Sustainable Production, Life Cycle Engineering and Management

Series Editors: Christoph Herrmann, Sami Kara

Tim Heinemann

Energy and Resource Efficiency in Aluminium Die Casting

Springer

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Series editors

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Modern production enables a high standard of living worldwide through products and services. Global responsibility requires a comprehensive integration of sustainable development fostered by new paradigms, innovative technologies, methods and tools as well as business models. Minimizing material and energy usage, adapting material and energy flows to better fit natural process capacities, and changing consumption behaviour are important aspects of future production. A life cycle perspective and an integrated economic, ecological and social evaluation are essential requirements in management and engineering. This series will focus on the issues and latest developments towards sustainability in production based on life cycle thinking.

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Energy and Resource Efficiency in Aluminium Die Casting

Springer

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Foreword

Manufacturing is at the centre of the economies of most industrialised countries. It is also crucial for developing and emerging economies, as it helps them work towards a higher standard of living. However, manufacture of products and goods also causes environmental concerns especially linked to CO_2 emissions. A combination of easily available cheap fossil fuels, together with growing demand and populations and the drive to increase GDPs, have significantly increased CO_2 emissions and global warming beyond agreed targets. As such, there is a pressing need for efficiency measures and innovations within the manufacturing stage and the associated up- and downstream manufacturing. The major share of energy consumption and CO_2 emissions related to the manufacturing of infrastructure and goods can be attributed to just five materials: steel, cement, paper, plastics and aluminium.

In Germany, the Federal Ministry of Education and Research (BMBF) has called for proposals to increase energy and resource efficiency in different areas of manufacturing. The supported research project ProGRess was the base for Tim Heinemann's work, looking at the aluminium die casting industry, which accounts for about one-fifth of the yearly global aluminium product output.

The presented approach includes a view on production from process up to the value chain level to identify potentials towards energy and resource efficiency. Detailed data about energy and resource flows along the value chain are presented on each hierarchical level. Based on this, a generic model of energy and resource flows along the aluminium die casting value chain is presented and used as a reference for the assessment of diverse improvement measures.

The developed framework provides a definition of hierarchically organised production systems, a procedural approach towards energy and resource efficiency and a methodological toolbox for a synergetic application of methods/tools, which can be easily adapted to other industries. The work provides valuable guidance for manufacturing companies to improve their energy and resource efficiency.

With this published work as well as with his active role, Tim Heinemann has strongly contributed to build up of “Die Lernfabrik” in Braunschweig and to foster the development of the Joint German-Australian Research Group “Sustainable Manufacturing and Life Cycle Engineering”.

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As a research associate at the Institute of Machine Tools and Production Technology, I was part of an outstanding team of highly motivated colleagues, who have become close friends. Dear colleagues, I thank you very much for creating such an inspirational, collaborative and positive atmosphere and for the great teamwork. In particular, I want to thank Dr. Sebastian Thiede for his very personal and stimulating guidance through the past years and for his exceptional effort in reviewing my thesis. Furthermore, I want to thank Dr. Mark Mennenga and Dr. Gerrit Posselt, who have accompanied me during the past years at the institute and who have conducted their theses in parallel. It was a pleasure to work with you, to bring our theses and several joint projects to a successful ending and to have such great teammates! A special thanks goes also to my officemates Patricia Egede and Malte Schönemann for the fruitful discussions across all sorts of academic topics, the mutual motivation and recreative lunch breaks during the last years.

Above all, I thank my family, who has enabled me to conduct my studies and my research project and to finalise my thesis. Dear mum and dad, I would have loved to celebrate the end of this project with both of you…

Lovely and endless thanks go to my wife Kerstin Heinemann and my little sons for their selfless understanding and exceptional support during the last months, while finalising this book. I know, you have had tough times and I have missed far too much of our family time. I cannot express how much I owe you for your sacrifices and your infinite love. I dedicate this book to my sons. Maintain your playful curiosity and pure lust for life!

Thank you!

Braunschweig Tim Heinemann
March 2015

Contents

Symbols and Abbreviations

Symbols

Symbol	Description
E	Energy (J, kWh, $\frac{kg}{m^2\,s^2}$)
F	Force (N, $\frac{kg}{m\,s^2}$)
m	Mass (kg, t)
i, *j*, *m*, *n*	Counting indices (–)
T	Temperature (°C, K)
t	Time (s, min, d)

Abbreviations

ABS	Agent-based simulation
Al	Aluminium
BAT	Best available technology
BOF	Basic oxygen furnace
ca.	Circa
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2eq.	Carbon dioxide equivalent
CO_x	Carbonic oxides
Cu	Copper
DIN	Deutsches Institut für Normung/German Institute for Standardization
DSD	Duales System Deutschland (German waste separation system)
EAF	Electric arc furnace
EDRP	Energy Demand Research Project

e.g.	Exempli gratia, for example
eq.	Equivalent
EoL	End-of-life
ESO	Energy systems optimisation
EU	European Union
GDM	Generic design model
HCl	Hydrogen chloride
HF	Hydrogen fluoride
HLA	High-level architecture
IT	Information technology
KaCl	Potassium chloride
LCA	Life cycle assessment
LCI	Life cycle inventory
max.	Maximum, maximal
MFCA	Material flow cost accounting
MIKADO	Model of the environmental impact of an aluminium die casting plant and options to reduce this impact
min.	Minimum, minimal
min	Minute
Mg	Magnesium
Mn	Manganese
MP	Manufacturing process
NaCl	Sodium chloride
NADCA	North American Die Casting Association
Ni	Nickel
NMVOC	Non-methane volatile organic compound
no.	Number
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
OEE	Overall equipment effectiveness
PC	Process chain
pc	Piece
prim.	Primary
ProGRess	Gestaltung ressourceneffizienter Prozessketten am Beispiel Aluminium-druckguss (research project)
ren.	Renewable
RTD	Real-time display
SD	System dynamics
sec	Secondary
Si	Silicon
SME	Small and medium enterprise
SO_x	Sulphur oxides

THD	Total harmonic distortion
Ti	Titanium
UK	United Kingdom of Great Britain and Northern Ireland
U.S.	United States of America
VOC	Volatile organic compound
Zn	Zinc

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Chapter 1
Introduction

This chapter explains the motivation for this work and its structure. The structure of this book is induced by central objectives, which correlate to the general motivation.

1.1 Motivation

Most worldwide economies strive to ensure and increase their citizens' quality of life. Thus, they strive to maximise the income per capita and to translate it into means of a quality of life (BCG 2013). This positive, and often wealth-oriented, motivation is complemented by the United Nations millennium development goal, to eradicate extreme poverty and hunger. As a consequence of the millennium development goal formulation and its resulting actions, the target to cut extreme poverty rates into halves was already met five years ahead of the deadline in 2015 (UN 2012).

The increase in worldwide wealth is closely linked to industrial progress and growth (Bormann et al. 2009; Meadows et al. 1972). Thus, industrial growth could be evaluated as a wise strategy for human well-being. However, a major risk for the population's well-being results from industrial production as well. Until today, industrial growth has always been correlated to increasing carbon dioxide (CO_2) emissions, which are a major cause for global climate change (IPCC 2014; UNEP 2011a).

Figure 1.1 shows the sources of global CO_2 emissions (Allwood and Cullen 2012). It indicates that about two thirds of the global CO_2 emissions are caused by the generation of energy carriers or related processes. Industry accounts for about one third of this share, which equals a yearly emission of 10 Gt of CO_2. The industrial carbon dioxide emissions are mainly driven by the generation and processing of five materials, which together account for 55 % of the industrial CO_2 emissions. One of these relevant materials is aluminium, which causes about 3 % of the global industrial emissions (Allwood and Cullen 2012).

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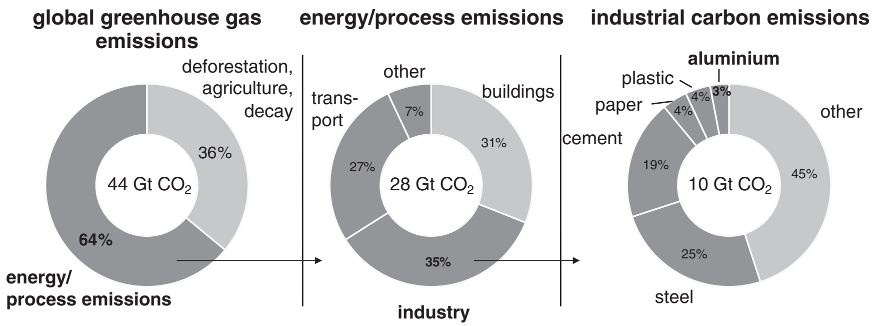

Fig. 1.1 Sources of global CO_2 emissions (Allwood and Cullen 2012)

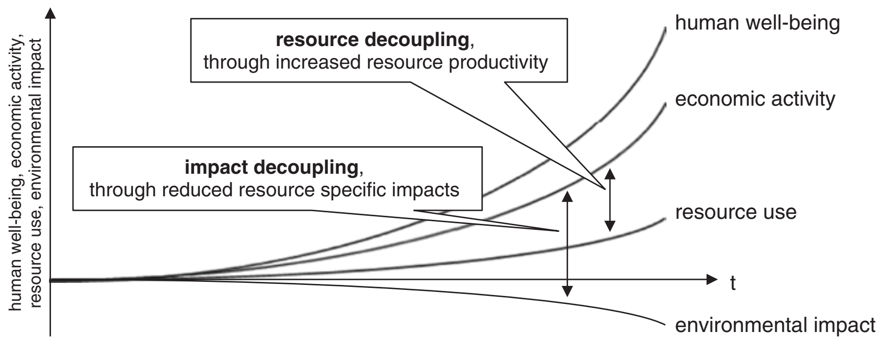

Fig. 1.2 Decoupling of resource use and environmental impact from human well-being and economic activity (UNEP 2011a; Bringezu 2006)

One important technology for the processing of aluminium into final products is the aluminium die casting technology. About 20.1 % of globally produced final aluminium products in the year 2007 have been produced in a die casting process (gravity or high pressure die casting). The share of die casted aluminium products is increasing e.g., due to its feasibility for lightweight design, which plays an important role, e.g., in automotive design. Thus, with continuing worldwide wealth and consumption of (luxury) goods the amount of die casted products will also increase (Cullen and Allwood 2013; Stich 2013).

To ensure future well-being without overexploitation of natural resources and causing environmental harm, economic activity and well-being need to be decoupled from resource use and environmental impacts. This can be achieved through increased resource productivity and reduced resource specific impacts (see Fig. 1.2; UNEP 2011a; Bringezu 2006; Meadows et al. 1972).

The first activities to reduce especially the environmental impact of the aluminium industry have already been started. However, *Cullen and Allwood* state that up to the present, these efforts have mainly focused on the decarbonising of energy supplies, while disregarding other fields of action (Cullen and Allwood 2013).

Additionally, the International Energy Agency states that only a few clean energy technologies are currently available (IEA 2014). Thus, according to *Cullen and Allwood*, “a shift in attention toward the demand side [of aluminium and energy carriers]” is recommended (Cullen and Allwood 2013).

Therefore, this book focuses on methodological support for reducing the energy and resource demand of the aluminium die casting technology. An aggravating factor to this challenge is that especially industrial production is a very complex system regarding its dynamic behaviour and externally enforced flexibility (e.g. ElMaraghy 2014; Efthymiou et al. 2012). This flexibility comes from e.g. increasing product variances and shortened product life cycles (e.g. Herrmann 2010; Günthner et al. 2006).

Besides this perspective on the dynamic behaviour and flexibility of production, the complexity of production systems can be addressed specifically also by regarding their physical and functional structure. Production systems can be decomposed into large numbers of multifaceted sub-systems and system elements respectively functions and functional elements (e.g. Bergmann 2010; Wiendahl 2009; Ke et al. 2013). Thus, methodological support, as well as measures for reducing the energy and resource demand of industrial production, can tackle manifold system levels and actors. Against this background, this book provides methodological support for the generation and comparison of improvement measures towards energy and resource efficient industrial production.

1.2 Research Objective and Approach

Against the described challenge of necessary energy and resource efficiency enhancements in complex, hierarchically organised production systems (especially for the case of aluminium die casting), the central objectives of this research can be formulated as follows:

1. To develop an approach, which synergetically assigns methods and tools towards an energy and resource efficient, hierarchically organised industrial production.
2. To apply this approach extensively to aluminium die casting.

These central objectives induce the structure of this book, which is shown in Fig. 1.3. It also reflects the sub-goals for achieving the central objectives and relates them to the proposed structure of this research approach.

After this introduction the necessary technical background about hierarchically organised production and the technical specifications of aluminium die casting are explained in Chap. 2. Thereby, the sub-goal of a

technical analysis of structures and impacts of the aluminium die casting technology

gets fulfilled. Based on this technical background, current research approaches are reviewed in Chap. 3. This review on the state of the research is conducted to

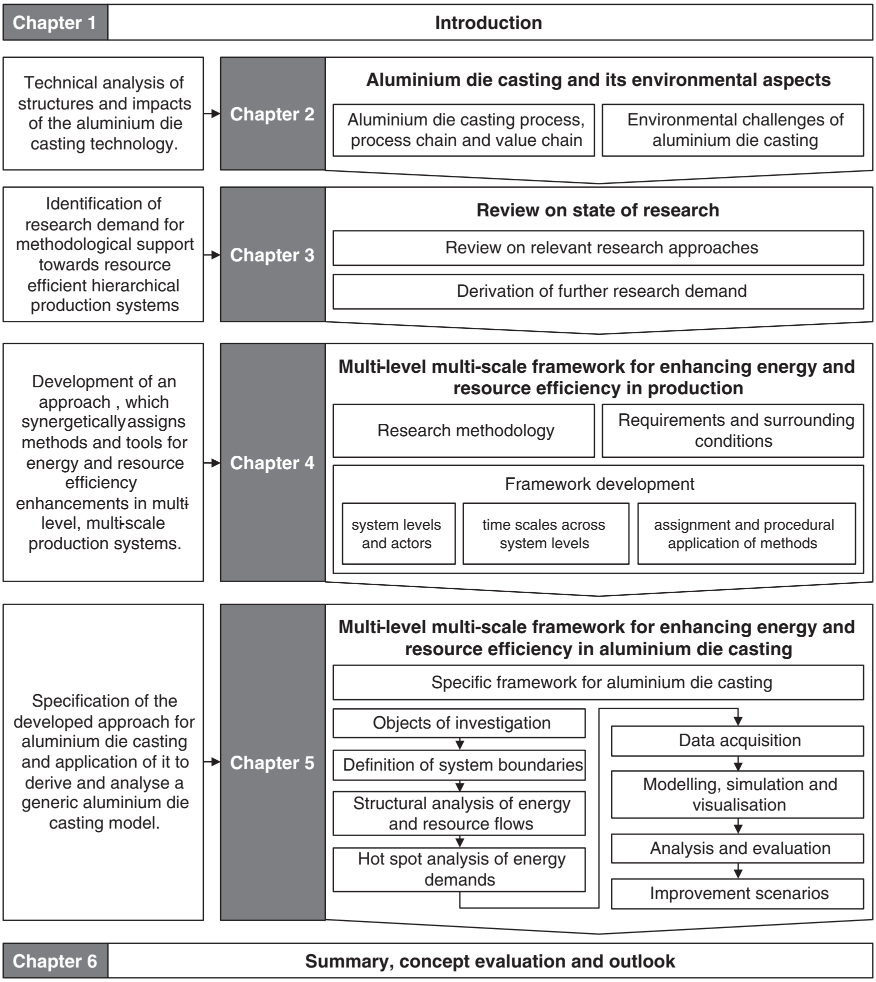

Fig. 1.3 Objectives and related structure of the research approach

> identify research demand for methodological support towards resource efficient hierarchical production systems.

Regarding the current deficits of the state of research, this work shall contribute to it by pursuing the sub-goal, which determines the content of Chap. 4:

> Development of an approach, which synergetically assigns methods and tools for energy and resource efficiency enhancements in multi-level, multi-scale production systems.

The development of this approach builds upon an analysis of further requirements and surrounding conditions. Therefore, a joint perspective on system levels and actors, varying time scales per system level and on a synergetic assignment of available methods gets formulated and synthesised in an integrated framework.

This multi-level and multi-scale framework for enhancing energy and resource efficiency in production is of a generic nature. However, to fulfil the aforementioned second central objective, a specific approach for aluminium die casting in particular shall also be deduced. Therefore, Chap. 5 aims to fulfil the following sub-goal:

> Specification of the developed approach for aluminium die casting and application of it to derive and analyse a generic aluminium die casting model.

A result of the application of the developed approach in Chap. 5 is a generic model of energy and material flows in aluminium die casting. As a basis for the derivation of this model, extensive and detailed studies on twelve value chains are conducted. These field studies include a structural analysis of energy and material flows in aluminium die casting in combination with a detection of hot spots along the value chain. This is followed by detailed activities for data acquisition, modelling, simulation and evaluation of the detected flows. Thus, a quantitative model can be deduced as a representative entity for aluminium die casting in general. With the help of this model, a selection of improvement measures can be virtually implemented and evaluated to rank their improvement potential and to derive recommendations for action.

Chapter 6 concludes this work with a summary and critical evaluation of the developed approach. Based on this critical review, fields of action for further research can be identified.

Chapter 2
Aluminium Die Casting and Its Environmental Aspects

Against the scope and objectives of the planned research work, this chapter provides the necessary theoretical background about hierarchically organized industrial value chains, the aluminium die casting process, the connected chain of upstream and downstream processes and the resulting challenges for energy as well as resource intensity of die casted products. Therefore this chapter serves as a basis for the later derivation of further research demand in order to increase the energy and resource efficiency of the aluminium die casting value chain.

2.1 Industrial Value Chains and Aluminium Die Casting

The present section introduces the aluminium die casting technology from a technical perspective. As this technology can be viewed as a hierarchically organised production system, corresponding system levels from the process level to the value chain level are introduced before.

2.1.1 Industrial Process, Process- and Value Chains

2.1.1.1 Manufacturing Process

A process is defined as a transformation of inputs of a system to outputs of the same system (Denkena and Tönshoff 2011). This implies that a process can relate to manifold entities at different levels of size and complexity. A manufacturing process therefore is a process within a production system (Dyckhoff and Spengler 2007). This specific process uses and transforms inputs like operating resources, human labour, physical materials, etc. into valuable outputs (wanted products) and non-valuable outputs (not wanted products, emissions and waste) (see Fig. 2.1; Schenk et al. 2014).

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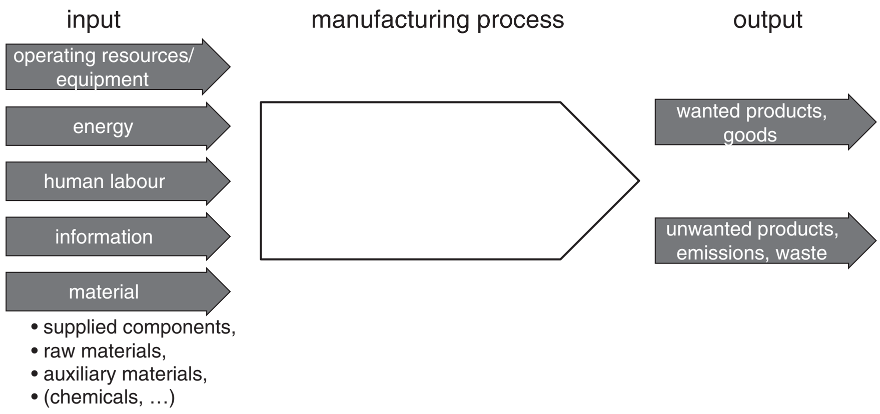


Fig. 2.1 The manufacturing process as a transformation process (according to Schenk et al. 2014)

2.1.1.2 Process Chains

The term process chain can be found in literature in manifold contexts e.g. in business administration, natural sciences as well as engineering sciences like production engineering. Even within these disciplines this term can have different meanings. In production engineering the term process chains is used to describe the following subjects (Schäfer 2003):

- interlinked product life cycle phases
- combination of logistical handling, transportation and storage processes
- linkage of design phases in the product creation process
- integrated usage of harmonised data formats and data sets for information and data processing in product design, manufacturing, production planning and quality assurance
- sequence of manufacturing processes in manufacturing engineering

The further discussion will be based on the last mentioned interpretation of the term process chain, whereas the energy and resource consumption of interlinked sequences of manufacturing processes will be especially considered. To enrich this perspective, also some aspects from a logistical perspective on process chains will be incorporated as well as supporting peripheral activities, which provide defined conditions for the considered manufacturing processes.

Therefore, the process chain in production engineering describes a sequence of value adding manufacturing processes as well as auxiliary processes (e.g., handling and transportation) and peripheral processes, which are coupled through a common material flow. The sequence of value adding processes transforms the condition of input materials from an initial state to a predefined final state (Eichgrün 2003; Reinhardt 2013; see Fig. 2.2).

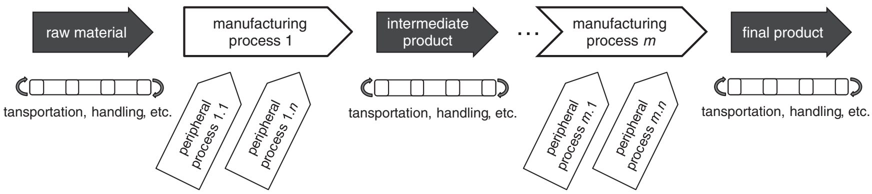


Fig. 2.2 Simplified manufacturing process chain with auxiliary and peripheral processes

2.1.1.3 Industrial Value Chains

Production is a value adding process (see Fig. 2.3). Value gets created in every process chain that transforms simple or complex parts or materials into more valuable goods (Günther and Tempelmeier 2012).

In our modern and globalized world not all of the necessary processes are performed at one single place and within one single enterprise. Rather an increasing (international) division of labour in order to generate value can be observed. The single (globally) distributed entities, which include and control an own internal manufacturing process chain, collaborate to produce final products and generate value. They constitute a value chain (Günther and Tempelmeier 2012; Westkämper and Warnecke 2010). Therefore, from a production engineering perspective an industrial value chain can be perceived as a cross company network, which integrates several intra-company process chains (see Fig. 2.4).

The understanding of industrial value chains shall provide the perspective, from which the aluminium die casting value chain will be observed in the following section. Nevertheless, it has to be stated that there are several other perspectives and definitions for value chains, especially in business sciences and micro economics. Here a value chain usually describes also business processes in combination with production processes, which are needed to satisfy a customer's need—starting from the expression of the customer's need along the whole internal order fulfilment process until the delivery of the service or good to the customer and the booking of the incoming money transfer from the customer. These processes can be distinguished into primary and supporting processes (Porter 2010).

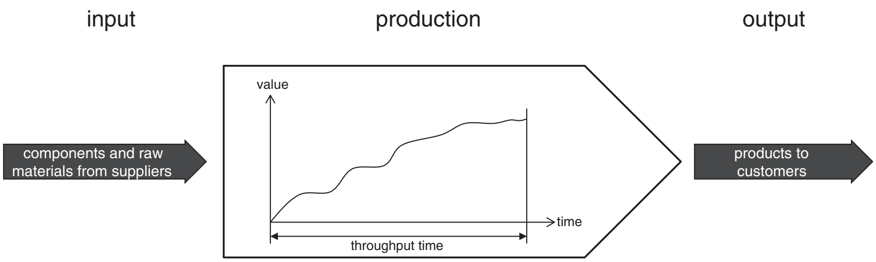


Fig. 2.3 Production as value adding process (Westkämper and Warnecke 2010)

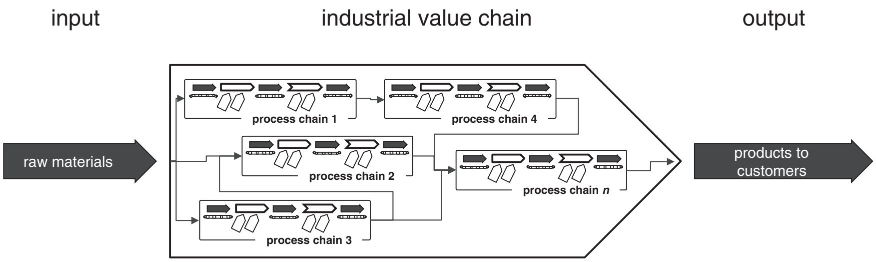


Fig. 2.4 Industrial cross-company value chain from a production engineering perspective

However, the basic principle of this perspective focuses on the sequential steps within the transformation process, which a product or service passes through—from the input material to the final product (Finkeißen 1999; Porter 2010). Therefore, this basic principle harmonizes both, the production engineering perspective as well as the microeconomic perspective on value chains.

2.1.1.4 Vertical and Horizontal Hierarchies Within Industrial Value Chains

As denoted above, industrial value chains describe networks or systems with manifold internal sub-systems. These systems can be in a vertical or hierarchical correlation to each other, which will be exemplarily described in the following section.

Vertical Hierarchies

There are manifold levels in industrial value chains which can be in a vertical hierarchical relationship to each other. This means that every system element within an industrial value chain can be part of a super-system and can contain sub-systems itself (Herrmann 2010).

Figure 2.5 exemplarily shows two attempts to classify possible hierarchical levels in industrial value chains. Herrmann et al. visualise the supply chains, factory buildings and machines as hierarchically arranged subsystems with detailed internal interrelationships, focussing on the energy related input and output flows on each hierarchical level (see Fig. 2.5a; Herrmann et al. 2010a). In contrast to this detailed system understanding Wiendahl focuses on a hierarchical order of the elements of a network introducing a common terminology for each level (see Fig. 2.5b; Wiendahl 2009).

Denkena and Tönshoff link the phrases process, process chain element and process chain into an own hierarchical order. Thereby they increase the granularity of hierarchical levels in manufacturing at a very detailed and intra-company level of the value chain. According to the presented model a process is the smallest and inseparable unit of a manufacturing system, which transforms inputs into outputs. A process chain element is a sequence of such processes and cannot contain parallel processes.

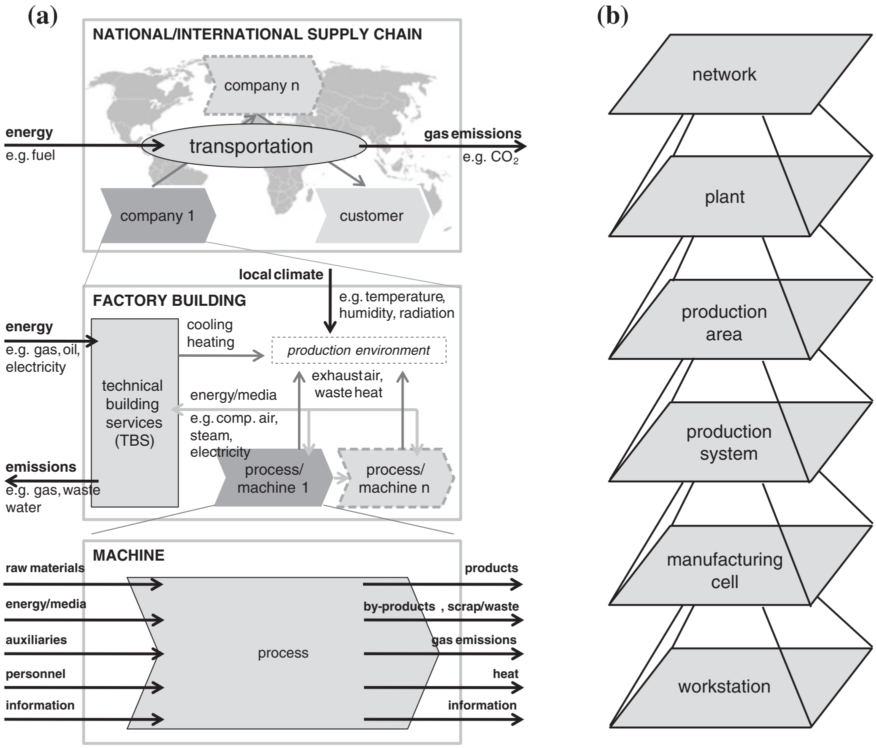


Fig. 2.5 Different (*vertical*) hierarchical levels of industrial value chains (Herrmann et al. 2010a; Wiendahl 2009; see also Heinemann et al. 2014)

The phrase process chain element can be used synonymously to the phrase process element, which describes, e.g., the processing of a work piece inside a machine tool. According to Denkena and Tönshoff the linkage of several process chain elements describes a process chain, which can contain sequential as well as parallel formations of process chain elements (see Fig. 2.6; Denkena and Tönshoff 2011).

Duflou et al. as well as Reich-Weiser et al. respect both presented perspectives (hierarchical order as well as system interdependencies) and state that the following granularity of system levels as well as the complex and individual energy and resource flows of every level need to be considered to evaluate the energy and resource efficiency as well as environmental impacts of manufacturing systems such as industrial value chains (Duflou et al. 2012; Reich-Weiser et al. 2010):

- device/unit process
- line/cell/multi-machine system
- facility
- multi-factory system
- enterprise/global supply chain

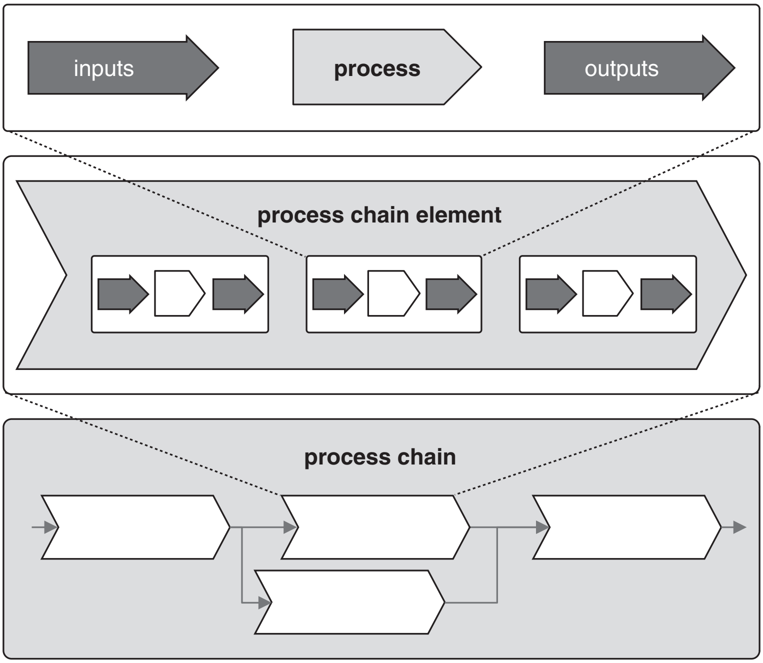


Fig. 2.6 Hierarchical order of processes, process chain elements and process chains (Denkena and Tönshoff 2011)

A similar perspective is taken by Verl et al. The authors consider multiple levels of a value chain as a conglomeration of various control loops that need to be managed to reduce the energy consumption of a manufacturing facility. Thus, every entity of a hierarchical level of a value chain depends on plans and constraints from a superior system element. These plans and constraints, which are determined by a system element, should consider energy cause models of the inferior system elements (see Fig. 2.7; Verl et al. 2011).

According to the introduced choices of the granularity of vertical manufacturing system levels, the specific aluminium die casting value chain will be introduced at the levels of the die casting process, the process chain (within the facilities of a foundry and an alloy supplier) and the cross-company die casting value chain—starting at Sect. 2.1.2.

Horizontal Hierarchies

Besides the vertical hierarchies in industrial value chains, there can be horizontal hierarchies between the single entities on a common hierarchical system level. These horizontal hierarchies can be expressed in a peripheral order of system elements (Müller 2009; Schenk et al. 2914).

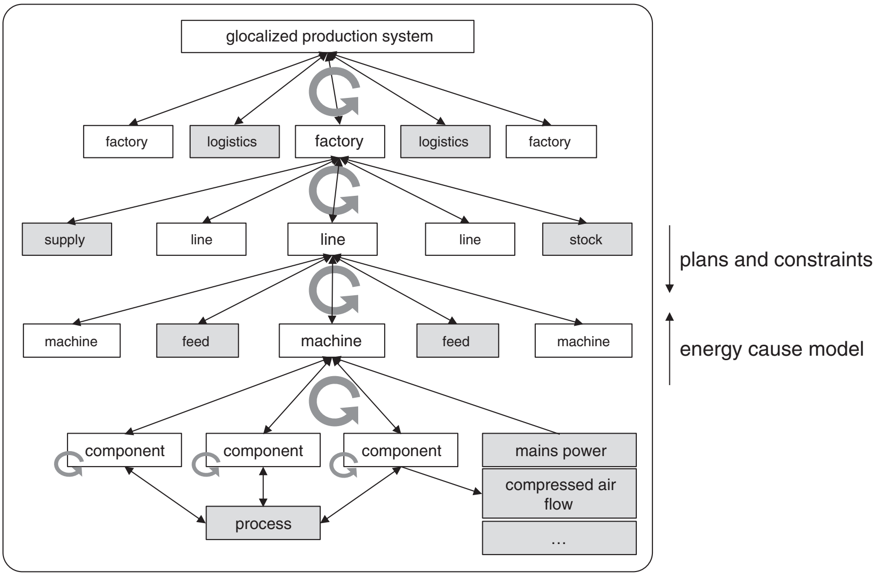


Fig. 2.7 Energy control loops in hierarchically structured value chains (Verl et al. 2011)

According to this peripheral order, the system elements within manufacturing systems are clustered into main processes and supporting processes in the first, second and third periphery. The assignment of processes into one of these four clusters happens according to their individual importance for the production of a predefined range of products (see Fig. 2.8; Schenk et al. 2014):

- Main processes are in the centre of this horizontally hierarchical model. They represent the value adding production machines.
- Processes of the 1st periphery represent processes, which are directly dependent from the main processes and the range of products (e.g. quality assurance).
- Processes of the 2nd periphery do not depend on the range of products, but on the main process (e.g. maintenance).
- Processes of the 3rd periphery represent processes, which are not dependent from the main process. Usually administrative processes and equipment from the staff rooms can be subsumed under this cluster.

The individual importance for the production of a predefined range of products often gives a hint about the degree to which the respective process contributes to the value adding of the value chain. Posselt et al. used a combination of the peripheral order and the degree of value adding of processes to generate rules for a pragmatic and cause-dependent allocation of energy consumption of peripheral processes to multi-product energy value streams (Posselt et al. 2014).

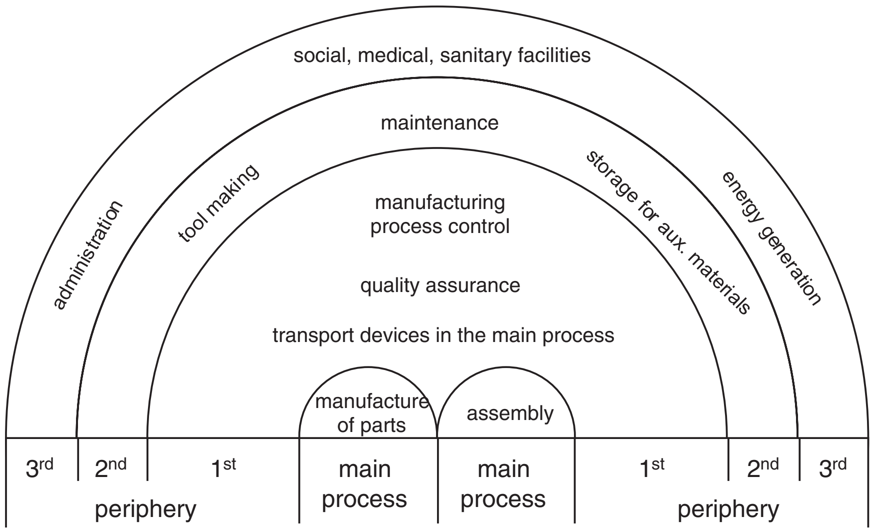


Fig. 2.8 Peripheral order of manufacturing's subsystems (Schenk et al. 2014)

Thiede highlights the importance of a holistic definition of factories to derive and evaluate measures for improving their energy efficiency. He horizontally divides the factory into the following three interacting subsystems, which together result in a complex control system (see Fig. 2.9; Thiede 2012):

- production (machines and employees, coordinated by production planning and control)
- technical building services (ensuring the required production conditions in terms of temperature, moisture and purity through cooling, heating and conditioning of the air)
- building shell (physically separating the internal value chain from the environment)

Manifold further differentiations for possible horizontally hierarchical clusters of manufacturing system elements can be imaginable. However, following the aforementioned ideas, it is necessary to respect the (often dynamic) interdependencies and interaction of value adding and not directly value adding processes at every level of abstraction of value chains.

This is especially true when, e.g., the energy demand of value adding and not directly value adding processes are compared. Using the example of an aluminium die casting cell, only about one third of the energy demand is determined by the die casting machine itself, while two thirds of the energy demand are caused by peripheral and not value adding processes (Hoffmann and Jordi 2013a).

Such effects need to be considered when the overall energy and resource efficiency of industrial production shall be improved towards a more resource efficient production of goods. Therefore, as a further groundwork, the following sections provide a technical insight in the aluminium die casting technology and

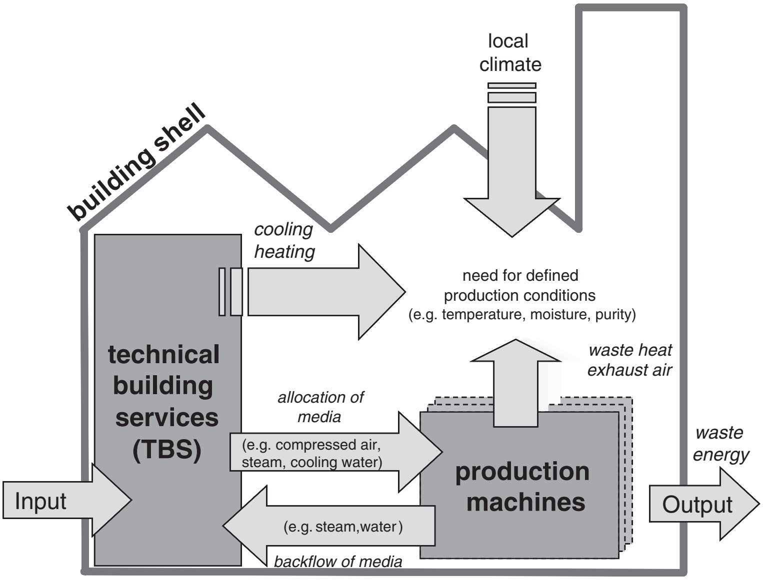


Fig. 2.9 Holistic definition of a factory (Thiede 2012)

its hierarchical system elements. Having this technical description in mind, also a necessary definition of energy and resource efficiency will be given, followed by a brief introduction of existing methodological support for their improvement. Subsequently, a deeper insight in the environmental challenges of the aluminium die casting technology will be provided.

2.1.2 Aluminium Die Casting

In this section the aluminium die casting technology is introduced based on the preceding conception of hierarchically organized industrial value chains, which can constitute different system levels of an industrial network. This technology also forms a corresponding hierarchically organized value chain (see Fig. 2.10; Heinemann et al. 2012). After an identification of the aluminium die casting value chain within the system of global aluminium flows and an overview over the German aluminium production volumes, the single steps of the value chain will be introduced in sequence. As a starting point of the value chain description, a broad perspective is taken, and the necessary activities for the generation and classification of the required raw materials from pure (primary) metals to recycled (secondary) metal products get introduced. These input flows are processed to alloyed aluminium ingots by the internal process chain of the alloy supplier (aluminium recycling company and smelting works). Its linkage to the foundry within the

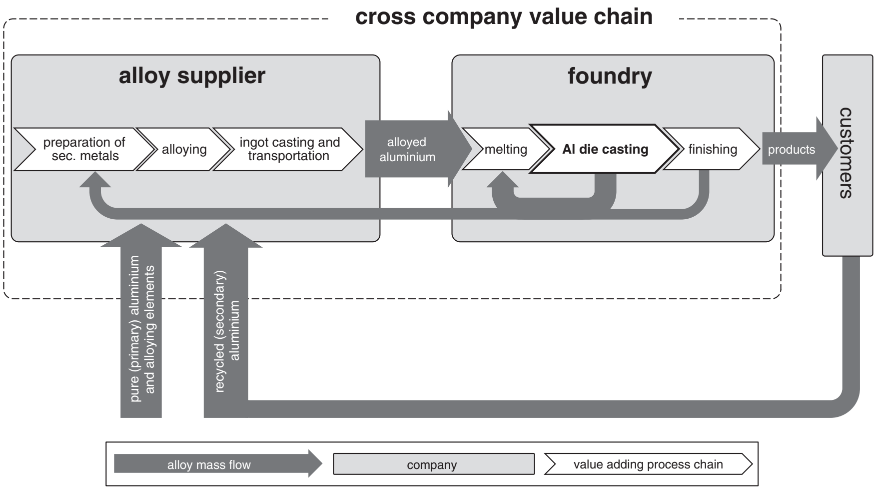


Fig. 2.10 Basic structure of the hierarchical aluminium die casting value chain (process sequence and alloy mass flow) (see also Heinemann et al. 2012)

cross company value chain is described through a brief overview over alloy transportation scenarios. The delivered ingots are transformed into final products by the internal process chain of the foundry. It also incorporates the die casting process itself, which has been classified before. This process gets further described from a technical perspective as closing point to this section.

2.1.2.1 Classification of the Aluminium Die Casting Process

Manufacturing technology is vital for the creation of products with defined shapes and characteristic. As manufacturing technology is manifold, the manufacturing processes can be divided into six main groups according to their main principal of manipulating the product's nature (Grote and Antonsson 2009). The DIN 8580 standard defines and divides all manufacturing processes (see Fig. 2.11) (DIN 8580 2003).

Amongst these main groups of manufacturing processes the main group of primary shaping can be further divided into seven sub groups according to the initial material state (see Fig. 2.12) (DIN 8580 2003; de Ciurana 2008).

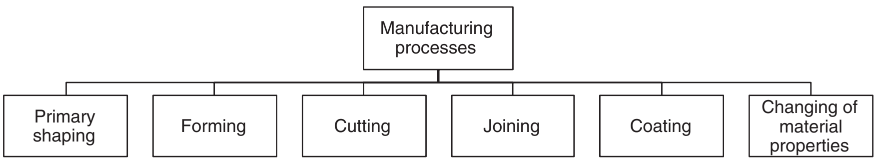


Fig. 2.11 Classification of manufacturing processes (main groups) (DIN 8580 2003)

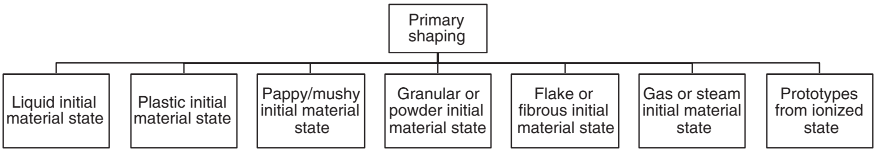


Fig. 2.12 Sub groups of the manufacturing process primary shaping (DIN 8580 2003; de Ciurana 2008)

Contrary to the other main groups of manufacturing processes, the group of primary shaping processes carries the ability to create most of the final products shape, characteristics and features with one single, integrated process step and only demands for some minor further treatment to add extra features or special qualities functional surfaces (Bühring-Polaczek 2014).

This ability leads to a high degree of material efficiency, and a relatively low energy intensity of this group of manufacturing processes compared to other main groups of manufacturing processes. Figure 2.13 illustrates this advantage by comparing the material efficiency and energy intensity of selected manufacturing processes out of the main groups primary shaping, forming and cutting (Fritz and Schulze 2010).

One representative example for such an advantageous process is the high pressure die casting (HPDC) process, which belongs to the sub group of "primary shaping from liquid initial state" (see Fig. 2.14) (DIN 8580 2003).

High pressure die casting is the most important casting process for non-ferrous metals (Westkämper and Warnecke 2010). It usually processes alloys which are based on the following metals (Brunhuber 1980):

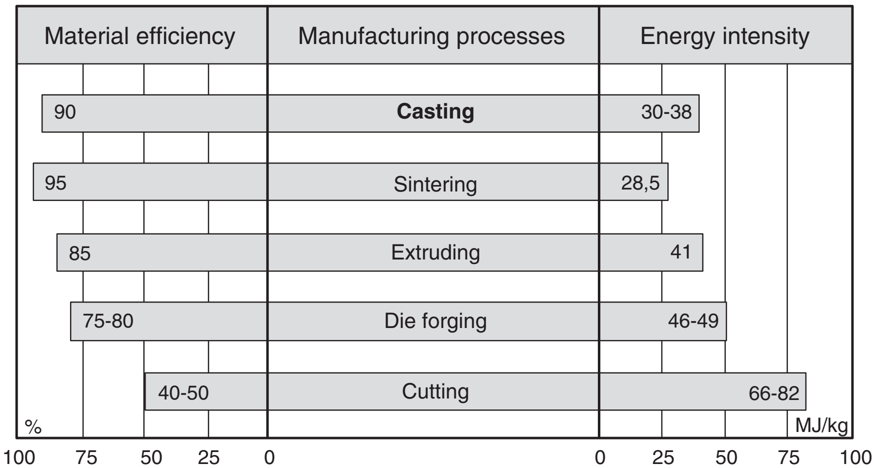


Fig. 2.13 Material efficiency and energy intensity of selected manufacturing processes (Fritz and Schulze 2010)

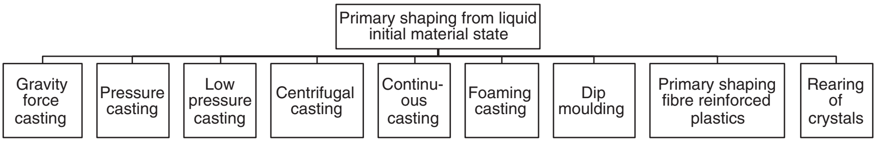


Fig. 2.14 Division of the main group primary shaping (DIN 8580 2003)

- aluminium
- zinc
- magnesium
- copper

However, most of the pressure die casted volumes in Germany are based on aluminium alloys (WirtschaftsVereinigung Metalle 2012). Aluminium die casting alloys distinguish themselves by a very good castability (for complex and thin-walled product geometries), a very good machinability, good resistance to atmospheric corrosion (especially aluminium-silicon alloys) as well as a low aggressiveness against the iron-based dies (Brunhuber 1980; Jochem et al. 2004).

Besides the possibility to create a high number of the final product's functions and characteristics within one fast and integrated process step, the high pressure die casting especially of aluminium parts delivers a wide range of further advantages, which distinguish this process from other manufacturing processes (see Table 2.1).

Besides the aforementioned advantages of the high pressure die casting process some disadvantages have to be taken into account. Table 2.2 delivers a small list of

Table 2.1 Selected advantages of the (aluminium) high pressure die casting process (Rockenschaub 2014; Pithan 2013a; Kalweit et al. 2012; Westkämper and Warnecke 2010)

Economic advantages	High degree of automation, whereas downstream processes—e.g. mechanical treatment—can be directly linked to the automated casting cell
	High productivity, and therefore good applicability, in the automotive parts industry
	High productive capacity
	High profitability as a result from the high degree of automation and productivity
Technological advantages	High dimensional accuracy
	Castability of complex geometries and small wall thicknesses
	Short cycle times
	Very good quality of the structural composition and microstructure of the casted metal
	Smooth cast surfaces
	Composite designs through integrally casted materials are possible
	Near net shape casting and low demand for further mechanical treatment

Table 2.2 Selected disadvantages of the (aluminium) high pressure die casting process (Rockenschaub 2014; Pithan 2013a; Westkämper and Warnecke 2010)

Economic disadvantages	High initial costs for tools (dies) and die casting machines
	High costs for tool replacements due to the high tool costs and cost intensive breakdown times
	Not profitable for small lot sizes
Technological disadvantages	Limited design options
	Danger of porosities due to air entrapments, which decrease the strength value and breaking strain
	High thermal and mechanical stress of the expensive dies
	Limited applicability for welding processes
	Limited applicability for heat treatment

economic as well as technological disadvantages which create a demand for a further development of the high pressure die casting process (Pithan 2013).

As the advantages of the aluminium high pressure die casting technology outbalance the disadvantages for many application scenarios, this technology (like many other casting technologies and aluminium products) has found its way into practical application very successfully. Therefore, the following section gives an overview over the system of global aluminium flows and identifies the aluminium die casting value chain within. The following section also quantifies the general German aluminium production volumes, the distribution of aluminium products over application areas and the German aluminium die casting production volumes to highlight the special relevance of this industry.

2.1.2.2 Global Aluminium Flows and German Aluminium Production Volumes

The environmental relevance of industrial value chains like the aluminium die casting value chain always has to be considered in a global context and regarding the life cycle of the manufactured products. By taking such a broad perspective, industrial value chains appear to be embedded in extensive material flow networks, in which manifold value chains are interlinked and diverse material flows are commuting between the single value chain systems.

However, not many complete maps of global material flows for selected materials are available. Therefore Allwood and Cullen have striven to map the flows of selected materials along their entire life cycle and including also flows of cycle material (Allwood and Cullen 2012). The total global aluminium flows for the year 2007 are shown in Fig. 2.15 (Cullen and Allwood 2012). This figure also identifies the aluminium die casting value chain within the system of global aluminium flows.

Aspects like the effects of bad material efficiency on cycle material volumes, energy intensive post industrial scrap as well as aluminium recycling cascades, which will correlate directly to the absolute material volumes, can already be perceived from the flow visualisation of Cullen and Allwood. Thus, even more aluminium

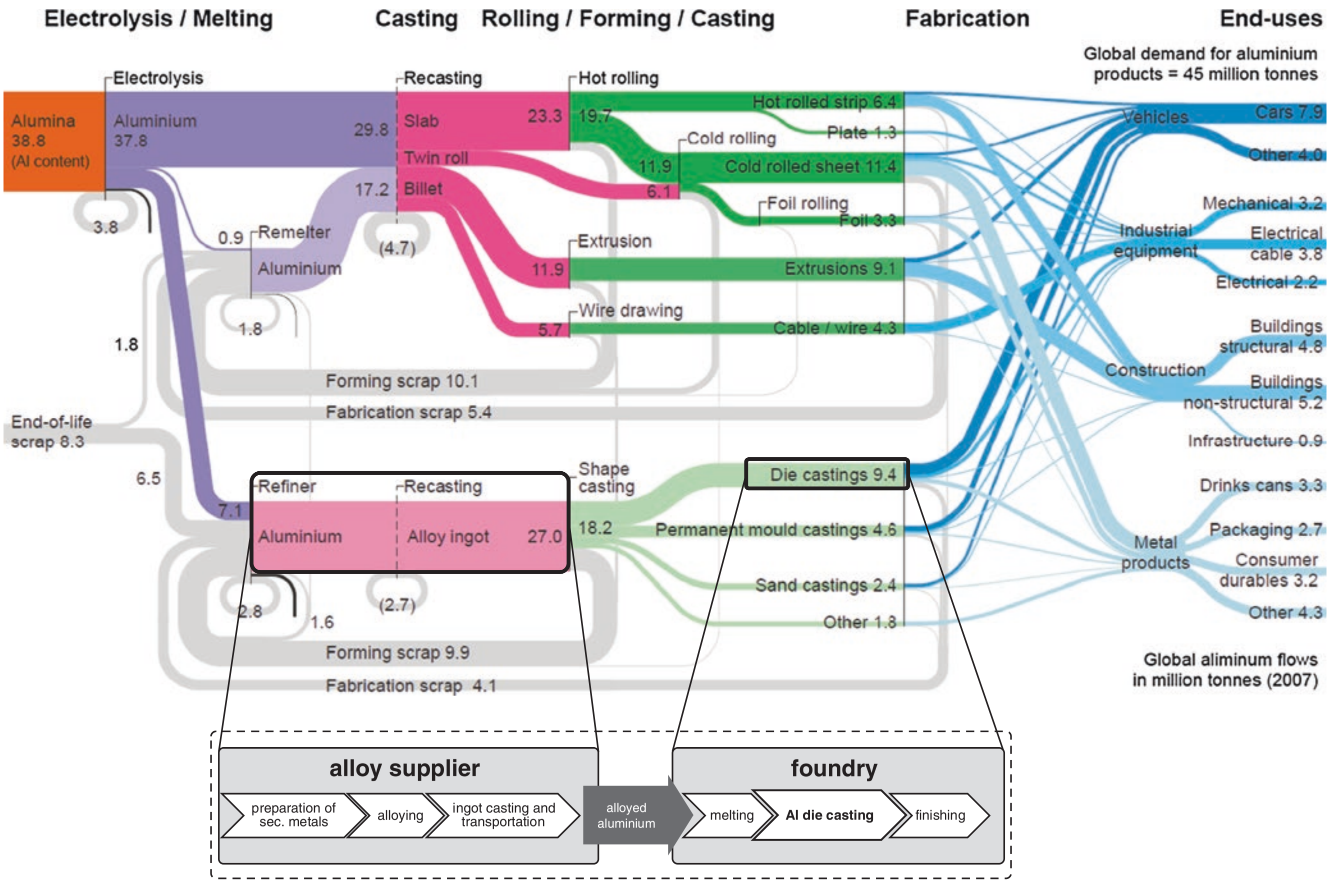


Fig. 2.15 Sankey diagram, tracing the global flow of aluminium and localising the aluminium die casting value chain (adapted from Cullen and Allwood 2013)

(55.2 Mt) is processed as cycle material than the total global demand of aluminium products (45 Mt). Furthermore, cycle material from forming scrap from ingot casting operations (9.9 Mt) incorporates even more material than the total aluminium die casting production output. According to Cullen and Allwood 9.4 Mt of die casted products have been delivered to customers in the year 2007. The majority of these products have been placed in vehicles (mainly cars). With this volume of produced parts, the aluminium die casting industry produces 51.6 % of the global shape castings (18.2 Mt) and about 20.1 % of the total global demand of aluminium products.

Although aluminium die casted parts are mainly based on secondary aluminium alloys still ca. 26 % of the aluminium, which gets processed by the alloy supplier in the aluminium die casting value chain (refiner and recasting) is primary aluminium. It is used for primary aluminium based alloys or for the dilution of secondary aluminium alloys (see also Sect. 2.2.3). The other 74 % of input material for the alloy supplier is scrap aluminium (19.9 Mt) whereas only about one third of these inputs come from end-of-life scrap (6.5 Mt). About two thirds of the alloy supplier's input material comes from post industrial scrap. These figures again point out the potential of better material efficiency and recycling processes in aluminium value chains (Cullen and Allwood 2012).

The same is true for the total global aluminium flows. Around half of all liquid aluminium (ca. 39 Mt) never enters a use-phase as a final product but stays in the aluminium system as cycle material. The resulting aluminium recycling, which basically is favourable as it substitutes high energy costs and emissions from primary aluminium production, requires ca. 8 Mt of primary aluminium for dilution and ca. 6 Mt of high quality aluminium alloys to substitute in-use-stocks of non-recycled aluminium, which are not available for secondary aluminium alloy production (Cullen and Allwood 2013).

However, the introduced global flows of aluminium are not fixed as is shown in Fig. 2.15. By now the global aluminium demand has increased 30-fold since 1950, and will reach two to three times today's level by 2050. Today's aluminium production uses 3.5 % of the global electricity and causes 1 % of the global CO_2 emissions. This development would make it necessary to achieve an 85 % reduction of the CO_2 emissions per tonne of aluminium if a global CO_2 emission reduction of 50 % is aimed for (Cullen and Allwood 2013).

Analyzing the production data of the German aluminium industry from the earlier past reveals that energy intensive primary aluminium production volumes have increased in the year 2013 after a continuous decrease in 2012. Secondary aluminium production volumes are still larger than primary aluminium production volumes, but are decreasing and have reached nearly the production level of primary aluminium (see Fig. 2.16; Trimet Aluminium AG 2013, 2014).

Both trends (increasing primary aluminium production and decreasing secondary aluminium production) seem to continue (see Fig. 2.17; Trimet Aluminium AG 2013, 2014).

The structure of the aluminium product demand and its distribution over application areas in Germany appears to be similar to the global distribution of products, which Cullen and Allwood have visualised. The transportation sector is

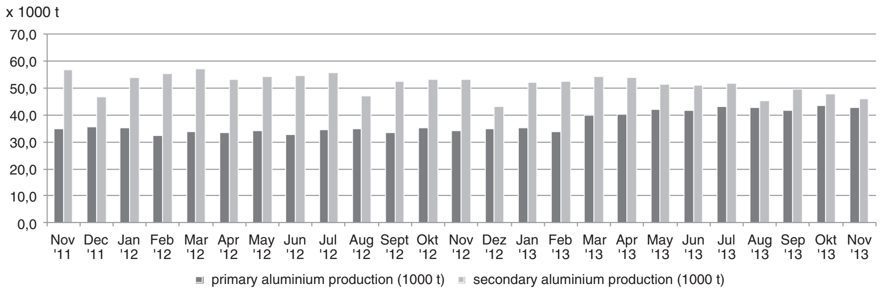


Fig. 2.16 Production output of the German aluminium industry (primary and secondary aluminium production) (Trimet Aluminium AG 2013, 2014)

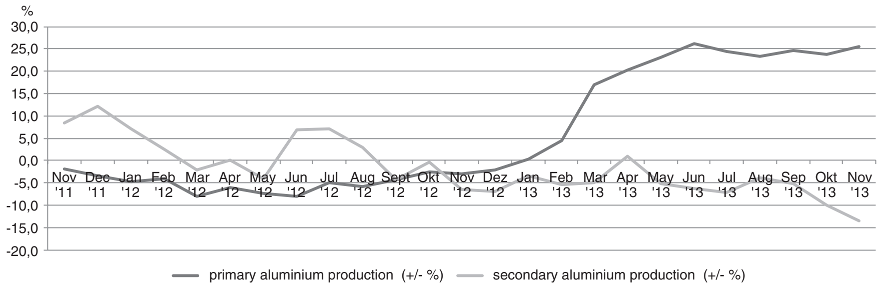


Fig. 2.17 Production volume changes of the German aluminium industry (increase/decrease of the primary and secondary aluminium production compared to the respective month of the previous year) (Trimet Aluminium AG 2013, 2014)

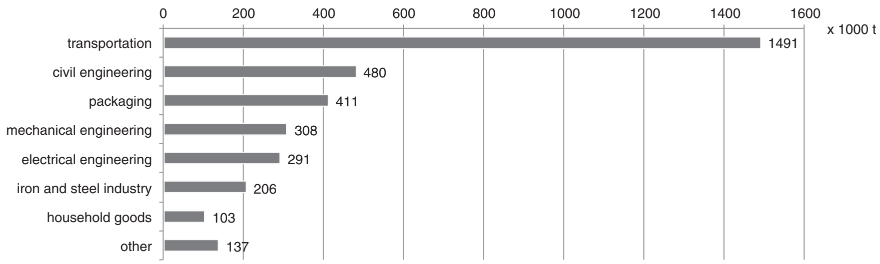


Fig. 2.18 Distribution of aluminium products over application areas in Germany in 2012 (statista.com 2014)

responsible for most of the aluminium demand in Germany as well. It represents a demand of 1.491 Mt (see Fig. 2.18; statista.com 2014; Cullen and Allwood 2012).

The output of the German aluminium die casting industry (ca. 432,400 t) represents a share of ca. 13 % of the German aluminium product demand (ca. 3,427,000 t). Its production volume is stable in recent years with respect to a

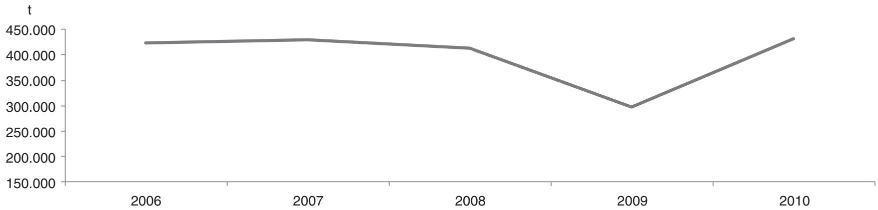


Fig. 2.19 Aluminium die casting production volumes in Germany (aluminium-recycling.com 2014)

weak production period during the heaviest year of the European economic crisis in 2009 (see Fig. 2.19; aluminium-recycling.com 2014; statista.com 2014).

After this introduction of global aluminium flows and German aluminium production volumes, the specific aluminium die casting value chain will be described in the following sections—starting with the introduction of raw material and secondary material input flows.

2.1.2.3 Raw and Secondary Material Input Flows

Due to the fact that the aluminium die casting value chain has to rely on further upstream activities, which provide it with input materials and have an impact on the performance of the overall value chain, this section provides an overview over the raw and secondary material input flows like the generation of primary aluminium and the processed secondary aluminium fractions. Figure 2.20 illustrates these important material flows (in dark grey) and their circular flow in the aluminium die casting value chain.

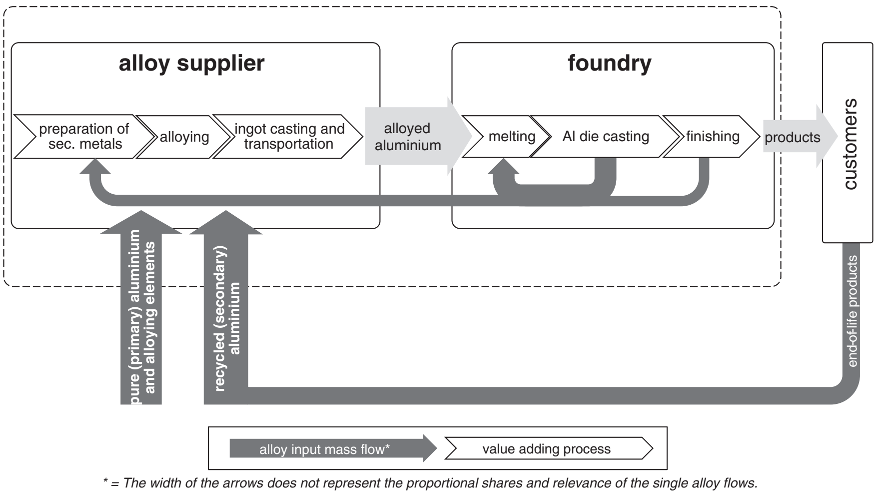


Fig. 2.20 Raw and secondary material input flows (in *dark grey*) of the aluminium die casting value chain

Primary Aluminium Production

Aluminium is a very electronegative metal, which means that its natural manifestation can only be found in chemical compounds, e.g., in oxidic or siliceous minerals. This makes chemical processing necessary to extract the pure aluminium. After the testing of some alternative technologies for the production of primary aluminium over the last decades, the following process sequence has come out to be the only one with industrial relevance along the worldwide aluminium industry: (1) bauxite mining, (2) Bayer process, (3) fused salt electrolysis (Kammer 2012a; Quinkertz 2002). Figure 2.21 visualises the process sequence and basic input flows for electrolytic production of primary aluminium.

The raw material for this process sequence is bauxite. Bauxite is an ore, which incorporates a conglomeration of diverse, mostly aluminium containing minerals such as hydrargillite (Al_2O_3), kaolinite ($Al_2Si_2O_5(OH)_4$), boehmite ($AlO(OH)$) and diaspore ($AlO(OH)$). Other iron, silicon, titanium or calcium based minerals need to be separated from the bauxite during the first step of the Bayer process (Quinkertz 2002; Kammer 2012a).

The Bayer process starts with a milling of the bauxite and the addition of sodium hydroxide at a temperature level of 100–360 °C. During this process the aluminium hydroxides dissolve in the sodium hydroxide and generate aluminate while other contaminating compounds precipitate without being dissolved. The conglomeration of these precipitated compounds is usually known as red mud and needs to be landfilled. When the aluminate brine cools down and seed crystals are added the pure aluminium hydroxide precipitates (Kammer 2012a; Dienhart 2003).

In a second step the extracted aluminium hydroxide gets dehydrated (calcinated) by adding thermal energy via rotary furnaces at a temperature level of 1000–1300 °C.

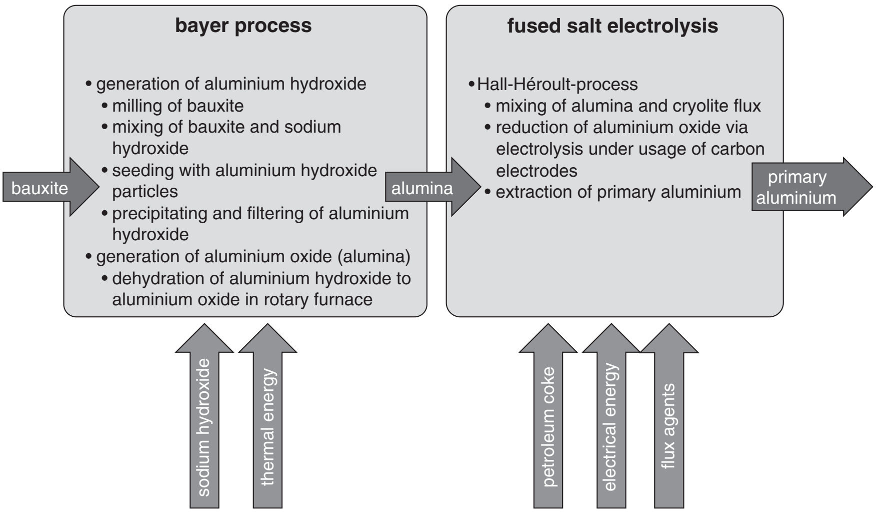


Fig. 2.21 Input flows and process sequence for electrolytic primary aluminium production (Kammer 2012a)

This process creates technically pure aluminium oxide with only negligible contaminations of other oxides (Kammer 2012a; Dienhart 2003).

This pure aluminium oxide can be further processed in a fused salt electrolysis according to the Hault-Héroult-process. The basis for this electrolysis is a solution of the aluminium oxide in liquid cryolite, which decreases the melting temperature of the aluminium oxides from ca. 2050 °C down to ca. 963 °C. By adding further flux agents the electrolysis can be done at a temperature level of about 950–980 °C. The concentration of aluminium oxides in the flux is at about 2 %. As carbon electrodes (out of petroleum coke) are used during the electrolysis, the anode gets corroded by emitting carbon monoxide and carbon dioxide. At the cathode at the bottom of the electrolysis cell pure aluminium gets produced which gets extracted by suction periodically and can be casted to ingots afterwards (Kammer 2012a).

Secondary Aluminium Input Fractions

The main input material for die casting alloys is scrap aluminium. Scrap aluminium can be collected from manifold sources at different qualities. The main scrap aluminium fractions can be distinguished as follows:

- post industrial scrap (gating systems, production waste, etc.)
- capital scrap (end-of-life products)
- dross (oxide skins from liquid alloys in melting or holding furnace)
- swarf (metal chips from mechanical treatment)
- aluminium foils, packaging materials, etc. from municipal waste separation and collection systems

Post-industrial scrap usually stands for relatively clean aluminium waste from foundries or smelting works, which does not enter a use-phase as a product, but can be resmelted directly after the production. Minor contaminations can come from coatings or oxides. The recycling rate of these scrap aluminium fractions is at nearly 100 % (Kammer 2012b; Boin et al. 2000; Kirchner 1989).

Capital scrap describes aluminium products after their use-phase, which have been collected as secondary aluminium fractions. Depending on their individual use case, these end-of-life-products usually are contaminated with paints, lubricants, sealings, other material compounds, etc. The recycling rates of these fractions regarding the contained aluminium vary between 80 and 90 % (Kammer 2012b; Boin et al. 2000; Kirchner 1989).

Dross arises through the oxidation of alloys at the surface of the molten metal mass. These oxides get skimmed from the molten metal mass and therefore can contain 80 % of pure alloy as well. As the contained amounts of liquid alloy tend to further oxidation, the dross often gets covered with salt after the skimming or already inside the melting or holding furnace (Boin et al. 2000; Krone 2000).

Swarf is a post-industrial waste as well, and arises directly during the production phase of the final aluminium product while certain product functionalities are realized through chip removing manufacturing processes. It gets considered as a separate fraction of scrap aluminium due to its disadvantageous ratio of surface to mass, which makes compressing activities necessary to prevent the swarf from burning during the melting (Boin et al. 2000).

Aluminium foils, packaging materials, etc. from municipal waste separation and collection systems (e.g., the German Duales System Deutschland) belong to the group of capital scrap but form a separate fraction of aluminium scrap due to their huge variation of contained alloys and usually strong contamination (Krone 2000).

The development of the single scrap aluminium fractions' total shares and how they are used in Germany to produce secondary aluminium alloys over the last decades allows the prognosis, that the share of post-industrial scrap in the German alloy production will decrease and the share of capital scrap will increase. This is due to improving scrap metal collection systems in Germany as well as due to increasing demands for post-industrial scrap in newly industrialising countries and in countries which do not operate their own production of primary aluminium like Japan (Boin et al. 2000).

The increasing share of capital scrap forces the German producers of secondary aluminium alloys to question their production equipment (esp. furnaces) as the efficiency and technical feasibility of the installed furnaces depends strongly on the quality and contamination of the inserted scrap aluminium (Boin et al. 2000).

The following section will introduce the process chain of an alloy supplier, which is a producer of secondary aluminium alloys and uses the above introduced raw and secondary material input flows for the generation of aluminium die casting alloys.

2.1.2.4 Process Chain of an Alloy Supplier

Since the later-developed concept shall serve as general guidance for producing companies in the manufacturing industry, the internal process chain of an alloy supplier (aluminium smelting works) will also be considered in detail. This will offer the opportunity to take an important cross company perspective, and evaluate and compare company specific measures which unfold their potential as a lever for upstream or downstream companies.

Assuming that all necessary mechanical treatments and finishing of the die casted part get done inside the foundry, there is only the upstream process chain of the alloy supplier in addition to the raw material generation, which complements the company spanning aluminium die casting value chain (see Fig. 2.22).

