for disassembly	(1,3)	(0,0)	(8,10	(0,0)	(2,4)	(2,4)	(4,6)	(6,8)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)
		R124.Single disassembly direction	(1,2)	(0,0)	(0,0)	(0,0)	(4,6)	(2,4)	(2,4)	(1,2)	(4,6)	(0,0)	(0,0)	(2,4)	(0,0)
		R125.Easy access to the joints /fasteners	(1,2)	(0,0)	(1,2)	(4,6)	(6,8)	(4,6)	(6,8)	(8,10	(0,0)	(0,0)	(0,0)	(2,4)	(0,0)
		R126.More operations within one setup	(1,2)	(0,0)	(0,0)	(0,0)	(4,6)	(1,2)	(1,2)	(1,2)	(1,2)	(0,0)	(0,0)	(0,0)	(0,0)
		R127.Easy access to the parts	(1,2)	(0,0)	(0,0)	(4,6)	(8,10	(1,2)	(1,2)	(2,4)	(2,4)	(6,8)	(0,0)	(2,4)	(0,0)
	R13.Easy sorting and inspection	R131.Easy classification and inspection	(1,2)	(0,0)	(4,6)	(4,6)	(2,4)	(8,10	(2,4)	(0,0)	(0,0)	(0,0)	(0,0)	(2,4)	(0,0)
		R132.Easy access and identification	(1,3)	(0,0)	(0,0)	(4,6)	(8,10	(1,2)	(2,4)	(1,2)	(1,2)	(0,0)	(0,0)	(0,0)	(0,0)
	R14.Easy cleaning	R141.Easy access to parts	(3,5)	(0,0)	(0,0)	(4,6)	(8,10	(6,8)	(1,2)	(2,4)	(0,0)	(0,0)	(0,0)	(2,4)	(0,0)
		R142.Smoothness of the surfaces	(1,2)	(0,0)	(0,0)	(0,0)	(2,4)	(8,10	(1,2)	(1,2)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)
		R143.No damage to the surface	(3,5)	(4,6)	(0,0)	(0,0)	(4,6)	(1,2)	(0,0)	(1,2)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)
		R144.Avoid accumulation of residue	(2,4)	(0,0)	(0,0)	(0,0)	(4,6)	(4,6)	(2,4)	(1,2)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)
		R145.Protect marks on the parts	(2,4)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(4,6)	(0,0)	(4,6)
	R15.Easy reconditioning	R151.Parts availability	(8,10)	(2,4)	(8,10	(0,0)	(0,0)	(0,0)	(4,6)	(0,0)	(4,6)	(8,10	(0,0)	(6,8)	(0,0)
		R152.Parts corrosion-resistance	(6,8)	(0,0)	(0,0)	(0,0)	(1,2)	(1,2)	(6,8)	(4,6)	(1,2)	(0,0)	(8,10)	(0,0)	(0,0)
		R153.Multiple cycles for reconditioning	(6,8)	(4,6)	(0,0)	(0,0)	(8,10	(1,2)	(2,4)	(2,4)	(0,0)	(0,0)	(8,10)	(0,0)	(6,8)
	R16.Easy assembly	R161.Less number of adjustments	(2,4)	(0,0)	(4,6)	(2,4)	(4,6)	(0,0)	(2,4)	(0,0)	(4,6)	(0,0)	(0,0)	(2,4)	(0,0)
R2. Reduce Environ-impact	R21.Less material usage		(2,4)	(4,6)	(0,0)	(2,4)	(4,6)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(8,10)	(1,2)	(2,4)
	R22.Less energy consumption		(2,4)	(4,6)	(2,4)	(4,6)	(8,10	(0,0)	(2,4)	(0,0)	(2,4)	(0,0)	(8,10)	(4,6)	(2,4)
	R23.Less waste generated		(2,4)	(4,6)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(6,8)	(0,0)	(0,0)
R3.Reduce cost	R31.Less part replacement cost		(7,9)	(4,6)	(8,10	(2,4)	(0,0)	(0,0)	(4,6)	(0,0)	(2,4)	(8,10	(6,8)	(2,4)	(4,6)
	R32.Less cleaning cost		(7,9)	(4,6)	(0,0)	(0,0)	(4,6)	(4,6)	(4,6)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(2,4)
	R33.Less parts refurbishment cost		(3,5)	(4,6)	(4,6)	(0,0)	(4,6)	(0,0)	(2,4)	(0,0)	(2,4)	(2,4)	(8,10)	(2,4)	(4,6)
R4.Fulfill user requirement	R41.Request for products with updated technology		(2,4)	(0,0)	(4,6)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(4,6)	(4,6)	(0,0)	(8,10	(0,0)
	R42.High reliability of the product		(6,8)	(8,10	(0,0)	(0,0)	(0,0)	(0,0)	(4,6)	(0,0)	(0,0)	(0,0)	(8,10)	(0,0)	(0,0)
Raw score				(200, 432)	(165, 330)	(62, 176)	(222, 538)	(118, 310)	(220, 520)	(81, 228)	(106, 282)	(152, 282)	(294, 572)	(120, 300)	(122, 296)
Defuzzied crispy value				316	248	119	380	214	370	155	194	217	433	210	209
Importance ranking				4	5	12	2	7	3	11	10	6	1	8	9

Table 2: HOQ for design for remanufacturing.

and “types of fasteners and joints” are important for designing products for remanufacturing, which are aligned with Yuksel’s results and supported by other design for remanufacturing literature [30-32].

Sensitivity analysis has been conducted by altering the value of the level of uncertainty α and the index of optimism ω to determine the weights of the engineering attributes. Results show that the general trends of ranking importance remain the same regardless of the values of α and ω. “Durable material and structure design”, “positions of parts and components” and “types of fasteners and joints” remain on top of the ranking. However, depending on different values of α and ω, there is a slight variation in the ranking between these closely ranked attributes. Figure.2 shows the resulted attribute weights for $\omega = 0$ and $\omega = 0.95$ when α equals 0.5. These variations provide possibility for taking various options from different decision makers and make more informed decision through a scientific approach.

6 SUMMARY

An integrated methodology for translating various remanufacturing design factors into engineering attributes and providing a compromising solution for different or sometimes conflicting design requirements is presented in this paper. This methodology is based on three key modifications to the traditional QFD methodology. The case study validates that the proposed methodology can be applied successfully to designing products for remanufacturing. The results obtained show that engineering attributes that have large influence on the requirements are “durable material and structure design”, “positions of parts and components” and “types of fasteners and joints” in the automobile industry. To further enhance the proposed methodology, other artificial intelligence techniques, such as the analytical hierarchy process, artificial neural network, etc., can be adopted to improve the reliability of the proposed methodology and provide more valuable information for product developers. Other phases of QFD can also be established according to these results. In addition to the automobile industry, this generic design for remanufacturing methodology can also be applied to other sectors, such as household appliances, medical equipment, office and computers devices, etc. The proposed methodology is designed for generic use, not for a specific product. Designers can ignore some of the requirements or divide the requirement into multiple items with more details, so as to use this methodology effectively.

7 REFERENCES

[1] Lund, R. (1984): Remanufacturing: The Experience of the United States and Implications for Developing Countries, World Bank, Washington DC.

[2] Ijomah, W., McMahon, C., Hammond, G., Newman, S. (2007a): Development of robust design-for-remanufacturing guidelines to further the aims of sustainable development, in: International Journal of Production Research, Vol.45, No.18, pp. 4513-4536.

[3] Ijomah, W., McMahon, C., Hammond, G., Newman, S. (2007b): Development of design for remanufacturing guidelines to Support sustainable manufacturing, in: Robotics and Computer Integrated Manufacturing Vol. 23, pp.712-719.

[4] Sullivan, L.P. (1986b): Quality function deployment, in: Quality Progress, Vol.19, No. 6, pp.39–50.

[5] Chan, L.K., Wu, M. L. (2002): Quality function deployment: A literature review, in: European Journal of Operational Research, Vol.143, No.3, pp. 463-497.

[6] King, A.M., Burgess, S.C. (2005): The Development of a Remanufacturing Platform Design: A Strategic Response to the Directive on Waste Electrical and Electronic Equipment, in: Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 219, No. 8, pp. 623-631.

[7] Steinhilper R. (1999): Remanufacturing: The ultimate form of recycling, in: Journal of Industrial Ecology Vol. 3, No. 2-3, pp.189–192.

[8] Shu, L., Flowers, W. (1999): Application of a design-for remanufacture Framework to the Selection of product life-cycle and joining methods, in: Robotics and Computer Integrated Manufacturing Vol.15, pp.179-190.

[9] Simon M., Fogg B., Chambellant F. (1991): Design for cost-elective disassembly. Design for Disassembly and Recycling Technical Report (DDR/TR1), Manchester Metropolitan University, U.K.

[10] Warnecke H.J.; Steinhilper R. (1983): Designing Products with Built-In Reconditioning Features, in: Proceedings of 6th Annual Conference on Design Engineering, pp.241-248, Birmingham, U.K.

[11] Hundal, M. S. (1997): Systematic Mechanical Designing: A Cost And Management Perspective, New York, ASME Press.

[12] Kutta R. (1980): Remanufacture of durable products: a value-preserving technology. MIT S.M. Thesis. MIT Cambridge, MA.

[13] Akao, Y., Mazur, G.A. (2003): The leading edge in QFD: past, present and future, in: International Journal of Quality and Reliability Management Vol.20, No.1, pp.20–35.

[14] Halog, A., Schultmann, F., Rentz, O. (2001): Using Quality Function Deployment (QFD) for Technique Selection for Optimum Environmental Performance Improvement, in: Journal of Cleaner Production, Vol.9. No.5, pp.387-394.

[15] Zadeh, L.A. (1965): Fuzzy Sets, Information and control, Vol. 8, pp.338-353.

[16] Kwong, C. K., Bai, H. (2003): Determining the important weights for the customer requirement in QFD using a fuzzy AHP with an extent analysis approach, in: IIE Transactions, Vol.35, No. 7, pp.619–626.

[17] Kauffman, A., Gupta, M. M. (1988): Fuzzy mathematical models in engineering and management science. Amsterdam, Netherlands: North-Holland.

[18] Promentilla, M. A. B. (2006): Development of a multiple criteria decision making method for remedial counter measures of contaminated sites, Division of Environment and Resources Engineering, Hokkaido University, http://ws3-er.eng.hokudai.ac.jp/egpsee/alumni/abstracts/Michael.pdf, accessed 20th October 2012.

[19] Khoo, L.P., Ho, N.C. (1996): Framework of a fuzzy quality function deployment system, in: International Journal of Production Research Vol.34, pp. 299–311.

[20] Vinodh S., Suresh K. C, (2011): Application of fuzzy QFD for enabling leanness in a manufacturing, in: International Journal of Production Research, Vol. 49, No. 6, pp.1627–1644.

[21] Yuksel, H. (2010): Design of Automobile engines for remanufacture with quality Function Deployment, in: International Journal Os sustainable Engineering Vol.3, No.3, pp.170-180.

[22] Eair (2009): European Automobile Industry Report 2009, www.acea.be, accessed 20th October 2012.

[23] Kim, H.J.; Severengiz, S.; Skleros, S.; Seliger, G. (2008): Economic and environmental assessment of remanufacturing in the automotive industry, in: 15th CIRP International Conference on Life Cycle Engineering, pp.195-200, Sydney, Australia.

[24] Hammond, R., Amezquita, T., Bras, B. (1998): Issues in the automotive parts remanufacturing industry- A discussion of results from surveys Performed among remanufacturers, in: International Journal of Engineering Design and Automation, Vol.4, No.1, pp.27-46.

[25] Smith, V. M., Gregory A. K. (2003): The Value of Remanufactured Engines: Life Cycle Environmental and Economic Perspectives, in: Journal of Industrial Ecology, Vol.8, No.1-2, pp.193-221.

[26] Bras, B., Hammond, R., (1996): Towards Remanufacturing-Metrics for Assessing Remanufacturability, in: 1st International Workshop on Reuse, pp. 35-52, Eindhoven, the Netherlands.

[27] Nasr, N., Thurston, M. (2006): Remanufacturing: A Key Enabler to Sustainable Product Systems, Rochester Institute of Technology.

[28] Charter, M., Gray, C. (2008): Remanufacturing and product design, in: International Journal of Product Development Vol.6, No.3-4, pp.375-392.

[29] Ayres, R., Ferrer, G., Van Leynseele, T.(1997): Eco-Efficiency, Asset Recovery and remanufacturing, in: European Management Journal, Vol. 15, No.5, pp.557-574.

[30] Sundin, E. (2004): Product and process design for successful remanufacturing, in: Linköping Studies in Science and Technology Dissertation, No. 906.

[31] Amezquita, T.; Hammond, R.; Bras, B.(1995): Characterizing the remanufacturability of engineering systems, in: Proceedings 1995 advances in design automation conference, Vol. 82, pp. 271–278.Boston, U.S.A.

[32] MtGlothlin, S.; Kroll, E. (1995): Systematic estimation of disassembly difficulties: application to computer monitors, in: Proceedings of the IEEE international symposium on electronics and the environment, Orland, Florida.

LCA-Based Comparative Evaluation of Newly Manufactured and Remanufactured Diesel Engine

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Abstract

Life Cycle Assessment (LCA) enables to estimate the potential materials, energy resources, and environmental emissions resulting from various activities in our economy. The present study intends to analyze the energy consumption and environmental emissions in the entire life cycle of originally manufactured diesel engine compared with its remanufactured counterpart. Furthermore, the paper attempts to find out the largest energy requirement and the severest environmental emissions contribution stage. This LCA is conducted by software E-Balance and data collection refers to the database CLCD. The result shows that energy consumption and environmental impacts are considerably reduced for the remanufactured engine compared to a newly manufactured engine. the greatest benefits are EP which is reduced by 90.57%, followed by ODP, PED, GWP, AP which can be reduced by 75.15%, 70.33%, 68.92%, 67.65% separately.

Keywords:

Life cycle assessment; remanufacture; diesel engine; energy consumption; environmental emissions

1 INTRODUCTION

1.1 Backgrounds

According to EIA, China emits 7710.5 Mt CO_2 in 2009 which are more than the US and Canada put together - up by 171% since the year 2000. Over 25% of these emissions given out by operations associated to direct manufacturing in which metal processing operations having a major share in the energy consumption and thus the large truck engines with a large amount of aluminum and steel contribute largely to CO_2 emissions. Faced with this serious environmental problem, Engine manufacturers are exploring ways to minimize the effects of their activities on the environment by providing “greener” products and using “greener” processes. Remanufacturing is such a method which can reduce the use of energy, material, operation cost, thus, ensuring environmental benefit without reducing performance of a product by diverting products to a new second life instead of being buried [1]. During World War II there was a tremendous need to reuse automotive and truck parts. Natural resources were scarce, since much of them were devoted to the war effort to build planes, ships, tanks, etc. Since the end of WW II remanufacturing has enjoyed steady growth in the US and later in Europe. Now in Europe, Remanufactured starters & generators have a market share of 80% and other car components have a market share of about 50% [2]. It is being realized that diesel engine remanufacturing has better environ-mental performance than originally manufacturing for the materials machining processes such as molding, casting etc. can be avoided. However, qualify and quantify the benefits of diesel engine remanufacturing compared to new manufacturing remains unsolved due to the difficulties of data collection in complex production processes and the lack of accurate and convinced evaluation method.

Life cycle assessment (LCA) is a “cradle to grave” approach for assessing industrial products and systems, which enables the estimation of the cumulative environmental impacts resulting from all stages in a product life cycle; often including impacts not considered in more traditional analyses [3].

According to the ISO 14040 and 14044 standards, an LCA consists of four components:

a. Goal and scope definition - Define and describe the product, process, or activity.

b. Life cycle inventory analysis - Identify and quantify energy, materials usage, and environmental releases.

c. Life cycle impact assessment - Assess the potential human and ecological effects of energy, materials usage and environmental releases, as identified in the inventory analysis.

d. Life cycle interpretation - Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process, or activity [4].

Former researchers have studied the environmental benefits of auto parts remanufacturing such as has manual transmission and injector [5, 6]. Also Sophie *et al.* and Hossein *et al.* have studied the environmental threats of different automotive fuels: electric compared to conventional gasoline fuel [7, 8].

Remanufacturing process is generally composed of several stages: disassembly, cleaning, testing, repair, inspection, updating, component replacement and reassembly [9], This LCA intend to identify the environmental benefits of remanufactured diesel engine compared with newly manufactured counterpart and identify the largest negative impact on the environment during the whole life cycle.

2 GOAL AND SCOPE DEFINITION

2.1 Goal

The goal of this LCA-study is to analyze and compare the energy and environmental impacts of two kinds of manufactured diesel engine. Life cycle inventory analyses, including energy consumption and air/water emissions were carried out for both the engines. Five environmental impacts categories are assessed in this study, which are: Global Warming Potential (GWP), Acidification Potential (AP), Photochemical Ozone Creation Potential (POCP), Eutrophication Potential (EP), and Ozone Depletion Potential (ODP). Besides primary energy demand, coal, crude oil, and natural gas requirements are also examined in this study.

2.2 Functional Unit

The functional unit in this study is defined as one STR series WD615/87 diesel engine for a particular use in China. Table 1 shows the material composition of the diesel engine by weight of different materials. In this study, three species of raw materials are considered which are steel, cast iron, and aluminum.

Materials	Mass（kg）	Remanufacturing Materials Mass (kg)	Wt.%
Steel	204	154.5	0.757
Cast iron	581.3	579	0.996
Aluminum	46.33	40	0.863
Else	41.36	13.47	0.325
Total	872.99	786.97	0.901

Table 1: Material composition of one diesel engine.

2.3 System Boundary

The scope of this life cycle assessment is shown in Fig 1 (emissions to air/water and energy consumptions are not shown). The manufacturing process begins with raw material mining and production, materials transportation to workshop, and diesel engine manufacturing; while the remanufacturing process begins with old diesel engine recycling, disassembly/sorting, and components remanufacturing, which includes cleaning, testing, machining and repairing, post testing and assembly in detail.

The use phases of the two engine types are considered to be identical because the remanufactured diesel engines are reprocessed to recover component quality and therefore meet the same fuel requirements as a newly manufactured engine. The phases of diesel engine transportation to market and end of life disposal are also considered identical, therefore, are excluded from the evaluation scopes.

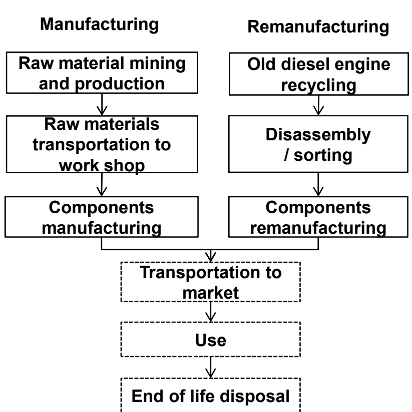

Figure 1: A simplified life cycle of diesel engine, indicating the system boundary.

2.4 Data Collection

2.4.1 Materials Production

The raw materials need to be extracted and refined from the minerals and then undergoes various manufacturing processes to manufacture the engine parts. Energy and resources are used for that purpose. Aluminum, Cast iron and Steel are three major materials of a diesel engine which brings about large amount of energy consumption and environmental emissions. The other materials such as rubber and small amount of polymeric compounds are ignored due to the fact that remanufacturing parts made by these two materials are replaced by new ones (in fact, the parts which need to be replaced by new when remanufacturing are not considered into the system boundary).

The data related to energy requirements, air/water emissions of materials, mining, and production phases are referred from the CLCD of E-balance software developed by IKE, China. The CLCD database can reflect the average production levels existed currently.

2.4.2 Materials Transportation and Old Engine Recycling

Shanghai Baosteel is the steel and cast iron materials provider of SINOTRUK, the materials are transported by train with the distance of 600km, and we ignored the transportation of the other materials to workshop; The old diesel engines for remanufacturing are all recycled back from the CNHTC 4S shop by truck (carrying capacity: 8 tons), the average distance covered for the old engine recycling is estimated to be 800km based on our investigation.

Fuel consumption and environmental emissions in these two processes are referred to the relative CLCD databases, as available in the software of E-Balance.

2.4.3 Parts Manufacturing/Remanufacturing and Assembly

The data related to diesel engine manufacturing/remanufacturing processes are collected from the diesel engine manufacturer, SINOTRUK, using the method of In-depth approach put forward by CO_2PE [10]. The in-depth approach includes time, power, consumables, and emission studies and leads to more accurate and complete LCI data, and supports the identification of potentials for environmental and economic improvements of the studied manufacturing equipment.

2.4.4 Air/Water Emissions

The data for the air/water emissions have been discussed in detail in the data collection sheets. The different gases involved are CO_2, CO, H_2S, N_2O and chlorofluorocarbons (CFC) etc. The water emissions contain ammonium which is extremely harmful for the environment. The data for the energy demand and environmental emissions are all from CLCD fundamental database development by IKE Company in China.

The data related to energy requirements, air/water emissions of materials, mining, and production phases are referred from the CLCD of E-balance software developed by IKE, China. The CLCD database can reflect the average production levels exisiting currently.

3 LIFE CYCLE INVENTORY ANALYSIS

The final life cycle inventory results of the newly manufactured / remanufactured diesel engine are shown in table Table 2 & 3. The primary energy demand and air/water emissions considered into the system boundary are significantly reduced by remanufacturing. From the detailed item value, we can find that the largest reduction item is achieved in CO_2 emission which is a key factor in global warming potential (a reduction of 2884.3kg), accounting for 73.9% of the total CO_2 emissions in manufacturing. Regarding resources consumptions, the greatest savings is observed in hard coal consumption (a reduction of 1607.2kg), which accounts for 73.1% of the total coal consumption in manufacturing. Fig 2 shows, graphically, the detailed reduction proportion of each item.

Categories	Raw material production	Materials transporta-tion	Components Manufact-uring	Total
Hard coal	1.22E+03	1.18E+00	9.76E+02	2.20E+03
Crude oil	5.28E+01	8.68E-01	5.82E+00	5.95E+01
Natural gas	8.33E+00	1.49E-02	8.69E+00	1.70E+01
CO	5.54E-01	5.75E-03	3.38E-01	8.98E-01
CO2	2.38E+03	4.26E+00	1.52E+03	3.90E+03
SO2	6.21E+00	9.54E-03	5.30E+00	1.15E+01
NOx	3.71E+00	4.13E-02	4.38E+00	8.13E+00
CH4	5.87E+00	1.96E-02	4.50E+00	1.04E+01
H2S	2.43E-02	1.01E-06	7.30E-04	2.50E-02
HCL	2.14E-01	5.20E-04	4.33E-01	6.48E-01
CFCs	1.77E-06	2.01E-09	1.15E-06	2.92E-06
COD	4.87E+00	6.34E-03	1.39E-01	5.02E+00
NH4	2.65E-02	1.52E-04	2.84E-03	2.95E-02

Table 2: Life cycle inventory of the a newly manufactured diesel engine.

Categories	Old diesel engine recycling	Additional materials production	Components Remanufact-uring	Total
Hard coal	2.46E+00	6.61E-01	5.87E+02	5.90E+02
Crude oil	3.42E+01	1.08E+01	3.50E+00	4.85E+01
Natural gas	0.00E+00	4.03E-03	5.23E+00	5.23E+00
CO	4.78E-01	3.84E-03	2.03E-01	6.85E-01
CO2	1.04E+02	3.03E+00	9.13E+02	1.02E+03
SO2	1.54E-01	2.02E-02	3.19E+00	3.36E+00
NOx	4.72E-01	5.14E-03	2.63E+00	3.11E+00
CH4	5.82E-01	1.83E-01	2.70E+00	3.47E+00
H2S	6.87E-06	2.09E-06	4.39E-04	4.48E-04
HCL	8.80E-04	2.27E-04	2.60E-01	2.61E-01
CFCs	2.75E-08	8.58E-09	6.90E-07	7.26E-07
COD	2.46E-01	6.97E-02	8.39E-02	4.00E-01
NH4	5.89E-03	5.03E-05	1.71E-03	7.65E-03

Table 3: Life cycle inventory of the a remanufactured diesel engine.

4 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Based on the life cycle inventory data, LCIA is conducted for the environmental impacts mentioned in sub-section 2.1 according to ISO 14042 [11].

4.1 Classification

The LCI results are organized and combined into impacts categories by classification. According to the rules of classification from ISO 1998, CO2, CO, NOx, and CH4 can be classified into the global warming potentials; SO2, NOx, H2S, and HCL can be classified into the acidification potentials; NH4 and COD can be classified into the Eutrophication potentials; while CFCs and CO are classified into the ozone depletion potential and photochemical ozone creation potential (POCP), respectively.

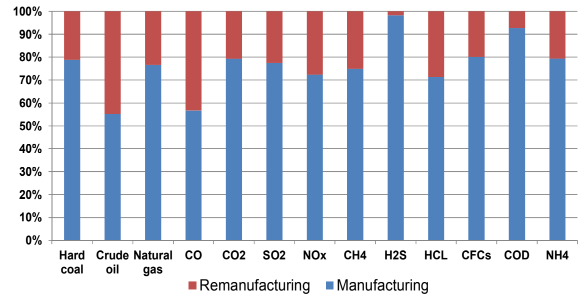

Figure 2: The life cycle inventory results of the manufactured / remanufactured diesel engine.

4.2 Characterization

After the classification, the LCI results are converted into representative indicators of impacts to human and ecological health. Characterization factors, in this study, mainly refer to GBT, IPCC, CML, and WMO methodologies [12, 13].

4.3 Normalization

The impacts indicator data are compared by the way of normalization. In this LCA, the impacts indicator results are normalized according to the reference [12].

Characterization and normalization factors chosen in this study are shown in table 4.

Category	**Characterization Method**	**Normalization (kg/(person•a))**	**Unit (Kg)**
PED	GBT2589-2008	828	ce eq
GWP	IPCC2007	8700	CO_2 eq
AP	CML2002	36	SO_2 eq
EP	CML2002	62	NO_3 eq
POCP	CML2002	0.65	C_2H_4 eq
ODP	WMO1992	0.2	CFC eq

Table 4: Characterization and normalization factors.

Figure 3 presents the energy requirements and environmental impacts of the production of a newly manufactured diesel engine compared with those produced by diesel engine remanufacturing after characterization and normalization. The reductions in primary energy demand and environmental impacts are also distinct; PED, GWP, AP, ODP, EP, and POCP can be reduced by 70.33%, 68.92%, 67.65%, 75.15%, 90.57%, and 23.7%, respectively by diesel engine remanufacturing.

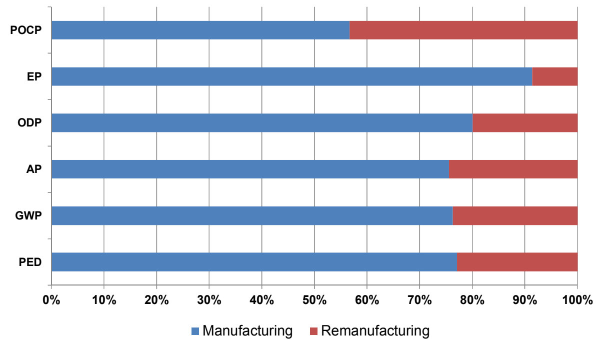

Figure 3: Energy requirements and environmental impacts of diesel engine's entire life cycle.

5 LIFE CYCLE INTERPRETATION

Contribution analysis is conducted in order to find out the different contribution of the life cycle stages to the total results. The inventory results of different life cycle stages of manufacturing and remanufacturing after characterization and normalization is shown in Table 5 & 6. Figs 4 & 5 illustrate the environmental impacts of different life cycle stages of manufacturing and remanufacturing with the data in Table 5 & 6. In the life cycle of a new manufactured diesel engine, PED and GWP are two main environmental categories, which are mainly determined by the processes of raw material production and component manufacturing. Materials transportation accounts for only a small fraction of total environmental impacts. When we look at the life cycle of remanufacturing, the remanufactured components contribute most to the total results of PED,

Environmental Impacts	Raw material production	Materials transporting	Components Manufacturing
PED	1.15E+00	2.54E-03	8.61E-01
GWP	4.28E-01	1.37E-01	3.48E-01
AP	2.51E-01	1.08E-03	2.43E-01
ODP	2.85E-08	3.24E-11	1.85E-08
EP	3.23E-01	3.05E-03	6.42E-02
POCP	8.30E-02	8.65E-04	5.05E-02

Table 5: Environmental impacts of the different life cycle stages of a newly manufactured diesel engine.

Environmental Impacts	Old diesel engine recycling	Additional materials production	Components Remanufact-uring
PED	6.11E-02	1.92E-02	5.18E-01
GWP	3.13E-02	1.06E-03	2.09E-01
AP	1.35E-02	6.67E-04	1.46E-01
ODP	4.44E-10	1.38E-10	1.11E-08
EP	1.18E-01	2.49E-02	3.88E-02
POCP	7.15E-02	5.75E-04	3.05E-02

Table 6: Environmental impacts of the different life cycle stages of a remanufactured diesel engine.

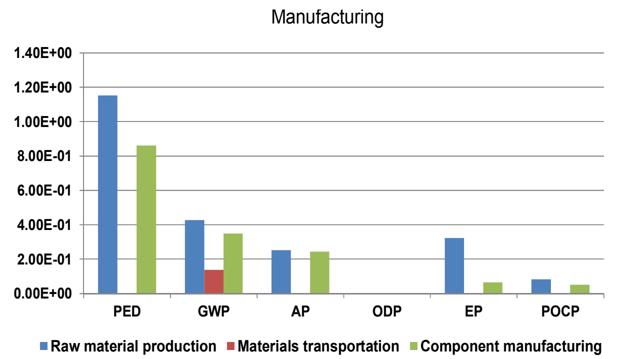

Figure 4: Environmental impacts of the various manufacturing life cycle stages.

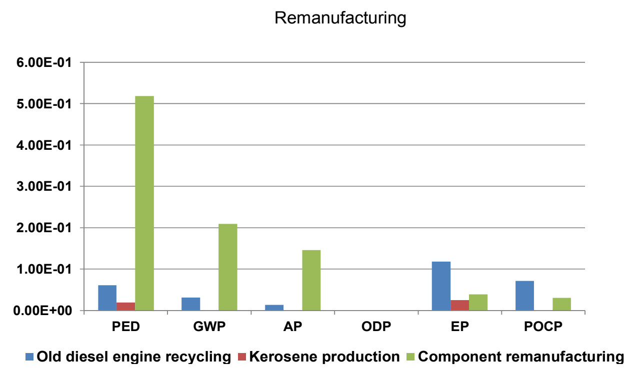

Figure 5: Environmental impacts of the various remanufacturing life cycle stages.

GWP, and AP due to electric consumption. Old diesel engine recycling process brings about more influences in EP and POCP due to fuel combustion, production of kerosene accounts for a small fraction to the total results.

6 CONCLUSIONS AND RECOMMENDATIONS

This study supports the argument that a new design conception plays a key role in determining economic and environmental benefits. The study results point to the fact that remanufacturing can contribute to reducing the primary energy demand as well as environmental impacts of a product system. Moreover, the savings are mainly due to component materials reuse and reduction of electricity consumption in remanufacturing processes.

This life cycle assessment results can help the decision makers select the remanufactured product for minimal energy requirement and impacts to the environment; this information should be used with the other factors, such as cost and performance data to make final decisions.

There are still some remaining environmental problems in the diesel engine remanufacturing processes, which are decided by electric consumption during components remanufacturing, due to high energy consumption and complex operation procedures. The next research emphasis for diesel engine remanufacturing optimization should be focused on new technologies development and applications such as laser cladding, forming, and nano-electro-brush plating.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] Lopez M., Zwolinski P., Brissaud D. (2006): Integrated design of remanufacturable products based on product profiles, Journal of Cleaner Production, Vol. 14, Issues 15-16, pp. 1333-1345.

[2] Http://www.apra-europe.org/main.php?target=history

[3] Environmental Protection Agency. (2006): Life Cycle Assessment: Principles and Practice. EPA 600/R-06/060. National Risk Management Research Laboratory. Cincinnati, Ohio, USA.

[4] International Standards Organization. (1998): Life Cycle Assessment-Principles and Framework ISO 14040.

[5] Jens, W., Marlisa, L., Wolfgang, M. (2011): Comparative Life Cycle Assessment of Remanufacturing and New Manufacturing of a Manual Transmission, Glocalized Solutions for Sustainability in Manufacturing , pp 67-72

[6] Jorge A., Peggy Z., Daniel B. (2010): Environmental benefits of parts remanufacturing: the truck injector case, Proceedings of 17th CIRP International Conference on Life Cycle Engineering, Hefei, ANHUI : China.

[7] Sophie, N. (2000): A Simplified LCA for Automotive Sector-comparison of ICE (diesel and petrol), Electric and Hybrid vehicles, 8th LCA Case Studies Symposium SETAC Europe.

[8] Hossein, M., Alireza, K., Hossein, M., Ugo, B., Ginevra, L., Touficel, A., (2009): Environmental Assessment of RAMseS Multipurpose Electric Vehicle Compared to a Conventional Combustion Engine Vehicle, Journal of Cleaner Production, Volume 17, Issue 9, Pages 781–790.

[9] Sherwood, M., Shu, L. (2000): “Supporting design for remanufacture through waste-stream analysis of automotive remanufacturers,” CIRP Annals, Vol. 49/1, pp. 87-90.

[10] Karel, K., Wim, D., Michael, O. (2012): Methodology for Systematic Analysis and Improvement of Manufacturing Unit Process Life-cycle Inventory (UPLCI)—CO2PE! Initiative (cooperative effort on process emissions in manufacturing).Part 1: Methodology description, Int J Life Cycle Assess, 17, pages: 69–78.

[11] International Standards Organization. (1998): Life Cycle Assessment-Impact Assessment ISO14042.

[12] Jian, X. Y., Cheng, Xu., Ru, S. W., (2002): Methodology and Application of Life Cycle Assessment. Beijing: China Meteorological Press.

[13] World Meteorological Organization. (1992): Scientific Assessment of Ozone Depletion. 6.1-6.17.

Remanufacturing versus Manufacturing – Analysis of Requirements and Constraints for a Study Case: Control Arm of a Suspension System

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Abstract

In order to attend to the requirements of the market many efforts have been centered on technical and economical performance together with environmental evaluations of the product. Nevertheless, few attempted an approach that integrates decision making criteria with the consumer expectations. The present paper proposes the voice of the client as a fourth factor to support decision making, rendering these decision more precise and sustainable. An approach was developed for choosing between a new product and a remanufactured product. A multi-criteria decision analysis is applied to the results, together with a sensitivity analysis with the purpose of aggregating to the results limitations and opportunities for decision making, apart from, basically, having a better awareness of the problem.

Keywords:

Life Cycle Engineering; Remanufacturing; Customer; Multi-Criteria Decision Aid

1 INTRODUCTION

The concern with reference to automobiles and the environment caused, in the European Union environment, the creation of a directive related to the end-of-life vehicles (Directive 2000/53/CE), with the purpose of avoiding and limiting residues and increasing reuse, recycling and recovery of the respective components, in order to improve environment performance during the life cycle of the automobile, especially at its end-of-life [1-2].

Included among the purposes of the policies are:

- Make the automotive industries responsible for the life cycle, from assembly to recycling of vehicles, and stipulate a 95% recyclability rate in relation to its weight (including reutilization and energy recovery) until 2015 [1-2]; and
- Prohibit the use of hazardous substances, such as, for example, led, mercury, cadmium and chrome, for new vehicles as of 2003, with the exception of parts for certain applications, according to a list which shall be regularly reviewed.

In Brazil there is no specific legislation, as occurs in the European Union, but a more extensive law (Law 12305/10), which establishes a National Policy for Solid Residues (PNRS). The mentioned law has the purpose of implementing shared responsibilities in the life-cycle of product among public powers and manufacturers, importers, distributors or merchants, encouraging the adoption of sustainable standards for production and consumption of goods and services; foresees a set of instruments favoring the increase of recycling and reuse of solid residues and environmentally adequate destination of rejects and; stimulating environmental labeling and sustainable consumption [3].

The Brazilian automotive industries are in the Center of the organization of the industrial chain for recycling the vehicles they produce, and the role of coordinating the recycling network belongs to the producers of the materials, such as steel, metal and plastic industries [4].

In this manner, the process known as remanufacturing, which consists of the disassembly, cleaning, inspection, painting, re-machining and assembly, could be economically advantageous in relation to the conventional manufacturing process due to the fact that it uses an inferior quantity of material resources, permitting a reduction in the level of waste [4-5].

A method for supporting decision making in the use or not of remanufactures parts is the Life Cycle Engineering.

LCE – Life Cycle Engineering is a set of activities concerned with the protection of the environment and conservation of resources, considering also the economic process, the sustainability and the optimization of the life-cycle of the product, reducing pollution and wastage. Thus the LCE concept consists of the incorporation of the analysis of environmental, economic and technical characteristics [6-7].

Nevertheless, the consideration of requirements and restrictions for choosing between a new product or a remanufactured product should consider a broadening of the life-cycle concept regarding the product, because independently of the extrapolated conditions establishing the advantage of the remanufacturing process, the voice of the customer has a strategic role in the decision making process. An awareness of the behavior of the market seeks to reduce risk and degree of uncertainty, supplying essential information for the feasibility analysis of the enterprise.

The incorporation of this factor in the decision making process establishes a necessity for a disruption of the traditional formulation in order to establish a manufacturing and assembly process of a new product.

In order to test this concept, a comparison was made between the McPherson control arm of an independent front suspension system of a recently manufactured automobile with a remanufactured control arm.

2 MATERIALS AND METHODS

2.1 Case Study

The control arm has three points of fixation and articulation: two points using elastic polymer bush with metal structures (Bush 1 and Bush 2), both connected to the body of the vehicle through the front platform or sub-frame, and the third point is fixed/articulated through a spherical articulation known as ball-joint to the frame which is fixed also to the shock absorber and spring set.

The control arm is made of nodular cast iron in "L" format, which is cleaned, painted, and the accommodations to receive, in a final phase, the articulation elements are machined, as well as Bushes 1 and 2, and the Ball-joint (Figure 1).

Figure 1: McPherson type front suspension control arm.

Figure 2 presents the life cycle flowcharts of the control arm for both manufacturing and remanufacturing processes. For a better presentation of the relevant similarities and differences between these two methods, the phases common to both life cycles are demonstrated in a unified manner, permitting the evidencing of only the processes that are different.

The main differences between the two manufacturing processes are:

- **Manufacturing:** Phases of foundry of the part and final machining for the preparation of the accommodations where the articulation components will be assembled/installed. The Recycling phase is the use of the part as raw-material for the foundry of a new part.
- **Remanufacturing:** There is a second phase of heavy cleaning (Type 2 Cleaning) which has the purpose of removing dirt and original paint. Type 1 Cleaning is maintained in order that a more detailed inspection of the reused part may be performed. Reuse is the phase of collecting the part in authorized workshops and sending these to the Remanufacturing sector (Transport 2). The final phase of re-machining is different than in the manufacturing phase, because the parts go through a second machining process.

2.2 Analysis Tools

The main variable used for an environmental analysis through the LCA – Life Cycle Assessment was the Global Warming Potential (GWP). The CO2 calculation used EcoInvent v2.2 data as its main data source.

An evaluation of the financial costs associated to each of the life-cycle phases was performed through the application of the LCC – Life Cycle Cost method. These analyses were performed considering that the remanufactured parts complied with all the necessary technical requirements for approval of their use in production lines.

