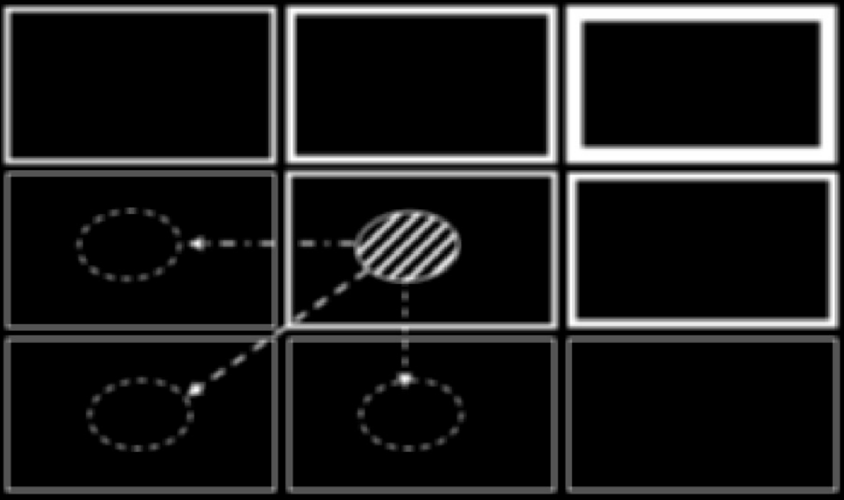
GREENING THE INDUSTRIAL FACILITY

Perspectives, Approaches, and Tools



Thomas E. Graedel and
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With 185 Illustrations

Springer

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Preface

The concept of "green engineering" is one that is both vitally important and increasingly discussed. The basic idea is that engineers and other technologists should take account of the potential environmental consequences of their engineering decisions, whether those consequences are immediate or may occur far into the future. The case can quite easily be made that green engineering is a necessary (though not sufficient) condition for the sustainable development of Planet Earth.

A major difficulty with implementing green engineering, however, is that only a tiny fraction of the world's engineers have any knowledge of the field, and few engineering curricula address the topic. This is in large part because reference material and textbooks have yet to be written for many specialties within this new field. One exception is in the field of chemical engineering, where Allen and Shonnard's *Green Engineering: Environmentally Responsible Designs of Chemical Processes* (Prentice Hall, 2002) has focused on green chemical process design. However, there remains a very large number of civil engineers, electrical engineers, industrial engineers, and mechanical engineers operating in diverse industrial sectors who can draw on no such text. Furthermore, managers, environmental specialists and policy makers can benefit from comprehensive and integrated information on the environmental aspects of industrial production.

We attempt in this book to fill the need for a textbook and reference book combining broad coverage of technology with the environmental implications of that technology. Our focus is on the industrial facility, and we address its progression toward a green facility in four stages: regulatory compliance, pollution prevention, life-cycle assessment, and sustainability. Our coverage is by industrial sector, from the resource extraction industries through the fabricators and manufacturers to the recyclers. For each sector we provide an overview of typical sector operations and their environmental implications, and potentially important transformations of sector operations. We discuss as well the probable aspects of sector operations that could occur under three scenarios for the future: "trend world" (business as usual), "brown world" (development without considerations of environmental or sustainable development issues), and "green world" (development with heightened levels of consideration of environmental and sustainable development issues). We conclude the book with a speculation as to the possible structure of industries a half-century from now, and thoughts on how industrial change may be brought about.

This book is written as a textbook for upper-level undergraduates or beginning graduate students in engineering or applied science, and is the product of a course by the same name that has been given at Yale University since 1997. Our approach in the course is to emphasize visits to several different industrial facilities, because only by doing so can students get a sense of the scale of industrial operations, the technical challenges presented by contemporary standards of quality, reliability, and manufacturing efficiency, and the commitment of employees to good environmental performance. Each facility visit is previewed with the host organization, and we encourage tours that emphasize the manufacturing process and sequence rather than the environmental aspects (which inevitably are addressed anyway). Accordingly, a typical tour begins at the receiving dock, follows the incoming materials and/or components as processes transform them, moves on to quality control and packaging, and concludes at the shipping dock. Throughout the tour, which ideally has a student to tour guide ratio of about 8:1, students gather and record relevant information on the facility. (A form that some find useful is included in Appendix A.) They then prepare and submit a report to the instructor. Our approach is to encourage students to work in groups to prepare process flow diagrams and tables of materials and processes, but to write reports individually.