The usage of alloys, which are based on recycled (secondary) aluminium that get refined with pure (primary) aluminium as well as other alloying elements, is of major importance in the aluminium casting industry (see exemplarily for the German aluminium die casting industry: GDA 2014). Therefore the considered alloy supplier does not produce the pure aluminium itself, but acts as a smelting works, which combines the required input materials (pure and recycled metals) into the required alloy. Furthermore the alloy supplier focuses on casting alloys which get produced through the refinement of scrap metal inputs and can contain up to 12 % alloying elements (Cullen and Allwood 2013; UNEP 2011b; Rombach 2004; Schucht 1999). The high share of possible alloying elements in casting alloys enables the usage of manifold secondary metal fractions from various sources (see previous paragraphs). Wrought alloys for rolled and extruded

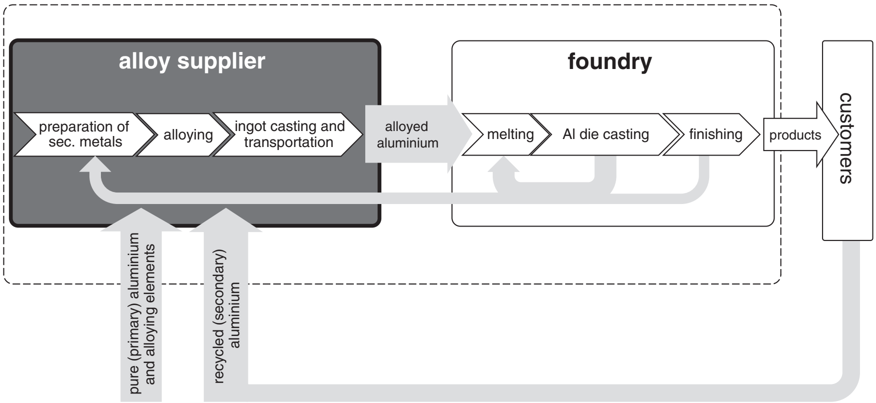


Fig. 2.22 The process chain of an alloy supplier within the aluminium die casting value chain

products that are produced through the remelting of very pure secondary metal inputs are not considered. These alloys must not contain more than 2 % of alloying elements, and therefore are not suitable to be produced through the refinement of scrap metal inputs (Schmitz 2006; Rombach 2004; Schucht 1999).

The process chain of an alloy supplier can be described as a set of activities or interlinked sub-processes similar to the later described foundry. Suppliers of secondary aluminium alloys run the following value adding activities, which are mandatory to combine different kinds of recycling inputs (scrap material and end-of-life products) from different sources and at different qualities (Schmitz 2006a, c):

- preparation of secondary materials and melting of scrap metal inputs
- alloying (setting of alloy characteristics by adding the individual amounts of alloying elements)
- ingot casting and transportation

Figure 2.23 illustrates the sequence of these main activities and their sub-processes as well as the value adding alloy mass flow through the foundry.

Input materials for the production of secondary aluminium casting alloys can be secondary material fractions from manifold sources like end-of-life-products,

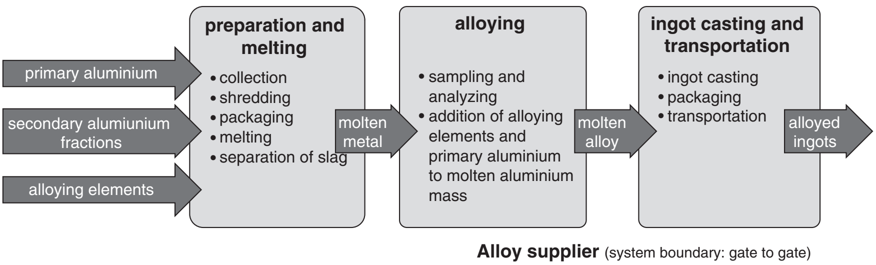


Fig. 2.23 Secondary aluminium alloy production process chain inside an aluminium supplier (production line, possible sub-processes and alloy mass flow)

post-industrial scrap, aluminium fractions from municipal waste, swarf, dross, etc. which need to be collected and transported to the alloy supplier. Depending on the quality of the aluminium fractions, some preparatory activities can become necessary to increase the possible yield of recovered aluminium or to prevent damages in the melting equipment. Such preparatory activities can include sorting and selecting of relatively pure secondary aluminium inputs or defined alloy qualities, de-coating, comminution, packaging and pressing of swarf, squeezing of dross, etc. (Schmitz 2006a).

After basic preparation, the collected aluminium fractions get melted in a drum melting furnace while adding melting salt. This salt extracts various contaminations from the molten metal but creates a slag, which needs to be treated separately after the melting process (Schmitz 2006c).

The molten metal, whose exact composition is not known to the very last detail at this step, gets transferred into a holding furnace (converter). At this holding furnace a sample of the molten metal gets taken and analyzed to detect the actual concentration of alloying elements and remaining contaminating materials. The result of this analysis is used to calculate the amount of alloying elements and pure aluminium, which need to be added to the molten metal afterwards to set up the final composition of the intended alloy (Schmitz 2006c).

Out of the holding furnace the final alloy is transferred into an ingot casting machine, so that the demanded alloy can be packaged and transported easily via lorries to the customer of the alloy supplier. The transportation of alloys to the foundry will be the topic of the following paragraphs.

2.1.2.5 Transportation Scenarios Between Alloy Supplier and Foundry

The most common scenario of metal supplies to a foundry is the transportation of solid ingots like described above to an external foundry (see Fig. 2.24). This external foundry is usually equipped with own melting capacities in its smelter (Kuom and Urbach 2007).

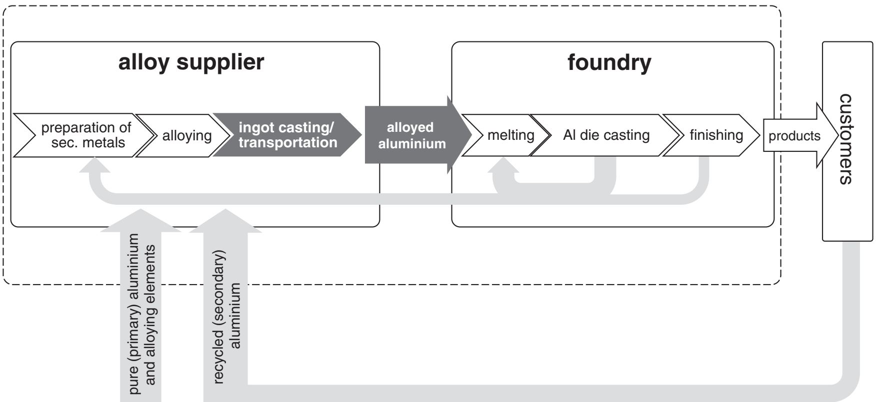


Fig. 2.24 Alloy transportation as linking element between alloy supplier and foundry

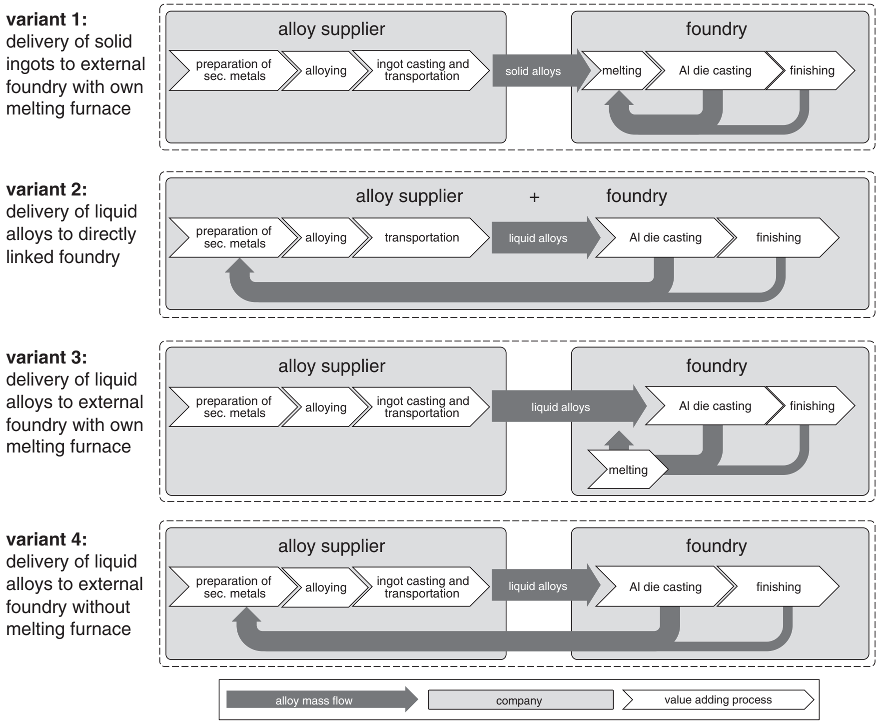


Fig. 2.25 Possible Transportation variants for the supply of aluminium alloys from alloy supplier to foundry (adapted from Heinemann and Kleine 2013)

However, other variants are possible as well, which differentiate in the distance between the alloy supplier and the foundry, in the aggregate state of the alloy and the amount of reversely transported cycle material depending on the availability of melting capacities at the foundry (see Fig. 2.25; Heinemann and Kleine 2013).

The aforementioned variant 1 (delivery of solid ingots to external foundry with own melting furnace) is the most common one because there are many more external foundries than alloy suppliers, of which only some possess a directly linked foundry. Even more important is the fact that solid ingots are tradable commodities, which can be stored and commissioned to various packaging sizes without changing their characteristics and quality. Therefore, the storability of the ingots is not only beneficial for the metal trading alloy supplier, but also for the logistic service provider, who can easily choose and manage the mode of transportation (usually lorries) and mix the ingot packages with other shipments. Furthermore, the storability of the solid ingot supplies also offers a lot of benefits especially for the foundry. At the foundry, safety stocks can be implemented effortlessly with solid ingots and different alloys can be picked easily at any time when they are needed in order to cast products with different mechanical characteristic (Kuom and Urbach 2007; Heinemann and Kleine 2013).

The delivery of liquid alloys decreases this degree of flexibility, as it offers only a very limited storability over time, and therefore is only possible up to a distance level of 500 km between the alloy supplier and the foundry. Furthermore, the foundry has to establish a very close relationship to the alloy supplier as the supplier has to guarantee a very steady supply of liquid alloy inputs. On the other hand, this transportation variant is only possible for foundries with nearly no changes in the casted alloy, and with only minor volatility in their alloy demand in order to guarantee a steady purchase of further metal inputs from the supplier. The big advantage of liquid alloy supplies lies in the absence of energy intensive melting activities at the foundry, which can directly process the liquid alloys as they enter the facility (Kuom and Urbach 2007; Krone 2000).

In variant 2 these liquid alloy suppliers get delivered in transfer ladles via forklift trucks from the holding furnace at the alloy supplier into the holding furnace at the die casting cell of the directly linked foundry. Obviously, this variant is relatively energy efficient but also very rare due to the little amount of alloy suppliers with directly linked foundries (Heinemann and Kleine 2013).

In the more likely case of a delivery of liquid alloys to external foundries, the molten metal gets transported via specialized lorries that are equipped with isolated transfer ladles in which the superheated alloy stays liquid at a transport temperature of 800–900 °C and a temperature loss of 10–20 K per hour (Kuom and Urbach 2007; Krone 2000). So the time until the liquid alloy cools down to its solidification temperature determines the maximum transportation distance between the alloy supplier and the foundry.

Besides the temperature losses and specialized vehicle equipment, the reverse transportation and smelting of post-industrial scrap (cycle material) also needs to be considered, regarding the possible transportation scenarios for liquid alloy supply to distant foundries. Usually, foundries are still equipped with smelting capacities (variant 3), which can be used in order to resmelt the pure internal cycle material (swarf, discarded products, die cutted gating systems, etc.). In this case no reverse transports from the foundry to the alloy supplier need to be considered, and the lorry of the alloy supplier returns empty to its starting point. However, if the foundry is planned and designed with the purpose to exclusively process liquid delivered alloys, it does not necessarily have to possess its own melting furnace (variant 4). In this case the transportation can be configured in a way that internal cycle material gets transported back to the alloy supplier, where it gets smelted together with the other collected secondary metal inputs (Heinemann and Kleine 2013).

For the following sections the most usual case of alloy transportation (variant 1) is taken as reference scenario. The following section will introduce the internal process chain of a foundry, which is supplied according to this variant.

2.1.2.6 Process Chain of a Die Casting Foundry

The internal aluminium die casting process chain inside a foundry does not only consist of the die casting process itself, but also includes some mandatory as well as facultative upstream and downstream processes (see Fig. 2.26).

The process chain inside a foundry can be described as a set of activities or interlinked sub-processes (Neto et al. 2009a). Every die casting foundry runs the

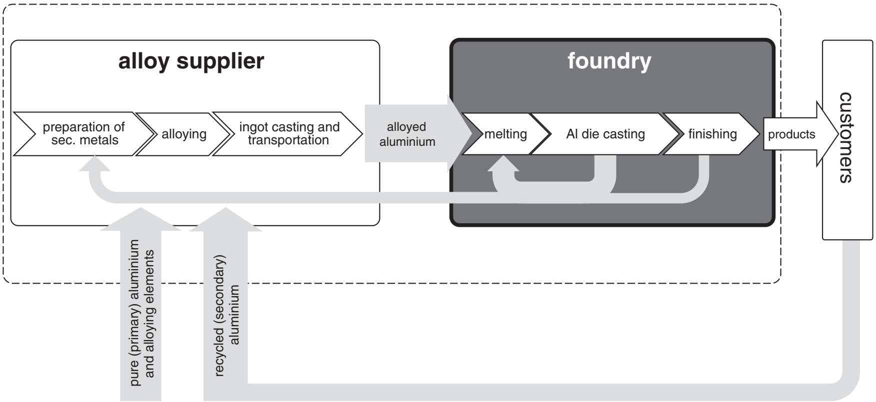


Fig. 2.26 The internal process chain of a foundry within the aluminium die casting value chain

following value adding activities, which are mandatory to produce die casted parts with a defined set of characteristics and functionalities (Neto et al. 2009a):

- melting (of an aluminium alloy)
- casting (shaping the alloy into a semi-product)
- finishing (several operating processes for surface finishing and product cleaning)

Figure 2.27 illustrates the sequence of these main activities and their sub-processes as well as the value adding alloy mass flow through the foundry.

Additionally, the facultative activity of heat treatment can be conducted between the casting and the finishing (Heinemann et al. 2013a; Brunhuber 1980).

The melting of the aluminium alloys usually takes place in separated smelting areas (smelter) inside the foundry. Pot-type furnaces or efficient shaft furnaces are used. Pot type furnaces can smelt up to 400 kg of aluminium alloy per hour and

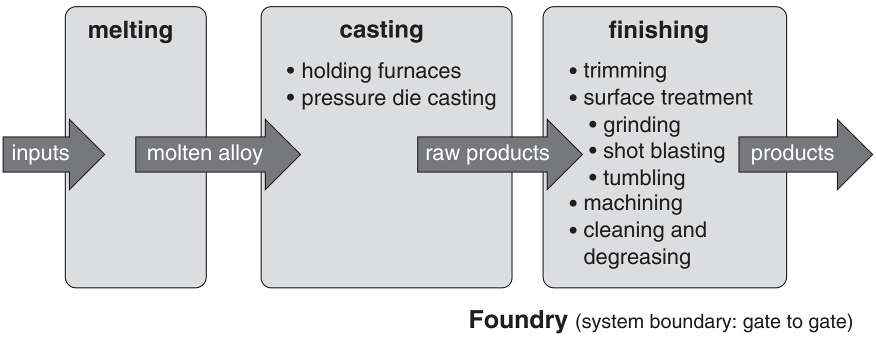


Fig. 2.27 Aluminium die casting process chain inside a foundry (production line, possible sub-processes and alloy mass flow) (Neto et al. 2008)

usually have a holding capacity of up to 1500 kg. The more energy efficient and productive shaft furnaces can smelt between 300 and 7000 kg of aluminium alloys per hour and have a holding capacity of up to 20,000 kg (Malpohl and Hillen 2009).

To reduce possible entrapments of hydrogen and oxidised metal particles, which decrease the machinability and quality of the cast, an additional treatment of the molten metal can be conducted. The liquid metal gets rinsed with inert gases like argon or nitrogen, which is flushed through the metal via an impeller (Kättlitz 2008).

When the metal is molten it gets transported to the casting area. This transport usually is done via forklift trucks in transfer ladles. At the die casting cell, the metal gets poured into a holding furnace, where the temperature of the liquid metal gets controlled above the solidification point. The holding furnace doses the required metal volume into the casting chamber, which is needed for one shot.

Out of the casting chamber the metal is squeezed into the mould cavity, where it solidifies. After the removal of the solid cast from the mould cavity, the gating system and sprue gets cut or sawed off from the casted raw product. The separated sprue, gating system other chips and possible reject parts get transported back to the smelter, where they get smelted again together with new alloy input material. Due to the fact that some shares of the molten metal get smelted, casted and cut off again and again this share of metal is called cycle material.

After the raw product has left the die casting cell, it can be further processed or finished in the mechanical treatment section of the foundry. Due to the great variety of possible treatments that can be done to the raw product in the mechanical treatment section, there is no standard set of clearly defined processes, which can be found at any die casting foundry. Nevertheless, several processes out of the main group cutting (e.g. drilling, milling, grinding) followed by further surface treatments and cleaning procedures can be found often as well as packaging and palletizing operations. Depending on the demanded quality and quality rate of the final product, several quality inspections as well as reworking operations can be found in an aluminium die casting process chain in a foundry (Neto et al. 2008).

If necessary, a heat treatment can be done to the raw product between the casting and the finishing in the mechanical treatment area. Commonly, a T4, T6 or T7 heat treatment is conducted to aluminium die casted parts (Koch et al. 2011). This means that the sub-processes solution annealing, quenching and artificial ageing are partially or completely performed. Due to the danger of potential gas entrapments of die casted parts, a temperature of about 250 °C should not be exceeded to avoid the formation of blisters. The heat treatment gets done preferably in convection ovens which can control a temperature level at a maximum deviation of 5 °C from the target temperature (Honsel 2014; DIN EN 515 1993). The ovens can be operated continuously via transfer lines, or as batch-type furnaces—depending on the batch size of the individual product (Kleine and Heinemann 2013). Most relevant process parameters of the heat treatment, which determine the mechanical properties of the product as well as the energy intensity of the process, are the temperatures and throughput times of the heat treatment's sub-processes (Rockenschaub et al. 2006).

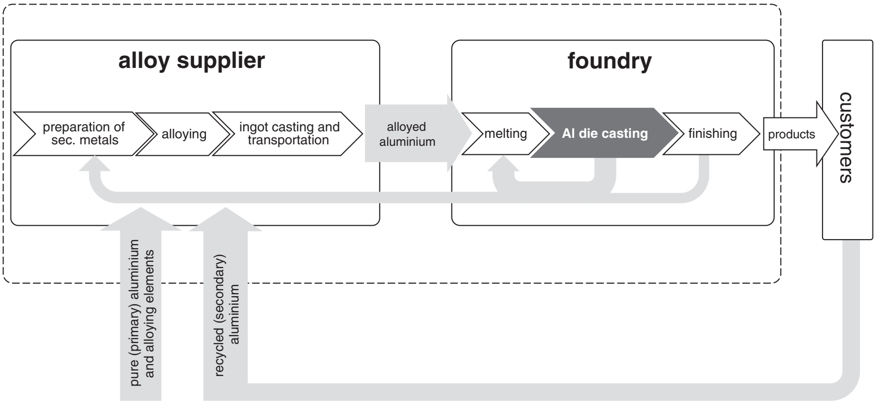


Fig. 2.28 The die casting process within the aluminium die casting value chain

2.1.2.7 Technical Description of the Aluminium Die Casting Process

The die casting process, which is eponymous for the above introduced value chain, will be introduced in the following section. The specific process sequence will be described before explaining its embedding in the die casting cell (see Fig. 2.28).

Process Sequence

Within the die casting process, liquid metal is forced into the cavity of a steel mould under high pressure. The squeezing of the liquid metal into the cavity is done by a plunger at a pressure level of up to 1200 bar. Due to this high pressure, closing forces of up to several tens of thousands kN have to be applied to the dies by the die casting machine. Despite the high pressure and temperature, the steel mould (die) is reusable up to 300,000 cycles (shots) of the die casting process (Westkämper and Warnecke 2010; Dalquist and Gutowski 2004).

Each cycle follows the same sequence, which is depicted in Fig. 2.29. As soon as the die halves are locked, the liquid metal is filled into a shot chamber (1). Afterwards, a plunger squeezes the metal into the cavity (2). Inside the cavity, the metal solidifies while the plunger keeps the metal under pressure for the required dwell time (3). After the solidification of the metal the two dies are separated so that the cast can be released (4), the plunger returns to its initial position and the dies can be prepared for the next shot (Aluminium Laufen AG 2014; Dalquist and Gutowski 2004).

The preparation of the dies includes some air-cleaning and relubrication with release agents (Dalquist and Gutowski 2004). The temperature of the dies is controlled continuously via tempering units, which serve tempering channels inside the dies with hot hydraulic fluids (Speckenheuer and Deisenroth 1989).

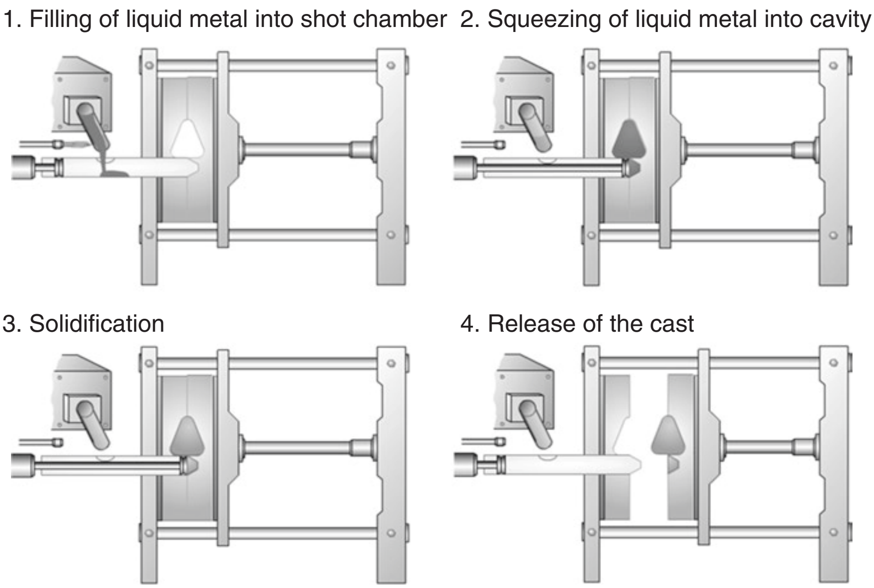


Fig. 2.29 Phases of the die casting process (Aluminium Laufen AG 2014)

Die Casting Cell and Equipment

The main device for conducting the die casting process is the die casting machine. Nevertheless, the die casting machine needs to be embedded in a die casting cell that is equipped with a set of necessary peripheral equipment. The most important elements of the die casting cell will be introduced in the following section.

The **die casting machine** can be broken down into three main components (Hoffmann and Jordi 2013b; Brunhuber 1980): Pump group or power unit, clamping unit, injection system.

The pump group delivers the hydraulic pressure, which is needed to operate the moving parts of the die casting machines. An electric motor powers pumps that compress hydraulic fluids up to pressure levels of 160–210 bars.

The clamping unit moves and closes the die casting mould. For this purpose, the non-fixed carrier plate gets moved along the machine base on slide shoes. Additional operations are the hydraulic control of the optional casting core systems as well as the activation of the repressing and ejector units.

The injection system's main task is to move the plunger, which squeezes the liquid metal into the cavity of the die casting mould. The injection system controls the movement of the plunger in order to guarantee a smooth entry of the metal into the gating system of the mould, a fast filling of the mould, and a sufficient holding-pressure while the metal is solidifying. The plunger movement also has to support the ejection system when the solid cast gets removed from the mould.

Figure 2.30 illustrates an example of a cold-chamber die casting machine with a double plate clamping unit. Alternatively, toggle clamping units can be applied and a holding furnace can be integrated into the die casting machine (hot-chamber die casting machine) (Hoffmann and Jordi 2013b; Nogowizin 2011; Brunhuber 1980).

The die casting cell is complemented by the following equipment: (Neto et al. 2008; Heinemann et al. 2013b; Brunhuber 1980)

- **holding furnace** (controlling the temperature of the liquid metal in the die casting cell, and dosing it into the casting chamber of the die casting machine)
- **die casting mould** (defining the shape of the case by being its negative)
- **tempering units** (controlling the temperature of the die casting moulds in order to guarantee a sufficient time for the solidification of the metal and preventing it from freezing on the surface of the mould, reducing the thermal stress of the mould)
- **handling equipment** (robot for automatically removing the cast from the mould and transferring it to the subsequent process step)
- **cutting device** (die cutter or saw for the removing of gating system and remainders from the final casted product)
- **spraying robot** (air-cleaning of the mould and application of release agents to the mould surface)

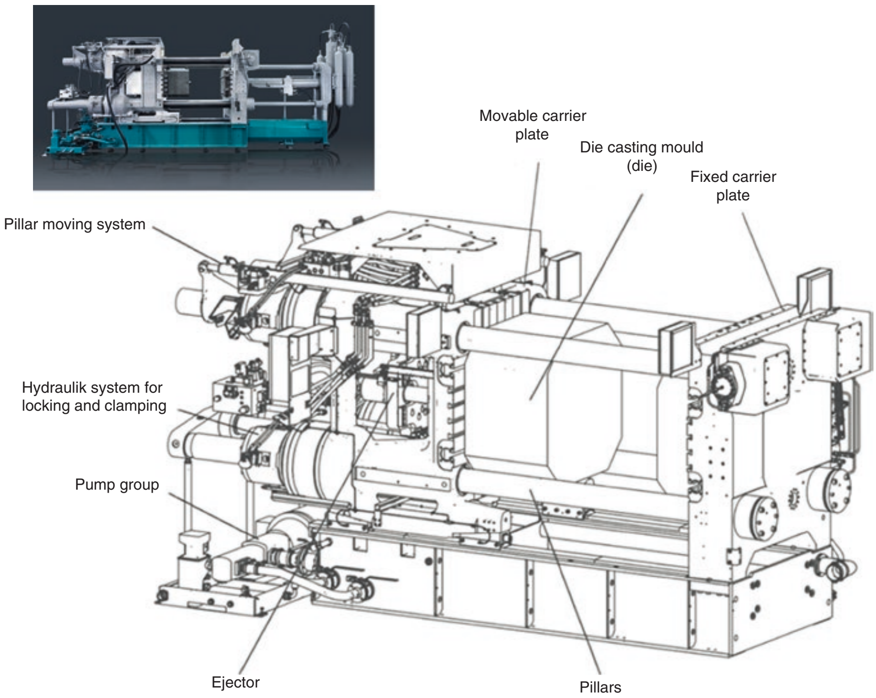


Fig. 2.30 Die casting machine (double plate clamping unit) (Hoffmann and Jordi 2013b)

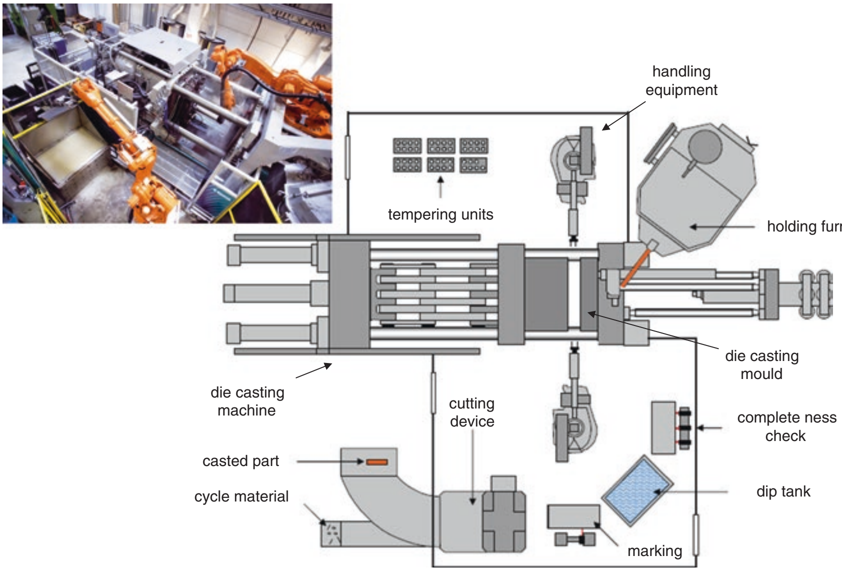


Fig. 2.31 Aluminium die casting cell (Kerber 2013; foundry-planet.com 2014)

The die casting cell is visualized in Fig. 2.31. It shows a sample configuration of the above mentioned equipment in a die casting cell schematically and adds a photograph of a similar, real aluminium die casting cell.

2.2 Environmental Aspects of Aluminium Die Casting

The preceding section introduced aluminium die casting from a technical perspective. The subsequent section provides an insight into the environmental challenges of aluminium die casting. Therefore, relevant terms like energy and resource efficiency, productivity and intensity as well as relevant methods to overcome environmental challenges in production will be introduced briefly.

2.2.1 Energy and Resource Efficiency

Environmental challenges result from energy and resource transformation. Metrics for measuring and comparing the quantitative input and output relation of such transformations are, e.g., the productivity, input related intensity or efficiency. Thus, the efficiency in particular is a central focus of many national energy and sustainability policies. However, only little attention has been given to a standardised and universal definition of this concept (Patterson 1996). Therefore, the terms productivity, intensity and efficiency for the evaluation of energy and resource transforming production systems will be explained briefly in the following paragraphs to constitute a common understanding for the further course of discussion.

From a strategic point of view, efficiency is one of the three strategies towards sustainable development. In this context, the strategies of sufficiency (self-determined limitation of environmentally harmful activities) and consistency (compliance of anthropogenic resource flows with common natural flows) are complemented by efficiency (WCED 1987; Dyckhoff and Souren 2008). Striving towards efficiency in production follows the idea of technological progress, which enables stable levels of utility or output (e.g., of products and processes) with continuously reduced input flows. Alternatively, an expansion of utility and production volumes while maintaining a stable level of input flows is a complementary example of increasing efficiency (Dyckhoff and Souren 2008).

Hence, metrics are necessary, which enable an assessment of actual input and output ratios. One common metric to assess the ratio of output factors to input factors of a transformation process is the **productivity** metric (e.g., Gronau and Lindemann 2010).

$$productivity = \frac{output}{input}$$

The productivity metric aims at evaluating physical input and output flows. Therefore, it is easily applicable and can be used to create a quick performance indicator of an observed system by metering its actual input and output flows. However, it adds qualitative information about the observed system only if there is a reference system against which the derived productivity value can be benchmarked. If systems with quantitatively and qualitatively constant output flows are observed or aimed for, Cantner et al. recommend the **input intensity** metric for the evaluation of input and output ratios (Cantner et al. 2007). The input intensity metric is the reciprocal value of the productivity metric. The denominator is constant when comparing different observed systems.

$$input\ intensity = \frac{input}{output_{const}}.$$

The input intensity metric therefore expresses the demand of certain input factors to create a fixed output unit. Thereby, it is a very intuitive metric to evaluate and compare the effect of improvement measures, which reduce the factor input of production processes by maintaining a defined product output (Cantner et al. 2007; Patterson 1996). Since the following discussion acts on the same assumption, that the output of the observed systems qualitatively and quantitatively stays the same, whatever measure is applied to this system, the input intensity metric will be the main metric for evaluating and comparing production systems and improvement measures.[1]

[1]The terms input intensity and intensity will be used synonymously.

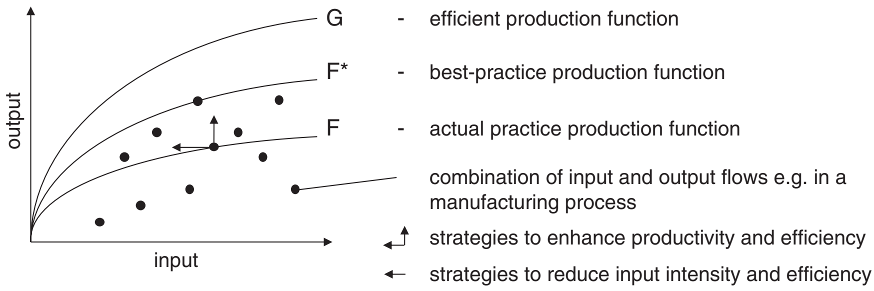


Fig. 2.32 Efficient, best- and actual-practice production functions (according to Cantner et al. 2007)

Input and output ratios or possible combinations of input and output flows are also specific characteristics of technologies. Production functions depict all possible input and output combinations of one technology (see Fig. 2.32).

This perspective introduces the concept of **efficiency**. A production function is efficient if there is no output flow, which can be produced with less input flows or if there is no input flow, which can produce more output flows in a different production function. According to this definition, technologies can only be efficient or not efficient without any graduation in between (Dyckhoff and Spengler 2007). As this optimum of an efficient production function (G, see Fig. 2.32) is rather of a theoretical nature and cannot be achieved in real production environments, actual-practice production functions (F) and best-practice production functions (F*) can be observed in reality. Best-practice functions represent the best possible combination of input and output combinations at the actual state of the art (Cantner et al. 2007). As an extension to this classical view on efficiency, the OECD defines efficiency as "the degree to which a production process reflects best practice" (OECD 2001). Thus, efficiency is not longer an absolute attribute of a theoretical production function, but can be expressed relatively by comparing actual practice with best practice. For such a comparison the above introduced productivity or input intensity metrics are feasible. Efficiency then represents the ratio of actual input intensity (resp. productivity) to best practice input intensity (resp. productivity) (OECD 2001).[2]

$$efficiency = \frac{input\ intensity_{actual}}{input\ intensity_{best\ practice}};\ efficiency = \frac{productivity_{actual}}{productivity_{best\ practice}}$$

Therefore, strategies for increasing efficiency can either increase the productivity or decrease the input intensity (see Fig. 2.32; Cantner et al. 2007; Dyckhoff and Souren 2008; see also Zein 2012). Further detailed overviews over concepts,

[2]Other authors and authorities define efficiency as synonym of productivity (e.g. DIN EN ISO 50001 2011; VDI 4800-1 2014). However, this perspective will not be taken in the following course of discussion.

indicators and methodological issues regarding (energy) efficiency are provided by Patterson and Zein (Patterson 1996; Zein 2012).

The above introduced metrics are applicable for many evaluation perspectives on production (e.g. labour-intensity, productivity of production equipment) (e.g. Gronau and Lindemann 2010). In the following chapters, physical input flows of energy carriers and materials will be focused and reduced to evaluate and improve the energy and resource efficiency of aluminium die casting.

2.2.2 Methods and Tools for Increasing Energy and Resource Efficiency

To reduce the energy and resource intensity in production with the goal to increase the energy and resource efficiency in a structured way, a methodological support is recommended (see e.g. Herrmann et al. 2010b). In this context, a methodological course of action, especially in the fields of data acquisition, modelling and visualisation, simulation and evaluation, helps to strive towards reduced energy and resource intensities. Therefore a brief insight in these methods will be given in the following section.

First, current developments for data acquisition in the context of energy and resource flows will be described as a basis for the generation of data sets, which will be processed by the other introduced methodologies or tools. Second, modelling approaches will be introduced, which depict their observed processes as a transformation of physical inputs into physical outputs. By generating such input/output matrices, e.g., life cycle inventories for the elaboration of life cycle assessments can be enabled. Thereby, a basis for a visualisation of resource flows is created, which enrich the information of purely quantitative approaches with intuitive, qualitative visual information about flow rates and volumes. Furthermore, these approaches add an underlying model about the correlation of the depicted flows, which makes first simulations possible. Simulation towards resource efficiency includes static as well as dynamic approaches, which will be addressed briefly. Afterwards examples for an environmental evaluation get introduced, which enrich the generated data about energy and material flows along the value chain with a life cycle spanning perspective on the resulting product, and with an assessment of the resulting environmental impacts (e.g. via a life cycle assessment).

2.2.2.1 Data Acquisition

Transformed resources on the process, process chain and value chain level are manifold. Thus the state of the art about the metering and monitoring of resource flows on different hierarchical levels is wide and complex (O'Driscoll et al. 2012). The most prominent resource in production, regarding the available metering approaches and strategies, is electricity. Kara et al. present an overview over the topic of electricity metering and monitoring in manufacturing systems. They state that from an electricity consumer perspective there are three hierarchical levels within a factory. According to that, electricity metering and monitoring can increase transparency about the electricity consumption of each hierarchical level and therefore support different further energy related activities. Examples are energy billing on factory level, identification of consumption hot-spots on department level or machine efficiency redesign on process level (see Fig. 2.33; Kara et al. 2011).

Kara et al. give an overview over basic electricity metering equipment for stationary and mobile application and give recommendations about suitable resolutions depending on the degree of dynamic behaviour of the object of interest. Furthermore, for each hierarchical level of the factory they define affected cost factors resulting from electricity consumption (e.g., peak power demand, specific energy demand, THD feedback) and potential benefits through electricity metering (e.g., adaption of energy supply contracts, energy intensive process scheduling, energy forecasting in production design) (Kara et al. 2011).

O'Driscoll and O'Donnel provide an update for the overview of metering equipment. They enrich it with an overview that covers communication platforms and protocols as well as with an overview over the current regulation and certification for energy and power monitoring (O'Driscoll and O'Donnel 2013).

A proposal for a technical implementation of a multi-level metering and monitoring architecture gets presented by Verl et al. They establish energy control loops in which metering based energy demand and cause models (feedbacks to higher

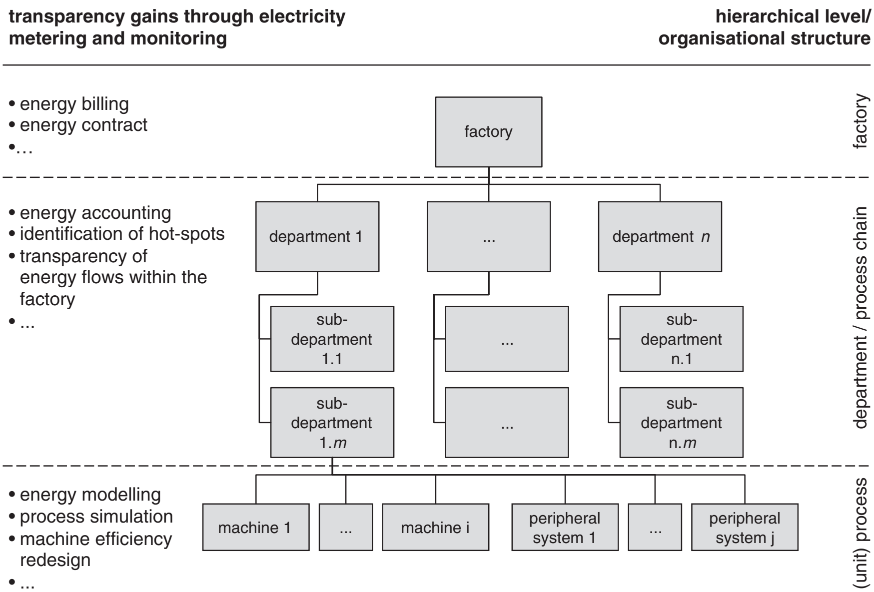


Fig. 2.33 Hierarchical levels of electricity consuming entities in a factory (Kara et al. 2011)

hierarchical system levels) build the basis for the derivation of plans and constraints for the operation of the actual system. By formulating such models for the individual system elements, a model based prediction of the energy demand, as well as an energy oriented planning and scheduling, becomes possible (Verl et al. 2011; see also Sect. 2.1.1, Fig. 2.7).

The generation of transparency about the usage of energy carriers, as well as auxiliary material flows via economically feasible metering devices and data processing equipment, has been in the focus of the EnHiPro project. Here generic metering strategies and metering data processing equipment, especially for the needs of small and medium enterprises (SME), have been developed. They build the basis for a continuous improvement circle towards energy and auxiliary material efficient SMEs (Herrmann et al. 2013c; Thiede et al. 2012, 2013).

In contrast to this SME focused approach the KAP project develops methodologies and equipment for complex event processing and real-time business intelligence on the shop floor of highly dynamic production systems, in order to feed evaluation and data mining algorithms. These algorithms shall support energy oriented production planning with respect to individually developed production performance indicators (kap-project.eu 2014; Swat et al. 2013; Emec et al. 2013).

The VDMA 24499 worksheet supports the metering of the machine specific electrical power demand of die casting machines with mobile metering devices for benchmarking reasons. Therefore, the VDMA 24499 worksheet defines standard process parameters for die casting machines depending on their closing force. Thereby, reproducible and comparable process sequences are defined for comparable metering results (VDMA 24499 2012; Hoffmann and Jordi 2013a; Kerber 2014).

Furthermore, simple data gathering methods like counting of parts or batches, interviews or the analysis of corporate production archives or databases can be done. In order to make such manually generated data more robust, statistical methodologies can be applied. Thus Bast and Strehle analyse gravity casting process chains and consolidate data about production parameters, quality rates and casting defects for the sub processes casting core production, moulding, and alloy supply. Bast and Strehle apply linear regression, multiple linear regression, maximum likelihood method, neuronal networks as well as cognitive networks to their generated data base and illustrate their potential for the identification of possible improvement measures for the reduction of scrap parts due to casting defects (Bast and Strehle 2010).

The evaluation and visualisation of data which has been generated via such procedures gets supported heavily by the use of input-/output matrices or modelling techniques as they will be introduced in the following section.

2.2.2.2 Modelling and Visualisation

On the manufacturing process or machine level, several approaches for modelling the energy and resource demand exist. As observed before, again the electricity demand has been the focus of most attempts to model the resource consumption. Balogun and Mativenga provide a comprehensive overview over energy oriented machine tool models (Balogun and Mativenga 2013).[3] They state that most of the approaches for modelling the energy consumption of machine tools take a machine state oriented perspective, which is similar to the basic principles of the methodology, which has been proposed by the Cooperative Effort in Process Emission project (CO2PE!) (Kellens 2013; Kellens et al. 2012). Furthermore, Balogun and Mativenga identify the following equation by Gutowski et al. to be a good basis for modelling and analyzing the direct energy demand in machining (Gutowski et al. 2006):

$$E = (P_0 + k\dot{v})$$

This equation processes the variables E [direct energy demand in a machining process (Ws)], P [power during operation readiness, before the machine starts cutting (W)], k [specific energy requirement for machining a particular work piece material (Ws/mm^3)] and $\dot{v}$ [material removal rate (mm^3/s)]. The equation has been further developed by several approaches (e.g. Mori et al. 2011; Diaz et al. 2011; He et al. 2012).

Balogun and Mativenga also identified another family of modelling approaches which gets constituted by Diaz et al., Draganescu et al. and Li and Kara. These modelling approaches analyse the machine tool's energy demand as a function of the material removal rate and individual coefficients, which need to be derived specifically via empirical studies (Balogun and Mativenga 2013; Diaz et al. 2011; Draganescu et al. 2003; Li and Kara 2011; Kara and Li 2011). Based on the same modelling philosophy, further manufacturing processes have been analysed and modelled. E.g., Li et al. empirically derived models for the specific energy consumption of turning, extruding and grinding processes (Li et al. 2012, 2013; Li and Kara 2011). Qureshi et al. and Chien and Dornfeld added further models about the injection moulding process (Chien and Dornfeld 2013; Qureshi et al. 2012).

Similar specific models for aluminium die casting processes do not exist yet. For the specific case of aluminium die casting, there are models about the (dynamic) flow of material and heat through the parts of the die casting machine or cell. However, their purpose is to support mould designers creating long lasting moulds. Therefore, they often fail to translate these flows consistently into energy demands. Nevertheless, a small number of approaches exist, which try to assess the energy consumption of shaping processes via modelling the thermo dynamical and fluid mechanical behaviour of the shaping process.

[3] Balogun and Mativenga covered the findings of (Kordonowy 2001; Dahmus and Gutowski 2004; Gutowski et al. 2006; Devoldere et al. 2007; Diaz et al. 2009; Vijayaraghavan and Dornfeld 2010; Rajemi et al. 2010; Anderberg et al. 2010; Avram and Xirouchakis 2011). Each of them performed in-depth studies about the state related energy demand of different manufacturing processes. The energy demand during operation readiness without value adding was identified as the machine state which contributes most to the energy demand of the whole process.

Ribeiro et al. model the heat flows within injection moulding machines, which can be considered to be familiar with die casting machines. They use thermodynamic equations from Mattis et al. (1996) and Thiriez and Gutowski (2006), and add process parameters like the cooling time to improve the design of die cooling channels (Ribeiro et al. 2012; Mattis et al. 1996; Thiriez and Gutowski 2006). A similar goal is pursued by Sundmaeker et al. (2013).

Specifically for the aluminium die casting process, Röders et al. have set up a static model about the overall heat transfers within an aluminium die casting cell. This static model was specifically set up to understand the heat balance of the die itself to find measures for an energy demand reduction. Figure 2.34 visualizes temperature fields of parts of the die casting cell, which have been analysed to derive the static model about the heat balance of the considered dies The considered heat transfers are visualised via coloured arrows (Röders et al. 2006; see also Sect. 2.2.3).

This way of visualising flows in production systems with coloured arrows is based on the idea of the Sankey diagram. Sankey diagrams were developed in the late 19th century. E.g., Schmidt explains this methodology extensively and reflects their history as well as application as one important method to support energy and resource efficiency in industrial production. Within a Sankey diagram, physical or monetary flows are depicted as arrows, which connect single transformation processes. The width of the arrows is proportional to their individual quantity. Thus, the structure, quantity, source and sink of (energy and material) flows can be visualised and compared very intuitively (Schmidt 2008).

An example for a Sankey diagram based visualisation of energy and material flows in an aluminium (gravity die casting) foundry has been provided by Krause et al. (see Fig. 2.35; Krause et al. 2012). It is divided in two visualisation

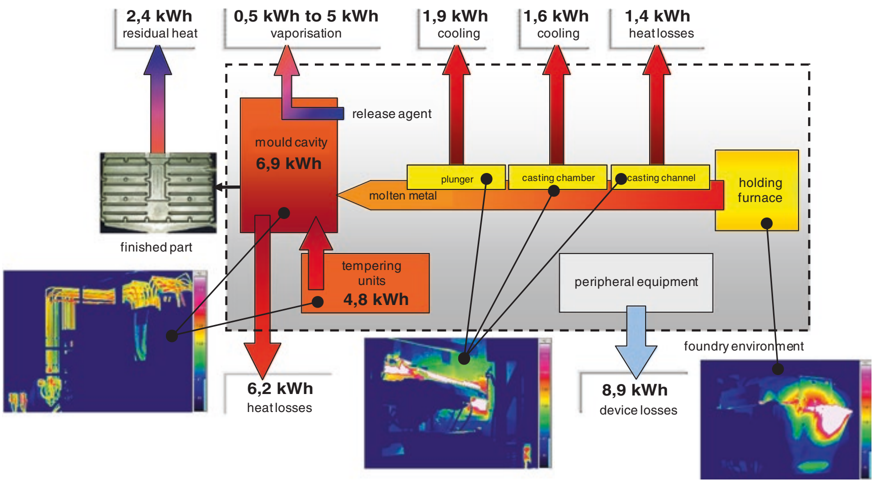


Fig. 2.34 Visualized heat flows in the aluminium die casting cell (Röders et al. 2006)

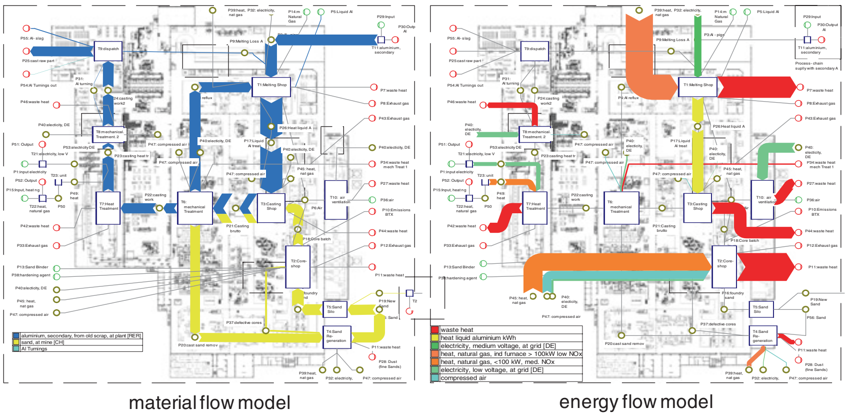


Fig. 2.35 Visualisation of material and energy flow in a gravity die casting foundry (Krause et al. 2012)

perspectives. Both perspectives build upon the same structure of modelled processes. The first perspective visualises the material flows, which connect the modelled processes. The second perspective visualises the energy flows between the same system elements. Therefore, the differences in the flow structures as well as the main influencing system elements can be identified and depicted based on the same model and visualisation approach.

A simple but powerful basis for the creation of Sankey diagrams are input/output balances of the observed transformation processes. They oppose all relevant input flows at the necessary quantities to the resulting output flows and quantities of a transformation process. Thus, the relative composition of input and output flows can be modelled and scaled up or down for the individually required product quantity. This way of modelling transformation processes within productions systems is one basic methodology within the overall concept of material and energy flow analysis (e.g. Lambrecht and Thißen 2014). Later, it will be pursued to model the energy and material flows of aluminium die casting.

2.2.2.3 Simulation

Simulation describes a procedure, in which a model is created of a real existing or imaginary system so that the model can be analysed by conducting experiments. The goal of this procedure is to gain knowledge about the system's behaviour and reaction to scenario experiments in order to generate recommendations for action (e.g. Hedtstück 2013). Thereby, it is a powerful tool to assess improvement scenarios for energy and resource efficiency in a virtual environment before their physical implementation.

Thiede provides a very comprehensive overview over energy oriented approaches for manufacturing system simulation. He states that discrete event

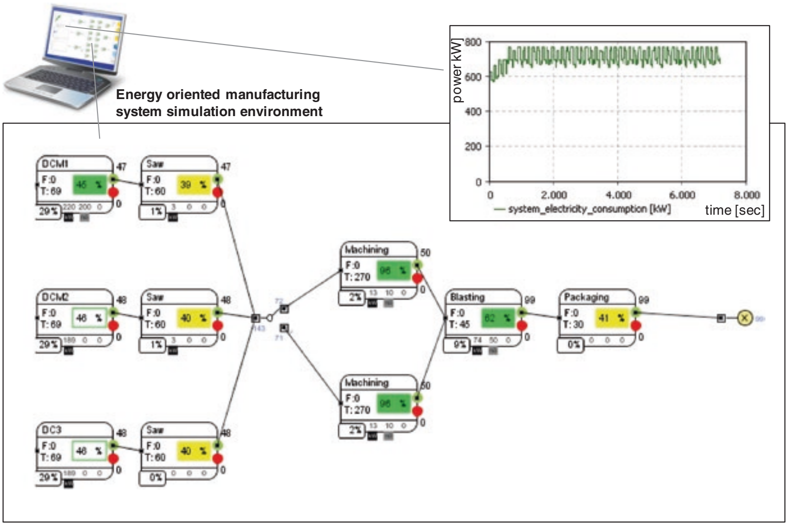


Fig. 2.36 Sample DES based model of an aluminium die casting process chain, modelled in an energy oriented material flow simulation (Thiede 2012)

simulation (DES) is the most relevant simulation class to support the methodological analysis and improvement of energy and resource efficiency in production (Thiede 2012).

Discrete event simulation models and calculates all dynamic events, which occur during one discrete process cycle. In doing so, for each event a specific routine can be executed, which affects the state of the simulated process (Hedtstück 2013).

This dynamic activation of system states and the evaluation of the caused results specifically qualify DES for the simulation of dynamic (state dependent) energy and resource demands in manufacturing systems. Furthermore, DES is already state of the art for commercial simulation tools for material flow simulation in industrial production (Thiede 2012). Thiede himself introduced a concept and sample application for an energy oriented material flow simulation, which integrates the simulation and evaluation of the state-related energy demand of production equipment with a material flow simulation. An exemplary case study about an aluminium die casting process chain has been conducted and fields of action for energy efficiency improvements could be identified (Thiede 2012) (Fig. 2.36).

In contrast to this system perspective on production, a broad variety of simulation approaches exist, which focus the modelling and evaluation of single production processes. For the case of aluminium die casting, the software MAGMASOFT™[4] provides an extensive simulation suite to simulate the process cycle within a die casting cavity at a time resolution of about one millisecond.

[4]See: http://www.magmasoft.de/.

Depending on more than hundred process parameters e.g., the mass flow into the cavity, its solidification over the observed time period and the resulting quality criteria can be modelled (Cleary et al. 2002, 2010). Evaluated quality criteria are e.g., porosities and shrinkage (Campatelli and Scippa 2012; Schneider 2011). To simulate the solidification behaviour of the molten metal, also the heat transfer through the dies and the cooling systems gets simulated. Thus, thermal balances can also be calculated and their variation over time. This can be an input variable to a superior evaluation system, which calculates the resulting energy demand of the die casting cell. Recently, software approaches like MAGMASOFT™ have been extended with optimisation algorithms. Therefore, under given restrictions, optimal process parameters for a previously defined target function can be suggested by the simulation software without the further need for extended empirical process knowledge of the software user (e.g. Hahn and Sturm 2012). Following this approach, the volume of the cycle material (regarding the geometrical parameters of the gating system, sprue, etc.) can also be included in the target function for an optimisation to reduce the overall material demand of this process (Sturm 2011). Similar simulation approaches are implemented in the software suites such as FLOW-3D™[5] or QuikCAST™.[6]

Besides the introduced dynamic simulation approaches on manufacturing system and process level also static simulation is possible. The previously introduced understanding of simulation described as a procedure, which creates and utilises a parameteriseable model for virtual experiments. Thus, static (not time-dependent) and model-based scenario calculations are also included in this definition.

One example for such a static simulation is the calculation of connected energy and material flows in production networks, in which the individual process's input and output flows are modelled via an input/output balance (Wang et al. 2014). E.g., the software Umberto™[7] provides an automated calculation of such harmonized energy and material flows along a modelled system of transformation processes. On the basis of the aforementioned input/output balances for each transformation process, this software computes the resulting energy and material demands (as well as emissions) of each process step to calculate a defined quantity of a specified reference output flow (Möller 2000; Wohlgemuth 2005).

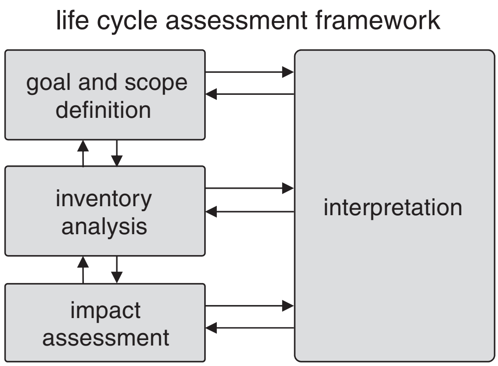
By varying single input/output balances of the structure of the connected flows, scenario oriented simulation experiments are possible to calculate and compare the resulting energy and material flows without a physical implementation (e.g., Ghadimi et al. 2014).

[5]See: http://www.flow3d.de/.

[6]See https://www.esi-group.com/software-services/virtual-manufacturing/casting/procast-quikcast.

[7]See: http://www.Umberto.de/.

Fig. 2.37 Phases of a life cycle assessment (DIN EN ISO 14040 2006)



2.2.2.4 Evaluation

The previously introduced software Umberto™ also offers functionalities to conduct an evaluation of the modelled production system. This evaluation can be done from an economic perspective e.g., via applying a software based material flow cost accounting (MFCA) (Viere et al. 2010). However, an environmental perspective is pursued here. To support this perspective, the Umberto™ software offers the functionality to conduct a life cycle assessment (LCA), based on the previously conducted energy and material flow analysis and modelling (see e.g., Herva et al. 2012). Software tools to conduct a LCA are e.g., GaBi™,[8] SimaPro™[9] or openLCA.[10] A life cycle assessment follows the following phases: goal and scope definition, inventory analysis, impact assessment and interpretation (see Fig. 2.37; DIN EN ISO 14040 2006).

During the goal and scope definition, the system boundary, the aim and the depth of the study are defined (DIN EN ISO 14040 2006). The inventory analysis (also: life cycle inventory—LCI) compiles and quantifies all relevant input and output flows of the observed system and over the regarded temporal system boundaries. These input and output flows are broken down to the level of elementary flows, which directly enter and leave the system to and from its surrounding ecosystem. Usually, a whole life cycle of the investigated object sets this temporal system boundary (DIN EN ISO 14040 2006). The inventory analysis can be supported via an energy and material flow analysis by applying the above introduced methodologies. Therefore, an understanding of the system's internal flows can be enhanced and potential fields of action for later improvements can be derived (e.g. Herva et al. 2012). The third phase (impact assessment) translates the quantified elementary flows into potential environmental impacts of the observed system. Therefore, impact categories are defined, which characterise the resulting

[8]See: http://www.gabi-software.com.

[9]See: http://www.simapro.de.

[10]See: http://www.openlca.org/.

environmental impacts. By conducting life cycle impact assessments (LCIA) conversion factors for each elementary flow into the different impact categories have been calculated. Thus, for each input and output flow of an observed system, its resulting impact according to different impact categories can be estimated (DIN EN ISO 14040 2006).

A widely used methodology for conducting an LCIA is provided by the Institute of Environmental Sciences (Centrum voor Milieukunde, CML) at the Leiden University, Netherlands. According to this methodology, the following impact categories have been defined: Depletion of abiotic resources, impacts of land use (land competition), climate change, stratospheric ozone depletion, human toxicity, ecotoxicity (freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, and terrestrial ecotoxicity), photo-oxidant formation, acidification, eutrophication (Guinée et al. 2002). Each impact category is expressed via characterising equivalence factors. E.g., all flows, which contribute to the impact category global warming potential, are expressed in carbon dioxide equivalents (CO_2eq.). This means, that their impact is scaled according to the equivalent amount of CO_2, which would have caused the same impact.

The impact categories, which are provided through the CML methodology can be characterised as midpoint impact categories, as they represent a problem oriented approach. They translate impacts into environmental schemes, which are expressed in the titles of the individual categories. Endpoint impact categories (like in the Eco-Indicator 99 methodology) follow a damage oriented approach (Goedkoop and Spriensma 2000). They translate impacts into more general issues of concern, which are represented by impact categories like human health, natural environment or natural resources (Bare et al. 2000).

The functionalities for modelling energy and material flows of production processes, simulating the resulting overall resource demand of whole production systems and evaluating them via an LCA are integrated in the software Umberto™. Therefore, this software is selected to support the later concept development and application.

Having the above described methodological support for the analysis, modelling and evaluation of energy and material flows in mind, the following section describes the specific environmental challenges and impacts of aluminium die casting from a technical perspective.

2.2.3 Environmental Impacts of Aluminium Die Casting

Following the taken perspective on energy and resource intensities and on the hierarchically organized aluminium die casting value chain, its environmental relevance will be introduced in the following section. After the aluminium die casting value chain has been technically introduced top-down from global aluminium flows to the die casting process in Sect. 2.1.2, it will now be discussed with a bottom-up-perspective. Starting from a process perspective over a process chain perspective (individual for foundry and alloy supplier) to the value chain perspective, selected energy and resource flows as well as environmental challenges (e.g., emissions, material efficiency) will be addressed.

2.2.3.1 Process Perspective

Input and Output Flows

Although manufacturing processes of the main group primary shaping are still known as comparatively energy and resource efficient, (see Sect. 2.1.2; Fritz and Schulze 2010; Duflou et al. 2012) these processes also offer a lot of potential for a further reduction of their specific energy and resource intensity and environmental impact. Using the example of aluminium die casting, primary shaping processes demand lot of energy carriers, raw materials and auxiliary materials, which are exemplarily listed in Fig. 2.38 (Neto et al. 2008; Heinemann et al. 2013b; Dalquist and Gutowski 2004; U.S. Department of Energy 1999; Kim et al. 2003). Besides these input flows, diverse output flows occur in the die casting process and the die casting cell, which can be (waste-) emissions, (waste-) effluents and solid waste besides (wanted) semi-manufactured products (Neto 2008; Dalquist and Gutowski 2004). Figure 2.38 visualises and lists the physical input and output flows of the aluminium die casting process and the die casting cell as one integrated process model.

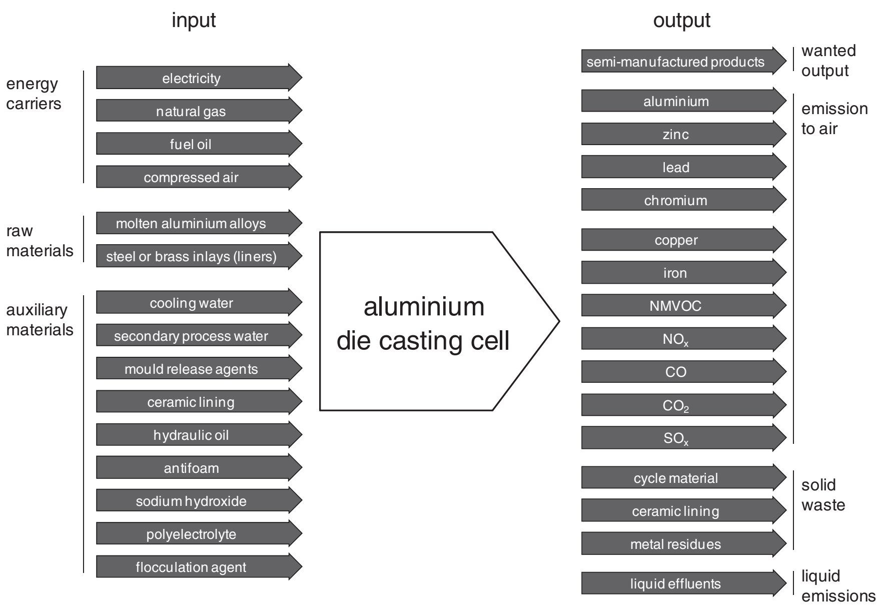


Fig. 2.38 Integrated process model of physical input and output flows of the aluminium die casting cell

Material Efficiency

Obviously, the biggest volumes and masses of the demanded materials are constituted by the processed aluminium alloys. This fact highlights the importance of material efficiency in the die casting process (Herrmann et al. 2011a; Hartmann 2013).

About one third of all aluminium products are near net shape castings. This means that about 30 % of their shot weight is removed from the product after the casting process, and gets resmelted as cycle material within the foundry. This ratio of non-value adding casted material to total shot weight stands for a very good material efficiency, compared to other manufacturing processes (Allwood et al. 2012).

Nevertheless, this ratio can vary a lot especially for different aluminium die casted products depending on the complexity of the product's geometry and the complexity of the gating system as well as the volume of the remainder, which depends on the geometry of the casting chamber and the plunger. Regarding some very complex products, up to 70 % of the shot weight cannot add value to the final product and have to be removed and resmelted iteratively within the foundry (see Fig. 2.39; Dilger et al. 2011).

This bad material efficiency is determined by the predefined geometry of the mould's cavity. Additionally, it often gets amplified by rejects, which result from suboptimal process parameters of the die casting machine during the ramp up phase of a new products (Heinemann and Herrmann 2013).

Energy Intensity

Besides the material efficiency, the energy intensity of the die casting process also offers options for improvement. Figure 2.40 shows an overview of the energy balance of the die casting cell, which is characterized by high non-value adding heat

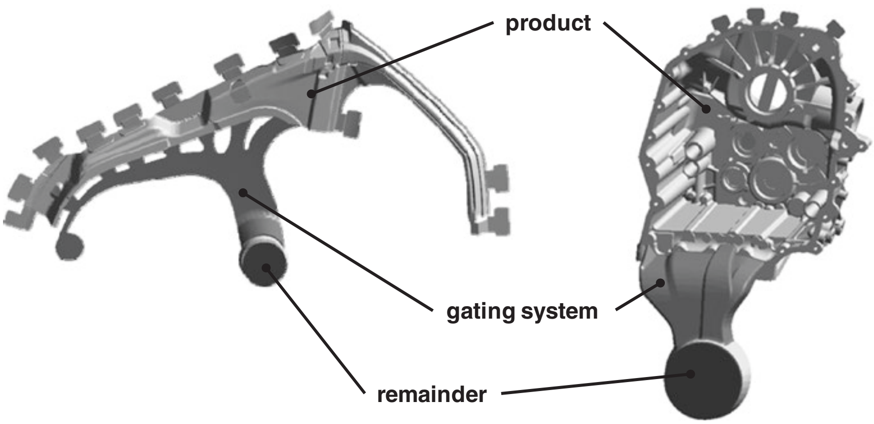


Fig. 2.39 Die casted product with gating system and remainder (Heinemann and Herrmann 2013)

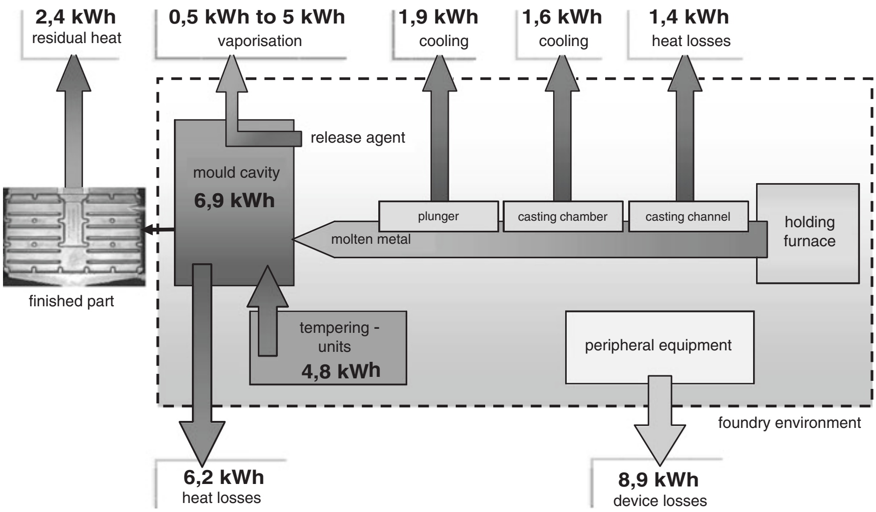


Fig. 2.40 Energy/heat flows in the aluminium die casting cell (Röders et al. 2006)

flows out of the die casting cell into the factory environment. The energy input of the die casting process is converted into heat and kinetic energy. Inside the die casting cell, which is the system boundary of Fig. 2.40, the energy is also transported via additional flows e.g., through the molten metal from the holding furnace into the mould cavity. The mould itself gets additional heat input from tempering units in order to guarantee a certain temperature level during the entry of the molten metal. Furthermore, the same tempering units can transport excess heat out of the mould via cooling channels. Further heat gets dissipated out of the mould and the die casting cell via the extraction of the warm cast, via the vaporisation of water and release agents, which get sprayed on the hot mould between the casting shots, as well as via the heat emissions of the mould (Röders et al. 2006).

Figure 2.40 also illustrates the interplay of all components of the die casting cell for the generation of a cast, as well as for the determination of the total energy intensity of the process. Regarding the total amount of dissipated energy in the die casting cell, the energy and resource intensity of the die casting process occurs to be non-satisfactory although the energy intensity is comparatively low compared to other manufacturing processes.

Focussing only on the electricity demand, Fig. 2.41 depicts the contribution of the single elements of the die casting cell to the cell's energy demand.

Again this breakdown of the electricity demand in a die casting cell points out the interplay of the main process with its peripheral equipment. The biggest contributors to the electricity demand beside the die casting machine are the heat generating processes, which take place in the tempering units and the holding furnace. Together with the die casting machine, they account for nearly three-fourths of the energy demand of the die casting cell during one process cycle. The peripheral

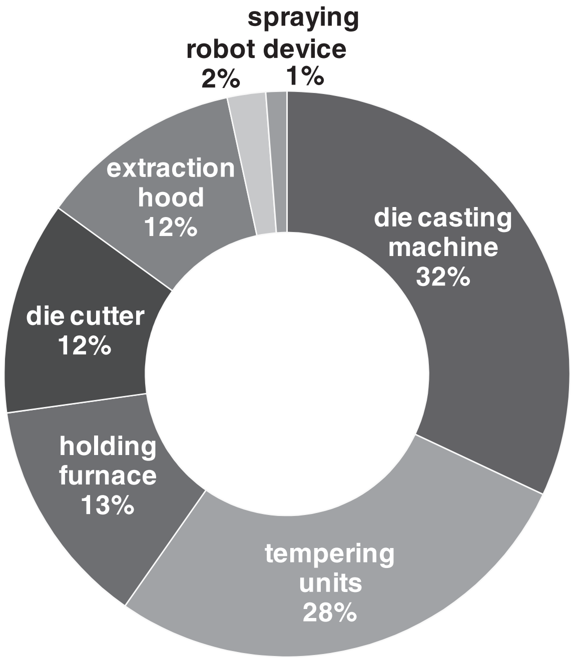


Fig. 2.41 Energy demand shares within a die casting cell during one process cycle (Hoffmann and Jordi 2013a; Jordi 2012)

machines die cutter and extraction hood account for nearly as much electricity demand as the holding furnace. Other peripheral processes sum up only to a negligible share of the cell's electricity demand.

2.2.3.2 Foundry Perspective

Energy Intensity

The aluminium die casting process chain defines the main shares of the energy and resource demand of the overall aluminium die casting foundry. Therefore, the total energy and resource demand of a foundry can give a hint about the dimension and relevance of the value adding process chain itself.

Electricity and natural gas are the main energy carriers that are processed in an aluminium die casting foundry. Electricity is used mainly for the following applications (Hoffmann and Jordi 2013c):

- building services (e.g., lighting, air conditioning, compressed air generation, exhaust air systems)
- IT infrastructure in administrative offices
- die casting cell (empowering hydraulic pump groups)
- furnaces (pot-type and shaft furnaces in smelters, holding furnaces in die casting cell)
- tempering units

Natural gas is used mainly for the following applications (Hoffmann and Jordi 2013c):

- melting of aluminium alloys
- heating the offices and production areas

The absolute amount of demanded energy carriers in the smelter is directly linked and proportional to the total mass of the molten metal (Neto et al. 2008; Solding et al. 2009). Extending the perspective and considering the entire foundry, the specific energy intensity along the aluminium die casting process chain seems to be connected to the overall capacity of the individual foundry. Thus, the specific energy intensity along the whole process chain in a foundry seems to decrease if the total mass of casted products increases. Verifying this assumption, Fig. 2.42 shows the total energy demand of 19 European aluminium die casting foundries in relation to their yearly output of aluminium die casted products (Jordi 2010; Hoffmann and Jordi 2013c).