The support of a multi criteria decision analysis (Macbeth) was used. Besides using performance indicators to support the benchmark final results, Macbeth can adapt each stakeholder point of view by easily changing the weight of each indicator. Thus Macbeth seems to be a user-friendly approach to evaluate not only the real importance of the selected indicators but also its correct weigh, considering the solution of best commitment for multiple and conflicting criteria [8]. Furthermore, Macbeth has a tool for sensibility analysis which, in turn, has the purpose of verifying the effects of the input parameters on the results obtained through the application of the model, determining the precision requirements of each input parameter.

Consumer expectations have been analyzed by the response of a questionnaire sent to professionals and potential buyers who do not technically know the product.

The mentioned questionnaire presented a question with four alternatives.

Question. Consider the process of buying a new car. If this car has remanufactured parts, within the technical specifications, what would be your reaction?

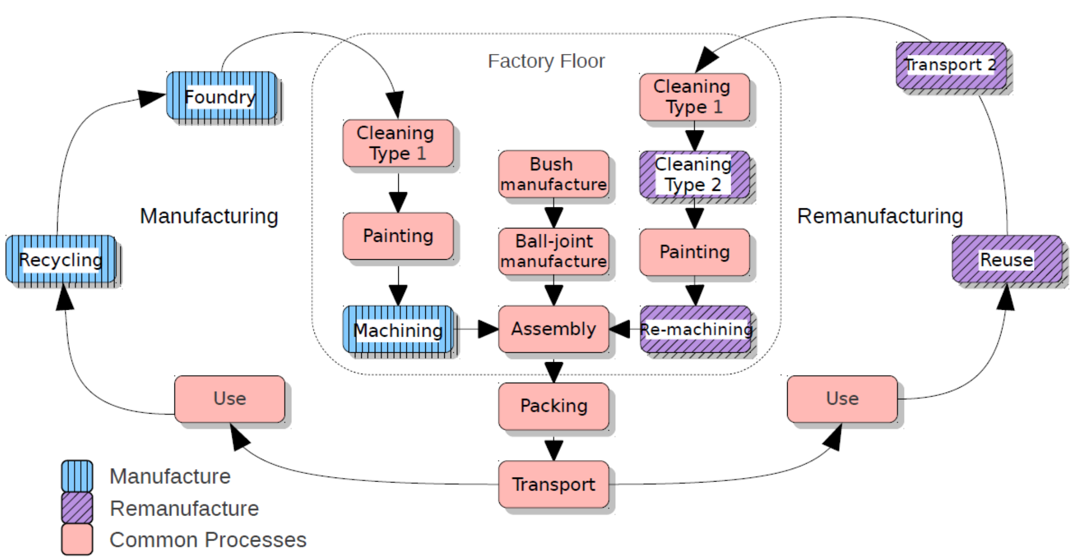


Figure 2: Flowchart of the life cycle of a control arm for the manufacturing and remanufacturing processes.

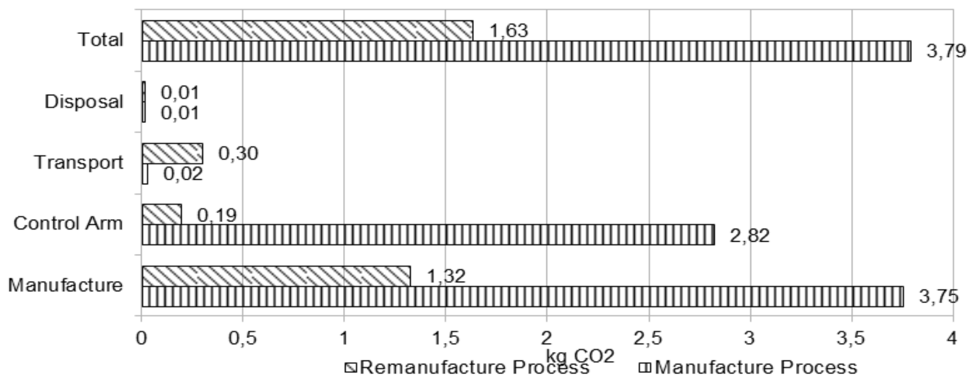


Figure 3: Life Cycle Assessment (LCA) Flowchart.

Answer.

1. Buy the car
2. Buy the car only if the value is below the same model car.
3. Buy the car only the value is below the same model car and with extended warranty
4. Would not buy the car under any circumstances.

The results of this questionnaire, which presents the expectation of the consumer in relation to the remanufacturing, were incorporated to a second decision making process, also used as support for multi-criteria decision analysis with its sensitivity analysis tool.

3 RESULTS

First the environmental and economic analyses are presented comparing the manufacturing and remanufacturing processes of the case-study.

The technical analysis was performed by a team of engineers of the company who verified that the manufactured parts presented excellent quality and the recycled parts, after an precise inspections presented a very good quality.

In sequence a multi-criteria decision making method is applied based on these three characteristics for obtaining the first result.

Next, the analysis of the expectation of the consumer (voice of the consumer) is presented and once again the multi-criteria decision making method is applied together with the three first characteristics, obtaining a second result of this comparison between the manufacturing and remanufacturing processes.

3.1 Life Cycle Assessment (LCA)

The measured Global-Warming Potential (GWP) indicator demonstrated a total value of product impact during the lifetime of 3.79 kgCO2 for the manufacturing process and 1.63 kgCO2 having been observed for the remanufactured component, which represented only 43% of the initial needs (Figure 3).

There was a value of approximately 0.30 kgCO2 associated to the impact related to the reverse logistic process for the remanufactured parts, due to the distances between points of collection and discharge performed by small sized trucks, in a distance of approximately 1,300 km.

The major environmental process impact was the Control Arm. The manufacturing process considering a new part consumed 2.82 kgCO2 and the remanufacturing one only 0.19 kgCO2, due to the fact that the foundry phase is totally suppressed for remanufactured parts.

3.2 Life Cycle Cost (LCC)

Despite the analysis having occurred in a complete and ample form in the life-cycle, only the phases presenting differences are presented in this paper, in percentages, with the purpose of preserving strategic aspects for the Company making the decision.

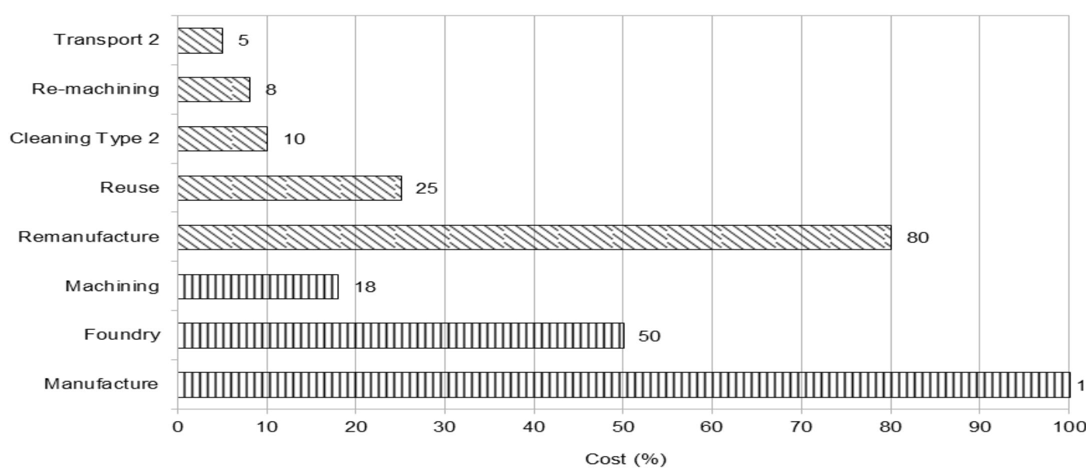


Figure 4: Life Cycle Cost (CCV) Flowchart.

The same point of view in terms of the foundry process can be applied for the cost analysis. As previously demonstrated, the foundry phase corresponds to approximately 50% of the value of a new manufactured product. The final cost associated to remanufactured parts was 20% lower than for the fully manufactured ones (Figure 4).

3.3 First Decision Making - Macbeth

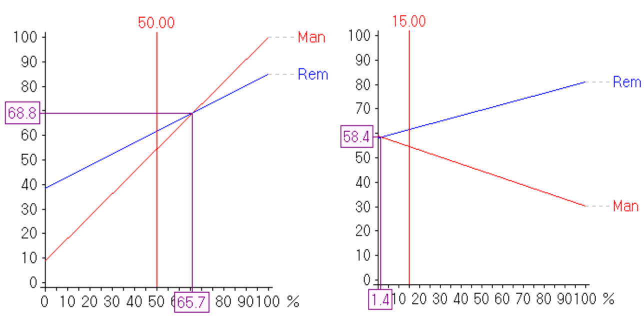
Decision making performed for the company interested in remanufacturing required from the person responsible the weights of the previously agreed-to criteria. In this manner, the decision maker determined 50% of the weight for technical performance (TP) criteria and 35 and 15% for the cost (Ct) and environmental impact (EI) criteria, respectively. The technical performance criterion has the greatest weight because any technical problem will incur in extra costs for resolving.

Therefore, with the use of the Macbeth method, the result is presented in Table.

		Scores			Performances		
Options	**Overall**	**Ct**	**EI**	**TP**	**Ct**	**EI**	**TP**
Man	**54.5**	0.0	30.3	100.0	100	3.8	Excellent
Rem	**61.5**	20.0	81.0	84.8	80	1.8	Very Good
Weights of Criteria					0.35	0.15	0.50

Table 1: Scores and Performances for the Manufacturing (Man) and Remanufacturing (Rem) processes.

The remanufacturing alternative (61.5) presented itself to be more attractive than the manufacturing alternative (54.5) for the criteria and weights established by the decision-maker.



(a) (b)

Figure 5: Sensitivity analysis of: (a) Technical Performance criteria and (b) Environmental Impact.

The sensitivity analysis indicated that there shall only be an inversion of the results if the weight for the Technical Performance criteria is of over 65.7% (Fig.5a) or the weight of the Environmental Impact criteria is less than 1.4% (Fig.5b).

3.4 Consumer Expectations

Figure 6 shows the consumer expectations analyzed by the response of the questionnaire sent to professionals and potential buyers who do not technically know the product, with the numbering of the respective answers: (1) Buy the car, (2) Buy the car only if the value is below the same model car, (3) Buy the car only if the value is below the same model car and with extended warranty and (4) Would not buy the car under any circumstances.

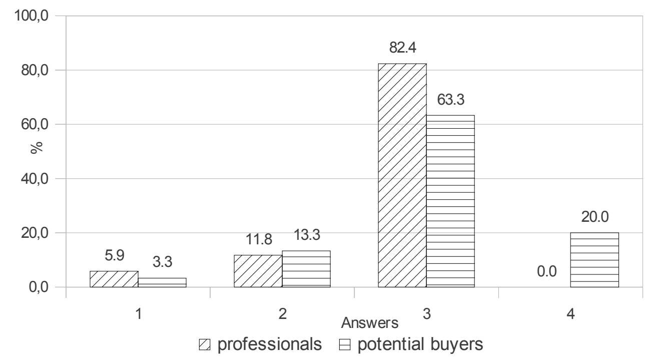


Figure 6: Results of analyzed expectations

A small difference is observed among the groups of professionals and potential buyers, most of which in item (4) de "Would not buy the car under any circumstances" (20%). It is also observed that the majority in both groups (94.2 – 76.6%) would buy the car with used parts if there were a return such as price reduction of warranty extension (2 and 3).

3.5 Second Decision Making – Macbeth

With the incorporation of the consumer expectations as a new decision-making criterion, the decision maker opted for 35% weight for technical performance (TP) criteria and 30 and 25% for cost (Ct) and consumer expectation (CE) criteria, respectively, and 10% for environmental impact criteria.

		Scores				Performances			
Option	**Overall**	**Ct**	**EI**	**TP**	**CE**	**Ct**	**EI**	**TP**	**CE**
Man	**63.0**	0.0	30.3	100.0	100.0	100	3.8	Excellent	0
Rem	**54.2**	20.0	81.0	84.8	41.7	80	1.8	Very Good	20
Weights of Criteria						0.30	0.10	0.35	0.25

Table 2: Scores and Performances for the manufacturing (Man) and remanufacturing (Rem) processes.

Once again using the Macbeth method, the result is presented in Table 2, but now the Manufacturing (63.0) process presented itself as being more attractive than the remanufacturing (54.2) process.

By means of the sensitivity analysis it is observed that this result would only be altered if:

- The Cost criteria is greater than 51.4% (Fig.7a), or
- The weight of the Consumer Expectation criteria is less than 11.6% (Fig.7b), or
- The environmental criteria is greater than 23.3% for the deciding party (Fig.7c), or
- The answers obtained from the consumers, item 4 (would not buy the car under any circumstances) decrease to 6.6% or less, or
- The costs of the remanufacturing process were 50.5% or less when compared to the manufacturing costs.

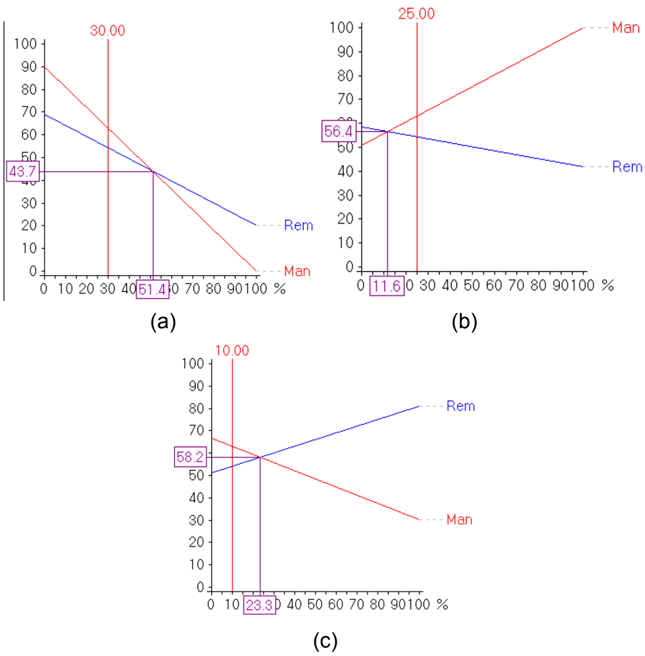


Figure 7: Sensitivity analysis of the criteria: (a) Costs, (b) Environmental Impact and (c) Consumer Expectations.

4 CONCLUSIONS

The remanufacturing process is feasible for the industry for implementation or to comply with the legislation when criteria such as technical performance, cost and environmental impacts are observed.

It can be observed, in the present research, that environmental impacts are 2.3 times lower only in the GWP analysis, with this difference being evidenced due to the inherent characteristic of the remanufacturing process not having the foundry phase, which is suppressed once this component is reused.

The cost difference between both processes is not expressive, with remanufacturing costs being 1.25 times higher. Final costs associated to remanufacturing could be even lower, should there be an increase in volume or in manufacturing scales, because the low volumes initially projected present a process with many manual actions. The costs of Type 2 Cleaning (10%) could also be reviewed, with the use of different products and processes to those used in the manufacturing plant.

When the technical performance, cost and environmental impact criteria are added to the consumer expectation criteria, the manufacturing process demonstrates itself as more attractive due, mainly, to the group of prospective buyers in item (4) “Would not buy the car under any circumstances” reached 20% for the remanufacturing process. In order to revert this information, intense marketing is necessary demonstrating that the products are as good as new products and in this manner cause the 20% percentage of clients to decrease.

The research performed with the client demonstrated that the reuse of parts in automobiles is still looked at with a certain mistrust by Brazilian consumers, despite the fact that the subject of sustainability is routinely present in all of the media, because a large portion of the market (20%) “would not buy a car under any circumstances”. But, upon observance of the control group (professionals) – 0% for the same question – one can suppose that this is due to lack of information on the efficiency of the used product.

On the other hand, the research also demonstrates that the Brazilian consumer would like to help in the quest for sustainable development, but does not want to shoulder the costs alone, the companies must also do their share, because 76.6% of potential buyers would buy a car with used parts if they had as a return a price reduction and warranty extension.

The present paper demonstrates that economic, environmental and technical analyses are not sufficient for the choice of a new product or remanufactured product, but, essentially, a fourth factor should be taken into consideration, the voice of the client. The strategic assimilation of this factor in the decision-making process shall bring about a more precise decision and guided towards new sustainability concepts.

5 REFERENCES

[1] Salla, L.D.E.; Cadioli,L.P.: Reciclagem de automóveis - Um novo conceito na produtividade ambientalmente correta. Revista de Ciências Exatas e Tecnologia, vol. 2, No 2. (2007)

[2] OJ L.269, 21.10.2000, p.34–43. Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles - Commission Statements.

[3] BRASIL. Law 12305, of August 2, 2012 established the National Policy of Solid Residues. In: http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/lei/l12305.htm.

[4] Zanette, E.T.A.: Remanufatura no Brasil e no Mundo - Conceitos e Condicionantes. Monograph. (Environmental Engineering Graduate). Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, SP. (2008)

[5] Lindahl, M.; Sundin, E.E.; Östlin, J.: Environmental Issues within the Remanufacturing Industry, Proceedings of CIRP International Conference on Life Cycle Engineering, Leuven, May 31 – June 02, pp. 447-452. (2006)

[6] Peças, P.; Ribeiro, I.; Henriques, E.: A Roadmap to the Implementation of Life Cycle Approach in the Design of Plastic Injection Moulds. 16th CIRP International Conference on Life Cycle Engineering, p. 353. Cairo – Egypt. (2009)

[7] Puglieri, F.N.: Proposição de um método para remanufatura baseado em QFD. Second International Workshop Advances in Cleaner Production - Key elements for sustainable World: Energy, Water and Climate change. São Paulo, SP, Brasil. (2009)

[8] Brans, J.P.; Mareschal, B.: Promethee Methods. in Figueira, J.; Greco, S. & Ehrgott, M. (eds.): Multiple Criteria Decision Analysis State of the Art Surveys. International Series in Operations Research. Management Science. v.78. Springer, New York, p.163-196. (2005)

Life Cycle Assessment: A Comparison of Manufacturing and Remanufacturing Processes of a Diesel Engine

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Abstract

The purpose of this study is to compare the environmental impacts and energy consumption of a newly manufactured and a remanufactured diesel engine with respect to the processes involved in manufacturing of a new diesel engine as well as remanufacturing of a used diesel engine. The result of the study shows that a remanufactured diesel engine is better than a newly manufactured one in terms of the amount of energy consumed in the process of manufacture and the environmental impacts resulting from the life cycle of the manufacturing and remanufacturing processes.

Keywords:

LCA; Remanufacturing; Diesel Engine

1 INTRODUCTION

According to the Bureau of Transportation Statistics (BTS) the total energy consumption of 28.927 quadrillion BTU in 2007 we have transportation consuming over 22.3 quadrillion BTU per year [1]. This consumption of energy is inevitable as this sector including the heavy trucks and trailer trucks are the backbone of the economy, transporting millions of tons of goods across the country. Over the years we have seen a steep rise in the total consumption of energy and we have had almost a rise of over 1% per year in ten years [1].

The major reason for these vehicles having such a large contribution of energy is due to their extensive driving cycles and also their low fuel economy. It is being realized that the largest component which leads to the most amount of energy consumption in the vehicles is the engine of the vehicle. Thus we have included in this investigation the potential of reusing and remanufacturing the engine of the vehicle.

Today when an engine has reached the end of its life we have three options which include landfill, recycling the entire engine where only the materials of the engine is recovered, or remanufacturing the engine and selling it like a new engine which can go on to another life cycle. If recycled, the entire processes such as molding, casting, machining, etc. can be conserved in the process of remanufacturing. According to the Production Engine Remanufacturers Association (PERA), remanufactured engines contribute to almost 2.5 billion dollars which encompasses over 2.4 million engines remanufactured every year [2].

In this study we have considered the total energy consumption and the environmental impact of manufacturing as well remanufacturing a heavy duty 6 cylinder truck engines and in doing so we have compared the amount of energy saved and the benefits obtained.

To begin with we quantify the energy consumption of manufacturing and remanufacturing of the engine. In the manufacturing sector itself we have witnessed a large influx of emissions as well as indirect emissions through the use of electricity. The breakdown of the energy consumptions in the United States in the manufacturing subsectors is shown in Figure 1 [3].

In the avenue of remanufacturing we consider the major sub events that would include disassembling, cleaning, refurbishing and reassembling of the parts so as to create a product which is almost like a new one.

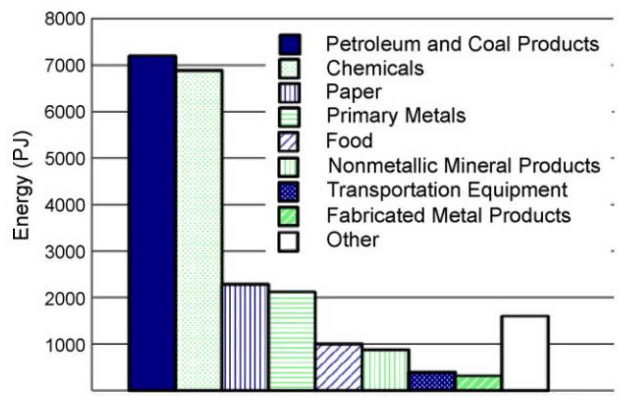

Figure 1: Energy consumption for the US manufacturing subsectors.

Having little research present on the remanufacturing energy consumption and the energy savings as well as emissions savings that it produces over the manufacturing, this study presents an extensive approach to comparison between the manufacturing and remanufacturing of a large diesel engine to analyze the potential that remanufacturing has in terms of energy savings and reduction in emissions.

2 SCOPE OF STUDY

The data from SINOTRUK™, commercial truck manufacturing company, was used for the study. The diesel engine under consideration was a 6 cylinders, in-line, water cooled and turbocharged engine. The scope of the analysis includes:

- The quantification of energy consumption and emissions directly related to the manufacturing of the engine.
- The quantification of energy consumption and emissions directly related to the remanufacturing of the engine.
- A quantitative comparison between the two processes so as to provide a holistic picture of the benefits of the remanufacturing over that of manufacturing a new diesel engine.
- The parts of the remanufactured engine are considered to be of the same quality as that of a newly manufactured one.

- The focus of the study is on the processes of manufacturing and remanufacturing, but the time of use of the car is not considered in the scope of the study.

2.1 Functional Unit

The functional unit considered in this study is the production processes of manufacturing and remanufacturing of a diesel engine.

2.2 System Boundary

Manufacturing

In the manufacturing process we consider the entire processes of manufacturing which include raw materials extraction, parts production, and parts assembly as well as the transportation of parts between the production plants. The flow chart of the manufacturing processes is shown in Figure 2.

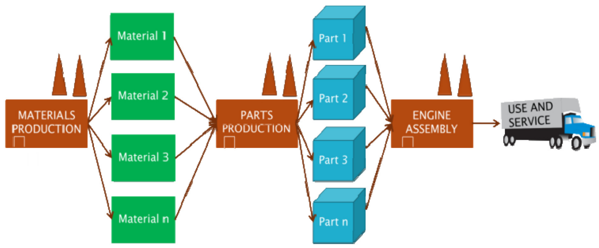

Figure 2: Flow chart of the manufacturing process.

Remanufacturing

In the remanufacturing process we consider disassembly of parts, parts cleaning, refurbishing and repairing of parts, finishing of parts, and final assembly. The flow chart of the remanufacturing processes is shown in Figure 3.

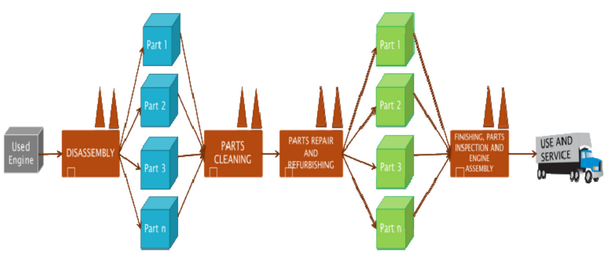

Figure 3: Flow chart of the remanufacturing process.

3 LIFE CYCLE INVENTORY (LCI)

3.1 Energy Consumption Analysis

The energy consumption for a new and remanufactured diesel engine was compared. The production of a new diesel engine required 6,016.68 MJ of energy, 1.66 times more than that of a remanufactured engine, which required 3,620.16 MJ. Thus, the use of a remanufactured diesel engine can potentially avoid the extra 2,396.52 MJ of energy that would be required to create a new one. As a result, there were about 40% savings for the remanufacturing of a diesel engine (Table 1).

3.2 Natural Resources Consumption Analysis

There are 3 kinds of natural resources used in the production of a new and remanufactured diesel engine. Remanufacturing offers significant savings in every natural resources consumption category with a range in reductions of 18.49% to 73.18% (Table 2).

	Manufacturing	Remanufacturing	Energy savings	% Reduction
Energy consumption (MJ)	6,016.68	3,620.16	2,396.52	39.83%

Table 1: Comparison of energy consumption.

Resource	Manufacturing	Remanufacturing	% Reduction
Coal (kg)	2,200.00	590.00	73.18%
Crude oil (kg)	59.50	48.50	18.49%
Natural gas (m^3)	17.00	5.23	69.24%

Table 2: Comparison of resources consumption.

3.4 Environmental Emissions Analysis

Remanufacturing resulted in significant reductions in air emissions as well as water emissions. The production of a new diesel engine produces 3.90 tons of carbon dioxide emissions. The production of a remanufactured diesel engine, on the other hand, produces 1.02 tons of CO_2 emissions. Overall carbon dioxide emissions were reduced by 73.88%. The remanufacturing of a diesel engine offered CO reductions of 22.83%, SO_2 reductions of 70.80%, etc (Table 3).

	Pollutant	Manufacturing	Remanufacturing	% Reduction
Air emissions (kg)	CO	0.89	0.68	22.83%
	CO_2 (t)	3.90	1.02	73.88%
	SO_2	11.52	3.36	70.80%
	NO_x	8.13	3.11	61.79%
	CH_4	5.90	4.10	30.65%
	H_2S	0.03	4.48E-04	98.21%
	HCL	0.65	0.26	59.68%
	CFCs	2.92E-06	7.26E-07	75.15%
Water emissions (kg)	COD	5.02	0.40	92.03%
	NH_4	0.03	0.01	74.07%

Table 3: Comparison of environmental emissions.

3.5 Effects of Remanufacturing

A comparison of the LCI of a new and remanufactured diesel engine shows that remanufacturing provides significant reductions in energy and natural resources consumption, and environmental emissions (air and water). A remanufactured engine requires fewer new parts and less manufacturing than a new engine and is more labor intensive rather than energy intensive. As a result, it can be produced with 39.83% less energy and reduces natural resources consumption by 18.49% to 73.18%. Carbon dioxide emissions were reduced by 73.88%. All other air emissions showed significant savings as well, with a range from 22.83% to 98.21%, and savings in water emissions were between 74.07% and 92.03%.

In summation, diesel engine remanufacturing offers environmental benefits in the form of increased material productivity and environmental savings.

4 LIFE CYCLE IMPACT ASSESSMENT

4.1 Methodology and Assessment Model

The Eco-indicator 99, damage oriented method for LCIA, is employed to assess the environmental impact. The main impact categories to be investigated under this study are: respiratory effects, climate change, ozone layer depletion, acidification, and fossil fuels.

At each process in manufacturing and remanufacturing, inventory data sets including resources extraction and air/water emissions were collected and classified into the impact categories. Through characterization, the environmental impacts were calculated at each category. Lastly, we investigated which process has the most significant impact on the environmental damage in manufacturing and remanufacturing, respectively. Also, we directly compared the impact of manufacturing with that of remanufacturing on the damages.

4.2 Environmental Impacts of Manufacturing

Based on the results of characterization, impact indicators at each process were converted into the ratio value to the total within each impact category. An overview of the relative contribution of the different stages of manufacturing to the different impact categories is presented (Figure 4).

The stage of raw material mining and production of a diesel engine plays an important role in the total environmental impacts. This process contributes more than 99 % to the most impact categories: respiratory effects (organic), climate change, and fossil fuels. It consumes a lot of fossil fuels such as coal, gas, and oil, and produces a lot of CO_2 which influence climate change, and CH4 which affect respiratory effects (organic). On the other hand, materials transportation yields only an insignificant contribution to all the impact categories considered in this study.

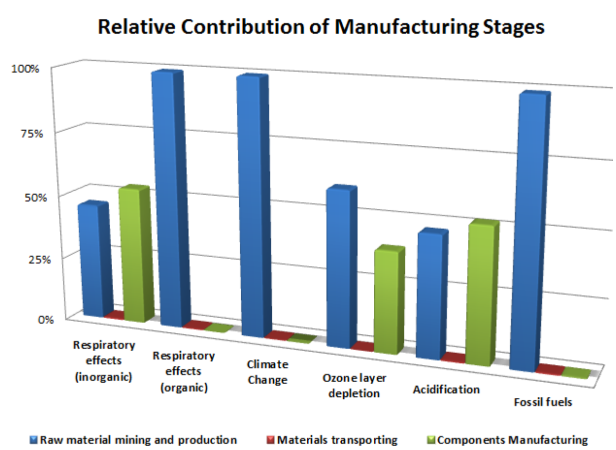

Figure 4: Environmental impacts of manufacturing.

4.3 Environmental Impacts of Remanufacturing

The relative contribution of remanufacturing a diesel engine to the total environmental impacts is presented (Figure 5). It can clearly be seen that the components remanufacturing of a diesel engine significantly contributes to all of impact categories. More specifically, this phase of the life cycle contributes to 95% to ozone layer depletion, 89% to climate change, 86% to acidification, 84.7% to respiratory effects (inorganic), 82.3% to respiratory effects (organic), and 65.5% to fossil fuels.

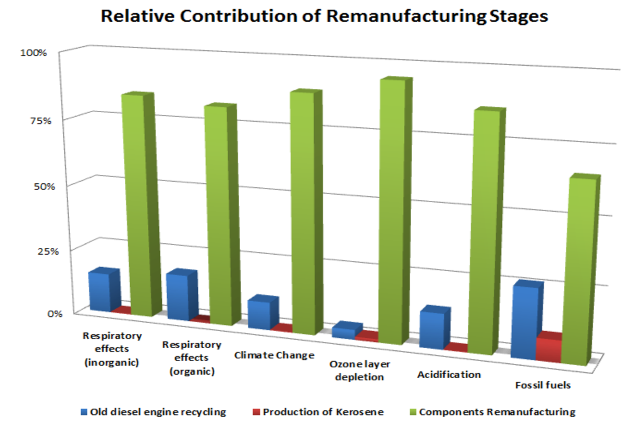

Figure 5: Environmental impacts of remanufacturing.

4.4 The Comparison: Manufacturing vs. Remanufacturing

In order to compare directly environmental impacts of manufacturing and remanufacturing, firstly, impact indicators within each impact category across each process were summed up by manufacturing and remanufacturing, respectively. Next, the results for each impact category have been normalized to the largest total impact. The environmental impacts of manufacturing and remanufacturing were compared for different impact categories and presented in a diagram (Figure 6). The highest contribution to a particular impact category is indicated with a 100 % bar.

The following figure shows the damage assessment results. Comparing the life cycle stages of the manufacturing and remanufacturing, it is remarkable that all of impact categories such as respiratory effects, climate change, ozone layer depletion, acidification, and fossil fuels have the greatest contribution to the overall environmental impacts by manufacturing of a diesel engine. In other words, remanufacturing of a diesel engine has lesser contribution to the environmental impacts when compared to manufacturing of a diesel engine.

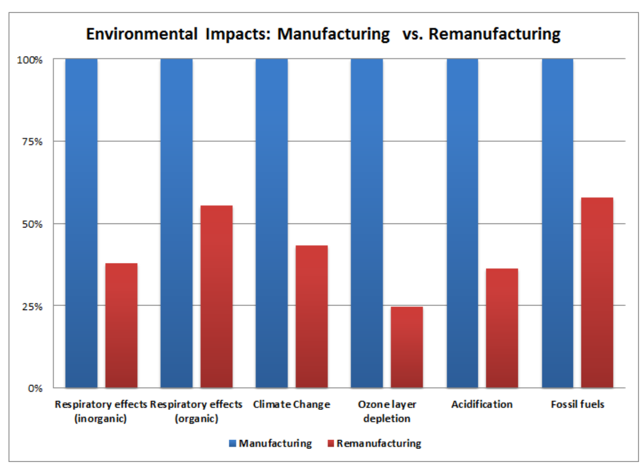

Figure 6: Comparison of manufacturing and remanufacturing.

5 CONCLUSION

From the analysis conducted above it is quite evident that the remanufacturing process is better than the manufacturing in terms of the amount of energy consumed in the process and the environmental impacts resulting from the life cycle of the manufacturing and remanufacturing processes.

This study can be further expanded to consider the use phases of both a newly manufactured engine and a remanufactured engine. The major impact from an engine could be realized during the use phases of the engine. The consumption of fuel and lubricants would be quantified based on an assumption that the new engine travels for 192,000km in 15 years during its lifetime and consumes 10L for every 100km. The same approach can been used for a remanufactured engine but in the remanufactured engine there has been a lot of conflicts with data procurement as the remanufacturing companies challenge that their engines work at the same standards as a new engine, but some customers using these engines do not agree to the assertion made by the remanufacturing companies. Hence this problem can be solved by means of considering a ‘sample space’ of a certain number of trucks, and the operation of these trucks can be monitored so as to give more quantitative results thus resulting in a more holistic comparison between the two engines by including the use phases in which they are being used. This will lead to develop a more quantified study which will actually convey on whether it is economical as well as environmentally feasible to use a remanufactured engine as compared to a newly manufactured engine.

6 REFERENCES

[1] Davis, S.C., Diegel, S.W., Boundry, R.G. (2009): Transportation Energy Data Book Edition 28. Prepared by The Oakridge National Laboratory for the US Department of Energy.

[2] Smith, V.M., Keoleian, G.A. (2004): The Value of Remanufactured Engines: Life-cycle Environmental and Economic Perspectives, Journal of Industrial Ecology. Vol. 8, No. 1-2, pp. 193-221.

[3] U.S. Energy Information Administration (2007): 2002 Energy Consumption by Manufacturers.

Challenges and Issues of Using Embedded Smart Sensors in Products to Facilitate Remanufacturing

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Abstract

The use of embedded smart sensors in products to monitor and register information associated with the products, e.g., their state-of-health, remaining service life, remanufacturing history, etc., has shown positive impact on product remanufacturing decision-making. This paper reviews the challenges and issues of using smart sensors pertaining to different phases of a product life-cycle, e.g., design, manufacture, distribution, service, remanufacture, and disposal phases. These issues are investigated considering the views of the manufacturers/remanufacturers, distributors and end-users. A conceptual framework for product remanufacturing decision-making is proposed based on the information gathered using smart sensors.

Keywords:

Remanufacturing; Embedded Smart Sensors; Product Life-cycle Monitoring; Remanufacturing Decision-making

1 INTRODUCTION

Product remanufacturing is regarded as one of the most beneficial product end-of-life (EOL) alternatives for manufacturers with increasingly more stringent environmental regulations and government legislations for sustainable product development. Product remanufacturing presents an environmentally more attractive option than material recycling as it retains the intrinsic values of a product, e.g., material and energy consumed during manufacturing. It differs from components reuse as it aims to return a used product to a condition with equivalent or better performance than a new product. Many research studies deal with reverse logistics and closed-loop supply chains while addressing product remanufacturing. Uncertainty in the quality, quantity and frequency of product returns has been identified as some of the prevalent issues faced by the remanufacturers, and they have significant impact on the decision-making for product remanufacturing. Various research studies have addressed this issue, e.g., the effect of quality categorization of product returns [1], customer incentives to promote core returns [2], etc. In particular, quality uncertainty of product returns is mainly due to a lack of information associated with the usage of the products [3-5]. Thus, the concept of using smart sensors to monitor useful information of a product has been explored. Such information could be product identity, constituent components, remaining service life, remanufacturing history, etc. At the time of a product return, all the information should be made available to the remanufacturers or recyclers for sound product EOL decision-making.

This paper reviews the current practices of using embedded smart sensors to facilitate remanufacturing. The challenges and issues pertaining to remanufacturing at different stages of product life-cycle are presented in Section 2 and Section 3. Section 4 presents a conceptual framework for product remanufacturing based on the information gathered using smart sensors. Section 5 summarizes the paper and gives the future work.

2 SENSOR-EMBEDDED PRODUCTS

2.1 Product Information

Information required for effective EOL decision-making can be classified into internal and external information [3-4]. External information includes information such as market trends, legislative policies, corporate policies, etc., which are not directly related to a product but have considerable impact on the choice of the recovery options. Internal information can be categorized into static attribute information and time-stamped historical information. Static attribute information is associated with the intrinsic characteristics of a product, such as bill of material, design information, production processes, disassembly sequence, designed life-span, etc. Such information is determined at the early product design and manufacturing stages, but subject to changes during the remanufacturing stage when modifications are being made to the product design. Time-stamped historical Information depends on how a product is being used, and refers to product characteristics that can be represented by a sequence of data with respect to time, e.g., the remaining life span of a product/component in its current use cycle, cumulative service time, number of times a product has been remanufactured or reused, part repair/replacement history, etc. In particular, the remaining service life of a product can be deduced from data obtained through embedding sensors to monitor product use. The part repair/replacement history can help identify the typical failure of a product due to factors such as design flaws, etc., Figure 1 shows a summary of product information during a product life-cycle.

2.2 Smart Sensors

Existing research studies have explored the use of embedded sensors to improve the efficiency of reverse logistics and closed-loop supply chains [4-5]. Radio-Frequency Identification (RFID) tags have been used to replace barcodes as product/component identifications (IDs) to provide easy access to retrieving, updating and managing product information in an entire life-cycle [4, 6]. A study has been reported that active RFID can be used for easy identification and localization of components within a remanufacturing facility, while passive RFID can be permanently tagged onto components of remanufacturable products at the beginning of their service life [7]. However, the limited storage capacity of the RFID tags cannot store the amount of data that has been gathered for a period of time. An alternative is to use a RFID tag as an ID to identify a specific smart sensor with embedded memory chip for data storage. Other examples of smart sensors are life-cycle unit [8], Watchdog [9], etc.

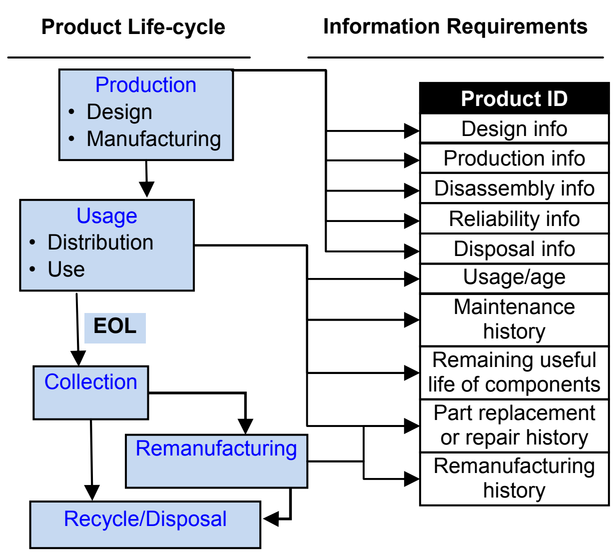

Figure 1: Product data in a product life-cycle.