This shows that for the energy intensity (energy input per product output) of aluminium die casting foundries there is a range from ca. 2–10 kWh/kg. As this range exists, it implies that there is room for improvements for all foundries that cannot rank themselves at the preferable frontier of this range.

This range of specific energy intensities also gets reflected when only the demand of single energy carriers is considered (see Table 2.3). This table lists the minimal, maximal and average energy intensities of 19 selected European aluminium die casting foundries, distributed over the energy carriers electricity and natural gas.

An earlier, non-representative survey among a small number of members of the North American Die Casting Association (NADCA) revealed a range of energy

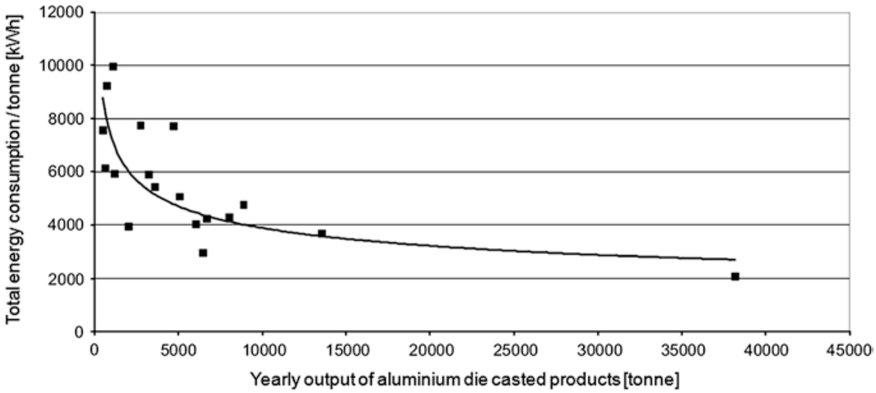


Fig. 2.42 Total energy demand (electricity, natural gas and fuel oil) of 19 foundries compared to their yearly production output (Jordi 2010; Hoffmann and Jordi 2013c)

Table 2.3 Specific energy intensity of 19 selected aluminium die casting foundries (displayed separately for electricity and natural gas) (Hoffmann and Jordi 2013c; Jordi 2012)

Energy intensity (kWh/t)	Minimum	Maximum	Average
Natural gas	1050	7390	3000
Electricity	790	4412	2603

Table 2.4 Specific energy intensities from North American sample foundries (displayed for the individual foundries with the biggest and the lowest energy intensity) (Brevick et al. 2004)

Energy intensity (kWh/t)	Minimum	Maximum
Natural gas	1179	17,598
Electricity	1241	1455
Total energy intensity	2419	19,053

intensities, which can be seen in Table 2.4. The responding die casting foundries had an annual output between 6713 and 24,983 t of aluminium die casted products (Brevick et al. 2004).

It can be observed that the smallest energy intensity (2.4 kWh/kg) is also close to the best European result (2 kWh/kg). In contrast, the largest energy intensity from the U.S. survey is nearly ten times higher, which is double the energy intensity compared to the largest result from the European survey. This fact becomes even more relevant, as the max. energy demanding foundry is already supplied with liquid aluminium alloys. This fact should decrease the energy demand of the smelter section of the foundry. However, the foundry with the biggest energy intensity is also the foundry with the smallest production output in this survey, which corresponds to the aforementioned assumption that bigger capacities and production volumes of foundries allow the implementation and operation of more energy efficient production processes.

Material Efficiency

One major influencing factor for the energy consumption of process chains inside aluminium die casting foundries is the mass of processed metal. In this context not only the absolute mass of metal input into the foundry system is relevant, but also the amount of internal cycle material as it gets resmelted again and again.

This challenge becomes evident when the average specific heat of aluminium alloys $\left(880\text{–}930\,\frac{\mathrm{J}}{\mathrm{kg}*\mathrm{K}}\right)$ as well as the range of melting and solidification temperatures (510–645 °C) are taken into consideration together with the fact, that up to 70 % of the shot weight of a product can be non-value adding cycle material (Honsel 2014).

But cycle material does not only have its source in the die casting cell: the mechanical treatment of the semi-manufactured casts also produces cycle material in the form of swarf (Allwood et al. 2012). Besides, rejects usually get detected in the mechanical treatment section as the main quality gates are located here (Pries et al. 2013; Heinemann et al. 2013b).

Besides the cycle material, which can be reused in the process chain directly, metal losses also decrease the material efficiency of the process chain within the foundry. According to Neto, these losses occur in all processes along the process chain. About 0.04 % of the mass of alloy inputs gets lost via air emissions, and 0.72 % of the mass of alloy inputs are lost as dross in the melting section of the foundry. In the die casting cell, a small share of the material (0.0005 % of the alloy entering the casting sub-process) also gets lost via air emissions. Lost swarf particles and other losses in the finishing department, can account for up to 2 % of the metal losses. Drag-out of aluminium via liquid effluents is negligible. The total losses along the process chain have to be compensated by adding up to 6 % more input material compared to the output of the process chain (Neto et al. 2008).

Due to the low material efficiency of the die casting process chain, a large extra amount of metal needs to be smelted iteratively and energy intensively to compensate the metal losses, and to resmelt the cycle material. Figure 2.43 illustrates this relation between material efficiency and energy intensity of the die casting process chain. Thus, with every cast a large portion of the used energy has not added value but was used to keeping material in the loop within the system.

2.2.3.3 Alloy Supplier Perspective

Energy and Material Efficiency

According to a study by the Austrian Federal Environment Agency, the specific energy intensity, as well as the material efficiency (yield) of an alloy supplier,

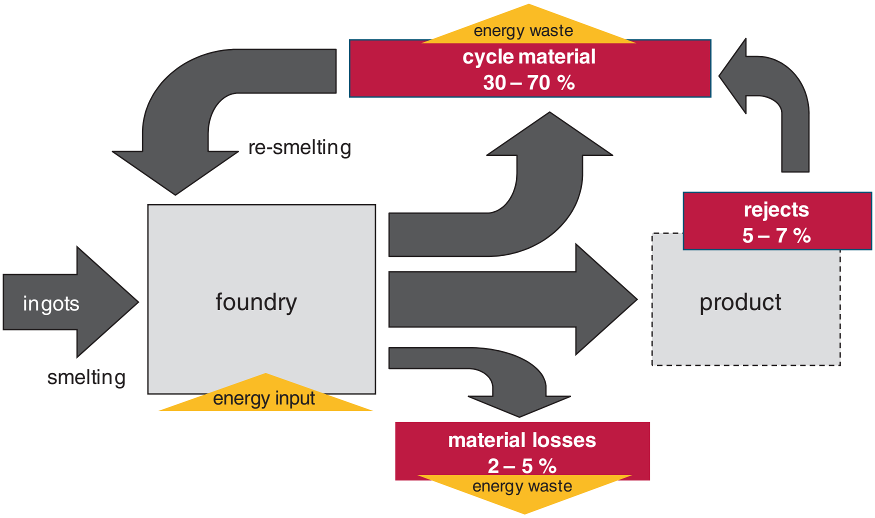


Fig. 2.43 Alloy mass flows, material efficiency and related energy flows in the aluminium die casting process chain inside a foundry (Herrmann et al. 2013b; Dilger et al. 2011)

which focuses on the generation of secondary aluminium alloys, strongly depends on the installed type of equipment. The energy intensity and yield of metal of the possible smelting aggregates especially depends a lot on their individual design and original purpose. Each smelting aggregate design is favourable for specific qualities of aluminium scrap input material. The quality of the scrap inputs is influenced by its granularity, the size of the single blocks or particles and the degree of organic contamination, which determines the amount of required salt additives. Table 2.5 lists possible types of smelting aggregates, the individual metal yield and specific energy intensity for the production of 1 t of molten metal as well as the individual quality of scrap input, which the smelting aggregate was intentionally designed for (Boin et al. 2000).

It needs to be stated that all introduced oven designs are also able to smelt other qualities of scrap input aluminium, and usually only a limited number of ovens and smelting aggregate designs are installed at an alloy supplier. Therefore, from an energy and material efficiency perspective, it is even more important that the alloy supplier chooses the right kind of equipment and input quality for his activities. If a pre-selection of the input qualities is not possible, a pre-treatment of the scrap input aluminium should be done (e.g., sorting, smouldering) in order to qualify the scrap also for more efficient oven designs (Boin et al. 2000).

Waste and Emissions

Besides input oriented aspects such as energy intensity and material efficiency, the consideration of process emissions also is of environmental relevance for the alloy

Table 2.5 Typical energy intensities and metal yields of secondary aluminium production processes (Boin et al. 2000)

Process, smelting aggregate design	Scrap input, input material	Typical yield of metal (%)	Energy intensity (kWh/t)
Swarf drying	Wet swarf and turnings	80–90	600–1050
Melting			
-Induction furnace	Pigs, ingots, swarf and turnings	95–99	700–928
-Closed-well-furnace	Clean scrap, organically contaminated scrap	88–95	700–1194
-Rotary drum furnace (static)	Swarf and turnings, pellets, shredder scrap, post industrial scrap	75–92	1225–1306
-Rotary drum furnace (static + O2-burner)	Swarf and turnings, pellets, shredder scrap, post industrial scrap	75–92	519–569
-Rotary drum furnace (tilting)	Dross, pellets	50–80	Approx. 742
Refining, alloying, holding	Alloying elements (e.g., Si, Cu, Zn, Ti, Mn, Mg, Ni)	95–98	400–722
Total alloy supplier		75–85	1200–2500

supplier. Similar to the consumption of input materials and energy carriers, waste in the form of solid salt-slag, as well as the composition of gaseous emissions, also depends on the chosen type of smelting aggregate. Further kinds of waste or residues are filter dust, furnace lining and dross. Table 2.6 shows the origin of the kinds of waste as well as their amount, which occurs during the production of 1 t of secondary aluminium alloys (Boin et al. 2000).

Table 2.7 shows the typical levels of emissions to air from selected furnaces, which can be used in the secondary aluminium production and the scrap quality, which was intended to be smelted in a furnace of the individual design. The emissions are referenced to 1 t of metal, which leaves the furnace as valuable output (Boin et al. 2000).

2.2.3.4 Value Chain Perspective

Material Efficiency and CO_2eq. Emissions

As mentioned above, the energy intensities of the aluminium die casting process and of its value chain go hand in hand with the overall material efficiency. The same goes for the corresponding CO_2eq. emissions of the value chain.

The energy intensities of the foundry and aluminium supplier have already been addressed in the previous paragraphs. Therefore this section shall link both

Table 2.6 Waste from secondary aluminium production (Boin et al. 2000)

Waste and/or residues	Origin	Volume (kg/t Al)
Salt slag	Melting in rotary drum furnace	300–500
Filter dust	Exhaust gas cleaning	10–35
Furnace lining	Melting furnace	Approx. 2
Dross	All furnaces not using salt, cleaning of smelter, foundries	Approx. 25

Table 2.7 Typical levels of emissions to air from selected processes in the secondary aluminium production (Boin et al. 2000)

Smelting aggregate	Scrap input	Emissions to air (g/t metal)					
		HCl	HF	Dust	NO_2	VOC	CO
Tilting hearth furnace	Clean scrap blocks	2–20	0.1–1.5	1–45	200–900	5–40	30–180
Closed-well-furnace	Clean scrap blocks, organically contaminated scrap	20–600	0.2–1.5	2–25	8–900	5–35	20–100
Rotary drum furnace (static)	Swarf and turnings, pellets, shredder scrap	50–400	3–15	4–55		150–250	

stakeholders, and give a hint on the resulting CO_2eq. emissions, which also result from further upstream activities of the value chain like the raw material generation.

Figure 2.44 illustrates this link by merging the visualized interaction of material and energy flows of the foundry and the alloy supplier in one common picture. This picture gets enriched with information about the carbon dioxide equivalent emissions, which occur from the consumption of energy carriers in the foundry and the alloy supplier, as well as from the upstream processes for the generation of input materials such as primary aluminium, scrap aluminium and alloying elements (Herrmann et al. 2013b).

It becomes obvious that the issue of material efficiency and intensity has a major influence on the energy consumption. The material efficiency of the aluminium die casting process determines the amount of cycle material, which needs to be resmelted. Furthermore, the overall material intensity, as well as the share of processed primary and secondary aluminium, determines a large share of the carbon dioxide equivalent emissions of the value chain (Herrmann et al. 2013b; Heinemann et al. 2013b). Thus, the foundry's consumption of energy carriers for the production of 1 t of final aluminium die casted products accounts for more than 2 t of CO_2eq emissions. The necessary upstream production and supply of alloyed aluminium ingots accounts for more than 1.6 t of CO_2eq. emissions (secondary aluminium alloys) and for more than 11.5 t of CO_2eq. emissions (in the case of primary aluminium alloys) respectively (Herrmann et al. 2013b; Heinemann et al. 2013b). The different environmental challenges using primary or secondary metal inputs will be analysed in the following section.

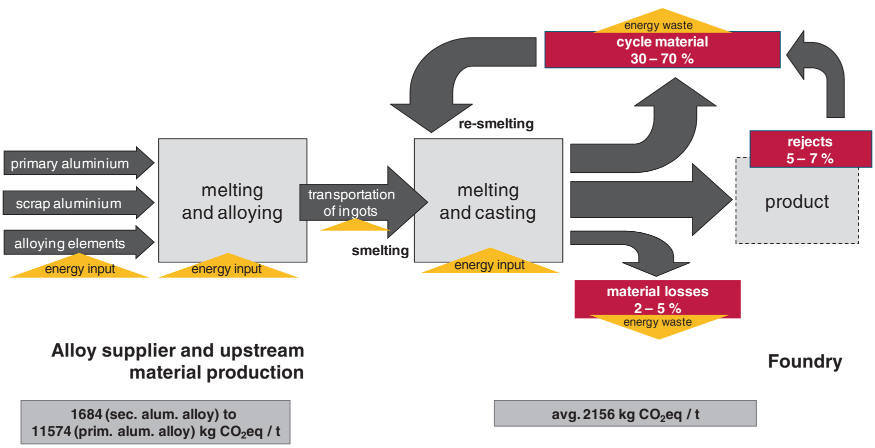


Fig. 2.44 Alloy mass flows and energy flows, material efficiency and related CO_2eq.-emissions along the aluminium die casting value chain (Herrmann et al. 2013b)

Primary Versus Secondary Aluminium Production

As stated above there is a significant difference in the global warming potential (in terms of carbon dioxide equivalent emissions) for producing aluminium alloys which are based on primary or secondary aluminium. The same is true for other environmental impact categories as a life cycle assessment from the European Aluminium Association can confirm (see Fig. 2.45; EAA 2013)

From the results of this life cycle assessment it can be seen that in every environmental impact category, the production of primary aluminium causes significantly more environmental harm than the secondary aluminium production. Furthermore the relevance of the large amount of demanded energy can be interpreted from this assessment.

Logožar et al., Quinkertz and Dienhart identified that the main energy demand contributors for producing 1 t of primary aluminium ingots represent the consumption of electricity, which increases its contribution to the carbon dioxide equivalent emissions, compared to the consumption of fossil fuels (Logožar et al. 2006; Quinkertz 2002; Dienhart 2003; www.umweltdatenbank.de 2014).

The total energy input (thermal energy and electricity), which is needed for the production of 1 t of primary aluminium, sums up to a range from 18610 to 33610 kWh (from bauxite mining to electrolysis) (Dienhart 2003).

Chapman and Roberts compare the energy intensities of primary and secondary metals for aluminium as well as for copper and steel. Again, the energy oriented advantage of secondary metals gets highlighted, especially when considering the comparatively large energy demand for the primary aluminium production,

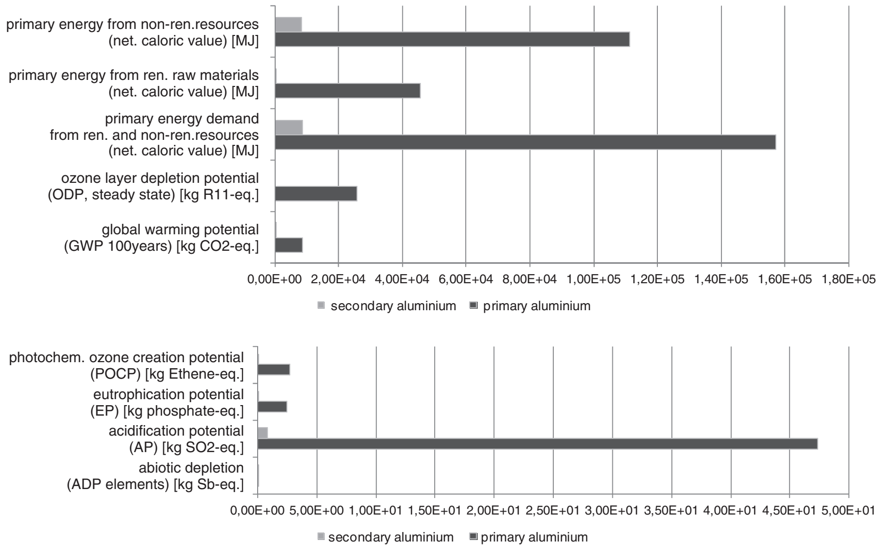


Fig. 2.45 Main environmental impacts from primary aluminium and secondary aluminium production (per t of ingot) (EAA 2013)

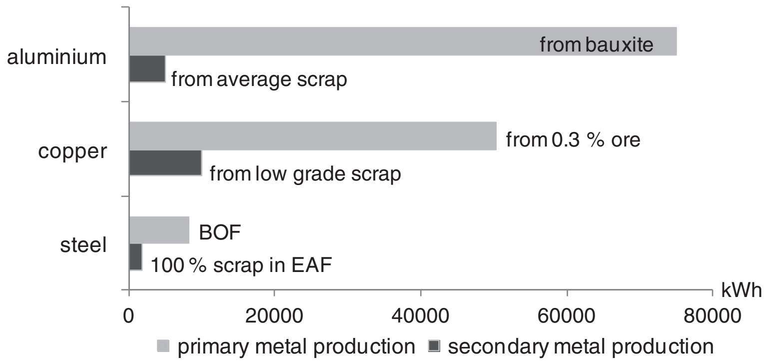


Fig. 2.46 Comparison of energy inputs for various metals: primary versus secondary production (Chapman and Roberts 1983; Wernick and Themelis 1998)

which was even higher two decades before the study of Dienhart (see Fig. 2.46; Chapman and Roberts 1983).

However, even if the large energy consumption and environmental impact of the primary aluminium production makes secondary aluminium appear more favourable, secondary aluminium is not feasible for all possible technical fields of application. Besides, the collection and preparation of the scrap metal inputs for the generation of secondary aluminium, as well as downgrading effects during redundant recycling circles, also create challenges for the increased use of secondary aluminium.

Recycling, Downgrading and in-Use-Stocks of Aluminium

Aluminium is often called a sustainable metal as its recycling should be redundantly possible without any decrease in the metal quality. This statement includes the assumption, that due to the good recyclability, a large share of the global demand can be satisfied by secondary aluminium (e.g., Efthymiou et al. 2010; Baldwin 2007; EAA 2007).

There are two arguments that contradict to this statement. On the one hand, a continuous recycling of aluminium end-of-life products usually leads to a concentration of alloying elements, which limits the possible use of the resulting secondary alloy (downgrading). This effect can only be abated by adding primary aluminium to reduce the concentration of contaminating elements/impurities (e.g., Paraskevas et al. 2013; Gaustad et al. 2011; Wernick and Themelis 1998). On the other hand, due to its long life time, large in-use-stocks and often poor recycling quotas of many aluminium products, there is not enough scrap aluminium input material to satisfy the global aluminium demand. Therefore, primary aluminium has to enter the global aluminium system continuously (e.g., Liu and Müller 2013; Rombach 2013).

Rombach performed a meta-analysis of different studies, which investigated the global recycling content of six different metals. Although the absolute results have to be compared and interpreted with caution due to inconsistent underlying calculation schemes, the resulting table is feasible to highlight the relatively small recycled content of aluminium. Rombach explains this small recycled content with incomplete collection of scrap, losses during the scrap processing and the large in-use-stock of aluminium products (see Table 2.8; Rombach 2013). Table 2.8 also reminds about the amounts of circulating post industrial scrap, which does not enter the use phase of a product, but gets resmelted directly in the value chain.

Liu and Müller illustrated that this global in-use-stock of aluminium is not even large, but also steadily growing (Liu and Müller 2013).

According to Rombach the total in-use-stock of aluminium has a size of about 700 Mt, which would be ca. 75 % of the total amount of the primary aluminium that has ever been produced. In 2010, 50 Mt of new aluminium products entered the use phase, whereas in the same year only 11 Mt of aluminium scrap have been collected and recycled. So the difference between product output and aluminium scrap input needs to be replenished by primary aluminium.

Nevertheless, recycling of aluminium is an important issue to decrease the energy intensity of aluminium products. Furthermore, the large in-use-stocks of aluminium can be considered as future raw material sources. Thus efficient recycling of aluminium alloys, which ideally maintain the quality and specifications of the recycled alloy, will become more and more important.

But the maintaining of alloy specifications is an especially critical issue in aluminium recycling as mentioned above. Besides magnesium and zinc, all other alloying elements are almost impossible to remove once they have been added to the alloy (Nakajima et al. 2010).

Due to increasing and further downgrading in-use-stocks of already downgraded aluminium alloys from automotive applications, Modaresi and Müller forecast that in 2050 an annual amount of 3.3–18.3 Mt of aluminium scrap will leave the industrial system without being recycled. This resource loss corresponds to 3–18 % of the primary aluminium production of the year 2050 and also represents a loss of energy saving potential of 240 TWh/year, which is close to the total annual energy demand of a medium-sized country like Spain (268 TWh/year) (Modaresi and Müller 2012).

Table 2.8 Recycled content of global metal production

Metal	World (%)	Europe (%)	Year
Steel	40[a]	50[a]	2008, 2004
Nickel	40	49[a]	2008, 2000
Aluminium	**22** (**37** %[a])	**23** (**40** %[a])	2010, 2007
Copper	37	65[a]	2006
Zinc	31	49 (Germany)	1997
Lead	57	74	2005

[a]Including post industrial scrap Rombach (2013)

Paraskevas et al. have visualized the problem of alloy downgrading during cascading recycling circles (Fig. 2.47; Paraskevas et al. 2013).

Due to the concentration of impurities, primary aluminium alloys as well as unalloyed primary aluminium degrade to low alloyed wrought aluminium alloys after the first recycling cycle. These alloys get transformed into high alloyed cast aluminium alloys after further recycling cycles, unless the molten aluminium scrap does not get diluted with primary aluminium. Another strategy to avoid the downgrading of the metal quality is to collect and sort only very clean high quality aluminium scrap of exactly that alloy, which shall be achieved after remelting the scrap inputs. Paraskevas et al. illustrated also the resulting open and closed recycling loops from these two abatement strategies (dilution with primary aluminium, single alloy strategy) (see Fig. 2.48; Paraskevas et al. 2013; see also: Graedel et al. 2011; Dubreuil et al. 2010).

Obviously, the single alloy strategy forces the alloy supplier and the foundry to gain maximum control over the scrap aluminium flows. So it can be applied usually only for post industrial scrap. Otherwise a strong collaboration with the

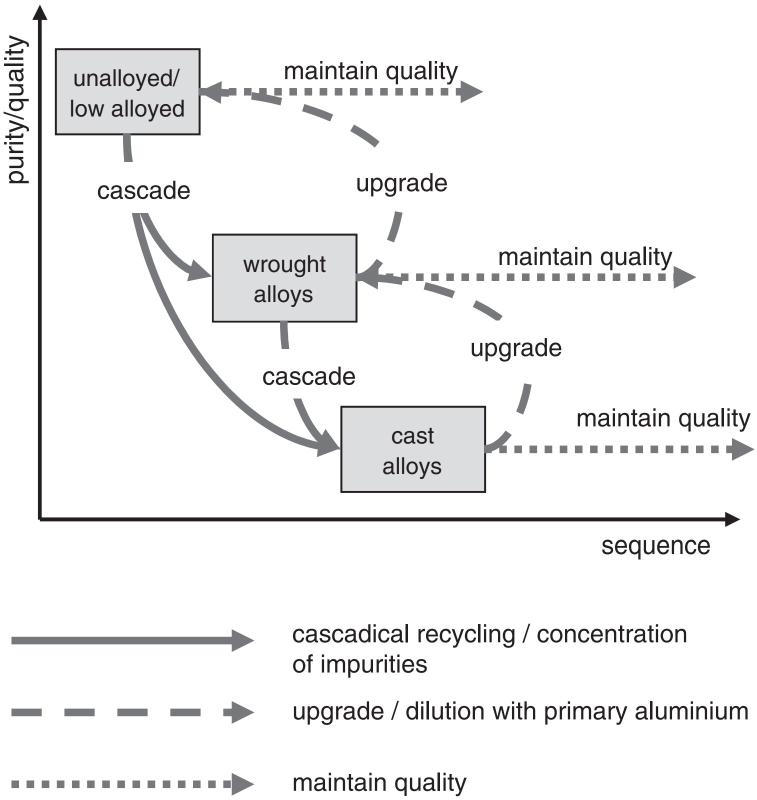


Fig. 2.47 Aluminium cascade recycling chain (Paraskevas et al. 2013)

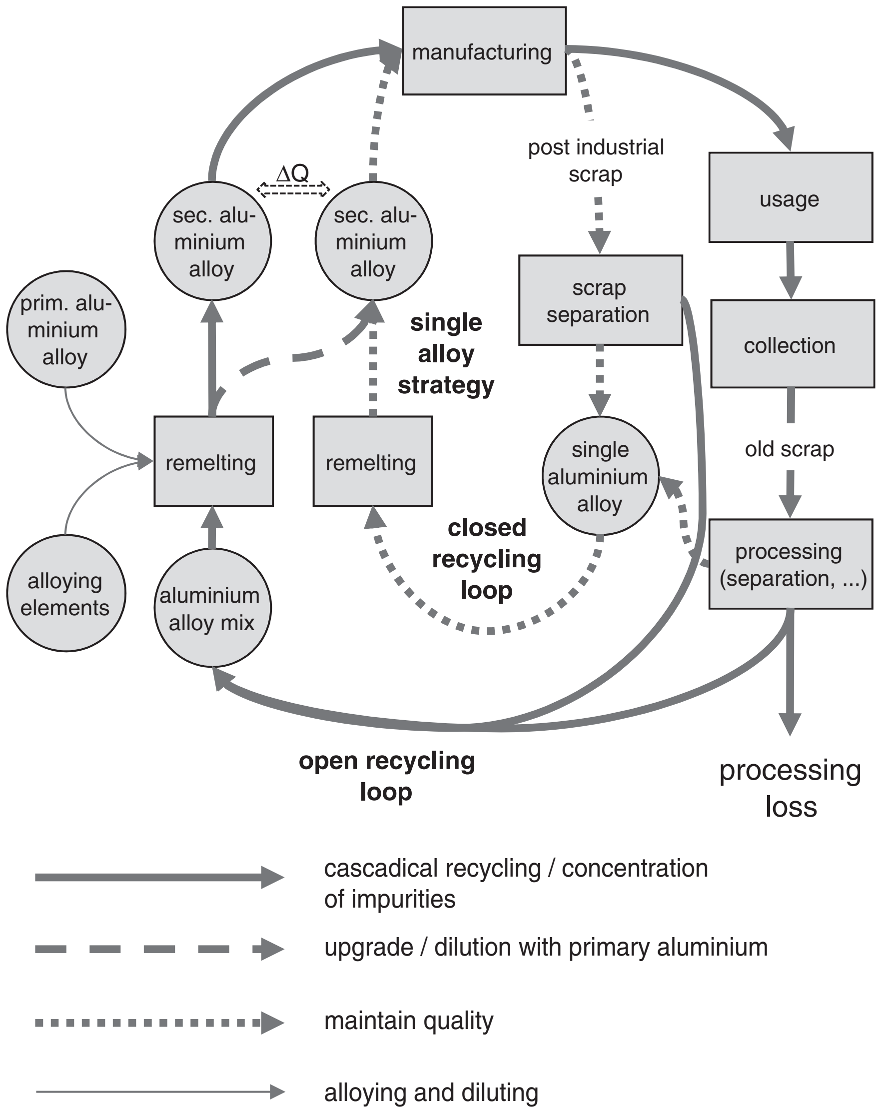


Fig. 2.48 Aluminium recycling options (Paraskevas et al. 2013)

customer of the final aluminium products as well as good control over the collecting system needs to be established (Paraskevas et al. 2013).

To support such strategies Koffler and Florin suggest the introduction of more diversified scrap metal prices, which are based on the scrap's pureness respectively on its incorporated concentration of alloying elements and other contaminants (Koffler and Florin 2013).

Concluding the aforementioned issues about aluminium recycling, downgrading and in-use-stocks it has to be stated, that despite its relatively good recyclability, the global society's demand for aluminium products can never be satisfied completely with secondary aluminium alloys. Thus, regarding the large environmental burdens from primary aluminium production, increasing material efficiency during manufacturing processes and decreasing material intensities of aluminium products are vital for making aluminium value chains more sustainable. The following chapter introduces first existing approaches, which try to cope with these challenges by increasing the energy and resource efficiency of industrial production.

Chapter 3
Existing Approaches

The previous section has provided an overview over the hierarchical levels of industrial production that need to be considered to identify and evaluate measures for strong improvements regarding the energy and material efficiency. As an example for highly energy and material intensive technologies, the aluminium die casting value chain was introduced from a technical perspective. Furthermore its complexity and environmental relevance was highlighted. There is a need to provide analysis and decision support for improving such production systems at the right and effective spot, as possible fields of action are manifold. Against this background, the following chapter analyses existing research approaches which reduce the environmental impact of complex industrial production systems. After a short description of existing approaches, a comparative evaluation of these approaches is conducted to differentiate the specific individual scopes and constraints. This detailed analysis of the current state of research will support the subsequent deduction of further research demand to support the transition towards energy and resource efficient industrial production.

3.1 Background for Selection and Evaluation of Existing Approaches

Industrial value chains are complex systems. Different levels of vertical and horizontal hierarchy can be distinguished. Numerous interdependencies between the single levels and manifold possible parameters exist, which can be influenced to try and make the system more energy and resource efficient.

Industrial production, and especially the aluminium die casting value chain, process large amounts of mostly non-renewable energy carriers, as well as primary raw materials and produce goods, which cannot be recycled in redundant circles without losing their mechanical properties and alloy quality. In general, besides the pure depletion of raw materials and fossil fuels, energy and material (metal) flows in aluminium value chains are from major importance regarding the

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environmental impact of such industrial systems. Furthermore, economic pressure comes from rising energy prices and decreasing but highly volatile metal prizes (destatis 2014; lme 2014). Therefore, a detailed understanding and an effective reduction of the aluminium die casting's energy and material intensity are a key for making the aluminium die casting value chain more sustainable (under the assumption that the usage of aluminium die casted products will not be substituted by other materials).

Thus, methods and tools need to be developed further, which support the modelling, holistic analysis and evaluation of the complex production systems like in aluminium die casting. By doing so, measures for true improvements can be developed and evaluated—focusing on real levers for the reduction of energy and material intensity, while avoiding problem shifting. Against this background this section introduces the background and limitations for the analysis of already existing approaches towards energy and resource efficient production. These approaches will be evaluated later based on the criteria, which are introduced in this section.

3.1.1 Procedure and Limitations of Analysis

Having in mind the highlighted relevance and characteristics of hierarchical industrial value chains and especially of the aluminium die casting value chain, necessary limitations regarding the selection of existing approaches in research need to be defined to focus the subsequent survey. Figure 3.1 illustrates the described limitations for the selection of current research approaches, which get reviewed to identify further research demand.

Manifold research approaches, methods and tools are available for the modelling and evaluation of diverse systems and system elements that are related to the single groups of manufacturing processes (DIN 8580 2003). However, due to focus on the aluminium die casting value chain, only those approaches will be selected, which can be applicable for systems or system elements within **primary shaping value chains** in terms of basically **discrete parts manufacturing on an industrial scale**. Nevertheless, these approaches shall have the ambition to be transferable to other value chains as well.

According to the focus of the previous chapter, **energy and material flows are of major interest**. So the considered research approaches should consider the energy and material flows within their individual system boundary, which have a contribution to value adding processes and the nearer peripheral processes at a certain level of detail.

All energy and material flows can be expressed by using vocabulary from finance and economics as well. Physical flows can be expressed as a financial flow by applying methods like material flow cost accounting (e.g., Viere et al. 2010; DIN EN ISO 14051 2011) or activity based costing (e.g., Lachnit and Müller 2012). However, as this book explicitly addresses the environmental dimension of sustainability, only research approaches regarding the **physical dimension of**

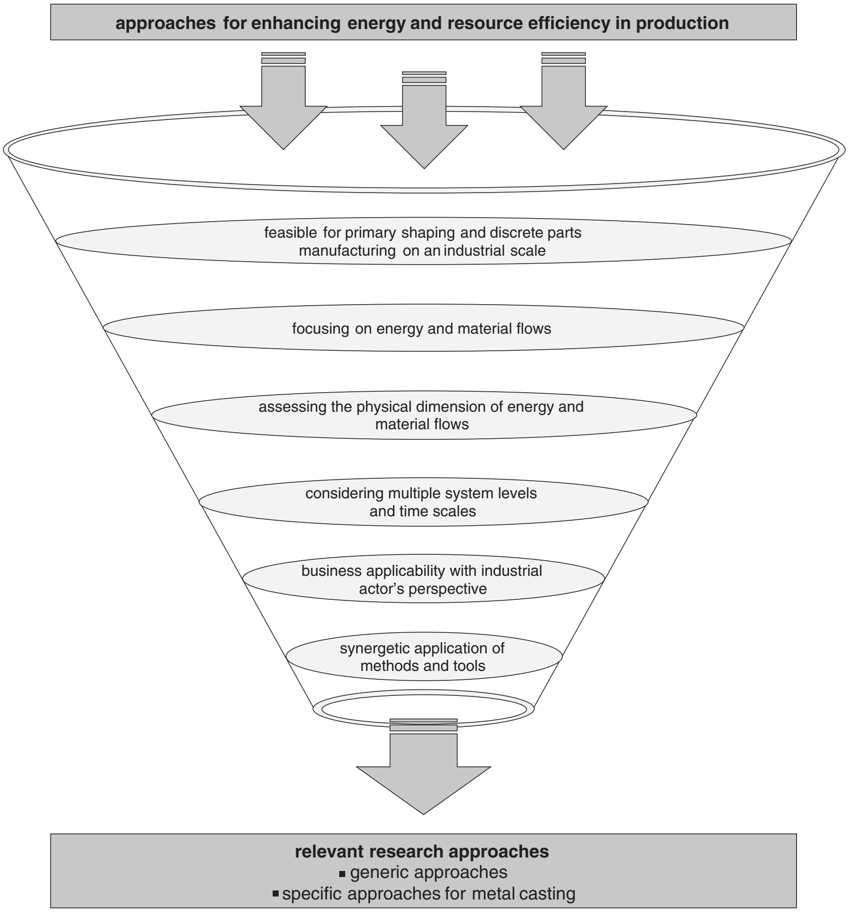

Fig. 3.1 Limitations for the review of the state of research

energy and material flows are considered. Nevertheless an ex-post conversion of the individual results into a monetary dimension (e.g., by applying flow prizes, Heinemann et al. 2013c) should remain possible.

Industrial production and especially aluminium die casting is a complex system. This system consists of system elements, which are located on **multiple system levels** and operate with **manifold time scales** regarding their individual time horizon for planning and evaluation. This has to be respected by the selected research approaches as well. They shall provide a system perspective on industrial production, and not focus on sole sub aspects. This excludes approaches, which focus on the modelling or evaluation of single manufacturing processes (e.g., Kellens 2013; Kellens et al. 2012; Gutowski et al. 2006; Mori et al. 2011; Diaz et al. 2011; He et al. 2012; Li and Kara 2011; Kara and Li 2011; Li et al. 2012; Dahmus and Gutowski 2004).

Measures for energy and resource efficiency have to be driven by business decisions and elaborated with help of the engineering domain. Therefore, relevant research approaches need to provide decision support and **business applicability with an industrial actor's perspective**. Thus, the identification, evaluation and prioritisation of improvement measures need to be focused. Therefore, approaches that take an abstract perspective on the energy and material flows of whole branches or economies (e.g., like in the industrial ecology domain), are excluded due to their extended width of scope beyond an industrial actor's scope of action (e.g., Allwood and Cullen 2012; Liu and Müller 2013).

It gets acknowledged, that single methods or tools often cannot provide comprehensive support for enhancing the energy and resource efficiency of entire and complex manufacturing systems as they are in focus here. Thus, the selected research approaches **focus on the application of diverse methods and tools and their synergetic interaction**. This excludes methodological approaches such as High Level Architecture (HLA), which solely provide a multi-level architecture for integrating third party methods and tools without addressing the energy and resource efficiency through an independent solution (e.g., Zülch et al. 2002; Klein et al. 1999; Schuhmann et al. 1997).

According to these limitations the following paragraphs strive to give an insight in current developments for the development, design and application of methods and tools, which support the improvement of manufacturing processes, process chains and value chains towards energy and resource efficiency. The selected research approaches are grouped into generic approaches and into specific approaches for metal casting value chains. Both groups are evaluated by using the same criteria, which will be described in the following section.

3.1.2 Definition of Criteria

Against the theoretical background regarding hierarchically organised industrial production and its environmental challenges, manifold criteria for the evaluation of related relevant research approaches have been derived. These criteria can be clustered into three main areas with seven subordinate criteria groups. They will be described in the following section, focusing on an ideal degree of fulfilment. The criteria's attributes are part of a cumulative evaluation scheme. Compliance of an approach with an attribute adds a quarter of a point and can sum up to a maximum of one (100 %) per criterion. If none of the attributes of the individual criteria can be selected for a selected approach, this criterion is marked with an empty point (0 %).

3.1.2.1 Scope

The first criteria main area clusters criteria, which evaluate the spatial, technological and temporal scope of the selected research approaches.

Industrial production (and especially aluminium die casting) is understood as complex system, in which the observed system elements span a horizontally, vertically and sequentially ordered space of observation. Thus, the **spatial scope** regards the composition of the observed system elements within this space. An ideal approach considers all hierarchical levels of production with an integrated, multi-level perspective and not only single system levels like manufacturing process, process chain or value chain (criterion *vertical hierarchy*). On the single hierarchical levels, besides the value adding activities also peripheral activities (directly/not directly linked to the value adding activities) and even other supporting entities (e.g., administration, staff facilities) need to be considered for a truly holistic perspective (criterion *horizontal hierarchy*). Furthermore, on each system level, not only single system elements need to be regarded independently, but their interlinkage in a sequential flow of production steps has to be considered (criterion *sequentiality on hierarchical levels*). By fulfilling these criteria in the criteria group spatial scope, the consideration of all relevant system elements in a vertically, horizontals and sequentially connected system is ensured.

Due to the specific scope of aluminium die casting, the **technological scope** of the selected research approaches also needs to be tested. All selected approaches should at least deal with discrete pats manufacturing in general. However, applicability for primary shaping value chains or metal casting is aimed for—ideally for the specific case of aluminium die casting (criterion *consideration of primary shaping*).

The described hierarchical complexity of production demands an individual perspective on the dynamics of business decisions per system level. In parallel to these individual ranges of different planning perspectives, the state of the processed objects along their individual life cycle also needs to be considered. Both aspects are addressed via the **temporal scope** of the considered research approaches. Perspectives on the dynamics of business decisions can be operational, tactical and strategic. Ideal approaches should integrate the different hierarchical system levels, so that all perspectives are applicable and a multi-time-scale perspective can be taken (criterion *planning/evaluation perspective on production*). In contrast to the perspective on the production system and the nature of its related business decisions, a perspective on the temporal state of the processed objects (materials and products) shall also be possible. Therefore, ideal approaches should distinguish the life cycle phase of its processed objects. As a result of this, aspects of circular economies can also be integrated (criterion *life cycle phase of processed objects*). Table 3.1 gives an overview over the above mentioned criteria of the main area **scope** with their individual set of attributes.

3.1.2.2 Data and Model Quality

The second criteria main area clusters criteria, which evaluate the data and model quality.

Table 3.1 Criteria and characteristic attributes of the main area scope

Criteria (groups)	Cumulative, characteristic attributes			
	+ ◔	+ ◔	+ ◔	+ ◔
Spatial scope				
Vertical hierarchy	Manufacturing process	Process chain	Value chain	Multi-level perspective
Horizontal hierarchy	Value adding entities	Peripheral entities, directly linked to value adding activity	Peripheral entities, no direct linkage to value adding activities	Other supporting entities (e.g., administration, staff facilities)
Sequentiality	Interlinked value adding processes	Cross process chain/section activities	Cross company interaction	Interlinked value chains
Technological scope				
Primary shaping	Discrete parts manufacturing in general is considered	Primary shaping in general is considered	Metal casting is considered	Specific example for aluminium die casting
Temporal scope				
Perspective	Operational	Tactical	Strategic	Multi-time-scale perspective
Life cycle phase	Raw material generation	Production	Usage	Recycling

Current research approaches should make use of validated data sets or generate new data. Furthermore, the addressed energy and resource flows should be considered completely. These two aspects are addressed by the criteria group **data quality**. Ideal approaches do not focus only on at least one energy or material flow within the observed system, but on all relevant energy and material flows. This ensures, that trade-offs between single flows can be integrated in the final evaluation of this system and of possible improvement measures (criterion *completeness of resource flows*). Ideal approaches shall also build upon validated data sets about energy and material flows from standardised LCI databases. Furthermore, they shall contribute to the pool of LCI data sets by adding newly generated data, which has not been gathered and published for the observed objects yet. If complex production systems are focused, data sets are often available only for some elements of these systems. In such a case, the ideal approaches shall offer a procedure for the joint application of existing LCI data sets and individually generated new data sets (criterion *data sources of resource flows*).

The gathered data about energy and resource flows of the observed system needs to be modelled to identify fields of action and derive measures for enhancing the energy and resource efficiency of this system. The criteria group **modelling quality** evaluates the supported level of modelling detail, and the structure of the mapped energy and resource flows. Energy and resource flows in complex and hierarchical systems like in production should be modelled on each of the

Table 3.2 Criteria and characteristic attributes of the main area data and model quality

Criteria (groups)	Cumulative, characteristic attributes			
	+◔	+◔	+◔	+◔
Data quality				
Resource flows	At least one material flow	All relevant material flows	At least one energy carrier	All relevant energy carries
Data sources	Standardised datasets from LCI data bases		Newly metered LCI data	
Model quality				
Modelling detail	Process model	Process chain models	Factory model	Value chain model
Structure of flows	Linear	Converging	Diverging	Cycling

system's system levels. Therefore, process models should be integrated in process chain models, which can be part of factory models or integrated in value chain models (criterion *supported modelling detail*). To investigate the complexity of the individual models, which are developed in the selected research approaches, the *structure of the considered flows* also needs to be evaluated. This is done via the correspondent criterion. The developed model is tested for its ability to depict linear, converging, diverging and circular flows. Table 3.2 gives an overview over the above mentioned criteria of the main area **data and model quality** with their individual set of attributes.

3.1.2.3 Application

The third criteria main area clusters criteria, which evaluate aspects regarding the application of the selected approaches. This considers the industrial applicability as well as the comprised evaluation schemes.

As this book shall make a contribution to an increased energy and resource efficiency in production, **industrial applicability** of the selected research approaches is vital. This criteria group regards the transferability of the considered approaches to other technologies and branches. It also evaluates the types of its incorporated methods, their combination into a procedural approach and the decision support of the approach's evaluation outcome. To ensure a relevant impact on industrial production, a broad applicability of the selected approaches among technologies, branches and in general for production ideally needs to be ensured (criterion *transferability*). As stated above, for complex systems like production, the synergetic combination of methods for energy and resource efficiency seems to be more promising than the sole application of single methods. Thus, ideally many interacting methods shall be combined. The criterion *methodology* evaluates the types of the applied methods from data acquisition, modelling and visualisation, over simulation to evaluation. Not only is there a need to apply different methods in parallel. This has to be done in a rather structured way to enable the methods to unfold their full potential synergetically. Therefore, a *procedural approach* is vital, which puts the selected methods in a common context and explains a workflow, which creates synergies of a joint application. The corresponding criterion detects whether a procedural approach is provided of the selected research approaches. Such a provided procedural approach can focus on single methods or ideally guide the joint application of multiple methods. As a result of every procedural approach for enhancing industrial energy and resource efficiency, there should be a decision supporting mechanism. This means that the corresponding criterion *decision support* evaluates the ability of the selected approaches to evaluate and rank multiple improvement scenarios or even their combination.

The capabilities of the considered **evaluation** schemes of the selected research approaches are also relevant aspects and get compared via different criteria groups. This includes an investigation of the individual evaluation dimension, its retrospective or prospective perspective and the way, how its results are displayed. All industrial decisions are challenged against the company's set of business targets. These target sets are traditionally focusing on economic targets, but environmental targets are becoming more and more important. Thus, improvement scenarios need to be evaluated by using similar evaluation dimensions like the company's business target dimensions. From an energy and resource efficiency perspective, the economic

Table 3.3 Criteria and characteristic attributes of the main area application

Criteria (groups)	Cumulative, characteristic attributes			
	+ ◔	+ ◔	+ ◔	+ ◔
Industrial applicability				
Transferability	Feasible for specific, case with reproducible basic conditions	Feasible for considered technology in general	Feasible for considered branch in general	Feasible for industrial production in general
Methodology	Data acquisition	Modelling and visualisation	Simulation	Evaluation
Procedure	Provided for single method		Provided for joint method application	
Decision support	Evaluation and ranking of single scenarios		Evaluation of scenario combination	
Evaluation				
Evaluation dimensions	Economic impact	Physical mass flow	Physical energy flow	Environmental impact
Evaluation perspective	Ex-post		Ex-ante	
Display of results	Qualitative statements	Quantitative, comparable presentation	Visualisation of energy flows	Visualisation of material flows

as well as the environmental evaluation dimension are affected by physical mass flows and physical energy flows. Thus, these quantifiable flows will be considered as evaluation dimension as well. The evaluation criterion *evaluation dimensions* tests the selected research approaches about which evaluation dimension has been used—ideally in combination. The capability of the evaluation scheme can also be exemplified via its perspective. By taking a retrospective evaluation perspective, a severe ex-post assessment of the status quo of an observed system is possible. Such a perspective can be based on detailed metering and further data acquisition. A prospective evaluation perspective integrates the consideration of future scenarios. Thus, also forecasting routines need to be integrated. The criterion *evaluation perspective* tests the selected approaches regarding their taken perspective, which should be combined in an ideal case. Finally, the selected approaches are evaluated regarding their way of displaying results with purely qualitative statements possible, as well as additional or independent quantitative presentation of results and the visualisation of the underlying energy and material flows (criterion *display of results*). Table 3.3 gives an overview over the above mentioned criteria of the main area **application** with their individual set of attributes.

3.2 Review on Relevant Research Approaches

Approaches are focused, which combine methodologies and tools as described in Sect. 2.2.2, which consider the hierarchical nature of industrial production and which focus ideally on primary shaping value chains. Thus, this section introduces relevant research approaches, which have been selected according to the above described limitations (see Sect. 3.1.1). They are clustered into specific approaches for metal casting (with a focus on aluminium die casting) and generic approaches. An evaluation of the described approaches will be done in the subsequent section (Sect. 3.3) according to the above introduced criteria.

3.2.1 Generic Approaches

The *ENOPA* project pursed the goal to make factory systems more energy efficient. To support this goal, a holistic perspective on factory systems has been defined and a first prototype of a coupled, dynamic co-simulation of factory elements has been set up (e.g., Junge 2007; Hesselbach et al. 2008). This holistic perspective on factory systems considers factories as hierarchical systems especially regarding horizontal hierarchies. Thus, the interaction of value adding production processes with peripheral entities like technical building services and the building shell are integrated in a common simulation framework. The ENOPA approach has been extended with an energy oriented perspective on material flow simulation (e.g., Thiede 2012).

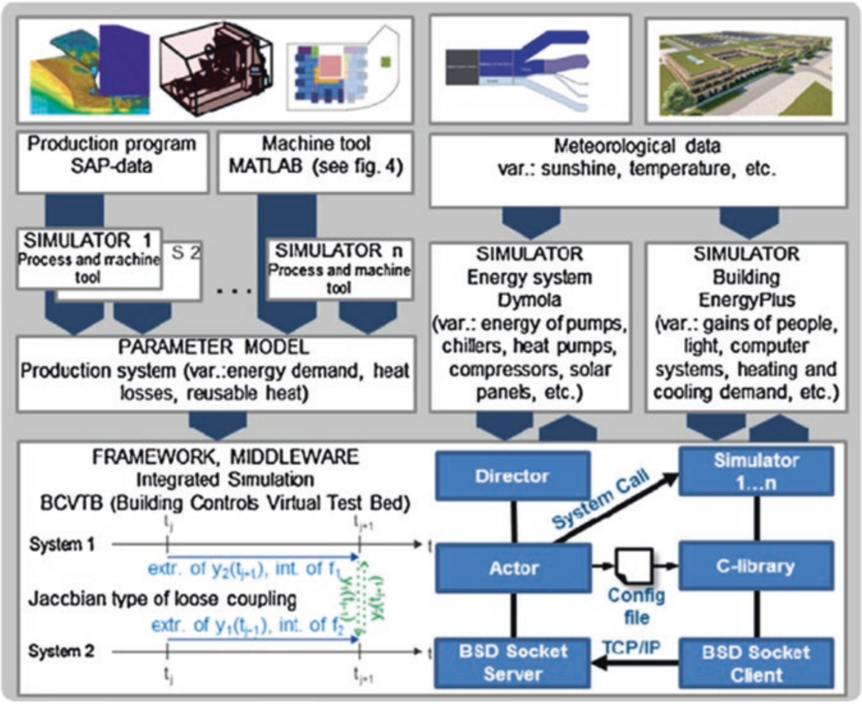

Fig. 3.2 Methodological approach for multi-level co-simulation of coupled simulation environments for industrial production (Bleicher et al. 2014)

A similar approach is proposed by Bleicher et al. (2014). The authors suggest an integrated simulation approach to assess and improve the energy efficiency of production systems. This approach aims to support factory planning processes at an early planning stage. The integrated simulation approach enables a dynamic co-simulation of specialised available simulation tools for the manifold subsystems of a factory. Following this general idea, but without taking material flows into account, Bleicher et al. focus on the technical coupling of the different simulation approaches. To cope with the challenge of differing time scales on the different system levels, which are also represented in the individual simulation tools, they suggest a loose coupling approach with periodic communication intervals between the single simulation modules. Figure 3.2 visualises the general approach and the interaction of its modules. The detailed modelling concepts for each system element are not explained in detail. The application of this approach is arranged into the following steps: First, the considered sub-systems (processes, machines, production system, building- and energy-system) are analysed and metered at reference facilities. The observed system elements are modelled and verified as specific sub-model afterwards. Then, their coupling is done via the developed coupling algorithms. Finally, the planned factory is simulated and scenario analyses are

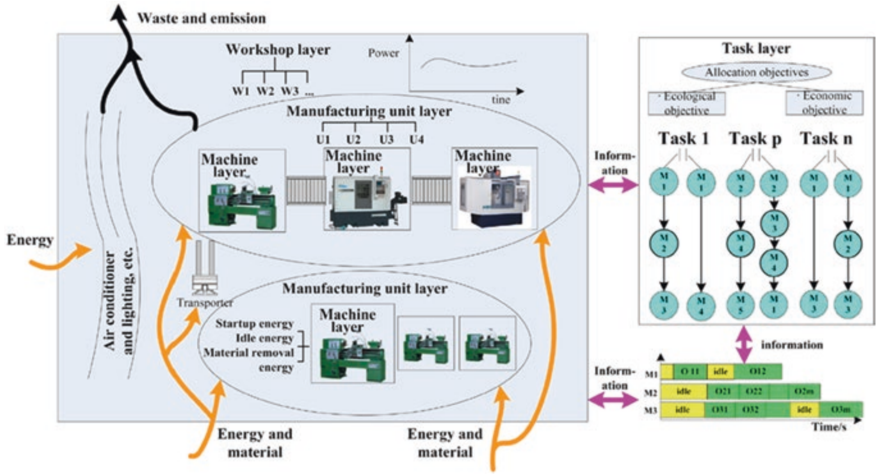

Fig. 3.3 Hierarchical energy assessment framework for a machining workshop according to Wang et al. (2013)

conducted to derive decision support for possible factory planning alternatives. As a result, the energy demand per scenario gets displayed.

Wang et al. (2013) introduce an approach for an energy efficiency evaluation of machining workshops. This approach considers the hierarchical layers machine tool, manufacturing unit and workshop and their individual electricity demand. A task layer is added, which represents the sequence of machining steps of one product, which has gone through the workshop. The purpose of this approach is to provide decision support when comparing machining schemes (combination of specific machine tools and cutting parameters). Thus, it also enables the comparison of process chain variants and technological alternatives. The main evaluation dimension is the energy efficiency of each system element and layer. It gets expressed via a broad variety of specific energy assessment metrics. The underlying energy demand data is gathered via metering campaigns and additional theoretical calculations. The metered and calculated energy demands are expressed per specific state of the individual system element. The theoretical energy demand calculation is done to reduce the metering effort. Material flows or the dynamic effects of connected system elements are not considered. Only via the task level does the cumulated energy demand of sequential process steps get aggregated per product. Figure 3.3 shows the hierarchical energy assessment framework and its observed layers.

The purpose of the THERM project is the development of software tools for modelling and simulating the energy and supply flows in production (Wright et al. 2013). These shall be coupled with thermal models of factory building shells to enable a holistic perspective on a factory's energy system. Thus, the interdependencies between operating manufacturing processes and the building shell can be evaluated to assess the overall energy demand of a factory building. As a result of the THERM project, Wright et al. introduced requirements and first solution approaches for integrated modelling of the process and building shell related energy flows within a factory. The named requirements for their model are the consideration of material flows and their transformation, the consideration of heat transfers between material flows and their environment, the consideration of the in-house climate profile (local variances in air pressure and temperature) and the consideration of stochastic events (e.g., unplanned interruptions of manufacturing processes). These requirements have been implemented in a software prototype, which is used to model and evaluate the energy flows of a factory section. Within the modelling approach, the integration of different modelling granularities is possible via nesting algorithms. The modelling of the material flows and its interaction with the building shell is implemented in a building physics tool. Therefore, it is not able to evaluate classical manufacturing oriented performance indicators like throughput time, quality rates, and manufacturing costs. However, it is able to calculate the overall energy demand of the building and delivers a library of tactics, which includes a set of sample measures for the reducing this energy demand. These measures can be integrated in the modelling tool and evaluated in the context of the observed factory. Ball et al. also describe this approach from the THERM project. They add the possibility to model also a sequential flow of processed material (Ball et al. 2013). However, the material flow is mainly considered as a heat transfer unit and source of material waste without further focusing on production performance criteria or further effects of this logistical flow.

Ke et al. (2013) provide a methodological approach for energy benchmarking of production systems from a systems engineering perspective. Following a top–down approach, they decompose complex production systems into process chains and process blocks. For each block the energy demand for the fulfilment of a defined task gets metered or calculated through the provided algorithms. The cumulated energy demands of all blocks add up to the energy demand of the superior system level. The decomposition of the production system enables an energy efficiency assessment on every observed system level. Thus, energy intensive system elements can be identified and benchmarked against reference processes or process chains. If fields of action for improvement measures have been identified this way, the proposed approach offers a supporting cost-benefit analysis for single energy efficiency improvement measures to support the decision making process. However, an internal routine for comparing improvement scenarios is not provided and the cost-benefit analysis is not further specified. The authors state that the approach currently gets very complex to handle if multiple energy carriers are involved. However, this approach should be especially feasible for complex production systems e.g., in large enterprises. Figure 3.4 schematically shows the hierarchical decomposition of production systems and a system diagram for energy benchmarking of the observed production system.

Löfgren and Tillman (2011) propose a methodological approach, which adds a life-cycle perspective in manufacturing decision. The proposed approach combines discrete event simulation (DES) with life-cycle assessment (LCA). Thereby, they build upon the general idea of Wohlgemuth et al. (2006), who combined DES with

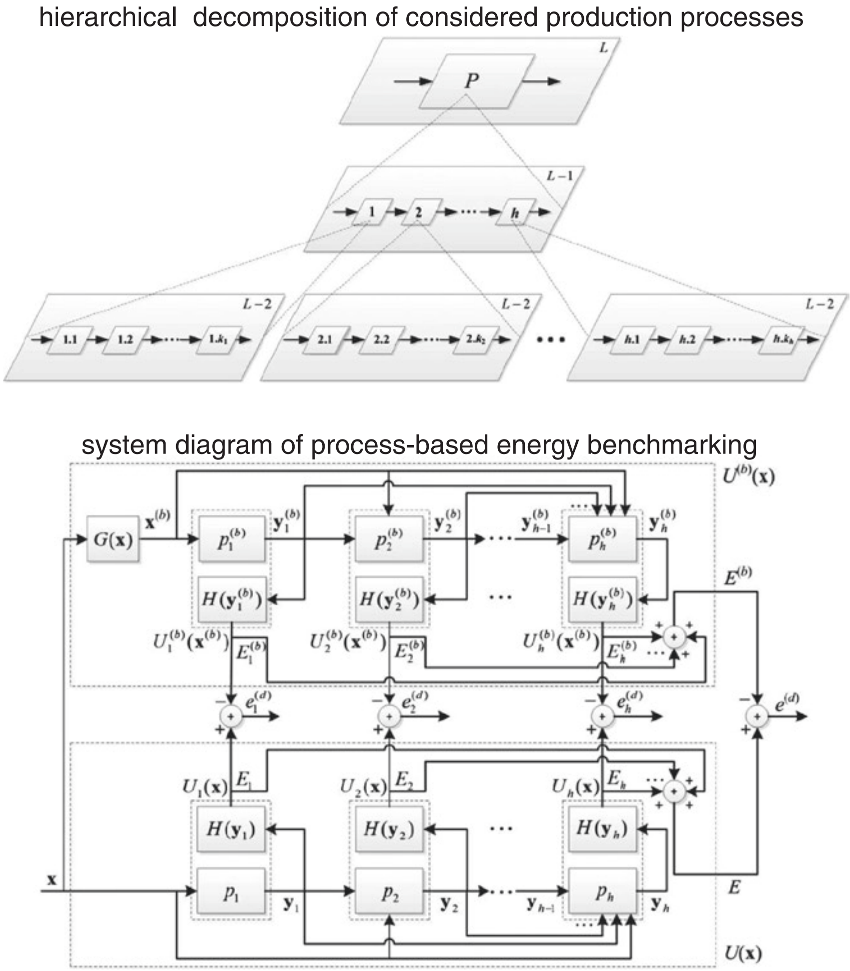

Fig. 3.4 Hierarchical decomposition of production processes and connected sub-processes in system diagram for energy benchmarking (Ke et al. 2013)

material flow analysis, which is one method in the context of LCA (Wohlgemuth 2005). Through the approach of Löfgren and Tillman, dynamic interrelationships of manufacturing processes and process chains can also be considered in rather static LCA models, which model the value chain of supplied energy and material flows. This means that energy demand profiles and material losses are calculated dynamically, which are evaluated in a later LCA to derive potential measures for improving the production system. Thus, the LCA gets enabled to evaluate the impact of e.g., configuration changes or adoptions in the production management strategy. For each material or component supplying process chain, an own LCA model gets created. These flows converge in the exemplary observed bearing unit production line, which is modelled as a DES model together with some peripheral processes. Within the DES model, material losses (here limited to steel), and the dynamic energy demand (here limited to electricity) are calculated. The resulting overall energy demand and material flows get translated into their environmental impact by multiplying them with impact factors, which have been calculated before by the LCA models. The evaluation dimensions are the overall electricity demand and the global warming potential (expressed in CO_2eq.). The developed approach is designed especially to also evaluate the outcome of changes in the employee's behaviour. Thus, the DES model can be parameterised in a way that the impact of the machine operators' decisions can be evaluated. Therefore, the DES simulation especially considers parameters, which can be influenced by the operators decisions such as mean time between failure, cycle time, compressed air demand, process power demand, fluid demand, machine ramp-up after setup, effective cutting tool changing time per machine, and scrap rate.

A similar approach is pursued by Sproedt (2013), who integrates the LCI datasets of the ecoinvent database into its own DES approach to enable automated life cycle assessments for industrial production systems. His approach aims to support decision making for eco-efficiency improvements in production systems. The approach is implemented prototypically and applied to four exploratory cases of the Swiss manufacturing industry.

3.2.2 Specific Approaches for Metal Casting

Jain et al. (2013) created a hierarchical simulation approach for estimating and improving the energy demand of a closed loop iron casting supply chain. The approach follows a top–down approach along the system levels of the value chain. The value chain is the highest system level. Single machines are the lowest system level. On the highest system level, an extremely aggregated system dynamics (SD) model regarding the status quo of the supply chain is created. In this model promising nodes get identified for deeper analysis and simulation experiments. Therefore, experts have to assess the SD model's result and to identify the main drivers of the energy demand. For identified energy demand hot spots such as these, discrete event simulation (DES) models are created—mainly on factory or process chain level. Amongst other parameters, these DES models get parameterized with the state dependent energy demand of single machines. Further machine or process models are not considered. If the interaction of multiple actors has been identified at a promising node in the SD model, an additional agent-based simulation (ABS) model gets created. By doing so also tradeoffs between different actors shall be assessable. The results of the DES and ABS simulation experiments are transferred manually into the SD model order to update it with possible scenario results. The SD model is the main layer for the integration of scenario results and their evaluation. The final evaluation dimension is only the energy demand of the supply chain. The DES and ABS modelling are only activated if a promising field of action has been identified and only as supporting activity to the overall

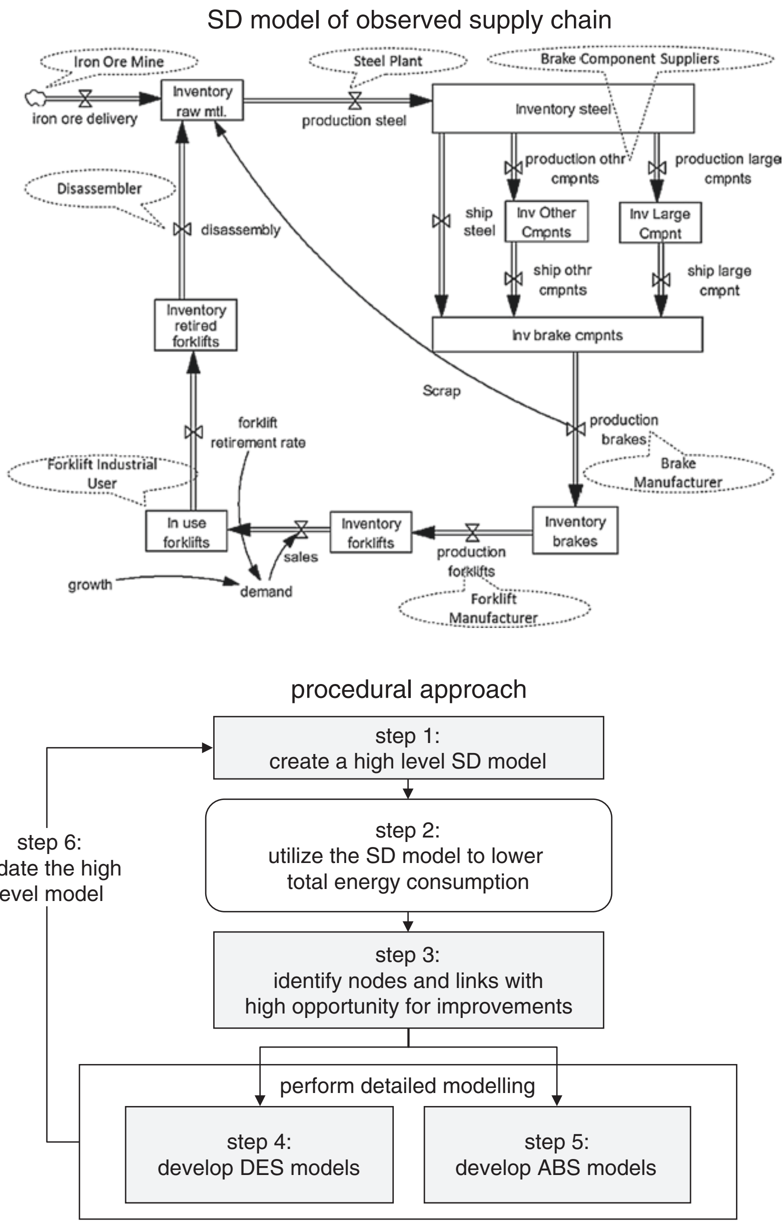

Fig. 3.5 SD supply chain model and procedural approach of Jain et al. (2013)

evaluation within the SD model. Figure 3.5 shows the top level SD model of the observed supply chain and the provided procedural approach including the DES and ABS modelling step. The very aggregate nature of the top level SD model is apparent from the presented picture. The underlying logic and data of the SD, DES and ABS models is presented at the same aggregate level so that the model approach seems to be at a conceptual stage. A rough evaluation of improvement measures seems possible without the consideration of too many detailed interdependencies among the considered system levels.

Mardan and Klahr (2012) build upon the previous works of Thollander et al. (2009), Solding, and Karlsson (2011) and combine a DES model of an iron foundry's main process chain with a software for energy systems optimisation (ESO) (Solding et al. 2009). ESO is an approach, which is widely applied in the Swedish foundry and steel industry in order to identify the impact of changing boundary conditions (e.g., energy and fuel prices) on the performance influence energy intensive production systems. The DES model is created to map the structure of the material and energy flow, (melting capacity, electricity demand for the melting and holding furnaces, efficiency) as well as the control parameter, (e.g., order lists, logistical boundary conditions, operator working schedules) and production performance (e.g., breakdown times, throughput times, processing times, disturbances). The ESO model is created to add optimisation algorithms, which allow the identification of optimal control strategies of the observed system. Both models are embedded in a joint procedural approach, which aims at a mutual validation and adoption of both models. Through the mutual validation it is ensured that the recommendations for optimal control strategies from the ESO model are applicable without confronting logistical boundary conditions, which can be tested in the DES model. The approach is applied to an iron foundry's main process chain. The effect of daytime-dependent, fluctuating energy prices on the foundry's energy costs is simulated in order to identify promising switch-off strategies for the production equipment.

Zhang et al. identified the gap of a missing energy and material flow analysis of Chinese steelmaking plants. They created a detailed hybrid energy and material flow model on process and factory level for a Chinese steelmaking plant including a casting and rolling section (Zhang et al. 2013). The energy and material flows have been detected comprehensively following a bottom up approach. First, single processes have been analysed regarding their internal energy and material flows also regarding possible backflows of cycle material or heat. All processes have been modelled via an input/output balance. Based on thermodynamic sub-models also hidden energy flows through chemical reactions have been mapped. All process models have been combined to a connected energy and material flow model of the entire plant (without a distinction of internal process chains). The energy and material flows are visualised via a Sankey diagram, and evaluated regarding manifold energy related performance indicators and their resulting CO_2eq. emissions. The conducted energy and material flow analysis aims to publish a status quo analysis of steelmaking plants, which serves as a basis for the identification of improvement potentials (e.g., through heat recovery). However, it does not provide guidance for the identification and evaluation of improvement measures.

Yilmaz et al. (2014) conduct a life cycle analysis of an iron foundry's process chain. Therefore, they create input/output balances of each process's energy and material flows, and link them in a top level energy and material flow model. This model gets visualised via a Sankey diagram. It serves as a basis to evaluate the improvement potential of an implementation of selected best available technologies (BAT) for a reduction of the foundry's environmental impact. These BAT consider the reduction and reuse of internal waste flows, the substitution of hazardous flows and energy efficiency measures. The model claims to be generic for the whole iron casting industry. It is based on average energy and resource flow data from European iron foundries, which have been taken from literature. All BAT are implemented in the generic model individually and in combination. They are evaluated regarding the resulting energy and material flows, the resulting environmental impacts (via a streamlined LCA and according to multiple impact categories) and also regarding the required investment versus the monetary saving potential.

Brevick et al. (2004) conducted a project with the aim to develop models for aluminium die casting operations that can be used to assess the influence of equipment or process changes on the overall energy consumption of a die casting process chain. They conducted a literature survey about energy demands in aluminium die casting, and extended their data acquisition with a broad survey among all corporate members of the North American Die Casting Association (NADCA). The survey results showed that the data about energy demands at the NADCA corporate members was quite poor. Thus, additional energy audits at research laboratories and die casting foundries have been conducted. Based on these data sources, Brevick et al. created an energy flow chart along the internal process chains of a die casting foundry. This flow chart was used to create the computer-based models TEAM (The Energy Assessment Model) and iThink®. TEAM combines an absorbing state Markov chain model of the foundry's process chain with an energy accounting model. The Markov chain model calculates the material demand along the whole process chain under consideration of metal losses, circulating material and material efficiencies even with incomplete information about all process steps. The energy accounting model uses the results from the Markov chain model, and calculates the resulting energy carrier demand (electricity and natural gas) of all processes to process the calculated material flows. iThink® is a dynamic model, which integrates all observed processes to a process chain and adds an efficiency attribute to each process. By varying the possible energy inputs and efficiencies of the processes, the user of this software can evaluate the impact of possible improvement measures on the overall energy demand of the system. Figure 3.6 shows the TEAM concept and a resulting absorbing state Markov chain model for one die casting process chain.

Neto et al. (2008, 2009a, b) have conducted the most intensive available study of emissions and air pollutants, which result from energy and material flows in an aluminium die casting plant (Neto 2007). With the aim to reduce the emissions to air, soil and water of an aluminium die casting foundry, Neto et al. conduct the four main steps: Identification of pollution reduction options, modelling of an aluminium die casting plant and its environmental impact, evaluation of strategies to reduce the environmental impact via a scenario analysis, and translating the gathered information into a decision making tool. As the considered emissions are closely linked to the energy and material demand and transformation, the

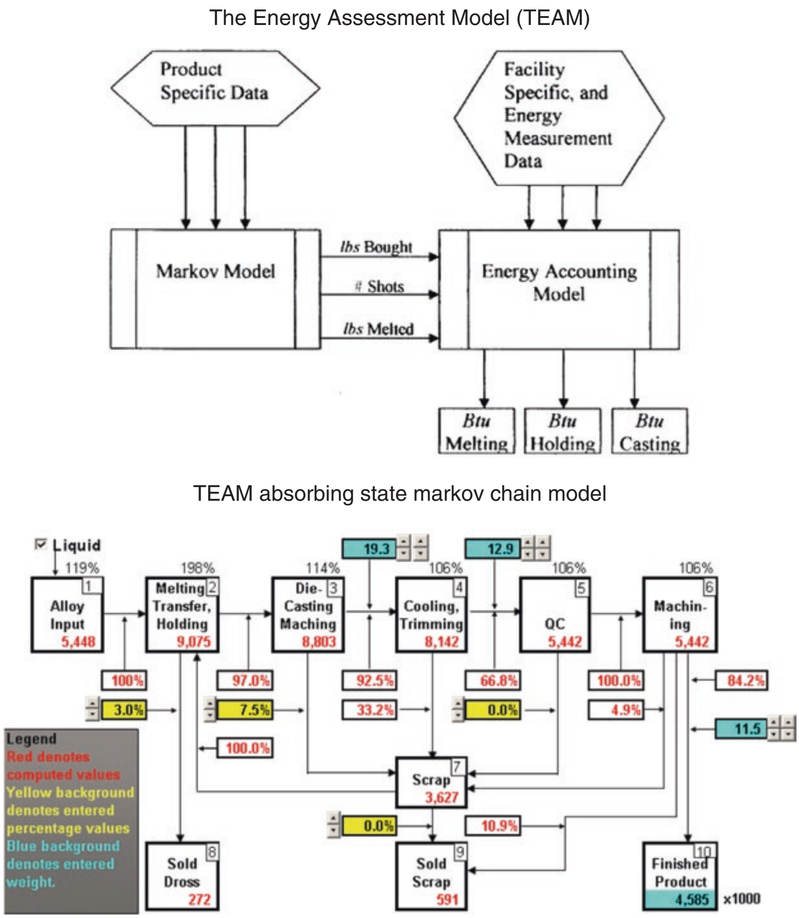

Fig. 3.6 TEAM concept and resulting absorbing state Markov chain model for one die casting process chain (Brevick et al. 2004)

considered measures to some extent also reduce the energy and resource demand of the considered foundry. To achieve their aim, Neto et al. created the aluminium die casting model MIKADO (Model of the environmental Impact of an Aluminium Die casting plant and Options to reduce this impact). Its structure and modelling approach are based on the object-oriented software DESIRE. Van Langen has proven before that this general software for the design of processes, together with a generic design model (GDM), is feasible to model the emissions from energy and material flows in production systems (Van Langen 2002). The software defines its own generic programming language, in which multi-level structures and objects with definable attributes, as well as methods, can be modelled and connected in one common system. Neto et al. use DESIRE to create a steady-state model of aluminium die casting with a focus on the environmental impact (especially the emissions) of each process. The objects within the model's structure are nested. Thus, hierarchical structures with superior and subordinate system elements (for process chains and processes) can be described. The foundry (process) is hierarchically structured into sub-processes and sub-sub-processes. Besides the sub-process transportation only value adding sub-processes are modelled. Activities describe the input flows into the system. Only emissions are considered as output flows, which are investigated intensively. All flows can be manipulated to perform scenario analyses. They are evaluated via a LCA by addressing multiple impact categories. A decision support tool complements the approach of Neto et al. It builds an interface to the above described evaluation and adds a monetary evaluation dimension in order to evaluate also the economic impact of possible improvement measures. Their environmental impact gets evaluated by performing scenario analyses.

Dalquist and Gutowski (2004) conducted a system-level environmental analysis of aluminium die casting. Along the major functions of metal preparation, die preparation, casting and finishing the die casting process chain is modelled and investigated. The energy and resource demands per process, as well as its emissions, are taken from aggregate national U.S. data and representative machine characteristics. Thus, the study by Dalquist and Gutowski is also a comprehensive overview over the available process specific energy and resource demand data in literature. The process specific data gets accumulated to groups of major functions of aluminium die casting and finally to the energy and resource demand of the whole process chain. In contrast to many other perspectives on the aluminium die casting process chain, the die preparation (including its fabrication and machining) is also included in the scope of Dalquist and Gutowski. Thereby, and by investigating also the metal preparation, the whole life cycle of the process chain shall be examined. The environmental impact is evaluated via expressing the total energy demand and the emission of greenhouse gases (CO_2, SO_x, NO_x) per major function of the foundry. The study by Dalquist and Gutowski does not offer decision support mechanisms or a procedure for actively improving the energy and resource efficiency in aluminium die casting. However, from a short analysis of selected aluminium die casting industry trends, they derive a recommendation for the implementation of energy efficiency measures (e.g., supply of liquid aluminium to the foundry, implementation of systems for heat recovery and preheating of metal inputs, insulation of equipment).

3.3 Comparative Overview

The described research approaches above can be compared regarding their individual fulfilment of the defined evaluation criteria. To review them in order to identify research gaps and demand for further research activities, the selected approaches are displayed in a matrix interconnecting the evaluation criteria (see Table 3.4). The fulfilment of the criteria is assessed for each approach according

Table 3.4 Comparison of evaluated research approaches

evaluation criteria			generic approaches					specific approaches for metal casting						
main area	criteria group	criterion	Bleicher et al. 2014, ENOPA	Wang et al. 2013	Wright et al. 2013	Ke et al. 2013	Löfgren and Tillman 2011	Jain et al. 2013	Mardan and Klahr 2012	Zhang et al 2013	Yilmaz et al 2014	Brevick et al. 2004	Neto 2007	Dalquist and Gutowski 2004
scope	spatial	vertical hierarchy	◕	◕	◑	◕	◕	●	◑	◑	◑	◑	◑	◑
		horizontal hierarchy	◕	◕	●	◕	◕	◑	◕	◑	◔	◔	◔	◑
		sequentiality	◔	○	○	◕	◕	◕	◑	◑	◔	◑	◑	◔
	techno-logical	primary shaping	◔	◔	◔	◔	◑	◕	◕	◕	◕	●	●	●
	tempo-ral	perspective	◕	◕	◕	◕	◕	◕	◑	◔	◑	◑	◑	◔
		life cycle phase	◔	◔	◔	◔	◑	●	◔	◔	◑	◔	◑	◕
data and model quality	data quality	resource flows	◑	◔	◑	◑	◑	◔	◕	●	●	●	●	●
		data sources	◑	◑	◑	◑	●	◑	◑	◑	◑	●	◑	◑
	model quality	modelling detail	◑	◕	◑	◕	◕	◑	◑	◑	◑	◑	◑	◑
		structure of flows	○	○	○	○	◑	◕	◑	●	◕	●	●	◕
application	indus-trial applica-bility	transferability	●	●	●	●	●	●	●	◑	◑	◔	◔	◑
		methodology	◕	◑	◕	◑	●	◕	◑	◑	◑	◕	●	◑
		procedure	◑	◑	○	◑	○	◑	◑	○	○	○	◑	○
		decision support	◑	◑	●	○	◑	◑	◑	○	●	◑	●	○
	evalua-tion	evaluation dimensions	◔	◔	◔	◔	◔	◔	◑	◕	●	◔	◕	◑
		evaluation perspective	◑	◑	●	◑	●	●	●	◑	◑	◑	◑	◑
		display of results	◑	◑	◑	◑	◑	◑	◑	●	●	◑	◑	◑
average			0.50	0.47	0.51	0.50	0.65	0.66	0.59	0.53	0.59	0.54	0.63	0.50

to a cumulative metric. Compliance with the attributes of an evaluation criterion adds a quarter point (+ ◔, in case of four attributes) or a half point (+ ◑, in case of two attributes). If an approach does not comply with any of the given attributes of an evaluation criterion, this approach is valuated with an empty point (○) for this criterion. Each quarter point counts for a value of 0.25. The points can sum up to 1 for each criterion. This translation into a quantitative metric allows calculating average fulfilments of the criteria over all approaches, and also the average fulfilment of the selected criteria per approach.

It can be observed that the fulfilment of the criteria and criteria groups varies significantly between the criteria and the reviewed approaches. To facilitate the comparative overview over the different approaches and an identification of possible research gaps, Fig. 3.7 visualises the average fulfilment of the selected evaluation criteria and the average fulfilment over all criteria groups.

Based on this analysis, the following conclusions can be stated:

- The average fulfilment of all criteria is at 0.56 (see Fig. 3.7), which equals roughly a half point (◗). No criterion is fully fulfilled. Only for the criterion transferability, a three quarter point in average is achieved. Thus, there is still room for improvement regarding approaches, which aim to fulfil all defined criteria.

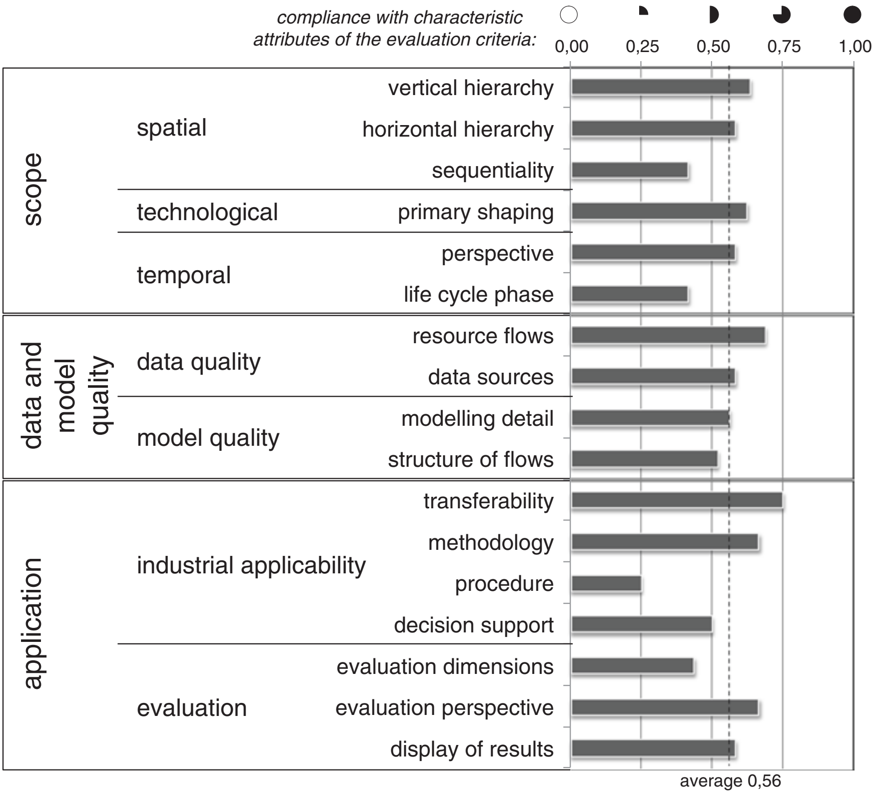

Fig. 3.7 Degree of compliance of selected research approaches with identified evaluation criteria

- The criteria within the main area data and modelling quality are fulfilled slightly above average (0.59). This is mainly due to relatively complete consideration of all relevant *resource flows* in the selected approaches. However, the used *data sources*, the *modelling details* and especially the considered *flow structures* reveal potential for deeper investigations.
- For the criterion *structure of flows* it is especially apparent, that this criterion is fulfilled for specific approaches in the area of metal casting. Thus, the consideration of this topic is important in the area of primary shaping. Current generic approaches seem to neglect this topic in order to enhance their universality.
- Besides the already mentioned criteria *transferability* and *resource flows*, the criteria *methodology* and *evaluation perspective* also belong to the group of the top four criteria regarding their individual fulfilment. This means that the combined application of different methods is already a relevant topic in current research approaches. This also affects the considered evaluation perspectives, as the combination of methods often includes ex-post data acquisition and modelling steps, which are combined with ex-ante forecasting approaches. However, these joint applications of different methods and the combined evaluation perspectives are often only presented exemplarily for specific cases without guidance for practical application.
- This missing guidance for practical application is also represented by the poor fulfilment of the criterion *procedure* (0.25). This makes the introduced approaches difficult to apply in industrial practice. This dilemma gets amplified by the often narrowed selection of *evaluation dimensions*. Many of the selected approaches solely focus on single evaluation dimensions (often the total energy demand). Therefore, the decision making process cannot be conducted holistically.
- Besides the criteria *procedure* and *evaluation dimensions,* the criteria *sequentiality on hierarchical levels* and *life cycle phase* are also poorly fulfilled in the average of the observed research approaches. This means that on the hierarchical levels of production, the system elements are often viewed as independent entities. Also the observed production systems is often viewed as independent entity, which has no influence on the preceding or succeeding life cycle phases of its products. E.g., the raw material selection and generation as well as the recycling of the produced goods are often not considered.
- Regarding the hierarchical nature of the selected approaches, it can be stated that hierarchical models and approaches exist. The *vertical dimension if hierarchy* is relatively well, but not fully, addressed (average 0.63). Often the value chain level is not considered. The consideration of peripheral activities (criterion *horizontal hierarchy*, average 0.58) and also the consideration of interacting sequential system elements per system level (criterion *sequentiality on hierarchical levels*, average 0.42) need to be improved. Regarding the consideration of different dynamics of business decisions within hierarchical production systems, this perspective (criterion *planning/evaluation perspective on production*, average 0.58) is addressed comparatively well by the selected generic approaches (average for generic approaches: 0.75). However, the approaches with a focus on metal casting especially show a deficit here (average for specific approaches: 0.46).

- Focusing on individual approaches, some of the observed research approaches fulfil the evaluation criteria relatively well. However, the best average fulfilment per research approach is 0.66 for Jain et al. This approach is followed by Löfgren and Tillman (0.65) and Neto (0.63). However, even those approaches show shortcomings regarding certain criteria (e.g., *criterion procedure*). Their common strength lies in the fulfilment of the criteria *transferability*, *methodology*, *structure of flows* and *evaluation perspectives*. Their fulfilment of other criteria is quite uneven compared to each other.
- Specific drawbacks of the three best fulfilling approaches are e.g., the representation of energy flows, which are not represented well on each system level (Jain et al.), the very aggregate consideration of selected system levels (Jain et al., Löfgren and Tillman), the focus on purely value adding processes (Neto) and the concentration of too narrow evaluation dimensions (Jain et al., Löfgren and Tillman).

To summarise these conclusions, further research demand towards approaches for energy and resource efficiency in hierarchical production systems will be expressed in the following section.

3.4 Derivation of Further Research Demand

The research demand can be reasoned from the discussion above. With a vision to create a comprehensive approach for enhancing energy and resource efficiency in hierarchically organised production (using the example of aluminium die casting), the following additional work is needed.

In general there is a gap between the often claimed holistic, **system oriented perspective on industrial production** and the provided **methodological support** to pursue this perspective. In a similar review on the state of research, Despeisse et al. (2012) confirm this finding about the lacking applicability of the existing approaches and add that no fully holistic approach for modelling and evaluation of production systems is available, which can fully **map possible synergetic effects and tradeoffs between connected resource flows** in production.

The above mentioned system oriented perspective on industrial production demands for a clear **system definition**. Thus, a clear definition of **hierarchical system levels** and the level's interaction (from process level to value chain level) is necessary. This vertical perspective has to be augmented via a clear definition of the level specific horizontal hierarchies and especially the **interactions of sequentially linked system elements** per system level.

Regarding the sequential nature of system elements, the system boundary and scope also needs to be defined cautiously. This includes a meaningful selection of observed actors, which have an influence on the considered production system. Furthermore, this is also true for the considered life cycle phases of the observed material and product flows. To set the scope and system boundary wisely for a true evaluation of the observed production system's environmental impact, **all relevant resource flows and life cycle phases of the processed objects** need to be taken into account. This means that the selection and generation of raw materials is also included in the taken perspective. Furthermore, end-of-life products and material fractions should be included as additional source of material.

Besides the organisational perspective on hierarchical levels, the **level specific consideration of scales** regarding planning and evaluation time horizons also needs to be included. This is crucial to provide a **clear selection and assignment of methods and tools** to observed objects and system levels. Thus, this assignment of methods needs to regard the **multiple time scales**, which determine the different dynamics in business decisions within each system level. There are disciplines like material sciences, which already use multi-scale (simulation) approaches extensively (e.g., de Borst 2008; Gates et al. 2005). However, these approaches are usually tailored for the consideration of different geometrical scales of the observed objects. Therefore, for the development of an approach towards energy and resource efficiency in production, a multi-scale approach is needed, which particularly addresses the multiple relevant time-scales in hierarchical production systems.

The clear assignment of methods and tools needs to be transformed into a **procedural approach** with clear guidance through the sequentially applied methods and tools. This is necessary to unfold their full synergetic potential, and to enhance the smooth applicability in industrial environments.

The industrial applicability gets further enhanced through **clear decision support mechanisms**. This means that the comparison and ranking of single and combined improvement scenarios must be possible, retrospective as well as prospective, and at a **broad variety of evaluation dimensions**. This includes also the possibility to identify and denominate possible conflicts of goals or **trade-offs between measures and actors**.

To support the multi-level and multi-scale perspective on production as well as decision support and evaluation mechanisms, a supporting **framework of level-specific key performance indicators** needs to be generated.

The additional research work needs to conclude in an approach, which is of generic nature. However, the state of the art review has revealed that the transferability of approaches is not the major focus for additional research work. Therefore, the focus of the later concept development lies on the **specific application of the developed approach to the energy and resource intensive aluminium die casting industry**. Therefore, this specific industry adds further demand for research work.

The defined generic procedural approach needs to be translated into a specific version for aluminium die casting regarding a clear assignment of specific methods and tools. As a result, the assigned methods and tools are feasible for the specific relevant energy and resource flows, which have to be identified as well. Thereby, the characteristic nature of the material flows in aluminium die casting (regarding circulating metal flows) also needs to be considered.

The application to the specific case of aluminium die casting needs to consider that literature in general is lacking of production process related general LCI data for many production technologies at the required level of detail. Thus, a contribution to a solution for this dilemma is needed, which is based upon existing data as long as individual extensive data acquisition is not possible (e.g., for upstream process chains). However, if possible, extensive metering campaigns shall contribute to the publicly available data sets about energy and resource flows in aluminium die casting. To provide this data in a universally applicable form, a generic model of aluminium die casting needs to be created, which incorporates the generated data and serves as a reference for aluminium die casting in general.

Chapter 4
Multi-level Multi-scale Framework for Enhancing Energy and Resource Efficiency in Production

As a conclusion from the previous chapters, there is a demand to transfer holistic views on production into a general concept for energy and resource oriented improvement of hierarchically organised industrial value chains, process chains and processes. Therefore, this chapter introduces a concept for a hierarchical view on (cross-company) production and interlinked methods and tools for energy and resource oriented improvements of such systems. The following section introduces the research methodology used and provides a framework which supports decision making processes for the analysis of resource flows, and for the prioritization and selection of improvement measures.

4.1 Research Methodology

As prerequisite for the aimed multi-level and multi-scale modelling, evaluation and improvement of production (using the example of aluminium die casting), the following research methodology has been defined (see Fig. 4.1).

The previously indentified research gap about a framework for multi-level and multi-scale evaluation and improvement of production will be enriched by an analysis of further requirements stemming from structural, methodological and user perspectives. These requirements can be deduced from the previously stated central objectives for this work. They are complemented by the research question, which is expressed at the same time. In addition, surrounding economic conditions and technological boundary conditions get explained, which challenge the application of such a framework.

Based on the analysis of requirements and boundary conditions, the framework gets developed to close the research gap. Until this stage, the generic nature of this framework will be highlighted. This makes it transferable to any kind of producing industry. Starting from the subsequent Chap. 5, the framework gets applied to the selected aluminium die casting technology and industry. Based on the analysis of twelve specific value chains, a generic model of aluminium die casting gets created.

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Sustainable Production, Life Cycle Engineering and Management,
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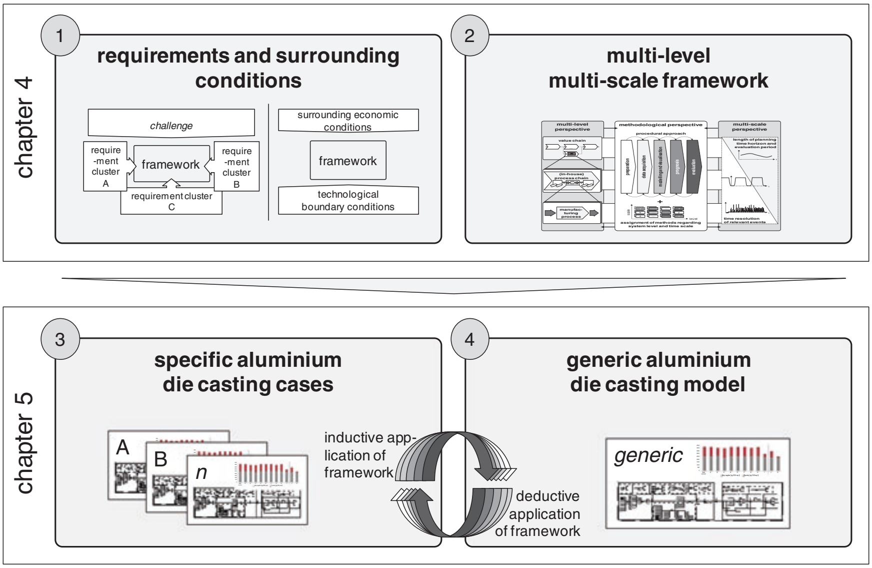

Fig. 4.1 Pursued research methodology

4.2 Requirements and Surrounding Conditions

The previous chapters have shown that measures for reducing the energy and resource intensity of industrial production are manifold, and can be derived via the application of various methodologies and tools. Depending on the individual role and expertise of the person who derives such measures, very special and diverse fields of action will occur. On the one hand, these fields of action can be of a very generic nature and target high volume resource flows, which makes them highly transferable amongst industries, technologies, etc. On the other hand, these fields of action can be very specific as well, e.g., focusing in detail on improvements of single process parameters of specialised high technology processes and production machines. Nevertheless, each single measure is valuable and important to reduce the overall industrial energy and resource consumption. Anyhow, due to the variety of complex fields of action and corresponding improvement measures, due to limited corporate resources for implementing such measures, and due to possible mutual influences and interactions of these measures it is hard to make a choice, if only a limited set of measures can be selected for implementation. This dilemma leads to the following research question—in coherence with the previously stated central objectives of this work:

> *How to evaluate and prioritize possible improvement measures regarding energy and resource efficiency in hierarchical, actor-spanning production systems?*

This question outlines that there is a need to assess energy and resource flows by taking a holistic perspective of industrial production systems. Furthermore,

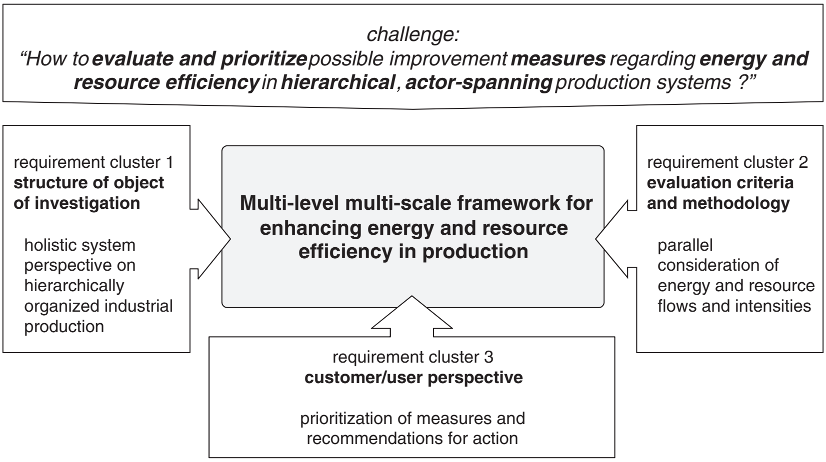

Fig. 4.2 Requirement clusters for a hierarchical framework for production

it requires the possibility to derive clear recommendations for a prioritization of improvement measures to enhance the industrial applicability. Therefore, according to the beforehand analysed state of the art about the analysis and evaluation of energy and resource intensities in industrial production, a new framework for a hierarchical evaluation and improvement of industrial production has to fulfil a set of requirements, which can be clustered as follows (see Fig. 4.2).

As described in Sect. 2.1 industrial production has to be considered holistically as a system, which incorporates manifold sub-systems on different subordinate hierarchical system levels. Therefore, answering the previously introduced research question requires considering the complex **structure of the object of investigation** (requirement cluster 1, see Fig. 4.2). This implies to regard the following requirements:

- **All hierarchical system levels** (from the manufacturing process level to the industrial, cross-company value chain level) and their interaction need to be **considered at equal importance**.
- The same has to be regarded for the **different relevant time scales** per system level.
- **Methods and tools for assessing energy and resource flows on all system levels** need to be selected.
- The framework needs to be **open to include the perspectives of separate actors** with individual interests.

The main evaluation focus shall be on the energy and resource demand of the object of investigation and its sub-systems. Therefore the **evaluation criteria and methodology** (requirement cluster 2, see Fig. 4.2) need to be appropriate and have to fulfil the following requirements:

- **Energy and resource flows** need to be **quantified**, **visualized** and prepared for a **comparative assessment** of improvement scenarios
- These flows and possible improvement measures need to be **traceable and quantifiable across the system boundaries of different actors** on all system levels.
- To enhance the comparability of the evaluation results, the energy and resource flows need to be communicated as ratio, which is **referenced to a unit of produced goods**. Therefore **energy and resource flows** need to be transformable into **intensity and efficiency ratios**.

To generate a benefit for industrial decision situations, the framework needs to provide a clear **customer perspective** (requirement cluster 3, see Fig. 4.2). The customer of this framework needs to assess and prioritize improvement measures regarding energy and resource efficiency. Therefore, he requires methodological support, which leads to clear recommendations for action. Thus, the customer perspective generates the following additional requirements:

- By providing **generic value chain structures and reference values** for specific value chains, **neutral basic scenarios** shall be creatable as a reference for benchmarking activities.
- Possible **trade-offs between across actors and systems levels** need to be **identified and evaluated** through this evaluation scheme.

Besides these requirements, it needs to be considered that industrial production systems are under pressure as a result of certain surrounding conditions. They challenge, and also call for, the development of an evaluation scheme, which has to meet the previously defined requirements. Regarding projects for enhancing the energy and resource efficiency of industrial production systems, these surrounding conditions are mainly driven by economic aspects and technological boundary conditions (see Fig. 4.3). Economic surrounding conditions challenge industrial production systems via targets, directives and restrictions from a top down management oriented perspective. Technological boundary conditions, which can provide potentials or restrictions, arise from a process oriented, bottom-up perspective and unfold their impact throughout the increasing hierarchical levels of the production system.

Measures for reducing the energy and resource intensity of industrial production have to obey to the internal target system of the involved actors. These target systems are mainly driven by economic performance indicators, which put special pressure on the right selection of measures. Thus, they can evince a conflict of goals between environmental soundness and economical performance. Such economical, internal targets can be profit margins and budget limits, which limit the financial resources that can be utilized for the implementation of the measures. Sales and turnover targets, as well as targets for the utilization rate of the installed equipment, can reduce the available time for installing measures as the focussed machines usually need to be switched off for implementing technological changes.

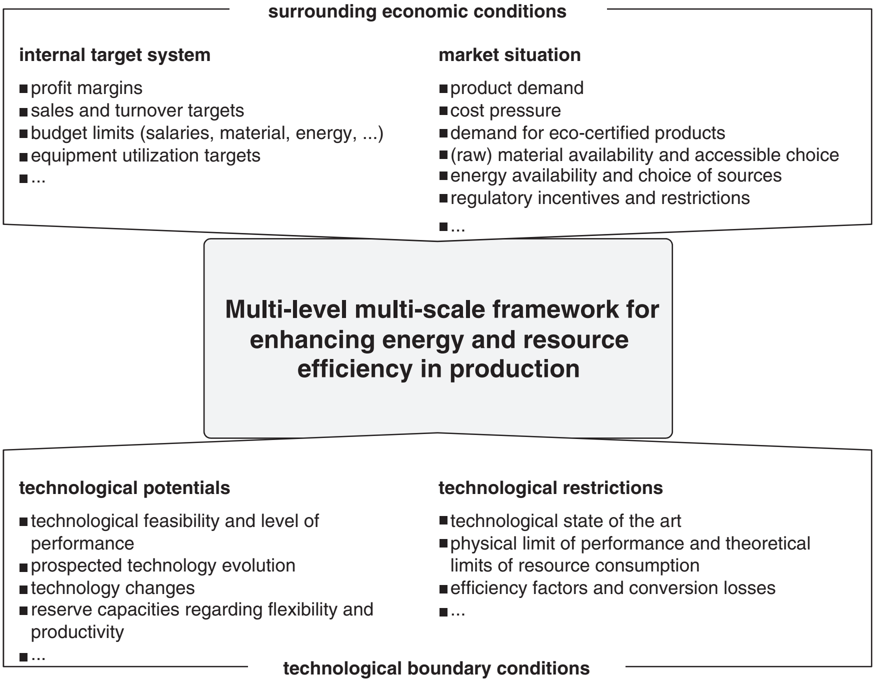

Fig. 4.3 Surrounding conditions for hierarchical evaluation schemes for industrial value chains regarding energy and resource intensities

Besides the internal target system, the external market situation also creates pressure on industrial value chains, and on the possibility to choose and implement effective improvement measures. E.g., a high and stable demand of produced goods reduces possible time slots for implementing measures as well due to highly utilized production equipment. On the other hand, customers request more and more products, which comply with certain environmental standards and which are produced as environmentally friendly as possible. This induces the need to implement measures for reducing the energy and resource intensity of such products at all stages within the product creating value chain. Also from a regulatory perspective there are incentives and penalties, which have been introduced to support the introduction of such measures. Such regulatory stimuli try to increase the cost pressure of actors, which do not follow the regulatory intentions. However, cost pressures usually exist already in order to stay competitive while competitors are also trying to reduce costs, increase profit margins or gain market shares by reducing product prices. Such cost pressure can impede the implementation of improvement measures if the individual actor is obliged to obey only business targets with a very short time horizon.

Besides the above mentioned aspects, which put pressure on the right selection of improvement measures, there are some aspects, which limit the choice of available measures. E.g., the geographical location and the economical power of the individual actor can be limiting factors for the availability of, and access to, the technology and (raw) material, which is needed to implement a certain measure. The same goes for the stability of the supplying electricity grid as well as for the accessible choice of energy carriers and their individual (renewable) sources.

These requirements and surrounding conditions, which are deduced from the introduced research question, need to be respected. They demand for a further discussion of hierarchies, actor roles and time scales in a concept for a holistic evaluation of production regarding energy and resource intensities. Accordingly, such an evaluation framework needs to discuss specific methods and tools (and their interaction) as a foundation for the synthesis of the framework.

4.3 Framework Development

Figure 4.4 depicts the multi-level multi-scale framework for the evaluation of production. It consists of the following three modules: **system definition (M1)**, **procedural approach (M2)** and **methodological toolbox (M3)**.

Module 1 (system definition) combines a multi-level perspective and a multi-scale perspective on production.

Taking a **multi-level perspective** on production takes into account that production is organized hierarchically regarding a vertical order (value chain level to manufacturing process level) and a horizontal order (different actors on the same system level). The relevant system levels and actors and their interplay will be described in Sect. 4.3.1.

The multi-level vertical differentiation of production demands also for a **multi-time-scale perspective**, regarding the time-wise resolution of relevant events and the lengths of planning time horizons and evaluation periods. Examples for such relevant events and sample items for planning and monitoring will be introduced in Sect. 4.3.1. This will provide a hint about the differences in the nature of business decisions on each system level. Furthermore, the different time scales support the selection of appropriate methods and tools for each level.

Module 2 (procedural approach) provides an application sequence of methodological groups to improve the energy and resource efficiency of industrial production (see Sect. 4.3.2). It builds upon the system definition from module 1, and respects the aforementioned system levels and time scales. The methods within the procedural approach are clustered into five phases with specific outcomes. These phases are named preparation, data acquisition, modelling and visualisation, simulation and evaluation. The procedural approach is a starting point for a continuous improvement cycle. It can be further specified with specific methods and tools per methodological group.

Thus, the described modules demand a supporting **methodological toolbox (module 3)**. In Sect. 4.3.3 module 3 **assigns selected methods** to specific

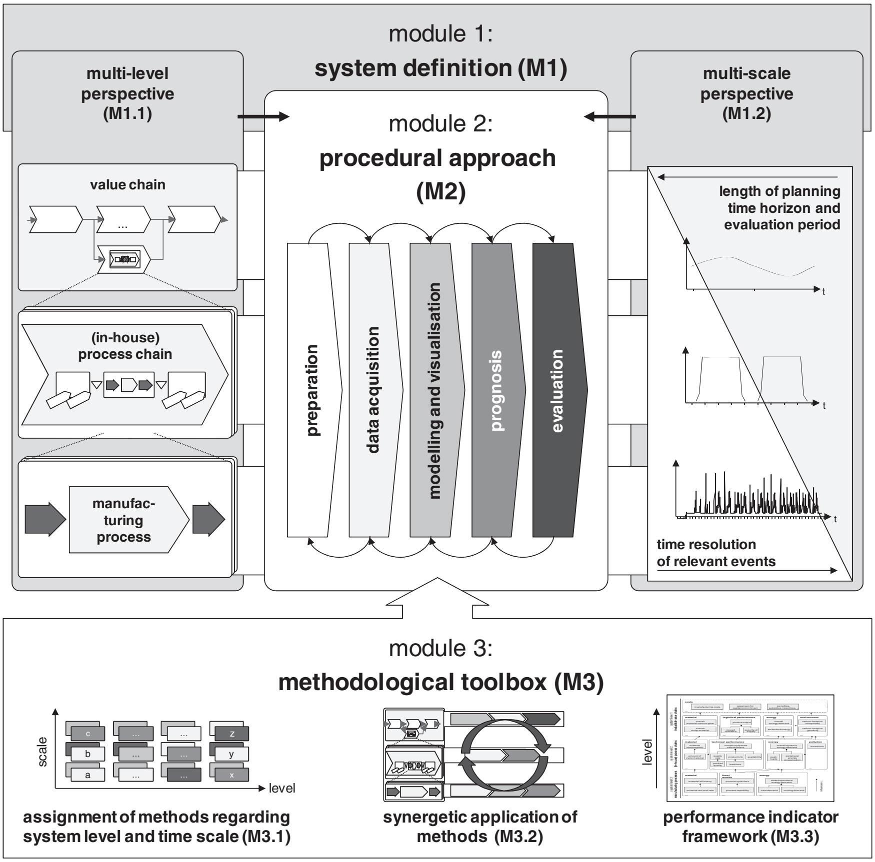

Fig. 4.4 Multi-level multi-scale framework for enhancing energy and resource efficiency in production

hierarchical system levels and time scales. Exemplarily, it also describes their **synergetic application** in iterative application loops within the described procedural approach. Additionally, a **performance indicator framework** is introduced in this section, which describes the different evaluation perspectives per system level by way of example. The three modules will be described in the following sections.

4.3.1 Module 1—System Definition

4.3.1.1 System Levels and Actors (M1.1)

As stated above, respecting the hierarchical structure of industrial production is vital for a holistic evaluation of such systems. This evaluation includes a comparative assessment of manifold improvement measures, which can tackle diverse hierarchical levels within the system. Therefore, the (vertical) hierarchical levels of industrial production and their specific intention as well as horizontally divided actors will be introduced briefly in the following section. Their basic vertical division into single system levels can be deduced from the description of vertical hierarchies in production in Sect. 2.1.

The basic intention of all hierarchical system levels of industrial value chains is the same. Similar to the definition of single manufacturing processes, each entity of industrial value chains has the main purpose to transform tangible as well as non-tangible inputs into outputs to create value (see Fig. 4.5, according to Schenk et al. 2014).

However, the intentions on the individual system levels can vary due to the scope of their individual planning time horizon or, due to the individual, subordinate business targets. Furthermore, from a traditional and strictly economic performance oriented perspective, many of the natural intentions of the individual system levels can lead to a conflict of goals. This conflict of goals can especially occur when regarding the environmental impact of the industrial value chains. Having this in mind, the individual system levels will be recapped in the following section by illustrating a selection of their individual intentions and performance indicators. Additionally, examples for related influences on the environmental impact of the included system elements are given. Finally, the roles of different actors on the same system level get explained as an example for horizontal hierarchies in production.

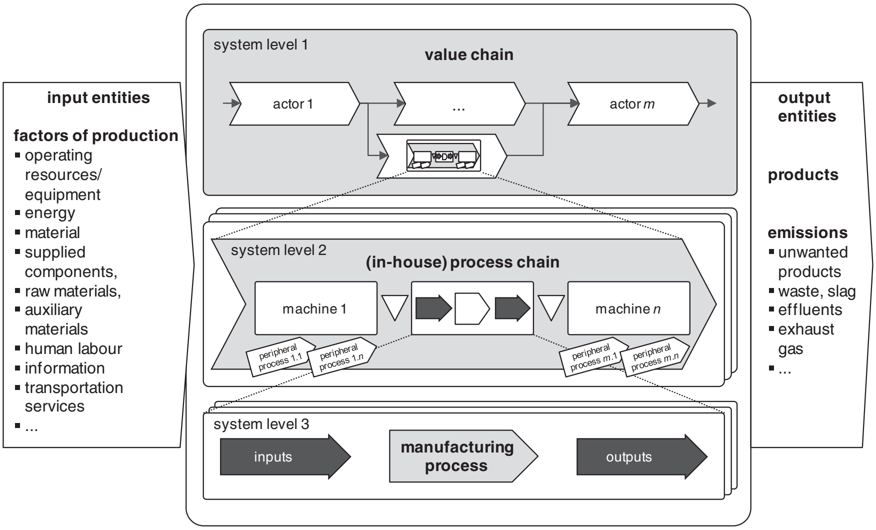

Fig. 4.5 Hierarchical system levels and input/output entities of industrial value chains (according to Schenk et al. 2014)

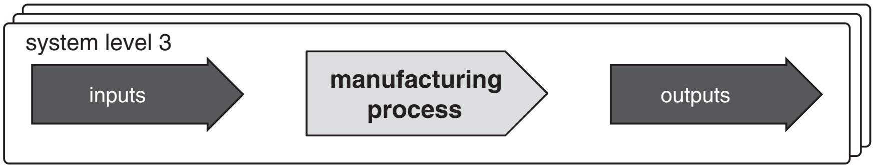

Fig. 4.6 System level 3: manufacturing processes

System Level 3—Manufacturing Process

The lowest hierarchical level of industrial value chains are manufacturing processes (see Fig. 4.6).

Here, the main manipulation of material properties, product geometries and characteristics gets done. Thereby, manufacturing processes increase the value of their focused work pieces. Therefore, the main intention on this system level is to ensure a defined quality level of the individual process task, while maintaining or increasing the individual process's performance. Hence, measures for improving the energy and resource efficiency on this system level usually tackle process parameters and/or product design properties as well as material substitution. Their technical feasibility has to be considered strongly respecting the main intention of this system level. The often high sensitivity of process parameters regarding the resulting quality outcomes as well as the tremendous choice of possible manufacturing processes make it hard to name general performance indicators as well as measures for improvement on this level. However, Table 4.1 introduces a choice of

Table 4.1 Exemplary performance indicators for manufacturing processes regarding their energy and resource intensity

Relevant performance indicators	Description	Unit	Environmental relevance (influence on…)
• Process cycle time	$T_{\text{entry product, n}} - T_{\text{entry product, n}-1}$	s	Dynamic energy demand
• Process capability	Index for stability and deviation of process parameters	[]	Quality rate
• (state dependent) energy demand	Energy demand during productive-, idle-, off-mode	kWh	Dynamic energy demand, grid dimensioning
• Heat demand	Process heating during one process cycle	kWh	Energy for heat generation
• Cooling demand	Extracted heat during one process cycle	kWh	Energy for inefficient cooling processes
• Material removal (or addition) rate	Cutting speed × feed × depth of cut	cm^3/s	Cycle time, surface quality
• Material efficiency	$m_{\text{output}}/m_{\text{input}}$	%	Amount of cycle material and waste
• (auxiliary) material demand	Amount of processed material	kg, l, m^3	Environmental impact of material production

performance indicators, which are used broadly to assess manufacturing processes regarding their technical performance, which can be directly linked to their energy and resource consumption.

Most relevant performance indicators in this layer are (besides others) the process cycle time and process capability, the (state dependent) energy demand for the components of the machine, which conducts the manufacturing process, as well as the energy demand, which needs to be satisfied to insert or extract heat of the process. Furthermore, the material removal rate, the material efficiency and the overall consumption of material need to be evaluated on manufacturing process level as they have a direct influence on the product quality and amount of cycle material. Moreover, due to the environmental impact of material production, the overall material consumption (which includes losses through scrap) determines the major share of a product's environmental foot print.

System Level 2—(in-House) Process Chain

Process chains constitute the second level of hierarchical industrial value chains. They smoothly link highly dynamic manufacturing processes and peripheral processes, organize the material transport, and due to stocks and delays, influence the idle/operative production modes of the included machines (see Fig. 4.7).

Machine cells can be seen as small process chains as they can link single (manufacturing) processes within one machine entity or within one cluster of value adding and peripheral processes. They jointly fulfil a common process step within the superior process chain. Usually, on this level the technical demands of the underlying manufacturing process are translated into energy demands of the machine cell. This can result in load profiles which represent dynamic energy consumption depending on the actual load of the machines.

Peripheral processes, as well as general technical building services (which are also peripheral entities), are connected to process chains. They provide defined production conditions (e.g., temperature, moisture, air purity, etc.) or supply the manufacturing processes with media, material, work pieces, transportation services, etc.

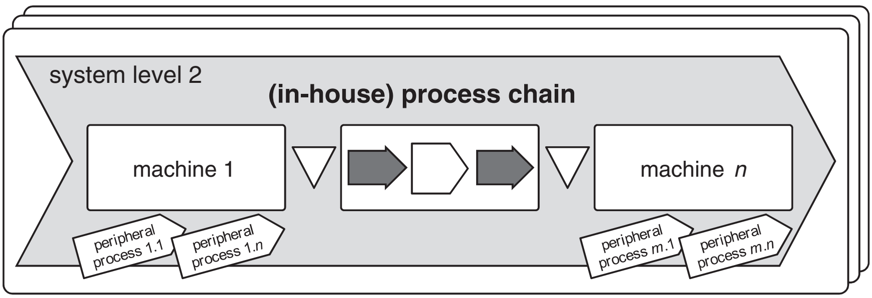

Fig. 4.7 System level 2: process chains

Due to the linking nature of process chains, the intention of this system level is more system focussed than on manufacturing process level. The main intention on this system level is to enable a smooth and stable production. Thus, the interplay and linkage of highly dynamic sub-systems (manufacturing processes), while ensuring a constant product quality and product output, continuous availability and high performance of the manufacturing line need to be regarded.

With regard to this linking nature of the system elements within process chains, Table 4.2 introduces a choice of performance indicators. They can be used to evaluate manufacturing process chains with a focus on their technical performance and closely linked energy and resource consumption.

Most relevant performance indicators on this layer are (besides others) the overall equipment effectiveness (product of availability, performance rate and quality rate) and lead time, which together give information about the overall performance of the process chain regarding speed, quality and utilization aspects. Therefore, these indicators can already be linked to the value adding and non-value adding shares of energy consumption. Likewise, non-value adding energy consumption can result from speed losses in the process chain as well as from

Table 4.2 Exemplary performance indicators for manufacturing process chains regarding their energy and resource intensity

Relevant performance indicators	Description	Unit	Environmental relevance (influence on …)
• Overall equipment effectiveness (OEE)	$A \times P \times Q$	%	See below
– Availability (A)	Operating time/available time	%	Share of energy consumption during idle and off mode
– Performance rate (productivity) (P)	(parts produced × planned cycle time)/operating time	%	Increased energy demand due to speed losses
– Quality rate (Q)	Good parts/parts produced	%	Amount of cycle material and waste
• Lead time	$T_{\text{exit product}} - T_{\text{entry product}}$	s	Risk of increased energy demand due to speed losses
• (overall, dynamic) energy demand	System energy demand during productive-, idle-, off-mode	kWh	Cumulated energy demand, grid dimensioning
• Peak loads	Electrical power consumption above defined thresholds	kW	Risk of preventive grid-overdesign
• Peripheral energy consumption	Energy consumption of peripheral equipment	kWh	Non value adding energy demand
• Amount of cycle material	Industrial waste that gets recycled internally	kg	Continuous increase of embodied energy
• Product quality	Amount of defects per product	pcs	Amount of cycle material, product lifetime and reparability
• Emissions	Direct (gaseous or liquid) process emissions	kg, l	Air and/or water pollution, energy demand of filters

defect goods and cycle material, which have been processed energy intensively. On this system level not only the cumulated energy demand is important. Also temporary peak loads, which result from overlapping peak loads of the sub-systems and peripheral systems, are relevant. They can add up to peak loads, which cause penalty costs in the company's energy bill. Furthermore, such peak loads on process chain level can harm the energy supply system of the process chain and therefore promote the risk of a preventive grid-overdesign.

Besides these energy and material oriented aspects, process emissions can also be a relevant performance indicator on process chain level as this is a proper level for corresponding monitoring activities. Process emissions can be manifold depending on the installed processes and equipment.

System Level 1—Cross Company Industrial Value Chain

Value chains constitute the most aggregate level of consideration. They bring together diverse process chains and organize the cross-company generation of final products from raw materials (see Fig. 4.8).

This system level is the decisive base for a holistic and comparative evaluation of improvement measures. This is also true for measures, which unfold their impact on a subordinate level. However, the effect of all possible improvement measures needs to be scaled into an impact on this highest hierarchical level to achieve comparability.

The natural intention of this system level and of corresponding improvement measures is more from an economic and logistical nature. Although this perspective is not the core of this book, it must be mentioned to understand the dynamics of this level as well as their potential for environmental improvements. Basically, the main intention for each independent actor on this highest system level is to produce and sell a demand satisfying amount of products at a profitable price and at the lowest possible manufacturing costs. Taking a cross-company perspective extends this perspective by logistical aspects, which ask for a stable supply network of actors that jointly pursue their individual goals. Nevertheless, due to increasing regulatory penalties and incentives, as well as due to changing customer

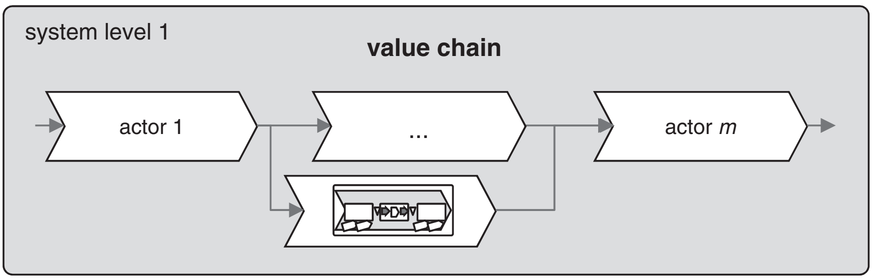

Fig. 4.8 System level 1: cross company, industrial value chains

preferences, more and more sustainability oriented intentions find their way into business decisions on this system level. Therefore, Table 4.3 gives an insight into a selection of possible relevant performance indicators for industrial value chains.

Each of the given performance indicators is relevant from a global cross-company perspective to assess the overall performance of the industrial value chain. However, all indicators are also feasible to check the company-specific target achievement regarding the introduced objectives and to fulfil the requirements of sustainability reports. Thus, taking an actor specific perspective, they will be discussed first in order to analyse the individual actor's performance. Nevertheless, combining these

Table 4.3 Exemplary performance indicators for industrial value chains also regarding their energy and resource intensity

Relevant performance indicators	Description	Unit	Environmental relevance (influence on …)
• Manufacturing costs	Overall costs for the generation of one product unit	€/pc	Risk to use cheap but high impact materials and processes
• Expenses for capital commitment	Expenses for the acquisition of capital to refinance the stock of inventory	€	Increased material transports due to reduced stocks
• Product output	Amount of produced goods to satisfy the customer's demands	pcs	Energy and resource demand
• Security of supply	Length and reliability of supplier	/	Risk to choose high impact suppliers with better reliability
• Lead time	Overall cross-company lead time	d	Risk of overdesigned capacities due to speed losses
• Material consumption	Cumulated raw material and auxiliary material consumption	kg	Environmental impact of material production
• Scrap material	Cumulated non-recyclable scrap material	kg	Env. impact of material production, non-value adding energy demand
• Energy consumption	(Overall and/or actor specific) energy consumption of production processes	kWh	Env. impact of energy carrier generation
• Embodied energy	All product related energy consumption incl. energy consumption for raw material generation and transports	kWh	Env. impact of energy carrier generation, risk of energy waste through overproduction
• Carbon footprint (corporate) • Carbon footprint (product)	Actor specific resp. product specific contribution to global warming through energy and resource consumption and process emissions	CO_2eq.	Global warming potential

two perspectives offers the chance, to identify trade-offs between different actors and their specific goals. Thereby, individual intentions can be balanced towards a global optimum of the cross-company value chain.

Following this idea, the main performance indicators for industrial value chains (regarding local assessments as well as global leverages) are from an economic perspective the overall direct manufacturing costs, which summarize costs e.g., for energy and resources, transportation services, wages. As these costs are usually the major cost drivers for producing enterprises, there is always a risk of choosing cheaper materials and processes which could go hand in hand with higher environmental impacts. Using the expenses for capital commitment as a performance indicator also incorporates an environmental risk. If these expenses shall be reduced by decreasing the stock of inventory and, thus, shortening supply intervals, this measure can lead to drastically increased material transportation.

When taking a look at the actors' supplies, the security of supply (for material as well as energy carriers) is also an important performance indicator as a stable supply is vital for smooth production operations. This could also mislead decision makers to prefer highly reliable suppliers over environmentally friendly suppliers. Yet, this negative correlation does not necessarily have to be inevitable true for every supplier. Taking a more customer centred perspective, the overall product output is the major performance indicator for the (technological as well as economic) capability of an industrial value chain. However, a growing product output usually goes hand in hand with increased energy and resource consumption as well, and does not solely have to be the best economic strategy. The overall lead time of the value chain can be a good indicator for the logistical and technological performance of the value chain as well. Nevertheless, slow lead times due to an inefficient design of the value chain can result in overdesigned production capacities to meet the customers demanded production volumes within a defined delivery time.

The economic perspective for evaluating industrial value chains is strongly influenced by the energy and resource intensity of the value chain. Therefore performance indicators become important, which focus on energy and material demand as well as on resulting environmental impacts. Besides the overall material consumption (including auxiliary materials, water, etc.), the amount of scrap material is also a relevant indicator. In addition to their natural information content about the consumption and usage of physical resources, they also already give a hint about the embodied energy of materials and products, and on the non-value adding energy consumption within the value chain. Besides the embodied energy, which is a product or material specific indicator and which is influenced by the overall amount of cycle material, the overall energy demand of individual actors or entities within the value chain is also a relevant performance indicator. The overall energy demand is directly linked to the manufacturing cost and is therefore in the focus of improvement measures.

Such energy and resource oriented performance indicators are directly linked to further environmental impact indices like carbon footprints. Unlike the above mentioned performance indicators, carbon footprints cannot be measured directly (like process emission, material consumption, etc.) or generated by accumulating different metered data sets (like embodied energy, overall material consumption, etc.). Instead, they result from an impact assessment according to the life cycle assessment methodology. Therefore, life cycle inventories of the industrial value chains get translated into a resulting global warming potential, which is expressed in theoretically emitted carbon dioxide equivalents (CO_2eq.). The corporate carbon footprint then accumulates all emissions, which result from the operations of one specific actor within his system boundaries. The product carbon footprint represents all resulting emissions from product related operations along the entire value chain and product life cycle. Although there are many more impact categories besides the global warming potential, it is the one category, which is currently becoming widely accepted in industrial manufacturing enterprises on this system level.

Actors Per System Level

A holistic evaluation of industrial production needs to have the ambition to include all relevant hierarchical levels and stakeholders to avoid problem shifting (between system boundaries, stakeholders or impact categories). Therefore, it has to consider that industrial production can consist of manifold actors with own systems of objectives and even competing goals. In order to achieve a global optimum of an entire industrial value chain regarding energy and resource efficiency, all relevant actors need to be encouraged to align their decision making processes for this global goal. However, this demands for actor spanning transparency about energy and resource consumption and about the actor spanning impact of single or combined measures for improvement. By generating transparency this way, a basis for the balancing of interests between different actors towards global energy and resource efficient value chains can be created. If needed, this basis can serve as a starting point for the negotiation of incentives, which enable all affected actors to benefit from actor spanning improvement measures.

Actors can be single enterprises as well as their internal departments and sections. They build up demarcations between the horizontal connections e.g., of a value chain's system elements. An individual actor can be characterized by its own competitive interests, own economic targets or externally defined system boundaries. Following the hierarchical logic of value chains, actors can be found on each system level.

On system level 3 e.g., manufacturing processes can be seen as individual actors with their own set of objectives that compete against other actors on this system level in case the wages of the process' operators are based on piece-rates. In this case, the different actors could compete for limited operating resources to increase their daily product output. However, the case of competing actors on system level 3 is more or less rare in industrial value chains (e.g., due to more and more process automation and multiple-machine operation of the employees). Therefore, there are usually no relevant obstacles for cooperation between actors on this level for energy and resource efficiency—unless this has been set as a goal by the superior organisation.

On system level 2 it is more common that individual actors have been installed within the superior organisation on purpose. Here, single process chains can constitute subsections of manufacturing sites or companies. Often such subsections are organized as own economic entities, which have to fulfil certain budget targets/restrictions (cost centre). They can be given even more autonomy if they are organized as profit centres. In this case, they do not only have to take the responsibility for their costs to meet their budget restrictions. Following the logic of profit centres, the process chains have to sell their intermediate products to the following entity at an internal transfer price. Therefore they also have the responsibility to meet individual profit margins. Thus, they contribute to the overall economic success by transferring their profits to the superior enterprise. Such an organizational structure bears the risk that the individual actors strive to increase their local performance and disregard the performance of the overall system although they belong to the same enterprise. However, due to their common integration into the same corporation, usually there is at least some transparency between actors on this system level. Usually the actors can be assumed to be willing to cooperate for energy and resource efficiency as this can lead to a better performance and decreased long-term charging of costs due to reduced energy and resource intensities.

The most natural way to differentiate industrial production into individual actors is to define companies (single legal entities) on the industrial value chain level as such actors. For entire companies, the full set of the above given objectives and performance indicators is valid. Traditionally the company's shareholders encourage the company to take the most profitable strategic as well as operational decisions. Therefore, they are often more focused on their own achievement of goals than on the performance of the overall industrial value chain, which they are a part of. Furthermore, due to corporate confidentiality policies, on this system level there is the least degree of cross-actor transparency regarding energy and resource intensities. Usually only the energy and resource related information, which is available via standardised sustainability reports, is available to other actors on this system level. Thus, a neutral analysis of the value chain and a fair balancing of interests between the actors are hard to do.

This fact reinforces the demand for methodological support for a holistic evaluation of energy and resource intensities especially on system level 1 while also considering the integrated effects of subordinate system levels. Such a support is needed in order to create transparency between the actors on system level 1 as one precondition for the identification, evaluation and prioritization of actor spanning improvement measures.

4.3.1.2 Varying Time Scales Across Hierarchical System Levels (M1.2)

Beside the multi-level perspective on the hierarchically organised production, a multi-time-scale perspective is also important, which takes into account that the different system levels can correlate to differing time-scales. These different time scales are valid for different planning time horizons and evaluation periods as well as for differing time resolutions of relevant events. As a groundwork for the later assignment of methods and tools, varying time scales of single hierarchical system levels will be introduced, which cause the majority of the differences between the corresponding methods and tools.

The above introduced specific objectives, which are measured by the described performance indicators, influence the individual selection of the installed technical equipment and focused objects or groups of objects. These objects and their configuration into process chains or value chains determine the required time scale for planning, monitoring and evaluation of the respective system level. However, between the system elements on each system level, different required time scales can also be possible.

Regarding the attempt to develop a multi-level multi-time-scale approach enhancing industrial production, the system level specific time scales can be described by using two perspectives (see Fig. 4.9).

On the one hand, the **time resolution of relevant events** describes the amount of substantial changes of a specific state from a focused object per defined time interval. Therefore, the time resolution of relevant events implies the usage of adequate metering methods and devices with correlating sampling rates in order to detect these state changes. Usually the time resolution of relevant events decreases with increasing hierarchical order of the system level. The more relevant events per time interval can be observed, the more dynamic the focused object's behaviour is. The fewer events can be observed or the longer the time interval must be

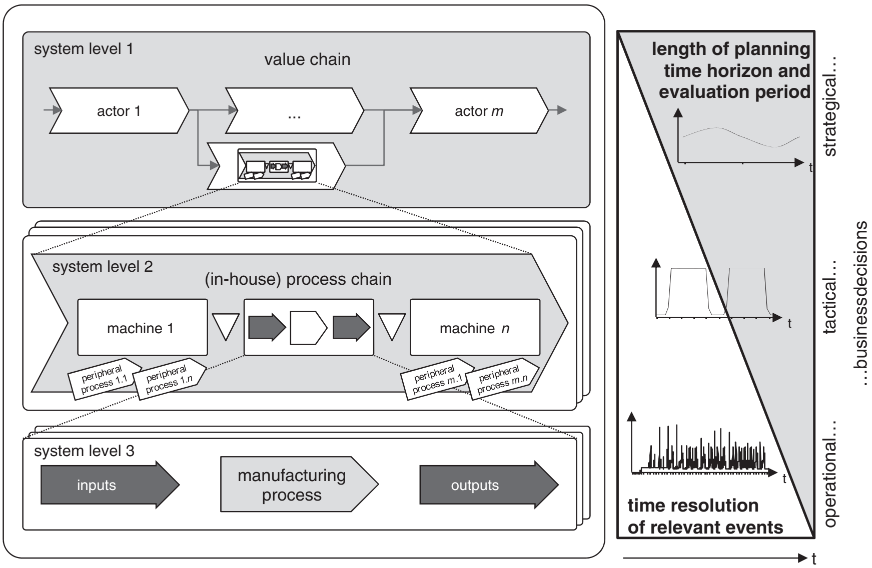

Fig. 4.9 Time resolution of relevant events versus planning time horizons and lengths of evaluation period on different hierarchical system levels

defined to detect relevant events, the less dynamic is the behaviour of this object. In general, more dynamic system elements can be found on lower system levels. The system elements on higher levels show a less dynamic behaviour. However, on subordinate system levels some system elements can also be found, which show a less dynamic behaviour, as there are only very few or slow and marginal changes of their individual states over time (e.g., industrial furnaces).

On the other hand, the **lengths of the individual planning time horizons** and **monitoring periods** vary per system level. Similar to the needed sampling rates of measuring methods and devices for the detection of relevant events also the monitoring and evaluation periods vary per system level. Those monitoring periods, which are used to track the fulfilment of plans with the same time horizon, increase with increasing system level. This is due to the fact that more and more information about increasing numbers of evaluation objects need to be aggregated on higher system levels, which demands a more concentrated and aggregated view on the monitoring results. This bottom up aggregation of information through the hierarchical levels of industrial production goes hand in hand with the top down dissemination of plans. It usually leads to more detailed plans, but also shorter planning time horizons for subordinate system levels.

In summary, these two perspectives represent the need for different **time scales** for planning, monitoring and evaluation activities on the individual system levels. For most of the system elements on the individual system levels, it can be stated that the required and meaningful time scales increase correspondingly with the system levels.

Furthermore, the increasing time scales corresponding to increasing hierarchical system levels get reflected by the **nature of business decisions** on the individual levels. Thus, business decisions which tackle lower system levels (like system level 3—manufacturing processes) are more of an operational nature. They deal with day to day decisions with a rather short planning horizon in reaction to fast changing states of the focused objects. Business decisions on higher system levels (like system level 2—in-house process chains) are more of a tactical nature. They deal with more forward-looking decision situations and are not only reactive, but also anticipatory to prepare the focused object for future production situations and production programs. Business decisions on the highest system level (system level 1—cross company industrial value chains) deal with strategic planning and decisions with a long-term impact. On this system level, planning periods are relevant, which are even longer than the individual accounting quarters or years. This is also reflected by the corresponding reporting periods, which are the basis for strategy adjustments.

Concluding the above described criteria for the differentiation of needed time scales on different system levels, Table 4.4 exemplarily illustrates different relevant events as well as sample items for planning and monitoring items as samples for the manifestations of these different level-specific scales. Furthermore, these manifestations get further allocated to their corresponding nature of business decisions.

Table 4.4 Relevant events, monitoring and planning items as manifestations of different relevant time scales per hierarchical system level

Hierarchical system level	Examples of relevant events	Sample items for planning and monitoring	Nature of business decisions
System level 1—cross company industrial value chains	Ramp up and fade out of product lines, implementation of new technologies, …	Yearly supply contracts, monthly/quarterly demand definition and corporate target evaluation, …	Strategical
System level 2—in-house process chains	Order shipments, output of produced batches, planned machine down times, …	Weekly production schedules, shift-wise production targets, …	Tactical
System level 3—manufacturing processes	Machine state changes, product output, unplanned machine interruptions, …	Cycle times, periodical (real-time machine) process monitoring and quality control, thermo dynamical process behaviour, …	Operational

The different time scales per hierarchical system level have lead to different methods and tools for an energy and resource oriented monitoring, modelling and evaluation, as well as planning, simulation and improvement on each individual level. A selection of these methodological groups will be introduced as a basis for the procedural approach, which is explained in the following section.

4.3.2 Module 2—Procedural Approach

The previous sections have provided insights in the structure of industrial production regarding their internal system levels and dynamics. To reduce the energy and resource demand of such complex systems, recommendations about the order of application of general methods need to be derived. Against this background, this section provides a procedural approach. The basis for this approach is the methodological groups, which have been introduced in Sect. 2.2.2. The approach is depicted in a flow-diagram for a sequence of (iterative) method application. The flow-diagram can be applied in case of first status quo analyses or ex post evaluations of implemented measures as well as for the case of ex ante evaluations about the estimated impacts of improvement measures.

The suggested procedural approach shall give recommendations for individual project managers within a selected company or value chain for how to evaluate their specific object of interest, and to prioritize the implementation of selected improvement measures regarding their comparative benefits. The procedure starts with the definition of the system boundaries of the observed system, and ends at the evaluation of its status quo respectively at the evaluation and implementation of improvement measures. However, all applied methods have their own set of individual outcomes. Therefore, manifold further starting and ending points within the procedure are imaginable, depending on the individually desired results for the actual problem of the user of this procedure. Finally, if applied ideally, the procedure describes a continuous improvement process towards energy and resource efficient industrial production (see Fig. 4.10).

If the object of interest is analysed for the first time or if already implemented improvement measures shall be evaluated for the first time, the procedural path of an **ex post analysis** is to follow, which describes the analysis of a technically implemented and operating status quo.

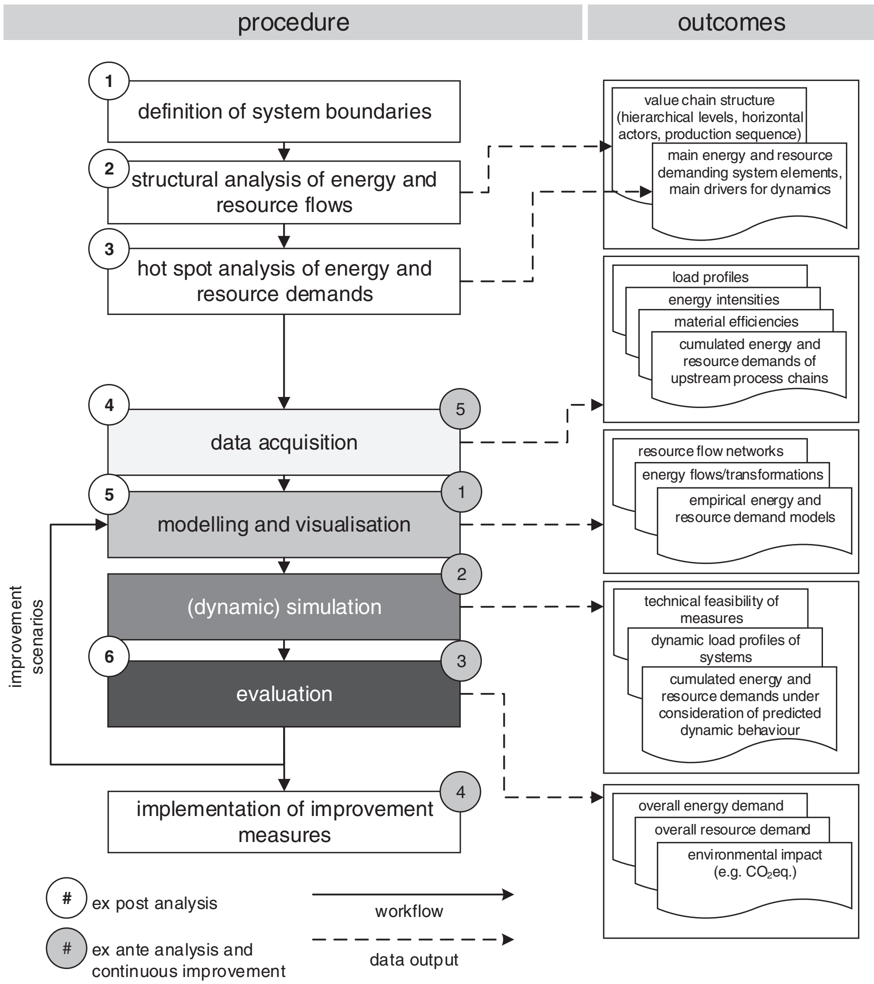

Fig. 4.10 Procedural steps and individual outcomes for enhancing the energy and resource efficiency of industrial production

The first step of a project to analyse and reduce the energy and resource intensities of industrial value chains is the **definition of system boundaries** of the object of interest. By doing so, organizational or energy and resource flow oriented boundaries are set, in which the further analyses and modelling activities shall take place. Furthermore, the considered energy and resource flows need to be defined in case a certain focus shall be taken. It is also important to identify those elements of the object of interest, which can be manipulated better than others and promise to be a good lever for improvement measures. These elements offer themselves for more detailed analyses than those elements, which cannot be affected by improvement measures or which are outside the system boundary. Hence, also some elements can be excluded from further investigations and declared to be outside the system boundary.

After the system boundaries have been defined, a **structural analysis of energy and resource flows** needs to be executed. This analyses is important to understand and describe the value chain‘s structure regarding its hierarchical levels, horizontal actors on each level as well as the sequence of value adding process chains and processes as well as their connected peripheral processes and technical building services.

If the structure of energy and resource flows, as well as the production sequence (including all relevant processes, equipment as well as technical building services) has been documented, a first **hot spot analysis of energy and resource demands** can be conducted. Through this analysis, the main energy and resource demanding system elements can be identified and noted for more detailed analyses. A sample for such an analysis is given by Thiede by ranking the previously identified (energy demanding) system elements according to the product of nominal energy demand and operating time per year (Thiede 2012).

These three steps (definition of system boundaries, structural analysis of energy and resource flows, hot spot analysis of energy and resource demands) constitute a preparation phase for the subsequent in-depth analyses. The following steps build upon the findings out of the previous discussions about hierarchical system levels and their specific performance indicators and time scales (see Sect. 4.3.1), and constitute preparatory work for the later assignment of methods and their synergetic application (see Sect. 4.3.3).

Due to these previous discussions, the specific methods for data acquisition, modelling, simulation and evaluation can be picked according to the individual considered system level and dynamic behaviour of the observed system element—and in line with the following sequence of application. However, even if the following procedural steps are introduced sequentially, an iterative application and resulting bidirectional information flow between the single methods shall not be neglected, and is still encouraged to be executed additionally.

After the hot spots about energy and resource demand (and negligible elements) have been identified, a detailed **data acquisition** needs to be conducted. Through the application of selected measuring methods for highly dynamic to less dynamic metering objects on the different system levels a thorough data base for further analyses gets generated. E.g., dynamic load profiles, energy intensities (per product or organisational unit) and material efficiencies as well as cumulated energy and resource demands of upstream process chains result from the data acquisition phase and get further processed later on.

By applying **modelling and visualisation** methods, the generated data gets prepared for further evaluations. These models describe correlations between energy and resource demands and possible influencing factors, and therefore also generate an important foundation for the evaluation of improvement measures. However, for the assessment of a status quo such models are also important. When it comes to the interaction of system elements, modelling methods which also visualise energy and resource flows can especially enrich the original data base to a level of information quality, which is already feasible for the deduction of possible improvement measures. These methods can calculate and visualise energy and resource flow networks, which later on can be used for the calculation of energy and resource intensities of the whole system.

Based on such networks and overall energy and resource demands, several **evaluation** methods can be applied. These evaluation methods (e.g., life cycle assessment) translate the previously modelled and calculated overall energy and resource demands (life cycle inventories) into several environmental impact categories (like global warming potential, expressed in CO_2eq.). By doing so, the previously quantified internal and external energy and resource flows can be interpreted according to the environmental target systems of the individual actors. The identification of gaps between the individual target system and the evaluation results can help to identify fields of action for the derivation of technical as well as organisational improvement measures.

If such improvement measures have been derived, their effect needs to be evaluated before a potential implementation in order to prioritise them. The procedural path of such an **ex ante analysis** benefits from the already generated database and models from prior ex post or status quo analyses. Therefore, possible improvement measures can be **modelled and visualized** in already existing energy and resource demand models by varying the affected model parameters.