Essential components of a generic smart sensor have been defined for product condition monitoring [10-11], and they include: (a) a sensing element to register the environmental parameters, e.g., temperature, pressure, etc., and convert them into suitable signal forms, (b) a microprocessor to process the received signals, (c) a memory to store the received sensor data and output from the microprocessor, (d) a data transmitter to transmit the data from the smart sensor to the communication network, (e) a power supply from product power source or a separate battery, and (f) a sensor ID, which could be an RFID tag.

3 CHALLENGES AND ISSUES ON THE USE OF EMBEDDED SMART SENSORS

There are many benefits of embedding smart sensors in products/components to monitor their life-span. However, there are challenges and issues that exist in the different phases of a product life-cycle that may prevent the use of these sensors, as illustrated in Figure 2.

3.1 Product Design Phase

The use of smart sensors to monitor a product during its life-cycle should be addressed in the product design stage. The general principle is that the performance of the product should not be compromised in terms of functionality and reliability when sensors are embedded in a product. The following aspects are of primary concerns so that the information collected can be used to facilitate product remanufacturing: (1) types of data to be monitored, (2) suitability of the smart sensors, (3) methods and locations to mount the sensors, (4) protective measures for the sensors, and (5) transmission of data from the smart sensors.

Not all components in a product have equal life-span. Some components can last considerably longer than other components. Using an automotive engine as an example, components with longer life-span, e.g., engine block, crankshaft, and connecting rods, which normally have significant residual values that can be retained, are usually reused after proper reconditioning. Critical components with shorter life-span, e.g., engine pistons, will always be replaced with new parts [12]. From this perspective, it would be useful to classify the components of a product based on their useful life-span such that different remanufacturing modes can be applied to different components. The conditions of the components would affect the viability and profitability of remanufacturing. Therefore, it is important to track the number of times these components have been reused and update their cumulative service history. The state-of-health of

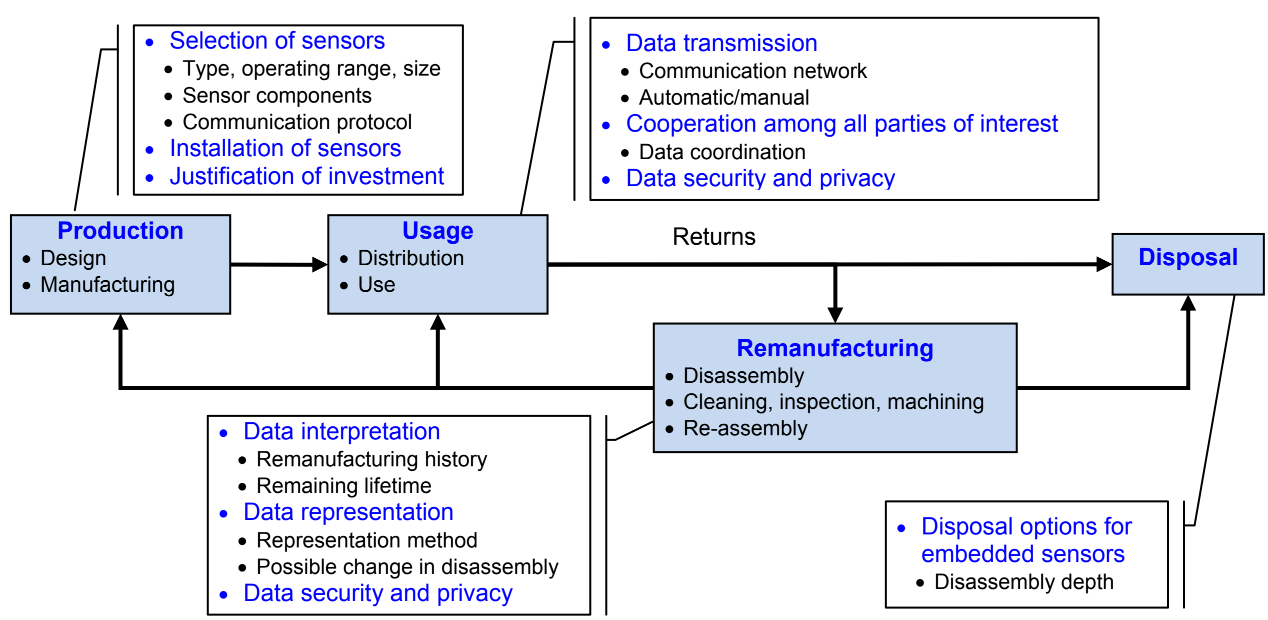

Figure 2: Challenges and issues of using embedded smart sensors in product life-span monitoring.

components with relatively shorter life-spans needs to be monitored continuously to determine whether these components have reached a stage suitable for replacement or remanufacturing.

Figure 3 outlines a general procedure for the selection of suitable sensors based on different life-spans of components. The type, operating range, size and life-span of the sensor should be determined according to the parameters to be monitored and the expected life-span of the components.

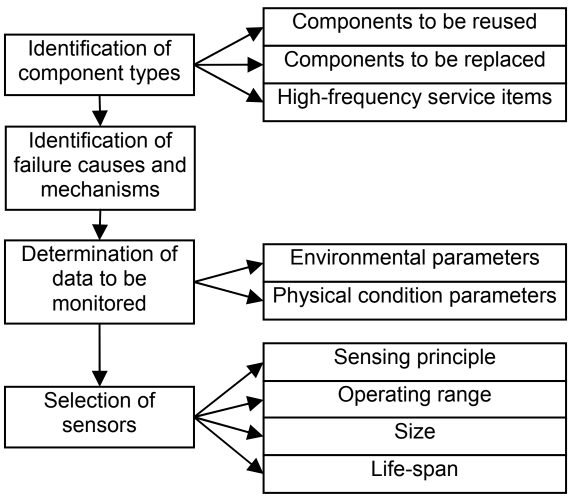

Figure 3: Sensor selection based on life-span of components.

The components that constitute a smart sensor, e.g., data transceiver, microprocessor, memory chip, power supply, etc., should be selected carefully. The data transceiver should comply with the communication protocol depending on whether the data needs to be transmitted via wired or wireless communication networks. The selection of the memory chip needs to consider the data volume to be stored between two data uploading intervals. The cost of embedding sensors in products should be economically justifiable [13] as it is normally borne by the manufacturers since there is no direct benefit offered to the end-users.

Embedding smart sensors in a product would need considerable domain expertise. Modifications would have to be made to the current product design. The challenge lies in the modular design of these sensors such that they can be disassembled and replaced easily. A faulty sensor should not affect the function and reliability of the products.

3.2 Distribution and Use Phases

In product distribution and use stages, data from the embedded smart sensors have to be harnessed by the manufacturing or remanufacturing sites. For stationary equipment or machines, e.g., CNC machines, power generators, etc., wired data transmission can be adopted. For other products, e.g., automotive engines, data can be transmitted to the servers at the manufacturing or remanufacturing sites whenever the products are brought back to these sites with data transmission facilities. There are two data transmission modes, namely, manual mode and automatic mode. The manual mode will need the end-users to set up the connection between the sensors and the server. In this mode, proper authorization and access control need to be established to protect the data from unauthorized viewing, modification, etc. In addition, ensuring data validity incurs cost [14]. In the automatic mode, the transmission can be started whenever a sensor is detected and recognized by the transmitter.

3.3 Disassembly and Disposal of Sensors

Sensors may need to be disassembled and disposed of, e.g., a malfunctioned embedded sensor has to be replaced, or a component has reached its end of life. In the second situation, the disposal or recycling of the component may require the embedded sensor to be separated from the component since sensors are often made of different materials than that of the component. This would require specific disassembly steps. In addition, the disposal of the sensors should not violate any environmental regulations, which may incur more cost for the remanufacturers/recyclers.

4 FRAMEWORK ON THE USE OF SENSOR DATA FOR PRODUCT REMANUFACTURING DECISION MAKING

When a used product has been returned to a remanufacturing plant, product information associated with this product, e.g., operating history, life-span, etc., should be made available to the remanufacturers. Figure 4 presents a conceptual framework on the use of this information to assist remanufacturers during remanufacturing operations, i.e., products collection, disassembly, cleaning, sorting, grading, reconditioning, machining, component replacement, reassembly, etc. The classification of components and the identification of critical component(s) are useful input to product reverse logistics.

4.1 Sensor Data Management and Interpretation

Management and Representation of Sensor Data

An efficient information system should be available so that relevant data can be retrieved in real-time. Different data storage methods can be used for different types of data to cater for easy data retrieval and update [6]. XML tools can be used to access and manipulate the static attribute data as the existing industry-standard XML schema allows unambiguous access to particular properties of an object and can be applied across all industry sectors. Relational databases can be used to handle historical data [4, 15].

The unintuitive representation of product information to the remanufacturers is a critical issue. An example is during a product disassembly, where the disassembly sequence can be registered with the product using sensors after it has been manufactured. However, disassembly during remanufacturing is often labor-intensive with low level of factory automation. Therefore, to improve the efficiency of the disassembly process, intuitive representations of such information can be provided to the disassembly technicians to guide the disassembly operations. Augmented reality assisted visualization tool has been explored, where virtual cues in the forms of texts, images, CAD files, video clips, etc., can be provided to assist the manual assembly tasks [16-17]. This concept can be applied in disassembly, where the disassembly sequence can be organized in a disassembly tree structure.

Sensor Data Interpretation

The remaining useful life is a commonly used parameter to assess the reliability (or reusability) of a used component/product. It is the difference between the mean life-time and the actual life of a product under a given condition of use [18-19]. The mean life-time of a product (T_{PM}) is governed by the critical component with the

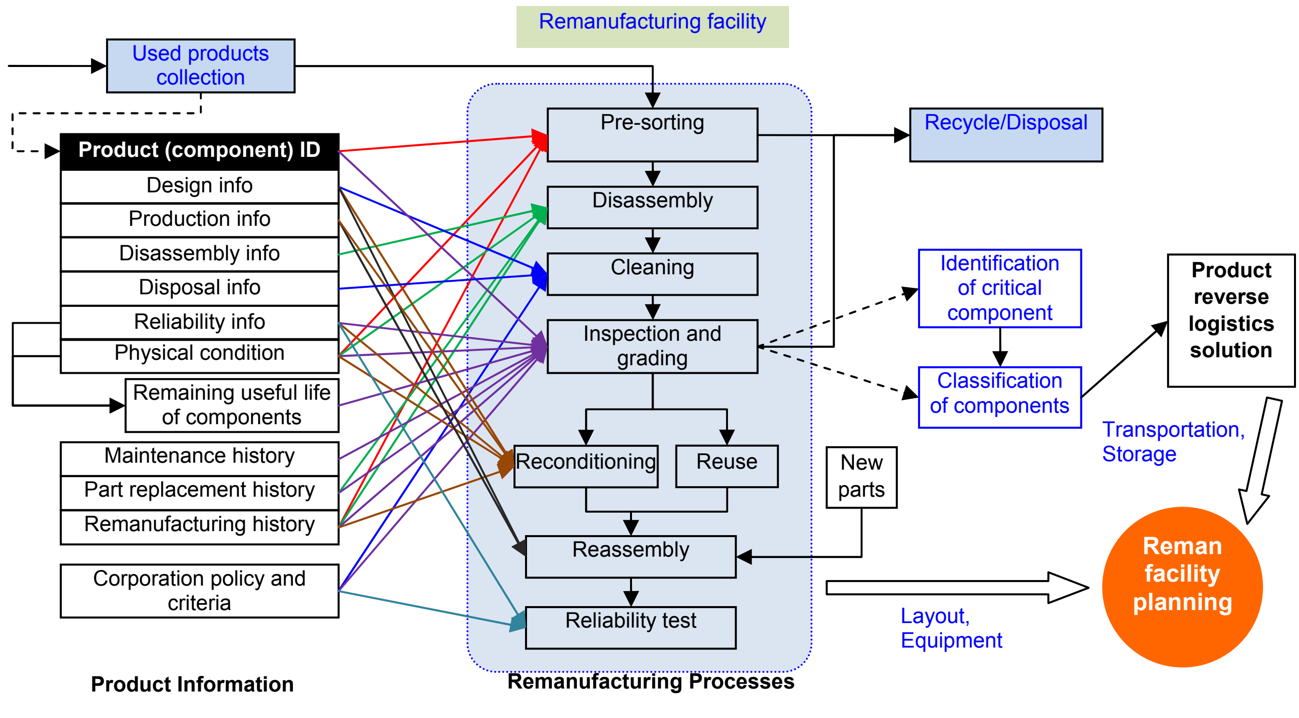

Figure 4: Conceptual framework on the use of sensor data to facilitate product remanufacturing decision making.

shortest life-span. Commonly used reliability indices are mean-time-to-failure (MTTF), mean-time-to-repair (MTTR), etc., which are normally provided by the product manufacturers. However, the experimental conditions used to determine these indices may not reflect the actual working conditions. Therefore, these indices should be rated to consider the actual working conditions. If the time-to-failure data of a component is available, the mean life-time of a component (T_{CM}) can be estimated by using the Weibull analysis [18] given in Equation (1), where η is defined as the life at which 63.2% of units will fail, β identifies the mode of failure, i.e., β<1 means infant mortality, β =1 indicates random failure and β>1 describes wear-out failure. β can be obtained from the Weibull distribution function given by Equation (2), where $F(t)$ represents the fraction of components failing and t is the time-to-failure [18].

$$T_{CM} = \eta \cdot \Gamma\left(\frac{1+\beta}{\beta}\right) \quad (1)$$

$$F(t) = 1 - \exp\left[\left(\frac{t}{\eta}\right)^{\beta}\right] \quad (2)$$

The life-time of a product/component can be defined in other forms, e.g., the mileage of a car, the amount of petrol consumed for an automotive engine [12], the number of starts and stops for an electric motor [19], etc. At the component level, it can be defined by the number of reusable cycles, e.g., the camera core for single-use cameras [20]. The remaining useful life can also be defined in similar forms accordingly.

As the state-of-health of a product is normally affected by many factors, multiple sensors have been used to monitor different aspects of the actual working conditions. Since these sensor data are often of different dimensions and units, and the information can be conflicting at times, data fusion is required to determine the actual condition of the product [21].

Figure 5 shows a procedure for sensor data interpretation. The actual usage life (T_O) of a component of a returned product can be estimated based on the data obtained during the use phase of the product. Some frequently used estimation techniques [18] are the regression analysis, Kriging techniques, artificial neural networks, etc. Once the actual usage life has been determined, the remaining useful life of a component can be obtained using Equation (3) [18]. It can also be obtained based on the number of remanufacturable (reusable) cycles N_{reman}, given in Equation (4).

$$T_{RUL} = T_{CM} - T_O \quad (3)$$

$$N_{reman} = Floor\left[\frac{T_{RUL}}{T_{PM}}\right] \quad (4)$$

4.2 Sensor Data for Remanufacturing Decision Making

Assuming that the historical data of a large number of returned products is available, (1) the mean life-time of a critical component (T_{PM}) and (2) the mean life-time of the core (T_{CM}), can be derived based on the analysis in Section 4.1. Based on the life-cycle data of a returned product and its components, the following information can then be determined and used to assist in decisions on recovery, inspection, assembly, disassembly, etc. They are (1) number of times a component has been remanufactured (N_{reman}) or directly reused (N_{reuse}), (2) maximum number of times a component can be remanufactured (N_{mreman}) or directly reused (N_{mreuse}), and (3) remaining useful life of a component (T_{RUL}).

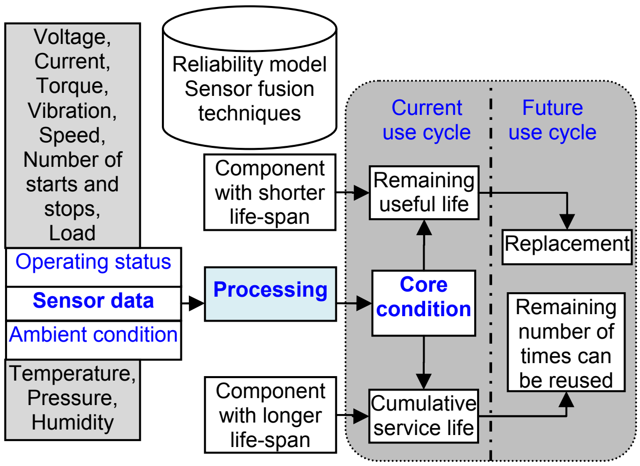

Figure 5: Interpretation of sensor data.

Collection and Pre-sorting

Both OEMs and independent remanufacturers have their own criteria for accepting cores and the corresponding core refund guidelines to facilitate used products acquisition. OEMs normally exhibit a more generous acceptance threshold, while independent remanufacturers may have more stringent core acceptance criteria, e.g., they may not accept a used product if the product condition is beyond remanufacturing. The end-user will receive alerts to return their products if these products are reaching their EOL stage whenever the life-time data of the products is uploaded to the server. The remanufacturers will be able to determine the quality of the incoming returns based on the sensor data. A general rule for core acceptance is given by Equation (5), where D_{col}=1 means the acceptance of the core, while D_{col}=0 refers to rejection.

$$D_{col} = \begin{cases} 1, \mathit{if}\ (T_{RUL} > T_{PM})\ \mathit{and}\ (N_{mreman} > N_{reman}) \\ 0, \mathit{otherwise} \end{cases} \quad (5)$$

Once the cores have been accepted, the product type, the technology used in the product, and the production date will be identified to sort them for storage and other subsequent operations.

Disassembly

Actual disassembly of a return is not necessarily an exact reverse of its assembly sequence due to factors, such as irreversible welded joints may have been used, degradation of components and damages to components during use, missing components, product upgrade during maintenance and remanufacturing tasks, etc. Therefore, the disassembly sequence should consider the changes that have occurred to the product during its entire life-time. The index for ease of disassembly of a product is determined by the joining methods used, e.g. mechanical fastening, welding, gluing, riveting, etc. and the physical damages to the product, such as corrosion, deformation, etc. In addition, the choice of product recovery plays an important role in disassembly. Some components, e.g., electric motors, can be reused directly without the need for further disassembly [22]. The cores, e.g., the crankshaft and engine block, require proper reconditioning so that they can be reused in a remanufactured product, such that they have to be disassembled completely. The disassembly level of a component based on different recovery options can be determined using Equation (6), in which D_{dis}=0 means no further disassembly is needed, D_{dis}=1 refers to complete disassembly, and D_{dis}=2 refers to the case where the component should be disassembled properly for disposal or material recycling.

$$D_{dis} = \begin{cases} 0, \mathit{if}\ (T_{RUL} > T_{PM})\ \mathit{and}\ (N_{mreuse} > N_{reuse}) \\ 1, \mathit{else\ if}\ (T_{RUL} > T_{PM})\ \mathit{and}\ (N_{mreman} > N_{reman}) \\ 2, \mathit{otherwise} \end{cases} \quad (6)$$

Cleaning

Cleaning is one of the most environmentally unfriendly processes in remanufacturing. The contamination level of a component and the cleanliness to be achieved affect the cleaning technology and cleaning equipment that can be used [23]. It is important to know the compatibility between the materials used in the components and the cleaning agents. Hence, product information needed for cleaning include (a) the bill of material of a component, (b) design features of the component, (c) required cleanliness level, and (d) company policies on the disposal of wastes generated by cleaning. The static information can be retrieved as they are available during the design stage. The contamination level of a component can be graded based on technician's expertise through which suitable cleaning methods can be adopted.

Inspection and Grading

Inspection is required to measure and detect the current condition of a component. For components with significant physical defects that cannot be recovered, they can be sorted for material recycling. Other information related to material fatigue, functional degradation, etc., which cannot be detected through simple visual inspection, can be monitored using embedded smarted sensors and assessed to determine the remaining useful life of the components. Table 1 shows a simple method for components grading based on the physical defects, the remaining useful life of the components, and the number of times they have been reused or remanufactured. In general, the components can be graded into three categories [24], namely, (a) directly reusable, (b) reusable after proper repair or reconditioning, and (c) cannot be repaired or reconditioned.

Conditions of components			Grading decision
Significant identifiable physical defects			Not remanufacturable
No obvious physical defects	T_{RUL} >= T_{PM}	T_{mruse} > T_{ruse}	Directly reusable
		T_{mreman} > T_{reman}	Reusable after repair
	T_{RUL} < T_{PM}		Not remanufacturable

Table 1: Grading of components based on conditions.

Based on these classifications, companies may apply different sorting criteria. The maintenance history can help identify components or parts that require frequent maintenance. In addition, the cores can be further classified based on the number of times they have been directly reused or remanufactured. However, there exists a trade-off between the accuracy of the grading and the economic profitability of remanufacturing [25].

Repair and Reconditioning

To restore a used part to a like-new condition, the specifications of the corresponding new part, e.g., geometric features, material, surface property, reliability, etc., should be known *a priori* by the remanufacturers. The current condition and the failure mode of the used parts affect the reconditioning strategies. For example, a damaged or worn part can be restored by removing the damaged area or adding new material to the worn area, depending on the severity of the damage or wear [26]. The remanufacturing history as well as the performance and reliability of the previous remanufactured versions of a component will provide feedback on the effectiveness of the reconditioning methods.

Reassembly and Reliability Test

The reassembly sequence may be the same as the original new product if there is no significant upgrade during remanufacturing. The original standards and reliability of the product should be known in advance. OEMs can have access to these data, and the independent remanufacturers will be able to access these data if they are within the closed-loop supply chain where such information may be readily available. Otherwise, detailed inspection and significant expertise will be needed to extract such information from a new product.

Design Feedback to Manufacturers

Through collecting used products, manufacturers can obtain feedback on the reliability and durability of these products [27]. The maintenance record and remanufacturing history can help identify components and parts that require frequent maintenance under certain working and environmental conditions. First, these information can be accumulated and used by the remanufacturers during subsequent inspecting and sorting of the used components and parts. Secondly, the information can assist the remanufacturers identify critical components that have the most significant impact on the useful life of a product. Through analyzing the failure causes, the failure rates and their relations with the working conditions, remanufacturers can provide feedback to the design teams on the weaknesses of the current design. However, it should be noted that components should not be designed only for remanufacturing, and other requirements, such as product functionality and initial manufacturability, etc., should be considered as well [26].

5 SUMMARY AND FUTURE WORK

The remanufacturing process is often labor-intensive and relies heavily on the expertise of the employees due to wide ranging variations in the return conditions. The use of embedded sensors has presented potentials to assist the remanufacturers in making more reliable decisions at each stage of the remanufacturing process. However, product condition monitoring using embedded sensors, particularly sensor data fusion and interpretation, remain challenging in the remanufacturing industry. This paper has reviewed the technical challenges of the different phases of the entire product life-cycle. A conceptual framework has been developed on the use of the sensor data in facilitating remanufacturing operations and decision-making at each remanufacturing stage. A number of improvements can be made to validate and extend the proposed conceptual framework. A few industrial case studies will be required to demonstrate the effectiveness of the developed framework, and provide useful input in order that the framework to be developed is generic.

6 REFERENCES

[1] Aras, N.; Boyaci, T.; Verter, V. (2004): The effect of categorizing returned products in remanufacturing, in: IIE Transaction, Vol. 36, No. 4, pp. 319-331.

[2] Liang, Y.; Pokharel, S.; Lim, G.H. (2009): Pricing used products for remanufacturing, in: European Journal of Operational Research, Vol. 193, No. 2, pp. 390-395.

[3] Klausner, M.; Grimm, W.M.; Hendrickson, C.; Horvath, A. (1998): Sensor-based data recording of use conditions for product takeback, in: Proceedings of the 1998 IEEE International Symposium on Electronics and the Environment (ISEE1998), pp. 138-143, Chicago, IL.

[4] Parlikad, A.K.; McFarlane, D. (2007): RFID-based product information in end-of-life decision making, in: Control Engineering Practice, Vol. 15, No. 11, pp. 1348-1363.

[5] Hribernik, K.A.; von Stietencron, M.; Hans, C.; Thoben, K.D. (2011): Intelligent products to support closed-loop reverse logistics, In: Globalized Solutions for Sustainability in Manufacturing (J. Hesselbach and C. Herrmann eds.), Proceedings of the 18th CIRP Conference on Life Cycle Engineering, Technische Universität Braunschweig, Braunschweig, Germany, 2-4 May 2011, pp. 486-491.

[6] Kiritsis, D.; Bufardi, A.; Xirouchakis, P. (2003): Research issues on product lifecycle management and information tracking using smart embedded systems, In: Advanced Engineering Informatics, Vol. 17, No. 3-4, pp. 189-202.

[7] Ferrer, G.; Heath, S.K.; Dew, N. (2011): An RFID application in large job shop remanufacturing operations, in: International Journal of Production Economics, Vol. 133, No. 2, pp. 612-621.

[8] Seliger, G.; Buchholz, A.; Grudzein, W. (2002): Multiple usage phases by component adaptation, in: Proceedings of the 9th CIRP International Seminar on Life Cycle Engineering, Erlangen, Germany, 9-10 April 2002, pp. 47-54.

[9] Lee, J.; Ni, J.; Djurdjanovic, D.; Qiu, H.; Liao, H. (2006): Intelligent prognostics tools and e-maintenance, in: Computers in Industry, Vol. 57, No. 6, pp. 476-489.

[10] Vadde, S.; Kamarthi, S.; Gupta, S.M.; Zeid, I. (2008): Product life cycle monitoring via embedded sensors, in: Environment conscious manufacturing (S.M. Gupta and A.J.D. Lambert eds.), CRC Press, pp. 91-103.

[11] Zeid, A.; Kamarthi, S.; Gupta, S.M. (2004): Product take-back: sensors-based approach, in: Proceedings of SPIE Vol. 5583, Environmentally Conscious Manufacturing IV (S.M. Gupta eds.), pp. 200-206, Bellingham, WA.

[12] Smith, V.M.; Keoleian, G.A. (2004): The value of remanufacturing of engine – lifecycle environmental and economic perspective, in: Journal of Industrial Ecology, Vol. 8, No. 1-2, pp. 193-221.

[13] Ilgin, M.A.; Gupta, S.M. (2010): Comparison of economic benefits of sensor embedded products and conventional products in a multi-product disassembly line, in: Computer & Industrial Engineering, Vol. 59, No. 4, pp. 748-763.

[14] Rostad, C.C.; Myklebust, O.; Mosenget, B. (2005): Closing the product life cycle information loops, in: Proceedings of the 18th International Conference on Production Research, 31 July – 2 August 2005, University of Salerno, Fisciamo, Italy.

[15] Harrison, M. (2003): EPC™ information service – data model and queries, white paper, Auto-ID centre, Institute for Manufacturing, University of Cambridge.

[16] Zhang, J.; Ong, S.K.; Nee, A.Y.C. (2011): RFID-assisted assembly guidance system in an augmented reality environment, in: International Journal of Production Research, Vol. 49, No. 13, pp. 3919-3938.

[17] Yuan, M.L.; Ong, S.K.; Nee, A.Y.C. (2008): Augmented reality for assembly guidance using a virtual interactive tool, International Journal of Production Research, Vol. 46, No. 7, pp. 1745-1767.

[18] Kara, S. (2010): Assessing remaining useful lifetime of products, in: Wiley Encyclopedia of Operations Research and Management Science (J.J. Cochran eds.), John Wiley & Sons, Inc.

[19] Kara, S.; Manmek, S.; Kaebernick H.; Ibbotson, S. (2008): Assessment of products for optimal lifetime, in: CIRP Annals – Manufacturing Technology, Vol. 57, No. 1, pp. 1-4.

[20] Geyer, R.; Van Wassenhove, L.N.; Atasu, A. (2007): The economics of remanufacturing under limited component durability and finite product life cycles, Management Science, Vol. 53, No. 1, pp. 88-100.

[21] Niu, G.; Yang, B.S.; Pecht, M. (2010): Development of an optimized condition-based maintenance system by data fusion and reliability-centered maintenance, in: Reliability Engineering and System Safety, Vol. 95, No. 7, pp. 786-796.

[22] Kaehernick, H.; Kara, S. (2008): Reuse and recycling technologies, in: Environmentally Conscious Mechanical Design (M. Kutz eds.), John Wiley & Sons, Inc., pp. 249-282.

[23] Schweinstig, S. (2010): Cleaning engineering – efficient cleaning in remanufacturing, in: ReMaTecNews, Vol. 10, No. 6, pp. 20-27.

[24] Steinhilper, R. (1998): Remanufacturing – The Ultimate Form of Recycling. Stuttgart, Germany: Fraunhofer IRB Verlag.

[25] Zikopoulos, C.; Tagaras, G. (2008): On the attractiveness of sorting before disassembly in remanufacturing, in: IIE Transactions, Vol. 40, No. 3, pp. 313-323.

[26] Bras. B. (2008): Design for remanufacturing processes, in: Environmentally Conscious Mechanical Design (M. Kutz eds.), John Wiley & Sons, Inc., pp. 283-318.

[27] Bras, B.; McIntosh, M.W. (1999): Product, process and organizational design for remanufacture – an overview of research, in: Robotics and Computer Integrated Manufacturing, Vol. 15, No.3, pp. 167-178.

Durability and Remaining Useful Fatigue Life Assessment of Welded Joint Using Impedance and Wave Propagation Techniques

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Abstract

All real-life aerospace and machine structures are prone to fatigue, which is the occurrence of localized but progressive damage due to continuous fluctuating stresses. Even if the magnitudes of the fluctuating tensile and compressive stresses are within the limits of the material strength, their alternating nature is responsible for fatigue. Fatigue damage can be monitored by observing changes in the structural stiffness as a function of the number of loading cycles. The problem is more severe if a welded joint is subjected to such fatigue behavior. This paper aims to employ the smart material based electromechancial impedance (EMI) technique to study the welded joint behaviour during cyclic loading for fatigue cracks. Piezoceramic transducers are surface bonded at several distinct locations near the weld and are subjected to actuation, so as to interrogate the joint for the desired frequency range. The interrogation resulted in the prediction of electromechanical admittance signatures. These signatures are then used as indicators to estimate the health/integrity of the welded joint, as changes in these signatures during the cyclic loading period are caused by cracks or damages in the welds. A comparative study is also conducted using strain gauges and guided wave propagation techniques during the period of cyclic loading on the specimen. An attempt has been made to correlate the remaining useful life of the welded joint and statistical indices for various numbers of cycles of load.

Keywords:

Structural health monitoring; Piezo-impedance; electromechanical impedance; vibrations; cracks; damages; wave propagation

1 INTRODUCTION

All real-life aerospace and machine structures are prone to fatigue, which is the occurrence of localized but progressive damage due to continuous fluctuating stresses [1]. Even if the magnitudes of the fluctuating tensile and compressive stresses are within the limits of the material strength, their alternating nature is responsible for fatigue. Fatigue damage can be monitored by observing changes in the structural stiffness as a function of the number of loading cycles [2]. The problem is more severe if a welded joint is subjected to such fatigue behaviour. This paper aims to employ advanced non destructive testing (NDT) methods, electromechancial impedance (EMI) [3] and guided wave propagation methods [4] to study the welded joint behaviour during cyclic loading for fatigue cracks. In the EMI method, a piezoceramic transducer (PZT) is usually surface bonded or embedded permanently on the structure to be monitored [5-6]. The PZT is excited using 1V RMS sinusoidal alternate current (AC) voltage for a frequency range of about 10 to 400 KHz with suitable sweep steps. The PZT, being a smart transducer, expands and contracts due to the AC supply resulting in continuous sensing for the period of monitoring the host structure. Furthermore, the single PZT acts as both actuator and sensor, i.e., inputs local vibrations to the structure and also captures/senses the resistances of the structure to these vibrations. This phenomenon results in unique health signature of the host. This is termed as electro-mechanical (EM) admittance signature, which when alters in the future period of monitoring indicates defects in the structure [7]. In the wave propagation method, at least two PZT transducers are attached to the structure at some distance apart (>150mm) where one is used as an actuator and the other as a sensor. Unlike the EMI method, the PZT transducers need not be permanently bonded on the structure to be monitored. However in the present case, the same permanently bonded PZT transducers are used for wave propagation method. When one PZT transducer acting as an actuator is excited with five cycles Hanning windowed sine wave burst, the wave will travel on the surface of the structure and gets captured by the other PZT transducers acting as sensors to result in a time domain signal. Any variations in the captured signal in the future monitoring periods indicate the presence of defects in the structure.

In this paper, two high strength steel fillet welded specimens as shown in Figure 1 were considered. The specimens were subjected to fatigue load between 4.5 KN to 94.5 KN at 15Hz frequency and stress range of 10 MPa to 210 MPa. Both the specimens were designed to work till 200,000 cycles of load for ideal experimental conditions. The fatigue cracks at the welds were monitored by several permanently bonded PZT transducers near the weld of each specimen. The first specimen was monitored by EMI method whereas the second specimen was monitored by both EMI and wave propagation method. Both EMI and wave propagation methods were successful in detecting the location of initial crack; but EMI was ahead in identifying the initial crack occurrence. However, both are successful in monitoring crack growth. A statistical root mean square deviation (RMSD) index was applied for the signatures obtained from the EMI signatures of the first specimen. This was adopted as the basis for monitoring the second specimen using both EMI and wave propagation methods. The wave propagation method used the pulse-echo signal acquisition approach where one of the PZT was used for generation of Hanning windowed sinusoidal bust on the surface of structure and the other PZT transducers captured the signal. A correlation between crack initiation and further growth till complete failure was studied.

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2 EXPERIMENTAL SPECIMENS

The experimental specimens used in this study are shown in Figure 1. Each specimen is made of three steel plates welded together, with properties as given in Table 1.

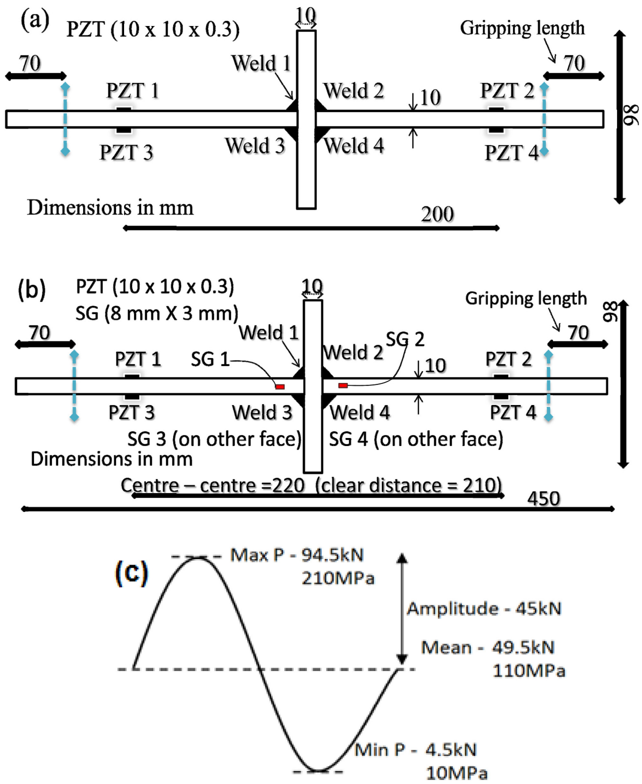

Figure 1: Experimental specimen with dimensions and cyclic load information (a) First specimen (b) Second specimen (c) Cyclic load magnitude.

The first specimen had four identical PZT transducers bonded using epoxy adhesive at locations as shown in Figure 1 (a). The second specimen was similar to the first specimen but with four strain gauges bonded close to the welds as shown in Figure 1 (b).

These specimens were subjected to fatigue test in a standard 25 Ton fatigue test machine. The complete setup comprising of EMI and wave propagation method is as shown in Figure 2. A WAYNE KERR 6420 Impedance Analyzer with communication VB software was used for the EMI method. A TABOR ELECTRIC ww1701 arbitrary function generator, a YOKOGAWA DL1740 oscilloscope and a NATIONAL INSTRUMENTS (NI) integrated digital signal acquisition system were used for the wave propagation method.

2.1 Working Principle of EMI Method for First Specimen

The EM admittance signature consists of real (conductance) and imaginary (susceptance) parts. These are acquired using an Impedance analyzer. The real conductance signature is mainly used while the imaginary susceptance is rarely used [3]. In the present case, as it is an axial cyclic loading test for fatigue study, it was decided to consider the conductance signatures. Impedance analyzer was adjusted for 1V RMS sinusoidal frequency range of 50 to 100 KHz with sweep steps of 0.1 KHz.

Before fixing the specimen onto the standard fatigue machine (Figure 2), baseline (initial-healthy) conductance signatures of all the four PZT transducers were recorded one after another by keeping the specimen on two simple supports at 70 mm away from both ends (Figure 1a).

Physical property	Value		
Mechanical	**Epoxy**	**Steel**	**PZT**
Density (kg/m^3), ρ	1180	2715	7800
Young's Modulus (N/m^2)x 10^9	2	200	66.67
Tensile Strength (N/m^2)x 10^6	-	1600	-
Yield Strength (N/m^2)x 10^6	-	1300	-
Poisson's ratio, υ	0.4	0.33	0.33
Loss factor, η	-	-	0.023
Electrical (for PZT only)			
Piezoelectric strain coefficients (m/V) d_{31} , d_{32} x10^{-10}			-2.10
Piezoelectric strain coefficient (m/V) d_{33} x10^{-10}			4.50
Dielectric loss factor, δ			0.015
Electric permittivity, ε_{33} (farad/m) x10^{-8}			1.75

Table 1: Key properties of epoxy adhesive, specimen and PZT

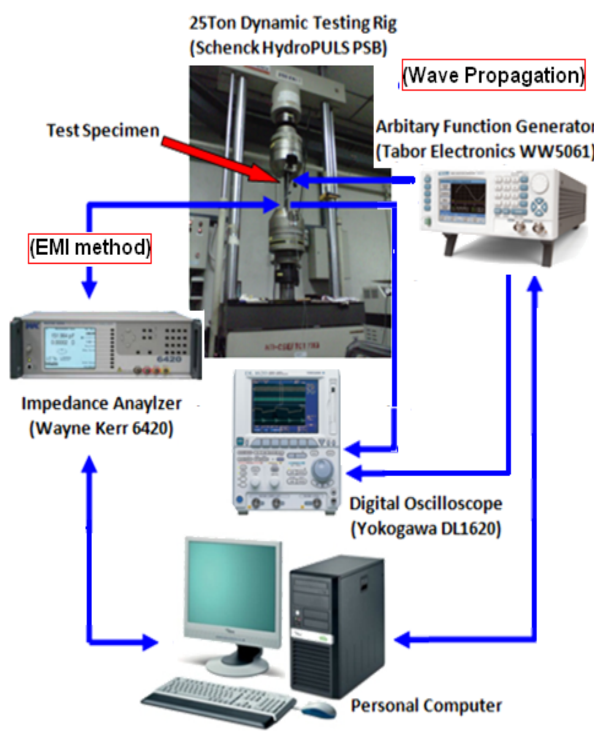

Figure 2: Experimental setup.

The specimen was fixed in the dynamic testing rig, such that 70 mm of both ends were clamped to the rig as shown in Figure 2. The specimen was then subjected to fatigue load between 4.5KN to 94.5KN at 15Hz frequency and stress range of 10 MPa to 210MPa as shown in Figure 1(c). The fatigue failure was expected to occur at about 200K cycles of load. The experiment was performed in cyclic steps (30K, 60K, 80K, 100K, 120K, 140K, etc) till fatigue failure. After end of each step, the specimen was removed from the testing rig and was placed as before on two simple supports. One after another, the conductance signatures were obtained for all the four PZT transducers in frequency range of 50 to 100KHz. All these signatures were analyzed, but only two appropriate representative signatures (PZT 3 and PZT 2) as shown in Figure 3 are presented, because these two are enough to explain the fatigue process effectively. It was further observed that only a narrow frequency range of 62.7 to 63.4 KHz is sufficient to capture the whole process.