If dynamic interdependencies with other system elements are affected by the improvement measures, and if the behaviour of complex systems cannot be calculated deterministically, **dynamic simulation** comes into play. Through the application of (thermo-) dynamic simulation approaches on system level 3 or energy oriented material flow simulation approaches on system level 2, the technical feasibility of process parameter changes (resulting from improvement measures) can be assessed. Furthermore, dynamic load profiles can be estimated and resulting cumulated energy and resource demands can be forecasted, under consideration of the predicted dynamic behaviour. Thus, also the effect of organisational measures, which affect non-technical parameters, can be assessed and integrated in the holistic assessment of improvement measures already before a physical implementation.

After the dynamic simulation has proven the measure’s technical feasibility, the newly generated overall energy and resource consumption data can be further processed again by **evaluation** methods to forecast the measure’s effect on the corporate (e.g., environmental) evaluation criteria. By benchmarking these new results of a set of possible improvement measures against the previously evaluated status quo, a ranking of promising measures for implementation can be generated.

The above described procedure introduced a sequential application of methods for a holistic analysis of industrial production (respecting the possibility of a synergetic, iterative application of single methods), which guides to a ranked set of improvement measures. However, it needs to be stated that the execution of this procedure is not meant to be a one-time event. It shall rather be a starting point for a process of **continuous improvement**. The introduced procedure is executed iteratively in this process. Therefore, the data acquisition phase shall start directly again after the implementation of measures. It needs to be executed to validate the predicted effect of the implemented measures and creates the database for further improvement campaigns.

A selection of specific methods will be introduced exemplarily in the following section by focusing on their interplay and synergetic interaction.

4.3.3 Module 3—Methodological Toolbox

The consideration of the above mentioned system definition and procedural approach makes it necessary to specify the methodological support. This need gets promoted also through the amount and complexity of the observed systems versus the available methods and tools. Available methods offer very powerful functionalities for a level specific application and can support decision making processes for the prioritization of improvement measures very fruitfully. However, by applying them jointly to evaluate entire production systems in an integrative way across all hierarchical system levels, these methods and tools mutually enrich the quality of their individual results. As a result even more powerful implications for action in complex manufacturing environments can be derived. Therefore this section introduces an exemplary interplay of selected, level specific methods and tools which are feasible to be integrated in a hierarchical evaluation scheme for likewise hierarchical industrial production. This interplay of methods gets introduced by considering their specific assignment to the dynamics (resp. time scales) and hierarchical position of the focussed object and by considering their synergetic application. This interplay gets further illuminated by the additional introduction of a performance indicator framework, which illustrates the mutual influence of the single system levels' performance indicators and their joint impact on overall corporate performance evaluation.

4.3.3.1 Assignment of Methods (M3.1)

The analysis and evaluation of energy and resource demands on all hierarchical system levels of industrial production gets supported by manifold methods, which can be applied for the evaluation of specific system levels and for diverse dynamics of the focused object. The following section will build upon the introduction of methods and tools from Sect. 2.2.2, and introduce a rough recommendation of general, representative approaches for data gathering, modelling and visualisation, (dynamic) simulation and evaluation. These approaches can be assigned to focused system levels and to the dynamics (resp. time scales) of their primary object of evaluation (see Fig. 4.11).

According to the explanations from Sect. 2.2.2 and to the introduced procedural approach, the assigned approaches are clustered pursuant to their possible position in an application sequence. Hence, approaches for data gathering about energy and resource consumption constitute the basis for any further evaluation. This data gets processed via modelling and visualisation techniques to facilitate the derivation of first findings. To address the dynamic interplay of system elements and to estimate possible impacts of improvement measures, approaches for (dynamic) simulation

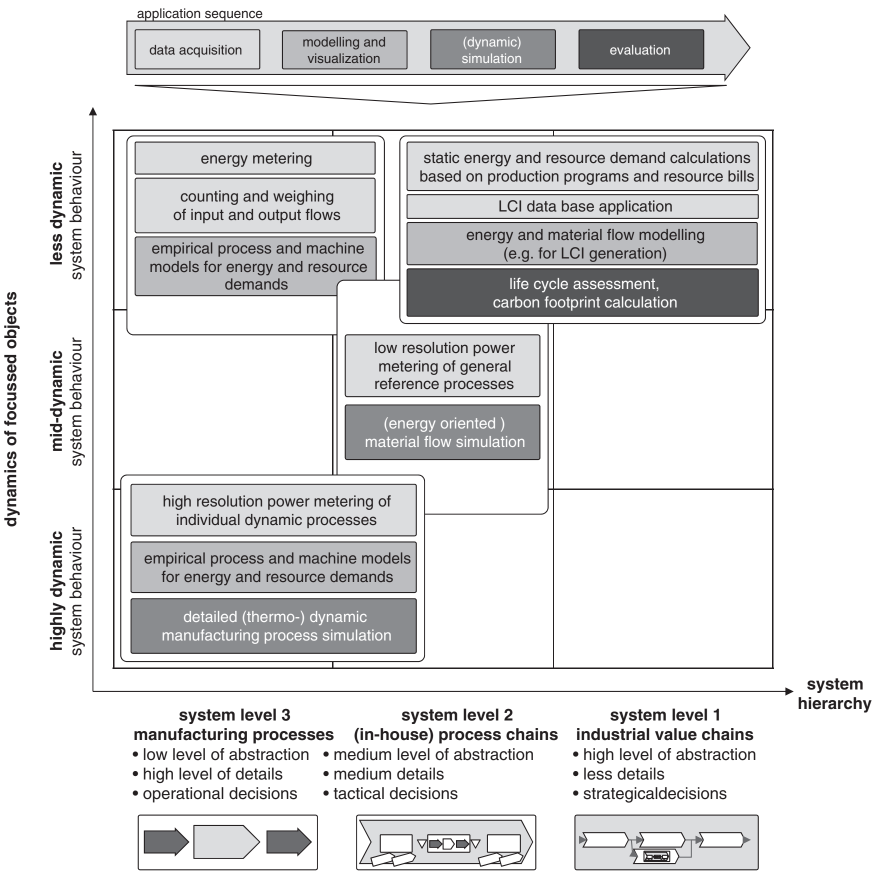

Fig. 4.11 Qualitative assignment of selected methods regarding dynamics (resp. time scales) and hierarchical application level

build up on previously generated models of the focused objects—unless they do not offer the possibility to model these objects internally. Finally, approaches for the evaluation of energy and resource intensities within industrial value chains can build upon the results of the previously applied approaches.

The individual methods can be assigned to systems and system elements with a highly dynamic behaviour, a mid-dynamic behaviour and less dynamic behaviour. Thereby, the aforementioned degree of dynamics reflects the different time scales per hierarchical system level. Although the system behaviour on level 1 can also be considered to be very volatile over longer time scales, it is considered to be less dynamic compared to the other system level's characteristic behaviour. Accordingly, as already illustrated in Sect. 4.3.1, the dynamics of the focused objects decrease with increasing hierarchical system levels and relevant time scales. So do most of the corresponding methods. However, hierarchical system levels of industrial production and the possible dynamics of system elements do not necessarily have to be strictly correlating. As Fig. 4.11 shows, through the assignment of methods and tools to certain dynamics and system levels, varying dynamics which are reflected by the recommended methods are possible per system level.

For system level 3, the existence of very dynamic processes (e.g., tool machines) in parallel with less dynamic processes (e.g., industrial furnaces) enables the application of specified methods for different kinds of dynamics. Thus, highly dynamic manufacturing processes demand feasible data gathering methods, which are able to handle the resulting speed and keep records about the individual state changes of the monitored system. Based on this, specific empirical models about the energy and resource consumption for each applied technology can be derived and parameterized. Afterwards, these models can serve as basis for the application of specific, detailed (thermo) dynamic manufacturing process simulation approaches to estimate the hypothetical behaviour of the process in case of parameter changes. In parallel to these diverse approaches for the analysis of highly dynamic manufacturing processes, methods for the analysis of less dynamic processes also exist. They are usually less sophisticated and demand less extensive technological support. Nevertheless, due to their easy to use simplicity, methods like energy metering (singular detection of the absolute energy consumption over a defined period of time) and simple counting and weighing of input and output flows are powerful approaches for a quick analysis of manufacturing processes with very low effort. However, the less dynamic nature of an individual process usually needs to be identified first through the application of metering methods for dynamic processes.

If knowledge about the dynamics of the single processes and corresponding models has been created on system level 3, the specific methods for in-house process chains (system level 2) can easily build upon this knowledge. In-house process chains are more of a generic nature than single highly dynamic and specialized manufacturing processes. Due to this fact, and after individual process models have been derived, additional data gathering campaigns can be done sufficiently by applying low resolution metering methods. By doing so, the models for general reference processes can be verified and supporting processes can be considered satisfactory. The previously derived process models, state dependent power load profiles and the logistical linkage of the individual processes then get modelled e.g., in (energy oriented) material flow simulation approaches. Such simulation approaches usually support the model generation for process chains internally and can be used to simulate possible variations in the interplay of processes (e.g., changed lot sizes, cycle times and media supply strategies). By doing so, the still existing dynamics of the second system level get considered with an accurate level of detail. However, the performance of the overall process chain is more in the focus of such tools than the individual technological behaviour of a single machine's components.

System level 1 (industrial value chains) is characterized by the mainly strategic nature of its corresponding business decisions. Accordingly, due to the long-term planning horizons on this level, the system behaviour gets perceived as less dynamic compared to the lower system levels. Therefore, data gathering methods on this level usually make use of existing company data bases which contain information on production programs and energy or resource bills. Based on such information, the energy and resource demand per time interval or product unit can be calculated and internal waste flows can be estimated. Furthermore, on this level, information about the energy and resource supply sources is available and can be included in the cross company modelling of energy and resource flows. Such modelling efforts are the basis for the generation of LCI datasets (see Sect. 2.2.2) and vice versa. If data about external energy and resource flows along the value chain (e.g., at different actors) cannot be generated specifically by analysing these external activities, LCI data bases can provide this data in general. If models about the energy and resource flows along the considered value chain are derived and substantiated with directly metered data or indirectly generated data from LCI data bases, then these models can be further evaluated by applying a life cycle assessment. As already discussed, environmental impacts are usually analysed and interpreted on the corporate level or for individual products, considering their entire life cycle and value chain. Therefore, LCA is tailored for such evaluations on system level 1, and can enrich the gathered data about physical flows and resource demands by transforming them into environmental impact categories.

As introduced above, the several available methods for the analysis and evaluation of energy and resource intensities on all levels of industrial production can be roughly assigned to a usage in single system levels, and for specific dynamics of the focussed object of evaluation. However, the frontiers between the system levels cannot always be set distinctly and the dynamics (resp. time scales) of system elements within industrial production can vary. Hence, also the assignment of methods should not be utilized dogmatically. Thus, it is important to understand, that individual methods unfold their full potential by focussing on specific hierarchical system levels and dynamics while aiming at specific findings.

Nevertheless, the dynamic interplay of the single system levels makes it necessary to apply the level specific methods jointly to assess their impact e.g., of selected improvement measures on the entire value chain. Although such a joint application only becomes necessary due to the limitations of single methods, still, the following paragraphs will illustrate the potential of a joint application of methods for a holistic improvement of energy and resource demands in industrial production.

4.3.3.2 Synergetic Application (M3.2)

As already introduced above, the methods for the analyses and evaluation of energy and resource intensities in industrial production usually are applied sequentially. Methods for data acquisition build the basis for modelling and visualisation activities, which can be followed by (dynamic) simulation approaches and finally evaluated with specific methods. As the methods build upon the results of the predecessors, their joint application is naturally synergetic (see Fig. 4.12).

Modelling and visualisation methods require the single energy and resource demand profiles of data acquisition activities, which get further processes via (dynamic) simulation e.g., into quantified impacts of possible interventions into the considered dynamic object of interest. Evaluation methods (esp. with a focus on system level 3) can build upon such quantified results in order to compare also dynamic interactions of system elements within their rather less dynamic and strategic perspective.

However, between the single methods an iterative application or data flows against the usual direction of the application sequence can also provide extra benefits. These benefits e.g., can be the enhancement of data qualities, the consideration of dynamic effects of subordinate system levels also on superior levels or the predefinition of upper and lower boundaries of parameter sets to reduce the effort for model generation and simulation (see also Heinemann et al. 2012, 2013b, 2014).

Due to the huge diversity of possible methods for the analysis and evaluation of energy and resource intensities, the potential synergies between the available tools are also multifaceted. Figure 4.13 exemplarily shows such a beneficial interplay

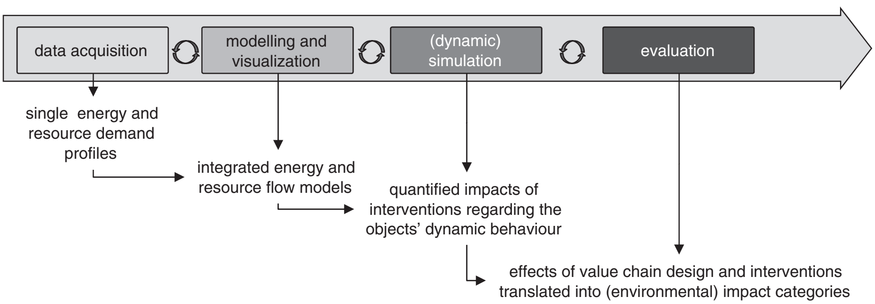

Fig. 4.12 Synergetic sequential application of methods for energy and resource intensity analysis and evaluation

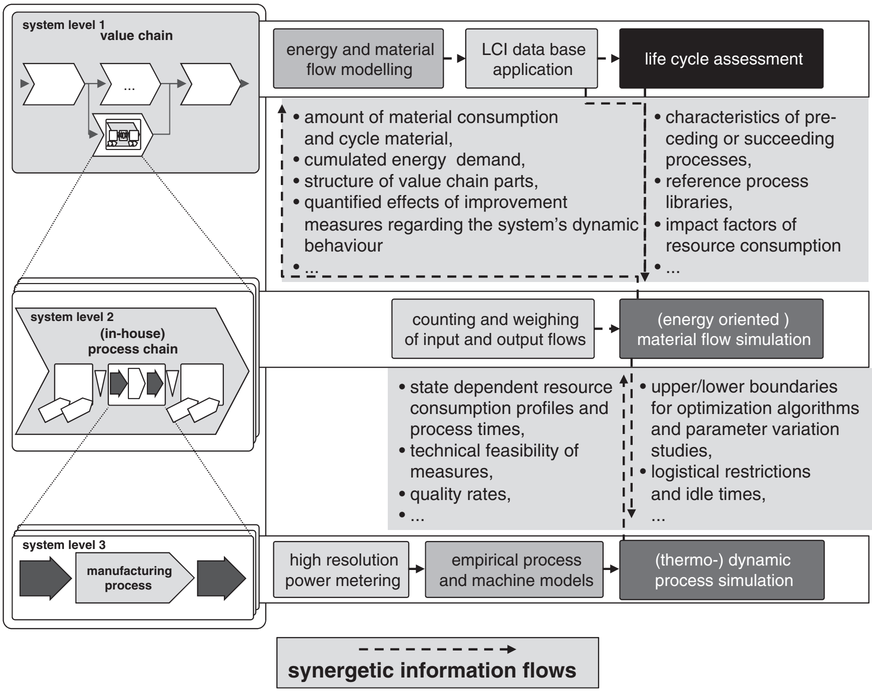

Fig. 4.13 Example for methodological synergies through bidirectional information flows and iterative application

of selected methods, which can be described through the bidirectional information flows between the system levels and specific methods. Here, modelling and simulation approaches especially take advantage of a bidirectional and iterative application.

As discussed in Sect. 2.2.2, typical (thermo-) dynamic simulation approaches on system level 3 usually focus on the technical feasibility of measures that manipulate process and design parameters. Therefore, an individual model for each applied technology needs to be created and parameterized regarding its high level of dynamics as well as internal thermo-dynamic and (flow) mechanical behaviour. The creation of such empirical process and machine models gets supported e.g., by high resolution power metering, which augments them with parameterized models about specific energy intensities, depending on the individual process behaviour. By including this information, common (thermo-) dynamic manufacturing process simulation approaches can forecast the technical feasibility of possible improvement measures. Additionally, their effect on the quality rate of the considered process, as well as the state related energy and resource demand of the process and the needed supply from technical building services, can be estimated.

The specific (thermo-) dynamic manufacturing process simulation approaches are very powerful and complex methods for a detailed view inside the physics of value adding processes. Some of them also include algorithms for an optimization of process parameters, or they can be used for parameter variation studies in order to identify beneficial combinations of parameters. However, due to their complexity, extensive parameter variation studies and optimization experiments are very laborious and time-consuming. Furthermore, as such simulation approaches are not linked to their production environment, such experiments cannot consider the effects of a dynamic interaction with other processes or transport systems. In addition, they cannot deliver information about the relative relevance of the individual process compared to the preceding or succeeding process in the superior process chain.

Therefore, the information backflow of the superior system level's (energy oriented) material flow simulation becomes important and can facilitate the application of manufacturing process simulation approaches on system level 3. Through the identification of bottleneck processes and the forecast of idle times as a result of the logistical linkage of the manufacturing processes, the material flow simulation can help to estimate waiting times for heating and cooling of the manufacturing process. Furthermore, it can also help to narrow down possible upper and lower boundaries of input parameters for optimization algorithms and parameter variations studies. Thereby, the required effort of process parameter optimization experiments can be decreased. Thus, for instance, maximum cycle times can be defined, which can be accepted without creating new bottleneck situations. This definition of allowed upper boundaries for cycle times can then enable the optimization algorithm to quickly focus on other process parameters, which take benefit of longer cycle times in order to enhance the product's quality (e.g., longer and smoother cooling periods).

The applied energy oriented material flow simulation on system level 2 itself focuses on the interdependencies of the installed individual processes resp. machines and their components. Usually, on this level the technical demands of the underlying process models are translated into energy demands of the interlinked machines along the process chain. This linkage includes information about their logistical sequence, the dynamic supply with (half finished) work pieces, probabilistic models about the machine's availability or missing supplies and load profiles which represent the dynamic energy consumption depending on the actual load of the machines (Thiede 2012). Furthermore, material oriented information from counting and weighing of input and output flows of the single manufacturing processes gets included to also consider the material supplies and resulting material efficiencies while estimating the overall material demand and the amount of cycle material in the process chain simulation.

The results of an application of the (energy oriented) material flow simulation on system level 2 can be used for the parameterization of energy and material flow models for the entire value chain on system level 1. Thus, realistic values for the total energy and material demand of in-house process chains can be included into the less dynamic and strategic considerations on system level 1 without neglecting technical feasibility, dynamic system behaviour and logistic linkage of system elements. Furthermore, besides the parameterization of energy and material flow models of the superior value chain, the structure, or at least of parts of it, can also be adapted from the energy oriented material flow simulation. Thus, the dynamic simulation on system level 2 can serve as a gateway, which aggregates the diverse manufacturing process related data from system level 2 for a great variety of processes. It augments them with information about material intensities and effects of the dynamic system behaviour. By doing so, it provides the energy and material flow models on system level 1 with a full picture of all relevant company internal flows, which are needed for cross-company modelling of such flows at a reasonable level of detail.

System level 1 itself constitutes the most aggregate level of consideration regarding the level of detail about single processes. By contrast, it also represents the broadest perspective regarding the overall considered system boundary. Therefore, it cannot be guaranteed that the data for all subordinate processes and process chains along the entire value chain are always available as described above. Therefore, LCI data bases are used on this level. They provide the missing aggregated data about energy and resource intensities e.g., for supplying processes and upstream process chains. Thus, on system level 1, energy and resource flow models under the usage of LCI data bases bring together all detailed results from different sub-systems and preceding or succeeding actors into one integrated environment and build up a decisive base for a holistic environmental evaluation (e.g. through applying an LCA).

However, in an iterative application, the methods from system level 1 can also provide valuable information for the energy oriented material flow simulation on system level 2. Especially in an environment of incomplete information and data availability for all processes along in-house process chains e.g., LCI data bases, which also include energy demand models for manufacturing processes, can provide the missing information. Furthermore, through the application of a full LCA, which calculates the environmental impact of the considered value chain, impact factors (e.g. CO_2eq. per Kg of the final product or CO_2eq. per kWh of electricity demand) can also be derived, which enable a quick pre-evaluation of the process chain's impact already in the material flow simulation.

As introduced in this section, the single methods for analysing energy and resource intensities on the different system levels of industrial value chains have specific purposes and focuses. There are methods, which focus on overall demand indicators and environmental impacts (system level 1) as well as methods, which focus on process chain performances (e.g., lead time and energy load profiles on system level 2) and specifically designed methods for proving the technical feasibility of process parameter changes (system level 3). However, their joint application can lead to mutual benefits for each method and its aimed analytical findings. Thus, this joint application enhances the results of the applied methods, and furthermore leads to the calculation of a great variety of performance indicators, which provide useful information for business decisions (see also Heinemann et al. 2012).

The following section exemplarily describes the interaction of such performance indicators across the borders of system levels. Thereby, it provides additional insights in the interaction of methodologically derived business decisions on each system level and their impact on the overall business targets.

4.3.3.3 Performance Indicator Framework (M3.3)

The system levels of industrial production depend on each other and mutually influence each other. Thus, level specific performance indicators can also be clustered into similar groups per system level. Usually, the main level for corporate decisions is the first system level as discussed above. Therefore, performance indicators on this level seem to be most important. However, these indicators get influenced by the performance of the subordinate system levels. The performance of all subordinate system levels directly influences the performance of superior levels, which can also be expressed as a hierarchical dependency of performance indicators. Figure 4.14 introduces a sample performance indicator framework, which assigns level specific clusters of such indicators and highlights their interdependencies exemplarily.

On the manufacturing process level (system level 3) the main performance indicators can be clustered into material, time/quality and energy related criteria. Within these clusters the process capability already has an influence on the actual material removal rate and process cycle time, as it depicts the deviation of quality related process parameters (like cutting depth, material removal, time shares, etc.). The material removal rate itself influences the material efficiency of the process. The state dependent energy demand of a manufacturing process depends on the energy demand of further sub-elements like supporting activities for heating, cooling, etc.

The energy and the time/quality cluster of criteria merge into the energy related group of criteria on system level 2 (in-house process chains). Here, depending on the dynamic linkage of manifold manufacturing processes, the single state related energy demands of the value adding processes and supporting peripheral processes cumulate into the overall dynamic energy demand of the process chain. Depending on the kind of energy carrier, this demand has an influence on the level of air pollution, which can be measured and evaluated on this system level. The aforementioned criteria cluster material merges into another material related cluster on the process chain level. This cluster gets influenced by the technical performance cluster, as it cumulates also product quality related aspects that can lead to higher amounts of scrap or cycle material.

This technical performance cluster is the most focused group of evaluation criteria in traditional manufacturing mindsets. On system level 1 (industrial value chains), this cluster mostly influences the overall lead time and the total product output, which basically can be seen as logistical performance evaluation criteria. Taking the environmental impact of industrial value chains under particular consideration, the overall material and energy demand becomes important again.

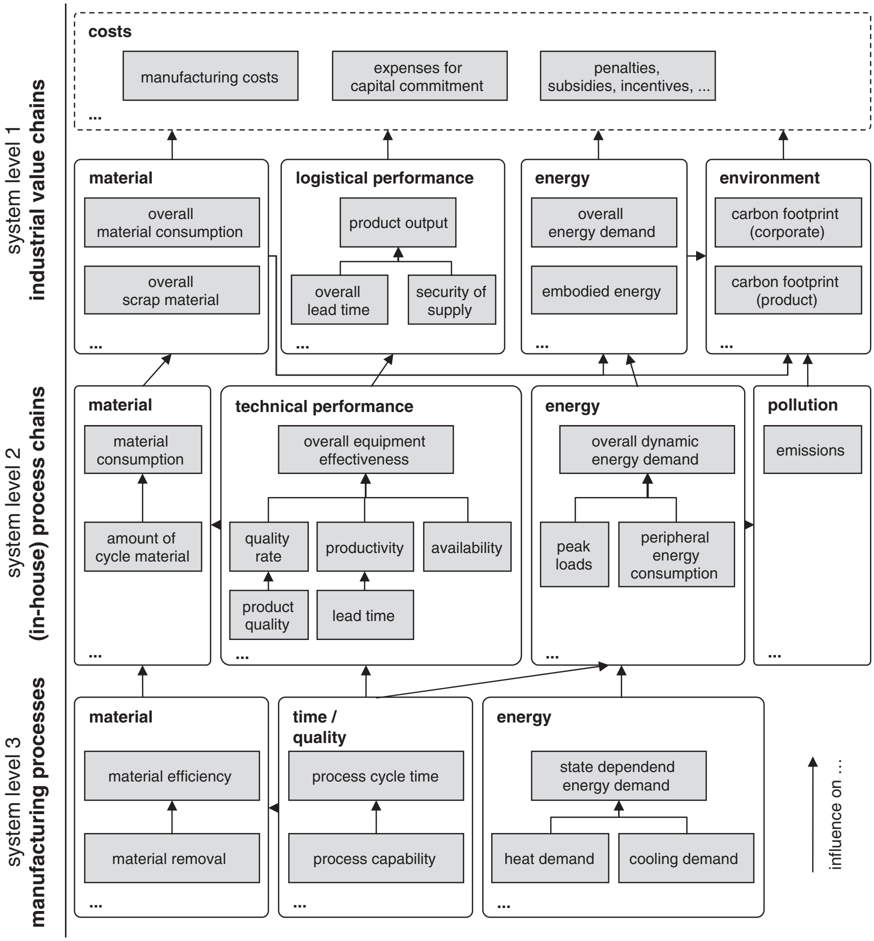

Fig. 4.14 Exemplary clusters and hierarchical interdependencies of level specific performance indicators

For the evaluation of the overall material demand, not only the pure material consumption is important to consider, but also the amount of scrap material needs to be assessed. By analysing the material consumption and also the circular flows of scrap material (including their redundant processing), information about the overall energy consumption and the material's embodied energy can also be deduced. This facilitates the calculation of product and corporate carbon footprints as one selected indicator for the environmental impact of industrial value chains that has already made his way into corporate decision making at manifold enterprises.

Finally all evaluation criteria, which measure the target achievement of the individual system levels, also measure influencing factors on the overall costs along the value chain and, thus, on the overall profits of the value chain's actors.

The logistical performance also has an impact on the expenses for capital commitment as it is affected by the stock turn rate. The material and energy costs (besides the costs for human labour) are the main drivers of manufacturing costs. Besides, the environmental impact of industrial value chains has an influence on incentives and subsidies, which can be acquired in order to reduce the overall manufacturing costs. If these impacts are above certain thresholds, incentives can be replaced by penalties, which can lead to a painful increase of overall corporate costs. Therefore, a behaviour and culture of decision making, which respects the importance of continuously reducing energy and material intensities, is not only praiseworthy from a societal point of view, but also vital from a strong economic perspective.

Of course, the interconnections and interdependencies of the introduced criteria clusters can be even more diverse and complex depending on the implemented processes and considered level of detail. Furthermore, they can be clustered differently according to the individual perspective. However, the introduced mutual hierarchical l influences of the performance indicators give a good hint about the hierarchical interplay of the system levels of industrial value chains. Understanding this fact enables the actors within industrial value chains to identify manifold fields of action at all system levels. Therefore, overall performance can be improved and manufacturing costs can be reduced within the actors' specific system boundaries or even beyond these demarcations.

As an example for this, the following chapter will serve an exemplary, specific application of the above introduced, general framework and procedure. The application domain is the aluminium die casting value chain and its system elements.

Chapter 5
Multi-level Multi-scale Framework for Enhancing Energy and Resource Efficiency in Aluminium Die Casting

After the technical introduction of the cross company aluminium die casting value chain and a multi-level and multi-scale framework for industrial production in general, this chapter serves a sample application of the derived framework by analysing and modelling a set of specific aluminium die casting value chains. The detailed analysis of these sample value chains is used for the creation of a generic energy and material flow model of aluminium die casting. Based on this model, further detailed investigations in the nature of the energy and resource usage are conducted. Furthermore, some selected improvement measures are introduced and evaluated to outline possible scenarios for making aluminium die casting more energy and resource efficient.

5.1 Course of Discussion

In concordance with the above introduced research methodology (see Sect. 4.1) and under usage of the developed procedural approach (see Sect. 4.3), this chapter applies the multi-level and multi-scale framework for enhancing energy and resource efficiency in production to the case of aluminium die casting. Therefore, Fig. 5.1 shows a synthesis of the research methodology and the procedural approach to introduce the course of the following discussion.

As a basis for the later modelling and evaluation, the previously developed general framework will be specified for aluminium die casting. The framework gets applied to specific objects of investigations (actors and products).

Then, by taking an ex post perspective, the specific objects of interest are investigated to derive a generic energy and material model for aluminium die casting. Therefore, the system boundaries need to be further specified before a structural analysis of energy and resource flows can be conducted. Resulting from the structural analysis, the investigation of the different specific objects of interest induces the generation of a first generic model about the structure of aluminium die casting. Proceeding from this generic structural model, the focused objects and their

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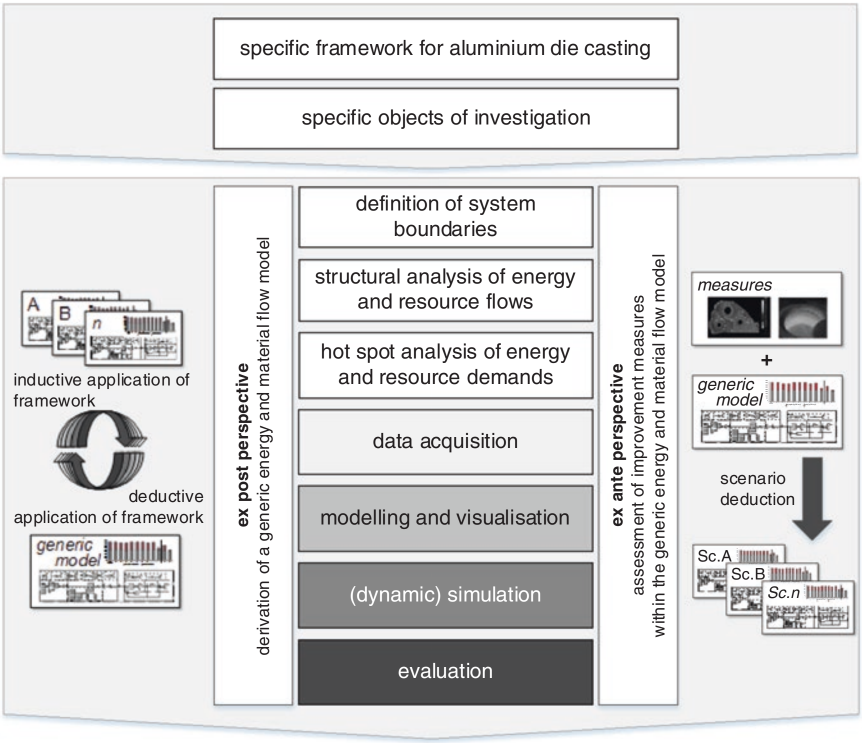

Fig. 5.1 Course of discussion of aluminium die casting case

structure for a subsequent hot spot analysis of energy and resource demands can be deduced. The relevant identified objects then build the focus for the following data acquisition. The generated data about energy and resource intensities in aluminium die casting gets analysed to induce general patterns. These patterns can be used to transform the structural aluminium die casting model into a valuated model with quantified information about energy and resource intensities for all included system elements and system levels. This interplay of data acquisition, inductive modelling and deductive derivation of fields of investigation is performed iteratively over the different system levels. By doing so, a profound, generic aluminium die casting model can be created. Afterwards, this model undergoes further in-depth investigations (e.g., parameter studies) to identify general fields of improvement and to support a final evaluation, regarding the overall energy consumption and environmental impact.

With this knowledge about the characteristics of generic aluminium die casting, improvement measures can be created, of which a selection is introduced later. The detailed development of such improvement measures will not be described. However, the displayed selection shall serve as a vehicle for the presentation of the evaluation potential of the developed framework and model.

By taking an ex ante perspective, the individual improvement measures are implemented virtually. For this purpose, corresponding parameter variations are conducted within the generic model, and improvement scenarios get deduced. To support this, (dynamic) simulation approaches on the process and process chain levels can be applied in case the dynamic behaviour of single machines or dynamic interdependencies within connected system elements are affected. As a result, the improved energy and resource intensities as well as the logistical performance and technical feasibility can be forecasted. Thereby, improvement measures can be benchmarked against each other as well as against the generic model. Thus, priorities for a later physical implementation can be set.

5.2 Specific Framework for Aluminium Die Casting

In this chapter the previously developed multi-level multi-scale framework for energy and resource efficiency in production will be applied to several cases of aluminium die casting. Measures for reducing the energy and resource intensity of aluminium die casting can be tackled from various points of application on an inter-company level as well as on a single process level. Furthermore, one or multiple actors can be involved. Therefore, the following sections address the different actors and system levels of the specific cases before selected methods will be introduced briefly and arranged into an individual procedural approach for this technology.

5.2.1 Actors and System Levels

According to the introduction of aluminium die casting in Chap. 2, there are two different actors that constitute the main parts of this value chain: The **alloy supplier** and the **foundry** itself. They are located on **system level 1** of the value chain and have been identified as main actors, as they incorporate the main value adding processes, the most voluminous material flows and the main fields of action for improvement within the considered specific value chain. Figure 5.2 illustrates the position of these on system level 1 as well as all further subordinate system levels, selected process chains and processes.

The alloy supplier buys primary aluminium as well as secondary (recycled) metals, auxiliary materials (e.g., salt) and energy carriers (e.g., natural gas and electricity). He refines the sourced input materials to aluminium die casting alloys that get transported to the foundry. To fulfil this task, the alloy supplier can be subdivided into the sequential subsections preparation/melting, alloying and ingot casting (see Sect. 2.1.2).

Subsequently, there is the foundry that consists of the subsections for melting of aluminium (in-house smelter), the die casting process itself, a facultative

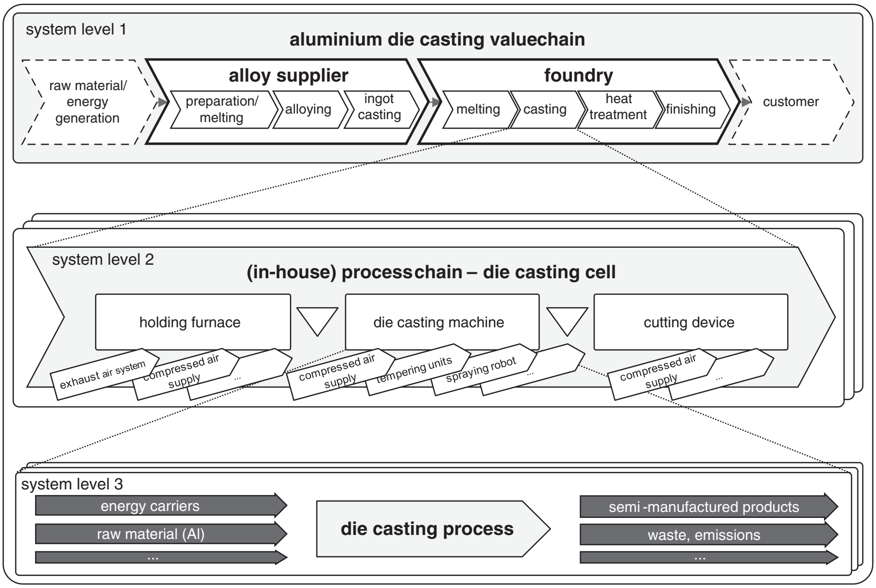

Fig. 5.2 Hierarchical structure and actors of the aluminium die casting value chain (see also Heinemann et al. 2012)

heat treatment section to produce the required metal properties and one or several machining processes to realize the final geometry and surface quality (see Sect. 2.1.2). The foundry sources its alloys (liquid or solid) from the alloy supplier. Further input materials (e.g., energy carriers like natural gas or electricity) are sourced from the market. The main material flow within the foundry goes downstream from one subsection to the other. One exception is the recycled material (swarf, scrap material, sprue waste, stamped-off gating systems) that gets resmelted in the in-house melting section after leaving the die casting and mechanical treatment/finishing departments.

The alloy supplier's and foundry's subsections can be considered as individual actors as they are sometimes organized as own internal business units. However, for the following course of analysis, only the main actors alloy supplier and foundry on system level 1 shall act as individual and self-organizing entities with specific sets of interests and objectives.

The final step of the aluminium die casting value chain on system level 1 is represented by a customer, or rather by the delivery of a predefined amount of products at a predefined quality to a customer destination.

On **system level 2** each of the main actor's subsections (from the melting section at the alloy supplier to the finishing section at the foundry) incorporates its own (in-house) process chain, which contributes to the value adding in a sequential order with the connected subsections. Within the process chains, the value adding processes are technically linked via band conveyors, forklift trucks or other more or less rigidly linking technical solutions. Peripheral processes (and/or elements of the technical building services) provide the necessary working conditions and media supplies to enable the value adding processes.

Besides the differentiation of the subsections according to the previous explanation, it is also possible that selected subsections appear merged into one single process chain and one joint subsection. E.g., due to high production volumes and a high degree of automation a rigid linkage of manufacturing processes can be installed also between the usual boarders of single subsections. This would expand the process chain from one subsection into another and lead to one joint process chain over different subsections of one actor.

Using the example of the foundry's casting subsection and focussing on the aluminium die casting cell as an own process chain, the main sequentially linked processes are the holding furnace, which holds the molten alloy's temperature and charges the alloy into the die casting cell, the die casting machine itself and a cutting device, which separates the gating system from the casted product.

Peripheral processes in this process chain are e.g., the compressed air generation, the exhaust air system, spraying robots and tempering units.

On **system level 3,** where the single (value adding) manufacturing processes are located, the main parts of the superior process chain are jointly constituted. On this level the aluminium die casting process transforms the molten alloy input into semi-manufactured product outputs, waste and emissions by using energy carries and auxiliary materials. This level is also responsible for the realisation of the demanded product quality in terms of surface properties, geometry, material integrity, etc.

5.2.2 Assignment of Selected Methods and Tools to System Elements

As this framework supports the evaluation of the aluminium die casting value chain, it shall also give a recommendation about the specific selection of methods regarding the relevant time scale (resp. degree of dynamics) and system level of the individual objects of interests. As groundwork for this recommendation, Table 5.1 characterises a selection of the main value adding system elements of the aluminium die casting value chain, which have been introduced in Sect. 2.1.2, according to their dynamic behaviour and hierarchical system level.

Due to the inert system behaviour of industrial furnaces, which can be characterized by rather slow heating and cooling phases and a very smooth temperature regulation during the continuous heating and melting of metal, most of the processes which use industrial furnaces, can be classified as less-dynamic. This also influences the degree of dynamics of the superior subsections and actors, which consist mainly of furnaces or ovens like the melting subsections of the alloy supplier and the foundry.

Table 5.1 Characterisation of system elements within aluminium die casting regarding dynamic behaviour and system level

Actor	System element	Examples for planning and monitoring items and periods	Dynamics of focused element	System level
Raw material/ energy carrier generation	Aggregated upstream process chains	Perennial supply contracts, monthly/quarterly demand definition	Less dynamic	1
Alloy supplier	Alloy supplier's facility	Several months/years lasting supply and delivery contracts, monthly/quarterly demand definition	Less dynamic	1
	Drum melting furnace	Shift-wise demand definition, nearly no or weekly/monthly alloy changes, continuous melting, material delivery every quarter of an hour	Less dynamic	3
	Converter (holding furnace)	Shift-wise demand definition, nearly no or weekly/ monthly alloy changes, continuous melting, material delivery every quarter of an hour	Less dynamic	3
Foundry	Foundry facility	Several months/years lasting supply and delivery contracts, monthly/quarterly demand definition	Less dynamic	1
	Melting subsection	Weekly/monthly demand definition, nearly no or weekly/monthly alloy changes, continuous melting, material delivery every quarter of an hour	Less dynamic	2
	Melting oven	Shift-wise demand definition, nearly no or weekly/monthly alloy changes, continuous melting, material delivery every quarter of an hour	Less dynamic	3
	Die casting cell	Weekly/monthly demand definition, tact time according to die casting machine, steady product output piece by piece or batch-wise, mid-dynamic overall load profile	Mid-dynamic	2
	Holding furnace	Shift-wise demand definition, nearly no or weekly/ monthly alloy changes, continuous heating and holding of temperature, material delivery at each cycle of the die casting machine	Less dynamic	3

(continued)

Table 5.1 (continued)

Actor	System element	Examples for planning and monitoring items and periods	Dynamics of focused element	System level
	Die casting machine	Shift-wise demand definition, shift-wise to quarterly product and tool changes, cycle times from less than 1 min up to 5 min, highly dynamic load profile, less than 1/100 s duration of quality-impacting sub-process steps	Highly dynamic	3
	Cutting device	Demand definition and cycle times according to die casting machine, mid-dynamic load profile	Mid-dynamic	3
	Heat treatment subsection	Weekly/monthly demand definition, steady product output piece by piece or batch-wise, quasi-static overall load profile	Less dynamic	2
	Heat treatment oven	Shift-wise demand definition, steady product output piece by piece or batch-wise, continuous heating, quasi-static load profile	Less dynamic	3
	Finishing subsection	Weekly/monthly demand definition, steady product output piece by piece or batch-wise, mid-dynamic overall load profile	Mid-dynamic	2
	Machine tool e.g., drilling, milling	Shift-wise demand definition, shift-wise to quarterly product and tool changes, cycle times from less than 1 min up to 5 min, highly dynamic load profile, high variety of possible sub-process steps during one cycle	Highly dynamic	3

Contrary to the continuously heating and melting industrial furnaces, those processes which are used for a discrete manufacturing of parts at a high pace and high production volumes (like die casting machines or machine tools for drilling and milling) show a highly dynamic system behaviour. Due to the high production pace and short cycle times, a variety of sub-processes and components fulfils its manufacturing task redundantly within very short intervals, which results in a dynamic load profile and very high dynamics of these system elements of industrial value chains.

Less complex processes on system level 3 (e.g., cutting devices) with less interacting components and sub-processes usually show a mid-dynamic system behaviour.

The superior subsections like the die casting cell or the finishing subsection can balance some of the dynamics of their incorporated manufacturing processes due to the aggregating nature of their system level. They can accumulate the individual load profiles to flattened overall load profiles, and can aggregate the individual product outputs to batches, which proceed to the subsequent subsection at a slower pace. However, these subsections still can be classified at least with mid-dynamic system behaviour.

The above introduced classification of aluminium die casting's system elements according to their dynamic behaviour and system level can also be visualized as depicted in Fig. 5.3.

As the portfolio, which is shown in Fig. 5.3, also matches with the portfolio of assigned methods for the modelling and evaluation of industrial production (see Sect. 4.3.3), a recommendation about methods and tools for data gathering, modelling and visualisation, (dynamic) simulation and evaluation for the specific system elements of aluminium die casting can be derived.

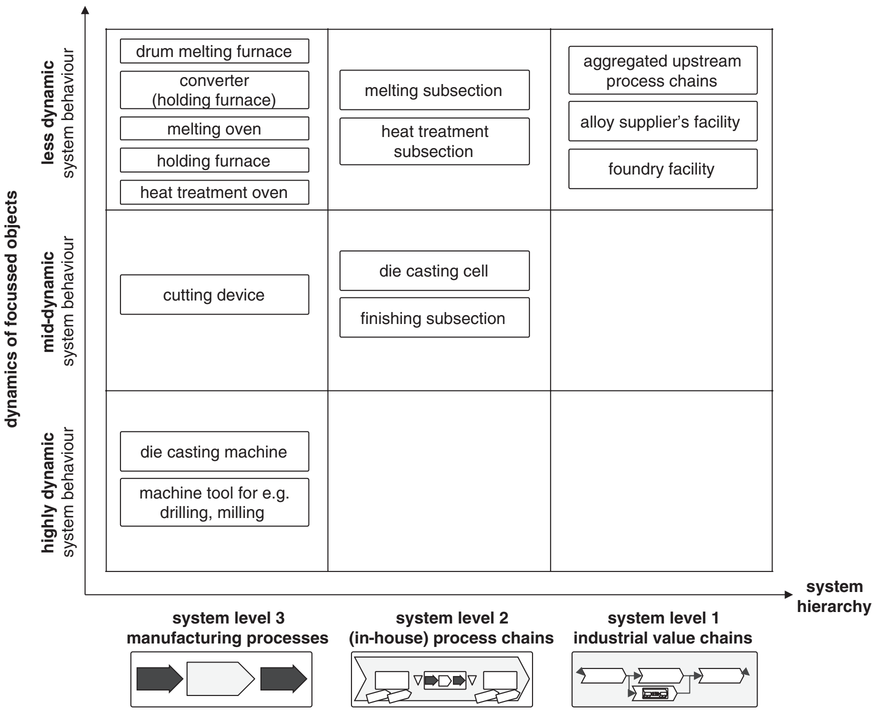

Fig. 5.3 Visual characterisation of system elements of aluminium die casting regarding their degree of dynamics and system level

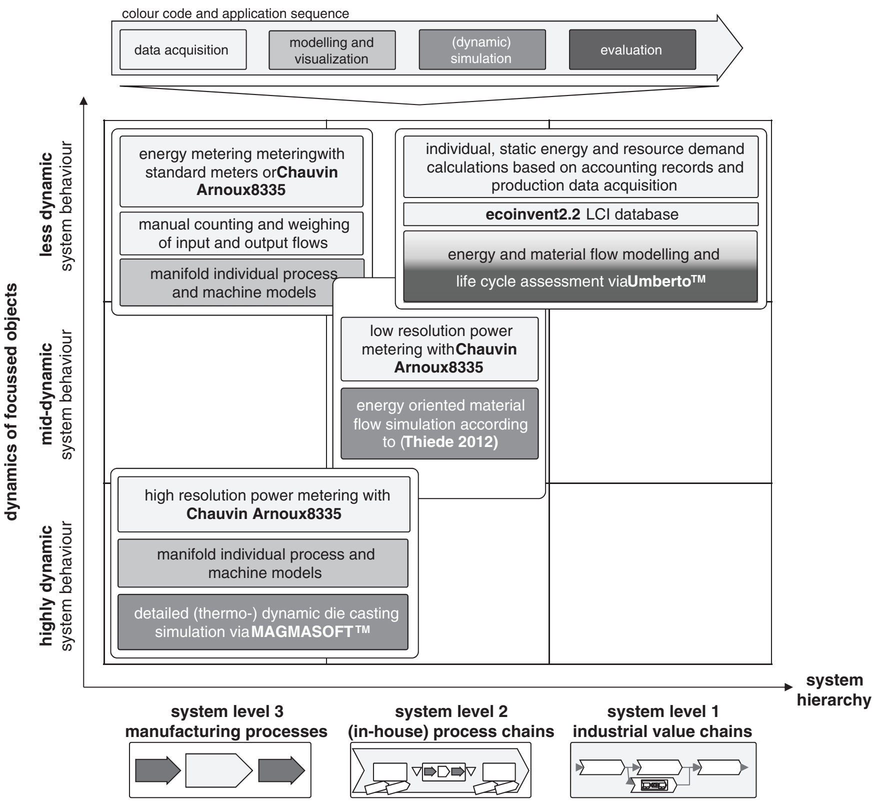

Fig. 5.4 Assignment of specific methods and tools for the evaluation of aluminium die casting

Therefore, based on the methodological discussions in Chap. 2, the following paragraphs shall briefly introduce a selection of methods and tools, which can be specifically applied for an analysis and evaluation of an aluminium die casting's system elements, respecting their individual system level and dynamic behaviour.

Figure 5.4 illustrates a recommendation about the assignment of specific methods and tools (see Chap. 2) to system levels and dynamics of the focused objects within aluminium die casting.

The data acquisition can be conducted via (electrical) power or energy metering (e.g., with a ChauvinArnoux 8335 QualiSTAR+[1]) and via additional manual counting and weighing campaigns of physical input and output flows on system levels 2 and 3. It gets supported by individual, static energy and resource demand calculations based on accounting records and production data acquisition. These demand calculations depend on the individual data availability of the considered actor in the value chain, and need to be adjusted accordingly. Information about

[1]See: http://www.chauvin-arnoux.at/.

the upstream energy and resource consumption due to the usage of energy carriers and (raw) materials can be gathered from the ecoinvent database.[2]

The modelling and visualisation on the process level needs to be done via manifold specific process or machine models if necessary. For the aluminium die casting process, a complex process model is included in the process simulation software MAGMASOFT[3] and constitutes the basis for its simulation algorithms. Similarly, necessary models of process chains can be composed within the energy oriented material flow simulation according to Thiede (2012).

The most relevant system level for the modelling and visualisation of energy and resource flows is system level 1. Here the petri net based software Umberto[4] plays an important role as it is feasible for a detailed modelling on different system levels within one integrated model. Umberto integrates all generated energy and resource demand data of processes and process chains, and visualizes the resulting flows via Sankey diagrams and accumulates the flows to life cycle inventories for a later life cycle assessment in the same software tool. By doing so, Umberto also offers the relevant functionality for a final evaluation of the aluminium die casting value chain.

Giving a résumé on these thoughts, Table 5.2 illustrates an exemplary assignment of methods and tools to the individual system elements of the aluminium die casting value chain. This assignment will be used in the later course for the analysis and evaluation of selected different aluminium die casting value chains.

It becomes obvious, that for system elements on lower system levels, an accurate data gathering with the help of metering equipment and manual efforts for counting and weighing is important. E.g., electrical power metering gets applied usually in case of dynamic processes, and even in case of mid-dynamic entities on system level 2. Manual weighing efforts are vital in cases of bad material efficiencies like at cutting equipment in the die casting cell. An energy oriented material flow simulation comes into play, when effects of improvement measures on mid-dynamic process chains (system level 2) shall be estimated. As introduced in Sect. 4.3.3, such simulation efforts get supported by an additional application of thermo-dynamic process simulation like MAGMASOFT™. A less dynamic heat treatment subsection only needs to be considered in an energy oriented material flow simulation if it is the connector between mid-dynamic subsections like the die casting cell or the finishing subsection.

The main tool, which covers all actors and all of their individual subsections for a modelling of energy and material flows as well as for a subsequent environmental assessment, is the petri net based software Umberto™. It integrates all energy and material flows of mid-dynamic to less dynamic system elements, and can connect and visualise them in an overall model of the entire value chain. Due to the fact that especially for the alloy supplier, the only less dynamic system

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[2]See: http://www.ecoinvent.org/.

[3]See: http://www.magmasoft.de/.

[4]See: http://www.Umberto.de/.

Table 5.2 Assignment of methods and tools to system elements of the aluminium die casting value chain

System element			Method or tool							
Superior actor	Title	System level	Metering with ChauvinArnoux 8335	Manual counting and weighing of flows	Resource demand calculations based on accounting records	Individual process and machine models	Detailed (thermo-) dynamic die casting simulation via MAGMA-SOFT	Energy oriented material flow simulation according to (Thiede 2012)	Ecoinvent 2.2 LCI-database	Energy and material flow modelling and life cycle assessment via Umberto™
Raw material and energy carrier generation	Aggregated upstream process chains	1			X				X	X
Alloy supplier	Alloy supplier's facility	1			X				X	X
	Drum melting furnace	3	X	X		X				
	Converter (holding furnace)	3	X	X		X				
Foundry	Foundry facility	1			X			X	X	X
	Melting subsection	2			X					X
	Melting oven	3	X	X		X				
	Die casting cell	2	(X)					X		X
	Holding furnace	3	X	X		X				
	Die casting machine	3	X			X	X			
	Cutting device	3	X	X		X				

(continued)

Table 5.2 (continued)

System element			Method or tool							
Superior actor	Title	System level	Metering with ChauvinArnoux 8335	Manual counting and weighing of flows	Resource demand calculations based on accounting records	Individual process and machine models	Detailed (thermo-) dynamic die casting simulation via MAGMA-SOFT	Energy oriented material flow simulation according to (Thiede 2012)	Ecoinvent 2.2 LCI-database	Energy and material flow modelling and life cycle assessment via Umberto™
	Heat treatment subsection	2			X			(X)		X
	Heat treatment oven	3	X			X				
	Finishing subsection	2	(X)		X			X		X
	Machine tool for e.g. drilling, milling	3	X			X				

elements in foundry's melting and heat treatment subsection have been identified, Umberto will be used to model their energy and material flows without a further tool-supported data processing. Thus, the integrated modelling of system levels 1 and 2 will play a major role in the later evaluation of different real aluminium die casting value chains. Data about the accumulated energy and material demands for the generation of raw materials and energy carriers in further upstream process chains, which supply the alloy supplier and the foundry, get taken from the life cycle inventory data base ecoinvent 2.2.

5.2.3 Specific Procedure for Aluminium Die Casting Production

Figure 5.5 synthesizes the assignment of selected methods and tools to individual system elements of the aluminium die casting value chain (see Table 5.2, Sect. 5.2.2) with the above introduced procedure for an improvement of energy and resource intensities in industrial production (see Fig. 4.10, Sect. 4.3.2) into one joint picture.

The synthesised procedure starts from a rough preparation phase, which defines the system boundaries of the observed value chain, analyses the structure of the focussed energy and resource flows and identifies hotspots of their related individual demands. The specific procedure then builds upon the same already introduced procedure for general industrial value chains. It substantiates this general procedure by giving a recommendation about the usage of selected methods and tools that get practically assigned to individual system elements on different hierarchical levels. By following this procedure, a systematic first (ex post) analysis and evaluation of the status quo of aluminium die casting production is possible. Through the recommendation of specific simulation tools also a systematic (ex ante) analysis of impacts of improvement measures gets supported with a focus on the most dynamic system elements (die casting machine and die casting cell).

Figure 5.5 gives a recommendation for the assignment of a selection of methods and tools to a selection of the most relevant value adding system elements along the aluminium die casting value chain. However, this selection of system elements shall not neglect the relevance of peripheral processes and technical building services. Such system elements can be characterised according to their system level and according to the dynamics of their individual system behaviour as well—like it was introduced for the selection of value adding system elements before. Thus, also the same recommendation of methods and tools can be applied.

The following sections will introduce the objects of investigation and apply the introduced procedure to investigate different aluminium die casting value chains afterwards. In order to increase the transferability of the derived findings, a generic model of the aluminium die casting value chain will be created, which is based on the individual analyses. According to the above introduced procedure, which suggests the software Umberto for the modelling and evaluation of cross company energy and resource

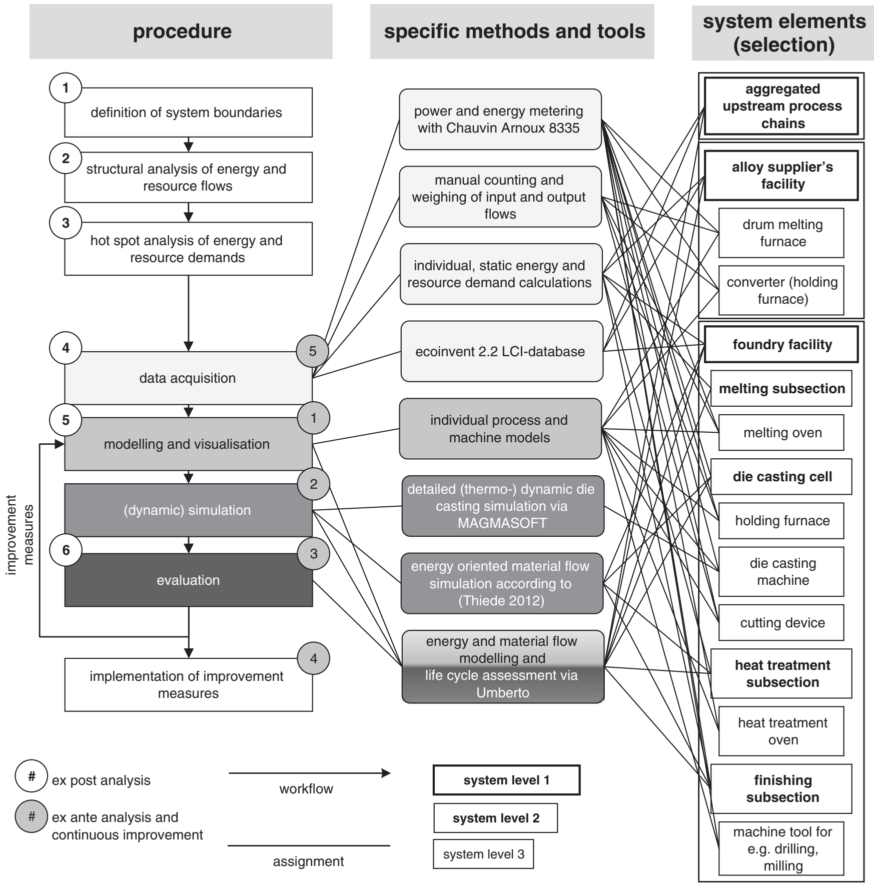


Fig. 5.5 Synthesis of a procedure for the analysis and evaluation of aluminium die casting

flows, a focus will be put on the analysis of this generic value chain model and corresponding improvement measures, which can be modelled in Umberto as well.

5.3 Objects of Investigation

The present book shall not only represent the specific situation of one single manifestation of aluminium die casting. Rather a generic study about the corresponding value chain shall be delivered. However, the underlying data needs to be obtained for specific cases. Three different foundries and one alloy supplier (**actors**), which constitute twelve different configurations of the aluminium die casting value chain (each of them with one individual **product or product family**), are the specific objects of investigation.

5.3.1 Actors

Twelve specific aluminium die casting value chains build the basis for the later generation of a generic model of the aluminium die casting value chain. They will be analysed and evaluated equally according to the previously introduced procedure (see Sect. 5.2.3)

These twelve value chains are given through twelve products or product families of three different foundries, which are assumed to be supplied by the same alloy supplier (see Fig. 5.6).

Table 5.3 gives a short classification of the investigated actors along the considered value chains. They are classified according to their size (measured in

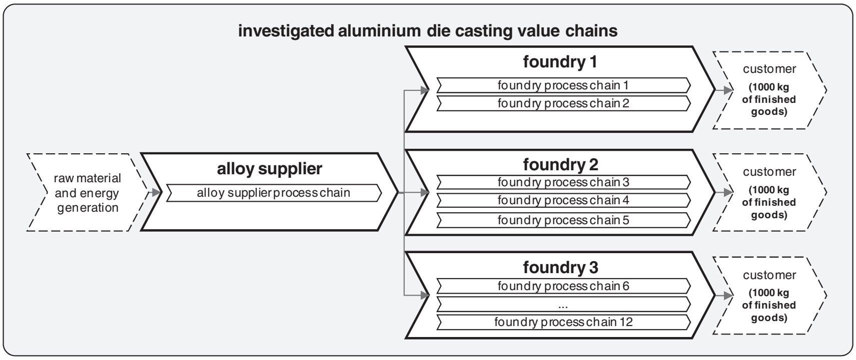


Fig. 5.6 Overview over investigated aluminium die casting value chains

Table 5.3 Classification of investigated actors (see also: Heinemann and Herrmann 2013)

Actor	Employees	Main customer branches	Products	Product size	Production type
Alloy supplier	1900	Foundries, automotive	Non-ferrous alloys, aluminium castings	Standard ingots, midsized castings	Large batch production
Foundry 1	2500	Automotive	Aluminium and magnesium castings, aluminium frames and sheets	Midsized/ heavy	Line production
Foundry 2	2900	Automotive	Aluminium and magnesium castings,	Midsized	Line production
Foundry 3	240	Automotive, aerospace, medical, control engineering	Aluminium and zinc castings, injection moulded parts	Light	Small series production

number of employees), main customer branches, products, product size and type of production.

The investigated foundries cover a broad range of possible configurations—ranging from a medium sized foundry with very diversified products, which get produced in a very small series, to a large automotive supplier with a nearly continuous production of a set of relatively few products. All further analyses and evaluations are referenced to a standardised functional unit of 1000 kg of finished aluminium die casted products in order to make the single process chains comparable (see also Sect. 5.4).

5.3.2 Products

The above mentioned variety of actors, which is covered by the objects of investigation, also gets reflected in the diversity of the investigated products. The twelve value chains, which pass through the observed actors, each represent one specific product or one product family (group of products with same operations and differing but similar geometries and alloys). All of them are well-running products, which are produced with first-rate working processes so that the later analysis can be considered as a brown field analysis in a well established production environment. Therefore, easy to achieve improvement potential during ramp-up-phases has already been realised and the value chains should already be configured to produce as profitable as possible.

Table 5.4 offers a short overview over the products, which represent the investigated value chains.

Table 5.4 Selected characteristics of investigated products

Product number/value chain number	Product mass (kg)	Material efficiency (%)	Alloy	Description
1	39.60	52	AlSi9Cu3	Gear box
2	29.56	69	AlSi9Cu3	Engine block
3	1.15	40	AlSi9Cu3	Structural part
4	0.75	47	AlSi12(Fe)	Structural part
5	8.23	63	AlSi9Cu3	Gear box
6	0.10	43	Product families of products with same necessary manufacturing operations and differing but similar geometries and alloys	
7	0.56	58		
8	0.02	10		
9	0.12	44		
10	0.01	9		
11	0.02	33		
12	0.28	56		
Average	6.7	45	AlSi9Cu3	–/–

The observed products and product families are mainly based on the most casted aluminium casting alloy (AlSi9Cu3) or on one of its manifold derivatives. They range from very small products (0.01 kg) to medium sized structural parts (0.75–1.15 kg) to heavy gear boxes (39.60 kg). The material efficiency (here: the ratio from final product mass to shot weight in die casting process) also covers a wide range. Figure 5.7 illustrates the product masses and corresponding material efficiencies, which have been ordered by their final product masses.

The material efficiencies range from 9 to 69 % at an average of 45 %. The trend line over the material efficiencies shows an increase of the material efficiency with increasing product masses. It can be observed that with increasing product volume, the volume of the gating system and remainder do not increase proportionally. Furthermore, the relatively low material efficiency of the lighter observed products is often the result of a relatively high complexity of these products, which demands complex dies to enable the production on standard die casting machines.

Due to this fact, the considered objects of interest—actors and products—offer a broad variety of possible foundries and castings; this setting offers the chance to identify patterns about the generic nature of aluminium die casting.

To achieve this for the introduced objects of investigation, the previously introduced procedural approach for aluminium die casting is pursued in the following section.

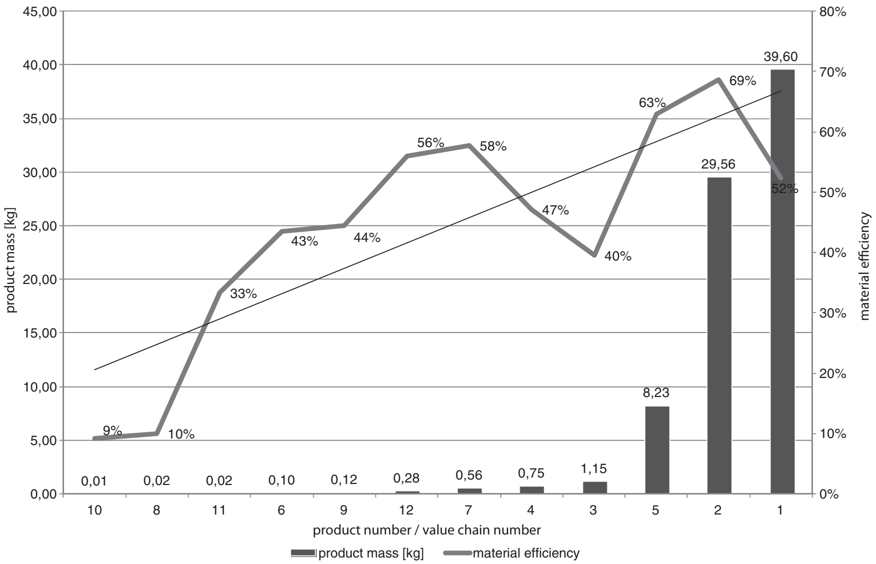


Fig. 5.7 Masses and material efficiencies of investigated products, ordered by product mass

5.4 Definition of System Boundaries

The analyses of the generic aluminium die casting value chain and of its specific representatives examine the transformation of their main input materials under the usage of the main energy carriers into finished products.

The functional unit for the final evaluation is set to 1000 kg of finished aluminium die casted products, which leave the gates of the foundry in order to be shipped to a customer.

The considered main input materials are pure and recycled aluminium as well as alloying elements. The considered main energy carriers are electricity and natural gas.

The considered value chain includes the generation of the mentioned material and energy carrier inputs, the alloy supplier and the foundry (see Fig. 5.8).

The alloy supplier itself in this case is not responsible for the fabrication of primary aluminium from bauxite. However, the environmental impact of these (and further) upstream processes for the material generation will be charged also on the impact of the alloy supplier, as the alloy supplier represents the first step in the focused value chain. By this reason transportation from the alloy supplier to its individual customer is also allocated to the aluminium supplier.

In regards to the considered actors (alloy supplier and foundry), only the value adding processes along the value chain are considered and a selection of directly linked peripheral processes. Therefore, non-value adding and peripheral processes from a low peripheral order (e.g., staff canteen, water treatment) are neglected together with processes from minor relevance for the energy and resource consumption (e.g., conveyor belts, internal transportation). Relevant peripheral processes, which offer potential for improvement (e.g., filtering units, salt treatment and disposal, compressed air generation), are included in the further investigation.

The evaluation criteria for the later comparison of the status quo and of selected improvement measures will be the direct energy intensity at the considered actors alloy supplier and foundry (as the total demanded energy per produced output unit) as well as the global warming potential (in CO_2eq.) along the whole value chain (also including the generation of raw materials and energy carriers). Due to the fact that business decisions at companies like the alloy supplier and the foundry are mainly based on economic data, the energy intensity is chosen as the evaluation criterion here. It can be transformed into financial impacts easily. However, to evaluate the environmental performance and impact of the aluminium

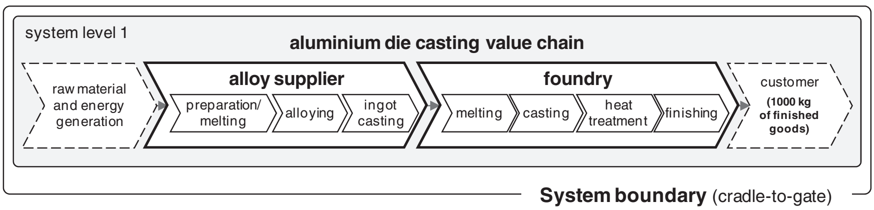


Fig. 5.8 Considered system boundary of the aluminium die casting value chain

die casting value chain, a broader focus should be taken. Therefore, the generation of raw materials and energy carriers is included in the scope of evaluation for the calculation of the global warming potential.

This definition of system boundaries also specifies the focus for the following structural analysis of energy and resource flows. It will also identify the relevant system elements, which process these flows. Therefore, other (non-relevant) system elements, which could be located within the spatial system boundaries as well, are neglected in the further course of the analysis.

5.5 Structural Analysis of Energy and Resource Flows

5.5.1 System Elements

The basic sequence and structure of aluminium die casting along its value chain has already been introduced in Sect. 2.1.2. Based on this description, a corresponding hierarchical framework could be derived (see Sect. 5.2.1). However, this section will provide a more detailed look into the structure of the aforementioned specific objects of investigation to derive a more detailed generic structural model.

A survey among the investigated actors reveals the following configuration of processes along the internal process chains of the alloy supplier and the different foundries, which are depicted in Tables 5.5 and 5.6.

Due to the similarity of the casted alloys of the products (see Sect. 5.3.2), which represent the single value chains, it is assumed that the one observed alloy supplier supplies all subsequent foundries and internal foundry process chains. Therefore, the same alloy supplier process chain (see Fig. 5.9) is used as a reference for the later analysis of the different value chains.

The internal foundry process chains show a more diverse configuration (see Table 5.6).

Not surprisingly, it can be observed that the melting section and the casting section are equipped nearly equally among all die casting value chains regarding the type of installed equipment (at different sizes). There are only minor deviations regarding the removal of the cycle material so that the following general structure can be derived for the melting and casting sections (see Figs. 5.10 and 5.11).

Due to the variety of final product properties (surface quality, functionalities, etc.) the aforementioned diversity within the foundry is mostly determined by the

Table 5.5 Configuration of the internal process chains of the observed alloy supplier

Actor	Section	Process	Product number/value chain number											
			1	2	3	4	5	6	7	8	9	10	11	12
Alloy supplier	Preparation/ melting	Drum melting furnace	x											
		Dross treatment	x											
		Exhaust air filter	x											
	Alloying	Converter	x											
	Ingot casting	Ingot casting	x											

Table 5.6 Configuration of the internal process chains of the observed foundries

Actor	Section	Process	Product number/value chain number											
			1	2	3	4	5	6	7	8	9	10	11	12
Foundry	Melting	Melting furnace	x	x	x	x	x	x	x	x	x	x	x	x
		Exhaust air system	x	x	x	x	x	x	x	x	x	x	x	x
	Casting	Holding furnace	x	x	x	x	x	x	x	x	x	x	x	x
		Die casting machine	x	x	x	x	x	x	x	x	x	x	x	x
		Spraying device	x	x	x	x	x	x	x	x	x	x	x	x
		Tempering units	x	x	x	x	x	x	x	x	x	x	x	x
		Die cutter	x	x	x	x	x	x	x		x	x		x
		Saw		x										
	Finishing	Precision milling		x										
		Vibratory grinding						x	x	x				x
		Drying chamber						x	x	x				x
		Mill									x	x		
		Machining centre		x	x	x			x					
		Drilling station					x							x
		Drill hole quality control		x										
		Abrasive blasting	x	x		x	x				x			
		Ball burnishing										x		
		Exhaust air system for abrasive blasting		x										
		Washer			x	x			x		x			x
		Leakage test		x	x	x								
		Palletising		x										
		Exhaust air system for machining centres			x	x								

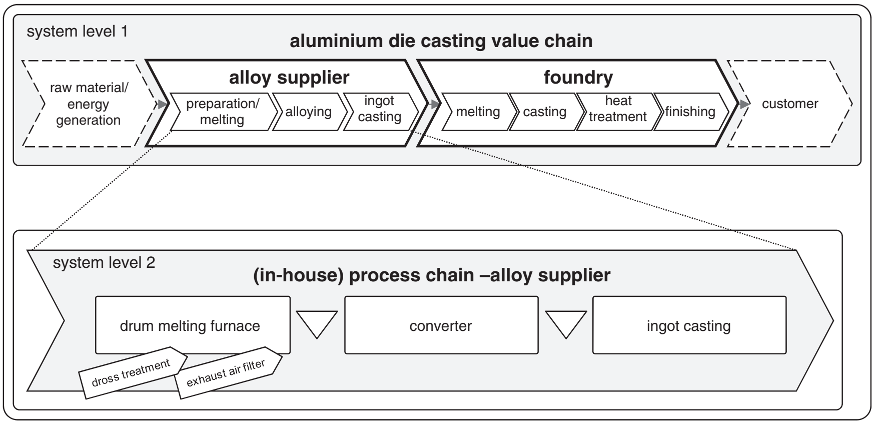


Fig. 5.9 Structure of the observed alloy supplier

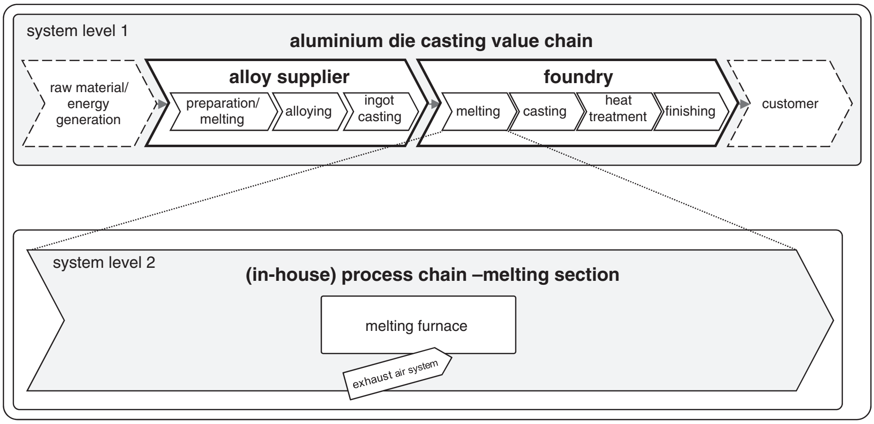


Fig. 5.10 General structure of the melting section within the observed foundries

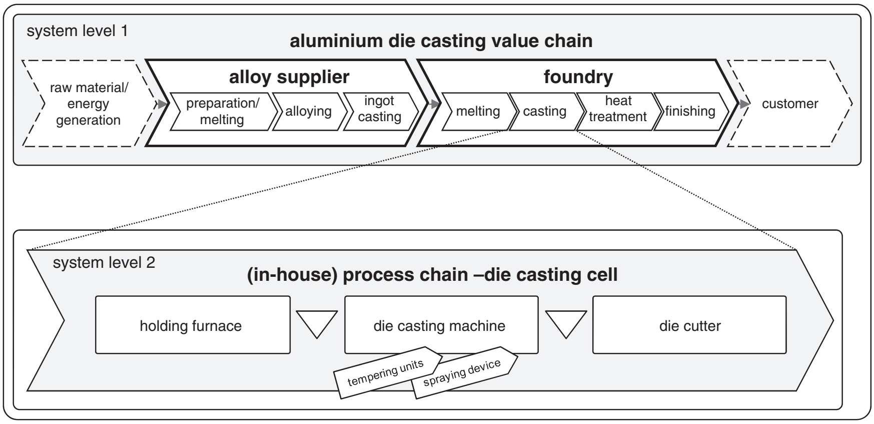


Fig. 5.11 General structure of the casting section (die casting cell) within the observed foundries

diversity of installed processes within the finishing section. There are manifold value adding operations like milling or drilling stations, and peripheral or supporting processes like washers and exhaust air systems. However, these processes can be clustered as follows:

- cutting (milling stations, drilling stations, machining centres, etc.)
- special treatments (washers, drying chambers, etc.)
- checking (leakage test, drill hole quality control, etc.)
- handling (e.g., palletizing)
- filtering (of cooling lubricants)
- cooling
- exhaust air systems

This clustering enables the derivation of a general structure also of the finishing sections of the observed foundries (see Fig. 5.12).

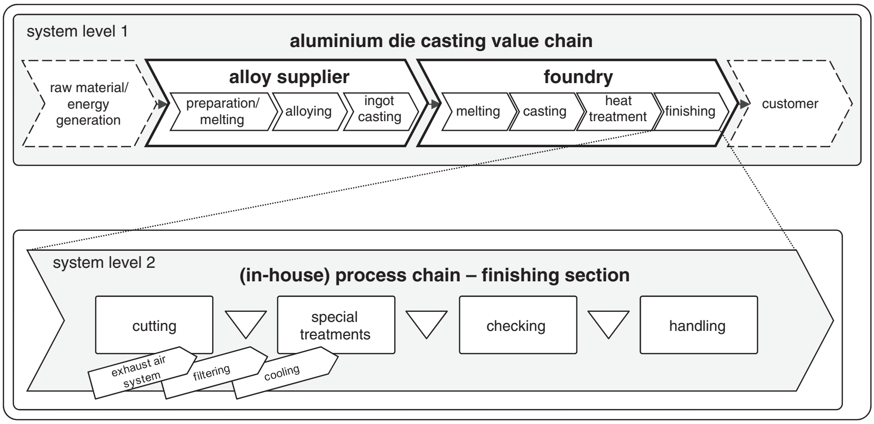


Fig. 5.12 General structure of the finishing section within the observed foundries

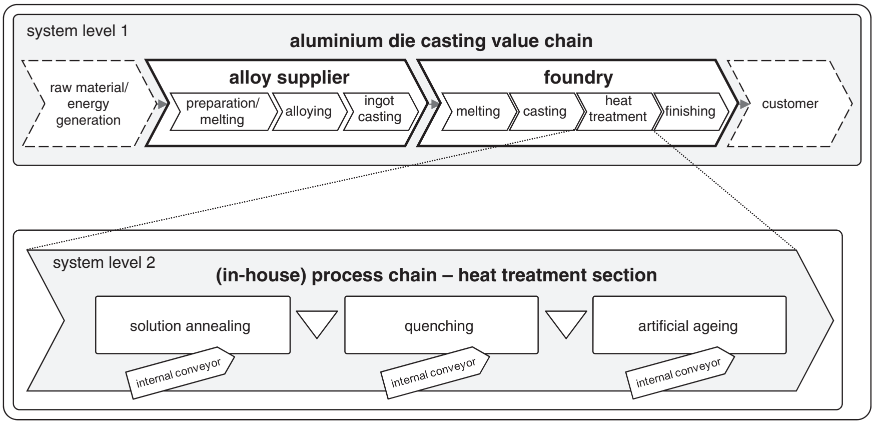


Fig. 5.13 General structure of a heat treatment section within aluminium die casting foundries

Despite the general relevance of heat treatment for many aluminium die casted products (see Sect. 2.1; Koch et al. 2011; Kleine and Heinemann 2013), there are no corresponding operations at the observed foundries. However, to address the relevance of heat treatment, a heat treatment transfer line (conducting a T7 heat treatment process) also gets included in the general structure of the aluminium die casting value chain. As the T7 heat treatment process consists of three different phases, which are usually conducted in individual machines (ovens), the heat treatment section is also structured into the following three parts (which include their own transport system for transferring the parts through the thermo zones and into the next process step) (see also Diener and Janssen 2013). Therefore, the heat treatment section of a die casting foundry can be assumed to have the following structure (see Fig. 5.13).

By linking the above introduced figures about the general structures of in-house process chains, the following structural picture of the overall aluminium die casting value chain can be created (see Fig. 5.14).

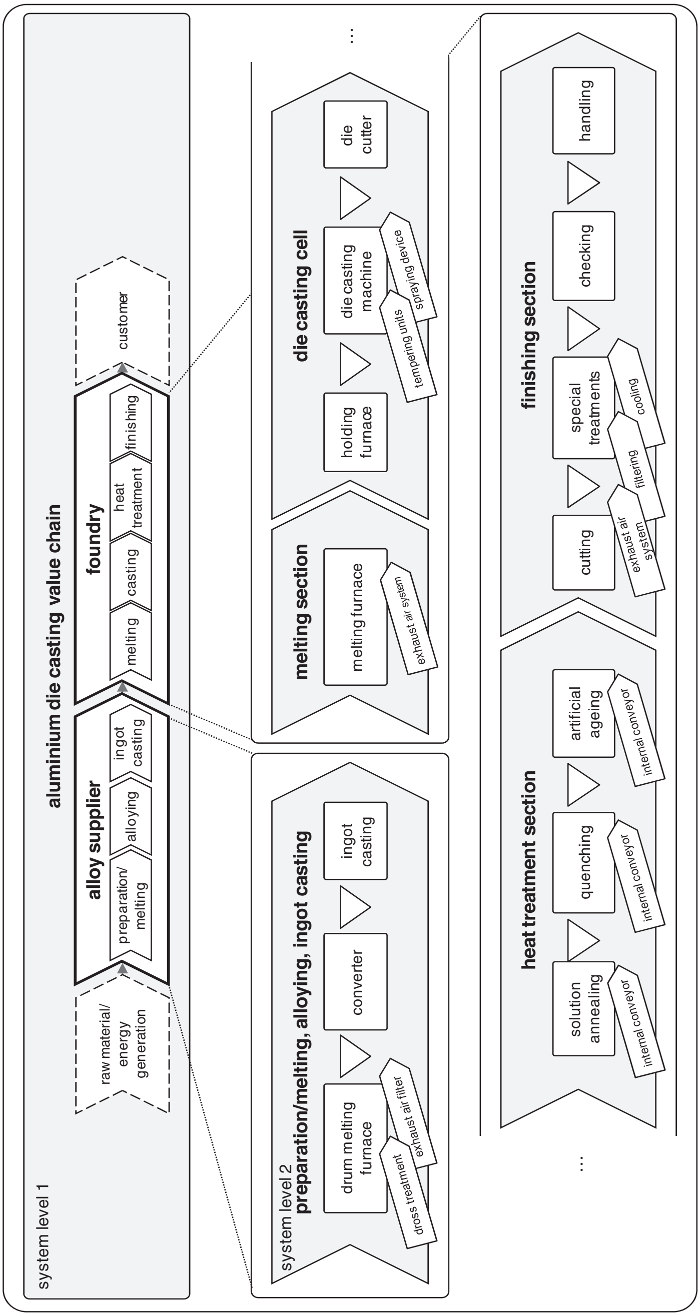


Fig. 5.14 General structure of aluminium die casting value chain

This picture of the general structure of the overall aluminium die casting value chain serves as the basis for the further investigations. It does not aim to include all possible elements of the facilities of a foundry and an alloy supplier. Nevertheless, based on a survey amongst these actors, it includes the most relevant elements, which are linked to the value adding material flow. The following section will enhance this structural analysis with information about the energy and material flows, which pass through the identified system elements.

5.5.2 *Considered Energy and Material Flows*

Against the introduced structure above of the inner system elements of the aluminium die casting value chain, this section introduces the main energy and material input and output flows, which connect these elements with each other or with external upstream processes.

According to the survey amongst the observed actors, the following main input flows from external upstream processes have been named (see Table 5.7).

The value adding transformation of these inputs leads to the following relevant output flows, which have been named by the observed actors (see Table 5.8).

Those given input and output flows are used to model the flow relationships between the single system elements and between the overall value chain and its environment. Of course, there are manifold further input and output flows. However, the following analysis will focus on this selection as it was named to be the most (quantitatively) relevant selection for the investigated actors.

As a preparatory work for the later hierarchical modelling of aluminium die casting, Tables 5.9 and 5.10 allocate the given input and output flows or services to the aforementioned individual system elements. Furthermore, these tables already

Table 5.7 Main input flows into aluminium die casting value chain

Energy carriers	Electricity
	Natural gas
Raw materials	Primary aluminium
	Alloying elements
	Secondary aluminium fractions
Auxiliary materials and services	Salt
	Oxygen
	Nitrogen
	Water
	Release agents
	Transportation

Table 5.8 Main output flows from aluminium die casting value chain

Valuable output	Products
Non valuable output	Emissions
	Salt slag
	Land filled filter dust

Table 5.9 Main energy and material flows per system element and available data sources at actor alloy supplier

Section	Process	Input	Output	Available data sources
Preparation/ melting	Drum melting furnace	• Piled secondary aluminium fractions • Salt • Electricity • Natural gas • Oxygen • Transportation	• Liquid aluminium • Salt slag • Exhaust air	Gas meter, electrical power metering, accounting records, production data
	Dross treatment	• Salt slag • Electricity • Natural gas	• Treated slag	Krone (2000)
	Exhaust air filter	• Exhaust air • Electricity • Transportation and disposal services	• Land filled filter dust • Emissions	Electrical power metering, ecoinvent 2.2 database, (Boin et al. 2000)
Alloying	Converter	• Liquid aluminium • Nitrogen • Alloying elements • Pure (primary) aluminium • Nitrogen • Electricity • Natural gas • Transportation	• Liquid alloyed aluminium • Exhaust air • Slag • Emissions	Gas meter, electrical power metering, accounting records, production data
Ingot casting	Ingot casting	• Liquid alloyed aluminium • Electricity	• Aluminium alloy ingot piles	Gas meter, electrical power metering, production data
	Truck trans-port	• Aluminium alloy ingots • Transportation	• Aluminium alloy ingots • Emissions	Ecoinvent 2.2 database
Auxiliary processes	Electricity provision	• Input for electricity generation (upstream process chain)	• Electricity • Emissions	Ecoinvent 2.2 database
	Natural gas provision	• Input for natural gas generation (upstream process chain)	• Natural gas • Emissions	Ecoinvent 2.2 database
	Salt provision	• Input for NaCl generation (upstream process chain) • Input for KaCl generation (upstream process chain)	• Salt • Emissions	Ecoinvent 2.2 database, (Krone 2000)
	Preparation of secondary aluminium fractions	• Diverse aluminium scrap fractions • Transportation • Electricity	• Piled secondary aluminium fractions	Accounting records, production data, ecoinvent 2.2 database

(continued)

Table 5.9 (continued)

Section	Process	Input	Output	Available data sources
	Provision of alloying elements and auxiliary materials	• Input for generation of pure (primary) aluminium • Input for generation of (pure) alloying elements • Input for generation of nitrogen • Transportation	• Pure (primary) aluminium • Alloying elements • Nitrogen • Emissions	Ecoinvent 2.2 database, accounting records, production data

Table 5.10 Main energy and material flows per system element and available data sources at actor foundry

Section	Process	Input	Output	Available data sources
Melting	Melting furnace	• Aluminium alloy ingots • Natural gas • Electricity	• Liquid aluminium alloy • Dross	Gas meter, electrical power metering, accounting records, production data
	Exhaust air system	• Electricity		Electrical power metering, production data
	Charging of cycle material	• Cycle material • Additional cycle material	• Aluminium alloy ingots • Excess cycle material	Production data, manual counting and weighing of input and output flows
Casting	Holding furnace	• Liquid aluminium alloy • Electricity	• Liquid aluminium alloy	Electrical power metering, production data
	Die casting machine	• Liquid aluminium alloy • Electricity	• Aluminium cast • Aluminium cycle material	Electrical power metering, production data, manual counting and weighing of input and output flows
	Spraying device	• Electricity • Water • Release agents		Electrical power metering, production data
	Tempering units	• Electricity		Electrical power metering, production data
	Die cutter/saw	• Aluminium cast • Electricity	• Semi-finished aluminium cast • Cycle material (gating system, etc.)	Electrical power metering, production data, manual counting and weighing of input and output flows
	Compressed air generation	• Electricity		Electrical power metering, production data

(continued)

Table 5.10 (continued)

Section	Process	Input	Output	Available data sources
Heat treatment	Solution annealing	• Semi-finished aluminium cast • Electricity • Natural gas	• Semi-finished aluminium cast	Theoretical process models (Kleine and Heinemann 2013; Diener and Janssen 2013)
	Quenching	• Semi-finished aluminium cast • Electricity • Natural gas	• Semi-finished aluminium cast	Theoretical process models (Kleine and Heinemann 2013; Diener and Janssen 2013)
	Artificial ageing	• Semi-finished aluminium cast • Electricity • Natural gas	• Semi-finished aluminium cast	Theoretical process models (Kleine and Heinemann 2013; Diener and Janssen 2013)
Finishing	Cutting	• Semi-finished aluminium cast • Electricity	• Semi-finished aluminium cast • Cycle material (swarf)	Electrical power metering, production data, manual counting and weighing of input and output flows
	Special treatments	• Semi-finished aluminium cast • Electricity	• Semi-finished aluminium cast	Electrical power metering, production data, manual counting and weighing of input and output flows
	checking	• Semi-finished aluminium cast • Electricity	• Semi-finished aluminium cast • Cycle material (scrap)	Electrical power metering, production data, manual counting and weighing of input and output flows
	Handling	• Semi-finished aluminium cast • Electricity	• Finished aluminium die casted products	Electrical power metering, production data, manual counting and weighing of input and output flows
	Exhaust air system	• Electricity		Electrical power metering, production data
	Filtering	• Electricity		Electrical power metering, production data
	Cooling	• Electricity		Electrical power metering, production data

(continued)

Table 5.10 (continued)

Section	Process	Input	Output	Available data sources
Auxiliary processes	Electricity provision	• Input for electricity generation (upstream process chain)	• Electricity • Emissions	Ecoinvent 2.2 database
	Natural gas provision	• Input for natural gas generation (upstream process chain)	• Natural gas • Emissions	Ecoinvent 2.2 database
	Water provision	• Input for water generation (upstream process chain)	• Water • Emissions	Ecoinvent 2.2 database
	Release agents	• Water • Release agent base material (neutral mass flow)	• Release agent	Ecoinvent 2.2 database (Dilger et al. 2003)

give a hint about available data sources for further in-depth investigations. For most of the highly dynamic system elements, in depth metering can be done at the observed actors. For system elements or input and output flows, which cannot be metered directly, life cycle inventory databases (like ecoinvent 2.2™) can be used. Accounting records and production data can be acquired from the observed actors to enrich the measured results with contextual information for the later allocation of flows, time studies etc.

Additionally, the different types of data sources also give a hint about the level specific and interacting data acquisition and modelling methods, as they have been introduced in Sect. 5.2.

5.5.3 *Synthesis of a Generic Structural Model*

By linking the introduced system above, elements and individual input and output flows, a first generic, structural model of the energy and resource flows in aluminium die casting can be derived. This model is implemented in the petri net based software Umberto™ (see Sect. 2.2). Due to its hierarchical structure via sub-networks it is feasible to express the hierarchical nature of production as introduced above.

Within the network editor of Umberto™, models can be created with simple and petri net based graphical elements (see Fig. 5.15).

Those graphical elements can be divided into two groups, which can be further specified. Transitions are used to model active system elements, which represent a transformation of input to output flows. They are depicted as rectangles. In the case of additional subordinate system levels, single transactions can also include detailed models of sub-networks. Places represent passive system elements, which

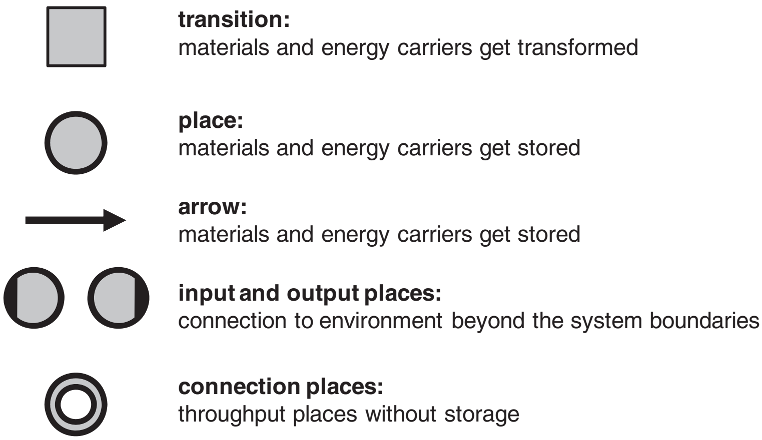


Fig. 5.15 Graphical petri net based notation of system elements and energy as well as material flows within the software Umberto™ (Dyckhoff and Souren 2008)

store materials or energy carriers at a defined state before or after the transformation processes. Places are depicted via circles. Within an energy and material flow network, places get further specified according to their functionality. Input places (or output places) have no predecessors (resp. successors), and represent the network's interface to the environment beyond the system boundary. Usually input and output places are used to integrate the life cycle inventory data from upstream or downstream processes and process chains, which are available from databases like ecoinvent™. Connection places have predecessors and successors and are used to model an energy or material flow between the transactions. The links between places and transitions are modelled with arrows. Arrows represent the logical relation between the petri net's main elements but no real elements of the modelled system (Reisig 2010; Dyckhoff and Souren 2008).

According to the above introduced structural analysis of aluminium die casting, the considered system elements can be modelled via transitions. These transactions transform the identified main energy and material inputs (input places), to intermediate goods (connection places) and finally into products and emissions (output places).

Figure 5.16 shows the resulting, generic structural model of energy and material flows with a focus on system level 1. The actors alloy supplier and foundry get depicted successively. They are modelled by linking their main sections (alloy supplier: preparation, alloying, ingot casting—foundry: smelter, die casting cell, heat treatment, finishing) and supporting processes (e.g., electricity generation, exhaust air filters).

According to the hierarchical perspective on aluminium die casting, the generic models of the individual actor's subsystems (system level 2) will be displayed in the following section with a focus on the value adding aluminium flow. During the later data acquisition phase, these models will be fed with quantifiable information about their internal energy and resource transformation, and about their individual input and output flows.

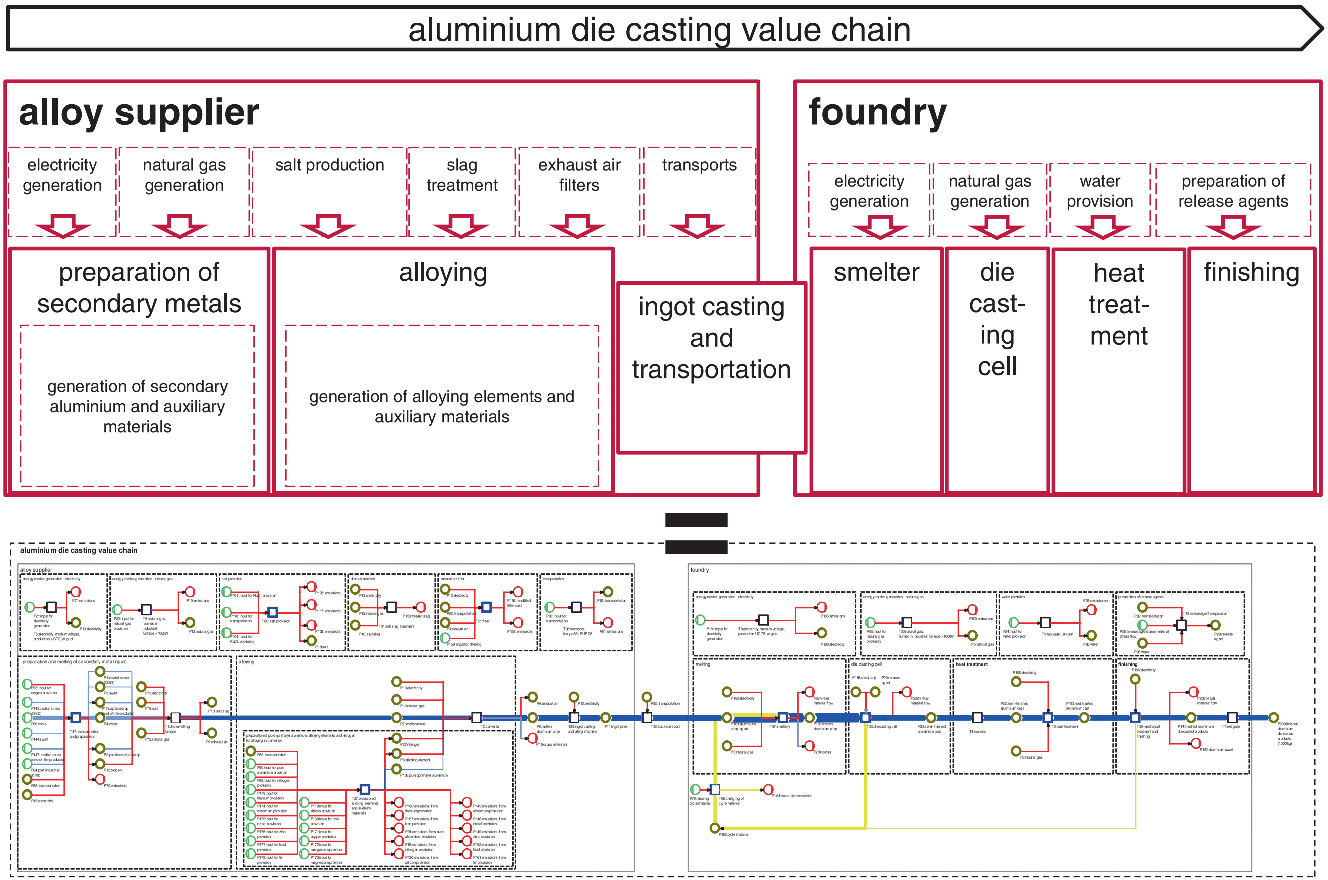


Fig. 5.16 Generic structural model of energy and material flows in aluminium die casting (modelled in Umberto™, see also Heinemann et al. 2013b)

5.5.3.1 Alloy Supplier

At the alloy supplier all sections and processes are modelled, which are necessary to deliver solid or liquid aluminium alloys to the foundry. Therefore, upstream processes for the extraction of primary materials are allocated to the alloy supplier as well (see Sect. 5.4).

The modelled relevant system elements within the alloy supplier are the preparation and the first melting of (secondary) aluminium fractions in the drum melting furnace, the provision of alloying elements and auxiliary materials, the alloying in a converter and the ingot casting and transportation to the foundry.

The generic sub-model for the preparation and melting of secondary metal inputs and auxiliary materials includes the transitions *transportation and preparation* as well as the *drum melting furnace* (see Fig. 5.17).

Within the transition *transportation and preparation*, all recyclable secondary aluminium fractions are collected and prepared (e.g., shredded, piled) for a later melting in the drum melting furnace. In the *drum melting furnace*, the metal fractions get melted and purified by adding salt, which binds impurities and can be extracted as salt slag.

The generic sub-model for the **preparation of alloying elements and alloying in converter** includes the transitions *provision of alloying elements and auxiliary materials* as well as the *converter* (see Fig. 5.18).

Within the transition *provision of alloying elements and auxiliary materials* all necessary primary and secondary alloying elements get prepared, which also includes their necessary extraction and transportation in upstream process chains.

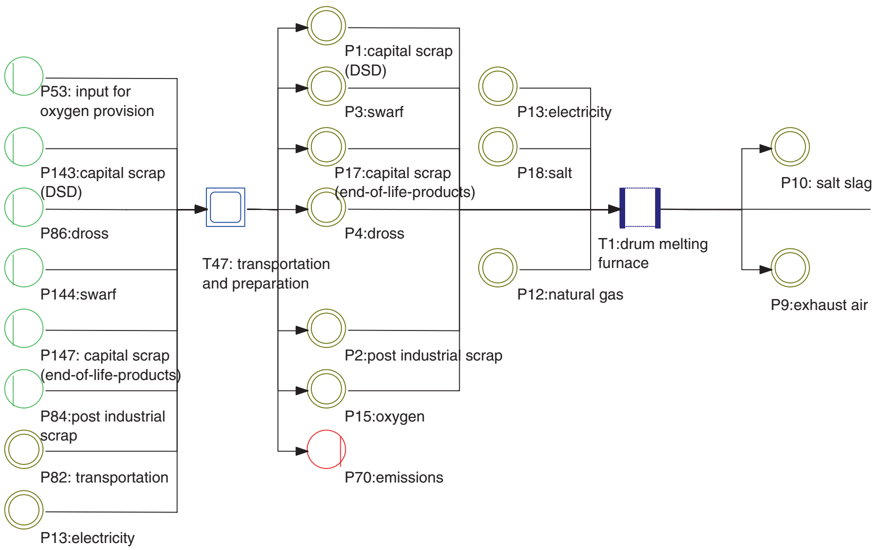


Fig. 5.17 Structural model of transportation, preparation and melting of secondary metal and auxiliary material inputs

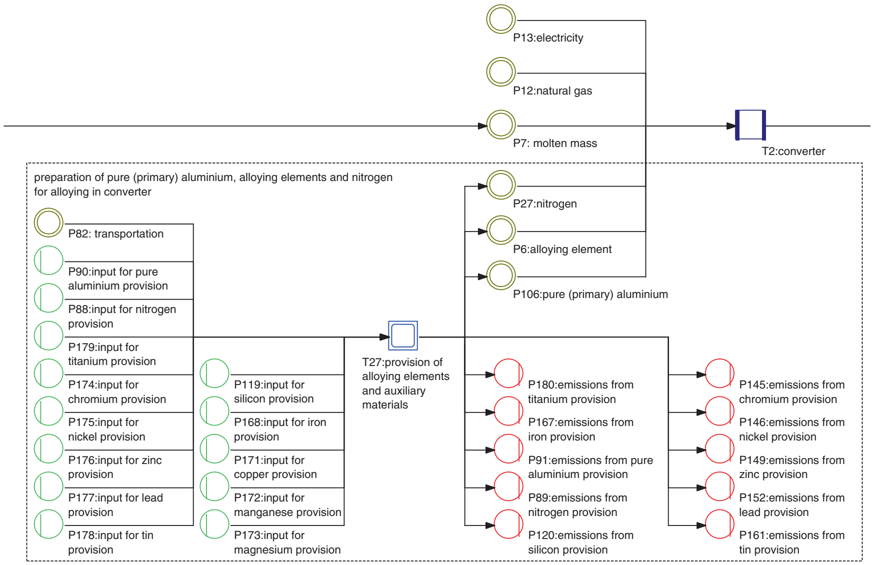


Fig. 5.18 Structural model of preparation of alloying elements and alloying in converter

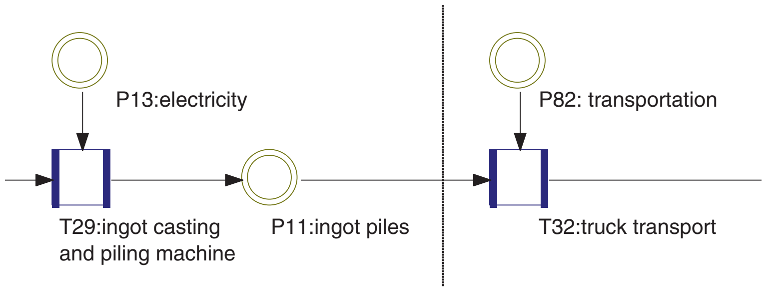


Fig. 5.19 Structural model of ingot casting and transportation

Together with further auxiliary materials, they get charged to adjust the right composition of the molten secondary aluminium fractions for the aimed aluminium alloy. The alloying itself is done in the *converter* oven, in which the molten secondary fractions are blended with the previously prepared alloying elements.

The generic sub-model for the **ingot casting and transportation** includes the transitions *ingot casting and piling machine* as well as the *truck transport* (see Fig. 5.19).

Within the transition *ingot casting and piling machine*, the molten aluminium alloy gets casted into ingot moulds, which get propelled by an electric motor. The solidified ingots then get transported to the alloy supplier's customer (foundry) via the transition *truck transport*.

5.5.3.2 Foundry

At the foundry all sections and processes are modelled, which are necessary to transform the delivered aluminium alloy ingots into final die casted products.

The modelled relevant system elements within the foundry are the smelter, the die casting cell, the heat treatment and the finishing section.

The generic sub-model for the **smelter** represents a sub-network, which includes the transitions *shaft melting furnace* and a peripheral *exhaust air system* (see Fig. 5.20).

Within the transition *shaft melting furnace*, the delivered aluminium alloy ingots get smelted again under the usage of natural gas and electricity. Some amount of aluminium leaves the furnace as dross or gets burned at the molten metal's surface. Besides the aluminium supplies from the alloy supplier, in-house cycle material is also resmelted in the shaft melting furnace. Exhaust air gets extracted under the usage of electricity in the transition *exhaust air system*. Virtual material gets introduced, which connects the shaft melting furnace and the exhaust air system. It is proportional to the amount of molten metal. Thereby, the electricity demand of the exhaust air system, which serves the entire melting section, can be allocated proportionally to the amount of molten metal of the considered object of investigation.

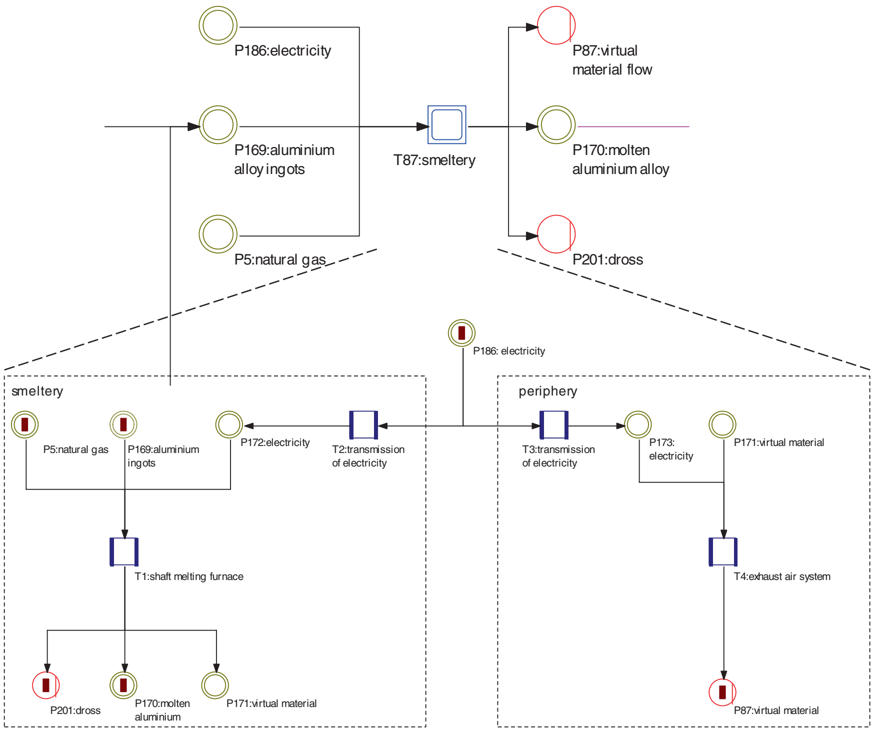


Fig. 5.20 Structural model of the smelter

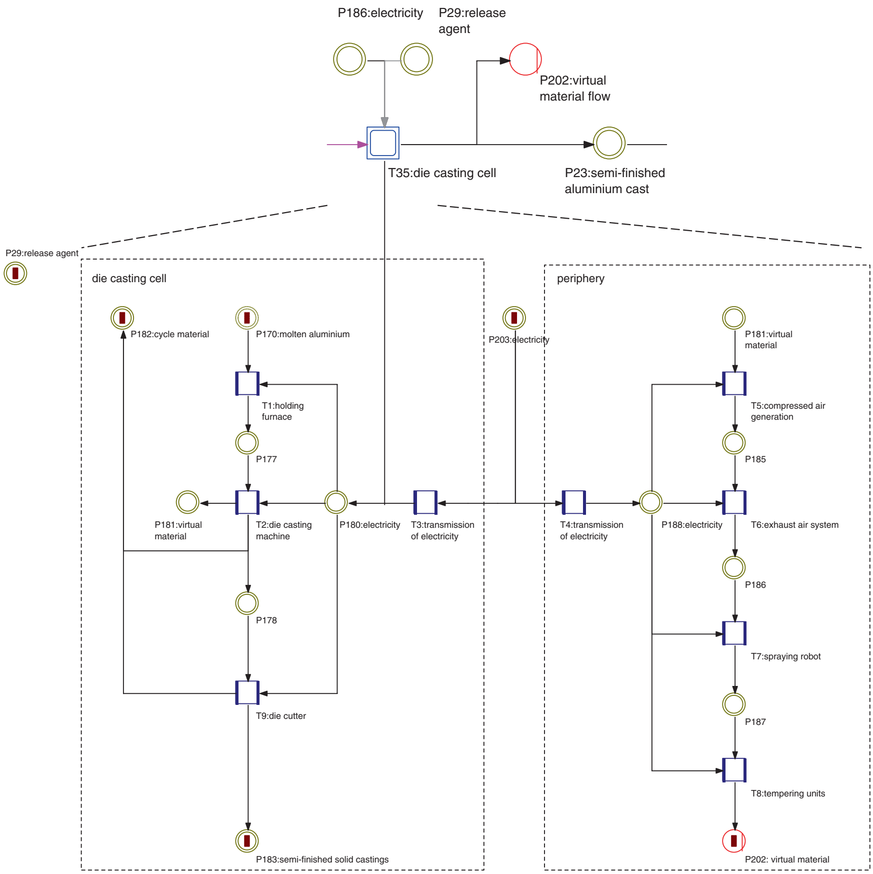


Fig. 5.21 Structural model of the die casting cell

The generic sub-model for the **die casting cell** represents a sub-network, which includes several value adding as well as peripheral transitions (see Fig. 5.21). The value adding transitions include the *holding furnace*, the *die casting machine* as well as the *die cutter*. The peripheral transitions include the *compressed air generation*, the *exhaust air system*, the *spraying robot* as well as the *tempering units*.

Within the transition *holding furnace*, the molten metal from the smelter gets buffered and dosed into the die casting machine under the usage of electricity and compressed air. The *die casting machine* transforms the molten metal into semi-finished solid castings under the usage of electricity, compressed air and release agents.

Gating systems, sprue etc. are stamped off the solid castings in the *die cutter* under the usage of electricity. Therefore, cycle material leaves this transition as an output and gets transferred back to the smelter. A further cycle material flow is created by the die casting machine due to waste parts.

The die casting cell's value adding system elements are supported by the *exhaust air system*, the *spraying robot* and the *tempering units*. The electricity

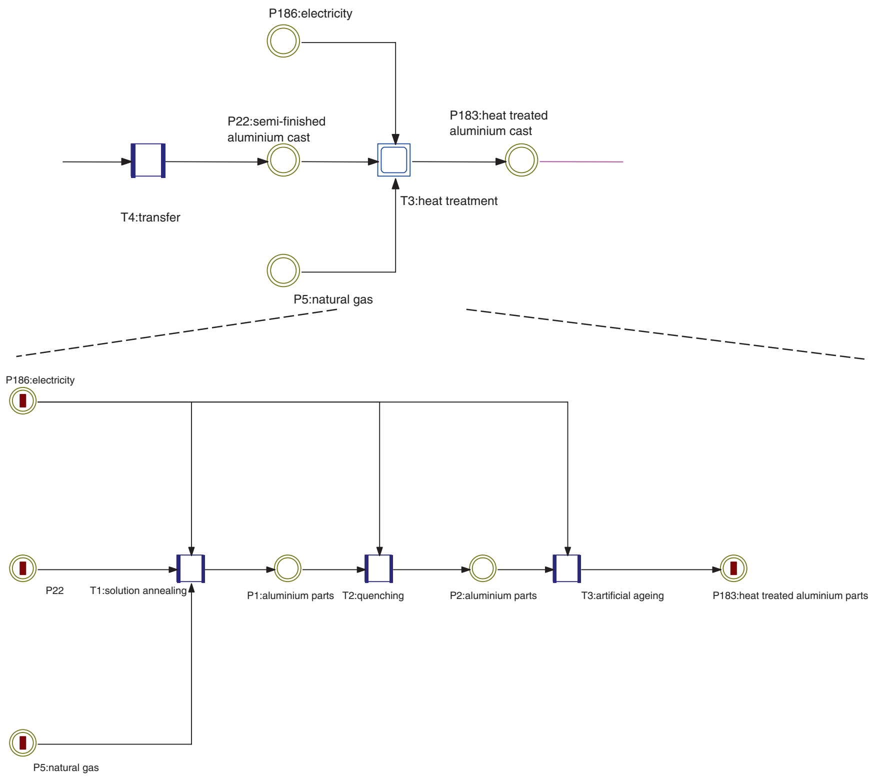


Fig. 5.22 Structural model of the heat treatment section

consumption of these peripheral system elements and of the *compressed air generation* is modelled to be proportional to the die casting machine's metal throughput. Therefore, these transitions are connected to the die casting machine via a virtual material as already introduced for the smelter.

The generic sub-model for the **heat treatment** represents a sub-network, which includes the transitions *solution annealing*, *quenching* and *artificial ageing* (see Fig. 5.22).

The model for the heat treatment section is based on the work of Diener and Janssen (2013) and on further studies within the ProGRess project (Kleine and Heinemann 2013). Therefore, and exceptionally, the three transitions *solution annealing*, *quenching* and *artificial ageing* do not represent individual system elements of aluminium die casting production. However, they represent the three process steps of a T7 heat treatment, which can be interpreted as parts of an industrial heat treatment oven (conveyor belt based transfer line with individual heat zones). The individual heat zones burn natural gas to maintain the required temperature level, to level out heat losses and to heat up the aluminium parts. The parts are moved through the heat zones via an electrically driven transfer line, whose energy consumption is allocated to the solution annealing transition.

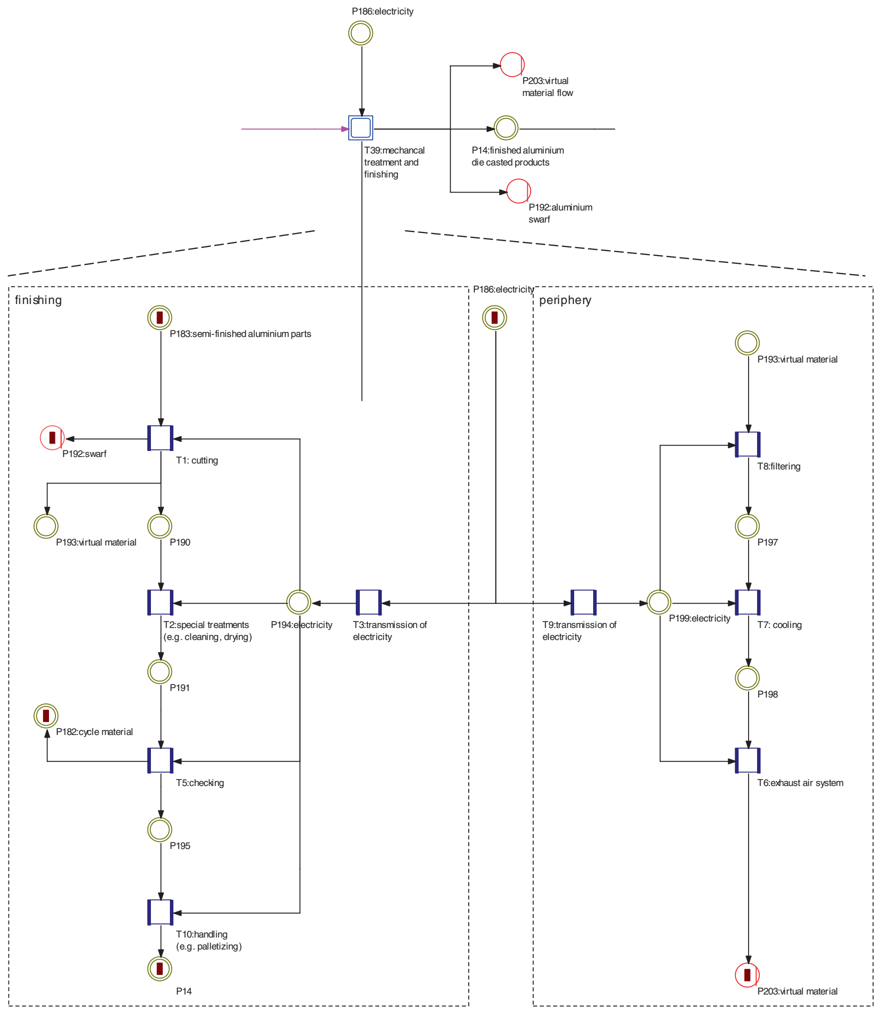


Fig. 5.23 Structural model of the finishing section

The generic sub-model for the **finishing section** represents a sub-network, which includes several value adding as well as peripheral transitions like the die casting cell (see Fig. 5.23).

The value adding transitions include the *cutting*, the *special treatments*, *checking* as well as *handling*. The peripheral transitions include the *filtering*, the cooling, as well as the *exhaust air system*.

Within the transition *cutting* all shape cutting processes are subsumed, which can be integrated in the value chain to generate the final product geometry and functionality. They are working under the usage of electricity. The necessary value adding processes are supported by the transitions *filtering* (of coolant lubricants), *cooling* and the *exhaust air system*, which are working under the usage of electricity as well. The cutting processes generate swarf, which enters the smelter as cycle material.

The subsequent transition *special treatments* subsumes processes, which add further functionalities or ensure certain required properties (e.g., surface quality) without additional cutting (e.g., cleaning, drying).

A *checking* transition subsumes quality surveillance processes. The represented processes demand electricity and sort out scrap parts, which are transferred to the smelter as cycle material.

The remaining flawless and finished aluminium die casted products are palletized in the *handling* transition under the usage of electricity. Afterwards, they leave the factory gate (system boundary) and are shipped to the customer.

During the further course of this analysis the above introduced generic, structural model will be enriched with quantifiable data about the generic energy and resource demands of each system element. Therefore, the above introduced main value adding system elements (transitions) serve to deduce modular blocks, which will be analysed individually regarding their energy and resource demand. Based on these studies, the generic energy and resource demand will be induced for the generic model—based on detailed data acquisition at the presented objects of investigation.

Before the data acquisition starts a hot spot analysis of energy and resource demands will be conducted in the following section. Thereby, the relevance of the above introduced system elements can be validated, and focused system elements for in-depth metering can be identified if necessary.

5.6 Hot Spot Analysis of Energy Demands

During the structural analysis introduced above, the system elements of the aluminium die casting value chain, as well as the main energy and material flows, could be named. This information has been used to create a generic energy and material flow model. This model already has a cross-company scope. It incorporates hierarchical system levels and aims to depict the most relevant system elements. However, the underlying machinery still also needs to be validated to be the most relevant from a quantitative perspective.

Therefore, for each of the observed foundries (representing the twelve observed products) a Pareto analysis of calculated yearly energy demands will be done in the following section. This Pareto analysis follows the application example of Thiede, who analyses the calculatory yearly energy demand of production equipment as a product of nominal load and planned yearly hours of operating service (Thiede 2012). The machinery data (name, nominal load, planned yearly hours of operating service) has been delivered by the observed actors.

Due to the relatively low number and previously denoted less-dynamic behaviour of natural gas demanding system elements, the Pareto analysis concentrates on the electricity demand of the observed system elements within the focussed foundries. Therefore, it helps to identify relevant objects for (electrical) power metering campaigns in foundries. Furthermore, it helps to validate the completeness of the generated structural model. This prioritisation is not necessary for value adding natural gas demanding machines.

5.6.1 Foundry 1 (Products 1 and 2)

Figure 5.24 shows the calculatory yearly energy demands of the production equipment at foundry 1. This foundry and its production equipment are responsible for the production of the observed products 1 and 2. Within Fig. 5.24, the anonymised machinery is sorted by their calculatory energy demands. The anonymised machinery is clustered roughly according to their type in Fig. 5.24.

13 % of the listed machines in foundry 1 account for more than 55 % of the cumulated yearly (calculatory) energy demand. In this group mainly die casting machines, abrasive blasting machines, saws and die cutters can be found. Further relevant machine groups are CNC machining centres, holding furnaces and tempering units. Other machines like robots, leakage detection systems, etc. do not represent the majority of the calculatory energy demand. However, they still contribute to the total energy demand and shall not be neglected.

A comparison of the listed machinery and the system elements of the generic structural aluminium die casting model shows a high amount of overlap. This indicates a correct selection of system elements within the model.

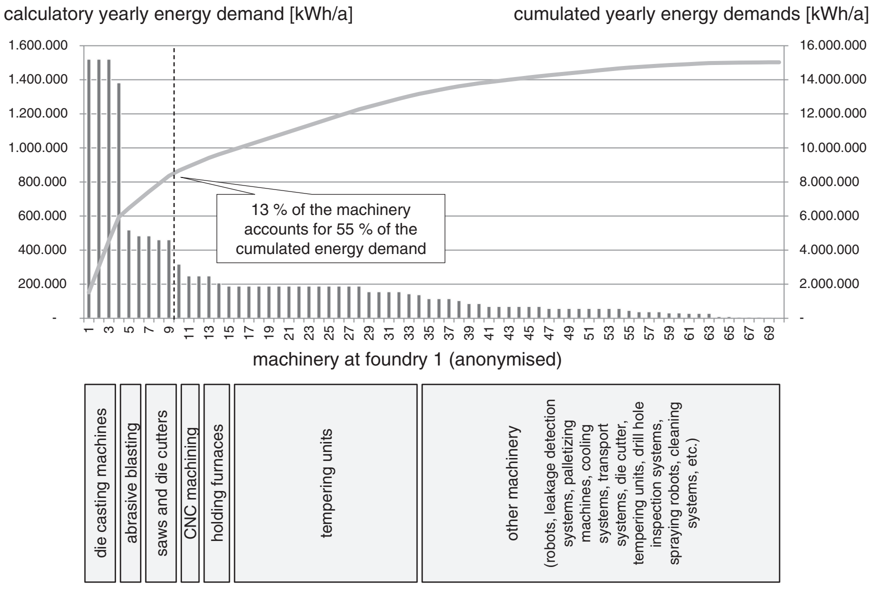


Fig. 5.24 Calculatory yearly energy demands of production equipment in foundry 1

5.6.2 Foundry 2 (Products 3, 4 and 5)

Figure 5.25 shows the calculatory energy demands of the production equipment at foundry 2 which have been extrapolated over one year. This foundry and its production equipment are responsible for the production of the observed products 3, 4 and 5. Within Fig. 5.25, the anonymised machinery is sorted by their calculatory energy demands. The anonymised machinery is clustered roughly according to their type in Fig. 5.25.

13 % of the listed machines in foundry 2 account for more than 50 % of the cumulated yearly (calculatory) energy demand. In this group mainly a cleaning machine, CNC machining centres and die casting machines can be found. Further relevant machine groups are die cutters, lubricant filters and holding furnaces. Other machines like exhaust air systems, cooling systems, further cleaning systems, robots and spraying devices, etc. do not represent the majority of the calculatory energy demand. However, they still contribute to the total energy demand and shall not be neglected.

As with foundry 1, a comparison of the listed machinery and the system elements of the generic structural aluminium die casting model shows a high amount of overlap. This indicates a correct selection of system elements within the model.

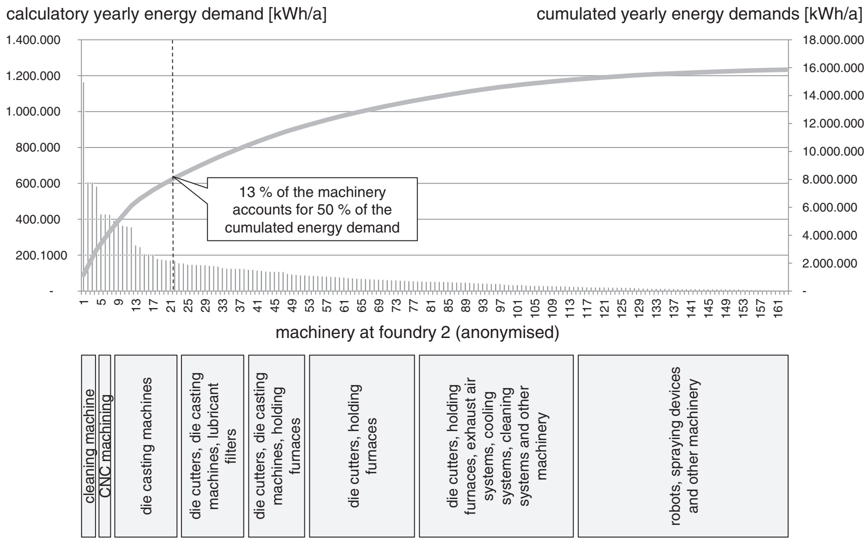


Fig. 5.25 Calculatory energy demands of production equipment in foundry 2, extrapolated for one year

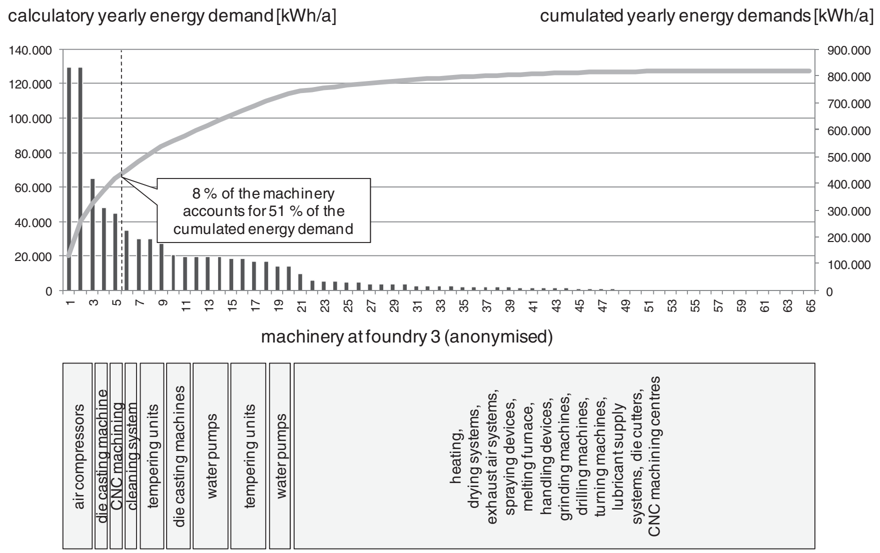


Fig. 5.26 Calculatory yearly energy demands of production equipment in foundry 3

5.6.3 Foundry 3 (Product Families 6–12)

Figure 5.26 shows the calculatory yearly energy demands of the production equipment at foundry 3. This foundry and its production equipment are responsible for the production of a wide range of products, which are clustered in the product families 6–12. Within Fig. 5.26, the anonymised machinery is sorted by its calculatory energy demands. Again, the anonymised machinery is clustered roughly according to its type in Fig. 5.26.

8 % of the listed machines in foundry 3 account for about 50 % of the cumulated yearly (calculatory) energy demand. Besides hot spot machine types which have been identified for foundry 1 and 2 (die casting machines, CNC machining centres), air compressors can also be found in the group of hot spot machines at foundry 3. Further relevant machine groups are cleaning systems, tempering units and water pumps. Other machines like heating systems, drying systems, exhaust air systems, spraying devices, etc., do not represent the majority of the calculatory energy demand. However, they shall not be neglected as mentioned for foundry 1 and 2. Water pumps will be excluded from the further studies as they are out of the scope of the defined system boundaries and of the underlying research project.

5.6.4 Conclusion of Hot Spot Analysis

A comparison of the above identified groups of hot spot machines reveals a recurrent group of highly relevant machines (die casting machines, abrasive blasting machines, saws and die cutters, cleaning machines, CNC machining centres).

Furthermore, other groups of relevant machines can be found (tempering units, holding furnaces, cleaning systems, exhaust air systems lubricant filters, air compressors). These machines are represented well in the generic structural aluminium die casting model (at the actor foundry). This implies that the correct system elements have been selected for modelling and further analysis (regarding the calculatory demand of electrical energy).

The hot spot analysis also revealed that there are numerous less relevant machines within foundries (handling robots, transport systems, etc.), which can be excluded from an aluminium die casting model, without a negative impact on the significance of this model.

Besides the hot spot system elements, natural gas consuming value adding system elements (and their periphery) are also included in the structural model as they represent the transformation of the second main energy carrier within foundries. Due to the fact that these system elements are only few and each represents a high demand of natural gas consumption (see Chap. 2), an additional hot spot analysis is not necessary. By modelling those natural gas demanding system elements in combination with the hot spot elements regarding electricity demand, a profound model of the energy transformation and demand in aluminium die casting foundries can be created. Additionally, the mentioned system elements will be modelled in connection to each other and to their main peripheral system elements.

The data acquisition about the energy and resource (metal) demand of the main system elements will be introduced in the following section. It deduces its fields of action from the generic structural aluminium die casting model, and induces the quantitative composition of the generic model's system elements.

5.7 Data Acquisition

This section introduces the detailed data acquisition at the objects of investigation. This phase builds the foundation for the generation of a generic, quantitative model about energy and resource flows in aluminium die casting. Therefore, the main value adding system elements and selected peripheral system elements will be analysed in the sequence of the value adding aluminium flow. At each value adding system element, an exemplary data acquisition case gets briefly introduced with a focus on the energy carrier and metal demand. This field data, which has been generated directly at the observed actors, will be enriched with other data sources as introduced in Sect. 5.2.2 (e.g., life cycle inventory data bases, corporate production data, resource bills).

5.7.1 Alloy Supplier

At the alloy supplier, the main system elements *preparation and melting of secondary metal inputs*, *alloying* and *ingot casting* have been identified on system level 2. For each of these sections, an overview over the data acquisition regarding data source, quality and exemplary results will be given in the following section.

5.7.1.1 Preparation and Melting of Secondary Metal Inputs

The preparation and melting of secondary inputs represents the first value adding activity within the system boundary of this study. Therefore, it is the interface to the surrounding environment, and most of the metal input volumes enter the system here. These metal volumes are **secondary metal fractions**, which need to be collected, shredded and cleaned. Afterwards they are melted in a **drum melting furnace**, and further impurities of the molten mass are removed under the usage of salt.

The individual shares of the **secondary metal fractions** have been calculated based on the production data and accounting records of the observed alloy supplier. Over an observation period of four months, the following average mass fractions of secondary metal inputs could be counted (see Fig. 5.27).

The composition of secondary metal fractions reflects the two different main sources of secondary aluminium—cycle material out of production processes and end-of-life products (including packaging products). A high share of input material is determined by the dross (50 %). It incorporates a high share of aluminium and gets resmelted before a final treatment (disposal) in order to retrieve the valuable metal contents. Pure aluminium (15 %) can also be a secondary metal input fraction. In this case, it represents end of life products (e.g., wire), which consist of a very low alloyed primary aluminium alloy so that it can be treated as pure aluminium.

The metal fractions get melted in a **drum melting furnace**. The natural gas demand has been detected through low resolution metering with a gas flow meter. Figure 5.28 shows a sample profile of the natural gas demand per output unit of a drum melting furnace over four months.

The natural gas demand is fluctuating very low within a small bandwidth. The small fluctuations depend on the varying composition of the charged materials, as

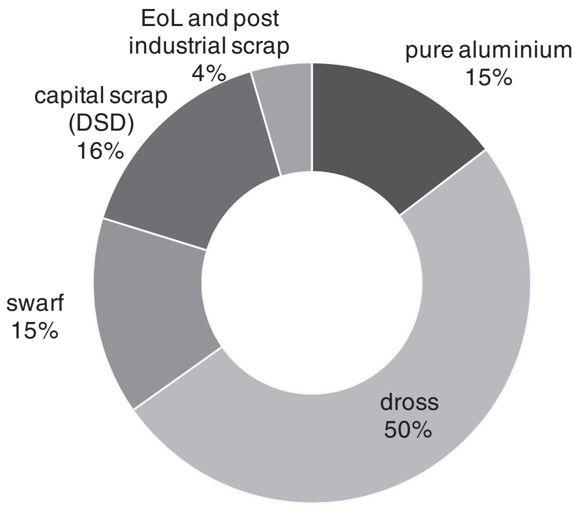


Fig. 5.27 Mass fractions of secondary metal inputs at the alloy supplier; documented from accounting records, observation period: four months

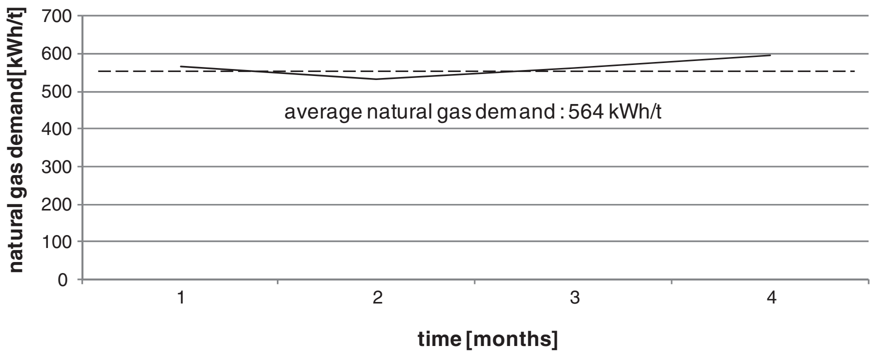


Fig. 5.28 Sample natural gas demand of a drum melting furnace per tonne of molten aluminium output, metered with a gas flow meter, resolution: 1 month

Table 5.11 Average input and output flows of the drum melting furnace per tonne of molten aluminium output

Input	Natural gas	564 kWh
	Oxygen	0.14 t
	Salt	0.57 t
	Secondary metal fractions	1.46 t
Output	Molten aluminium output	1.00 t
	Salt slag	1.03 t

these different materials have different melting points as well. Over an observation period of four months, an average of 564 kWh/t of molten aluminium output could be documented.

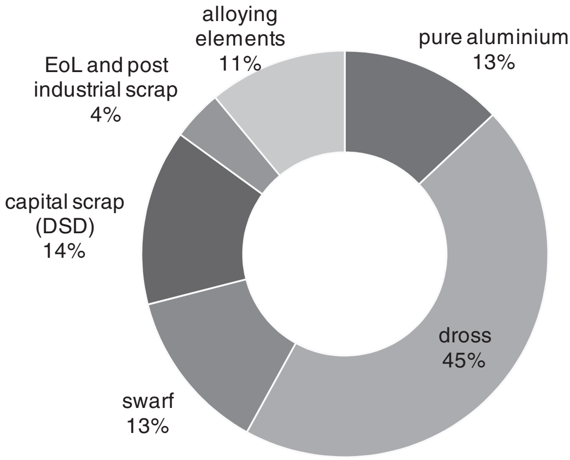
Over the same observation period the following energy and material flows per tonne of molten aluminium output could be documented as well for the drum melting furnace (see Table 5.11). The high amount of salt slag (dross) output corresponds to the high share of dross input and represents a variant of cycle material, in which aluminium is ligated internally.

5.7.1.2 Alloying

The previously introduced preparation and melting of secondary metal inputs creates the basis metal input to the adjacent alloying section. The **provision of alloying elements and auxiliary materials** describes further input flows, which enter the system here and are added to the metal flow in the **converter**.

The individual shares of the **alloying elements and auxiliary materials** have been calculated based on the production data and accounting records of the observed alloy supplier. Over an observation period of four months, the alloying elements add the following average share to the mass fractions of secondary metal inputs, which have been documented above (see Fig. 5.29).

Fig. 5.29 Mass fractions of secondary metal inputs and alloying elements at the alloy supplier, documented from accounting records, observation period: four months



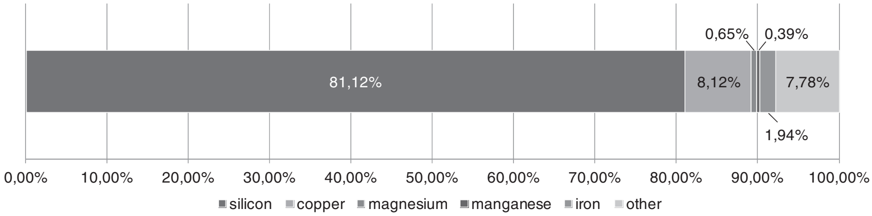


Fig. 5.30 Demand of the main alloying elements as share of total alloying element input, documented from accounting records, observation period: four months

Thus, alloying elements can add up to 11 % of the overall metal inputs of the alloy supplier. Depending on the aimed alloy these alloying elements can vary. Figure 5.30 shows the demand of the five main alloying elements over an observation period of four months.

The main alloying element is silicon with a share of 81 %. The five main alloying elements add up to an average of 92 % of the total inserted alloying elements. The missing percentages are varying compositions of diverse further alloying elements and primary aluminium ingots.

The alloying elements get combined with the previously molten secondary metal fractions in a **converter**. The natural gas demand of the converter has been detected through low resolution metering with a gas flow meter. Figure 5.31 shows a sample profile of the natural gas demand per output unit of a converter over four months.

Over the observation period of four months, an average of 634 kWh/t of molten aluminium output could be documented.

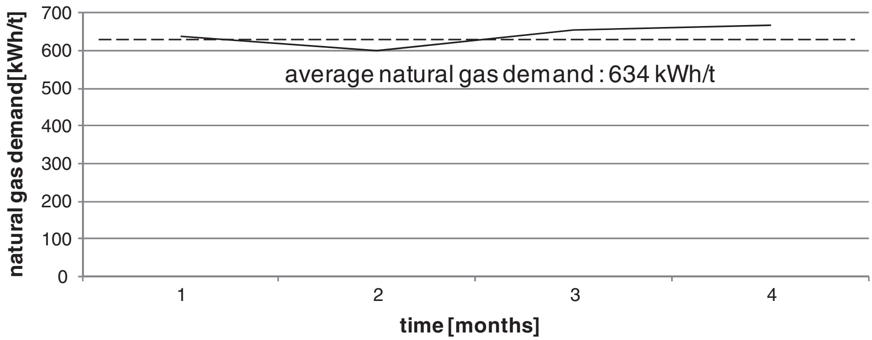


Fig. 5.31 Sample natural gas demand of a converter per tonne of molten aluminium output, metered with a gas flow meter, resolution: 1 month

5.7.2 Foundry

At the foundry, the main system elements *smelter, die casting cell*, *heat treatment* and *finishing* have been identified on system level 2. For each of these sections, an overview over the data acquisition regarding data source, quality and exemplary results will be given in the following section.

5.7.2.1 Smelter

The melting of the aluminium alloy ingots, which have been delivered by the alloy supplier, is the first value adding activity at the foundry. The smelter contains manifold melting furnaces and some peripheral equipment (esp. exhaust air systems). However, the energy and resource demand profiles within this section can be classified as less-dynamic in comparison with others.

The melting of aluminium ingots usually gets done in a **shaft melting furnace**, in which hot exhaust gas flows are used to preheat the ingots. The natural gas demand of the shaft melting furnace has been detected through low resolution metering with a gas flow meter. Due to its less-dynamic behaviour, the electrical energy demand period has also been detected through low resolution metering with electricity meters. The material in- and output flows have been taken from accounting records and production data. Table 5.12 shows the results of this data gathering regarding energy carrier demands and material in- and output flows at the shaft melting furnace.

The main energy carrier at the shaft melting furnace is natural gas—here with an average demand of 714.7 kWh/t of molten aluminium output. The natural gas is used for the generation of heat to melt the aluminium ingots. The electrical energy demand mainly results from the installed hydraulic pumps, which tilt the whole furnace in order to discharge the molten aluminium from the smelting chamber. About 2 % of the aluminium input gets lost as melting loss or ligated into dross

Table 5.12 Average input and output flows of the shaft melting furnace per tonne of molten aluminium output

Input	Natural gas	714.7 kWh
	Electrical energy	3.8 kWh
	Aluminium alloy ingots and cycle material	1.022 t
Output	Molten aluminium output	1.00 t
	Dross and melting loss	0.02 t

so that 1.02 t of input material are necessary to generate 1 t of molten aluminium output.

An important peripheral process of the smelter is the **exhaust air system**, as massive amounts of natural gas get burned, and dust resulting from the melting losses needs to be extracted from the melting area. Usually, there is one centralised exhaust air system, which extracts the exhaust air flows from the diverse furnaces in the smelting section. For the above described shaft melting furnace, the corresponding exhaust air system has a quasi-constant electrical power demand of ca. 93 kW (see also Fig. 5.35), which has been detected through high resolution electrical power metering with a ChauvinArnaux 8335 measurement device. It serves twelve melting furnaces with different melting capacities. In the case of product 4 of this study, 13.63 % of the installed melting capacity of foundry 2 is allocated to this product. Thus, the same share of the electrical power demand of the exhaust air system is allocated to this product as well. Thereby, for the creation of 1 t of molten aluminium output for this product, an extra electrical energy demand of 8.5 kWh can be documented due to the allocated share of electrical energy demand from the exhaust air system.

5.7.2.2 Die Casting Cell

The die casting cell incorporates the most main value adding, as well as most complex and diverse, processes within the aluminium die casting value chain. Using examples from different value chains, for each of the main value adding and peripheral processes the data acquisition gets introduced briefly in the following section. Additionally, typical data acquisition results get introduced exemplarily.

The dynamic electrical energy demand of all observed **holding furnaces** has been detected through high resolution electrical power measuring with a ChauvinArnaux 8335 measurement device and parallel time studies. Figure 5.32 shows a sample load profile of the effective electrical power demand of a holding furnace over several machine cycles of the associated die casting machine. The average power demand here is 11.7 kW.