Figure 3(a) shows the conductance signatures of various steps obtained from PZT 3. The baseline and 3 more signatures at 30K, 60K and 80K load cyclic steps resulted in an interesting peak at the frequency of 63.2 KHz. This peak shifted when the specimen was further subjected to cyclic loading. At 100K cycles, the peak shifted from 63.2 to 63 KHz, indicating initial crack occurrence. To view the cracks clearly at 100K, a dye-penetrant was sprayed on the surface. Figure 4(a) shows the photo of the two cracks on the surface. The locations of these cracks were found to be closer to PZT 3 (weld 3, see location in Figure 1a) and hence PZT 3 was the first to indicate the presence of crack. The signatures obtained from the other PZT transducers did not shown any change in peaks up till 100K cycles. The test was allowed to continue for the next step. Subsequent signatures obtained from PZTs 1, 2 and 4 shown to shift at 120K cycles where as PZT 3 has already shifted at previous step and continued shifting at 120K. Figure 3(b) shows conductance signatures of various steps obtained from PZT 2. Furthermore, the signatures obtained by PZT 1 shown to have higher amplitude over PZT 2 as it was mounted directly below PZT 3 (i.e., closer to the crack). Figure 4(b) shows the photo of the extended crack (narrow red line) on the surface. At 140K cycles, signatures from all PZT transducers indicated a leftward shift with an increase in amplitude suggesting a relatively clear damage/ failure in the structure. In addition, the amplitude at 140K cycles shown a smaller value for signatures of PZT 2 as compared to PZT 3. The final photo of the failure is as shown in Figure 5. This fatigue failure can be analyzed in a series of steps. The first step was the appearance of microscopic cracks at the surface (near the weld toe as shown in Figure 4a) at 100K cycles. The next step was the increased crack length along the weld toe as the load cycle increased (redline in Figure 4b) and finally, the crack resulted in a complete fracture as shown in Figure 5.

A statistical Root Mean Square Deviation (RMSD) was employed to study the deviation of signatures (PZT 3) in frequency range of 50 - 100 KHz. Figure 6 shows the RMSD versus load cycles. The values of RMSD increased up to 100K cycles, but later abruptly decreased. Thus, frequency range of 50 – 100 kHz does not provide a good representation of fatigue. Hence, a narrow frequency range of 62.6 – 63.4 kHz was considered. This frequency range provided a linear trend of RMSD as the load cycles progressed. Thus, it can be concluded that the wide range of frequency (50 - 100 KHz) is not required for the present type of welded specimen using EMI method.

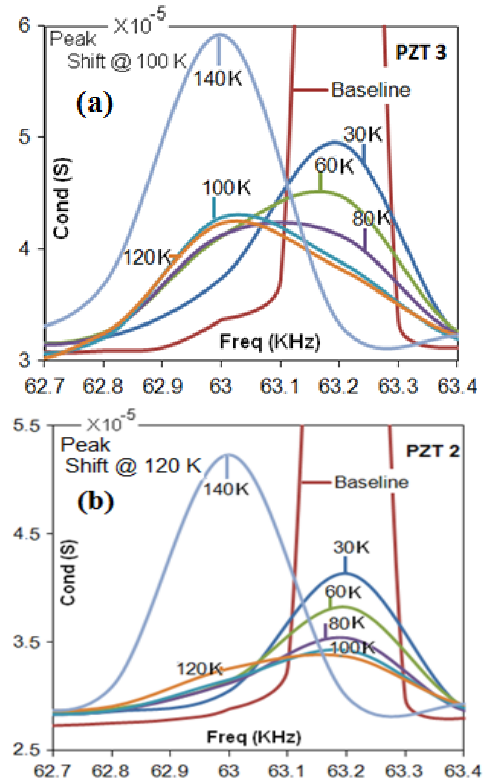

Figure 3: Conductance verses Frequency signatures obtained from (a) PZT 3 (b) PZT 2.

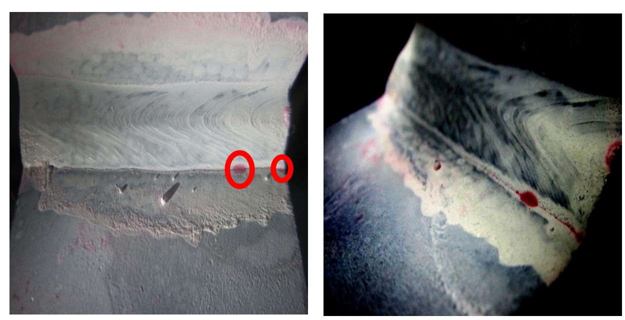

Figure 4: Initial crack on the surface (a) initial crack after 100K cycles (b) cracks after 120K cycles.

Figure 5: Final failure of the specimen at 140 K cycles.

The first specimen was monitored with an objective of optimizing frequency range of excitations required for EMI method from a wide range to a reasonably narrow range, and hence the wave propagation method was not considered. Furthermore, from literature [4], the optimized frequency range for using wave propagation method is expected to be between 100 to 200 KHz. Hence for the next specimen, both the EMI and wave propagation methods were considered for optimal frequencies as obtained from the first specimen and from the literature.

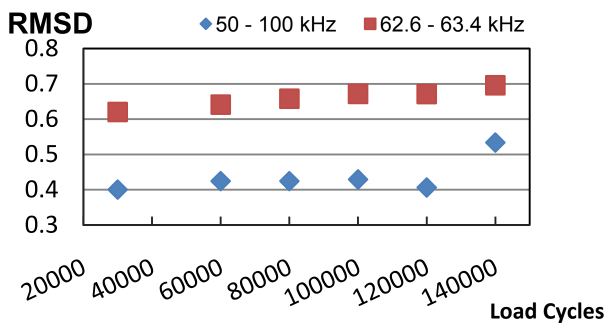

Figure 6: RMSD variations for load cycles.

2.2 Results and Discussion of Second Specimen

- **EMI method**

From the first specimen, it is known that a narrow frequency range of about 62.6 - 63.4 KHz is sufficient for EMI method. However in this case, a wider range of 60-70 KHz is adopted as the second specimen may not exactly replicate the first specimen. There was no change in the applied magnitudes of fatigue load (Figure 1c).

Four PZT transducers were bonded on the specimen as for the previous case. Four strain gauges, such that two on one face and another two on other face, were bonded at a distance of 2.5 cm away from the centre on either side as shown in Figure 1(b). Figure 7 shows the strain readings obtained for various conditions such as load-free condition (0KN load), mean load (49.5KN), and a few intermittent load values after certain load cycles. Dye penetrant inspection was carried out after 100K cycles, at each step till complete failure of the specimen.

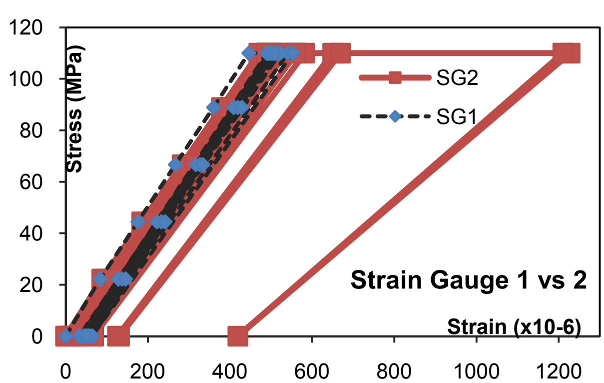

Figure 7: Strain gauge readings.

Location of the fatigue crack was determined by comparison of the strain gauge readings for different conditions. If crack occurs near a particular strain gauge, the readings must register an increase in value for the considered condition (before or after crack at 0KN load or mean load, see Figure 1c). Here, considered condition implies the situation of the specimen after certain cycles of load, say the strain value returns back to the initial position (at 0KN load) and the specimen is still within its elastic deformation range - this is considered as one condition before crack. Another condition after crack is when the specimen exceeds its elastic deformation range (due to cyclic loading) and enters into the plastic deformation region without further load (at 0KN load). Several intermittent conditions are feasible from no crack stage to crack initiation and propagation stages. Figure 7 shows the absolute values of strain gauge readings at all these conditions. It shows that strain gauge SG 2 readings have higher shift of strain values (deformations) as compared to SG 1, hence implied that the crack occurred near SG 2.

After 135K cycles, SG 2 near the crack started to show signs of *crack initiation* in the specimen. An increase in strain reading of 24×10^{-6} was observed when the specimen was at 0KN. Between 135K to 145K cycles, the strain gauge started to show clear indication of *crack propagation*. After 145K cycles, SG 2 reading increased by 63×10^{-6} when the specimen was at 0kN. The shift in readings between 135K to 145K cycles was very rapid and almost similar to the strain values from 0 to 135K cycles. Thus, it shows that crack propagated for at least another 10 to 15K cycles beyond 135K cycles of load.

At 135K cycles, two cracks with length of 9.7mm and 4.2mm were observed in weld 2 (see Figure 1b). At 145K cycles, the two cracks merged into an extended crack of length 20 mm. At 155K cycles, through crack of 45 mm was observed as shown in Figure 8(a). A through crack was observed after 155K cycles for a mean load of 49.5KN. SG 2 registered an increase in value of 559×10^{-6} in another 10K cycles increase, showing cracks forming in PZT 2/4 region. When the specimen was unloaded (brought back to relaxed position), strain readings did not go back to its previous values but instead increased by another 293×10^{-6} (shows a plastic deformation condition). The complete facture occurred at 159,654 cycles (Figure 8b-c).

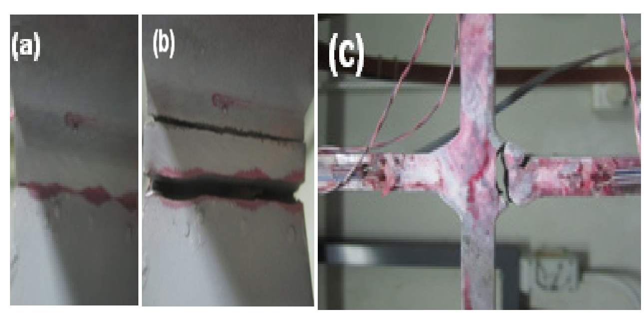

Figure 8: cracks on the surface leading to failure (a) Through crack (b) side view- complete fracture (c) front view- complete fracture.

As seen in the previous specimen, here again the EMI method was found efficient in detecting the fatigue crack initiation. Thus, the location of fatigue crack was determined by the first shift in peak frequency from EMI readings without physically looking at the specimen for presence of cracks. Figure 9 shows the comparisons of signatures obtained by four PZT transducers at 90K cycles of load on second specimen. In this experiment, at 90K cycles, PZTs 2 and 4 were first observed to have a leftward shift in peak frequency indicating the possibility of simultaneous crack occurrences at weld 2 and weld 4 locations. Furthermore, the peak of PZT 2 showed a slightly greater shift over PZT 4. This implied another possibility of single crack occurrence nearer to PZT 2 (i.e. on weld 2). However confirmation was required to prove the crack propagation location and direction. Hence loading was continued, at next cyclic load step, and weld 2 region shown greater visible cracks on the surface. Further cyclic loading proved that crack occurred at both weld 2 and weld 4 regions. Final fracture was observed at 159,654 cycles as shown in Figure 8(c).

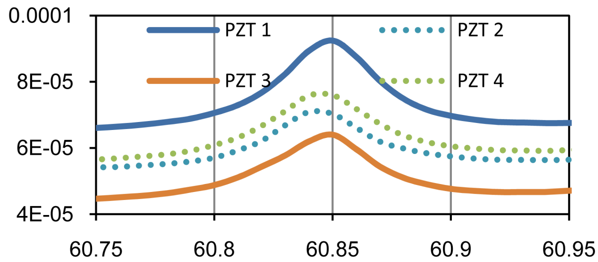

Figure 9: Comparison of 4 PZT transducers at 90K cycles of load.

- **Wave Propagation method**

In wave propagation method, usually five cycles (group) of sinusoidal Hanning windowed (time domain) wave at certain frequency is sent by an actuator through a function generator. This grouped wave propagates with certain group velocity [4, 8] on the structure under investigation and finally gets captured by the other sensors through oscilloscope within predetermined time. The variation in the predetermined time, which is referred to as time of flight (TOF) of the group wave, is the key for identification of cracks in the structure.

In this study, the waves used were classified as S_0 group [8], the frequency of the wave group was selected as 150KHz and the group velocity was estimated as 4.55 mm/μs for steel material. The distance from the actuator (say PZT 1 or 3) to the sensor (say PZT 2 or 4) was 210mm (clear distance as shown in Figure 1b) for this specimen. Thus the TOF of this propagation path for the S_0 group wave was approximately estimated as 46μs (however due to initial noise in the time domain signal, the adjusted TOF was 63μs).

Figure 10 shows a typical representative sensor signal before cyclic load. In order to focus on this propagation path for the S_0 group wave, the analysis was conducted in the time domain of 50 to 80μs (which included the adjusted TOF). The waves presented within this window also included reflections from the end and the edges. As there was no change in the dimensions and no damage other than the fatigue crack was expected at the weld, the waves due to the end and edge reflection were not considered. Therefore, any change in the signal within this time domain was due to fatigue crack of the welded connection. The peak-to-peak amplitude for the wave at approximately 63μs was used to quantify the damage.

When fatigue crack initiated and propagated in the specimen, the amplitude of the signal reduced due to scattering of the waves. This can be observed in the sensor signal obtained when PZT 1 behaved as an actuator and PZT 4 behaved as a sensor, as shown in Figure 11. This figure compares the baseline sensor signal with the signals collected after 105K and 135K cycles of load. The experiments were carried out for several combinations of actuator (A) and sensors (S) with A-S distance of 210 mm as shown in Figure 1(b). These combinations were 1A(3S) (PZT 1 used as actuator and PZT 3 as sensor), 3A(1S), 2A(4S) and 4A(2S).

Figure 12 shows a comparison of peak-to-peak amplitude of these experimental combinations. After 105K cycles of load, larger changes in amplitudes were observed when PZT 2 and PZT 4 acted as actuators compared to PZT 1 and PZT 3 as actuators. This indicated that crack was present either at weld 2 or weld 4 (similar to observation of EMI method). Furthermore, at higher cycles of load, i.e. between 120K and 135K cycles, actuator PZT 1 showed smaller amplitudes, which indicated absence of crack at weld 1. Similarly, actuator PZT 3 indicated constant amplitude indicating no change in signal, which indicated absence of crack in weld 3. This indicated the crack propagation was between weld 2 and weld 4. Figure 8(c) shows the clear displacement of one steel plate near weld 2 and weld 4. Thus, after significant cycles of load the crack initiated at weld 2 and weld 4, and completely fractured the joint as the load cycles increased. This observation agrees with the visual inspection, dye penetration test, strain gauge reading and the EMI technique.

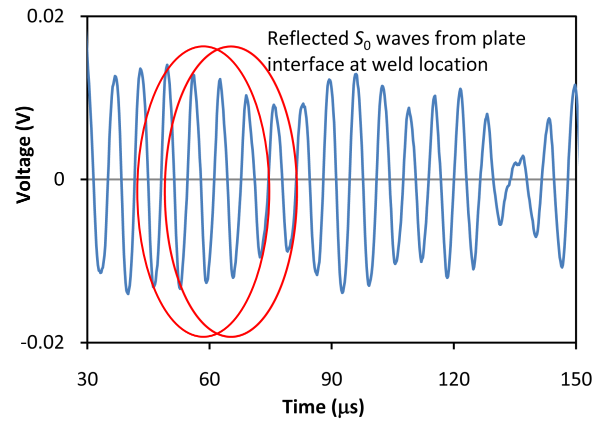

Figure 10: Typical sensor signal before cyclic load.

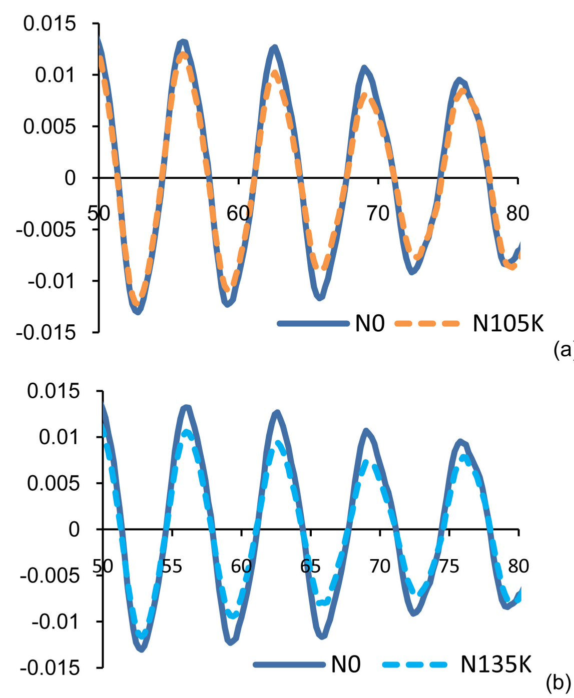

Figure 11: Sensor signal of PZT 4 (a) just after crack initiation (b) after significant crack propagation.

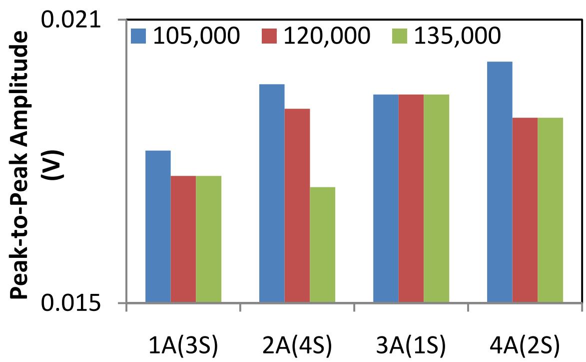

Figure 12: Comparison of peak-to-peak amplitude.

3 SUMMARY

This paper presented the fatigue crack growth monitoring of two welded joint specimens using the EMI and wave propagation methods. Fatigue test of the first specimen resulted in multiple cracks, initiating at the weld toe, and finally fractured at much lower than the intended life of 200K cycles. On the other hand, the second specimen had shown more resistance to fatigue as compared to the first specimen. However, in the second specimen, simultaneous cracks appeared near weld 2 and weld 4 which propagated into a complete fracture.

The RMSD indices obtained from the signatures of EMI method for the first specimen demonstrated that a narrow frequency range of 60 to 70 KHz is sufficient to monitor welded joints subjected to fatigue. This narrow frequency range was used in the second specimen, which has proven to be good indicator of presence of initial crack and its propagation. Thus a good consistency existed between signatures of the two specimens. It can be recommended that, for any future fatigue test with similar material properties and dimensions, the same narrow frequency range can be used.

The wave propagation method demonstrated that a time domain between 50 to 80ms is suitable for monitoring welded joints subjected to fatigue with similar properties. Due to limitations of the length of the paper, all the results related to the study are not included but more or less both the EMI and wave propagation methods were effective in understanding fatigue crack initiation and growth. Even though the present study did not conclusively estimate the co-relationship between remaining life and signals, the futures of these methods are still very promising.

4 ACKNOWLEDGEMENTS

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5 REFERENCES

[1] Bhalla, S. (2012): Fatigue Life Assessment of Structures Using Electro-mechanical Impedance Technique, Proceedings of the 25th International Congress on Condition Monitoring and Diagnostic Engineering, Journal of Physics Conference Series, Vol. 364, paper No. 012127.

[2] Lim, Y. Y.; Soh, C. K. (2010): Estimation of fatigue life using electromechanical impedance technique. Proc. SPIE, Vol. 7647, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2010, pp.764722 (March 31, 2010), U.S.A, doi:10.1117/12.846902.

[3] Annamdas, V. G. M., Soh C. K. (2010): Application of Electromechanical impedance technique for Engineering Structures: Review and Future Issues, Journal of intelligent material systems and structures, Vol. 21, No. 1, pp. 41-59.

[4] Lim, S. I.; Cui, L.; Liu, Y.; Soh, C. K. (2011): Monitoring fatigue crack growth in narrow structural components using Lamb wave technique. Proc. SPIE, Vol. 7981, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2011, 798143 (April 15, 2011); U.S.A, doi:10.1117/12.880327.

[5] Annamdas, V. G. M. (2012): Facts of Piezo Impedance Technique in Crack Propagation Studies for an Engineering Structure, International Journal of Aerospace Sciences, Vol. 1, No. 2, pp. 8-15.

[6] Annamdas V. G. M., Soh C. K. (2006): Embedded piezoelectric ceramic transducers in sandwiched beams, Smart Materials and Structures, Vol. 15, No. 2, pp. 538-549,

[7] Annamdas, V. G. M., Soh C. K. (2007): Three Dimensional Electromechanical Impedance Model II: Damage analysis and PZT characterization, Journal of Aerospace Engineering, Vol. 20, No. 1, pp. 63-71.

[8] Prosser, W. H., Michael D. S., Barry T. S. (1999) : Time-frequency analysis of the dispersion of Lamb modes, Journal of the Acoustical Society of America, Vol. 105, No. 5, pp. 2669-2676.

Detecting and Monitoring of Stress on Beams Using Lamb Waves

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Abstract
A stress magnitude higher than the ultimate stress is harmful to the structural reliability of many critical components in the aerospace, civil and mechanical (ACM) industries. However, very often the presence of excessive stress (even if it is nominal) tends to be undetectable as they may not initially crack the ACM structures. The use of smart material based structural health monitoring (SHM) is of great significance to estimate even the minimal rise of stress levels, and to improve the reliability of the structure. The non-destructive testing methods like the visual inspection, magnetic particle and ultrasonic are effective only for crack detection but not stress detection. The persistence of such stresses can lead to structural failure at later stages unless routine maintenance or inspections are being carried out. This paper thus investigates a lamb wave propagation based SHM method using peizoelectric transducers (PZTs) to investigate the minimal increments of the stress on a beam. Experiments were conducted with the introduction of stresses at mid points by attaching weights on the beam. Lamb waves are then generated on the specimen using one of the attached PZT transducers as an actuator, and the resulting waves are received on the other end by the another PZT, which acts as a sensor. These PZT transducers were reusable with excellent repeatability. This paper explores the suitability and sensitivity of lamb wave based wave propagation method for transverse load monitoring with nominal stress increments.

Keywords:
Load monitoring; piezoelectric patches; lamb waves; structural health monitoring (SHM)

1 INTRODUCTION

Damage [1-3] and load [4] are the two harmful parameters threatening the stability of the engineering components and structures, if limits are exceeded. However the carelessness in monitoring these parameters can lead to failures of the structure resulting in loss of life and money. The present study concentrated on establishing the methodology to monitor loads on few laboratory beams. A stress, which is a result of load placement on the structure, must not have magnitude higher than ultimate stress especially for the engineering structural components in the aerospace, civil and mechanical (ACM) industries. However, very often the presence of excessive stress tends to be undetectable as they may not initially crack the ACM structures. The non-destructive testing methods like visual inspection, magnetic particle and ultrasonic are effective only for crack detection after its occurrence but not stress detection until it leads to crack. The persistence of such stresses can lead to structural failure at later stages unless routine maintenance or inspections are being carried out. The use of piezoelectric (PZT) transducer in structural health monitoring (SHM) is of great significance to improve the reliability of the structure with the application of lamb waves. This paper thus investigates load monitoring for three different boundary conditions of the beam using lamb waves. In the past, lamb wave based wave propagation method was mainly used for monitoring axial loads [5] such as tensile loads starting at 0 MPa to a maximum of 57.5 MPa in steps of 5.75 MPa on a specimen [6]. But the magnitude of load was so high that the influence is felt on any SHM method. Thus in the present work, transverse loading rather than axial load with small load increment steps was considered to verify the sensitivity of this wave propagation based SHM method.

In the present study, three laboratory beams were considered with each subjected to different boundary conditions. Two PZT transducers were bonded on each specimen where one PZT behaved as an actuator and the other as a sensor. A 5 cycle Hanning windowed sinusoidal wave of 10 volt at 150 kHz, was sent to the actuator via function generator. This was captured by the senor, which was sent to oscilloscope. As the load was gradually applied on the beams, shifts in the output sinusoidal amplitude were observed. All the amplitudes were recorded for various load magnitudes of different boundary conditions, viz simply supported, fixed ends, and a cantilever beam. Thus different sets of amplitude data was obtained and processed for useful information. The results were plotted in several time domain graphs of peak to peak voltages. Further, the stress variation of a representative simply supported beam was carried out using the Euler–Bernoulli beam theory. The maximum bending stress in a beam is estimated and was compared with the variations in the signals of lamb wave. The experiments were performed using the reusable PZT transducers. It was observed that there was a very good repeatability in the signals even after using these reusable PZT transducers for significant times as actuator and sensor.

2 EXPERIMENTAL INVESTIGATION

The experimental specimens used in this study are shown in Figures 1 and 2. Each specimen consists of aluminium beam, reusable PZT actuator and sensor as shown in Figure 1 with properties as given in Table 1. The dimensions of PZT and specimens are shown in Figure 2.

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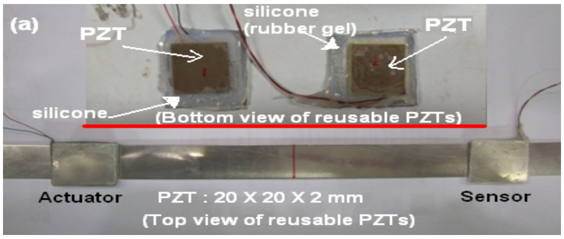

Figure 1: PZT with protection details and their attachments on the experimental specimen.

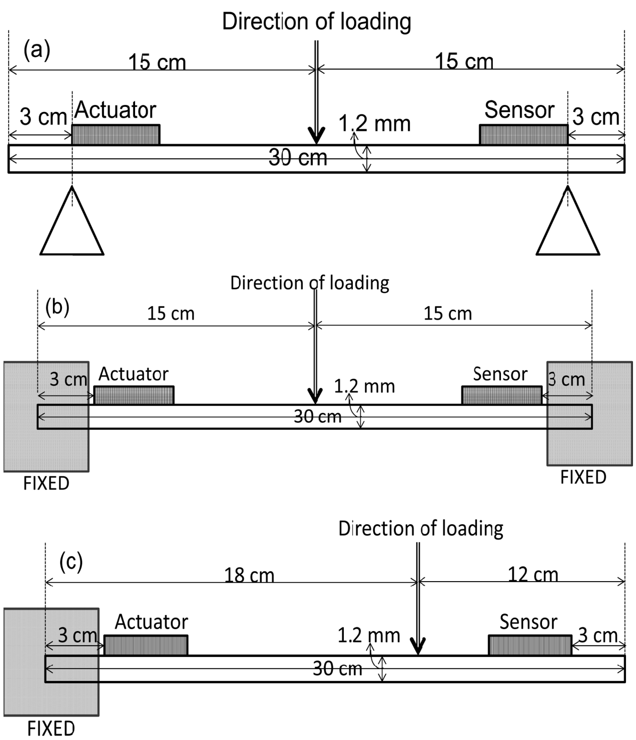

Figure 2: Different boundary conditions of specimens (a) simply support (b) fixed ends (c) cantilever support.

PZT Transducer	PZT	Aluminium
Dimensions *l* x *w* x *h* (mm)	20x20x2	30 X 30 X 2
Density, ρ_a (kg/m^3)	7800	2715
Young's modulus, E_a (GPa)	65	68.95
Poisson's ratio	0.33	0.33
Mechanical loss factor, η	0.023	-
Piezoelectric strain coefficients, d_{31}, d_{32} (m/V) x 10^{-10}	-1.9	-
d_{33} (m/V) x 10^{-10}	4.18	-
Dielectric loss factor, δ	0.015	-
Electric permittivity, ε_{33} (farad/m)	0.98	-

Table 1: Dimensions and properties of PZT transducers.

Both PZT actuator and sensor were provided sufficient protection using a silicone rubber casing and aluminium cover (30 x 30 x 2 mm). However only the top surface of PZT is given enough protection whereas the bottom surface is allowed to be free (no protection), so that bottom surface can directly bonded on the specimen by any commercially available super or fast hardening glue. This ensures proper interaction between PZT and the specimen. The rubber casing and aluminium cover provided additional robustness and stiffness required for reusing PZT setup as actuator and sensor (Figure 1). After performing the experimental study, the reusable PZT was removed by gently pulling out. This reusable PZT was used several times repeatedly by bonding using super glue and removing gently. It was observed that this is robust enough compared to studies carried out by Lim et al [7], using PZT transducers bonded permanently on the structure applying epoxy adhesive.

2.1 Experimental Setup

The experimental setup consists of a Tabor Electric WW1701 arbitrary function generator, a Yokagawa DL1740 Oscilloscope and a National Instruments (NI) integrated digital signal acquisition (DAQ) system assembled in a computer as shown in Figure 3.

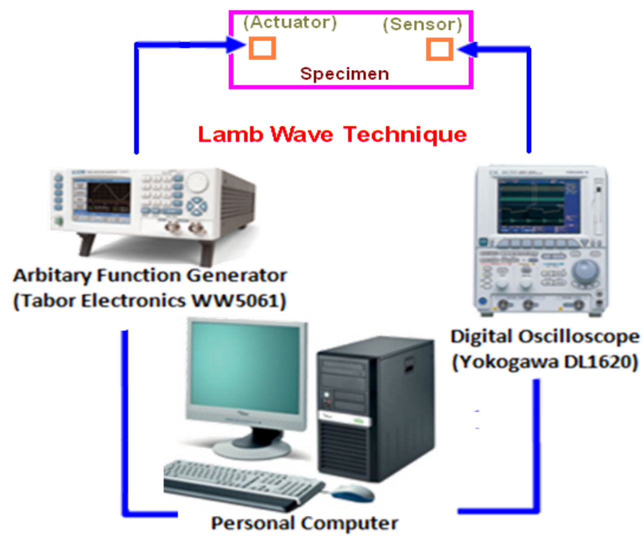

Figure 3: Experimental setup.

In this study, a 5-cycle hanning windowed sine burst was used as the actuation signal with an actuation frequency of 150 kHz and voltage of 10V. A 32-cycles averaging acquisition mode was used to reduce the random noise in the signal. The input signal is provided by funtion generator and the ouptut signal is captured by oscilloscope via DAQ enabled computer as shown in Figure 3.

2.2 Influence of Applied Load on Beams

From basic Euler- Bernoulli's beam theory, the maximum bending stress in a beam is given as

$$\sigma_s = -My / I \tag{1}$$

where *M* is the maximum bending moment, *y* is the distance from the neutral axis of the beam to the extreme surface, and in this case it is ½*H* since the specimens are homogeneous and symmetrical; and $I = WH^3/12$ is the moment of inertia.

In this study, the simply supported (Figure 2a) and the fixed supported beam with central load (Figure 2b) were considered. The loads (subsequent stresses) resulted in the maximum bending moment at the centre of the specimen. Figure 2(c) shows a cantilever beam subjected to non central load, which resulted in maximum bending moment at the support. In general, PZT transducers will function as long as they are stressed within the operational design stress limit [8-9] but the stresses used in this study are nominal and much below the design stress limits. Figure 4 shows the schematic diagram of stress distribution of a representative simply supported beam [10].

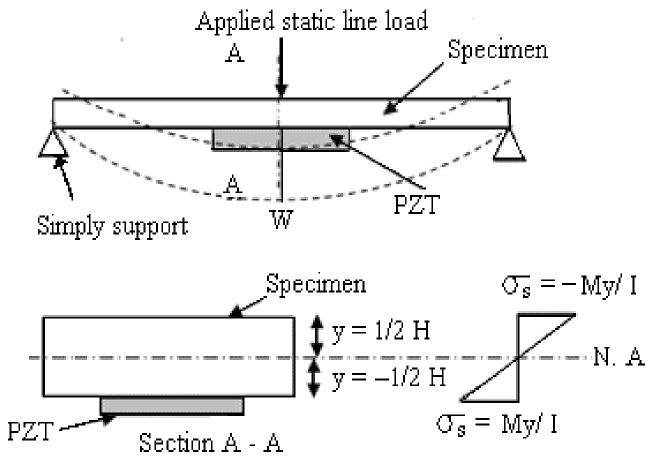

Figure 4: Stress distribution in a typical specimen.

3 EXPERIMENTAL DISCUSSION

3.1 Influence of Applied Load on a Simply Supported Beam

Simply supported beam as shown in Figure 2(a) was subjected to various transverse loading at the centre of the beam in steps of 2N, from 0N to 12 N. The maximum stress calculation experienced by the specimen under different loadings for simply supported condition ignoring the over hangs is as given in Table 2.

Load (N)	Maximum stress (MPa)
0	0
2	0.24
4	0.48
6	0.72
8	0.96
10	1.2
12	1.44

Table 2: Maximum stress for simply supported specimen.

Figure 5 shows the output voltage signal for a time domain of 0 - 400 μs. From the figure it is difficult to understand the pattern of the load increments and the subsequent output signal. Thus a closer view (Figure 6) in a time window of 203-212 μs gave a better correlation with the increasing load. It can be observed that with increasing load, the amplitude decreases and the peak shifts to the left. A progressive decreasing trend is identified in the Figure 7 where peak to peak value of the amplitude verses time domain is shown. A polynomial equation of 5th degree satisfies this incremental trend with R^2 =0.9989 accuracy.

Table 3 shows absolute peak to peak voltage differences in the time domain of 203-212μs. It shows that there is a decrease in the value as load magnitude increases. Even though increase in the load magnitude is less, still the signals were able to show variations. This shows the sensitivity of wave propagation method even for a small increment load of 2N.

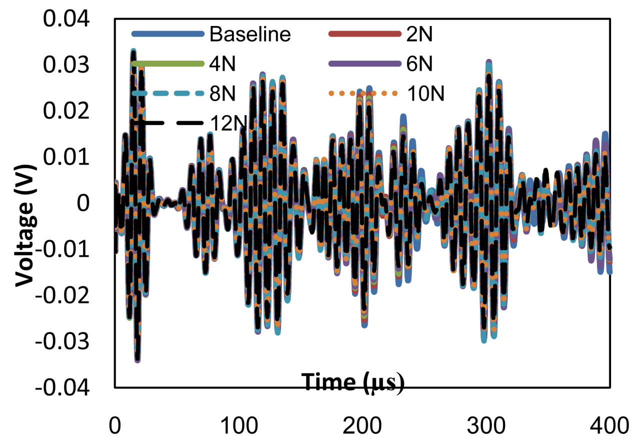

Figure 5: Compilation of sensor signatures for first experiment (simply supported condition).

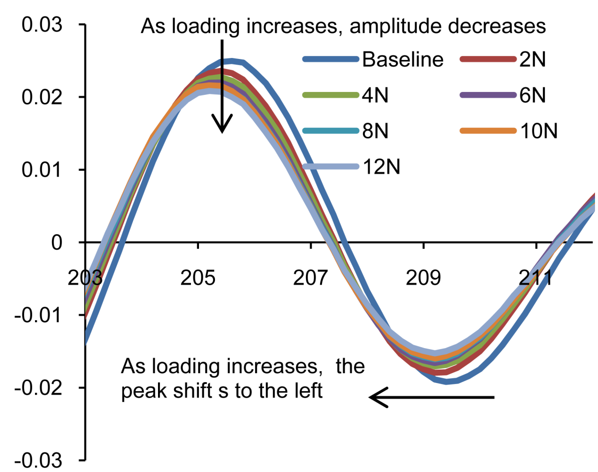

Figure 6: A close up time window analysis from 203-212μs.

3.2 Influence of Applied Load on a Beam under Fixed Boundary Conditions

Figure 2(b) shows the experimental speicmen used for the transverse load monitoring of a beam with fixed supports. This specimen was subjected to loading at the centre from 0N to 14N with a step of 2N. Input signal as similar to the simply supported beam was provided by function generator. Ouput signal was recorded by osciloscope at each load step. The resultant signal is as shown in Figure 8. Here again figure does not provide any trend during continuous load increment. However, a close-up view of time domain between 70-80µs as show in Figure 9, displays a proper trend with respect to increasing load. As load increases the peak continously shifts towards right with continues reduction in amplitude. Figure 10 shows the plot of peak to peak voltage vs applied load. A polynomial equation of 5th degree represents the output signal. Table 3 shows the absolute peak to peak voltage difference for this boundary condition. It can be observed that there is continues decrement in values as load increases.

Applied Load (N)	Peak-Peak (Pk-Pk) 203-212µs [Simply support]	Pk-Pk 70-80µs [Fixed ends]	Pk-Pk 151-166µs [cantilever beam]
0	0.044	0.028	0.0275
2	0.0415	0.0283	0.0160
4	0.0398	0.0245	0.0131
6	0.0386	0.023	0.0117
8	0.0375	0.0221	-
10	0.0375	0.0204	-
12	0.036	0.0157	-
14	-	0.0066	-

Table 3: Absolute peak-peak voltage values at various boundaries.

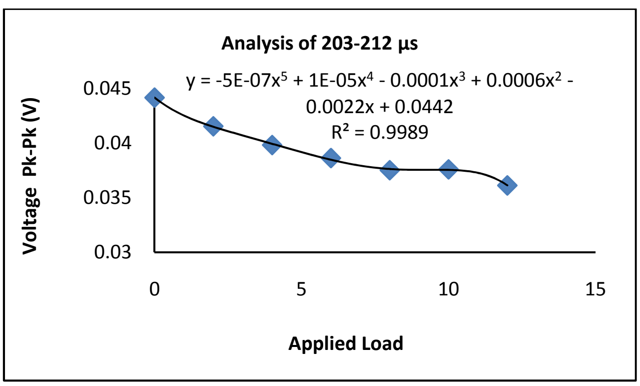

Figure 7: Pk-Pk voltage (V) versus Applied Load (N) for simply support.

Figures 6 and 9 shows that the signals of fixed boundary conditions are opposite to simply supported beam even though time domain is different.

3.3 Influence of Applied Load on Beam under Cantilever Boundary Conditions

Figure 2(c) shows the cantilever specimen subjected to applied loading. Here again the specimen was subjected to incremental loading from 0N to 12N with step of 2N. Figure 11 shows the output signal of the cantilever beam. It does not show any particular trend as load increases. Large deviations were observed in signals for increasing load, and there was large in-consistencies as the physical deflection of the cantiliver beam was much larger and

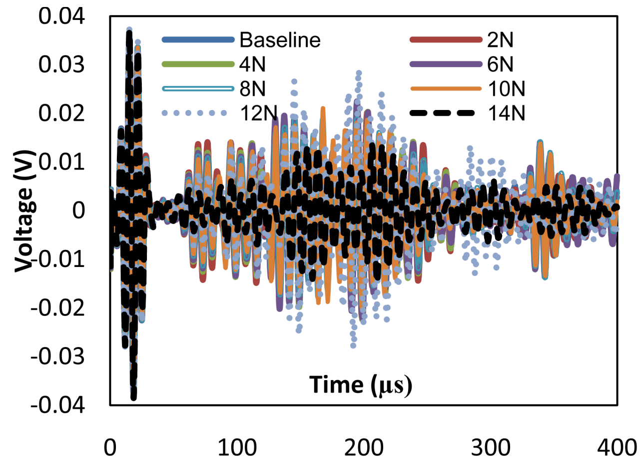

Figure 8: Compilation of sensor signature for second experiment (fixed boundary condition).