The power demand of the holding furnace is independent from the die casting machines' machine cycle. It depends on the temperature level of the internal molten aluminium and on the frequency of aluminium replenishments. Here the

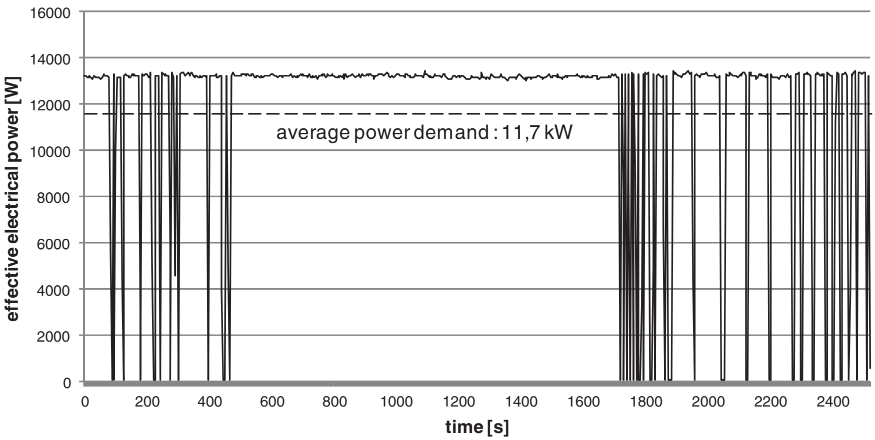


Fig. 5.32 Sample load profile (electrical power) of a holding furnace, measured with a ChauvinArnaux 8335, resolution: 4s

set temperature is 690°C. The holding furnace demands electrical power input, when the actual temperature is below this temperature level and needs to be heated up. If the set temperature level is achieved, the heating elements of the holding furnace shut off until further heating is needed. Due to its independent and relatively stable load profile, the holding furnace's power demand is assumed to be constant at a level of 11.7 kW (here).

The input and output of liquid aluminium into the die casting machine can be detected by the oven control system and read off the screen. As losses due to oxidation are negligible in holding furnaces, the mass of liquid aluminium input and output per casted product unit in this exemplary case is 68.0 kg. Due to the fact that holding furnaces get replenished batch wise, the input batch of liquid aluminium contains multiple times the input mass per product unit.

At the **die casting machine** the input of liquid aluminium from the preceding holding furnace can be directly adopted from the holding furnaces' documented output (here: 68.0 kg). Besides minor, negligible material losses (flitter) the output aluminium mass (shot weight) can be assumed to be equal to the input mass (here: 68.0 kg).

The dynamic electrical energy demand of all observed die casting machines has been detected through high resolution electrical power metering with a ChauvinArnaux 8335 measurement device and parallel time studies. During the power metering the individual machine status as well as its duration and the machine's output (flawless and defect parts) have been documented. Figure 5.33 shows a sample load profile of the effective electrical power demand of a die casting machine and an additional assignment of one single machine cycle, in which one aluminium part has been casted. The single machine cycle is sub-divided into a productive and a non-productive (idle) part.

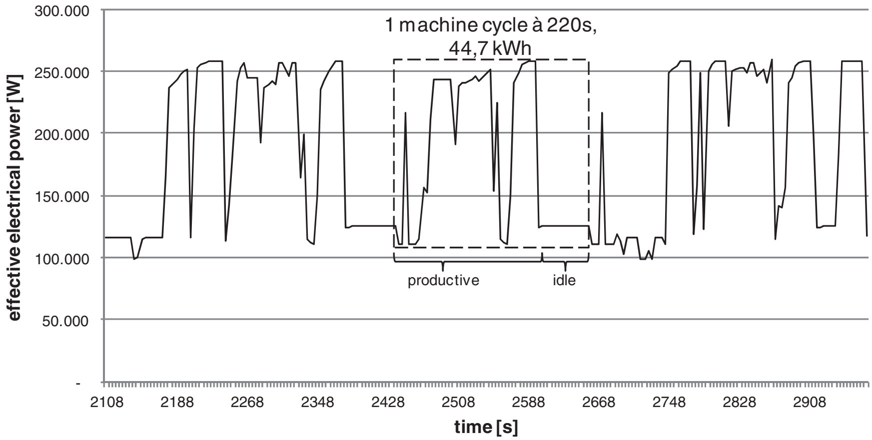


Fig. 5.33 Sample load profile (electrical power) of a die casting machine, metered with a ChauvinArnaux 8335, resolution: 4s

By using the average power load and the average cycle time of manifold machine cycles, the average energy demand during one machine cycle can be calculated (here: 44.7 kWh). In the case of single product dies, which produce one part per machine cycle, the calculated energy demand per machine cycle represents also the energy demand for the casting of one aluminium part. The sub-division of machine cycles into productive and idle parts helps for the later application of dynamic process chain simulation approaches.

The dynamic electrical energy demand of all observed **die cutters** has been detected through high resolution electrical power metering and parallel time studies as well. During the power metering the individual machine status as well as its duration and the machine's output (cycle material and product related material) have been documented. Figure 5.34 shows a sample load profile of the effective electrical power demand of a die cutter and an additional assignment of one single machine cycle, in which the gating system of one aluminium cast has been stamped off. The single machine cycle is sub-divided into a productive and a non-productive (idle) part.

Like for the die casting machine, the average electrical energy demand for one die cutter's machine cycle can be calculated as product of average cycle time and average power demand (here: 0.092 kWh).

The aluminium input and output of the die cutters has been counted and weighed during the power metering. The share of cycle material and product-related output has been determined by manual weighing. By doing so, the material efficiency of the die casting process could be calculated as the quotient of product-related material weight (without cycle material) and shot weight. Here, 68.0 kg of material input (aluminium cast) has been separated into 39.6 kg of product-related material (semi-finished solid castings) and 28.4 kg of cycle material. Thereby, the material efficiency of the die casting cell is 58.2 %.

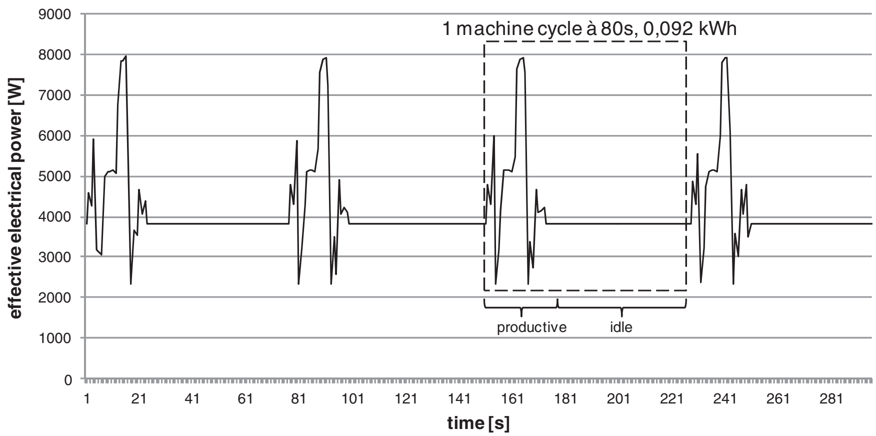


Fig. 5.34 Sample load profile (electrical power) of a die cutter, metered with a ChauvinArnaux 8335, resolution: 1s

An important peripheral process of a die casting cell is **compressed air generation.** As the compressed air gets generated within the system boundary, it is less important to analyse the dynamic compressed air demand itself. It is more important to investigate the electrical energy demand, which results from the compressed air generation. Therefore, the compressed air demand of all die casting cell has been metered with flow meters and translated into an energy demand of the supplying air compressors. The manufacturers of air compressors provide data about the specific electrical energy demand per generated volume unit of compressed air at a certain pressure level (here: 0.11 kWh/m^3 at a pressure level of 6 bar). With this information, a metered compressed air flow can be translated into a resulting energy demand. Exemplary metering at a die casting cell during 31 die casting machine cycles (using a double product die) has documented a compressed air demand of 131 m^3. Thus, 2.11 m^3 have been used to create one single cast, which results in energy demand of 0.23 kWh at the supplying compressed air generators.

Another peripheral system, which serves many die casting cells in parallel, is the **exhaust air system**. The dynamic electrical energy demand of all observed exhaust air systems has been detected through high resolution electrical power metering. Figure 5.35 shows a sample load profile of the effective electrical power demand of an exhaust air system.

The metered sample exhaust air system shows a quasi-constant electrical power demand (here with an average of 14.5 kW), which does not show any dependencies or interactions with the served machinery of the die casting cell. The exhaust air system is working without interruptions if the die casting cell is operating as well. Therefore, the energy demand per product unit can be calculated as product of average power demand of the exhaust air system and average cycle time of the die casting machine. If one exhaust air system serves multiple (identical) die casting cells, the calculated energy demand has to be divided by the number of served cells.

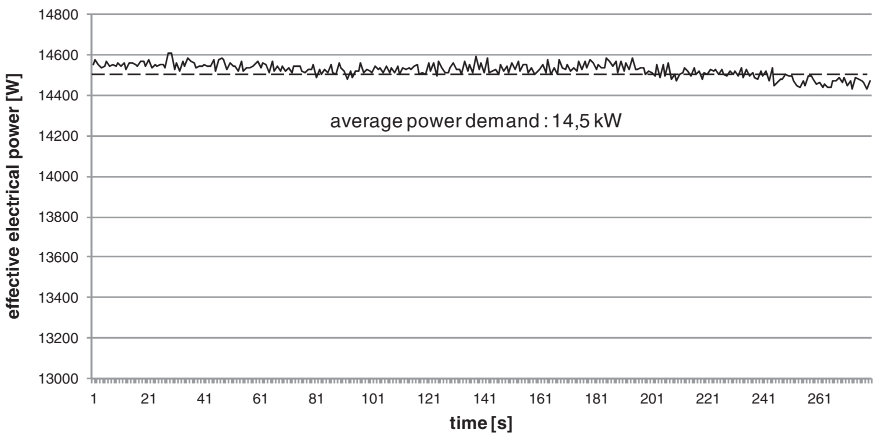


Fig. 5.35 Sample load profile (electrical power) of an exhaust air system, metered with a ChauvinArnaux 8335, resolution: 1s

In contrast to the compressed air generation and the exhaust air system, the **spraying (and removal) robots** are directly linked to single die casting cells and serve only single die casting machines. Via a large share of the above introduced compressed air flow and under the usage of water, spraying robots coat the dies of the die casting machines with release agents. The electricity demand of all spraying robots, which mainly derives from the robots' drives, has been detected through high resolution electrical power metering with parallel time studies. The water and release agent demand has been taken from production data and replenishment records.

Figure 5.36 shows a sample load profile of the effective electrical power demand of a spraying robot and an additional assignment of one single machine cycle, in which one aluminium part has been casted. The single machine cycle is sub-divided into a productive and a non-productive (idle) part.

By using the average power load and the average cycle time of manifold machine cycles, the average energy demand during one machine cycle can be calculated (here: 0.01 kWh).

The release agents within the spraying robot get replenished batch wise as a mixture of water and release agent concentrate. Thereby, the input of water and release agents per cast can be calculated based on the replenishment frequency, the amount of water and concentrate per replenishment and the number of produced casts between two replenishments. Thus, in the metered example, 42.3 g water and 2.5 g release agent concentrate are necessary to produce one cast.[5]

[5]Later, the release agent concentrate will be modelled as an impact-neutral mass flow. Thus, the upstream process chain for the generation of this concentrate is out of the scope of this study. However, this mass flow gets considered as possible later improvement measures have an impact on it and, thereby, can induce secondary positive effects on the overall energy consumption (e.g., due to reduced compressed air demands for the application of release agents).

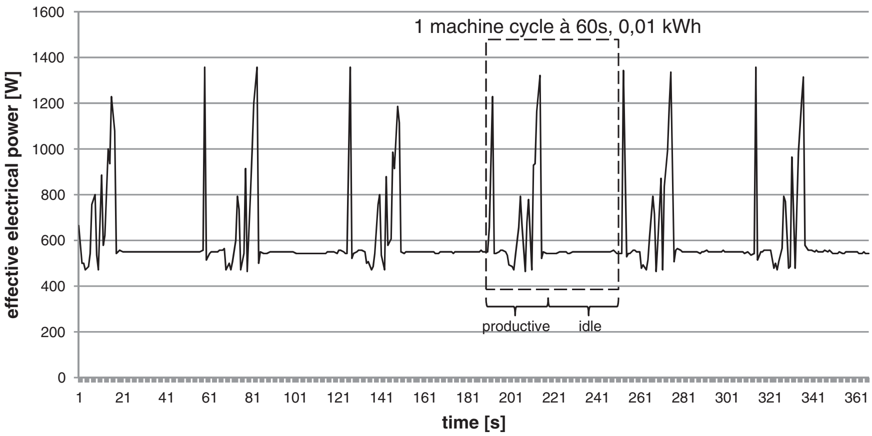


Fig. 5.36 Sample load profile (electrical power) of a spraying robot, metered with a ChauvinArnaux 8335, resolution: 1s

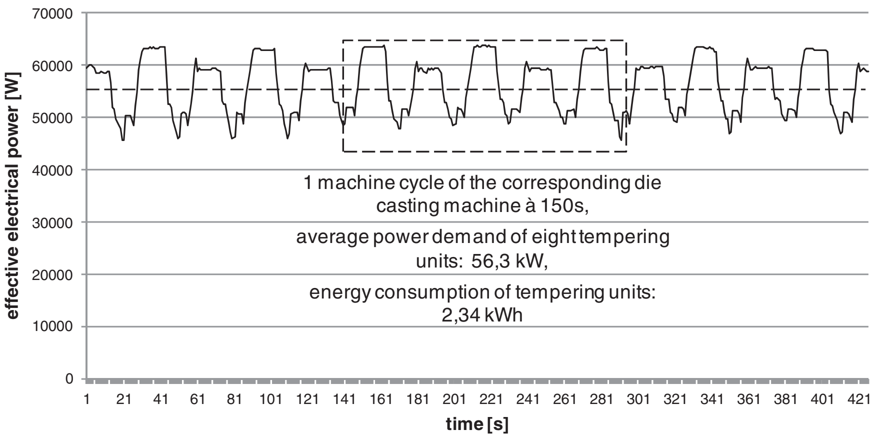


Fig. 5.37 Sample load profile (electrical power) of eight tempering units, metered with a ChauvinArnaux 8335, resolution: 1s

Similar to the spraying robot, the **tempering units** serve only single die casting cells. Multiple tempering units can be installed in one cell and control the temperature of the dies. The dynamic electrical energy demand of all observed tempering units has been detected through high resolution electrical power metering and parallel time studies. Figure 5.37 shows a sample load profile of the effective electrical power demand of eight joint tempering units, which serve one single die casting machine.

The metered tempering units show a cyclic behaviour, in which their internal heater circuits switch on and off periodically. This periodical behaviour is linked to the machine cycle of the die casting cell. The periodic filling of molten metal into the die and the withdrawal of casts out of the die cause a periodic deviation from the set target temperature, which determines the activity of the temperature controlling tempering units. The average power demand of the eight tempering units here is 56.3 kW. Thus, the energy consumption of the tempering units during one machine cycle of the die casting machine is 2.34 kWh.

5.7.2.3 Heat Treatment

Along the selected observed die casting value chains, no heat treatment ovens have been installed. However, as stated above, it has been decided to include heat treatment operations in the study of this book and in the resulting energy and material flow model as it is an important process for aluminium die casting in general. Therefore, the data acquisition for this section builds upon the work of Kleine and Heinemann as well as of Diener and Janssen (Kleine and Heinemann 2013; Diener and Janssen 2013).

Diener and Janssen have created a theoretical model about the energy demand of industrial heat treatment transfer line. This model integrates models of the temperature dependent specific heat capacities of the heat treatment transfer line (including its shell, subcomponents and internal products), of its electrical drives and of its heat losses during operation. Here, the heat generation is done by burning natural gas (solution annealing) and under the usage of electrical energy (artificial ageing).

Kleine and Heinemann have conducted experiments on the energy saving potential of parameter variations of a T7 heat treatment process under laboratory conditions. The relative saving potential, which could be documented from these experiments, has been translated into the saving potential of an industrial heat treatment transfer line by using the model of Diener and Janssen (see also Sect. 5.10).

According to this model, the following input and output flows can be assumed for the T7 heat treatment of 1 t of aluminium products (see Table 5.13).

5.7.2.4 Finishing Section

The choice of possible manufacturing operations in the finishing section is manifold. In contrast to the die casting cell, there are no typical machine types, which can be found in every die casting value chain. However, according to the clusters

Table 5.13 Calculated input and output flows of an industrial heat treatment transfer line per tonne of treated aluminium products

Input	Natural gas	178.2 kWh
	Electrical energy	152.1 kWh
	Aluminium products	1.00 t
Output	Heat treated aluminium products	1.00 t

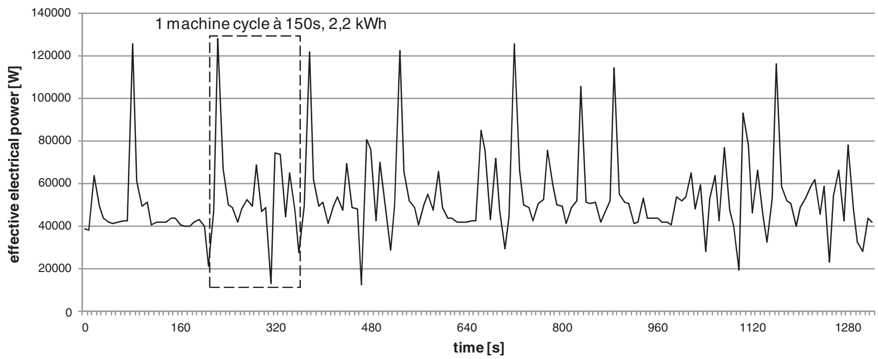


Fig. 5.38 Sample load profile (electrical power) of a CNC machining centre, metered with a ChauvinArnaux 8335, resolution: 8s

of relevant machine groups, which have been identified in Sect. 5.5.1, sample data acquisition results for each cluster will be introduced in the following section.

Popular value adding operations in the finishing section are **cutting** processes. The dynamic electrical energy demand of all relevant observed machines, which performed cutting processes, has been detected through high resolution electrical power metering with a ChauvinArnaux 8335 measurement device and parallel time studies. Figure 5.38 shows a sample load profile of the effective electrical power demand of a CNC machining centre.

During one machine cycle, CNC machining centres can perform multiple operations to one work piece. Here, during one machine cycle of 150 s drill holes and functional surfaces get manufactured in the observed machine. The machining centre has an average electrical power demand of 53.0 kW to perform these operations to one semi-finished aluminium part. Thus, the energy demand for one average machine cycle is 2.2 kWh.

The cluster of **special treatments** unites processes, which contribute to the value of the product but cannot be assigned to a single group of manufacturing processes due to their diversity among the aluminium die casting industry. The dynamic electrical energy demand of all relevant special treatment machines has been detected through high resolution electrical power metering with a ChauvinArnaux 8335 measurement device and parallel time studies. As representatives of this cluster, an abrasive blasting process and a washing process have been chosen.

Figure 5.39 shows a sample load profile of the effective electrical power demand of an abrasive blasting machine.

The abrasive blasting machine is served with semi-finished aluminium parts in a one piece flow. Whenever a work piece reaches the blasting machine, the blasting blowers accelerate until a peak power of ca. 47 kW is attained. After the blasting process, the blasting blowers slow down until the machine reaches a waiting mode at ca. 28 kW, in which the machine awaits the arrival of new work pieces.

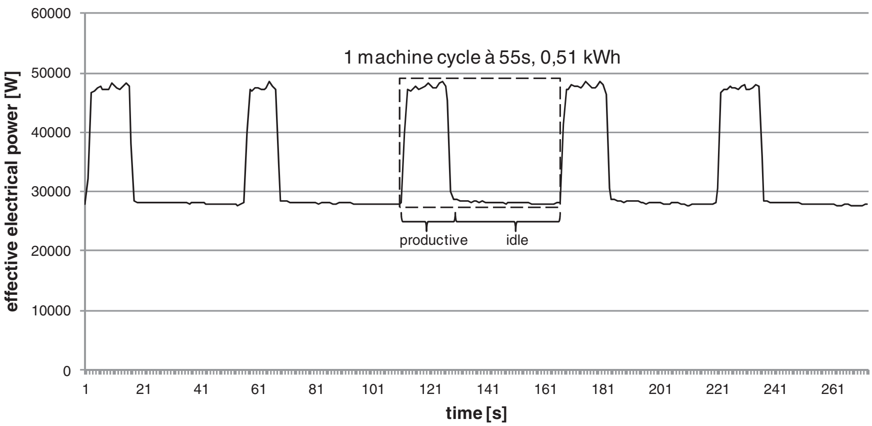


Fig. 5.39 Sample load profile (electrical power) of an abrasive blasting machine, metered with a ChauvinArnaux 8335, resolution: 1s

A whole machine cycle lasts 55 s. During one cycle, the machine demands an average of 0.51 kWh of electrical energy.

Figure 5.40 shows a sample load profile of the effective electrical power demand of a washing machine.

Similar to the abrasive blasting machine, the washing machine gets supplied in batches. Here, four products constitute one batch. During its productive operation, the washing machine has an electrical power demand of ca. 66 kW. During this operational mode, the heating circuits and pump drives increase their power demand. Between the batches the machine maintains its operational readiness

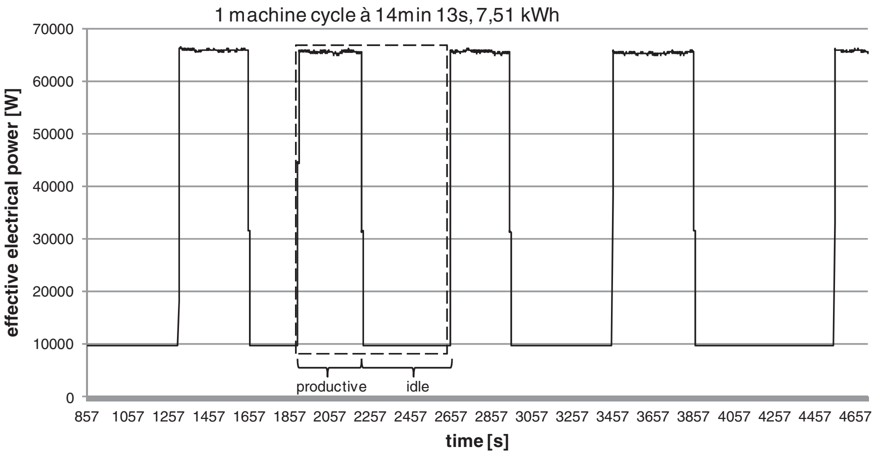


Fig. 5.40 Sample load profile (electrical power) of a washing machine, metered with a ChauvinArnaux 8335, resolution: 1s

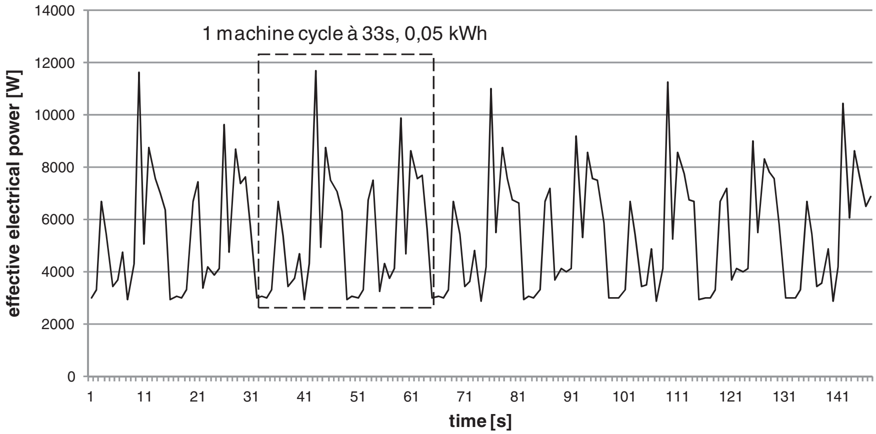


Fig. 5.41 Sample load profile (electrical power) of a leakage test machine, metered with a ChauvinArnaux 8335, resolution: 1s

(by holding the washing fluids temperature) at a power demand of ca. 10 kW. The energy demand for one average machine cycle is 7.51 kWh.

A typical **checking** process is a leakage test. Like the leakage test, the checking cluster unites processes, which do not add value to the product, but rather detect products with failures. Such detected defective products are sent back to the smelter as cycle material. The dynamic electrical energy demand of all relevant checking machines has been detected through high resolution electrical power metering with a ChauvinArnaux 8335 measurement device and parallel time studies. Figure 5.41 shows a sample load profile of the effective electrical power demand of a leakage test machine.

The leakage test machine tests four work pieces during each machine cycle of 33 s. During each machine cycle, it demands an electrical power input between 2.9 kW and 11.6 kW. Thus, the average electrical energy demand of one machine cycle is 0.05 kWh.

Along the aluminium die casting value chain there are many **handling** machines. Handling machines do not add value, but are necessary for automation and for the reduction of manual activities. The dynamic electrical energy demand of all relevant handling machines has been detected through high resolution electrical power metering with a ChauvinArnaux 8335 measurement device and parallel time studies. Figure 5.42 shows a sample load profile of the effective electrical power demand of a leakage test machine.

The palletizing machine is a multi-axis handling robot, which is the last station in the process chain of foundries. It places the finished aluminium die casted products on pallets and stacks them on each other. Due to the multi-axis movements of this robot, the load profile shows a highly fluctuating structure. However, by using the average power load and the average cycle time of manifold machine cycles, the average energy demand during one machine cycle can be calculated (here: 0.01 kWh).

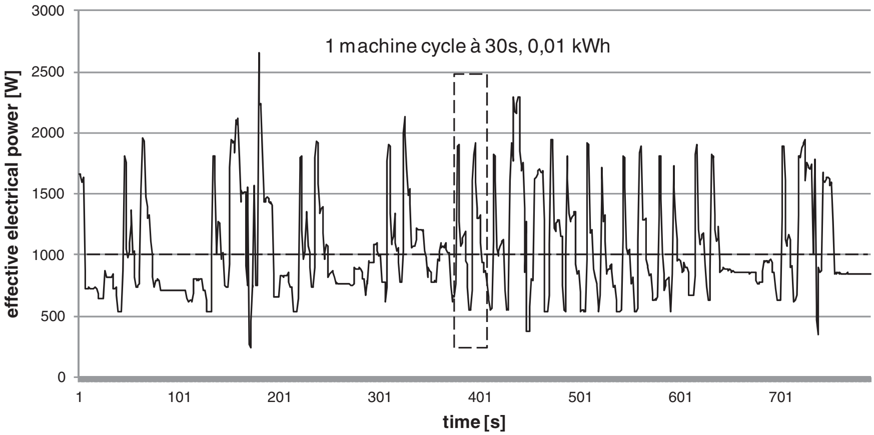


Fig. 5.42 Sample load profile (electrical power) of a palletizing machine, metered with a ChauvinArnaux 8335, resolution: 1s

For the support of the value adding processes in the finishing section, diverse peripheral processes are necessary. An essential supporting process for many cutting processes is the **filtering** of cooling lubricants. Such filtering machines can be installed in a decentralized manner to serve directly linked cutting machines or centralized to serve several cutting machines. The dynamic electrical energy demand of all relevant filtering units has been detected through high resolution electrical power metering with a ChauvinArnaux 8335 measurement device and parallel time studies. Figure 5.43 shows a sample load profile of the effective electrical power demand of one centralised filtering unit, which serves two identical CNC machining centres, which perform identical operations.

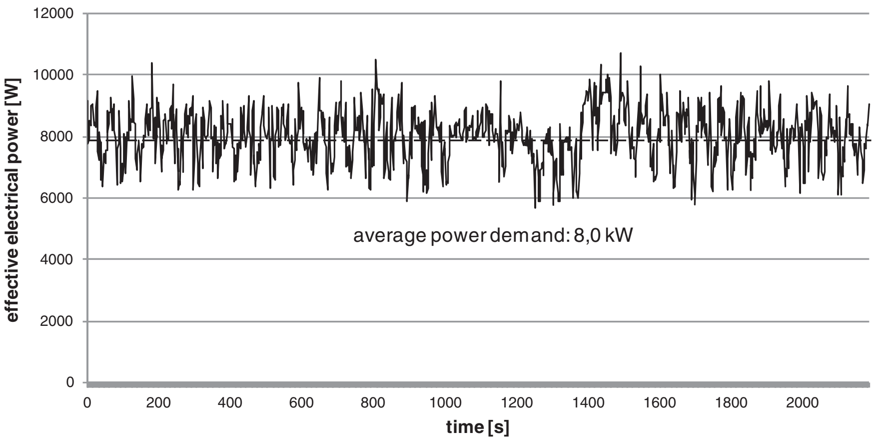


Fig. 5.43 Sample load profile (electrical power) of a cooling lubricant filter, metered with a ChauvinArnaux 8335, resolution: 2s

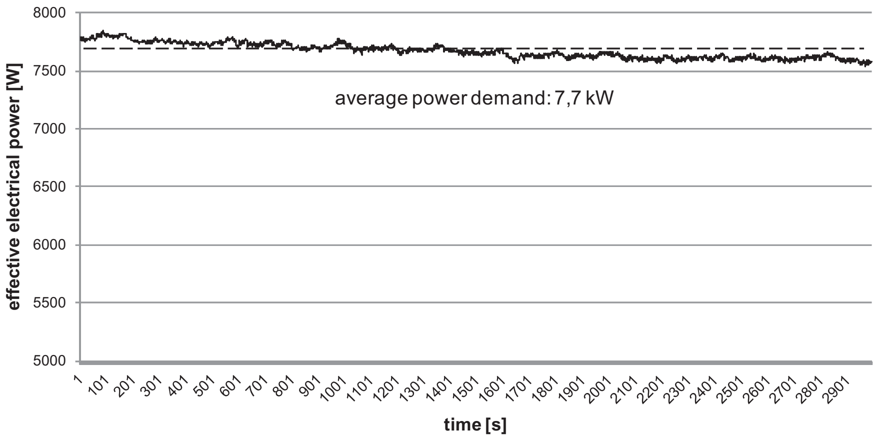


Fig. 5.44 Sample load profile (electrical power) of a cooling system, metered with a ChauvinArnaux 8335, resolution: 2s

The cooling lubricant filter's load profile is independent from the connected CNC machining centre's behaviour. It works constantly while the cutting processes are operating as well. Therefore, its average electrical power demand of 8.0 kW can be allocated constantly to the two CNC machining centres.

Besides the cluster of filtering processes, **cooling** processes can also especially serve the cutting processes in aluminium die casting. The dynamic electrical energy demand of all relevant cooling units has been detected through high resolution electrical power metering with a ChauvinArnaux 8335 measurement device and parallel time studies. Figure 5.44 shows a sample load profile of the effective electrical power demand of one cooling machine.

Similar to the filtering unit, the cooling system has a load profile, which is independent from the behaviour of the value adding cutting processes. It shows a very smooth and consistent structure. Therefore, the electrical power demand can be assumed to be constant at a level of ca. 7.7 kW.

The last relevant peripheral process in the finishing section is the **exhaust air system**. Usually in the finishing section, these systems show the same functional principle and design (and resulting load profile) as in the smelter or die casting cell.

5.7.3 Upstream Process Chains

Raw material inputs and energy carriers like natural gas and electricity are generated outside of the system boundary of the observed value chains. Still, their transformation and consumption, which are vital for the operational capability of the value chain's system elements, shall also be assessed including the environmental

Table 5.14 Life cycle inventory data sets of upstream processes from the ecoinvent 2.2 data base

Input/output flow	Ecoinvent 2.2 dataset	Remarks and ecoinvent references
Electricity	Electricity, medium voltage, production UCTE, at grid	European energy mix (Dones et al. 2007)
Natural gas	Natural gas, burned in industrial furnace >100 kW	Including high pressure transportation to industrial furnace (Faist-Emmenegger et al. 2007)
Transportation	Transport, lorry >32 t, Euro 5	Including diesel generation and combustion (Spielmann et al. 2007)
Oxygen	Oxygen, liquid, at plant	Excluding transportation to furnace (Frischknecht et al. 2007; Primas and Capello 2007)
Nitrogen	Nitrogen, liquid, at plant	Excluding transportation to furnace (Primas and Capello 2007)
Pure (primary) aluminium	Aluminium, production mix, at plant	Aluminium produced in Europe, excluding transportation to the point of use (Classen et al. 2009; Frischknecht and Jungbluth 2007)
Silicon	MG-silicon, at plant	Primary silicon, metallurgical grade with a purity of 99 %, excluding transportation to the point of use (Jungbluth 2007)
Potassium chloride (KCl)	Potassium chloride, as K_2O, at regional storehouse	Drying and concentration of KCl is included (Nemecek and Kägi 2007)
Sodium chloride (NaCl)	Sodium chloride, powder, at plant	Produced in Europe, excluding transportation to the point of use 8 (Althaus et al. 2007a)
Iron	Cast iron, at plant	Secondary iron (Classen et al. 2007a)
Chromium	Chromium, at regional storage	Primary chromium (Althaus et al. 2007b)
Nickel	Nickel, 99.5 %, at plant	Primary nickel with little impurities from copper, for use in alloying processes (Althaus et al. 2004)
Zinc	Zinc, primary, at regional storage	Primary zinc, produced in Europe (Classen et al. 2007b)
Lead	Lead, at regional storage	European supply mix, 25 % primary and 75 % secondary lead (Classen et al. 2007c)
Tin	Tin, at regional storage	Global production data, usage in Europe (Althaus et al. 2007c)
Titanium	Titanium dioxide, production mix, at plant	Theoretical European production mix (Althaus et al. 2007d)
Disposal of filter dust	Disposal, filter dust AL electrolysis, 0 % water, to residual material landfill	Excluding transportation to landfill, similar treatment of filter dust from primary and secondary aluminium production is assumed (Claasen et al. 2009)

impacts from their generation. Such upstream process chains for the generation of all external input flows into the observed value chain are documented in life cycle inventory data bases like ecoinvent.[6] Ecoinvent lists all necessary further input and output flows, which are necessary to generate a specific amount of all considered input/output flows of aluminium die casting. A selection of relevant data sets out of this data base, which have been used for this study, is introduced in Table 5.14.

If the transportation to the point of use of some input flows is not included in the ecoinvent data sets, an additional transport process has been added individually at the preparation of alloying elements (transport, lorry > 32t, Euro 5). The composition of alloying elements represents the average mixture to alloy the detected quality of the molten secondary aluminium fractions into a standard aluminium die casting alloy (EN AC-Al Si9Cu3(Fe)). The upstream process chains for the creation of the recycled secondary aluminium fractions are not included in this study, as their environmental impact gets allocated to their prior product life cycle (according to DIN EN ISO 14044 2006).

The objects for data acquisition have been deduced from the prior generation of a generic structural energy and material flow model for aluminium die casting in combination with a hot spot analysis of the foundries' energy carrier demands. Based on the exemplarily described individual metering and data gathering campaigns at all relevant system elements among all observed actors, generic quantitative models for the energy and resource demand of the individual system elements will be derived in the following section. Together, these models enable to induce a generic, quantitative aluminium die casting model.

5.8 Modelling, Simulation and Visualisation

This section translates the multiple data acquisition results into a quantitative generic model of aluminium die casting. Therefore, the previously introduced generic structural model gets parameterized with the acquired data sets about the energy and resource demand of every transition. This primary parameterisation of the single elements of the model creates input/output balances per transition. However, they still need to be scaled to ensure a harmonised flow of energy and material between the transitions. Therefore, taking an ex post perspective on the status quo of the observed value chains, the calculation routines of the software Umberto™ simulate the overall and harmonised energy and resource demand of the whole value chain. Based on this, selected energy and resource demand can be visualized on process chain and value chain level. As a consequence of the utilised software, Umberto™, which makes it feasible to integrate the steps modelling, simulation and visualisation in one software environment, these steps are integrated into this Sect. 5.8 as well.

[6]See http://www.ecoinvent.ch/.

5.8.1 Input and Output Modelling of System Elements

Figure 5.45 introduces the sub-procedure, which will be used here to specify the module *modelling and visualisation* from the above introduced procedural approach (see Sects. 4.3.2 and 5.2.3).

As a first step, all acquired data about energy and resource demands along all observed aluminium die casting value chain get translated into **input/output balances for each of the observed processes**. These balances represent the characteristic relation of input and output flows of the individual processes to produce

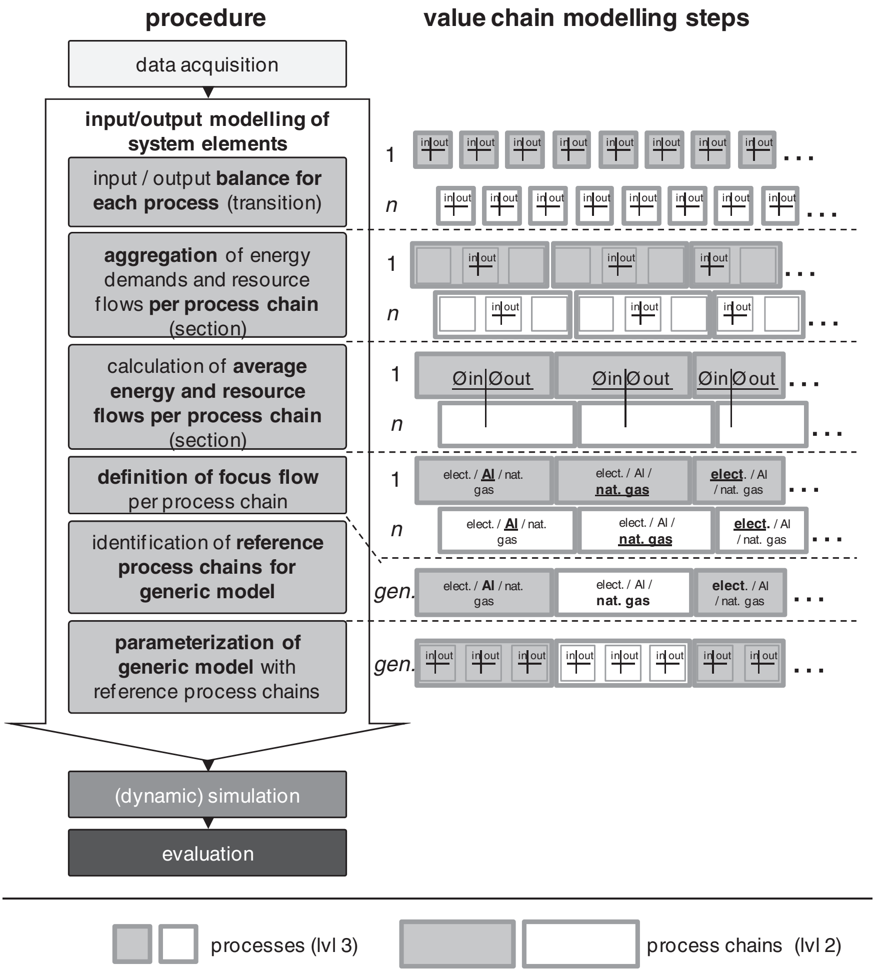


Fig. 5.45 The procedure for input and output modelling of system elements and their synthesis into a generic model

a specific amount of output unit. However, this relation does not yet represent the absolute quantities of the input and output flows for the production of 1 t of finished aluminium die casting products, which leave the system boundary to the customer. At the end of this step, the generic structural model can be parameterized to create an individual image of every single observed value chain.

Afterwards, an **aggregation of all energy and resource flows** of all processes **within one process chain** (section) takes place in order to enhance the comparability of the sections. By doing so, also an input/output balance per process chain can be created.

The subsequent **calculation of average energy and resource flows per process chain** then helps to get a first impression about the quantitative composition of average aluminium die casting value chains.

When the average energy and resource demand per process chain are known, a **focus flow per process chain gets defined**. This flow represents the energy carrier (electricity or natural gas) or resource (aluminium alloy), which characterises the energy or resource demand of the process chain most. Thus, this focus flow describes the major share of resource demand, which is caused by the observed system element. For example, the natural gas demand of a shaft melting furnace characterises this process more than its electricity demand. Therefore, the natural gas flow through a shaft melting furnace is selected as its focus flow.

All parameterized process chains of the twelve observed products are checked in order to **identify reference process chains for the generic model.** A reference process chain is the process chain out of the observed case studies, which is closest to the calculated average demand regarding the particularly selected focus flow. For each process chain on system level 2 of the generic structural model, one reference process chain out of the observed case studies needs to be named.

The identified reference process chains are used for a **parameterization of the generic model.** Thus, the structural model of each individual process chain and of its subordinate processes gets parameterized with the input and output models of the selected reference process chain.

As a result of this approach, the resulting generic quantitative model will not exactly represent the average energy and resource consumption of all observed die casting value chains. This is due to the fact that on system level 2, reference process chains have been selected and adopted, which are close to the average, but not absolutely converging to the arithmetical mean of the energy and resource demand. However, the selected process chains with their subordinate processes rather represent real, existing and well operating technical entities. Thereby, the generic aluminium die casting model offers the opportunity to assess the virtual implementation of improvement measures not only to an averaged hypothetical model, but to a reproduction of manufacturing entities, which have proven their ability to produce goods in the exact way, in which they are also composed in the model.

5.8.1.1 Sample Input and Output Balances

All acquired data about energy and resource demands, along the whole observed aluminium die casting value chain, has been translated into input/output balances for each of the observed processes. These balances have been implemented in the Umberto™ modelling software for energy and resource flows. The following figures show screenshots of sample input/output balances, which have been documented this way.

Figure 5.46 depicts the input/output balance of a sample transition *composition of alloying elements*, which has been modelled in Umberto™. It shows the quantitative composition of alloying elements and further flows for the generation of an output unit of alloying addition. This alloying addition is used to set up a defined alloying quality in the subsequent converter.

Figure 5.47 depicts the input/output balance of a sample transition *converter*, which has been modelled in Umberto™. It shows the quantitative composition of the input and output flows of the furnace, in which the molten aluminium mass from the drum melting furnace gets alloyed to the targeted alloy by adding pure aluminium and alloying additions.

Figure 5.48 depicts the input/output balance of a sample transition *die casting machine*, which has been modelled in Umberto™. It shows the quantitative

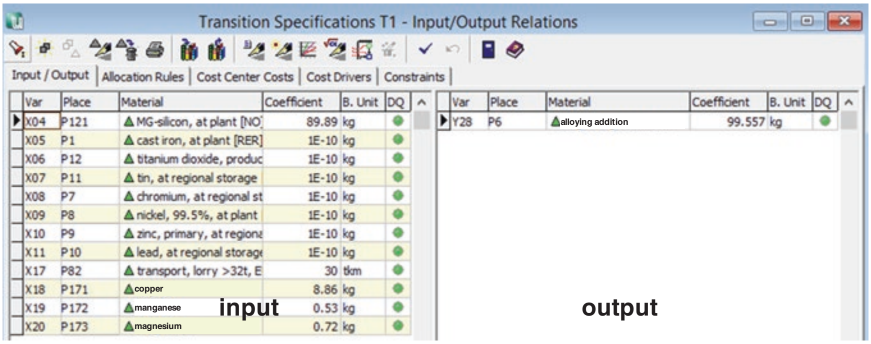


Fig. 5.46 Screenshot of transition *composition of alloying elements* (modelled in Umberto™)

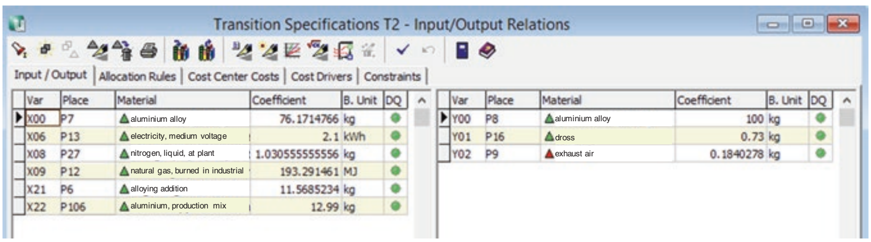


Fig. 5.47 Screenshot of transition *converter* (modelled in Umberto™)

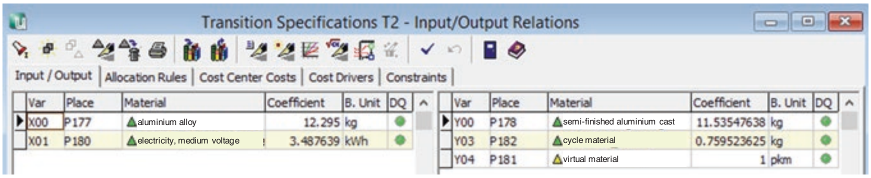


Fig. 5.48 Screenshot of transition *die casting machine* (modelled in Umberto™)

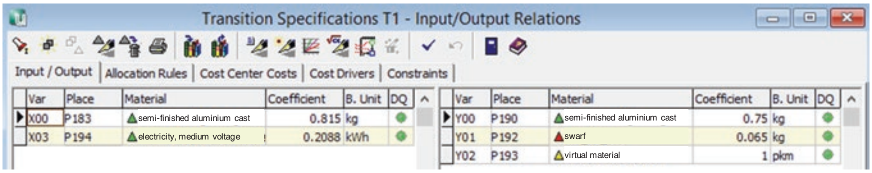


Fig. 5.49 Screenshot of transition *cutting* (modelled in Umberto™)

composition of energy and alloy demand to produce semi-finished cast, cycle material and the above introduced virtual material (operand of the model without impact).

Figure 5.49 depicts the input/output balance of a sample transition *cutting*, which has been modelled in Umberto™. It shows the quantitative composition of the inputs energy and semi-finished products and the resulting outputs of (cut) semi-finished casts, cycle material and virtual material.

The sample transitions shown above represent input/output balances of real processes, which have been investigated individually at the observed actors. They can be aggregated on the process chain level, which leads to the following results.

5.8.1.2 Aggregation of Energy Carrier and Resource Flows Per Process Chain/Section

The gathered quantitative data about energy and resource flows along all observed processes (system level 3), which has been translated into input/output balances, has been aggregated on the process chain level and the resp. section level (system level 2). Thereby, the comparability of the sections gets enhanced. For the value adding transitions on system level 2, Table 5.15 introduces the quantities of selected energy and resource flows (input or output), which have been calculated by aggregating the process specific input/output balances. Input flows are marked with the index “in”. Output flows are marked with the index “out”.

The combination of these aggregated flows per process chain/section[7] depicts the individual energy and resource related characteristic of every single observed

[7]For the modelled energy and resource flows of the heat treatment section, please refer to Sect. 5.7.2 as it has not been investigated at the observed actor’s value chains. It has been modelled based on externally available data and process models.

Table 5.15 Aggregated energy and resource flows (selection) for the value adding process chains/sections (system level 2) in aluminium die casting

Transition and flow	Product/value chain											
	1	2	3	4	5	6	7	8	9	10	11	12
Preparation of sec. Al fractions												
Electricity (kWh_{in})	28.9	28.8	32.4	31.4	29.0	28.5	28.2	31.8	28.5	32.0	28.7	28.2
End of life products (kg_{in})	191.1	190.2	214.3	207.8	191.8	188.5	186.6	210.3	188.6	211.3	190.0	186.8
Swarf (kg_{in})	157.1	156.3	176.2	170.9	157.7	155.0	153.4	172.9	188.6	173.8	156.2	153.5
Clean scrap (kg_{in})	5.0	5.0	5.6	5.5	5.0	4.9	4.9	5.5	4.9	5.5	5.0	4.9
Dross (kg_{in})	751.2	747.3	842.1	816.8	753.8	740.9	733.5	826.6	741.1	830.6	746.5	734.0
Post-industrial scrap (kg_{in})	40.0	39.8	44.8	43.5	40.1	39.5	39.1	44.0	39.5	44.2	39.8	39.1
Drum melting furnace												
Electricity (kWh_{in})	27.2	27.1	30.5	29.6	27.3	26.8	26.6	29.9	26.8	30.1	27.0	26.6
Natural gas (kWh_{in})	447	444	501	486	448	441	436	491	441	494	444	436
Aluminium (kg_{out})	790.9	786.8	886.6	860.0	793.7	780.1	772.3	870.4	780.3	874.5	786.0	772.8
Provision of alloying elements												
Pure aluminium (kg_{out})	135.0	134.3	151.3	131.3	135.4	133.1	131.8	148.5	133.2	149.2	134.1	131.9
Alloying elements (kg_{out})	120.7	120.1	135.3	146.8	121.2	119.1	117.9	132.9	119.1	133.5	120.0	118.0
Converter												
Electricity (kWh_{in})	21.8	21.7	24.5	23.7	21.9	21.5	21.3	24.0	21.5	24.1	21.7	21.3
Natural gas (kWh_{in})	558	555	625	607	560	550	545	614	550	617	554	545
Aluminium (kg_{out})	1039.0	1033.7	1164.7	1129.8	1042.7	1024.8	1014.6	1143.4	1025.1	1148.8	1032.6	1015.3
Ingot casting and piling												
Electricity (kWh_{in})	5.2	5.1	5.8	5.6	5.2	5.1	5.0	5.7	5.1	5.7	5.1	5.0
Aluminium (kg_{out})	1039.0	1033.7	1164.7	1129.8	1042.7	1024.8	1014.6	1143.4	1025.1	1148.8	1032.6	1015.3
Smelter												
Electricity (kWh_{in})	7.8	6.1	10.5	8.8	6.4	5.0	2.9	28.6	5.0	29.7	6.5	3.0
Natural gas (kWh_{in})	1364	858	2440	2082	1481	1986	1167	11,472	2005	11,907	2608	1221

(continued)

Table 5.15 (continued)

Transition and flow	Product/value chain											
	1	2	3	4	5	6	7	8	9	10	11	12
Aluminium (kg_{out})	1908.0	1458.0	2624.8	2207.9	1593.3	1216.2	714.5	7026.9	1228.4	7293.1	1597.6	747.6
Die casting cell												
Electricity (kWh_{in})	344.2	363.2	986.8	1133.3	739.8	647.5	314.2	6965.0	835.6	2036.6	1764.2	1202.0
Natural gas (kWh_{in})	/	/	/	/	/	44,372	34,235	161,772	44,618	167,150	52,078	34,904
Aluminium (kg_{out})	1000.0	1011.5	1104.0	1089.1	1001.2	1007.7	1007.7	1007.7	1007.7	1007.7	1007.7	1007.7
Cycle material (kg_{out})	908.0	446.5	1520.7	1118.8	592.0	1233.3	721.4	7162.6	1245.8	7434.3	1622.6	755.2
Finishing section												
Electricity (kWh_{in})	32.9	62.5	603.1	1039.0	56.9	203.8	390.7	1419.8	335.5	0.6	0.0	370.6
Swarf (kg_{out})	/	1.4	96.4	86.9	1.2	/	/	/	/	/	/	/
Cycle material (kg_{out})	/	10.1	7.7	2.2	/	7.7	7.7	7.7	7.7	7.7	7.7	7.7

Due to confidentiality reasons, the single depicted flows are already scaled roughly for meeting the required quantities to produce about 1000 kg of finished products. However, the important proportions of the processed flows are unaffected through this measure, and are even more comparable. Nevertheless, these flows still need to be harmonised to meet the exact overall demanded quantities per process. This step is conducted in the next section via a static simulation in the software Umberto™

value chain (system level 1) and the proportional relations between the energy and material flows. Based on this aggregation, the average energy and resource flows per process chain/section will be introduced in the following section.

5.8.1.3 Average Energy and Resource Flows Per Process Chain (Section) and Definition of Focus Flows

Based on the known energy and resource flows through all processes and process chains of the observed value chains, an average can be calculated per process chain. Thereby, a first impression about the quantitative composition of typical aluminium die casting value chains can be created. By comparing the average flows per process chain, a focus flow can be defined, which characterises this process chain best and represents the dominant flow. Table 5.16 lists the average values and standard deviations of the main flows per process chain and a selection of further relevant flows, which characterise the respective process chain. The selected focus flow is marked with bold letters.

Table 5.16 Average and focussed energy and resource flows (selection) for value adding process chains/sections (system level 2)

Transition and flow	Average quantity	Standard deviation	Focus flow
Preparation of sec. Al fractions			
Electricity (kWh_{in})	**29.7**	**1.7**	Electricity input is defined as focus flow as the aluminium flows are mainly depending on the aluminium demand of the subsequent process chains.
End of life products (kg_{in})	196.5	10.9	
Swarf (kg_{in})	164.3	11.3	
Clean scrap (kg_{in})	5.2	0.3	
Dross (kg_{in})	772.0	42.9	
Post-industrial scrap (kg_{in})	41.1	2.3	
Drum melting furnace			
Electricity (kWh_{in})	28.0	1.6	Natural gas input is defined as focus flow due to its high quantity and as the aluminium flow is mainly depending on the aluminium demand of the subsequent process chains.
Natural gas (kWh_{in})	**459.0**	**92**	
Aluminium (kg_{out})	812.9	45.2	
Converter			
Electricity (kWh_{in})	22.4	1.2	Natural gas input is defined as focus flow due to its high quantity and as the aluminium flow is mainly depending on the aluminium demand of the subsequent process chains.
Natural gas (kWh_{in})	**573.4**	**115**	
Aluminium (kg_{out})	1067.9	59.3	

(continued)

Table 5.16 (continued)

Transition and flow	Average quantity	Standard deviation	Focus flow
Ingot casting and piling			
Electricity (kWh_{in})	**5.3**	**0.3**	Electricity input is defined as focus flow as the aluminium flow is just passing through this transition without any substantial transformation.
Aluminium (kg_{out})	1067.9	59.3	
Smelter			
Electricity (kWh_{in})	10.0	8.8	Natural gas input is defined as focus flow due to its high quantity and as the aluminium flow is mainly depending on the aluminium demand of the subsequent process chains.
Natural gas (kWh_{in})	**3383.0**	**13,564**	
Aluminium (kg_{out})	2468.0	2164.4	
Die casting cell			
Electricity (kWh_{in})	**1444.4**	**1745.1**	Electricity input is defined as focus flow as the natural gas flow does not exist at about half of the observed die casting cells. The aluminium and cycle material flows are characteristic for the product but not for the process.
Natural gas (kWh_{in})	12,480	59,505	
Aluminium (kg_{out})	1021.6	394	
Cycle material (kg_{out})	2063.4	2381.4	
Finishing section			
Electricity (kWh_{in})	**376.3**	**447.1**	Electricity is defined as focus flow as it is demanded in every sub process and the main object of improvement measures in this section.
Swarf (kg_{out})	46.5	48.8	
Cycle material (kg_{out})	7.4	1.9	

The calculation of average energy and resource flows for the value adding process chains/sections allows for differentiation between the process chains regarding their comparative relevance. Here, the die casting cell represents the highest average electricity as well as natural gas demands—although natural gas is demanded here only by about half of the observed value chains. The smelter represents the highest natural gas demand of those process chains, which demand natural gas over all observed value chains.

In the following section, reference process chains out of the real case studies will be selected, which are close to the average per individual focus flow. These reference process chains will serve as modular parts for the parameterization of the generic model.

5.8.1.4 Identification of Reference Process Chains and Parameterization of Generic Model

Out of the table about aggregated energy and resource flows per process chain (see Table 5.15), the process chain gets selected as a reference process chain, whose focus flow has a quantity, that is as close as possible to the calculated average. Table 5.17 lists the selected reference process chains and the considered main flows.

For most of the selected reference process chains, the deviation from the average energy and resource flows is negligible (below 5 %) or small (up to 10 %). Thus, at this point, the selection of the reference process chains is feasible to represent a generic composition of aluminium die casting process chains. At this point, the process chains of value chain number 5 represent the generic aluminium die casting process chains best. Only for the smelter do the electricity demand and aluminium output show a larger deviation. The deviation of the electricity demand is negligible due to its relatively small absolute amount compared to the focus

Table 5.17 Selected reference process chains and resulting flows

Transition and flow	Reference quantity	Deviation from average (%)	Origin of reference process chain
Preparation of sec. Al fractions			
Electricity (kWh_{in})	**29.0**	**−2.36**	Product/value chain nr. 5
End of life products (kg_{in})	191.8	−2.36	
Swarf (kg_{in})	157.7	4.97	
Clean scrap (kg_{in})	5.0	−2.36	
Dross (kg_{in})	753.8	−2.36	
Post-industrial scrap (kg_{in})	40.1	−2.36	
Drum melting furnace			
Electricity (kWh_{in})	27.3	−2.36	Product/value chain nr. 5
Natural gas (kWh_{in})	**448.2**	**−2.36**	
Aluminium (kg_{out})	793.7	−2.36	
Converter			
Electricity (kWh_{in})	21.9	−2.36	Product/value chain nr. 5
Natural gas (kWh_{in})	**559.8**	**−2.36**	
Aluminium (kg_{out})	1042.7	−2.36	
Ingot casting and piling			
Electricity (kWh_{in})	**5.17**	**−2.36**	Product/value chain nr. 5
Aluminium (kg_{out})	1042.7	−2.36	
Smelter			
Electricity (kWh_{in})	6.4	−36.0[a]	Product/value chain nr. 5
Natural gas (kWh_{in})	**1481.1**	**10.0**[a]	
Aluminium (kg_{out})	1593.3	−18.6[a]	
Die casting cell			
Electricity (kWh_{in})	**739.8**	**3.69**[a]	Product/value chain nr. 5
Aluminium (kg_{out})	1001.2	−3.84[a]	
Cycle material (kg_{out})	592.0	−35.5[a]	

[a]Since an additional (uncommon) melting within the die casting cell takes place within half of the observed value chains (no. 6–no. 12), these value chains are excluded for the selection of reference process chains and the corresponding calculations in the case of smeltery and die casting cell

Table 5.18 Electrical energy demands in the finishing section and reference values (kWh)

Product/value chain nr.	Cutting	Special treatments	Checking	Handling	Periphery
Average	136.7	222.85	9.1	0.3	187.5
1	32.9				
2	55.73		(2.67)[a]	**0.28**	3.80
3	459.09	82.87	**10.47**		236.03
4	353.60	362.15	0.74		**322.52**
5	56.91				
6	12.92	190.83			
7	**219.63**	**171.03**	16.19		
8		(1391.48)[b]			
9	144.87	190.64			
10	0.57				
11					
12	30.98	339.58			

[a]This value is excluded from the average calculation, here, due to the implementation of a specifically designed, non-transferable checking system for this particular product
[b]Outlier due to relatively large product surface compared to product weight. The drying of this large surface demands for out of scale extra energy inputs. Therefore, this process cluster is excluded from the average calculation presented here

flow. The deviation of the aluminium output (−18.6 %) can be accepted since the resulting energy intensity of this section (0.933 kWh/kg) is only 9.5 % higher than the average for common smelters (0.844 kWh/kg) without additional melting in the later die casting cell.[8]

At the finishing section, the diversity of installed processes makes it necessary to have a deeper look into this process chain. Therefore, instead of one reference for the whole process chain, references for each process cluster will be selected in the following section. Table 5.18 shows the electrical energy demands of the single process clusters along the different finishing sections and their average. In contrast to the procedure so far, a reference process will be selected per process cluster, which complements the aimed generic process chain best towards a mapping of a multifaceted but representative mechanical treatment section. Therefore, the selection of reference processes will be done on individual basis. The selected reference electrical energy demands per reference cluster are marked with bold letters in Table 5.18.

For the process cluster *cutting*, the processes of value chain nr. 7 are selected as reference clusters. They incorporate the broadest field of cutting processes (according to DIN 8580) incl. a grinding process and CNC machining centres (DIN 8580 2003).

[8]Since an additional (uncommon) melting within the die casting cell takes place within half of the observed value chains (no. 6–no. 12), these value chains are excluded for the selection of reference process chains and the corresponding calculations in the case of smeltery and die casting cell.

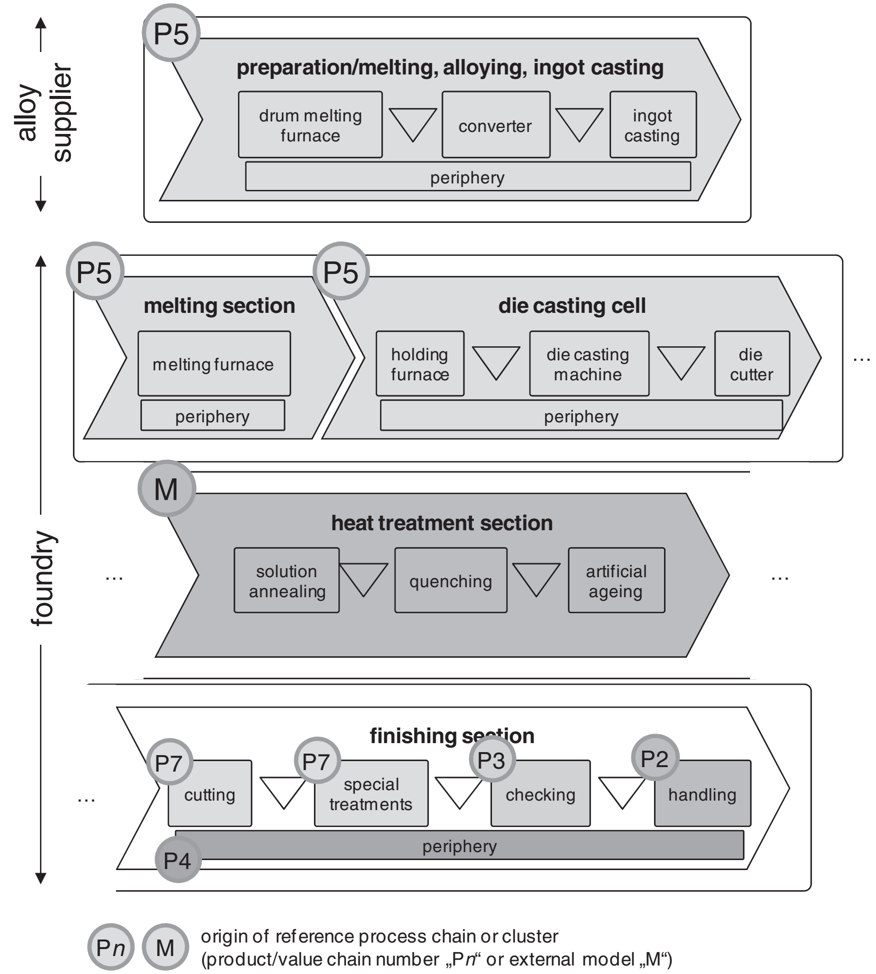


Fig. 5.50 Composition of a generic value chain based on reference process chains and clusters

The process cluster *special treatments* incorporates the main processes of washing and drying. Both are installed in combination only within the value chains 7 and 12. The processes of value chain nr. 7 are selected as reference cluster as they are closest to the average.

At the process cluster *checking*, the processes of value chain nr. 3 are closest to the average and, therefore, define the reference cluster.

A discrete *handling* process cluster can only be found at value chain nr. 2. It is selected as reference cluster.

For the process cluster *periphery*, the processes of value chain nr. 4 are selected as a reference since they represent the broadest selection of installed peripheral processes (including cooling lubricant filters, cooling systems, exhaust air systems, etc.).

Through the selection of the aforementioned representative process clusters within the finishing section, a broad selection of relevant processes can be mapped in the resulting generic value chain. In return, it needs to be accepted, that the selected process are not always as close as possible to the average resource flows in this section. However, compared to other process chains, the absolute deviations are acceptable.

Figure 5.50 shows an overview over the selected reference process chains and clusters and their origin for the composition of a representative, generic model of the whole aluminium die casting value chain.

By using the identified reference process chains and clusters, the generic structural model is parameterized and a generic quantitative model can be induced. Thus, for each process chain or process cluster, the process-specific input/output balances of each single process out of the reference process chain or cluster get inserted into the generic model. Thereby, the generic quantitative aluminium die casting model represents a sequence of real existing and technically operating process chains or clusters with close to average energy and resource flows. The interplay of these single input/output balances in joint process chains can be simulated in order to calculate the overall energy and resource demand of each process chain for the generation of 1000 kg of finished aluminium die casted products, which leave the system boundary to the customer. The results of such a simulation are shown in the following section.

5.8.2 Simulation of the Generic Quantitative Model

This section introduces the results of a (static) simulation with the help of the Umberto™ software. It harmonizes output and input flows of sequentially linked transitions with the aim to produce 1000 kg of finished aluminium die casted products, which leave the foundry's factory gates. As a result, for each single process, the simulated aluminium die casting model documents the exact amount of input and output flows, which are necessary to reach this aim. Table 5.19 lists a selection of the main flows for the value adding processes. These processes are clustered according to their superior process chain.

The conducted simulation harmonizes and adjusts the input and output flows of each process, so that a first perspective on the value chain as a whole becomes possible. The actual ex post analysis is based on energy and resource demand measurements at real existing and continuous operating processes, so this perspective on the overall value chain is possible only by conducting a static simulation. Dynamic simulation comes into play during the ex-ante evaluation of improvement measures, for which measurements are not available yet and which affect the dynamic interplay of processes.

The calculated results reflect the first imagination of energy and resource flows, which could already be gathered during the data acquisition and modelling phases. However, the view on the harmonized flows highlights even more the already stated high energy demands of the foundry—especially the natural gas demand of the smelter and the electricity demands of the die casting cell and the finishing

Table 5.19 Main energy and resource flows through the value adding system elements after static simulation with Umberto™ to produce 1000 kg of finished aluminium die casted products

Transition and flow	Simulated quantity
Alloy supplier—preparation/melting, alloying, ingot casting	
Preparation of sec. Al fractions	
Electricity (kWh_{in})	31.73
Molten aluminium (kg_{out})	1256.09
Drum melting furnace	
Electricity (kWh_{in})	29.86
Natural gas (kWh_{in})	490.18
Aluminium (kg_{out})	868.04
Converter	
Electricity (kWh_{in})	23.95
Natural gas (kWh_{in})	612.28
Aluminium (kg_{out})	1140.36
Ingot casting and piling	
Electricity (kWh_{in})	5.66
Aluminium (kg_{out})	1140.36
Foundry—smelter	
Aggregated flows of smeltery	
Electricity (kWh_{in})	21.98
Natural gas (kWh_{in})	1619.85
Aluminium (kg_{out})	1742.48
Shaft melting furnace	
Electricity (kWh_{in})	6.87
Natural gas (kWh_{in})	1619.85
Aluminium (kg_{out})	1742.48
Periphery	
Electricity (kWh_{in})	15.12
Foundry—die casting cell	
Aggregated flows of die casting cell	
Electricity (kWh_{in})	809.05
Natural gas (kWh_{in})	0.00
Aluminium (kg_{out})	1094.99
Cycle material (kg_{out})	647.49
Holding furnace	
Electricity (kWh_{in})	29.34
Natural gas (kWh_{in})	0.00
Aluminium (kg_{out})	1742.48
Die casting machine	
Electricity (kWh_{in})	494.28
Aluminium (kg_{out})	1634.84
Cycle material (kg_{out})	107.64

(continued)

Table 5.19 (continued)

Transition and flow	Simulated quantity
Die cutter	
Electricity (kWh_{in})	16.30
Aluminium (kg_{out})	1094.99
Cycle material (kg_{out})	539.85
Periphery	
Electricity (kWh_{in})	269.13
Foundry—heat treatment	
Aggregated flows of modelled heat treatment	
Electricity (kWh_{in})	166.38
Natural gas (kWh_{in})	195.09
Aluminium (kg_{out})	1094.99
Foundry—finishing section	
Aggregated flows of finishing section	
Electricity (kWh_{in})	825.20
Swarf (kg_{out})	87.33
Cycle material (kg_{out})	7.66
Cutting	
Electricity (kWh_{in})	280.53
Special treatments	
Electricity (kWh_{in})	193.20
Checking	
Electricity (kWh_{in})	16.06
Handling	
Electricity (kWh_{in})	11.13
Periphery	
Electricity (kWh_{in})	324.28

section. Besides the high energy demand, the view on the harmonized material flows along the value chain reveals the relevance of cycle material in aluminium die casting again. 37 % of the material input of the die casting cell leave this process chain as cycle material and needs to be resmelted again at the foundry's smelter, which directly influences the high energy demand of this section.

The redundantly melted cycle material, as well as other quantitative results of the above displayed simulation, will be visualised in the following section.

5.8.3 Visualisation of Energy and Resource Flows

The energy and resource flows electricity, natural gas and aluminium (aluminium fractions, molten mass and semi-finished products) get visualised along the value chain. To do so, corresponding Sankey diagrams are created as an overlay over the structural model of aluminium die casting in the software Umberto™. In a Sankey diagram, every observed flow of different transformatory steps e.g., in a manufacturing system, is depicted as an arrow, whose width is proportional to the flow's quantity. In this section, a selection of the resulting Sankey diagrams is introduced on value chain level (level 1) and on process chain level (level 2).

5.8.3.1 Value Chain Level

Figure 5.51 shows a Sankey diagram of electricity, natural gas and aluminium flows along the whole aluminium die casting value chain. The aluminium flow is depicted in blue. Electricity flows are painted orange. Natural gas flows are marked red. In this overview picture, the aluminium flow proceeds from left to right, with increasing value added through the progression. Regarding the different flows and sizes of the Sankey arrows, the diversity of flow intensities can already be imagined.

Figure 5.52 shows an excerpt of the aluminium flow Sankey diagram with a special focus on recycled aluminium. This recycled aluminium can be the intra foundry cycle material, which is marked in yellow as well as the secondary metal input fractions, which are processed at the alloy supplier and are marked in light blue.

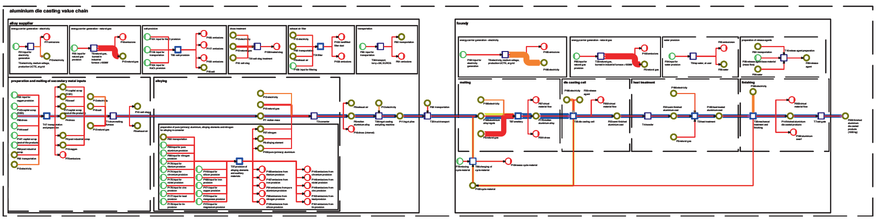


Fig. 5.51 Sankey diagram of energy carrier and aluminium flows along the aluminium die casting value chain

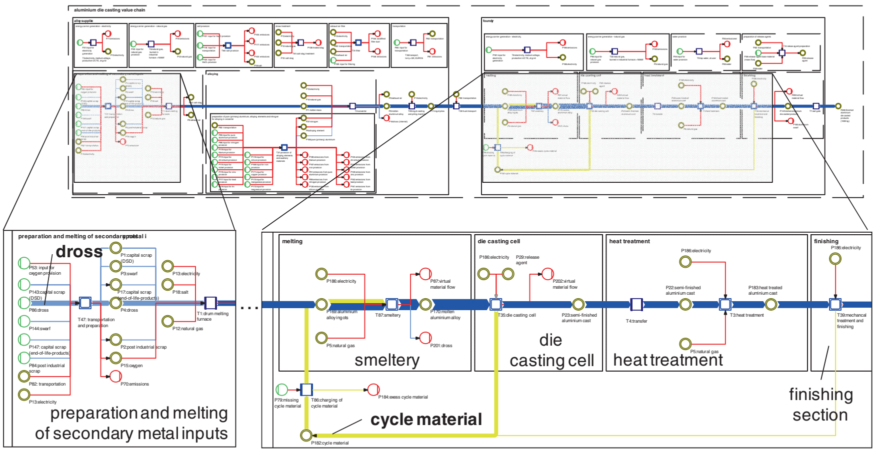


Fig. 5.52 Visualisation of aluminium and cycle material flows along the aluminium die casting value chain

It can be seen, that besides the manifold secondary aluminium input fractions, the dross input into the drum melting furnace especially accounts for a high share of the secondary metal inputs. Besides the positive aspect, that the dross gets recycled intensively, this high amount of dross also reflects the high amount of contaminations. These contaminations enter the value chain together with the secondary metals and are skimmed from the molten metal as dross.

As stated in prior sections, the high relevance of intra foundry cycle material becomes evident in this picture as well. It can be seen that the majority of the cycle material arises from the die casting cell (mainly at the die cutter). Thus, the amount of cycle material is determined by the design of the die's geometry and the resulting volume of the gating system, sprue, etc. Therefore, the die's geometry is an obvious object of possible improvement measures, which reduce this volume. Further smaller amounts of internal cycle material arise from the die casting machine itself as flitter, from the finishing section as swarf or as scrap material. As the small amounts of flitter and swarf result from directly value adding operations, they are not relevant objects of improvement measures. In contrast, the amount of scrap material represents a loss of value and needs to be avoided from economical (loss of value) and environmental (loss of embodied energy) reasons.

Deeper insight into the flows of energy carriers will be given in the following section, which focuses on the visualisation of flows on process chain level.

5.8.3.2 (In-House) Process Chain Level

Figure 5.53 shows a Sankey diagram of the energy carrier and aluminium flow in the foundry's smelter. It can be seen that in this case, the peripheral and non-value adding exhaust air system accounts for a larger share of the electricity demand (orange flow) than the value adding shaft melting furnace itself. The main energy carrier for the shaft melting furnace is natural gas (red flow), which is needed to melt the aluminium flows. The aluminium flows enter the furnace from the prior

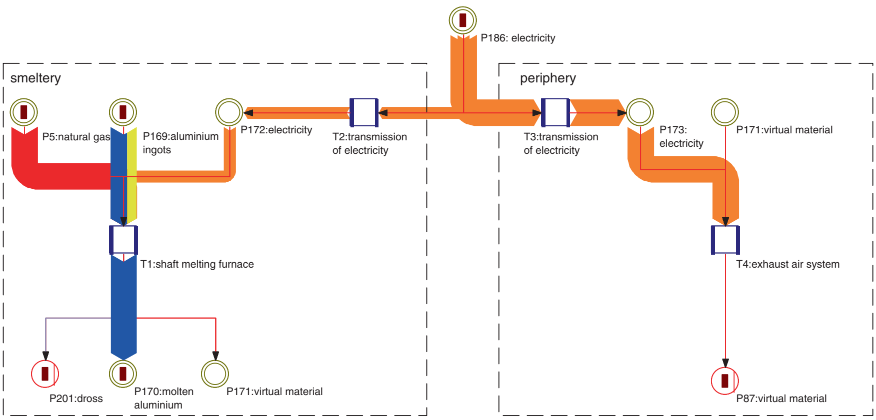


Fig. 5.53 Sankey diagram of energy carrier and aluminium flows in the foundry's smelter

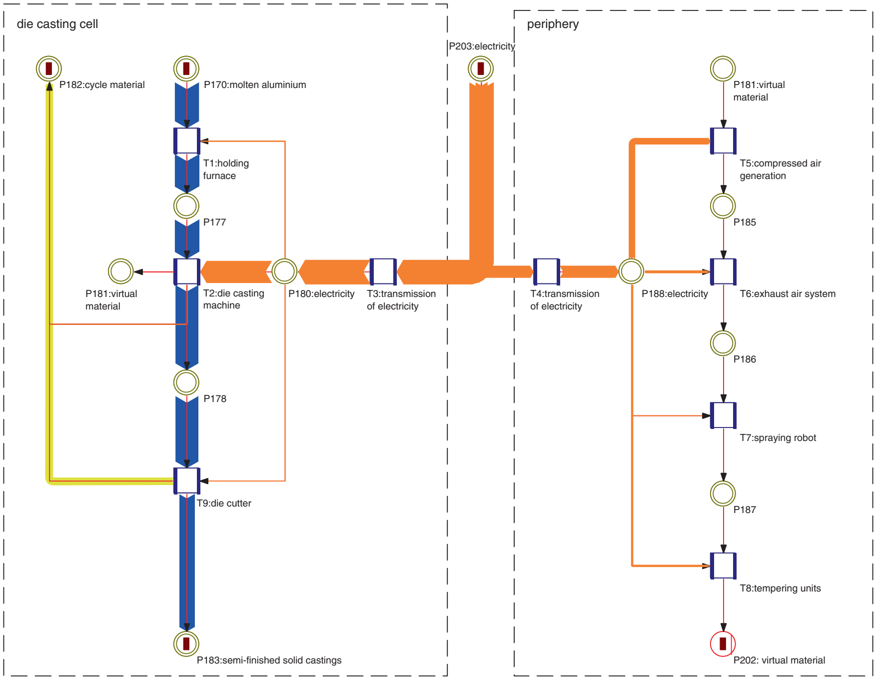


Fig. 5.54 Sankey diagram of energy carrier and aluminium flows in the foundry's die casting cell

alloy supplier (blue material flow) and in the form of internal cycle material (yellow material flow). Thus, the reduction of cycle material is a possible field of action for reducing the smelter's energy demand. Furthermore, a reduction of the exhaust air system's electricity demand seems to be promising.

Figure 5.54 shows a Sankey diagram of the electricity and aluminium flow in the foundry's die casting cell. It can be reassured that the origin of a large share of the above mentioned cycle material (yellow material flow) is the die cutter in the die casting cell. The largest electricity demand (orange flow) in this process chain arises by far from the die casting machine itself. It is followed by the energy demand of the compressed air generation, which serves the die casting machine and its spraying robot. Thus, besides an optimization of the die casting process itself, a reduction of the compressed air demand (e.g., by introducing alternative release agents or application procedures for release agents) is one possible field of action for improvement measures.

Figure 5.55 shows a Sankey diagram of the electricity and aluminium flow in the foundry's finishing section. Only a small amount of cycle material (yellow flow) arises in this section, which is mainly due to scrap parts. Such parts are detected in the process cluster *checking*. The largest energy demand (electricity, orange flow) occurs at the process cluster *cutting*, followed by *special treatments*, *filtering* and *cooling*.

The above introduced and visualised quantitative simulation results from the energy carrier and resource flows in aluminium die casting can be further evaluated regarding their distribution over actors and process chains. Furthermore, these flows constitute a LCI data set, which can be used as a starting point for a further environmental

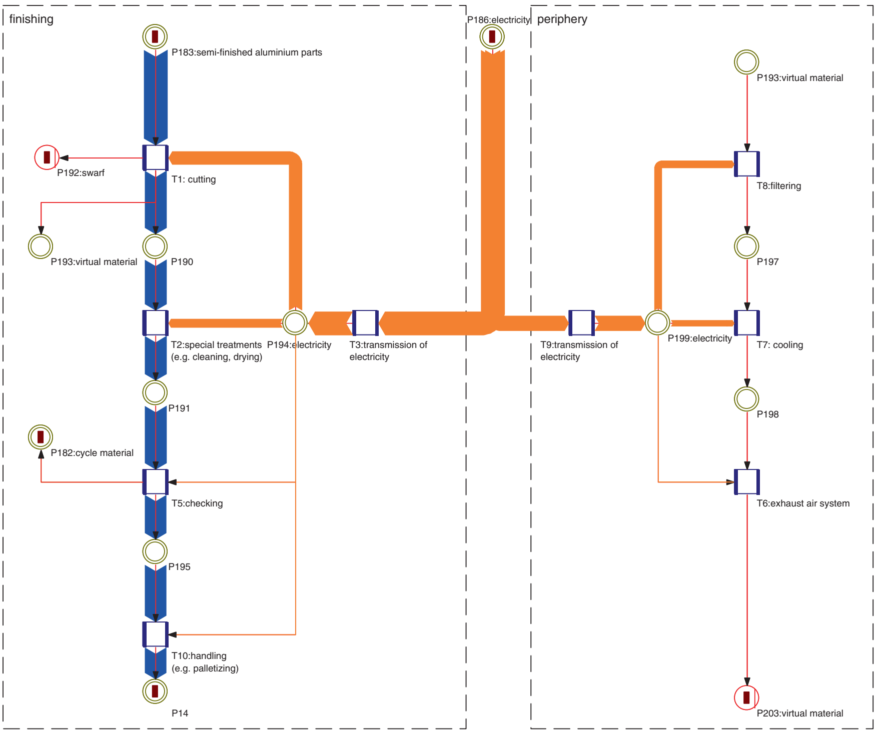


Fig. 5.55 Sankey diagram of energy carrier and aluminium flows in the foundry's finishing section

assessment according to the LCA methodology. Both evaluation perspectives will be pursued in the following section. Based on the results of this following evaluation, fields of action for individual improvement measures can be deduced again.

5.9 Analysis and Evaluation of the Generic Model

In this section the aluminium die casting value chain, which has been depicted in a generic energy and material flow model, shall be analysed and evaluated. The analysis and evaluation will be done regarding the actor specific, in-house energy demand. Furthermore, it will consider the overall environmental impact, which results from this energy and resource demand. The environmental assessment also includes the impact of the individual upstream process chains for the generation of the demanded resources and energy carriers. All analysis and evaluation refers to a functional unit of 1000 kg of finished aluminium products, which leave the foundry's gate to be delivered to the customer.[9]

[9]An overview over the environmental impact of the aluminium die casting chain value can be found at Heinemann et al. as well (Heinemann et al. 2013b). This overview gets complemented with detailed analysis in the present section.

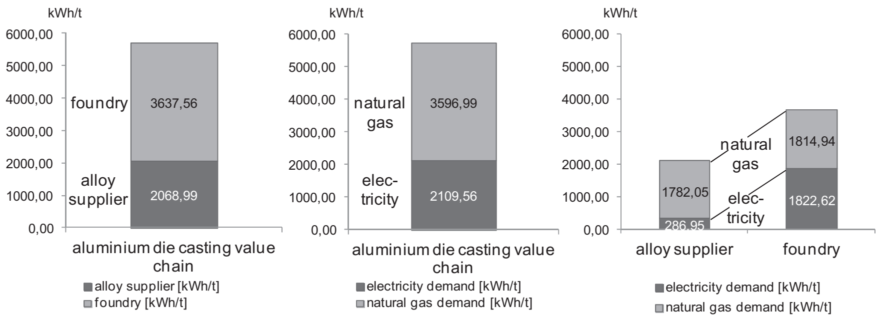


Fig. 5.56 Energy demand of the generic aluminium die casting value chain and its actors per tonne of finished aluminium products

5.9.1 Actor Specific Energy Demand Evaluation

Based on the results of the previous simulation of harmonized energy and resource demands along the aluminium die casting value chain, the actor specific energy demand can be calculated.

Figure 5.56 shows this actor specific energy demand and accumulates it into the overall energy demand of the observed actors in aluminium die casting (excluding energy demands in upstream process chains). The energy demand is displayed per actor and divided per energy carrier.

In total the actors foundry and alloy supplier demand 5706.55 kWh (in the form of electricity and natural gas) to produce 1000 kg of final products. For this task, the foundry demands for 76 % more energy than the alloy supplier. The higher energy demand of the foundry is due to higher vertical integration and value adding compared to the alloy supplier. Furthermore, the higher energy demand also results from the larger operating melting capacity at the foundry as it has to resmelt the cycle material redundantly in addition to the value adding aluminium flow, which gets delivered from the alloy supplier.

The high energy demand for melting is also reflected in the overall distribution of energy carriers along the value chain. The most relevant energy carrier in aluminium die casting is natural gas, which is mainly used for the melting of aluminium. Per tonne of finished product, the alloy supplier and foundry use 3596.99 kWh of energy, which gets provided from natural gas. Both actors account only for an electricity demand of 2109.56 kWh.

The energy carrier demands can be further subdivided for the actors foundry and alloy supplier. The dominating character of the natural gas demand becomes evident again. The electricity demand of the foundry is a little higher than its natural gas demand. However, due to the only marginal share of electricity demand regarding the total energy demand of the alloy supplier, the overall share of natural gas along the whole value chain describes the main energy carrier in aluminium die casting.

The calculated overall energy carrier demands and flows constitute an important part of the life cycle inventory of the aluminium die casting value chain. Together with the value chain's material demand and the upstream process chains, which create such materials and energy carriers, an environmental assessment will be done in the following section.

5.9.2 Environmental Assessment

The Umberto™ software offers the function to translate the simulated life cycle inventory data of modelled process or value chains into environmental life cycle assessments under the usage of the CML-methodology (see also Sect. 2.2.2). According to this methodology the environmental impact of the focused system can be expressed in the following baseline impact categories: Depletion of abiotic resources, impacts of land use (land competition), climate change, stratospheric ozone depletion, human toxicity, ecotoxicity (freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity), photo-oxidant formation, acidification, eutrophication (Guinée et al. 2002).

As already discussed above, the most accepted impact category at die casting companies is the climate change resp. global warming potential, which is measured in CO_2eq. This impact category is selected for the environmental assessment of the aluminium die casting value chain.

Figure 5.57 shows the evaluation results regarding the aluminium die casting value chain's environmental impact—expressed as global warming potential and measured in CO_2eq. Upstream process chains, which supply the foundry with energy carriers and the alloy supplier with energy carriers and raw materials, are allocated to this individual actor. Thus, the share of the alloy supplier's environmental impact is about 86 % higher than the impact of the foundry. However, this does not diminish the environmental relevance of the foundry operations, and both actors should be object of environmentally driven improvement measures.

The high total impact of the alloy supplier highlights the environmental influence of the raw material and energy carrier process chains. In order to identify levers within these upstream process chains and at the observed actors, sensitivity analyses about the actor specific energy demand and the environmental impact of the value chain will be conducted in the following section.

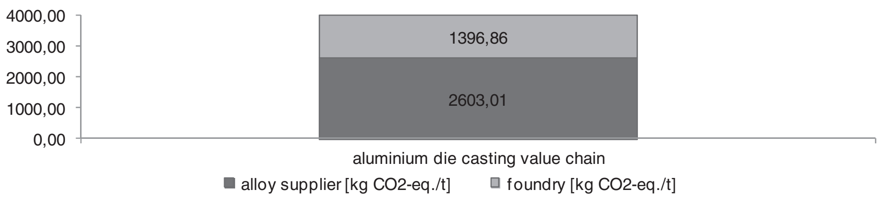


Fig. 5.57 Global warming potential of the aluminium die casting's value chain and its actors

5.9.3 Sensitivity Analyses

This section introduces sensitivity analyses, which have been applied to the generic aluminium die casting model in order to identify processes and flows, which have a relevant lever on the in-house energy demand of the observed actors as well as on the overall environmental impact of the value chain.

These sensitivity analyses will be done with a focus on the flows of energy carriers (natural gas and electricity) as well as aluminium (especially cycle material). Additionally the main alloying element silicon will be included in the sensitivity analyses in order to investigate the impact of its upstream process chain and its representation in an aluminium alloy.

For a selection of transitions, each of the named flows (electricity, natural gas, cycle material and silicon) will be manipulated incrementally, as long as it is incorporated in the transition's input/output balance. Thus, each flow will be increased and decreased by 5, 10 and 15 % individual for single transitions in order to evaluate the effect of this manipulation on the actor specific energy demand and the overall environmental impact of the value chain. The effect on the named evaluation categories, expressed in percents, will be compared to the effects of other flow manipulations at the same and other transitions. Thereby, the lever of possible improvement measures on selected transitions can be compared and the development and selection of promising improvement measures can be done more purposeful.

The sensitivity analyses will focus on transitions, which lead one to assume that they can be a lever for improvement measures due to the quantity of their individual input and output flows. Thus, for the sensitivity analyses, which focus on the electricity demand, only transitions with a demand of more than 100 kWh are considered. For those analyses, which focus on the natural gas demand, only transitions with a demand of more than 400 kWh are considered. For the sensitivity analyses, which focus on the amount of cycle material that leaves a transition, all affected transitions will be considered due to their relatively small number. The alloying element silicon is only processed in the transition *provision of alloying elements and auxiliary materials*. Therefore, this transition will be considered as well.

5.9.3.1 Electricity

In order to investigate the lever of single transitions' electricity demands on the overall energy demand of the alloy supplier and foundry, the following transitions have been object to a sensitivity analysis: die casting machine, cutting, special treatments, filtering, compressed air generation, cooling.

Figure 5.58 shows the deviation from an incremental increase and decrease of these single transition's electricity demands on the overall energy demand of the alloy supplier and foundry.

The die casting machine's electricity demand shows the largest lever on the overall energy demand of the observed actors. A decrease of 15 % of its electricity demand

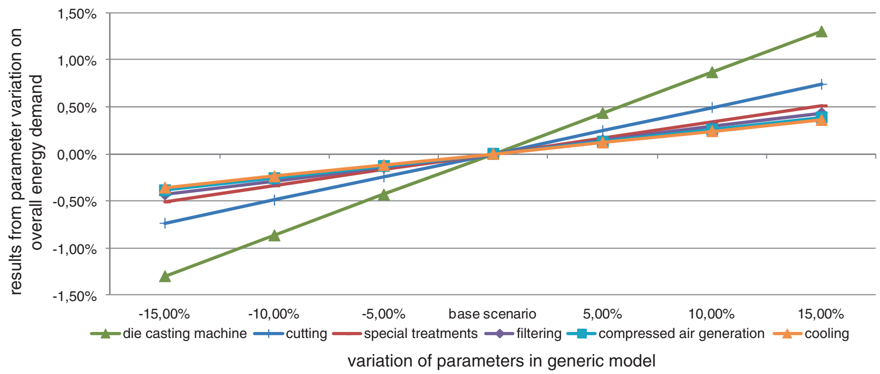


Fig. 5.58 Deviation of overall energy demand of the alloy supplier and foundry depending on incremental changes of selected transitions' electricity demand

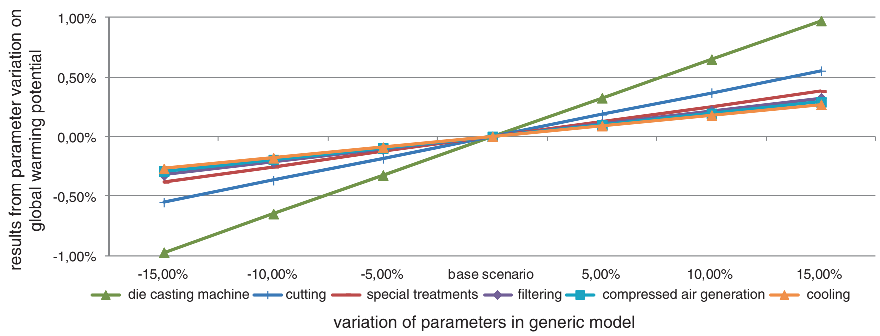


Fig. 5.59 Deviation of the global warming potential of the aluminium die casting's value chain after incremental changes of selected transitions' electricity demand

would result in a decrease of 1.3 % of the two actors energy demand. It is followed by the transitions cutting and special treatments. Thus, when the electricity demand at the observed actors is reduced, the die casting machine and cutting processes should be prioritized during the allocation of research and development resources.

Figure 5.59 shows the resulting global warming potential of the aluminium die casting value chain. The aforementioned reduction of the die casting machine's electricity demand would lead to a decrease of 0.97 % in the value chain's global warming potential.

5.9.3.2 Natural Gas

To investigate the lever of the natural gas demand of single transitions on the overall energy demand of the alloy supplier and foundry, the following transitions have been object to a sensitivity analysis: shaft melting furnace, converter, drum melting furnace.

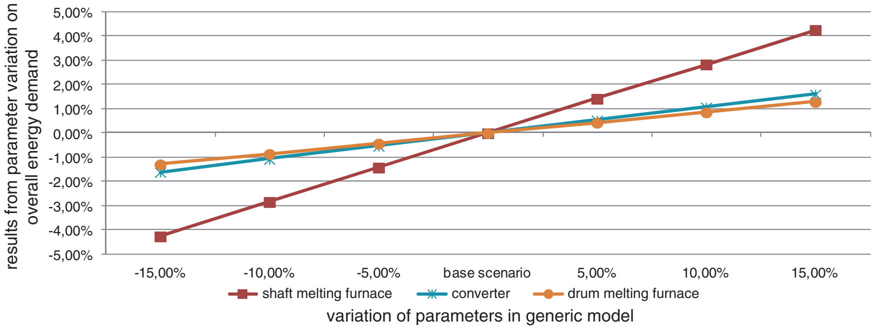


Fig. 5.60 Deviation of overall energy demand of the alloy supplier and foundry depending on incremental changes of selected transitions' natural gas demand

Figure 5.60 shows the deviation from an incremental increase and decrease of these single transitions' natural gas demands on the overall energy demand of the alloy supplier and foundry.

Due to the higher absolute natural gas demand, a higher lever can be identified here, compared to the sensitivity analysis of electricity demands. The shaft melting furnace's natural gas demand shows the largest lever on the overall energy demand of the observed actors. A decrease of 15 % of its natural gas demand would result in a decrease of 4.3 % of the two actors' energy demand. It is followed by the transitions converter and drum melting furnace, which both have an equal or larger effect than the die casting machine's electricity demand. Thus, measures for the reduction of natural gas demands should be prioritized if a reduction of the overall energy demand is the aim.

Figure 5.61 shows the resulting global warming potential of the aluminium die casting value chain. The aforementioned reduction of the shaft melting furnace's

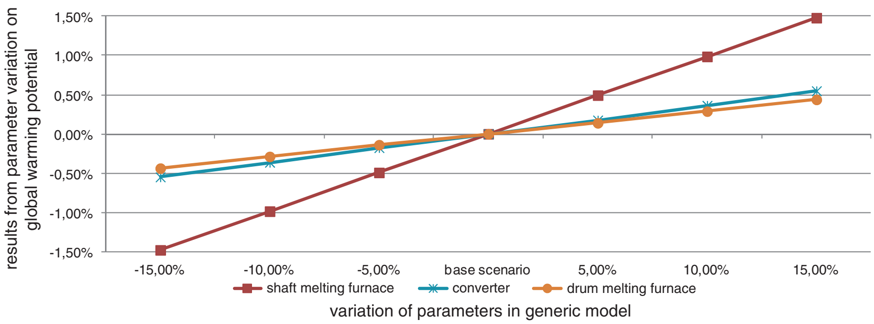


Fig. 5.61 Deviation of the global warming potential of the aluminium die casting's value chain after incremental changes of selected transitions' natural gas demand

natural gas demand would lead to a decrease of 1.48 % of the value chain's global warming potential.

5.9.3.3 Aluminium (Cycle Material)

As measures for reducing the natural gas demand shall be prioritized, the reduction of cycle material is one promising option. A reduction of the circulating material, which needs to be resmelted redundantly, directly influences the needed melting capacity and its natural gas demand. Furthermore, due to less melting losses, it can also reduce the aluminium supply demand of the value chain and, therefore, decrease the impact of the upstream process chains.

To investigate the lever of a cycle material reduction on the value chain's energy demand and the overall environmental impact, the following transitions have been object to a sensitivity analysis: die cutter, cutting, checking.

Figure 5.62 shows the deviation from an incremental increase and decrease of these single transitions' cycle material output on the overall energy demand of the alloy supplier and foundry.

The die cutter's cycle material output shows the largest lever on the overall energy demand of the observed actors. A decrease of 15 % of its cycle material output would result in a decrease of 3.9 % of the two actors' energy demand. The lever of the other two transitions is negligible. Thus, when the electricity demand (especially the natural gas demand) at the observed actors shall be reduced, a reduction of the cycle material, which gets stamped of the cast at the die cutter, should be prioritized during the allocation of research and development resources. This means, that a change in the product and die design has a larger lever on the overall energy efficiency of the value chain than any measures to reduce scrap or defect parts.

Figure 5.63 shows the resulting global warming potential of the aluminium die casting value chain. The aforementioned reduction of the die cutter's cycle material output would lead to a decrease of 5.9 % of the value chain's global warming potential.

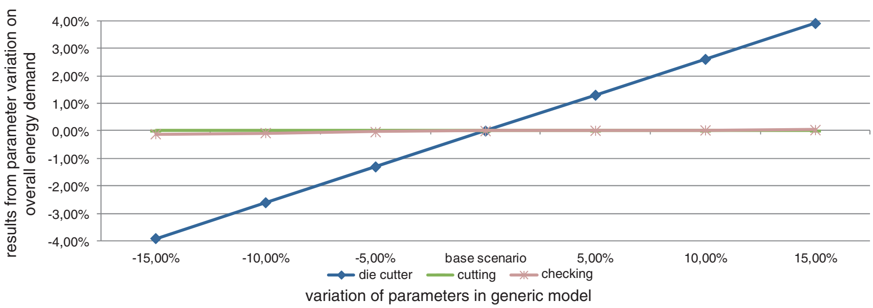


Fig. 5.62 Deviation of overall energy demand of the alloy supplier and foundry depending on incremental changes of selected transitions' cycle material output

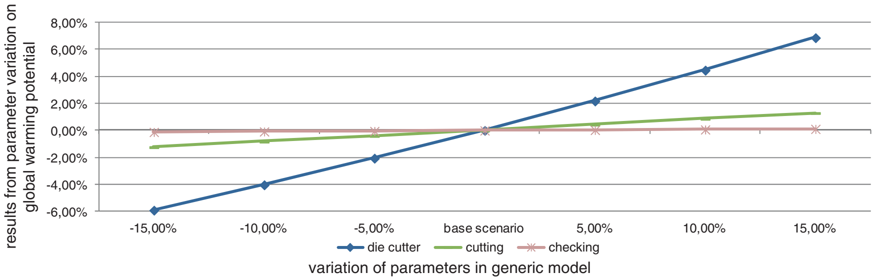


Fig. 5.63 Deviation of the global warming potential of the aluminium die casting's value chain after incremental changes of selected transitions' cycle material output

5.9.3.4 Alloying Elements

In consideration of the fact, that the processed aluminium alloy does not only consist of aluminium but also of manifold alloying elements (mainly silicon and copper); a deviation of the alloy composition shall be considered in the following section. This affects mainly the environmental impact of the upstream process chain. The deviation of the necessary melting energy at the two actors is negligible due to the relatively small deviation in specific melting energy of the added alloying elements and added volumes.

To investigate the lever of an alloying element variation exemplarily, the following alloying elements have been object to a sensitivity analysis within the transition *provision of alloying elements and auxiliary materials*: silicon (primary silicon for alloying purposes), copper (secondary copper for alloying purposes.

The added silicon represents primary silicon, which has been created energy intensively. The added copper represents a secondary copper flow, which gets collected and sorted externally before it is added at the alloy supplier as further secondary metal fraction. Therefore, the environmental impact of the copper's prior generation and usage are allocated to this prior life cycle. Thus, it has a quasi-neutral environmental impact in the actual sensitivity analysis. The deviation of the silicon and copper shares within the alloy gets compensated through an increase or decrease of the other alloying elements and aluminium fractions in equal measure.

Figure 5.64 shows the resulting global warming potential of the aluminium die casting value chain after a deviation of the added silicon and copper shares regarding the aluminium alloy composition.

A decrease of 15 % of the added silicon mass into the aluminium alloy would result in a decrease of 1.9 % of the overall environmental impact of the value chain. This shows that a manipulation of the alloy composition can have a comparable or even higher impact on the environmental performance of the value chain compared to technical process improvement measures at the alloy supplier or foundry. In the case of copper, even an increase of the added copper can lead to a decrease of the environmental impact. This is due to the fact

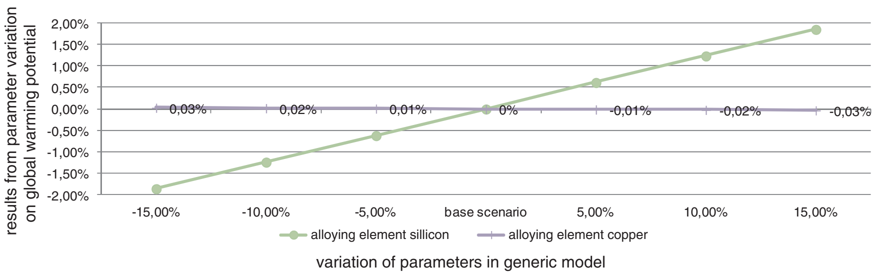


Fig. 5.64 Deviation of the global warming potential of the aluminium die casting's value chain after incremental changes of the alloy composition regarding its shares of added silicon and copper

that an addition of the environmentally relatively harmless secondary copper replaces other more environmentally harmful alloying elements. However, this effect is rather small.

In conclusion, it can be stated that a leveraging effect on the actors' energy demand, as well as on the overall environmental impact of the value chain, can be observed especially as a result of a variation of the total smelted aluminium masses. Therefore, a reduction of the processed material flow should be the focus of improvement measures. Furthermore, the die casting machine and all melting operations offer fields of action for promising improvement measures due to their high absolute energy carrier demands. Thus the most important process for multi-dimensional improvements is the die casting process itself, as it is located in a high energy demanding process and as it determines the amount of cycle material due to the design of its internal dies.

Having this information in mind, improvement measures can be developed purposefully. They can be implemented and evaluated again according to the above introduced procedural approach (see Sect. 5.2.3).

The following section introduces a sample selection of such measures. These measures tackle the aluminium die casting value chain at different fields of action, at different actors and on different system levels. However, their potential gets assessed within the same generic model.

5.10 Improvement Scenarios

The above introduced sensitivity analyses have manipulated the main energy and resource flows of aluminium die casting, and identified quantitative saving potentials per considered process. This has been done under the assumption, that these hypothetical flow manipulations are technically possible. The present section will introduce a sample selection of improvement measures, which have been developed and tested. For most of them the actual saving potential has been assessed (via data acquisition) after their implementation according to the above introduced procedural approach by taking an ex-post perspective. However, not all measures have been implemented directly or it would have been too effortful to implement them without a prior assessment (e.g., via dynamic simulation). For those measures, the taken ex-ante perspective will also be explained in the following section. For each presented measure, the resulting actor specific energy demand and the resulting overall environmental impact of the value chain will be evaluated. The common basis for all evaluation is the presented generic model of the aluminium die casting value chain.[10]

The following measures have been selected and will be compared with the base scenario. The base scenario represents the evaluation results of the generic aluminium die casting model without implemented improvement measures.

- reduced cycle material due to optimised gating systems (scenario A)
- delivery of liquid aluminium to foundry (scenario B)
- salt-free smelting of purified secondary aluminium in shaft melting furnaces at alloy supplier (scenario C)
- deactivation of filters at melting furnaces (scenario D)
- electricity savings at the finishing section due to organizational changes (scenario E)
- reduced compressed air demand due to fixed leakages (scenario F)
- reduced compressed air demand and less die tempering due to optimized spray heads for form release agents (scenario G)
- improved process parameters for the T7 heat treatment (scenario H)
- renewable electricity supplies from hydropower plants (scenario I)
- combination of scenarios A-H (scenario J)
- combination of scenarios A-I (scenario K)

Figure 5.65 adopts Fig. 5.16 and additionally displays the point of application of the selected measures along the value chain.

The displayed points of application illustrate the diversity of measures, which will be evaluated and compared on the common basis of the generic aluminium die casting model, though it needs to be stated that the displayed points of application describe only the main and characterising point of action. Due to the interdependencies of the manifold transitions within the model, further flows than those at the point of action can be tackled by single measures.

The selected measures will be introduced in the following section before their impact on the actor specific energy demand and the value chain's global warming potential will be presented.

[10]Please note that the introduced improvement measures have been developed in the research project ProGRess (www.progress-aluminum.de) by the involved consortium. The presented results are anonymised and alienated due to confidentiality reasons. However, the ranking of the measures, which is possible with the help of the generic model, still reflects their real comparative potential. For further information about the project and the introduced measures please also have a look at Herrmann et al. (2013a).

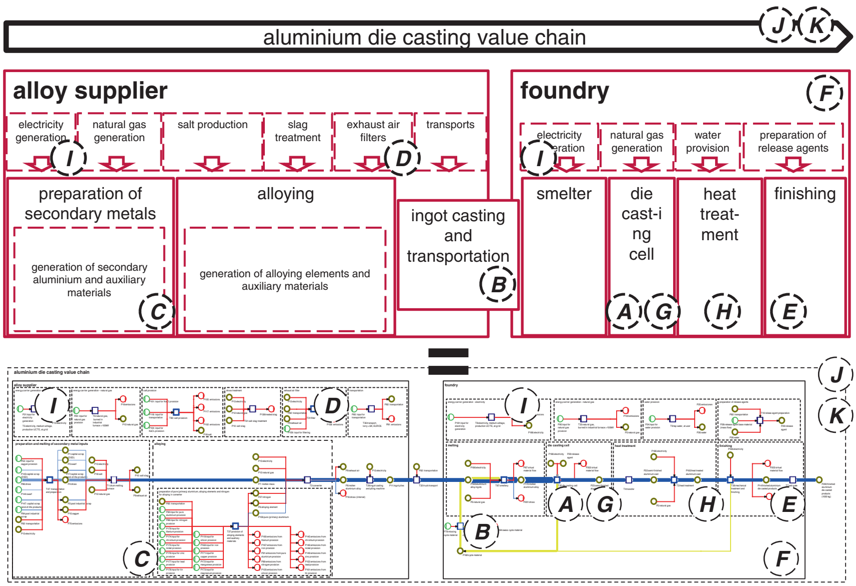


Fig. 5.65 Points of application of selected improvement measures (according to Heinemann et al. 2013b)

5.10.1 Description of Improvement Measures

This section gives a short introduction to the basics of the developed improvement measures and their influence on the transitions and structure of the generic aluminium die casting model.

5.10.1.1 Scenario A: Reduced Cycle Material Due to Optimised Gating Systems

According to the procedural approach for aluminium die casting (see Sect. 5.2.3) and the introduced synergetic application of methods (see Sect. 4.3.3), manifold detailed product and process simulations for the die casting process in dependency of the product's and die's geometry have been conducted (Hartmann 2013). These simulation runs has been done with the software MAGMASOFT™. As a result, for many observed products the volume of the gating system can be reduced significantly without reducing the products quality (in terms of porosities, solidification behaviour, mechanical properties, etc.). Figure 5.66 shows the comparison of two geometries of a representative sample product's gating system. As a result of the improved gating system design, the gating system's material volume (cycle

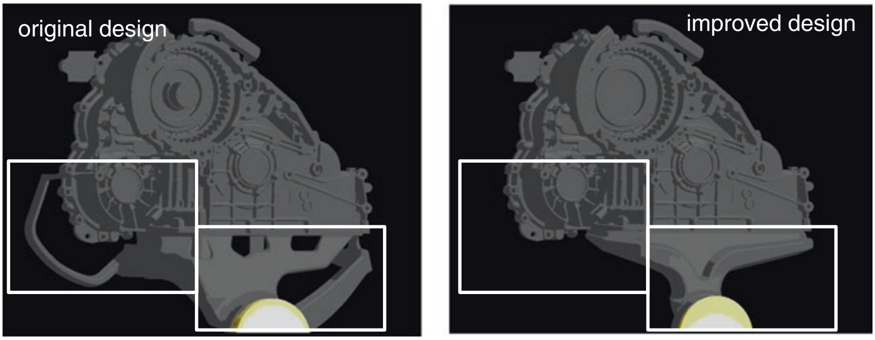


Fig. 5.66 Original design of gating system and improved geometry after application of software MAGMASOFT™ (according to Hartmann 2013)

material) could be reduced by 25 %. The total material volume per cast could be reduced by 12 % (Hartmann 2013).[11]

The information about the possible cycle material reduction has been transferred into the generic die casting model through an adaption of the transition *die cutter*. Here, the cycle material output has been reduced by 25 % and the required aluminium input has been reduced by 12 %. During the later simulation of the harmonized flows along the value chain, this adaption induces a decrease of the aluminium input flow at all upstream processes from the die cutter's perspective. Due to the reduced aluminium input flows, it also induces reduced energy demands and melting losses at smelting operations.

5.10.1.2 Scenario B: Delivery of Liquid Aluminium to Foundry

Overheating of the molten alloy at the alloy supplier allows the transportation of liquid aluminium supplies to the foundry. This makes an energy-intensive resmelting at the foundry unnecessary. However, the smelter at the foundry is still necessary as it has to smelt the internal flow of cycle material.[12]

To enable the transport of liquid aluminium alloys, the following preconditions need to be fulfilled and adapted to the generic die casting model. The distance between alloy supplier and foundry is assumed to be 100 km. Due to heat losses during transportation, the molten aluminium needs to be overheated by 120 °C up to a temperature of ca. 880 °C in order to reach the foundry at a castable temperature. This overheating is represented through an additional transition *overheating*.

[11]The presented product is not one of the observed objects of investigation. However, the identified material saving potential is transferable also to the products, which are modelled in the generic aluminium die casting model.

[12]For a description of logistical configuration alternatives of aluminium supplies from alloy supplier to the foundry, please see Sect. 2.1.2 and Heinemann and Kleine (2013).

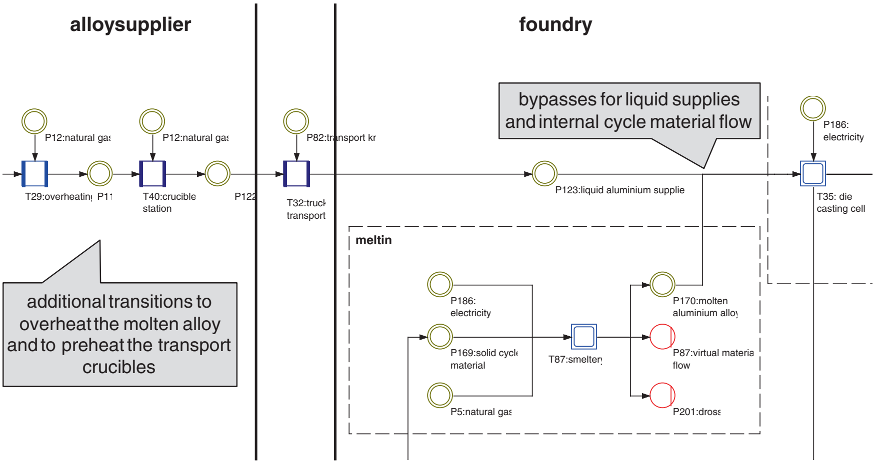


Fig. 5.67 Structural adaption of the generic model to enable liquid aluminium supplies from the alloy supplier to the foundry

Furthermore, the pouring of the molten aluminium into transport crucibles takes longer than the casting of aluminium ingots. Due to the longer length of stay of the alloy in the converter, the energy demand of the transition *converter* also needs to be increased slightly. An additional preheating of the required transport crucibles, in which the molten alloy gets transported to the foundry, is represented in an additional transition *crucible station*. Figure 5.67 shows the structural adoptions of the generic aluminium die casting model, which result from the described requirements of the liquid aluminium supply.

The described extra energy demands at the alloy supplier enable larger energy savings at the foundry as this actor only needs to resmelt its internal cycle material. Below, the quantitative additional efforts of saving potential per actor will be evaluated and compared to the other measures.

5.10.1.3 Scenario C: Salt-Free Smelting of Purified Secondary Aluminium in Shaft Melting Furnaces at Alloy Supplier

In contrast to the base scenario, the scenario C describes an extensive preparation of the processed secondary aluminium fractions. Originally, the base scenario models the smelting of these metal inputs without extensive preparation in the drum melting furnace. The impurities of the metal inputs get extracted from the molten mass by adding salt and skimming it as dross and salt slag. The dross itself gets resmelted and the slag has to be disposed. Against this conventional procedure, impurities are already removed during an extensive preparation of the secondary metal fractions. This enables the later smelting of the secondary metal fractions in a more efficient shaft melting furnace without the addition of salt,

Table 5.20 Additional transitions per secondary aluminium fraction in subnet *transportation and preparation of secondary aluminium fractions*

Secondary aluminium fraction	Additional transition (preparation process)
Post industrial scrap	Smouldering
capital scrap (end-of-life products)	Smouldering
Dross	Shredder, sieving
Swarf	Drying, magnetic separator
Capital scrap (DSD)	Magnetic separator, swim float separator

and without a subsequent treatment and disposal of the salt slag. For this purpose, Table 5.20 lists the added energy demanding transitions per secondary metal fraction, which has been added to the generic models subnet *transportation and preparation of secondary aluminium fractions*.

The resulting structural adoption of the generic model's subnet is depicted in Fig. 5.68.

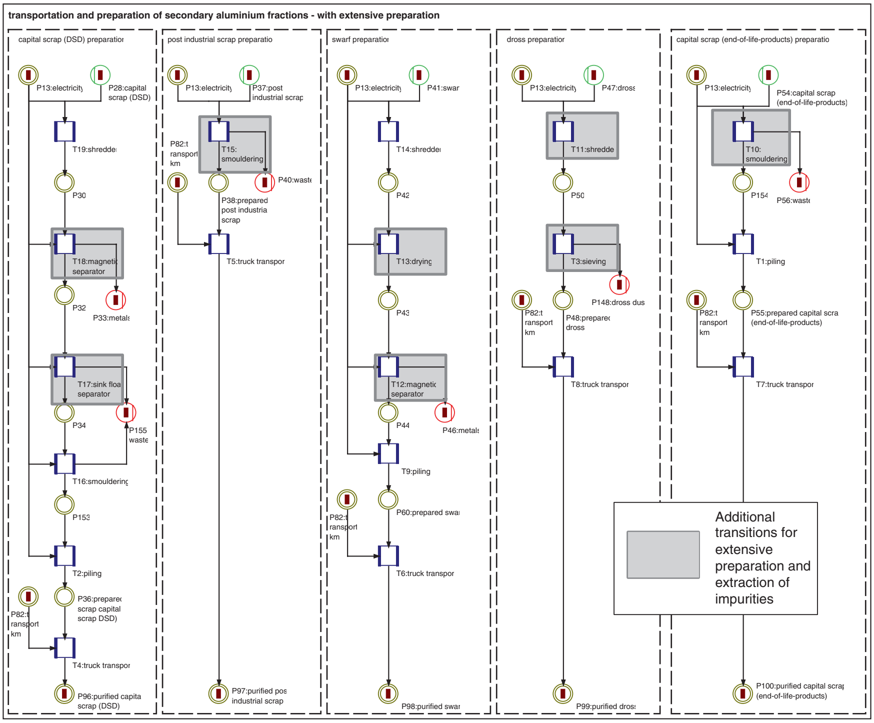


Fig. 5.68 Structural adaption of the generic model's subnet *transportation and preparation of secondary aluminium fractions* to enable salt free smelting of secondary aluminium fractions in shaft melting furnace

This alternative procedure for an extensive preparation and purifying of secondary metal input materials does not only decrease the alloy supplier's energy demand although it adds some additional transitions, it also decreases the environmental impact of the value chain due to a decreased salt demand and disposal volumes. The quantitative results of this evaluation will be compared to the other measures after the introduction of the further measures.

5.10.1.4 Scenario D: Deactivation of Filters at Melting Furnaces

Due to the partially unhealthy emissions of melting furnaces, they are supported by exhaust air filters, which have a high electrical power demand during operation. Pithan has investigated the actual emissions of a shaft melting furnace during melting and charging operations in order to identify potential off times of the connected energy intensive exhaust air filtering system. During his investigations, the emission hydrogen fluoride (HF), gaseous inorganic chlorine compounds (expressed in HCL) and dust (including respirable dust), have been metered in the exhaust air flow. Based on Pithan's results, a deactivation of the filtering system seems to be possible without exceeding the legal threshold values for the observed emissions (Pithan 2013b, 2014)

Due to this reason, in the actual scenario, the transition *exhaust air filter* (including its electricity demand) in the foundry's smelter has been deleted from the generic aluminium die casting model. The effect of this measure will be compared to the other measures in Sect. 5.10.2.

5.10.1.5 Scenario E: Electricity Savings at the Finishing Section Due to Organizational Changes

From the data acquisition, it is known that many processes especially in the finishing section show a large electrical energy demand during waiting times. Thus, the reduction of waiting times of such machines combined with an automated intermediate switching off during inevitable waiting times could offer an energy saving potential. For the case of an abrasive blasting process, this is especially true (see Sect. 5.7.2, Fig. 5.39). The considered blasting process is supplied with parts in a one piece flow. Between two parts, it is idling with a very high electrical power demand. It can be idling due to the fact that at the implemented one piece flow the blasting process is not the bottle neck. Thus, the introduction of a batch flow of parts into the blasting process combined with an automated switching off could offer energy saving potential. However, the batch size needs to be chosen carefully, so that no new bottleneck situations are caused by the blasting process. Therefore, Herrmann et al. and Thiede have conducted several simulation experiments to an interlinked process chain of three die casting cells and a finishing section. As a result, an optimal lot size for the blasting process of four parts could be identified, which led to a decreased electrical energy demand of 7 % of the observed production line. This saving potential can be allocated to the finishing section (Herrmann et al. 2011a, 2013b; Thiede 2012).

According to the procedural approach for aluminium die casting (see Sect. 5.2.3) and the introduced synergetic application of methods (see Sect. 4.3.3), these simulation results can be conveyed to an evaluation within the generic aluminium die casting model. In combination with further possible organisational improvement measures (see e.g. Herrmann et al. 2011a, 2013b; Thiede 2012), an overall reduction of 10 % of the electricity demand at all value adding processes in the finishing section is assumed (Herrmann et al. 2011a, 2013b; Thiede 2012). Therefore, this demand has been reduced by 10 % in all corresponding transitions in the finishing section. This enables the exemplary evaluation of organisational measures, which have been tested in an energy oriented material flow simulation before.

5.10.1.6 Scenario F: Reduced Compressed Air Demand Due to Fixed Leakages

Through the reduction of leakages in the compressed air system of a foundry, about 20 % of the air compressor's energy demand can be reduced (Geisler 2013; Röders et al. 2006). In the actual scenario F, the electricity demand of all air compressors in the foundry has been reduced by 20 %.

5.10.1.7 Scenario G: Reduced Compressed Air Demand and Less Die Tempering Due to Optimized Spray Heads for Form Release Agents

The implementation of an efficient spray head at the spraying robot in combination with the use of an innovative release agent concentrate leads to a large saving potential regarding the compressed air and water flow for the spraying of the release agent. The release agent is designed for a minimal quantity spraying onto the die. Thus, the demand of release agent concentrates can be reduced by 94 %. In parallel, the water demand can be reduced by 85 %. Due to the reduced mass flow, which needs to be sprayed onto the die via compressed air, the electricity demand of the air compressors of the die casting cell can also be reduced by 90 %. Due to the reduced spraying onto the die, less heat also gets extracted via vaporisation. Thus, the supply temperature of the tempering units can also be reduced by 20 °C. This reduces the electricity demand of the tempering units by about 30 % (Dilger et al. 2003; Tomazic et al. 2013).

The transitions *spraying robot*, *tempering units*, *compressed air generation* and *release agent preparation* at the die casting cell have been manipulated corresponding to the above described reduced demands for electricity, water and release agent concentrate.

Table 5.21 Best variation of process parameters of a T7 heat treatment process regarding the resulting energy saving potential (see also Kleine and Heinemann 2013)

Process step	Time variation (min)	Temperature variation	Energy demand of this process step (%)
Solution annealing	−95	Constant	−83
Artificial ageing	−75	+15 °C	−74

5.10.1.8 Scenario H: Improved Process Parameters for the T7 Heat Treatment

For many T7 heat treatment operations, the process parameters (temperatures and duration for solution annealing and artificial ageing) were defined with a large safety margin to ensure constant mechanical properties and a flawless quality of the heat treated product. However, the definition of these process parameters usually did not take the necessary energy input into account, which mainly depends on the temperatures and duration of the process steps. Thus, a reduction of temperatures and duration offers a potential for a reduction of the heat treatment's energy demand.

Kleine and Heinemann have tested the impact of time and temperature variations of the heat treatment process on the resulting mechanical properties of sample products. The effect on elasticity limit ($Rp_{0.2}$), tensile strength (Rm) and breaking elongation (A_5) has been tested. It could be observed that even at drastically reduced durations of the heat treatment, steps in combination with stable or slightly increased temperatures still lead to acceptable mechanical properties but to largely decreased energy demands. Acceptable mechanical properties could still be reached with the following heat treatment parameter variations, which resulted in a strongly reduced energy demand (see Table 5.21; Kleine and Heinemann 2013).

The process step *quenching* has not been manipulated. All energy measurements have been done in a laboratory environment at electric holding furnaces. However, it is assumed that the energy savings expressed as a percentage are also transferable to industrial, continuous furnaces. The electricity and natural gas demands of the transitions *solution annealing* and *artificial ageing* have been reduced according to the above illustrated energy saving potential.

5.10.1.9 Scenario I: Renewable Electricity Supplies from Hydropower Plants

In addition to the above described measures, which describe technical and organisational adoptions within the alloy supplier or foundry, the measure of scenario I describes the impact of an organisational decision, which unfolds its potential upstream of the observed actors. To estimate the impact of the upstream electricity generation as one external lever on the aluminium die casting value chain's environmental impact, the used electricity mix has been adopted.

Instead of the standard European energy mix, which has been modelled with the ecoinvent dataset "electricity, medium voltage production UCTE, at grid", the source of the electricity supplies in the actual scenario is a purely hydropower based electricity generation. This electricity generation has been modelled via the ecoinvent dataset "run-of-river hydropower plant" (Bolliger and Bauer 2007). It represents an energy mix, which is based on the average of Swiss run-of-river hydropower plants.

Such measures are not specific for the aluminium die casting value chain, and can be integrated in the majority of other industrial value chains unless the volume of supply is ensured. However, the universality of this measure makes it even more interesting to be evaluated for the observed specific value chain. The individual changes in the resulting environmental impact will be compared to the results of the aforementioned measures in Sect. 5.10.2.

5.10.1.10 Scenario J: Combination of Scenarios A–H

The actual scenario J represents a combined application of all aforementioned measures (scenarios A–H). This combination represents the technical and organisational measures, which have a specific background for aluminium die casting.

5.10.1.11 Scenario K: Combination of Scenarios A–I

The actual scenario K represents a combined application of all aforementioned measures (scenarios A–I). This combination represents all specific die casting measures in combination with the universal adoption of the electricity mix, which has been described in scenario I.

5.10.2 Comparative Evaluation of Improvement Measures

In this section, the above described sample improvement measures will be evaluated and compared with each other and with the base scenario. For each scenario, a simulation of the adopted resulting harmonized flows has been done with the help of the software Umberto™. As a result the actor specific energy demand can be documented. By conducting a subsequent evaluation according to the CML-methodology (see Sects. 2.2.2 and 5.9.2) within the same software Umberto™, the overall environmental impact (expressed in global warming potential, measured in CO_2eq.) can be calculated for each scenario as well.

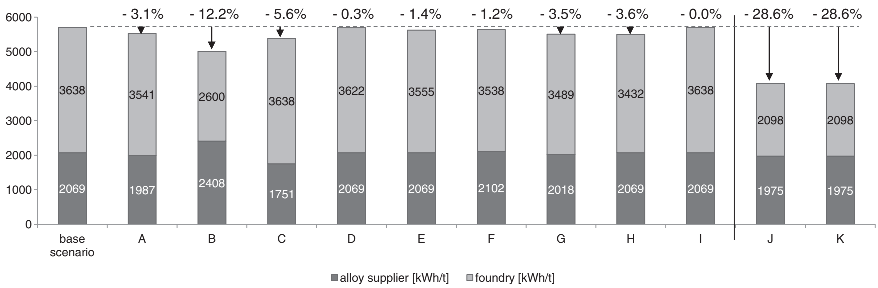


Fig. 5.69 Impact of improvement measures on actor specific energy demands along the aluminium die casting value chain

Figure 5.69 shows the results of the actor specific energy demand calculation. It can be observed that except for scenario I, all improvement measures lead to a reduced energy demand compared to the base scenario. The measures' effect on energy savings has a range from about one percent or less (scenarios D, E, F, I) up to more than ten percent (scenario B). Scenario B is especially interesting as it shows an example in which one actor (alloy supplier) has to accept a less favourable energy demand from its individual perspective to enable an energy saving potential at another actor (foundry), which more than compensates for the extra efforts of the first actor. As a result, in total a remarkable amount of energy saving potential over the whole value chain can be achieved.

The change in the supplied energy mix (scenario I) does not have an impact on the actors' energy demand, as it only changes the source of it. By implementing all introduced measures in parallel, up to 28.6 % of the combined energy demand of the alloy supplier and the foundry can be saved. This equals an energy saving potential of about 1634 kWh/t of final aluminium die casted products, which leave the foundry's factory gates to the customer.

Figure 5.70 shows the distribution of energy carrier demands, which results from the implemented improvement measures. The absolute saving potential per measure in this picture is of course the same as in Fig. 5.69. However, this

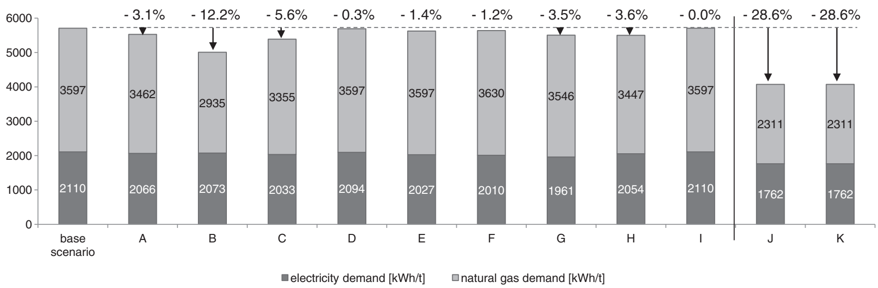


Fig. 5.70 Distribution of energy carrier demands per improvement scenario

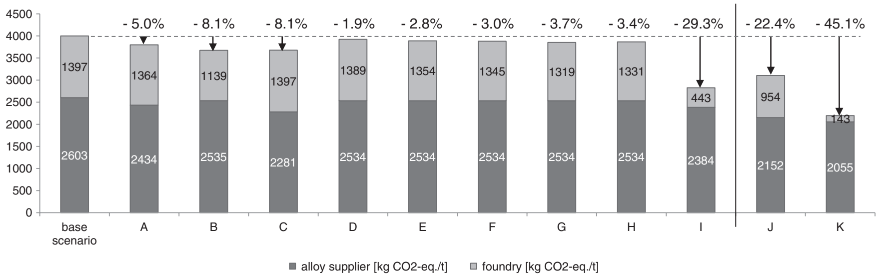


Fig. 5.71 Resulting global warming potential of the aluminium die casting value chain after the implementation of improvement measures

distribution provides a first insight in the resulting environmental impact of the value chain. For scenario B, it can be seen that the large energy saving potential affects mainly the energy carrier natural gas, which is less environmental harmful to provide than electricity. Other scenarios focus more on electricity savings (e.g., scenarios C, E, F, G).

Figure 5.71 shows the resulting global warming potential after the implementation of the improvement measures. All introduced measures are able to reduce the global warming potential of the aluminium die casting value chain. The potential of the measures' CO_2eq. savings potential ranges from small effects at about 2 % (scenario D) over medium effects at about 5 % to 8 % (scenarios A, B, C) to large effects at about 29 % (scenario I). By implementing all introduced measures (except scenario I) in parallel, up to 22.4 % of the overall global warming potential of the value chain can be saved. This equals an energy saving potential of about 894 kg CO_2eq. per tonne of final aluminium die casted products leaving the foundry's factory gates to the customer. The saving potential expressed in percentages is less than the energy saving potential due to the relatively higher natural gas saving potential compared to the electricity saving potential. Scenario I is one option to reduce especially the global warming potential, which results from satisfying the electricity demand. Implementing scenario I (substitution of electricity from common European energy mix with electricity from Swiss hydropower plants) in parallel to the other scenarios also promises a CO_2eq. saving potential up to 45 %. This equals an energy saving potential of about 1802 kg CO_2eq. per tonne of final aluminium die casted products. Due to the high share of electricity demand at the foundry, an implementation of scenario I would drastically decrease its global warming potential compared to the current global warming potential, which results from the activities of the alloy supplier and its connected upstream process chains.

The differing environmental impact potential of the two energy carriers (electricity and natural gas) becomes evident via a comparison of scenario B and scenario C. Although scenario B shows a much larger energy saving potential (12.2 %) compared to scenario C (5.6 %) both enable the same reduction of the value chain's global warming potential (8.1 %) due to the higher share of electricity, which can be saved in scenario C.

Table 5.22 Comparison of energy and CO_2eq. saving potentials

Scenario		Saving potential compared to base scenario	
		Energy demand (%)	Global warming potential (%)
A	Reduced cycle material due to optimised gating systems	3.1	5.0
B	Delivery of liquid aluminium to foundry	12.2	8.1
C	Salt-free smelting of purified secondary aluminium in shaft melting furnaces at alloy supplier	5.6	8.1
D	Deactivation of filters at melting furnaces	0.3	1.9
E	Electricity savings at the finishing section due to organizational changes	1.4	2.8
F	Reduced compressed air demand due to fixed leakages	1.2	3.0
G	Reduced compressed air demand and less die tempering due to optimized spray heads for form release agents	3.5	3.7
H	Improved process parameters for the T7 heat treatment	3.6	3.4
I	Renewable electricity supplies from hydropower plants	0.0	29.3
J	Combination of scenarios A–H	28.6	22.4
K	Combination of scenarios A–I	28.6	45.1

Table 5.22 lists the saving potentials regarding energy demand and global warming potential per scenario. The quantitative saving potential of each scenario should justify an implementation of the underlying measure in order to reduce the environmental impact of aluminium die casting and the affected actor's energy costs. Nevertheless, the overview over the evaluation results, which is presented in Table 5.22, allows a reasonable prioritisation of these measures. A prioritisation of such diverse measures, which tackle the observed value chain's energy and material flows at different actors and on different hierarchical system levels, has only been possible through the developed procedural approach and the deduced generic aluminium die casting model, and the extensive data which has been gathered and used to parameterise this model.

Chapter 6
Summary and Outlook

This chapter summarizes the provided work of the previous chapters. The contents in general, and the developed approach in particular, will be briefly recapitulated. Having the identified research demand in mind, this chapter also tests the demand fulfilment of the developed novel multi-level and multi-scale approach for enhancing energy and resource efficiency in production. Additionally, an outlook of potential research fields will be given, which could complement the presented work.

6.1 Summary

The purpose of this book is to raise a holistic perspective on hierarchically organised production systems, to provide a methodological approach for increasing energy and resource efficiency in such systems and to elaborate the specific case of aluminium die casting while pursuing this perspective and approach. The motivation for such a perspective and approach in energy and resource intensive industries like aluminium die casting is outlined in Chap. 1.

In Chap. 2, aluminium die casting gets introduced from a technical perspective and regarding its environmental challenges. To support these two aspects, the basic concepts of hierarchical production organisation and methodologies for mitigating the environmental impact of production are also presented. As a result, the large environmental impact of aluminium die casting is elaborated and challenges for its reduction are illustrated. The chapter identifies a demand for extended methodological support in this area to drive industrial production and especially aluminium die casting towards sustainable production.

Having this demand in mind, Chap. 3 identifies and evaluates the current relevant research approaches about multi-level and multi-scale approaches for energy and resource efficiency in production. These approaches are clustered in generic approaches and specific approaches with a focus on metal casting or related

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DOI 10.1007/978-3-319-18815-7_6

application examples. Based on the evaluation of the state of research, the general demand for methodological support, which has been stated already in the previous chapter, can be further specified.

This specified demand induces the requirements and surrounding conditions for a novel framework, which is developed in Chap. 4. This framework aims to provide support for enhancing the energy and resource efficiency in hierarchically organised production systems. Therefore, it suggests a clear system definition of vertical and horizontal hierarchies in production, and assigns methods for data acquisition, modelling, simulation and evaluation to the system elements. The synergetic application of these methods is discussed and composed in a procedural approach for the joint application of methods. Furthermore, an exemplary KPI-framework is provided, which also highlights the level-specific perspective on planning and evaluation as well as the level-spanning interrelationship of performance indicators.

Chapter 5 transfers the developed concept to the specific case of aluminium die casting. After a detailed specification of the framework's elements for this specific case, the developed procedural approach gets applied to twelve existing aluminium die casting value chains at three different foundries. After an introduction of these objects of investigation and a clear definition of system boundaries, the structure of the considered value chains and subordinate system elements gets analysed to derive a generic structural model of aluminium die casting. This model gets parameterised with extensively generated data about the energy and resource demands of representative, real existing system elements. As a result, a quantitative generic model of energy and resource flows in aluminium die casting gets presented and evaluated. Against this generic model, possible examples of improvement measures are tested. They tackle the value chain at different actors and on manifold system levels. The measures are compared on the common basis of the developed model to enable a ranking and derivation of recommendations for action.

The chapter at hand concludes this work with a critical evaluation of the developed concept. The concept itself delivers a great contribution to the available data about energy and resource flows. However, compliance with the further identified research demand also gets evaluated. Although this critical evaluation of the developed concept proves significant advances compared to the state of research, some open aspects can still be identified. Therefore, this book closes with an outlook on possible adjacent research topics.

6.2 Concept Evaluation

The presented approach for a multi-level and multi-scale framework towards energy and resource efficiency in production represents a suggestion to satisfy the identified research demand. This approach shall be evaluated against the same criteria like the state of research (see Chap. 3) to ensure an objective and comparative

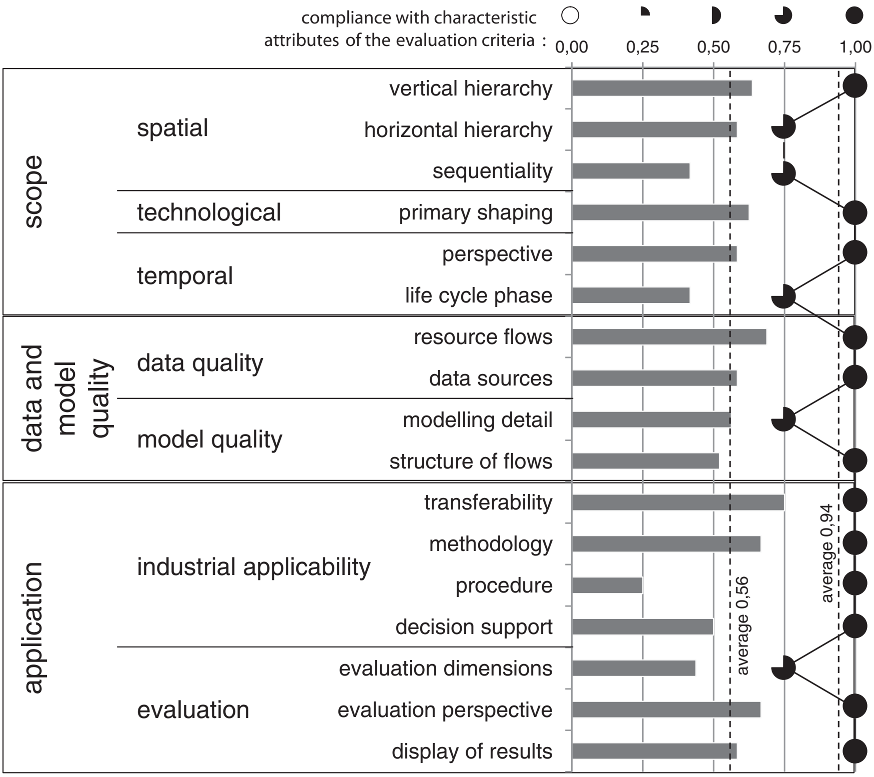

Fig. 6.1 Evaluation of proposed framework against the state of research

assessment. Figure 6.1 shows an overview over the results of this evaluation. In this figure the individual classification according to the evaluation criteria's attributes is depicted through the same cumulative metric, which is expressed in empty points (○) to full points (●). This classification is mapped against the average evaluation results per criterion. The overall fulfilment of the evaluation criteria counts for 0.94 for the novel approach. This is a significant improvement compared to the average evaluation result of the state of research (0.56). The individual classification will be explained in the following section.

Regarding the spatial scope, it can be stated that the developed approach fully fulfils the criterion *vertical hierarchy* by considering all system levels from process level to value chain level. Nevertheless, the criteria *horizontal hierarchy,* as well as *sequentiality,* are only valuated with a three-quarter point due to the clear focus of product-centred value chains. Peripheral system elements without any contribution to the value adding (staff rooms) and a sequential connection of whole value chains are not fully considered. However, the provided approach enables a thorough investigation of single value chains at every system level including most of the peripheral activities, which is an advantage compared to the state of research. Due to the detailed sample application for the specific and relevant case of aluminium die casting, the related criterion *primary shaping* is fully fulfilled. However, due to the universality of the developed approach, (besides its specific translation for aluminium die casting) the criterion *transferability* is also fully fulfilled. This goes hand in hand with the full fulfilment of the criterion *planning/evaluation perspective on production*, which ensures decision support for operational (e.g., change of machine parameters) up to strategic scenarios (e.g., material and technology selection). The temporal scope regarding the considered *life cycle phases* is valued with a three-quarter point as the use phase of the produced aluminium goods is not considered. However, input materials from end-of-life metal fractions and their specific treatment, as well as the evaluation of the raw material generation, are considered. This broad perspective extends the usual perspective of the state of research.

Regarding data and model quality, it can be stated that the developed approach and generic model consider all relevant energy and material flows in their complete and complex structure, which fully fulfils the criteria *resource flows* and *structure of flows*. Not each single flow is considered, but rather all relevant flows are. This means that metal flows, as well as electricity and natural gas flows, are especially modelled. Therefore, individual and extensive metering campaigns for novel data sets, as well as standardised LCI databases, have been used as *data sources*. Furthermore, it can be stated, that the extensive contribution of this work to publicly available data about energy and resource flows in aluminium die casting represent a valuable contribution to production engineering. Only the criterion *supported modelling detail* is missing a quarter point to full fulfilment. This is due to the fact that there are no specific factory models addressed as own modelling entities. However, they can be included as well by combining the right combination of processes and process chains.

Besides the already mentioned *transferability* of the approach, the industrial applicability is also fully ensured as a detailed *procedural approach* provides clear guidance for the application of the approach while including all relevant *methodologies*. This procedural approach also provides *decision support* by ranking single scenarios and their combined application.

This applicability gets amplified by the visual support for the quantitative *display of results*, which can be evaluated by taking an ex-ante as well as an ex-post *evaluation perspective*. For a truly holistic evaluation, an economic perspective besides the *evaluation dimensions* of physical flows and environmental impacts is missing. However, this perspective can be added easily e.g., through an activity based costing model, which is supported by the proposed software tools, or by prizing the considered physical flows.

As a résumé of this criteria based evaluation, the developed approach adds value to the pool of available concepts for enhancing the energy and resource efficiency in production. With its broad focus regarding vertical, as well as horizontal system levels, in parallel to its capability of regarding a high level of detail at the right spots, this approach is unique. Nevertheless, not all criteria for full compliance with the identified research demands are met. However, the degree of fulfilment for these criteria, which are not fully met, is above average. Furthermore, the remaining deficiencies can easily be solved by future research work. The developed approach has already been tested at industrial partners in a research project. It has contributed well to a target-oriented allocation of development resources due to its ranking of measures and to a final, comparative evaluation of complex and diverse improvement measures.

6.3 Outlook

The developed approach provides significant advantages compared to the state of research. Nevertheless, the approach itself and its specific application reveal potential fields for further research work, which will be introduced exemplarily in the following examples:

- Based on the multi-level, and especially the multi-scale perspective of the presented approach, an integrated software suite can be developed which combines and couples the proposed methods and corresponding tools according to the procedural approach. The basic challenge for such a one stop solution is to implement a logical connection of the different level-specific software modules, regarding the different time resolutions and computing times. This means that a wise method for synchronising the different tools needs to be developed, which requires the definition of software-spanning synchronised time stamps and a wise reduction of complexity e.g., for detailed process simulation to reduce and harmonise the computing efforts.
- Such a software suite can also be extended with an optimisation algorithm, which generates suggestions for alternative configurations of the observed production systems. Thus, the optimal alloying composition from an environmental point of view can be calculated via such an algorithm, after upper and lower boundaries for the alloying elements concentrations have been set to maintain the required alloy characteristics. Based on the results of this work, such an optimisation could also take into account the effects on other system elements along the value chain such as the heat treatment section and its alloy-dependent energy demand.
- As stated above, the evaluation dimensions of the provided approach and its specific application can be extended easily by an economic dimension. By doing so, the evaluation of actor-specific tradeoffs should also be extended. As it has been presented for the case of liquid aluminium supplies, an investigation of actor spanning activities can lead to overall improvement potentials, which request one actor to accept individual drawbacks. Assuming that the observed actors are not always linked in a collaborative relationship, available mechanisms like game theory need to be adopted or developed, which support the negotiation of mutual rewards to encourage both actors for a global improvement scenario. Such encouragements can also be provided by government authorities, which

build upon the presented actor-spanning approach and generic model to develop precise incentive schemes for cross-company collaboration towards resource efficient economies.

- To achieve the ideal goal of a resource efficient economy, the global hotspots of resource depletion and environmental impacts must be investigated and reduced. Based on the identified hotspots of this present work, and besides all highlighted fields of action at the observed actors, the focus for upcoming research projects must also lie on the generation or substitution of raw materials. Furthermore, their complete and pure recovery after their use phase within products needs to be aimed for. This is especially true for the case of aluminium. As could be seen, the environmental impact of aluminium generation overrules the environmental impact of the two observed actors even in the case of secondary alloys. Additionally, die casting alloys will always be produced by adding some shares of virgin, primary aluminium to dilute impurities, which even increases the impact of the upstream process chain.

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