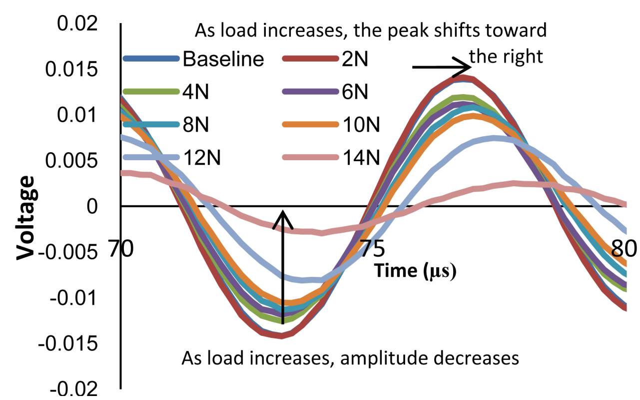

Figure 9: Close-up time window analysis from 70-80µs.

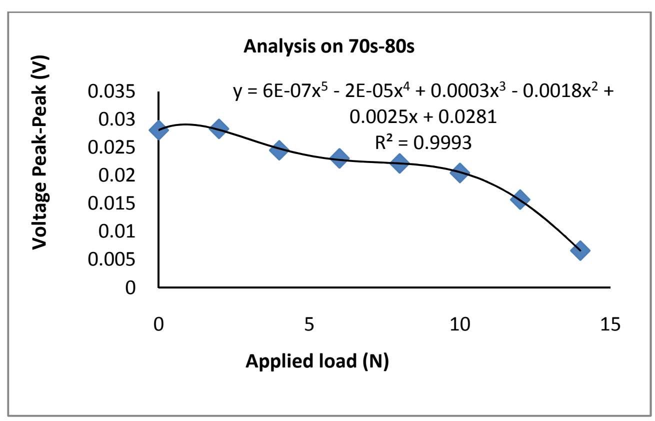

Figure 10: Plotting a graph of Pk-Pk voltage (V) against Applied Load (N) for fixed.

beyond the elastic limit. However, a close-up view of time window 151-166µs (Figure 12) displays a better outlook. Anomalies were observed for applied loads 8N, 10N and 12N due to the large deflections in the specimen i.e physical geometry of the specimen.

Therefore, ignoring the result caused by higher load magnitudes of 8N, 10N and 12N. A polynomial equation of 3rd degree can be plotted with a R^2 value of 1 as shown in Figure 13. Table 3 shows the absolute peak to peak voltage difference for this boundary condition.

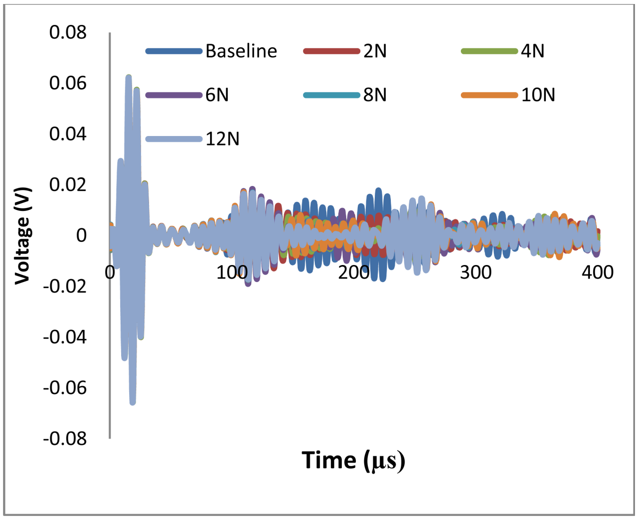

Figure 11: Compilation of sensor signatures for third experiment (cantilever condition).

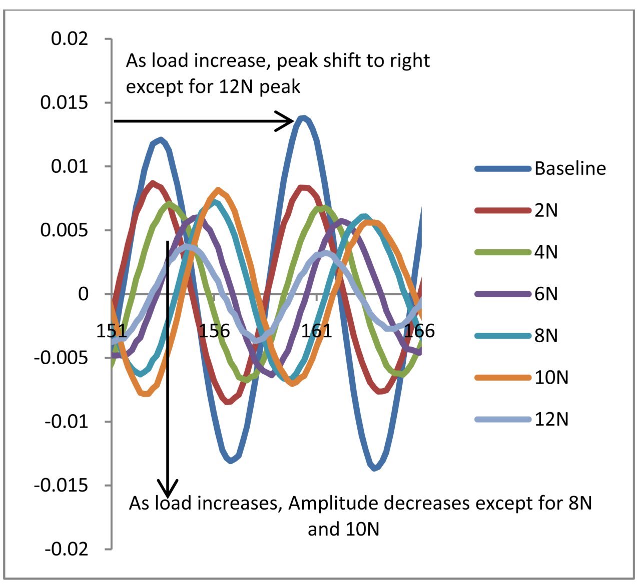

Figure 12: Close-up time window analysis from 151-166µs.

3.4 Comparaison of Boundary Conditions

Figure 14 shows a comparison between various boundary conditions for a baseline (no loading) of three specimens as shown in Figure 2. It was observed that simply supported and fixed end beams were showing some contrasting results, using this it may be possible to indentify the nature of boundary condition (Figures 6 and 9). The amplitudes of the simply supported signal was larger most of the time. The signal in the initial time domain (0-60 µs) was usually ignored as it is due to noise in the specimen. It can be observed that the cantiliver specimen resulted in larger noise level as the amplitude is much larger than the other two loading cases. This figure thus explains the feasibility of applying wave propagation method for transverse load monitoring of laboratory specimens subjected to different boundary locations.

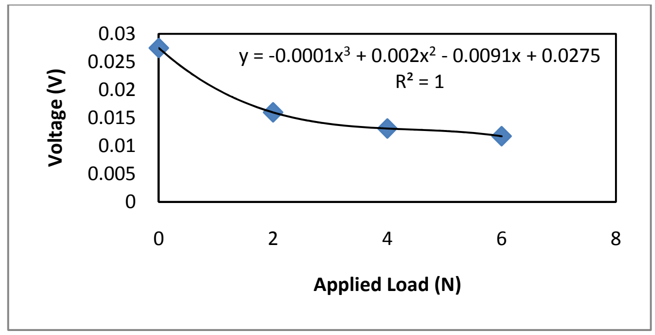

Figure 13: Plotting a graph of Pk-Pk voltage (V) against Applied Load (N) for cantilever.

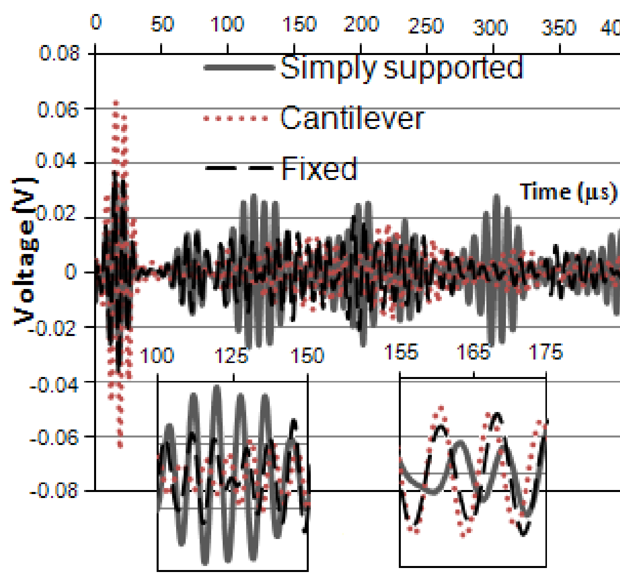

Figure 14: Signal comparisons for various boundary conditions.

4 SUMMARY

This paper investigated load monitoring for three different boundary conditions of a beam using lamb waves. In the past, lamb wave based wave propagation method was not much explored for load monitoring especially for transverse loads. The reusable actuator and sensor used in the present study were fabricated using PZT transducers, silicone gel and aluminium cover. These reusable transducers were tested many times for repeatability of the signals. Even though the load increments on the specimens were minimal, but still the output signal was effective in indicating the variations. Further, the output signals indicated that there exist changes in the amplitudes for various boundary conditions. The simply supported specimen resulted in relatively larger amplitudes compared to the fixed boundary conditions. The noise is more in cantilever beam compared to other two specimens.

5 ACKNOWLEDGMENTS

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6 REFERENCES

[1] Giurgiutiu, V.; Bao, J.; Zhao, W. (2001): Active Sensor Wave Propagation Health Monitoring of Beam and Plate Structures, Proceedings of the SPIE's 8th International Symposium on Smart Structures and Materials, 4-8 March 2001, Newport Beach, CA

[2] Wang, X, Lu, Y, Tang, J. (2008): Damage detection using piezoelectric transducers and the Lamb wave approach: I. System analysis, Smart Material and Structures, Vol.17, 025033 (15pp) doi:10.1088/0964-1726/17/2/025033

[3] Liu, H., Yang, Y., Annamdas. V. G. M. (2010): Parallel Interrogation of Piezoceramic Transducers in Electromechanical Impedance Technique for Quick Damage Detection", Materials and Manufacturing Processes, Vol. 25, No. 4, pp. 249-254.

[4] Das, R; Clearly, P. W. (2006): Uniaxial Compression Test and Stress wave Propagation Modelling using SPH, Fifth International Conference on CFD in the Process Industries CSIRO, Melbourne, Australia, 13-15 December

[5] Lee, S. J; Gandhi, N; Michaels, J. E; Michaels, T. E. (2011): Comparison of the Effects of Applied Loads and Temperature variation on Guided wave Propagation, AIP Conf. Proc. 1335, 175-182.

[6] Michaels, J. E.; Lee, S. J.; Michaels T. E. (2011): Impact of Applied loads on Guided wave Structural Health Monitoring, AIP Conf. Proc. 1335, pp. 1515-1522.

[7] Lim, S. I.; Cui, L.; Liu, Y.; Soh, C. K. (2011): Monitoring fatigue crack growth in narrow structural components using Lamb wave technique. Proc. SPIE, Vol. 7981, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2011, 798143 (April 15, 2011); doi:10.1117/12.880327.

[8] Mall, S. (2002): Integrity of graphite/epoxy laminate embedded with piezoelectric sensor/ actuator under monotonic and fatigue loads, Smart Materials and Structures, Vol. 11, No. 4, pp 527-533.

[9] Annamdas, V. G. M., Soh, C. K. (2010): Application of Electromechanical impedance technique for Engineering Structures: Review and Future Issues, Journal of intelligent material systems and structures, Vol. 21, No. 1, pp. 41-59.

[10] Annamdas, V. G. M., Yang, Y., Soh, C. K. (2007): Influence of loading on the electromechanical admittance of piezoceramic transducers, Smart Materials and Structures, Vol. 16, No. 5, pp.1888-1897.

Analysis of Time-to-Failure Data with Weibull Model in Product Life Cycle Management

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Abstract

In remanufacturing practices, understanding and communicating the failure risk and reliability of a critical part, component or subsystem plays a crucial role as it has a significant impact on the lifecycle management of the product and thus determines the success of the remanufacturing process. In this respect, statistical time-to-failure analysis provides a very powerful and versatile analytical tool for reliability analysis and risk assessment. Among various statistical tools available, Weibull model which uses time series data on records of failure incidents of a product for the fitting of a parametric distribution, is a powerful approach to characterizing the time-to-failure probability function of the product. It is able to provide valuable information for optimized lifecycle management and remanufacturing process. This paper demonstrates successful applications of Weibull model for time-to-failure analysis using case studies in remanufacturing practices and proposes a statistical approach to assess the reliability of critical parts and components for remanufacturing in the product's lifecycle management. It is envisaged that the research results are able to benefit remanufacturing practices in many ways such as reducing warranty loss by minimizing probability of failure of remanufactured critical parts and components.

Keywords:

Weibull Distribution; Life Cycle Engineering; Remanufacturing; Time-to-Failure Analysis

1 INTRODUCTION

Management of products and materials at the End of Life (EOL) is being recognized as an integral part of the product life cycle engineering. Among various EOL management strategies, remanufacturing as a sustainable manufacturing process has received more attention in recent years. In remanufacturing practices, understanding and communicating the failure risk and reliability of a critical part, component or subsystem plays a crucial role as it has a significant impact on the lifecycle management of the product and also determines the success of the remanufacturing process. In such a context, it is envisaged that many of the life cycle engineering techniques will have a significant impact on remanufacturing practices such as reliability and remanufacturability analysis of valuable parts and components, remaining useful life prediction and warranty cost of remanufactured products etc.

In life cycle engineering as well as in remanufacturing industry, estimation of product mean life is an important task as it provides valuable information for effective life cycle management, in particular, the core management and inventories in remanufacturing. Usually a product's mean life is determined by analyzing its time-to-failure data from a wide range of the same category of products operated under the same conditions of use [1]. Another important issue in life cycle engineering and remanufacturing is the quantitative analysis of product or component reliabilities, based on which the product or the component's expected useful life can be estimated. Understanding the probability of product or component failures at different stages of its life can be very useful to make optimized decisions in life cycle management and remanufacturing practices.

Among various techniques developed for life cycle engineering, a very useful general method for analyzing product life data is the Weibull distribution named after the Swedish professor Waloddi Weibull (1887-1979), who demonstrated the appropriateness of this distribution for modeling a wide variety of different data sets [2]. Weibull analysis can make predictions about a product's life, analyze the reliability of the product, statistically establish warranty policies or proactively manage inventories, and many other common industrial applications in remanufacturing practices. Weibull analysis has been also extensively utilized in maintenance procedures because it provides a powerful tool for reliability assessment that can be used to classify failures and to model failure behavior [1, 3]. Weibull analysis can be used to determine the optimum replacement/repair interval for components, subject to wear-out failure.

This paper attempts to use Weibull analysis to facilitate decision-making process in remanufacturing practices particularly in reliability analysis and remaining useful life estimation etc. [4, 5]. The rest of the paper is organized as follows: Section 2 presents the fundamentals of Weibull analysis as well as its advantages in life data analysis. Section 3 presents a case study with complete life data and results are discussed. Finally, discussion and conclusion are summarized in Section 4.

2 RELIABILITY ANALYSIS AND WEIBULL DISTRIBUTION

2.1 Weibull Model for Reliability Analysis

In life cycle management, one of the simplest approaches to predicting failure is based on statistical reliability models of past failures [6]. Reliability is defined as the probability that a product will continue to perform its intended function without failure for a specified period of time under stated conditions [7, 8]. Usually, reliability predictions are used to estimate future failure based on past failure records by applying a probability distribution such as the exponential distribution. However, one of the principal shortcomings of using the exponential distribution is that it imposes a “Markov” assumption, meaning that the future prediction of a failure is independent of the history of the unit given the current measurement [9]. In this respect, Weibull distribution for prediction provides an alternative reliability method as it relaxes the assumption of constant failure rates as well as the Markov assumption [10]. In fact, the most common distribution function in EOL management is Weibull distribution due to its ability to fit a greater variety of data and life characteristics by changing its shape parameter [11]. Today, Weibull analysis is the leading method in the world for fitting and analyzing life data. In most cases of application, Weibull distribution is able to provide the best fit of life data. This is due in part to the broad range of distribution shapes that are included in the Weibull family. Many other distributions are included in the Weibull family either exactly or approximately, including the normal, the exponential, the Rayleigh, and sometimes the Poisson and the Binomial [3].

Compared with classic statistical methods, Weibull analysis uses failure reference and mean-time-to-failure (MTTF) to forecast failures whereas statistical pattern analysis uses test data to identify a statistical pattern such as trend lines [12]. Another most salient feature to be noted for Weibull analysis is its ability to provide reasonably accurate failure analysis and failure forecasts with extremely small samples of life data, where most of other distributions fail to give meaningful result (usually when the sample size is smaller than 20) [3]. This feature of Weibull analysis makes it very valuable in remanufacturing decision-making practices because it is a common case that the life data of very big and especially very expensive parts/components collected in remanufacturing process are either incomplete or small in size.

2.2 Basics of Weibull Distribution

In general, a typical Weibull probability distribution function (PDF) is defined by:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{1}$$

where $t \geq 0$ represents time, $\beta > 0$ is the shape or slope parameter and $\eta > 0$ is the scale parameter of the distribution. Equation (1) is usually referred to as the 2-parameter Weibull distribution. Among the two parameters, the slope of the Weibull distribution, β, is very important as it determines which member of the family of Weibull failure distributions best fits or describes the data. It also indicates the class of failures in the “bathtub curve” failure modes as shown in Figure 1. The Weibull shape parameter β indicates whether the failure rate is increasing, constant or decreasing. If β<1 it indicates that the product has a decreasing failure rate. This scenario is typical of "infant mortality" and indicates that the product is failing during its "burn-in" period. If β=1 it indicates a constant failure rate. Frequently, components that have survived burn-in will subsequently exhibit a constant failure rate. If β>1 it indicates an increasing failure rate. This is typical for products that are wearing out. To summarize:

- β < 1 indicates infant mortality;
- β = 1 means random failures (i.e. independent of time);
- β > 1 indicates wear-out failures.

The information about the β value is extremely useful for reliability centred maintenance planning and product life cycle management. This is because it can provide a clue to the physics of the failures and tell the analyst whether or not scheduled inspections and overhauls are needed. For instance, if β is less than or equal to one, overhauls are not cost effective. With β greater than one, the overhaul period or scheduled inspection interval can be read directly from the plot at an acceptable or allowable probability of failures. For wear-out failure modes, if the cost of an unplanned failure is much greater than the cost of a planned replacement, there will be an optimum replacement interval for minimum cost.

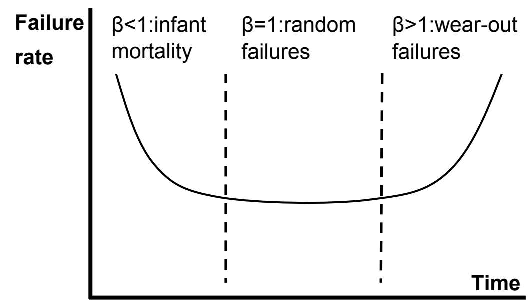

Figure 1: The “bathtub curve” failure modes.

On the other hand, the scale parameter, or spread, η, sometimes also called the characteristic life, represents the typical time-to-failure in Weibull analysis. It is related to the Mean-Time-to-Failure (MTTF). In Weibull analysis, η is defined as the time at which 63.2% of the products will have failed [13].

There are basically two fitting methods for parameter estimation in widespread use in reliability analysis, namely the Maximum Likelihood Estimation (MLE) and regression methods. MLE involves developing a likelihood function based on the available data and finding the values of the parameter estimates that maximize the likelihood function. Regression method generally works best with data sets with smaller sample sizes that contain only complete data (i.e., data in which all of the units under consideration have been run or tested to failure). This failure-only data is best analyzed with rank regression on time, as it is preferable to regress in the direction of uncertainty. In Weibull analysis, Median Rank Regression (MRR) method which uses median ranking for regression fitting is often deployed to find out the shape and scale parameters for complete life data [3].

The probability of failure at time *t*, also referred to as the Weibull distribution or the Cumulative Distribution Function (CDF), can be derived from Equation (1) and expressed as:

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{2}$$

Thus, the Weibull reliability at time *t*, which is 1 - *F*(*t*) = *R*(*t*), is defined as:

$$R(t) = 1 - F(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{3}$$

This can be written as:

$$\frac{1}{1-F(t)} = e^{\left(\frac{t}{\eta}\right)^{\beta}} \quad (4)$$

Taking two times the natural logarithms of both sides gives an equation of a straight line:

$$\ln\ln\left(\frac{1}{1-F(t)}\right) = \beta \ln t - \beta \ln \eta \quad (5)$$

Equation (5) represents a straight line in the form of “y = ax + b” on log/log(Y) versus log(X), where the slope of the straight line in the plot is β, namely the shape parameter of Weibull distribution. Through the above transformation, the life data samples can be fitted in the Weibull model and the two Weibull parameters can be estimated.

The mean of the Weibull PDF, $\overline{T}$, which is the MTTF in Weibull analysis, is given by:

$$\overline{T} = \eta \cdot \Gamma\left(\frac{1}{\beta}+1\right) \quad (6)$$

where Γ is the gamma function.

It is noted that when β=1, MTTF is equal to η. In fact, as a rough approximation, in practices of Weibull analysis where β is equal to or slightly larger than 1, the characteristic life can be approximated as MTTF. However, for β that is much larger than 1, MTTF should be calculated using Equation (6). This will be further discussed in the example elaborated in the next section.

3 WEIBULL ANALYSIS OF LIFE DATA: AN EXAMPLE

3.1 Background

In the life cycle management of a certain type of heavy-duty diesel engine, it is required to quantify the life characteristics of a critical component in order to understand its reliability and remanufacturability. The engine manufacturer has provided a past record of 10 failure cases of the said component under normal use conditions. The complete life data, i.e. the failure time of each sample is shown in Table 1.

No.	Failure time (hours)
1	38456
2	48334
3	50806
4	51521
5	61544
6	66667
7	72605
8	75521
9	80785
10	84894

Table 1: Life data of a critical component in a diesel engine.

Assume that our objectives in this case study include:

1) Determine the Weibull parameters and derive the Weibull distribution model for the data given;
2) Estimate the average life of the component (i.e. the MTTF or mean life);
3) Estimate the time by which 5% of the components will fail, or the time by which there is a 5% probability that the component will fail;
4) Estimate the reliability of the components after a given number of hours of operation;
5) Estimate the warranty time for the component if the manufacturer does not want failures during the warranty period to exceed 5%.

In the following sections, Weibull analysis will be conducted to address the above objectives.

3.2 Determination of Weibull Parameters and Distribution Model

In this case study, the 2-parameter Weibull analysis is deployed to analyze the life data characteristics of the diesel engine component. First of all, the parameters are estimated based on the 2-parameter Weibull analysis, in which the standard ranking method and median rank regression are used to fit the given data in Table 1. As discussed earlier in Section 2.2, regression method should be selected to fit the data when the data sample is small and contains complete life data. The fitting plot is shown in Figure 2 and the two Weibull distribution parameters are calculated as follows: β = 4.40 and η = 69079.89 (hours).

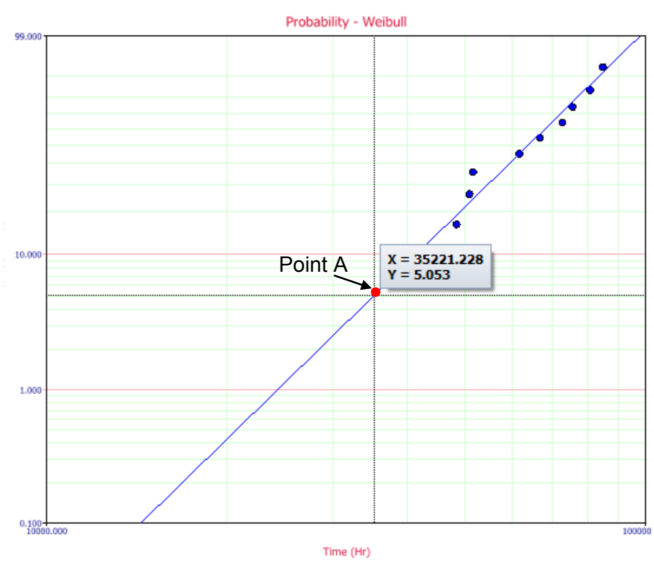

Figure 2: Weibull probability plot.

After the two parameters of β and η are determined, the Weibull PDF expressed by Equation (1) can be obtained as shown below:

$$f(t) = \frac{4.4}{69079.89}\left(\frac{t}{69079.89}\right)^{3.4} e^{-\left(\frac{t}{69079.89}\right)^{4.4}}$$

After simplification the Weibull PDF is plotted as shown in Figure 3.

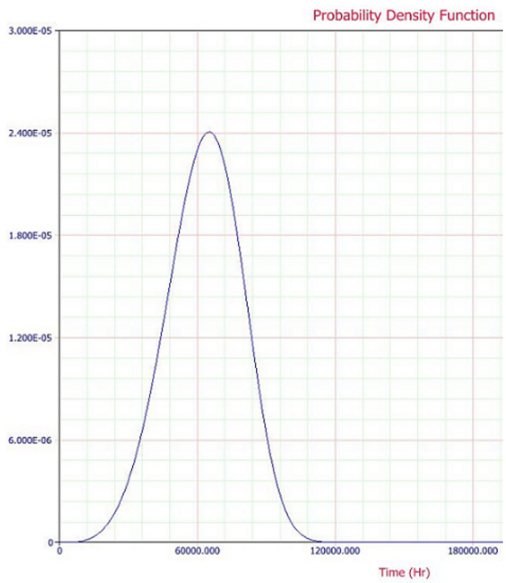

Figure 3: Weibull probability density function.

3.3 Estimation of Average Life or MTTF

As discussed earlier, the MTTF or mean life is a very important indicator of the life data characteristics in life cycle engineering. MTTF can be either approximated by the value of η in cases where β is slightly larger but close to 1, or calculated using the Equation (6) if β is much larger than 1 or a more accurate value is required. In this case study, β = 4.40 and therefore Equation (6) is used to calculate the exact MTTF instead. The MTTF calculated is 62952.73 hours and it is much smaller than the value of characteristic life η, which is 69079.89 hours.

3.4 Estimation of Time for Any Failure Probability

As shown in Figure 2, in the Weibull probability fitting plot of the case study, the x-axis represents time using a logarithm scale and the probability of failure is displayed on the y-axis using a double log reciprocal scale. Such a Weibull probability plot is able to tell very important information about the characteristics of the failures. From the plot, we can obtain the probability of failure at a given time or vice versa. For example, it may be of interest to determine the time at which 1% of the population will have failed. For more serious or catastrophic failures, a lower risk may be required, for instance, Six-sigma quality program goals often equate to 3.4 parts per million (PPM) allowable failure proportion. Such important information can be easily obtained from the Weibull probability plot. In this case study, for the red dot (Point A) shown on the plot in Figure 2, the x and y coordinates are x = 35221.228 hours and y = 5.053 respectively, which can be interpreted in the following way: the failure probability of the component at the time of 35221.228 hours is 5.053%, or the average time by which 5.053% of the components will fail is 35221.228 hours.

3.5 Estimation of Reliability

It is known that reliability analysis is a very important issue in life cycle engineering. In this case study, the Weibull reliability function can be calculated based on Equation (3) and its plot is shown in Figure 4. Figure 4 can be easily used to answer the estimate of reliability of the component after a certain number of hours of operation. For example, for Point B shown on the plot in Figure 4, the x and y coordinates are x = 32090.306 hours and y = 0.966 respectively, which can be interpreted in the following way: the reliability of the component after 32090.306 hours of operation is 96.6%.

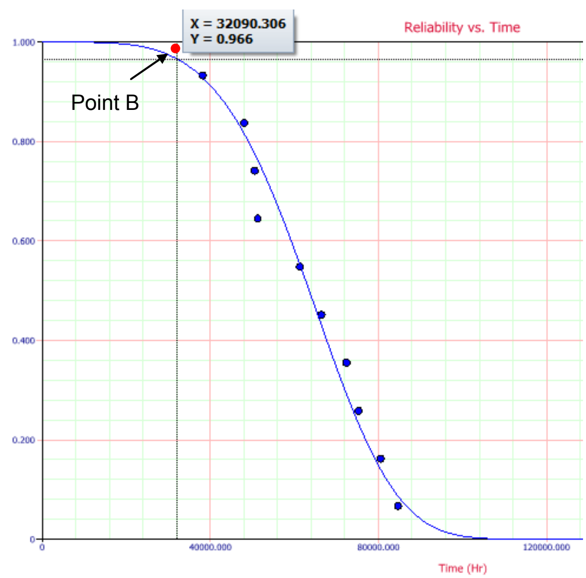

Figure 4: Weibull reliability plot.

3.6 Estimation of Warranty Time for Allowable Failure Probability

This is in fact the reverse interpretation of the coordinates of x and y in Figure 4. For example, if the manufacturer does not want failures during the warranty period to exceed 3.4% (i.e., the required reliability is 96.6%), then the maximum warranty time promised to customers should not exceed 32090.306 hours, as shown by Point B in Figure 4.

In life cycle engineering, failure rate is another important indicator of life data characteristics. Failure rate is usually defined as the frequency with which a product or component fails and it is often expressed in failures per unit of time (e.g., per hour in this case study). The failure rate of a product usually depends on time, with the rate varying over the life cycle of the product, as shown in the “bathtub curve” failure modes in Figure 1. The failure rate of the case study is calculated and shown in Figure 5. The increasing failure rate shown in the figure confirms that the life data in Table 1 follow a wear-out failure mode.

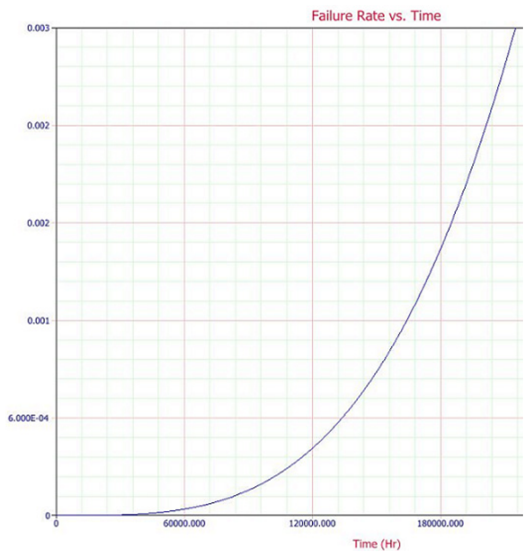

Figure 5: Failure rate versus time

4 SUMMARY

Weibull distribution is among the most popular in the field of life cycle engineering and reliability analysis because it is able to accommodate various types of failure data by manipulation of its parameters. The case study presented in this paper has successfully shown that Weibull analysis can provide a simple and informative graphical representation of characteristics of life data, especially when the life data sample is small and other statistical tools fail to given useful information. Weibull analysis is able to answer many life cycle engineering problems such as mean life estimation, reliability of products at any operational time and warranty cost estimation etc. The advantages of Weibull model in life data analysis can be extended to facilitate decision-making processes in many remanufacturing practices such as prediction of the number of cores returned for remanufacturing, estimation of spare parts or remedy resources needed for each failure mode, and so on. Future work of this study will include: 1) the analysis of incomplete life data for the support of decision-making in product EOL management and remanufacturing processes; and 2) comparison and optimization of parameter estimation methods in Weibull model. It is envisaged that the extension of this research will see more robust capabilities of Weibull analysis in life cycle engineering applications.

5 ACKNOWLEDGMENTS

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6 REFERENCES

[1] Li, W. (2004): Evaluating Mean Life of Power System Equipment with Limited End-of-life Failure Data, IEEE Trans. Power Sys., Vol. 19, No. 1, pp. 236 – 242.

[2] Weibull, W. (1951): A Statistical Distribution Function of Wide Applicability, J. Appl. Mech.-Trans. ASME, Vol. 18, No. 3, pp. 293–297.

[3] Abernethy, R. B. (2006): The New Weibull Handbook, 5th edition.

[4] Mazhar, M. I.; S. Kara; H. Kaebernick (2007): Remaining Life Estimation of Used Components in Consumer Products: Life Cycle Data Analysis by Weibull and Artificial Neural Networks, Journal of Operations Management, Vol. 25, No. 6, pp. 1184-1193.

[5] Mazhar, M.I.; M. Salman; Ian H. (2010): Assessing the Reliability of System Modules Used in Multiple Life Cycles, Engineering Asset Lifecycle Management, pp. 567-573.

[6] Gu, Y.; Li, J. (2012): Engine Failure Data Analysis Method Based on Weibull Distribution Model, Applied Mechanics and Materials, Vol. 128-129, pp. 850-854.

[7] Pham, H. (2006): Springer Handbook of Engineering Statistics, 1st edition.

[8] Calixto E. (2013): Gas and Oil Reliability Engineering, Elsevier Inc.

[9] Lourenco, R.B.R.; Mello, D.A.A. (2012): On the Exponential Assumption for the Time-to-repair in Optical Network Availability Analysis, in: proceedings of 14th International Conference on Transparent Optical Networks (ICTON), 2-5 July 2012, pp.1 – 4.

[10] Groer, P. G. (2000): Analysis of Time-to-Failure with a Weibull Model, in: Proceedings of the Maintenance and Reliability Conference, MARCON 2000, Knoxville, TN.

[11] Artana, K. B.; Ishida, K. (2002): Spreadsheet Modeling of Optimal Maintenance Schedule for Components in Wear-out Phase, Reliability Engineering and System Safety, Vol. 77, No. 1, pp. 81-91.

[12] Fitzgibbon, K.; R. Barker; T. Clayton; N. Wilson (2002): A Failure-Forecast Method Based on Weibull and Statistical-Pattern Analysis, Reliability and Maintainability Symposium (IEEE), pp. 516 - 521.

[13] Pasha, G.R.; M. Shuaib Khan; Ahmed Hesham Pasha (2006): Empirical Analysis of The Weibull Distribution for Failure Data, Journal of Statistics, Vol. 13, No.1, pp.33-45.

The Study of Measurement Procedures for Remanufacture Based on MMMT and XRD

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Abstract

Remanufacturing engineering is one of the important ways to develop recycle economy and energy saving. It can make the most of the potential value of waste resource. This paper puts forward that the prediction of fatigue life is the important basis for the operation time of active remanufacturing. The product information of magnetic memory and residual stress are used for analyzing the fatigue life. Come up with the combination of metal magnetic memory testing and X way diffraction to establish the evaluation and prediction model for fatigue life. The different measurement procedures are established on the basis of different products.

Keywords:

Active Remanufacturing Engineering; MMMT; Testing Residual Stress Technology; Fatigue Life; Measurement Procedure

1 INTRODUCTION

With the development of remanufacture theory, scholars at home presented a concept of active remanufacture. Selecting the active remanufacture time area is the vital task of remanufacture. In order to avoid the condition of "overusing" or "premature remanufacture", we should select the active remanufacture time area reasonably. It can also help us to reduce the consumption of natural resources and energy, relieve environmental load [1-3].

Non destructive testing can test the defect and discontinuity of materials, without damaging or affecting the object usability, provide the relevant information, such as the dimension, location, properties and quantity. With that information, the condition (such as qualified or not, residual life and so on) of detected object can be confirmed. As two kind of important nondestructive detection means, MMMT and XRD are widely used in the industry of metallurgy, electricity, petrochemical engineering, ship, space navigation, nuclear energy. Compared with the traditional detection means, the macroscopical flaws and the region of stress concentration can be discovered by MMMT; residual stress value and full width at half maximum can be tested accurately by XRD. By the combination of MMMT and XRD, the superiority of MMMT and XRD can be brought into full play, macroscopical flaws and the region of stress concentration can be detected quickly and residual stress value can be tested accurately in the stress concentration region [4-5].

This paper put forward that the fatigue life of mechanical component can be tracked by the combination of MMMT and XRD. The measurement procedures of building fatigue life evaluation criteria and fatigue life prediction model are established. It can provide a basis for confirming active remanufacture time area. It also has important practical significance for the study of decision method of remanufacturing time.

2 ANALYSIS OF INFLUENCE FACTORS FOR FATIGUE LIFE

Fatigue was defined that "the property of metal material is changed by the repeated action of stress or strain". The concept was come up with by international standardization organization (ISO) in the report of "the general principle of metal fatigue test" in 1964. Many experts and scholars have made relevant research on the influence factors on fatigue life, and achievements were made in this field. As we all know, there are many influence factors on fatigue life. A consistent view is that fatigue life is seriously affected by material essence(such as chemical composition, metallographic structure, fiber direction and internal defect distribution), working conditions(such as load characteristics, loading frequency and temperature range), parts state(such as stress concentration, size effect and surface working)[6-10].

The quality performance of mechanical component is determined by the chemical composition, metallographic structure, fiber direction and internal defect distribution. They are basic elements for metal components resisting fatigue failure. Fatigue failure forms are influenced by the external key factors, such as load characteristics, loading frequency and temperature range. Parts size, shape and surface processing roughness are the important factors for fatigue life of mechanical component.

The above factors are the comprehensive consideration of affecting fatigue life. To determine the main influence factors, the specific material property, working condition and parts state should be deliberated, when we establish the prediction model for fatigue life. This paper suggest that the mechanical component fatigue state can be comprehensively reflected by material's stress concentration, residual stress, FWHM which can reflect material's elastic-plastic deformation information. The process of combining MMMT and XRD is come up with for the testing of ferromagnetic material.

3 THE FEASIBILITY OF MMMT AND XRD USED FOR ANALYZING THE FATIGUE LIFE

The feasibility of MMMT and XRD used for analyzing the fatigue life will be analyzed from the perspective of detection principle and applications.

3.1 Principle of MMMT

The magnetic memory testing principle can be expressed as follows. The internal magnetic domain organization of ferromagnetic components will be oriented or irreversibly oriented anew, when they are loaded in the magnetic field environment. The other results are that the leakage magnetic field is changed, and the specific phenomenon is zero-crossing of the normal component Hp(y) and peak value of the tangential component Hp(x).

The irreversible change of magnetic state will be reserved in the ferromagnetic component when the load is removed. Stress concentration and preliminary damage area can be inferred from the phenomenon of zero-crossing or the Hp(y) gradient which can be tested by measuring magnetic instrument.

3.2 Application of Metal Magnetic Memory

The concept of metal magnetic memory was first put forward by Russian professor Douboy in his paper of “Metal magnetic memory” in 1994. Since then, many research results have been made in basic theory research, the development of instrument and equipment, basic test research, signal processing research, quantitative and damage assessment research and engineering detection application, etc.

At present, metal magnetic memory testing technology is mainly used in several aspects as follows.

(1) Determine the strain state of nonuniformity and the area of stress concentration in the equipment and component.

(2) Determine the metal sampling position and the metal structure state evaluation in the area of stress concentration.

(3) Make early diagnosis of the fatigue damage and the life evaluation of equipment or component.

(4) Reduce testing and materials costs through the combination of MMMT and other nondestructive detection methods.

(5) Control the quality of various types of welding.

(6) Make quick sort for the machinery products through the nonuniformity of materials.

A large number of fatigue failure accidents and the experimental results show that, fatigue source always appear in the stress concentration area, and the stress concentration lowers structure fatigue strength [11-15]. Many scholars have carried on the thorough research on the practical application of MMMT. The quantitative relation between magnetic memory signal, welding crack length and the depth of welding crack has been established by some scholars. The research results provide a basis for the detection and prediction of the metal fatigue crack [16]. Some scholars came up with a new fatigue damage model through the fatigue test and the detection of magnetic memory signal for the notch specimen of ferromagnetic material. They studied the feasibility of the quantitative evaluation for specimen fatigue damage by the method of computing the mean of K (intensity of magnetic field gradient) [17-18]. The application prospect that MMMT can be used in the early diagnosis and life anticipation for the ferromagnetic component has been widely accepted by academics and industry experts

3.3 Principle of XRD

The fundamental of XRD was raised by Russian scholar Akcehob in 1929. The basic idea is that the material lattice strain which is caused by stress is consistent with the macro-strain. Lattice strain can be measured by X-way diffraction technology; macro strain can be obtained by the elastic mechanics; therefore, the lattice stress can be inferred from the lattice strain.

3.4 Application of XRD

The residual stress is the result of inhomogeneous elastic deformation or uneven elastic-plastic deformation. In the condition of low stress and high cycle fatigue, the elastic deformation is mainly occurs in the materials; as for the low cycle fatigue, the stress amplitude is usually quite large [20]. Therefore, residual stress and FWHM which can reflect the elastic-plastic deformation can be used for evaluating and predicting the fatigue life of materials.

At present, many scholars track, evaluate, predict the fatigue life of materials by the use of XRD, and many great progress have been made. The damage of low cycle fatigue had been studied by SanjayRai, etc. They assessed the fatigue damage using FWHM. The result shows that FWHM reduce rapidly with the initiation and propagation of the surface crack [21]. The quantitative relation between welding residual stress and fatigue life had been studied by BIAN Ru-gang etc. The research shows that the growth trend of crack can not be changed by the residual stress, but accelerates the process of crack propagation and reduces the fatigue life of pressure structure obviously [22]. This technology is applied to the evaluation of fatigue life has great potential.

We can know that MMMT and XRD can reflect the state of metal material from its detection principle. The present research achievements laid the foundation for the evaluation and prediction model for the fatigue life. Therefore, MMMT and XRD are suitable for the prediction of fatigue life.

4 ESTABLISH THE MEASUREMENT PROCEDURES BASED ON THE MMMT AND XRD

The different mechanical structure brings enormous difficulty to the unified inspection standard. For this reason, the detected object is divided into two categories according to the fatigue life standard be established or not. The two categories are the products which are not built the evaluation standard and the products which are built the evaluation. The product information of size, magnetic memory information, residual stress and FWHM are the primary acquisitions in the measurement procedures.

4.1 The Measurement Procedure of the Products Which Are Not Established the Evaluation Standard

As mechanical component fatigue failure often occurs in specific area, the first step is structural analysis for the products to confirm the principal mating dimensions, the key parts of the production, the lower strength area and the probable stress concentration parts. Next, fatigue tests are carried out on to the product. Stop loading at the preset loading frequency nodes; implement size examination for the principal mating dimensions and the key parts of the production; carry out magnetic memory testing for the key parts of the production, the lower strength area and the probable stress concentration parts; implement XRD testing for the stress concentration areas which are informed in the last step. Analyze the relation between fatigue life, size, magnetic memory information, residual stress and FWHM. Establish the corresponding fatigue life evaluation and prediction model. See Figure 1 for measurement procedures of the products which are not established the evaluation standard.

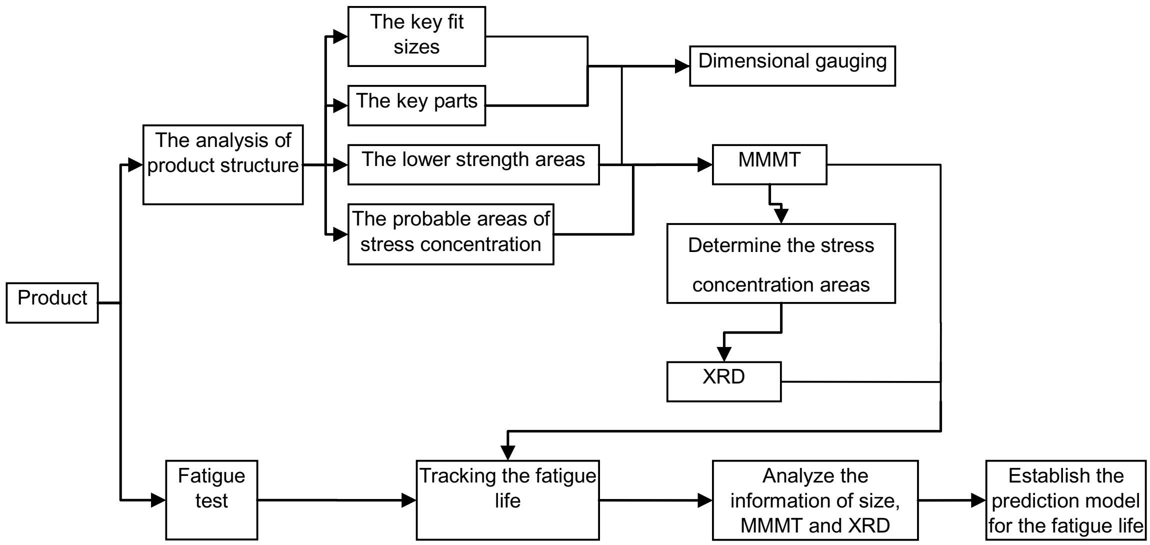

Figure 1: The measurement procedures of the products which are not established the evaluation standard.

4.2 The Measurement Procedure of the Products Which Are Established the Evaluation Standard

For the products which have been established the evaluation standard, the fatigue life evaluation and prediction model have been established, and the purpose of test is different from the former. Therefore, the test process is also different from the former. The detection information is to provide basis for the active remanufacturing of the failure products, we just collect the products' size, magnetic memory information, residual stress and FWHM without fatigue test. The decision that the failure products can enter the active remanufacturing process can be made by comparing the collection information with the established fatigue life standard. In this measurement procedure, whether the product can enter the MMMT and XRD test depends on the product size whether conformed to the established standard. The main reason is that the product size often changes greatly when material occur large plastic deformation, and the product is no longer suitable for remanufacturing. It can avoid unnecessary testing process, and save the testing cost. See Figure 2 for measurement procedures of the products which are established the evaluation standard.

MMMT and XRD are important nondestructive testing technology, which are used in the above two detection process. MMMT can detect the stress concentration area quickly, but the stress can not be quantified. XRD can detect the residual stress value, but the stress concentration can not be detected. Therefore, the combination of MMMT and XRD can make full use of their respective advantages, and avoid the blindness of detection and save the detection time and cost.

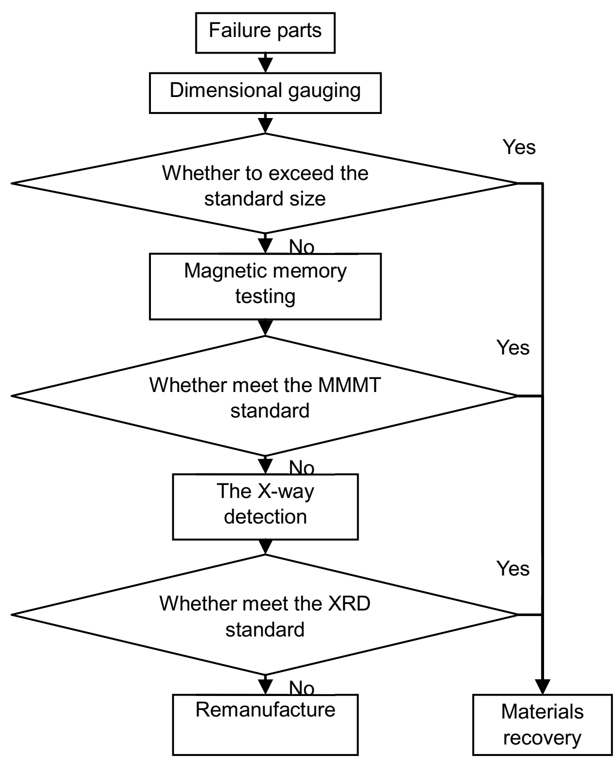

Figure 2: The measurement procedures of the products which are established the evaluation standard.

5 CASE STUDY

Take a domestic production of a series of rear axle, found the specific detection process according to the above process of detection.

5.1 The Analysis for the Structure of Rear Axle

The ontology material of the rear axle is 16Mn, and the axle tube material is 40Mn. See Figure 3 for the 3D model of rear axle.

The project of size detection

Through the analysis of the technical requirements of the rear axle, we can know that the axle has many important key sizes. But, according to the fault statistical analysis of the scrap axle, we found that the largest failure proportion is the fit size of shaft and bearing (see the place of number 5). The failure proportion reaches up to 98.9% in the all key sizes. As for the lower strength of the materials, we can know that the circular weld of the axle and shell joint (see the place of number 4) is the lowest. But, there is no fit size requirement, and the size is also not suitable for detection. For this reason, we can choose the size as the size detection project without considering others.

The area of MMMT and XRD

The phenomenon of stress concentration will exist in the transition arc and the circular weld of the axle and shell joint (see the place of number 1, 2, 3 and 4). Fatigue fracture will occur in the above parts easily. According to the fault statistical analysis of the scrap axle, the proportion of the fatigue fracture reach up to 67.7%. Therefore, the places are chosen for the project of magnetic memory test. The areas will be the surveyed areas for XRD, which are confirmed as the real stress concentration area on the basis of MMMT.

The fatigue test for the rear axle

The testing schedule should be drawn up on the basis of national or industry standards. Based on QC/T533-1999 <the method of bench test for cars drive axle> and QC/T534-1999 <the bench test evaluation index for the cars drive axle>, we drew up the testing schedule.

The median fatigue life no less than 80.0×104 times and the least life less than 50.0×104 times are ruled in the government standard. In order to track the fatigue life of the rear axle preferably, the frequency of fatigue loading is designed as 20, 30, 40, 50, 60, 70, 80 and the times of axle failure (units: ten thousand times). Stop loading and collect the information of size, magnetic memory, residual stress and FWHM at every node of loading frequency.

In order to eliminate the influence of accidental factors damaging the rear axle, five rear axles are used in the fatigue test. Analyze the relation between the loading times and the average of every testing data. Then, establish the evaluation and prediction of the fatigue life.

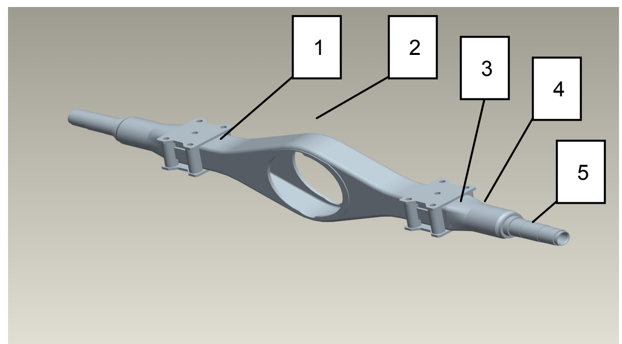

Figure 3: The 3D model of rear axle.

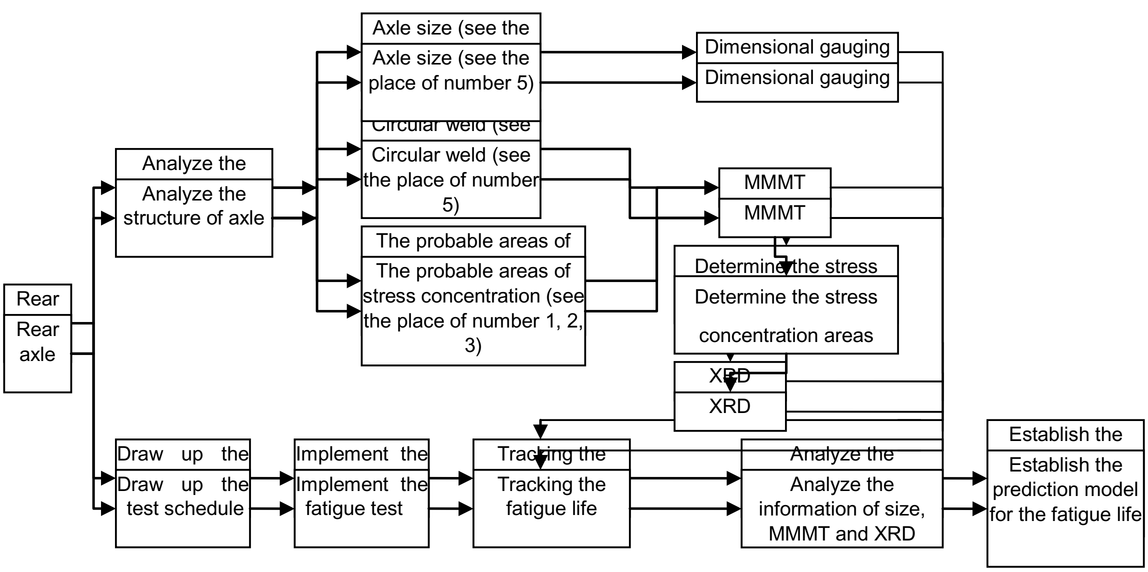

Figure 4: The measurement procedure of the rear axle which is not established the evaluation standard.

5.2 The Measurement Procedure for the Rear Axles Which Are Not Established the Evaluation Standard

Based on the above analysis, the measurement procedure of the rear axle is showed in the figure 4, which is not established the evaluation standard.

The measurement procedure of the rear axle which is established the evaluation standard can refer to the figure 7. The measurement procedure is omitted here.

The measurement procedures laid foundation for the establishment of the fatigue life, and have great significance for the selection of active remanufacturing time. Compared with other detection process, the measurement procedures of the rear axles have both dimensional gauging which can reflect the macroscopic information and stress testing which reflects the microcosmic information; MMMT can guide XRD to detect more effective; improve the detection efficiency, save the test cost and have the practicability for the engineering.

6 SUMMERY

(1) The main influence factors of fatigue life are divided into three categories: the nature of material, working conditions and parts states.

(2) The combination of MMMT and XRD can make full use of their respective advantages, and avoid the blindness of detection and save the detection time and cost.

(3) In order to provide a basis for the judgment of the active remanufacturing feasibility, different measurement procedures should be established in accordance with different products.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] LIU Tao (2012): Research on Time Interval Decision-Making and Control Methods for Active Remanufacturing

[2] Iberahim, F.; Wahab, D.A.; Nopiah, Z.M. . (2011): Establishment of Remanufacturing Index for Locally Manufactured Automotive Components, in: Key Engineering Materials, No. 486, pp. 77-80.

[3] Lund, R.T.; Hauser, W.M. . (2007): Remanufacturing - An American Perspective, in: 5th International Conference on Responsive Manufacturing - Green Manufacturing (ICRM 2010), pp. 1-6, Ningbo, China

[4] Zhang Yuanliang; Zhou Di; Jiang Pengsen. (2011): The State-of-the-art Surveys for Application of Metal Magnetic Memory Testing in Remanufacturing, in: 2nd International Conference on Advanced Measurement and Test (AMT 2011), pp.366-372, Nanchang, China.

[5] Jiancheng Leng; Minqiang Xu; Shuai Zhao, etc. (2009): Fatigue damage evaluation on ferromagnetic materials using magnetic memory method, in: 2009 International Conference on Measuring Technology and Mechatronics Automation (ICMTMA), pp. 784-786,Hunan, China.

[6] Murakami, Yukitak. (2012): Material defects as the basis of fatigue design, in: INTERNATIONAL JOURNAL OF FATIGUE, pp. 2-10.

[7] Li, S. X. (2007): An evaluation model of product upgradeability for remanufacture, in: INTERNATIONAL MATERIALS REVIEWS l, Vol. 57, No. 2, pp. 92-114.

[8] Watanabe, C.; Monzen, R. (2012): Effects of microstructures on fatigue behavior of an Al-Mg-Sc alloy at an elevated temperature, in: Materials Science Forum, pp.426-430.

[9] Dongxing Du; Daoxin Liu; Yufeng Sun. (2012): The effects of machined workpiece surface integrity on the fatigue life of TC21 titanium alloy, in: Advanced Materials Research pp.382-389.

[10] Hao Lu; Yimin Zhang; Xufang Zhang. (2011): Fatigue Reliability Sensitivity Analysis of Complex Mechanical Components under Random Excitation, in: Mathematical Problems in Engineering pp. 17.

[11] Choi, Woosung; Fujiyama, Kazunari; Kim, Bumshin. (2012): Development of thermal stress concentration factors for life assessment of turbine casings, in: INTERNATIONAL JOURNAL OF PRESSURE VESSELS AND PIPING, pp. 1-7.

[12] Masoumi Khalil Abad, Ehsan; Pasini, Damiano; Cecere, Renzo. (2012): Shape optimization of stress concentration-free lattice for self-expandable Nitinol stent-grafts, in: Journal of biomechanics, Vol. 47, No. 6, pp. 1028-1035.

[13] Yu Jianghong. (2012): Magnetic memory testing and intensity failure analysis of fractured bolt of cylinder head on hydrogen gas compressor, in: Advanced Materials Research, pp. 772-775.

[14] Nami, Mohammad Rahim; Eskandari, Hadi. (2012): stress intensity factors in a rotating impeller containing semi-elliptical surface crack, in: MECHANICS BASED DESIGN OF STRUCTURES AND MACHINES, Vol. 40, No. 1, pp. 1-18.

[15] Ahmadi, Hamid; Lotfollahi-Yaghin, Mohammad Ali; Aminfar, Mohammad H. (2011): Effect of stress concentration factors on the structural integrity assessment of multi-planar offshore tubular DKT-joints based on the fracture mechanics fatigue reliability approach , in: OCEAN ENGINEERING, Vol. 38, No. 17-18, pp. 1883-1893.

[16] Di Xinjie, Li Wushen, Bai Shiwu, etc. (2006): Quantitative evaluation study on metal magnetic memory of welding cracks, in: Materials Engineering, pp. 56-60.

[17] Liu Changkui, Tao Chunkui, ChenXing, etc. (2009): Research on quantitative assessment of fatigue damage by metal magnetic memory method, in: Materials Engineering, pp. 33-37.

[18] Li Xinlei, Ren Jilin, Ren Shangkun, etc. (2010): Acta aeronautica ET astronautica sinica, in: Beijing press bureau, aviation journal magazine, Vol. 31, No. 10, pp. 2109-2114.

[19] Wang Renzhi, Zhang Dingshuan, Lv Kema, etc. (2007): Basic knowneledge of stress determination by x-way lecture, in: handan stress technologies institute, Vol. 4-12, pp. 1-53.

[20] S. Suresh, (1998): fatigue of materials, in: National defence industry press.

[21] Rai, S.; Choudhary, B.K.; Jayakumar, T (1999): Characterization of low cycle fatigue damage in 9Cr-1Mo ferritic steel using X-ray diffraction technique, in: International Journal of Pressure Vessels and Piping, Vol. 76, No. 5, pp. 275-8.

[22] Bian Rugang, Cui Cheng, Wan Zhengquan, etc. A quantitative study on the effect of welding residual stresses of fatigue life, in: journal of ship mechanics, Vol. 15, No. 7, pp. 776-783.

Social Impact Assessment of Sugar Production Operations in South Africa: A Social Life Cycle Assessment Perspective

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Abstract

The objectives of the study were guided by the guidelines on social life cycle assessment of products of the South African Sugar Industry developed by the United Nations Environmental Programme and SETAC initiatives. The study's main focus is on health and safety, freedom of association, employee's wages, and Gender equality in the workplace, working conditions, crime and the social wellbeing of the communities that surround the sugar industry's operations. Field research, historic comparative research, interviews and questionnaires were used for the collection of relevant data. Although it is good that the sugar industry decreases the level of employment in some areas, the decrease in sugar production during the season of 2010-2011 could have major financial and social challenges for these areas, and could also impact the rest of South Africa.

Keywords:

Social life cycle impacts; Sugar production social sustainability; social LCA methods development and use

1 INTRODUCTION

The study will focus on the social impact of the sugar industry in South Africa. A social impact assessment is a method that aims to assess social features of the product and their positive and negative aspects in terms of its processing of raw material to the final stages of its disposal Maloa (2001). The South African Sugar Industry employs 77000 people, who work directly for the industry and 350 000 who are employed indirectly employment, this makes the sugar industry in South Africa to be one of the largest contributors to employment in agriculture within the country. There are more than 42 000 registered cane growers, 1660 farmers have large farms, and 40 600 have small plots of sugar cane, Voigt (2009).

1.1 Goal and Scopes

The following were the objectives of the study:

- To identify the social impacts of the sugar growing and milling within the sugar industry
- To determine how employees of the sugar industry relate with the organisation in terms of freedom of association, wages, gender equality, working conditions and health and safety.
- To identify how the local communities are view the operations of the sugar industry in relation to community services, service facilities, environment, crime and health and safety.

The results of this study are meant to be communicated to the external affairs department at the South African Sugar Association (SASA), the other various decision makers within the sugar industry, and to government for better strategic and tactical planning. The functional unit was set at one tonne of sugar produced using the current methods of cane growing and cane milling in South Africa.

1.2 System Boundary

The system considered for this study was one in which sugar is produced from sugar cane stalks. The sugar processes that the study is concerned with are, the sugar growing phase, the harvesting phase and the Milling phase. These are explained as following subsystems for SLCA were taken into account:

- Growing Phase: Sugar cane is grown in various stages. The first stage is land preparation, were the soil is fed with fertilisers and enough moisture to accommodate and grow the cane stalks. The second stage becomes the germinating stage where only about two leaves appear on the stem of the planted cane. The next stages are the Tillering, grand growth and maturation stages. These stages vary from 15- 20 days and 3 months from the cane plantation day, at these stages the cane stalks grow to maturity. The last stage is the cane cutting were the matured cane stalks are prepared for transportation and processing.

The figure 1 illustrates the highlighted areas within the flow chart of sugar production that the researcher focused on.

- Milling Phase: Sugar milling is concerned with the processing of the cane stalks, Cane preparation, Milling, Diffusion, Evaporation, Sugar boiling, Separation of crystals from molasses Sugar drying and Sugar refining. These are illustrated in Figure 2, which a diagrammatic representation of the sugar milling process.

2 INVENTORY ANALYSIS

The inventory analysis is concerned with the process in which the data is collected. Within this chapter, the data is validated and the system boundaries established. This chapter focuses on the assembling of data which is later used in the impact assessment, UNEP (2009).

The data for the study was collected using two sets of questionnaires. One set was used to gather data from the employees of the sugar industry, specifically the sugar millers and the sugar growers. The second set of questionnaires was directed to the local communities, which are directly and indirectly impacted by the operations of both the sugar millers and the sugar growers. Both sets of questionnaires were distributed to the three main sugar growing and milling areas in South Africa, namely Kwa-Zulu Natal, Mpumalanga and the Eastern Cape.

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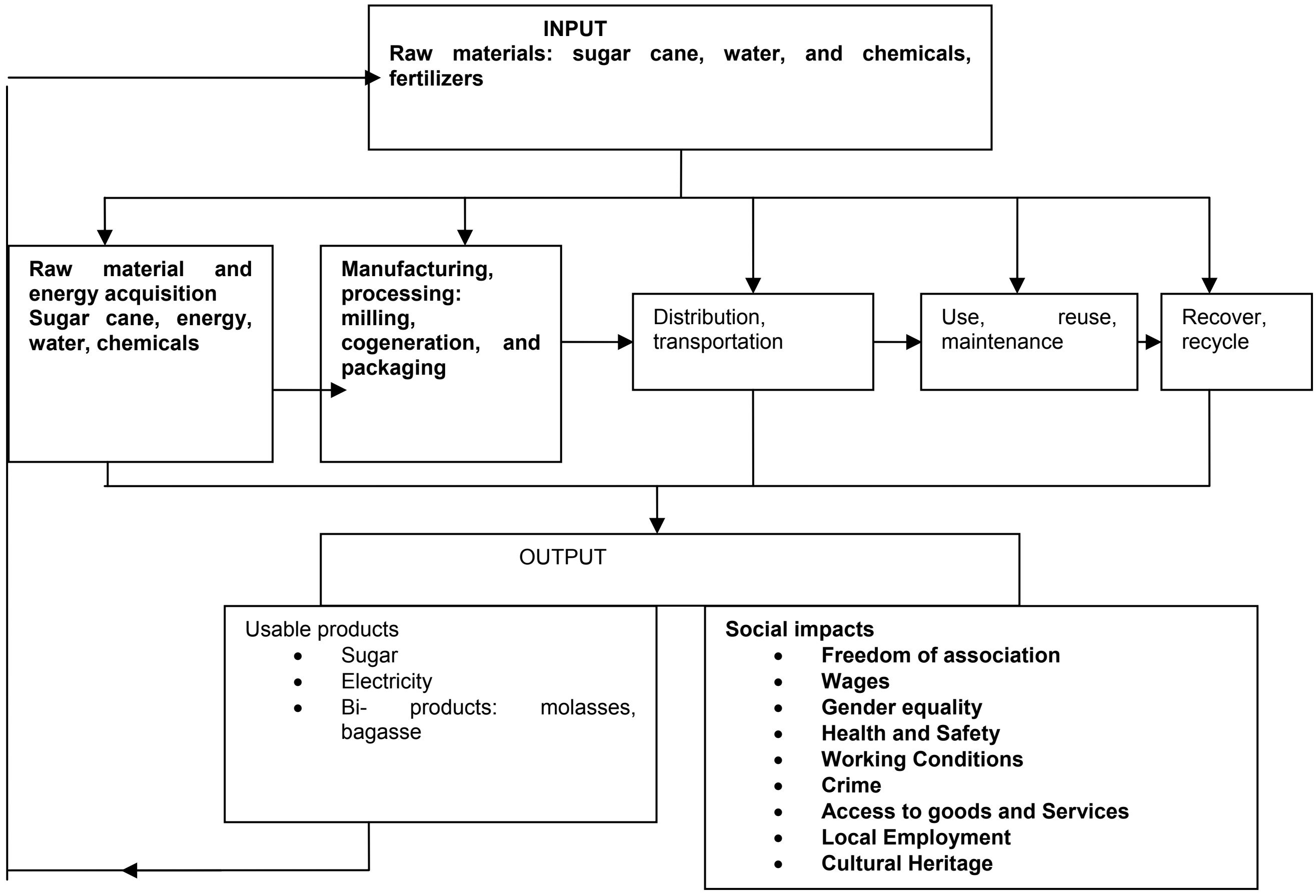

Figure 1: Illustrates the revised Flow Chart for Production of Sugar Cane (Mashoko 2010).

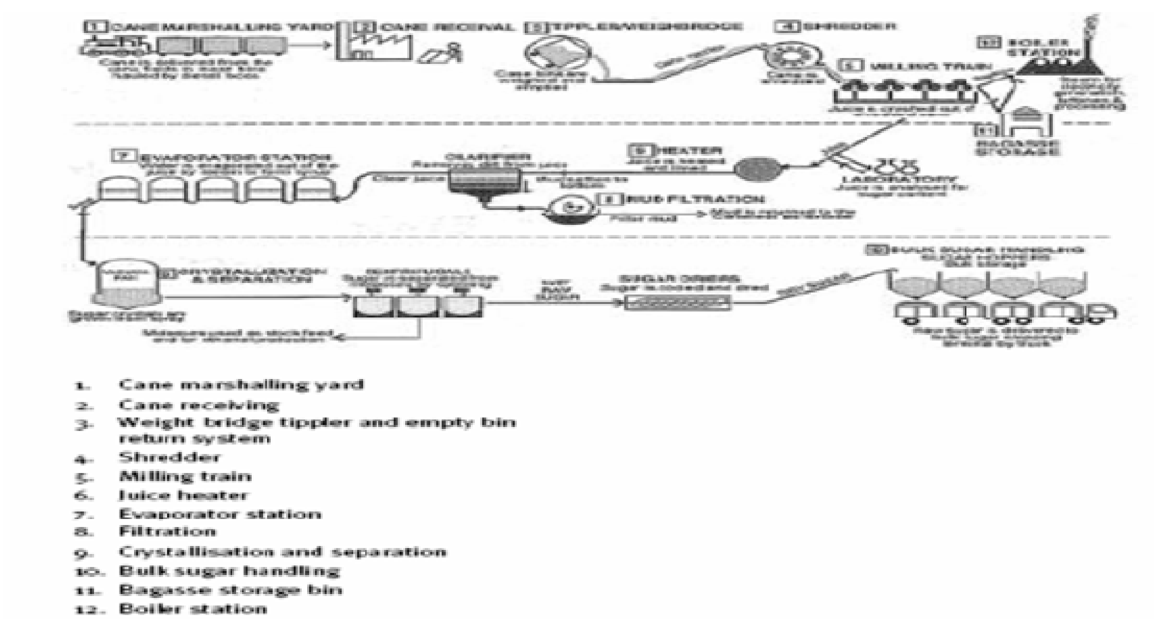

Figure 2: Which a diagrammatic representation of the sugar milling process. (Source: Centre for Disease Control and Prevention 2009).

Province	Frequency	Percent	Valid percent	Cumulative percentage
Kwa-Zulu Natal	50	33.3	33.3	33.3
Mpumalanga	51	34.0	34.0	67.3
Eastern cape	49	32.7	32.7	100
Total	150	100.00	100.00	

Table 1: Community questionnaire distribution across provinces.

The local community's questionnaires were distributed across the three provinces as follows, 50 in Kwa-Zulu Natal, 51 in Mpumalanga and 49 in the Eastern Cape. These values are indicated in table 1.

Province	Frequency	Percent	Valid percent	Cumulative percentage
Kwa-Zulu Natal	50	33.3	33.3	33.3
Mpumalanga	48	32.0	32.0	65.3
Eastern cape	52	34.7	34.7	100
Total	150	100.00	100.00	

Table 2: Worker's questionnaire distribution across provinces.

The table 2 illustrates the distribution of the worker's questionnaire across the various provinces. 50 questionnaires were distributed in Kwa-Zulu Natal, 49 distributed in Mpumalanga and 52 distributed in the Eastern Cape. A total number of 151 questionnaires were filled out by the workers from all three provinces, while 150 questionnaires were filled out by the members of the local communities.

For the purpose of classification, the workers were categorised into millers and growers. 78 millers and 70 growers were questioned. See table. 3. The local communities were categorised by their ages and genders.

Occupation	Frequency	Percent	Valid percent	Cumulative percent
Millers	77	51.3	52.4	52.4
Growers	70	46.7	47.6	100
Total	**147**	**98.0**	**100**	
Missing	3	2.0		
Total	**150**	**100**		

Table 3: Categorisation of workers

2.1 Characterisation Structure of Workers and Local Communities

The table 4, below is the areas of focus for both the workers and the communities. The following factors were chosen, health and safety, Freedom of association, wages, working conditions, gender equality, service facilities and crime.

Characterisation	*Growers & Millers*	*Local Communities*
Health and safety	• Exposure to physical hazards • Protective equipment available	Illnesses caused by exposure to mills or cane fields
Freedom of Association	• Freedom to join unions • Level of union independence • Freedom to engage in collective bargaining negotiations • Key issues in collective bargaining negotiations	*Not Applicable*
Wages	• Satisfaction of wages and commission • Availability of wage related incentives • Basic expenditure of wages	*Not Applicable*
Gender Equality	• The ratio of men to women in the workplace • Treatment of men to woman in the workplace • Favouritism in company policies based on gender	*Not Applicable*
Service facilities	*Not Applicable*	Importance and Satisfaction levels
Environment	*Not Applicable*	Seriousness of exposure
Crime	*Not Applicable*	• Safety in relation to the sugar growth phases • Common crimes in the areas due to cane field and mills • Security structures for human and property safety

Table 4: Characterisation structure of workers and local communities.

3 IMPACT ASSESSMENT AND DISCUSSION

The analysis of the Inventory data is carried out in this chapter. This chapter also deals with the establishment of categories and subcategories of the study. The results on this characterisation are discussed.

3.1 Freedom of Association

The level of freedom to join associations within the millers and growers has shown minor variations. 84.2% of the interviewed millers and 88.6% of the growers sample reported that they do have the freedom to join associations. In table 5, it was thus discovered that only a small portion of the workers within the sugar millers and growers, ranging between 11% and 16% reported that they were restricted in terms of being members of any association.

3.2 Wages

It was discovered that amongst the Millers, who have a high percentage of members who are unaware of the minimum rate for their jobs was, this is indicated in table 6. 75.3% were not satisfied with the wages that they earned and stated that it should be increased. This means that only 24.7% of the sampled Millers, which is only 9 Millers, were satisfied with their wages. These satisfied millers were new employees who had just started earning wages. The sugar growers also displayed large percentages of dissatisfaction in terms of the wages earned. 87% of the interviewed growers reported dissatisfaction with the wages that they earn, with only 23% being satisfied.
The high levels of dissatisfaction with the wages earned amongst both the millers and growers was supported by lack of wage related incentives and bonuses.

Freedom of Association				
B1 Please answer the following questions regarding your freedom of association in your workplace.				
		Yes	No	Total
B1.1 Do you have the organisational freedom to join any association	Count	129	20	149
	Row N %	86.6%	13.4%	100.0%
B1.2 Are you a member of any association	Count	103	46	149
	Row N %	69.1%	30.9%	100.0%
B1.3 Do your employers provide full independence and freedom in the functioning of your association	Count	89	52	141
	Row N %	63.1%	36.9%	100.0%
B1.4 Do you have the freedom to organise unions	Count	89	55	144
	Row N %	61.8%	38.2%	100.0%
B1.5 Do you have the freedom to industrial action	Count	103	35	138
	Row N %	74.6%	25.4%	100.0%
B1.6 Do you have the freedom to engage in collective bargaining	Count	114	24	138
	Row N %	82.6%	17.4%	100.0%

Table 5: Freedom of association.

Wages				
C1 Please answer the following questions regarding your wages.				
		Yes	No	Total
C1.1 Do you know th value of the minimum wage for your job	Count	90	59	149
	Row N %	60.4%	39.6%	100.0%
C1.2 Based on your income, do you feel that the minimum wage should be increased	Count	70	79	149
	Row N %	47.0%	53.0%	100.0%
C1.3 Are you satisfied with the wage that you earn	Count	28	121	149
	Row N %	18.8%	81.2%	100.0%
C1.4 Do you have wage-related incentives (overtime, commission, etc)	Count	59	90	149
	Row N %	39.6%	60.4%	100.0%
C1.5 Do you think that the minimum wage rate should be increased urgently	Count	45	22	67
	Row N %	67.2%	32.8%	100.0%
C1.6 Has your wage increased in the past two years	Count	36	28	64
	Row N %	56.3%	43.8%	100.0%

Table 6: Wages.

3.3 Gender Equality

It was found that 63.2% of the males in the Sugar Millers were treated more favourable as compared to woman in terms of remuneration. This means that the men working at the sugar mills earned higher wages as compared to their woman colleagues. 47.8% of the sampled growers indicated both men and woman are treated equally when it comes to being remunerated; however 46.4% still felt that Men had higher wages compared to the Woman. Table 7 also indicates how only a small percentage of the millers and the growers feel that woman are favoured in wage payments, this small group ranges between 5.8% and 7.9%.

A dominating percentage of men over woman were also found in relation to the training and development of workers, in both the Sugar Mills and Sugar Growers.

3.4 Crime

78% of the questioned community members specified that they are at the least safe during the maturation and ripening phase. This is when the sugarcane stalk has grown to maximum length and is ready for harvesting. Only 18% stated that they are at the greatest risk during the grand-growth phase, this occurs 120 days after planting. Further analysis showed that both the males and the

D3 In your opinion and experience, which of these factors are favourable to either men or women within the organisation?		Men and Women treated equally	Men treated more favourable than women	Women treated more favourable than men	Total
D3.1 Recruitment & Selection	Count	53	39	57	149
	Row N %	35.6%	26.2%	38.3%	100.0%
D3.2 Remuneration	Count	56	82	10	148
	Row N %	37.8%	55.4%	6.8%	100.0%
D3.3 Appraisal/Performance Management	Count	101	34	10	145
	Row N %	69.7%	23.4%	6.9%	100.0%
D3.4 Training & Development	Count	50	82	16	148
	Row N %	33.8%	55.4%	10.8%	100.0%
D3.5 Promotion Opportunities	Count	82	47	18	147
	Row N %	55.8%	32.0%	12.2%	100.0%
D3.6 Family-Friendly Policies	Count	34	14	95	143
	Row N %	23.8%	9.8%	66.4%	100.0%
D3.7 Flexible Working hours	Count	43	24	76	143
	Row N %	30.1%	16.8%	53.1%	100.0%
D3.8 Policies & Procedures (e.g. grievance & disciplinary policies)	Count	99	26	23	148
	Row N %	66.9%	17.6%	15.5%	100.0%

Table 7: Gender equality.

Valid	Growing seasons	Frequency	%	Valid %	Cumulative %
	Germination	1	.7	.7	.7
	Tillering	2	1.3	1.3	2.0
	Grand growth	28	18.7	18.8	20.8
	Maturation	11.8	78.7	79.2	100
	Total	149	99.3	100	
Missing	System	1	.7		
Total		150	100		

Table 8: Least unsafe sugar growing phases.

females were unsafe during the maturation and ripening phase. See table 8 below.

Even though there are members of community that are of the view that during the grand-growth phase is the most unsafe time in the communities, a large group of both the males and the females indicate that the maturation and ripening phase is the most unsafe. The most common crime that the community members identified around cane growing areas were theft, smash and grab attack, assault, rape and kidnapping, this is indicated in table 9.

Crimes	Responses		% of cases
	N	%	
Theft	68	30.1	46.9
Smash and grab	20	8.8	13.8
Assault	62	27.4	42.8
Rape	31	13.7	21.4
Kidnapping	15	6.6	10.3
Other	30	13.3	20.7
Total	226	100%	155.9%

Table 9: Crimes around cane growing areas.

Theft and Assault were specifically rated the most common in the sugar growing areas, more than 40% of the workers stated that they were either victims or knew someone who had been a victim of theft or assault. Rape was also rated as a common crime, 21.4% had indicated that they were exposed to someone who had been a victim of rape or had been victims of rape themselves. In table 9, other crimes included house-breaking and murder. It was found the security structures are not properly employed in the various communities, especially during the unsafe seasons of sugar growth.

3.5 Health

It was found that 21.8% and 20.9% of community members suffered from frequent headaches or migraines and disturbed eyesight. These were believed to have been caused by the frequent exposure to the sugar mills and sugar plantations. 41 various community

Health		Responses N	Responses Percent	Percent of Cases
$E1 Please state which of the following you or your family members suffer from, due to the exposure to the sugar cane field?	E1.1 Irritation of the airways (e.g. Coughing or difficulty	41	18.2%	29.5%
	E1.2 Decreased lung function	8	3.6%	5.8%
	E1.3 Aggravated asthma	24	10.7%	17.3%
	E1.4 Development of chronic bronchitis	14	6.2%	10.1%
	E1.5 Irregular heartbeat	6	2.7%	4.3%
	E1.6 Heart attacks	4	1.8%	2.9%
	E1.7 Premature death in people with heart or lung disease	4	1.8%	2.9%
	E1.8 Frequent headaches/ migraines	49	21.8%	35.3%
	E1.9 Disturbed eyesight	47	20.9%	33.8%
	E1.10 Other	28	12.4%	20.1%
Total		225	100.0%	161.9%

Table 10: Illnesses of community members in cane growing and cane milling areas.

members reported difficulty of coughing while 24 stated that the exposure to mills and sugar plantations caused an aggravation to their asthma. 8 people stated that they were experiencing decreased lung function, while 14 indicated that they had developed chronic bronchitis. See table 10.

4 RECOMMENDATIONS

The following recommendations were made based on the findings sated in the impact assessment.

4.1 Freedom of Association

It is recommended that the employers of both the millers and growers invite different unions to engage with their workers, this is because it was found that even though most of the workers from both the millers and growers stated that they have the right to join any association, many of them were not members of any associations. This problem was most evident amongst the millers. The invitation of unions will help to educate the workers on the benefits of being part of an association. This will also provide workers with the knowledge of their rights and what they are entitled to as workers. The engagement of unions with workers will decrease the opportunity of exploitation of workers by their employees.

4.2 Wages

Based on the findings that both the millers and growers are not satisfied with their current wages, it is recommended that the employers provide financial management workshops for the workers. These will help the workers to manage their finances better, which will decrease their dissatisfaction level with regard with their wages. The provision of these workshops should be based on how to draw up budgets, how to manage debts and how to save money wisely. The employers are also encouraged to provide wage-related incentives for their workers; these include overtime and target-based commissions. These have been proven to increase the motivation of workers while also increasing productivity levels. The presence of such incentives will also increase the worker's wages which then decrease their dissatisfaction level with their current wages.

4.3 Gender Equality

There are more men employed at both mills and sugar plants as compared to women. It is suggested that more women be developed to enable the scale of men to woman to be 50:50. The employer should provide the same opportunities to both the male and female workers. The empowerment of woman is then necessary in this regard to get the level of women to be the same as the men. Gender equality does not discriminate against any gender.
It is thus suggested that the employer does not discriminate against women in terms of remuneration, training and development and promotional opportunities.

4.4 Environment

It is suggested that the sugar mills and plants, provide warnings during the various stages of their sugar production that will alert community members of what to expect. The mills and growers are encouraged to inform the community members when they should expect, for example, dust, pests, unpleasant smells, and also provide ways of managing such factors. This will help the community members to be aware of their environment and also to manage it better.

4.5 Crime

It is recommended that the police services within the various communities become more visible and easily available to the community members. The police in these communities are recommended to teach the community members of the various ways they can keep their household and property safe, with regard to the high risk sugar growing seasons. The police are also recommended to increase their patrollers during the unsafe seasons, to enable a decrease in criminal activities, and also to increase the level of safety within the various communities. The community members are encouraged to also establish a more formal structure of community patrollers, and increase their visibility during unsafe seasons. This will help reduce the level of crime in these respective areas.

LIST OF REFERENCES

[1] CDC, 2009, *South African Cane Growers Association*, http://www.cdc.gov/od/ohs/sasa/compergo.htm last accessed 22 September 2012

[2] MALOA, M. 2001. *Sugar Cane: Development of crop in South Africa Land Reform and Poverty Alleviation in Southern Africa*. Proceedings of the 2001 Conference held SARPN. Pretoria.

[3] Mashoko,L. Mbohwa, C., and Kekana, M. (2009). *Bagasse energy cogeneration potential in the South African sugar industry*: International conference on energy security and climate change: issues, strategies, and options. (ESCC 2009)

[4] UNEP *Methodological Sheets for Social Life Cycle Assessment of Products*. 2009. Available at http://lcinitiative.unep.fr. Last accessed 12 October 2012

[5] Voigt, I. (2009). The implementation of South African sugar technology: The world's largest sugarcane diffusers. Journal of the South African Sugar Technology Assessment Vol. 82: 269 – 277

Re-use and Job Opportunities in Central-Europe

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Abstract

Increasing demands are shown regarding the reuse of the products - regardless of the countries - by means of differences of living and this is preferred also after the waste prevention based on the waste hierarchy in the Framework Directive of the European Union. These reasons can generate the increasing of the special kind of used item handling/trading work. The whole life-cycle assessment analyses a dynamically developing area (used item collection and trade) from environmental and sociological aspect. The aim of the research was the examination of the illegal activity for many years compared with alternative formalized ideas.

Keywords:

Re-Use; used-item collection and trading; life cycle assessment

1 INTRODUCTION

Waste management companies of the developed countries struggle with the high amount of waste, which is still increasing year by year. Certain part of the household waste is recyclable, but the remaining larger part needs other waste treatment technologies. The aim of the manufacturers is that their products would be produced from recyclable materials in greater part. The main goal is avoiding or preventing the waste status, and delaying the time of non waste regime. An option for this last one is the re-use of the product defined in the European Directive on Waste (2008/98/EC). There is a developed methodology for collection and marketing system but they are in rudimentary form in Central-Europe. Besides the initiatives coming from the "upper level", there are grassroots approaches in the topic rather based on social needs than environmental targets. Up to now, the inhabitants could made a clear sweep of their unwanted junk – furniture, books, articles, etc. – by the help of the official organized kerbside collections once or twice a year, the used electric or electronic appliances are taken to the collection centres where there is no functional check. . In most cases, there weren't any quality checking and nor sorting. These products – in waste status – end up in landfills. This "prodigality" is reduced in Europe by a newly established organization, which especially focuses on the reusable items.

2 COLLABORATION

The Bay Zoltán Nonprofit Ltd. is taking part two re-use related international projects within the Central-Europe Programme: TransWaste and CERREC.

The aim of project TransWaste is the survey of the illegal bulky waste collection activity, finding, developing and comparing of formalization possibilities. Another goal is the implementation of a pilot project, which offers acceptable and legal solutions for the stakeholders – providing them a win-win situation. The European project worked with representatives of five countries (Austria, Germany, Poland, Slovakia and Hungary).

The aim of project CERREC organically links to the TransWaste, but going another step forward: development of tools (within a transnational stakeholder participation process) as well standards for re-use and repair networks and centres and thus also for re-use, repair- and refurbishment businesses and re-use products. The project colligates economical, social and environmental aspects as well. The more emphasised implementation of re-use into national waste management policy and activities is crucial especially for CE countries.

3 THE INITIAL TASK FACTORS

In more than 20 years, socially vulnerable populations of Eastern European countries noticed that the bulky waste in Western Europe has such a good feature that they are suitable for re-use and they recognized the potential demand due to their quality and price. This phenomenon launched the illegal activity involving the increasing number of people. The collectors often cover several hundreds of kilometres for the used items, crossing Europe.

Most of these people collect items – often electric and electronic waste (WEEE): televisions, fridges or washing machines, etc. and metals - from the junk yard without permission (the junk kerb side bulky waste collection system – where the inhabitants place their bulky waste to the street- is changing.) These illegal activities lead to environmental (roadside litter, illegal waste incineration, irregular storage, etc.), social (it has caused difficulties to the inhabitants and authorities at the collection points) and economic (it has changed the financial demands of the waste processing in each countries due to the amount and composition of the waste) problems.

Figure 1: Typical transport ways of used items to Hungary

4 COLLECTION AND TRADING

The **supply chain** of the re-useable products may happen through different channels. Such as:

- kerbside collection of bulky waste is the first option, where inhabitants place their junk to public places – the collection is banned from this place in several European countries, because these goods have been in waste status;
- junk yard collection centre: It is only possible, if the yard deals with the sale of reusable products;
- flea markets – where the purchase invoice is generally missing;
- donation shops, charity organization;
- second hand shops, this is the cleanest way, but it is expensive for the collectors;
- from inhabitant people or institutions. The project targets these groups.

Figure 2: Transport and environmental problems in the way (source: Bay-Logi).

The **sale** can be done:

- Private houses – this is forbidden due to health and environmental problems;
- Flea markets – see previous point;
- Second hand stores - It requires an entrepreneur card, but the majority of the collectors haven't got this. They do their act in informal way;
- Online – control is not yet possible. The sold goods and the sellers are not verifiable (permission, income, tax, etc.)

Figure 3: Selling in flea market (Source: Bay-logi).

It proves the legacy of re-use that the social gap opens more and more between the different social classes. On one hand, a social class appears, who can afford to buy new, up-to-date, more beautiful and cheap products, – although their old equipment is still in satisfactory quality. On the other hand there is an increasing class, which can maintain only their necessity of poor life. The redundancies of the one side satisfy the demands of the other side. But a similar gap in the standards of living is also noticeable between the old socialist countries and the Western European countries. The Eastern countries have failed to achieve the level of west: neither with wages nor with other welfare issues.

5 POSSIBILITIES ON FORMALIZATION:

The project started with information collections and contacting stakeholders – authorities, ministries, waste management companies, Roma minority organizations and the informal sector. The members of the project developed the following solutions for the formalization –taking into account of all stakeholders' interests:

- **Re-use corner** scenario: a corner could be separated in the present waste yard (collection centre), where the collection of the reusable items could take place (this kind of solutions have already worked in Austria and Germany in moderate number)
- **Wise scenario**: An organization employing socially disadvantaged people. These workers convert the old product to negotiable product – which means the transportation, classification, reconstruction, cleaning and of course the sale of the product.
- **ISHS** (International Second Hand Service) scenario: redirecting the present bulky waste collection activities into formal way. The organization members – who had undergone a compulsory education – carry out their activities within the framework of a legal entity. The education material contains the environmental, commercial, entrepreneurship and transport knowledge.

6 JOB OPPROTUNITES TRIGGERED BY RE-USE

The results of the project TransWaste can contribute to the formalisation of collection and trading of wastes with re-use potential. It generates new workplaces only from legal aspect by formalising the (semi-) illegal activity.

Considering a wider scale (i.e. regional, national) re-use has more relevant and concrete potential on generating new workplaces: with the organised activities such as collection, refurbishment and selling of re-usable products within a re-use network can contribute to create new workplaces even on economical sense.

Revealing the value generating potential of re-use both from socio-economical and environmental views, the re-use is getting more and more stressed in the European Legislation: beside the WFD the recast of WEEE (2012/19/EU) also has explicitly deals with the re-use.

Though the implementation of the regulations in the related Directives is obligatory for all Member States, there are different status-quo situations between them: for example considering the given infrastructure, or precedent for such activities. Austria has the most developed re-use network in CE. But from the socio-economy side, the formal communist countries like Slovakia and Hungary have the most unrevealed potential due to the next reasons:

- significant demand on new workplaces (high level of unemployment rate)
- relatively low average salaries (more cheaper labour force) subservient the economical feasibility
- high demand on cheap, but reliable re-used products
- Tradition and reputation on second-hand markets.

7 LIFECYCLE ASSESSMENT

The positive economy impacts of the opportunities of formalization and re-use can be proofed with quantified results and its possible way is the sustainability analysis. The economic, social and environmental analyses together provide a final decision on the applicability and sense of a process. An accomplished environmental analysis makes some really interesting suggestions. However, a thorough lengthy constructive work was required to reach the final results (data collection, processing, model building, refinement, analysis).

The data collection was based on measurement, statistics, estimation, producer data and trade literatures, e.g.: definition of the amounts and composition of transhipped second-hand goods on cross borders, raw materials, manufacturing parameters, etc. We tried to use more own data in the long months of work, therefore the big part of the assessment consists of own data collection, model building and analysis. It was measured on such an analysis that 100 thousand tons used item are transported over the Austrian-Hungarian border per year; one third part of it has been constituted waste (metal, wood, etc.). This amount is 15% of the collected bulky waste in Austria per year: as regards its composition: fifty percent furniture, quarter part electronic and electrical products.

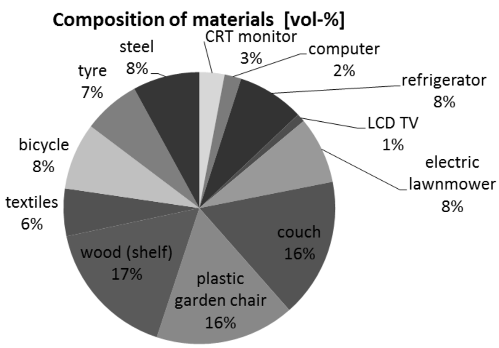

Figure 4: Composition of the collected and transported used items (source: ABF-BOKU).

The functional unit of the environmental assessment is: the amount of the transhipped used item per a year by a van (<7,5t), where the transport distance is 300km happens 75 times a year. The analysis includes the environmental impacts of the manufacture, usage, transfer and disposal of certain products, - so the whole lifecycle-, and a summarized analysis, which determines the values based on the distribution of the pie chart (Figure 4). The evaluation was based on the CML2001 (nov2010) impact assessment method, on which have been outlined the more reliable impact categories.

The analysis examined three different scenarios, in which it was looked for the answer that the present formal waste collection system, the present informal collect form or the system of the formalization ideas are favourable in environmental respect. The Austrian-Hungarian analysis will be presented, now form the several routes of the European countries. (Figure 5)

Through the analysis we searched the answers on the followings:

- Which impacts were given by (from) the several ideas from environmental aspect?
- Query on whether the present official system is better or no, where re-use can hardly find?
- Or does it prove that the present disorganised and informal system is a better solution which has lot of environmental problems?
- Which values does the imaginary formalized version give?

Results were determined in point of each product in every scenario. Exact environment values of the electric lawnmower or the rates in case of the fridge can be seen, etc. Of course, a summarized assessment was also made, which contains all analysed products. The LCA work team came to an understanding, by choosing the CML impact assessment method in West-Central-Europe as the best solution the. Within the Global Warming Potential category has the mean/main priority and it was detailed. This category has the greatest significances in this region.

8 SUMMARY OF LCA

The results of the environmental analysis showed that the re-use is much substantiated. Due to the shifting of the waste status commencement, the environment will be exempted from the impacts

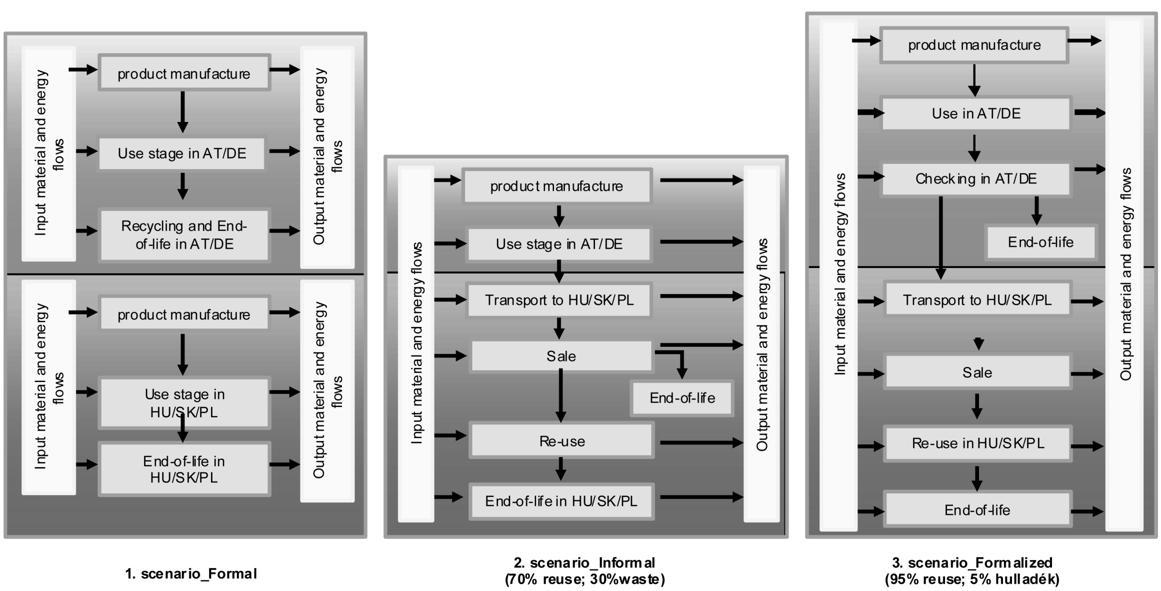

Figure 5: Scenarios and stages of the Life Cycle assessment (Source: Bay-Logi).

of the manufacture of a new product for that time. The clear conclusion is that the analysis is worth to be done for all product types, because there are products – mainly electronic products (fridge, computer, and television but in case of the washing machine due to the modernization the legitimacy of the re-usability can be seen) in which the environmental advantage of re-using the product is uncertain, due to the high energy consumption of the usage.

Based on the comparative analysis of several scenarios, in case of great majority of goods are reflected the usefulness of re-use. This is confirmed in Figure 6, which analyses the life-cycle of a bicycle. The individual scenarios show similar trends in case of the summarized assessment, which involves all analyzed used items.

The assessment took into consideration the data of more Central-Europe countries, therefore it is important to mention the

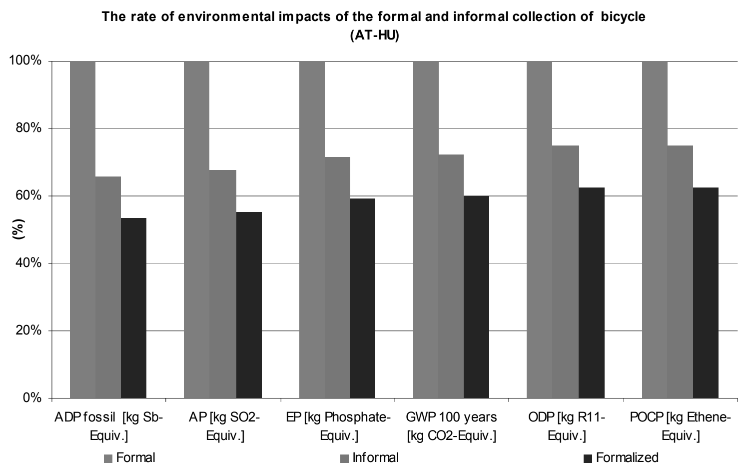

Figure 6: The results of the life cycle assessment of the project (Source: Bay-Logi).

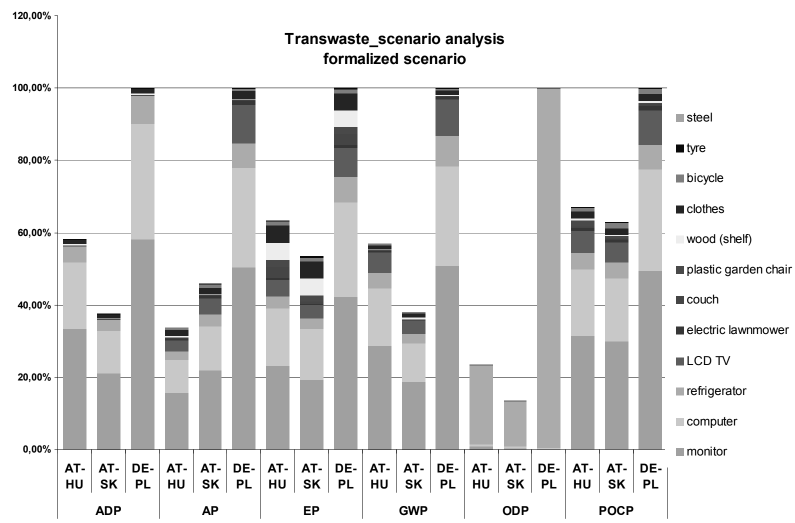

Figure 7: The difference of the several transportation routes and using places (Source: Bay-Logi).

significant differences of the energy-mix of these countries. There are considerable efforts on the application of the renewable energies in Poland in Northern-Europe, but currently the usage of the fossil fuels gives the big part of the energy production in the country. This is the main reason why using the same appliance gives worst environmental results in Poland than for example in Austria – where mainly wind and water power plants operate (Figure 7).

The sociology analysis (source: Wameco S.C.) pointed out the advantages of new employment opportunities, from the side of the employees and the economy as well. However it offered the combinability of scenarios resulting greater advantages. Economic analysis gave similar results with only one difference which is that the country specific properties – such as waste treatment technologies, utilization rates - are highly influential factors.

- According to the summary of sustainability analysis,
- Re-use is useful in case of more products,
- In case of certain products it must be applied in a prudent way,

- The background of the country's waste collection and treatment technologies is highly influential,
- Different needs for re-usable products,
- The social background of the country is an influence factor.

All things considered and it is absolutely advantageous to apply the formalized idea, which has benefit for the person, the economy and also for the environment.

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10 REFERENCES

Further information in the website (www.transwaste.eu)

1. B. Sándor R. (2012): Life-cycle assessment of informal "waste" collection, in: LCA Center Conference
2. B. Sándor R. (2012): Environmental analysis of bulky waste collection in Central-Europe with LCA approach, in: Hungarian Sanitation Conference
3. Scherhaufer S., B. Sándor R., Lange U., den Boer J., Obersteiner G., Linzner R., Pertl A., Schmied E.(2012): Sustainability assessment of transboundary re-use activities
4. B. Sándor R. (2012): Formalized idea – pilot case, in: Project meeting of TransWaste
5. Project team (2012): Deliverable 3 – Comparison of LCA for informal, formal and formalized collected waste (TransWaste)

Comparison of Drivers and Barriers to Green Manufacturing: A Case of India and Germany

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Abstract

In the recent past, environmental issues have gained momentum because of rapid economic and industrial growth of highly populated developing/emerging nations which are posing serious environmental and social problems not only in their own countries but also to the world. A growing number of organizations have begun or are willing to work towards implementing Green Manufacturing (GM) in these nations. But the adoption of GM is a challenge for the organizations in these nations as motivating factors (drivers) are not facilitated and inhibiting factors (barriers) are not mitigated, which pose a heavy burden. This paper aims to statistically analyze the drivers and barriers to GM implementation for developed and emerging nations so that the organizations can strategically focus on these factors to reach to a higher level of competitiveness. This study will help decision makers in manufacturing organizations and in policy of both nations to strategically leverage the collaborative efforts by effective implementation of GM.

Keywords:

Green Manufacturing; Drivers and Barriers; Comparison

1 INTRODUCTION

Environmentally sustainable development requires societies to manage all of their assets that can contribute to improving human well-being [1]. This goes along with rapid changes like the ongoing internationalization and globalization, technological improvements, new economic and financial systems or new information and communication systems. In addition, the world is facing challenges like rising world population, uneven living standards, shortage of natural resources, and environmental pollution [2]. These challenges of the future can be solved through joint efforts by all levels of society. The manufacturing system plays a vital role in environmentally sustainable development, as it is responsible for nearly one third of the global primary energy consumption [3,4,5]. The rising world population and improving living standards in developing countries may lead to tremendous future growth of manufacturing systems with its significant influence on the environment. The Department of Industry Policy and Promotion, India has endorsed the target to increase the manufacturing sector's contribution to the Gross Domestic Product (GDP) to 25 %, from its current level of about 16 % by the year 2022 [6]. The growth of the manufacturing sector is needed to achieve improved prosperity and life style of the people but at the same time it generates environmental impacts like the emissions of pollutants and the exploitation of natural resources, as raw materials are needed for production. The importance of environmental challenges has been increased due to the continuous degradation of the environment and increasing environmental disasters. One move to tackle the described situation is green and sustainable manufacturing which is lead to compliment the development and operation of efficient manufacturing operations with the requirements of reduced energy and resource utilization. Green Manufacturing (GM) concepts are often linked to other lean manufacturing approaches, which were developed before the current concerns about the environment and green manufacturing so many directly map onto GM. [7]. GM consists of methods and tools to achieve sustainable production through process optimizations across the supply chain with environmental costs in mind [8]. This means reshaping the industry towards future and addressing the above mentioned challenges. Due to the ongoing negative environmental developments, there is a need for strengthening the related methods and tools to implement them in industry. In particular, an emerging nation like India will accelerate the industrial environmental impact through a high economic growth. Thus, there is a need to develop those countries without associated negative ecological impacts.

This paper is an extension of a paper published in the proceedings of the 19th CIRP International Conference on Life Cycle Engineering 2012 [9] in UC Berkeley. The first paper lists and compares the drivers and barriers to GM in the manufacturing industry of India and Germany. In this paper the analysis is continued with statistical calculations to assess the differences between the drivers and barriers in a developed and a developing nation. The statistical analysis is done using the 'independent t-test', which is a statistical method to compare the significance of differences. The statistical analysis will provide the significance of the difference between the drivers and barriers of Germany and India. Also the magnitude of the difference in these factors is assessed, if the difference exists. Hence, this study will help the industry, government and other policy makers to understand the challenges of GM better and explore the solutions for effective and efficient environmental strategies by applying successful measures from one country in another.

2 RESEARCH METHODOLOGY

In the study itself a list of 13 drivers (as shown in table 1) and 12 barriers (as shown in table 2) are identified and listed from the review of reseach articles relating to topics like environmentally sound technology [10], cleaner technologies [11,12], environmentally benign manufacturing [13,14], environmentally conscious manufacturing [9], extended supply chain practices [15], environmentally conscious technology [16], which are almost synonyms of green manufacturing, and in discussion with experts and academicians working in the field of green manufacturing and industry people responsible for green initiatives. A questionnaire was developed to obtain opinions from Indian and German industrial experts and policy makers. In the questionnaire, the participants are asked to rate the importance of drivers and barriers to GM on a scale of 1 to 5, where 1 means no impact, 2 means low impact, 3 stands for medium impact, 4 means high impact and 5 means very high impact. However, participants are allowed to skip questions, so that a sixth option is available to express indecisiveness. Moreover, there is an option to give own comments on the presented drivers and barriers and participants are asked, if any driver or barrier is missing. Altogether, the survey is designed to get the respondents opinion about the importance of each identified driver and barrier from literature. The required participation time ranges from 6 to 10 minutes. Before the release of the questionnaire, it was reviewed by academic and industrial experts with knowledge in the field of GM regarding the clarity and understandability. As a pilot study, the questionnaire was filled by 11 industrial experts during the 1st Green Manufacturing Summit of Confederation of Indian Industry (CII) held in Delhi during February, 2011. The questionnaire was revised in terms of language to increase understandability and an online survey was started using the www.surveymonkey.com website. Altogether, more than 1000 companies have been contacted in India and Germany and the response rate to e-mail inquiries has been around 5.4%. Taken as a whole, 54 useful, completed and reasonable responses have been received out of which 22 reponses are from India and 32 responses are from Germany. Around 80% of the participants in India have positions within the middle or senior management of their companies. The remaining respondents are executives who are responsible for the manufacturing systems.

3 RESULTS AND DISCUSSIONS

Firstly, the reliability of the data collected through the questionnaire is assessed using the cronbach's alpha, which assesses the suitability of the data for further the analysis and a useful interpretation. Secondly, the mean values are calculated to assess the importance of the drivers and barriers. Very low mean values of any factor gives a clue that the particular factor is not important and should be eliminated from the study. Thirdly, the standard deviation values are calculated because the mean value is not always sufficient to measure the central tendency of the data. Lastly, an 'independent t-test' is done to assess the significance of the difference. The measures of central tendency and results of the tests conducted are presented in the following:

3.1 Descriptive Statistics

Group statistics for drivers are presented in Table 3. The mean value of all driving factors is more than 2.38 on a scale of 5, which represents that all the drivers are important in both countries. The internal consistency analysis is carried out using the software SPSS 16.0 for Windows®, to measure the reliability of each driver in term of the Cronbach's alpha. An alpha value of 0.7 is often considered as the criteria for establishing internal consistency on a scale of 0 to 1, where '0' means that the data is not reliable and '1' means that the data is fully reliable. However, a value of 0.6 is also considered sufficient for newly collected data. If necessary (alpha < 0.6), items are eliminated in order to achieve an increase of the Cronbach's alpha value. In this study, during the initial analysis, none of the factors were eliminated to improve the reliability. During the initial analysis, Cronbach's alpha values were very high for all the thirteen drivers.

The Cronbach's alpha value of 0.893 for the drivers and 0.907 for the barriers is achieved on the combined data in India and Germany

Driver	Description
Current Legislation	pollution control, landfill taxes, emissions trading, eco-label, etc.
Future Legislation	expected development of stricter law, increased level of enforcement
Incentives	investment subsidies, awards, R&D support
Public Pressure	local communities, politicians, NGOs, media, insurance companies, banks promote environmental topics
Peer Pressure	trade and business associations, networks, experts
Cost Savings	reduction of energy consumption compared to rising energy costs, less waste output
Competitiveness	better process performances, higher product quality, higher efficiency, competing with best-practices in sector
Customer Demand	end-user demand for environmentally friendly products
Supply Chain Pressure	demand of suppliers, distributors, OEM, compliance with legislation in global markets
Top Management Commitment	management, owner or investors are highly committed to enhance environmental performance, ethics, social values
Public Image	importance of a positive public perception of your company
Technology	opportunities, advantages or performances of available green technology
Organizational Resources	skilled and motivated staff, healthy financial situation or performance measurements

Table 1: Description of Green Manufacturing Drivers.

Barrier	Description
Weak Legislation	absence of environmental laws, complexity of law, ineffective legislation
Low Enforcement	weak or no enforcement of laws, corruption
Uncertain Future Legislation	uncertain developments in legislation, withholding investments for future regulations
Low Public Pressure	absence of pressure through local communities, media, NGOs or politicians
High Short-Term Costs	investment and implementing costs
Uncertain Benefits	uncertain or insignificant economic advantage, slow return on investment, amortization of older investments is prior
Low Customer Demand	customers are price sensitive, interest in cheaper products, environment does not carry enough weight in the market
Trade-Offs	rather trading emissions than reducing them, outsourcing of environmental problems, short product life cycles
Low Top Management Commitment	management or owner is not committed to green issues, "our company has not an impact in the world"
Lack of Organizational Resources	lack of skilled staff, lack of experiences, no financial resources or capital access, green issues have low priority
Technological Risk	risk of implementing new technology, fear of problems, no compatibility with existing systems, technological complexity
Lack of Awareness/Information	no awareness of green trends, limited access to green literature, not enough or not understandable information

Table 2: Description of Green Manufacturing Barriers.

which is considered good and therefore it is concluded that the data is highly reliable. Hence, it is approved to use this data for further analysis.

3.2 Standard Deviation of Drivers

The examination of the mean values of all driving factors suggests that the 'top management commitment' is the most important in India (mean of 4.05) and 'cost savings' in Germany (mean of 4.03). 'Public pressure' is least important in India and Germany with mean values of 2.95 and 2.38 respectively. In addition to expressing the variability of a population, the standard deviation is commonly used to measure confidence in statistical conclusions. A useful property of the standard deviation is that it is expressed in the same unit as the data. The standard deviation of data from both the countries varies from a minimum value of 0.842 for 'peer pressure' in Germany and maximum value of 1.336 for 'future legislation' in India.

Drivers	Country	Mean	Std. Deviation
Current Legislation [D_1]	India	3.05	1.214
	Germany	3.41	1.188
Future Legislation [D_2]	India	3.50	1.336
	Germany	3.25	1.047
Incentives [D_3]	India	3.55	1.143
	Germany	2.69	1.030
Public Pressure [D_4]	India	2.95	0.950
	Germany	2.38	1.129
Peer Pressure [D_5]	India	3.05	1.046
	Germany	2.50	0.842
Cost Savings [D_6]	India	3.82	1.053
	Germany	4.03	1.062
Competitiveness [D_7]	India	3.91	1.109
	Germany	3.94	0.982
Customer Demand [D_8]	India	3.73	0.935
	Germany	3.22	1.099
Supply Chain Pressure [D_9]	India	3.59	1.008
	Germany	2.75	1.191
Top Management Commitment [D_{10}]	India	4.05	1.046
	Germany	3.41	1.188
Public Image [D_{11}]	India	3.86	1.037
	Germany	2.91	1.174
Technology [D_{12}]	India	3.86	1.082
	Germany	2.91	1.146
Organizational Resources [D_{13}]	India	3.73	1.032
	Germany	3.34	1.181

Table 3: Group Statistics for Drivers.

3.3 Standard Deviation of Barriers

Group statistics for barriers are presented in Table 4. The mean value of all the barriers is more than 1.93 on a scale of 5, which indicates that all the barriers are important in both the countries.

The examination of means for various barriers suggest that the 'low customer demand' is the highest impact barrier with mean value of 3.10 in India and the 'uncertain benefits' and 'high short term costs' are the highest impact barriers with mean values of 3.43 in Germany. Further, it is evident from the group statistics that 'lack of top management commitment' is least impact barrier in India and Germany with mean values of 2.43 and 1.93 respectively. The standard deviation of data from both the countries varies from a minimum value of 0.784 for 'trade-offs' in India and maximum value of 1.401 for 'lack of organizational resources' again in India.

3.4 Comparing Means Using Independent T-Test

An independent T-test (two-tailed) is conducted on two entirely different and independent samples of respondents from Indian and German companies to compare the impact of drivers and barriers. The independent T-test is done to know, whether the difference in the drivers and barriers are statistically different for the two countries or not. The procedure to conduct an independent T-test is shown in Figure 1 below:

Barriers	Country	Mean	Std. Deviation
Weak Legislation [B_1]	India	2.95	1.322
	Germany	2.54	1.071
Low Enforcement [B_2]	India	2.81	1.289
	Germany	2.11	1.066
Uncertain Future Legislation [B_3]	India	2.67	1.155
	Germany	2.75	1.041
Low Public Pressure [B_4]	India	2.52	1.078
	Germany	2.29	1.182
High Short Term Costs [B_5]	India	2.90	1.044
	Germany	3.43	1.230
Uncertain Benefits [B_6]	India	2.76	1.136
	Germany	3.43	1.230
Low Customer demand [B_7]	India	3.10	1.261
	Germany	3.25	1.351
Trade-Offs [B_8]	India	2.71	0.784
	Germany	2.67	1.109
Lack of Top Mgt. Commitment [B_9]	India	2.43	1.248
	Germany	1.93	0.979
Lack of Org. Resources [B_{10}]	India	2.81	1.401
	Germany	2.68	1.090
Technology Risk [B_{11}]	India	2.67	1.278
	Germany	2.54	0.999
Lack of Awareness/Information [B_{12}]	India	2.81	1.327
	Germany	2.18	0.819

Table 4: Group Statistics for Barriers.

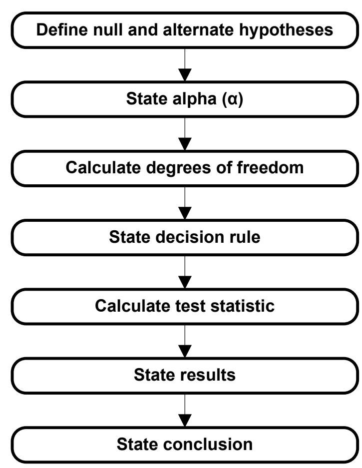

Figure 1: Independent T-test procedure.

The following hypotheses are set for the independent t-test:

The null hypothesis (H_0) assumed is

$$H_0: \mu_{India} = \mu_{Germany}$$

and the alternate hypothesis (H_1) is

$$H_1: \mu_{India} \neq \mu_{Germany}.$$

The alpha level used for the study is 0.05, which is a commonly accepted in statistical studies. The 't-distribution for critical value' for 52 degrees of freedom and alpha level of 0.05 is 2.007 as obtained from the t-table, which states the decision rule that the calculated 't' value should be between ± 2.007 to accept the null hypothesis and for the 't values beyond this range, the null hypothesis will be rejected because of a strange and unlikely case. Now the actual 't' value is calculated using the following formula:

$$t = \frac{(\bar{x}_{Ind} - \bar{x}_{Ger})}{\sqrt{\left(s^2_{Ind}/n_{Ind}\right) + \left(s^2_{Ger}/n_{Ger}\right)}}$$

where

$\bar{x} = Sample\ mean$

$s^2 = Pooled\ variance$

$n = Sample\ size$

In the Levene's test for equality of variances, if the variances are equal in both groups then the p-value ("Sig.") will be greater than 0.05. However, if the "Sig." value is less than 0.05, the variances are unequal. If variances are unequal then 'equal variances not assumed (EVNA)' row need to be used, otherwise 'equal variances assumed (EVA)' row is taken for interpreting t-test for equality of means.

In the case of drivers, the p-value of more than 0.05 is obtained for all the drivers for Levene's test so it is concluded that the variances are equal and 'EVA' column have to be selected. Looking down this column, it is seen that the group means are significantly different as the value in the "Sig. (2-tailed)" row is less than 0.05 as the t-test is conducted at a confidence interval of 95%. Based on this t-test for equality of means, the significance of difference of impact for drivers in both the countries are presented in Table 5.

In the second case of barriers, the p-value of more than 0.05 for all the barriers for Levene's test except barrier B_{11} and B_{12} i.e. 'technology risk' and 'lack of awareness and information' respectively so it is concluded that the variances are equal and 'EVA' row have to be selected for barriers B_1 to B_{10} and 'EVNA' for barriers B_{11} and B_{12}. Based on this t-test for equality of means, the significance of difference of impact for barriers in both the countries are presented in Table 6.

3.5 Effect Size for Independent T-Test

After performing independent t-test, it is important to calculate the 'effect size' which measures the magnitude of mean differences. It explains whether the difference in the 'means' are a little different or very different. This is usually calculated after rejecting the null hypothesis in a statistical test. If the null hypothesis is not rejected, then the 'effect size' has little or no meaning.

$$Cohen's\ d = (\bar{x}_1 - \bar{x}_2)/\sqrt{s^2_p}$$

$$s^2_p = Pooled\ variance = \frac{(n_{Ind}-1)s^2_{Ind} + (n_{Ger}-1)s^2_{Ger}}{(n_{Ind}+n_{Ger}-2)}$$

		Levene's Test for Equality of Variances		T-test for Equality of Means					Cohen's d (To assess effect size)
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	
D_1	EVA	0.057	0.812	-1.087	52	0.282	-0.361	0.332	-0.2997
	EVNA			-1.083	44.631	0.285	-0.361	0.333	
D_2	EVA	1.518	0.223	0.770	52	0.445	0.250	0.325	0.20829
	EVNA			0.736	37.901	0.466	0.250	0.340	
D_3	EVA	0.242	0.625	2.876	52	0.006	0.858	0.298	0.79046
	EVNA			2.820	42.087	0.007	0.858	0.304	
D_4	EVA	2.458	0.123	1.974	52	0.054	0.580	0.294	0.54631
	EVNA			2.038	49.780	0.047	0.580	0.284	
D_5	EVA	0.435	0.512	2.118	52	0.039	0.545	0.258	0.57925
	EVNA			2.035	38.707	0.049	0.545	0.268	
D_6	EVA	0.001	0.974	-0.727	52	0.471	-0.213	0.293	-0.1985
	EVNA			-0.728	45.561	0.470	-0.213	0.293	
D_7	EVA	0.324	0.571	-0.099	52	0.921	-0.028	0.287	-0.0286
	EVNA			-0.097	41.557	0.923	-0.028	0.293	
D_8	EVA	1.502	0.226	1.772	52	0.082	0.509	0.287	0.49985
	EVNA			1.826	49.559	0.074	0.509	0.278	
D_9	EVA	1.297	0.260	2.709	52	0.009	0.841	0.310	0.76135
	EVNA			2.795	49.680	0.007	0.841	0.301	
D_{10}	EVA	1.962	0.167	2.038	52	0.047	0.639	0.314	0.57180
	EVNA			2.088	48.779	0.042	0.639	0.306	
D_{11}	EVA	0.992	0.324	3.085	52	0.003	0.957	0.310	0.85769
	EVNA			3.157	48.693	0.003	0.957	0.303	
D_{12}	EVA	0.104	0.748	3.085	52	0.003	0.957	0.310	0.85243
	EVNA			3.118	46.960	0.003	0.957	0.307	
D_{13}	EVA	0.653	0.423	1.233	52	0.223	0.384	0.311	0.35166
	EVNA			1.265	48.951	0.212	0.384	0.303	

Table 5: Independent T-Test to compare drivers for India and Germany.

		Levene's Test for Equality of Variances		T-test for Equality of Means					Cohen's d (To assess effect size)
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	
B_1	EVA	1.441	0.236	1.219	47	0.229	0.417	0.342	0.34079
	EVNA			1.182	37.757	0.244	0.417	0.352	
B_2	EVA	1.377	0.247	2.086	47	0.042	0.702	0.337	0.59183
	EVNA			2.030	38.308	0.049	0.702	0.346	
B_3	EVA	0.004	0.952	-0.265	47	0.792	-0.083	0.315	-0.0727
	EVNA			-0.261	40.627	0.796	-0.083	0.320	
B_4	EVA	0.367	0.548	0.724	47	0.472	0.238	0.329	0.20332
	EVNA			0.734	45.141	0.467	0.238	0.324	
B_5	EVA	1.700	0.199	-1.571	47	0.123	-0.524	0.333	-0.4645
	EVNA			-1.609	46.214	0.114	-0.524	0.326	
B_6	EVA	0.071	0.791	-1.939	47	0.059	-0.667	0.344	-0.5659
	EVNA			-1.962	44.915	0.056	-0.667	0.340	
B_7	EVA	0.284	0.597	-0.408	47	0.685	-0.155	0.379	-0.1147
	EVNA			-0.412	44.704	0.682	-0.155	0.375	
B_8	EVA	4.067	0.050	0.167	46	0.868	0.048	0.285	0.04165
	EVNA			0.174	45.642	0.863	0.048	0.274	
B_9	EVA	2.083	0.156	1.573	47	0.122	0.500	0.318	0.44579
	EVNA			1.519	36.892	0.137	0.500	0.329	
B_{10}	EVA	2.566	0.116	0.368	47	0.714	0.131	0.356	0.10357
	EVNA			0.355	36.699	0.724	0.131	0.369	
B_{11}	EVA	5.704	0.021	0.403	47	0.689	0.131	0.325	0.11333
	EVNA			0.389	36.814	0.700	0.131	0.337	
B_{12}	EVA	14.173	0.000	2.052	47	0.046	0.631	0.308	0.57134
	EVNA			1.921	31.167	0.064	0.631	0.328	

Table 6: Independent T-Test to compare barriers for India and Germany.

d = 0.2, means small effect
d = 0.5, means medium effect
d = 0.8, means large effect

Table 7 presents the final results of the comparison of drivers and their effect size and Table 8 presents the final results of the comparison of barriers and their effect size.

Drivers	Comparison	Effect size
D_1	Equal	----------
D_2	Equal	----------
D_3	Significantly different	Large
D_4	Significantly different	Medium
D_5	Significantly different	Medium
D_6	Equal	----------
D_7	Equal	----------
D_8	Equal	----------
D_9	Significantly different	Large
D_{10}	Significantly different	Medium
D_{11}	Significantly different	Large
D_{12}	Significantly different	Large
D_{13}	Equal	----------

Table 7: Results of comparison for drivers.

Barriers	Comparison	Effect Size
B_1	Equal	----------
B_2	Significantly different	Medium
B_3 to B_{12}	Equal	----------

Table 8: Results of comparison for barriers.

It clearly shows the statistical significance either 'statistically different' or 'equal' in column 2 along with the magnitude of the difference if it exists in column 3. For example, large effect size means that the impact of drivers are highly different in both the nations.

4 CONCLUSIONS AND OUTLOOK

In this study, drivers and barriers to GM have been validated using a statistical analysis of the data collected through the questionnaire survey. This research has provided a broad perspective on the drivers and barriers to GM in two different economies - a developed economy and an emerging economy. The statistical significance of similarities and differences have been pointed out from these two perspectives. This study also reveals the size of the difference.

The impact of 'incentives' in India is higher than in Germany because the implementation of GM in India is rather driven by economic benefits than legislation. The 'supply chain pressure' is more important in India as the manufactured goods are supplied to many developed nations which have more stringent regulations for green products. As many Indian organizations have not yet implemented GM, they are striving for a better 'public image' which can create a competitiveness over other organizations in the market. The scarcity and cost of the newer green 'technology' in India makes it a better motivator than in Germany, where the technology is easily available. These four drivers are significantly different between the two countries with large differences.

The 'public and peer pressure' is more important in India because of increasing awareness among agencies like banks, insurance companies, NGOs etc and the involvement of peers by the government in policy making. The influence of the 'top management commitment' is higher in India, which can trigger voluntary initiatives amongst the top management to implement GM. However, due to the ineffective legislation and low enforcement of environmental laws and regulations these actions are seldom taken. These three drivers are significantly different among the two countries with medium difference.

Further, the 'low enforecement' is the only barrier, which is seen significantly different between India and Germany with medium difference, as revealed from the data. Because of the problems with corruption and a lack of supervisory infrastructure, the enforecement of the legislation is not possible to the full extent in India. The situation is different in Germany where the rules and regulations are enfored to a great extent. All other barriers are found to be equal in both countries.

These elaborations have been driven by the objectives to strengthen drivers and mitigate barriers; as well as to find opportunities for the two countries to learn from each other for collaborative efforts. The decision makers in the manufacturing organizations can consider to adopt the same strategies to facilitate the drivers and to mitigate the barriers if these factors are equal and can reduce the risk of adopting unproven strategies which are not yet tested.

5 SCOPE OF FUTURE WORK

It will be interesting to do further research to strengthen the drivers and mitigate of the barriers. Equal attention cannot be paid to all the factors within the existing infrastructure in India. Addressing a few root factors seems a better approach for the implementation of GM. Hence, the study to establish the casual relationship among these factors can pinpoint those few root factors which should be addressed first.

6 NOTE

This paper is an extension of the research paper entitled 'Drivers and Barriers of Environmentally Conscious Manufacturing: A Comparative Study of Indian and German Organizations' published in 'Leveraging Technology for a Sustainable World, pp. 97-102, Springer Berlin Heidelberg [9].

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] Wright, R.T., Boorse, D.F. (2010) Environmental Science - Towards a sustainable future, 11th ed., PHI Learning Pvt. Ltd. New Delhi.

[2] Herrmann, C. (2010): Ganzheitliches Life Cycle Management – Nachhaltigkeit und Lebenszyklusorientierung in Unternehmen, Berlin/Heidelberg/New York.

[3] IEA (2007): Tracking Industrial Energy Efficiency and CO2-Emissions – In support of the G8 Plan of Action, http://www.iea.org/textbase/nppdf/free/2007/tracking_emissions.pdf (checked: 01/07/2011).

[4] Statistisches Bundesamt (2011): Produzierendes Gewerbe. Kostenstruktur der Unternehmen des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden. Wiesbaden (Fachserie 4, Reihe 4.3).

[5] http://www.defra.gov.uk/statistics/environment/green-economy/scptb11-emmbysector (checked: 28/10/2012).

[6] National Manufacturing Policy NMP (2011) National manufacturing Policy 2011 released by Ministry of Commerce and Industry, New Delhi.

[7] Duflou, J.R., Sutherland, J.W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M. and Kellens, K. (2012) Towards energy and resource efficient manufacturing: A processes and systems approach, CIRP Annals - Manufacturing Technology, Vol. 61, pp. 587-609.

[8] Reich-Weiser, C., Vijayaraghavan, A., Dornfeld, D. (2010): Appropriate use of Green Manufacturing Frameworks, http://www.escholarship.org/uc/item/10w7h9rb (checked: 01/07/2011).

[9] Mittal, V.K., Sangwan, K.S., Herrmann, C., Egede, P., Wulbusch, C. (2012) 'Drivers and Barriers to Environmentally Conscious Manufacturing: A Comparative study of Indian and German organizations. In: proc. Of the 19th CIRP International Conference on Life Cycle Engineering (LCE 2012), University of California, Berkeley, CA, USA.

[10] Luken, R., Van Rompaey, F. (2008): Drivers for and barriers to environmentally sound technology adoption by manufacturing plants in nine developing countries, in: J. of Cleaner Production, Vol. 16, No. 1, Supplement 1, pp. 67-77.

[11] Montalvo, C. (2008): General wisdom concerning the factors affecting the adoption of cleaner technologies: a survey 1990-2007, in: J. of Cleaner Production, Vol. 16, No. 1, pp. 7-13.

[12] Shi, H., Peng, S.Z., Liu, Y., Zhong, P. (2008): Barriers to the implementation of cleaner production in Chinese SMEs – government, industry and expert stakeholders' perspectives, in: J. of Cleaner Production, Vol. 16, No. 7, pp. 842-852.

[13] Allen, D., Bauer, D., Bras, B., Gutowski, T., Murphy, C., Piwonka, T., Sheng, P., Sutherland, J., Thurston, D., Wolff, E. (2002): Environmentally Benign Manufacturing – Trends in Europe, Japan, and the USA, in: Journal of Manufacturing Science and Engineering, Vol. 124, No. 4, pp. 908-920.

[14] Seidel, M., Seidel, R., Des, T., Cross, R., Wait, L., Hämmerle, E. (2009): Overcoming Barriers to Implementing Environmentally Benign Manufacturing Practices – Strategic Tools for SMEs, in: Environmental Quality Management, Vol. 18, No. 3, pp. 37-55.

[15] Zhu, Q., Geng, Y. (2010): Drivers and barriers of extended supply chain practices for energy saving and emission reduction among Chinese manufacturers, J. of Cleaner Production, Vol. 40, pp. 6-12.

[16] Mittal, V.K., Sangwan, K.S. (2011) Development of an interpretive structural model of obstacles to environmentally conscious technology adoption in Indian industry. In: proc. Of the 18th CIRP International Conference on Life Cycle Engineering (LCE 2011), TU, Braunschweig, Germany.

A Multi-objective Tolerance Optimization Approach for Economic, Ecological, and Social Sustainability

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Abstract

Sustainable design requires simultaneous consideration of the economic, ecological, and social consequences of design decisions. The selection of dimensional tolerances and materials are two such decisions that have impacts in all three of these areas. This article presents an optimization framework along with generalized models for considering sustainability and understanding how different aspects of sustainability may trade off with one another. A mobile phone design is used as a case study to demonstrate the strengths of the approach when varying manufacturing tolerance and material choice, and the results include three-dimensional Pareto frontiers illustrating the design tradeoffs.

Keywords:

Sustainable Design; Tolerance Analysis; Multi-objective Optimization

1 INTRODUCTION

The three pillars of sustainability, defined by Elkington as economic, ecological, and social, are frequently seen as competing objectives in product design and business strategies [1]. Companies have internal pressure from employees and stockholders to ensure economic sustainability and continued profits, which are often the highest priorities, but external pressures from governments, private organizations, and consumers are also increasingly driving environmentally and socially sustainable behavior. Today, a company that neglects environmental and social concerns faces risks that include lawsuits, lowered reputations, and government fines. Therefore, it is essential that designers and decision-makers take all three aspects of sustainability into consideration.

While the design of a product is not the sole factor that influences sustainability, design plays an important role in the material usage, manufacturing processes, use phase energy consumption, and end-of-life disposal strategy. Embodiment design decisions such as material choice and dimensional tolerances can influence all of these sustainability factors, and this paper presents an approach for optimizing these design decisions for economic, ecological, and social sustainability. This method produces multi-objective optimization solutions that reveal the extent to which the three objectives trade off, allowing designers to better understand their choices and select solutions that align with their corporate goals. The paper is organized as follows: The next section presents a background of the state of the art in relevant research, followed by a presentation of the method, specific models and results for the case of a mobile phone design, discussions, and conclusions.

2 BACKGROUND

This section presents techniques and findings from previous studies that are relevant to the present design approach. The approach can be divided into four parts: understanding how variation propagates and influences assemblability, quality, and waste, measuring the ecological impacts of actions, quantifying the effects of ergonomic loading, and performing multi-objective optimization.

2.1 Variation Analysis

Geometric variation is an inevitable part of manufacturing, as no two components will ever be produced exactly alike. Designers account for this phenomenon by specifying tolerances along with every geometric dimension, essentially saying that the actual product may deviate from the specified dimensions by up to some set amount. For product quality assurance, tighter tolerances are preferred, but these are associated with higher manufacturing costs and thereby comprise a design tradeoff.

Some geometric dimensions are visible to the consumer or contribute to the assemblability or functionality of the product, called *critical* or *functional* dimensions, but even those non-critical dimensions often contribute to the critical dimensions through variation propagation. A number of techniques are used for estimating how variation in one component or dimension contributes, or propagates, to variation in an assembly or critical dimension [2]. Depending on the complexity and structure of the product, variation propagation estimation techniques range from simple linear or linearized tolerance accumulation models to more complex statistical tolerancing and Monte Carlo simulation-based methods [3]. These tolerance propagation methods are commonly used for tolerance-cost optimization, for which the results depend strongly on the problem formulation. Some approaches first select targets for allowed variations in critical dimensions, which act as constraints in the formulation where the objective is to minimize costs [4]. In these cases, the results depend on the choice of target allowed variation, which is often not chosen in a rigorously scientific manner [5]. Other approaches to tolerance-cost optimization minimize loss functions that combine costs with approximated values of decreased quality to the manufacturer and customer [6],[7]. These results rely on meaningful models of how geometric variation contributes to some loss in quality on a monetary or monetary-equivalent level.

Another key assumption in variation analysis and optimization is in estimating the relationship between tolerances and manufacturing costs. Because this relationship depends on many environmental variables and can vary from company to company, researchers often construct and use simple mathematical functions such as linear, reciprocal, or exponential models [8].

2.2 Ecological Impact

Sustainable businesses are defined today not only by their economic viability, but also by their environmental responsibility. Commitments to protecting wildlife, neutralizing carbon emissions, reducing pollution, and minimizing resource consumption and waste are now seen as valuable corporate endeavors from a public relations perspective. This presents a challenge in accountability, comparability, and standardization in reporting and measuring ecological impacts, particularly when there are many disparate impact areas such as ozone depletion, global warming, resource consumption, landfill use, and human health-related risks.

Several databases, assessment methods, and software tools have been developed to help quantify the environmental impacts associated with different activities, but there is still no consensus on which metric to use and how to report the results. Eco-Indicator 99 is one such assessment method that categorizes all impacts into three damage levels: human health, ecosystem quality, and resources [9]. This database then has the capability to further normalize the impacts to one unit, which corresponds with the average yearly impact of a European resident. Another method that normalizes all impacts into a single unit is Environmental Priority Strategies in product design (EPS), which associates all activities with an Environmental Load Unit (ELU) corresponding with an environmental damage cost in Euros [10]. Still others, like the United States Environmental Protection Agency (US EPA) Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), keep the impact area reporting separate to allow decision-makers to choose for themselves which impacts are important for their specific scenarios [11].

2.3 Ergonomic Load

The third sustainability component regards social well-being, and many definitions of social sustainability go well beyond the scope of the product development process to include satisfaction of basic human needs, quality of life, social justice, and social coherence [12]. Product developing firms have social responsibilities regarding health, safety, and quality of life of employees, customers, end-users, and communities that are impacted by the product or production process [13]. The Lowell Center for Sustainable Production highlights six main aspects of sustainable production, one of which deals with worker well-being, and its fifth principle suggests that workplaces be designed "to continuously minimize or eliminate physical, chemical, biological, and ergonomic hazards" [14]. Employee physical and ergonomic well-being is of interest to the present analysis, particularly as a result of repetitive and physically-demanding motion during assembly processes.

For workers who assemble small parts with their hands, one common risk is the development of repetitive motion disorders (RMDs), which typically result from repetitive motions that require unnatural postures or forceful exertions [15]. The United States Bureau of Labor Statistics reported that approximately 3% of 2011 occupational injuries resulted from "repetitive motion involving microtasks", resulting in an average of 23 days leave from work [16]. A survey of Australian statistics estimates that this type of injury results in a cost to the company that is on average 21,000 Australian dollars [17]. Ergonomic load, or the force exerted during such repetitive tasks, is one measurement that employers should seek to decrease to lower worker injury rates, though an explicit relationship between loading and injury rates has not yet been established.

2.4 Multi-objective Optimization

Design optimization can be conducted for any problem that is modeled mathematically, as long as there is a clearly-defined objective function and a set of continuous or discrete variables [18]. A number of mathematical techniques can solve such optimization problems, the most common of which are gradient-based methods such as sequential quadratic programming, provided that the problem formulation is differentiable. When the problem has more than one objective function, multi-objective optimization is typically performed using weighted objectives. This follows the formulation shown in equation (1).

$$\min_x \sum_{i=1}^{N} w_i F_i \tag{1}$$

Here, the optimization objective is to minimize the sum of N objectives F_i multiplied by their respective weights w_i. Solving this problem with different values for the weighting factors typically yields different solutions. The set of these solutions makes up a Pareto frontier, where each point in the set represents a solution that cannot be improved in one objective without sacrifices to another objective.

3 MODELING APPROACH

The three sustainability objectives of companies revolve around economics, ecology, and social well-being. Design optimization for

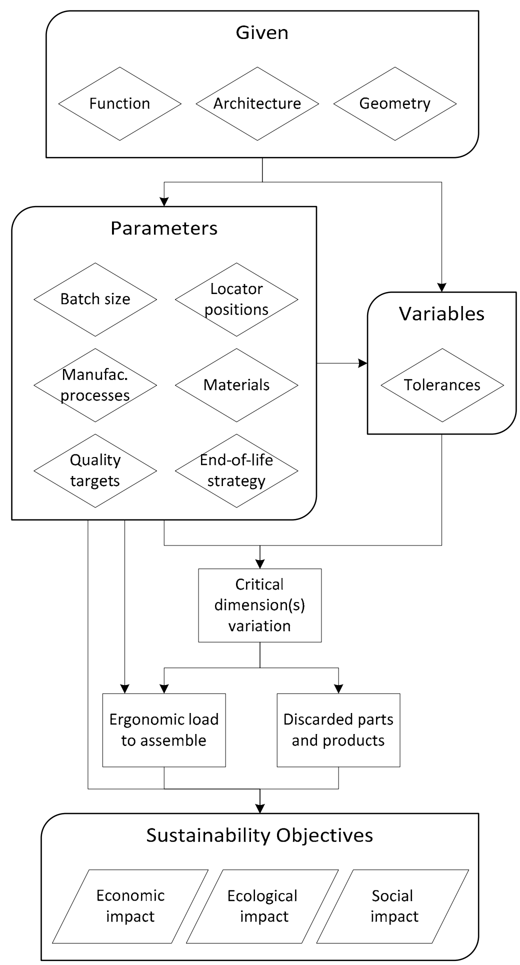

Figure 1: Framework for calculating sustainability outcomes.

improving a product's impacts in these areas requires models that predict the effects of changing certain variables and parameters. In this case, tolerances and material choice are the inputs of interest. A framework showing the relationship structure among the inputs and outputs is outlined in Figure 1.

3.1 Economic Sustainability

Firms are economically sustainable if they bring in more money than they spend. This framework only considers spending, in particular manufacturing costs, as the economic objective, since this is the component of economic sustainability most clearly affected by the variables and parameters of interest. If revenues and non-manufacturing costs do not change, a company should seek to lower its manufacturing costs to increase profits. Calculating these costs relies on several relationships: the ways that costs change with manufactured tolerances and material choices, how part tolerances propagate to influence assemblability and variation in critical dimensions of the assembly, and how critical dimension variation influences the quality and acceptability of the final product.

First, a cost-tolerance model must be chosen. Given the lack of available empirical data and following the choices in the literature [8], a reciprocal cost function is used, shown in equation (2) where C_{man} is the cost associated with manufacturing and t_i are the n manufactured tolerances.

$$C_{man} = \sum_{i=1}^{n} \frac{1}{t_i} \quad (2)$$

Manufacturers also must pay for the materials themselves, the costs of which depend on the choice of material as well as the quantity of material used in production. Equation (3) provides this relationship, where C_{mat} is the total material cost for the product, c_{mat} is the material cost per unit mass, and m is the mass.

$$C_{mat} = c_{mat} m \quad (3)$$

Next, variation propagation is modeled, which is associated with two outcomes: (1) the ability to physically assemble the parts without breaking them or imposing excessive internal stress in the product, and (2) the variation of critical dimensions in the assembled product. While the second of these outcomes typically dominates the first, i.e., parts that cannot be assembled would also have unacceptable critical dimensions, it is important to calculate both for understanding assembly ergonomics. Simple geometries can be modeled using mathematical relationships regarding statistical tolerancing and stress analysis. For more complex geometries, this is modeled using Monte Carlo simulations in RD&T, a software package specializing in variation propagation simulation and visualization [19]. This involves simulating the product geometry a large number of times with distributed input tolerances to generate a distribution of output variations. With these distributions, estimates can be made for the critical-to-assemble or critical-to-quality dimensional variation as a function of input tolerances, which can result in functions for $\varphi_{fail}(\boldsymbol{t})$, the percentage of parts that cannot be assembled, and $\varphi_{qual}(\boldsymbol{t})$, the percentage of products that do not meet the manufacturer's quality requirements and must be discarded, both of which are functions of $\boldsymbol{t}$, the vector of n input tolerances t_i.

When these quantities are correlated and failing assembly implies failure of the quality test, the formula for economic cost C can be written as equation (4).

$$C = \frac{\sum_{i=1}^{n} 1/t_i + c_{mat} m}{1 - \varphi_{qual}} \quad (4)$$

3.2 Ecological Sustainability

A product's ecological impact is also affected by the rate φ_{qual}, as discarding parts adds to the production and end-of-life phases of the lifecycle impact. To measure these impacts, however, the ecological consequences of producing and discarding parts and products must first be quantified. To do so in a comparable scale to the economic impact, the EPS framework is adopted for calculating the environmental impact of various activities in ELUs. Steen has developed a database that lists impacts of resource consumption E_{res}, material production E_{mat}, manufacturing processes E_{man}, energy generation or resource use in the use phase E_{use}, and disposal strategies E_{disp} [10]. Drawing from these databases and using the discard rates from the RD&T analysis, equation (5) represents the ecological impact E as it may relate to tolerances.

$$E = E_{use} + \frac{E_{res} + E_{mat} + E_{man} + E_{disp}}{1 - \varphi_{qual}} \quad (5)$$

3.3 Social Sustainability

The final sustainability component of the model regards ergonomic load, as higher forces required of assembly workers will likely result in more injuries. Employee injuries often result in worker compensation claims, giving companies a financial incentive to seek injury reduction, but they also have ramifications on personal health, employee morale, and the social structure of the workplace, which these companies should prioritize for social sustainability. In order to standardize the units among the three objectives, social sustainability is quantified in monetary terms from worker injury claims, but the analyses will show how optimization results change with different valuations and priorities toward worker injuries.

In assembly, ergonomic load requirements depend on the design of the components. Robust designs and tight tolerances correspond with lower forces required in assembly, since increased variation may cause locator positions to not align perfectly and require additional pressure from the workers to bend the materials and force the parts together. In hand assembly, workers are recommended to not exceed 10 newtons of routine force [20]. Due to a lack of specific injury risk data, this is assumed to carry a safety factor of 20, such that 200 newtons of force over a worker's lifetime corresponds with a 35% likelihood of one worker injury. For lack of a scientifically-validated hand injury probability curve and because these curves typically follow a Weibull function, the present analysis further assumes the structure of the femur injury probability curve used by the automotive industry [21]. This equation is scaled down by a factor of 1,000 and given as equation (6), where the force requirement F in newtons is ultimately a function of input tolerances $\boldsymbol{t}$. The specific function for F depends on the application, but in general it can follow the stress-strain relationship of equation (7), where σ is stress, A is cross-sectional area, δ is the distance compressed depending on $\boldsymbol{t}$, L is the total length, and E is the material-specific modulus of elasticity.

$$P_{injury} = \left(1 + e^{5.795 - 0.5196 F/20}\right)^{-1} \quad (6)$$

$$\sigma = F/A = \frac{\delta(\boldsymbol{t})}{L} \mathrm{E} \quad (7)$$

Once calculated, the probability of injury over the career of a worker P_{injury} is associated with a financial cost of injury-related leave L. Multiplying this by W, the number of worker-lifetimes needed to manufacture the full product line, and C_{injury}, the average economic cost per worker injury, and dividing by the number of total products produced $N_{product}$, L is calculated using equation (8).

$$L = \frac{W \cdot C_{injury}}{N_{product}} P_{injury} \quad (8)$$

3.4 Optimization

Using the models described in this section, an optimization formulation can be constructed following equation (1). Here, the three objectives are cost C, ecological impact E, and social cost of injury-related leave L. When the weighting is equal, i.e., $w_C = w_E = w_L$, a single solution dictates the optimal tolerance choices and outcomes. However, it is interesting to see how the outcomes may change when societies and corporations value the three sustainability pillars unequally, and so Pareto frontiers are used to show the relationships and tradeoffs among the objectives.

4 CASE STUDY: MOBILE PHONE

The approach of Section 3 is demonstrated through the design scenario of a touch-screen mobile phone. This section describes the modeling process and an analysis of the optimization results for this example case, revealing the capabilities of the approach detailed in the previous section.

4.1 Case-specific Models

The mobile phone of interest is pictured in Figure 2a, and the main components are a front and a back piece joined by four snap connectors, shown on the inside of the back piece in Figure 2b.

(a) (b)

Figure 2: Mobile phone model, (a) assembled and (b) back part.

Each of the four snap connectors on the top and bottom has a defined tolerance in both the lateral and longitudinal directions, for a total of sixteen tolerance inputs. Since these are form features of two symmetric parts, all of them are set to the same value, t. These tolerances affect two assembly outcomes: (1) the flushness of the edges of the two pieces, which can be measured by the alignment of the four corners between the front and back pieces, and (2) the ability to assemble the four snap connectors without excessive internal stress in the parts. The first of these outcomes is a perceivable quality concern, and the manufacturer is assumed to discard any device where the deviation on any corner exceeds one millimeter. The second regards assemblability; here, the assembly is prescribed by three locator points corresponding with three of the snaps, and the assemblability is defined by how well the fourth snap in the upper-left corner of the device aligns between the front and back pieces. Larger deviations between the fourth snap locations on the two pieces indicate more stress required during assembly and therefore a larger probability of the parts cracking or the assembly worker developing a repetitive motion injury.

First, the relationships between the tolerances and outcomes are studied using a Monte Carlo simulation over a range of input tolerances. The tolerances t were simulated with 300 values ranging from 0.01 to 3.0, and the resulting means and standard deviations of the outputs were recorded and fit to linear models as functions of t. The two corner measures at the top of the phone had equal and substantial output variation, and the corner deviations at the bottom of the phone were relatively insignificant. Quality is thus characterized by the mean and standard deviation of the top-right corner alignment, denoted μ_q and σ_q, and similar values for the top-right snap locator which define assemblability are denoted μ_a and σ_a. The regression models are given as equations (9-12), all of which fit with a coefficient of determination of at least 0.999.

$$\mu_q = 0.6055t \quad (9)$$

$$\sigma_q = 0.3896t \quad (10)$$

$$\mu_a = 0.08406t^2 + 0.1439t \quad (11)$$

$$\sigma_a = 0.05798t^2 + 0.2050t \quad (12)$$

Since the absolute values are represented here with means near zero, a folded normal distribution is assumed [22]. Thus, with quality target T_q representing the permitted variation, the cumulative distribution function is used to calculate φ_{qual} in equation (13).

$$\varphi_{qual} = 1 - \int_0^{T_q} \frac{1}{\sigma_q\sqrt{2\pi}} e^{-\frac{(-x-\mu_q)^2}{2\sigma_q^2}} dx - \int_0^{T_q} \frac{1}{\sigma_q\sqrt{2\pi}} e^{-\frac{(x-\mu_q)^2}{2\sigma_q^2}} dx \quad (13)$$

A similar formulation can be used for φ_{fail} when an assemblability threshold T_a exists, shown in equation (14). In this scenario, there is also a need for the distribution of this output, as it affects ergonomic load patterns. The probability distribution function f_{snap} is given as equation (15) for top-right snap offset δ, which depends on t.

$$\varphi_{fail} = 1 - \int_0^{T_a} \frac{1}{\sigma_a\sqrt{2\pi}} e^{-\frac{(-x-\mu_a)^2}{2\sigma_a^2}} dx - \int_0^{T_a} \frac{1}{\sigma_a\sqrt{2\pi}} e^{-\frac{(x-\mu_a)^2}{2\sigma_a^2}} dx \quad (14)$$

$$f_{snap}(\delta|\mu_a, \sigma_a) = \frac{1}{\sigma_a\sqrt{2\pi}} e^{-\frac{(-\delta-\mu_a)^2}{2\sigma_a^2}} + \frac{1}{\sigma_a\sqrt{2\pi}} e^{-\frac{(\delta-\mu_a)^2}{2\sigma_a^2}} \quad (15)$$

For this product, it is observed that all products failing assembly will also fail the quality test, following cost equation (4). With only one tolerance specification and a fixed product volume of 7.6 cubic centimeters, cost can be calculated as equation (16), where ρ is the material density in kg/cm^3, found along with the c_{mat} data in [23].

$$C = \frac{1/t + 7.6\rho c_{mat}}{1 - \varphi_{qual}} \quad (16)$$

Since the use phase impact of a mobile phone is primarily the electricity consumption, which is unrelated to tolerance and outer shell material choices, it is left out of the ecological sustainability calculation. This reduces equation (5) to equation (17), where the material-based values for the E_is are found in [10].

$$E = \frac{E_{res} + E_{mat} + E_{man} + E_{disp}}{1 - \varphi_{qual}} \quad (17)$$

The front and back pieces are expected to require elastic bending during assembly when the locator snaps do not line up correctly, and so force is calculated as a function of deflection distance, or the top-right snap offset δ. This is calculated using equation (7), where the cross-sectional area diagonally across the device is 130 square millimeters and the total length being compressed is 130 millimeters. The relationship is given in equation (18), where F is force in newtons and E is the material-specific modulus of elasticity in megapascals, found in [23].

$$F = \frac{130\delta \text{E}}{130} = \delta \text{E} \quad (18)$$

Finally, this force affects the likelihood of worker injury. Because F is not constant for every device assembled, the probability distribution from equation (15) is multiplied by the injury probability and integrated across the range of δ values to develop an expected injury probability per worker. This is then multiplied by the economic cost of an injury to a firm. Assuming 1,000 worker-lifetimes to create 10 million total products, and each injury costs the company an average €20,000 through a combination of worker compensation claims, paid leave, and other expenses, the financial cost of injury-related leave L is calculated as equation (19). Recalling equations (11), (12), and (15), this is ultimately a function of tolerance input t.

$$L = \frac{(1000)(20000)}{10000000} \int_0^{\delta_{max}(t)} P_{injury}(\delta) f_{snap}(\delta) d\delta \quad (19)$$

Here, $\delta_{max}(t)$ is the highest expected deviation given the maximum allowed variation T_q, which can be calculated using the means and standard deviations of the quality and assemblability variations from equations (9-12).

With C, E, and L as explicit functions of tolerances and materials, the tri-objective sustainability optimization formulation is complete.

4.2 Results

The optimization was first solved with all weights set equal, using ABS plastic and end-of-life disposal in a landfill. The results give an optimal design with tolerance t of 1.053 mm, which corresponds with an economic manufacturing cost C of €1.19, ecological cost E of 0.02 ELU, and worker injury costs L of €1.60. While this is an interesting result, the numbers are based on models that hold many assumptions. The present model is most useful to understand the tradeoffs among the objectives when the weighting changes.

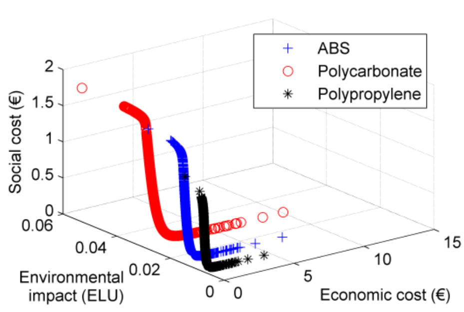

Figure 3: Three-dimensional Pareto curves.

Solving the same problem ten thousand times with different randomly-selected weights w_C, w_E, and w_L generates a three-dimensional Pareto frontier showing the tradeoffs among the economic, ecological, and social objectives. Since the problem only contains one variable, this frontier is a curve following a single path as the optimization suggests tighter or wider tolerances. This curve, depicted for three different materials in Figure 3, travels as the optimal tolerance increases from solutions with high C and low E and L values to those with lower C and higher L values to those with still lower C and higher E values.

Cross-sectional views of Figure 3 show more about the shape of the curves and the ways the material choice can influence the outcomes. A cross-section perpendicular to the “environmental impact” axis examines the first tradeoff as the optimum moves from the tightest tolerances toward looser tolerances, shown in Figure 4. This corresponds with initially decreasing economic costs and increasing social costs. Here, the size of the box corresponds with the tolerance, so a larger box indicates a wider optimal tolerance.

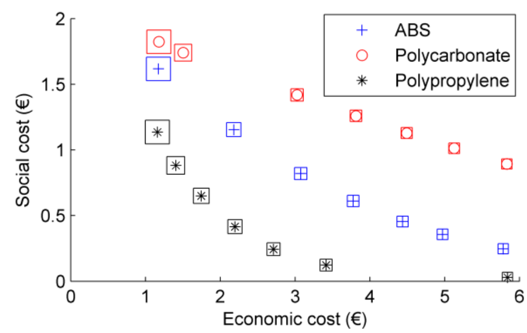

Figure 4: Tradeoff between economic and social objectives.

As the tolerances become even wider, economic cost continues to decrease and environmental impact begins to increase. This behavior is shown with a cross-section perpendicular to the “social cost” axis in Figure 5.

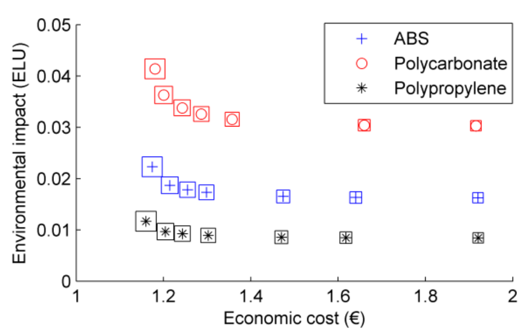

Figure 5: Tradeoff between economic and ecological objectives.

For both of the tradeoffs shown, polypropylene appears to be the most sustainable material choice, as it affords better solutions with respect to all objectives than those of ABS and polycarbonate.

5 DISCUSSION

Using multi-objective optimization for tolerance and material choices can reveal tradeoffs among sustainability objectives for economic, ecological, and social outcomes. The results presented in the previous section for the mobile phone case study show how, even with only one design variable, a firm’s and designer’s sustainability priorities can significantly influence the optimal design and outcomes. Depending on the objective function weighting, the solution may converge on any feasible tolerance choice within the allowed range. This behavior is due to the specific structure of the models used, as economic objectives demand wider tolerances while ecological and social objectives push for tighter tolerances.

In a scenario with more than one tolerance variable to be optimized, the three-dimensional Pareto frontier may consist of a convex surface rather than a single path through space. Each point on the surface would correspond with an optimal combination of the design variables and the associated sustainability outcomes.

As with any modeling work, additional considerations could be included to make for a more complete formulation. From an economic perspective, more information about specific cost-tolerance relationships as well as revenue-related models might be added. The ecological modeling might include additional considerations or variables such as the source of materials, manufacturing processes, and the impact of low-quality products failing early and needing replacement. The characterization of social sustainability could benefit from an empirical relationship between loading, frequency, and hand injuries, as well as additional injury or social well-being considerations for both the employees and the customers. The value of including such additional models depends on the case of interest, and this is left for future research and practical applications.

6 CONCLUSIONS

To make truly sustainable design decisions, all three of the sustainability pillars must be considered in the product modeling and optimization processes. Sustainable tolerancing must consider the economic impacts of material and manufacturing costs, the ecological impacts of material resources, processing, and disposal, and the social impacts of worker injuries. This paper demonstrates how an explicit tri-objective optimization formulation can inform sustainability decisions in tolerancing and material choice. Rising interest in ecological and social sustainability by policymakers and consumers is expected to further link these three objectives for when a manufacturer seeks to maximize its profits from a product.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] Elkington, John (1997): Cannibals with Forks: The Triple Bottom Line of 21st Century Business, Capstone, Oxford.

[2] Bjørke, Ø. (1989): Computer-Aided Tolerancing, 2nd Edition, ASME Press, New York.

[3] Hong, Y.S., Chang, T.C. (2002): A Comprehensive Review of Tolerancing Research, in: International Journal of Production Research, Vol. 40, No. 11, pp. 2425-2459.

[4] Ostwald, P.F., Huang, J. (1977): A Method for Optimal Tolerance Selection, in: Journal of Engineering for Industry, Vol. 99, No. 3, pp. 558-565.

[5] Hoffenson, S., Dagman, A., Söderberg, R. (2012): A Tolerance Optimization Framework for Economic and Ecological Sustainability, submitted to Journal of Mechanical Design (12 October).

[6] Söderberg, R. (1993): Tolerance Allocation Considering Customer and Manufacturer Objectives, in: B.J. Gilmore (ed) Advances in Design Automation, Albuquerque, ASME, pp. 149-157.

[7] Cheng, B.-W., Maghsoodloo, S. (1995): Optimization of Mechanical Assembly Tolerances by Incorporating Taguchi's Quality Loss Function, in: Journal of Manufacturing Systems, Vol. 14, No. 4, pp. 264–276.

[8] Chase, K.W., Parkinson, A. R. (1991): A Survey of Research in the Application of Tolerance Analysis to the Design of Mechanical Assemblies, in: Research in Engineering Design, Vol. 3, No. 1, pp. 23–38.

[9] The Netherlands Ministry of Housing, Spatial Planning and the Environment (2000): Eco-indicator 99 Manual for Designers, online: http://www.pre-sustainability.com/, accessed 30 August 2012.

[10] Steen, B. (1999): A Systematic Approach to Environmental Priority Strategies in Product Development (EPS), Version 2000 – General System Characteristics, technical report: Chalmers University of Technology, Technical Environmental Planning.

[11] Bare, J.C. (2002): The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, in: Journal of Industrial Ecology, Vol. 6, Nos. 3-4, pp. 49-78.

[12] Littig, B., Grießler, E. (2005): Social Sustainability: A Catchword between Political Pragmatism and Social Theory, in: International Journal of Sustainable Development, Vol. 8, Nos. 1-2, pp. 65-79.

[13] Labuschagne, C. (2005): Sustainable Project Life Cycle Management: Development of Social Criteria for Decision-Making, Doctoral Thesis, Department of Engineering & Technology Management, University of Pretoria, Pretoria.

[14] Veleva, V., Ellenbecker, M. (2001): Indicators of Sustainable Production: Framework and Methodology, in: Journal of Cleaner Production, Vol. 9, No. 6, pp. 519-549.

[15] Redcross, E.L., Marvin, S. (2011): Is Your Assembly Line Ergonomic? in: Assembly Magazine, June Issue, pp. 32-35.

[16] U.S. Bureau of Labor Statistics (2012): Nonfatal Occupational Injuries and Illnesses Requiring Days Away from Work, 2011, news release: No. USDL-12-2204, 8 November 2012.

[17] Rehabilitation and Compensation Section (2010): Workplace Injuries Statistical Report 2010, WorkCover, Tasmania.

[18] Papalambros, P.Y., Wilde, D.J. (2000): Principles of Optimal Design, Cambridge University Press, Cambridge.

[19] Söderberg, R., Lindkvist, L. (1999): Computer Aided Assembly Robustness Evaluation, in: Journal of Engineering Design, Vol. 10, No. 2, pp. 165-181.

[20] Kroemer, K.H.E., Grandjean, E. (1997): Fitting the Task to the Human, Fifth edition, Taylor & Francis, London.

[21] Eppinger, R., Sun, E., Bandak, F., Haffner, M., Khaewpong, N., Maltese, M., Kuppa, S., Nguyen, T., Takhounts, E., Tannous, R., Zhang, A., Saul, R. (1999): Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems – II, technical report: National Highway Traffic Safety Administration, Washington.

[22] Leone, F.C., Nelson, L.S., Nottingham, R.B. (1961): The Folded Normal Distribution, in: Technometrics, Vol. 3, No. 4, pp. 543-550.

[23] Ullman, D.G. (2003): The Mechanical Design Process, Third edition, McGraw Hill, Boston.

Erratum: Optimising Compressed Air System Energy Efficiency – The Role of Flow Metering and Exergy Analysis

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In the original version of this article some information are given wrong. They should read as follows:

1. In section 3.2 (page 130), the text should read "lead to an additional 3% to 8% error due to density differences..." instead of "80% error".
2. In section 5.1, table 4, the adiabatic specific power should be "Nm^3/min" instead of "Nm3/min".

The original online version for this chapter can be found at
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