We recommend four or five facility visits as the optimum number. This enables the students to think about and write one or two reports on each of the stages of facility environmental performance: compliance, pollution prevention, life-cycle assessment, and sustainability. It is helpful, if possible, if the facilities are visited in a sequence of increasing complexity, e.g., a plastic parts manufacturer before an appliance fabricator. Class lectures address Chapter 1–7 and 27–28, plus a selection of sector-specific chapters appropriate to the facility visits and the interests of the instructor and students.

In addition to formal course use, we recommend this book to practicing engineers and to corporate environment, health, and safety personnel. We think many of them will find the book useful as they help their corporations follow the road to sustainability. We are grateful to the students who have dealt with an evolving series of course notes over the years, to Ryan Bennett, William B. Ellis, Elizabeth Levy, Reid J. Lifset, and Peter J. Deschenes, who contributed ideas and initial text for several of the chapters, and to our editors at Kluwer Academic Publishers.

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November, 2004

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Introduction to Industry and Environmental Issues

Chapter 1

Technology and the Environment

1.1 INTRODUCTION

The fruits of modern technology provide humanity with capabilities far beyond those of the richest prince of yesterday—comfort, travel, communication, and a wide variety of food. As the past two or three decades have indicated, however, technology has brought with it a host of environmental problems. Initially perceived to be largely local (smokestack soot), these concerns have spread to the regional scale (acid rain), and more recently to the entire planet (stratospheric ozone depletion). The discovery in 1986 of the ozone hole over the Antarctic continent (Figure 1.1) was followed by the unambiguous linking of its cause to chlorofluorocarbon compounds (CFCs). These compounds, used as propellants, refrigerants, and cleaning compounds for several decades, are unknown in nature but readily synthesized by industrial techniques; thus, technology played a direct role in degradation of the earth's atmosphere. This and other occurrences made it clear that unbridled, environmentally thoughtless technology is an unpromising partner for the planet over the long term.

If such examples seem to suggest the desirability of less industrial activity, global trends seem to demand the opposite. Population, ultimately the source of all industrial activity, will increase by approximately 50% in the next half-century. The use of resources, both individually and in society as a whole, continues to rise—a trend that could be regarded as materialism, pure and simple. In a deeper vein, however, we need to recognize that resources fuel our technological society just as food fuels our bodies. The employment of materials, water, and energy can be optimized, but it cannot be avoided if we wish to retain the benefits that industrial activities provide.

The tacit bargain struck between industry and society is that society defines its needs and wants and industry attempts to satisfy them. These needs and wants are thus the driving forces that initiate the chain of activities (see Figure 1.2) that often

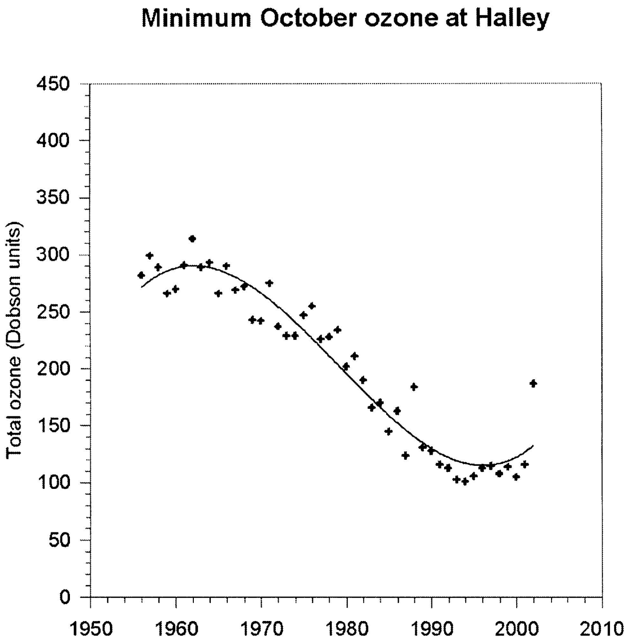

Figure 1.1. Total ozone over Halley Bay, Antarctica, for October of the years 1957 through 1993. (*Source:* http://www.antarctica.ac.uk/met/jds/ozone/split/split_files/frame.htm accessed May 18, 2004.)

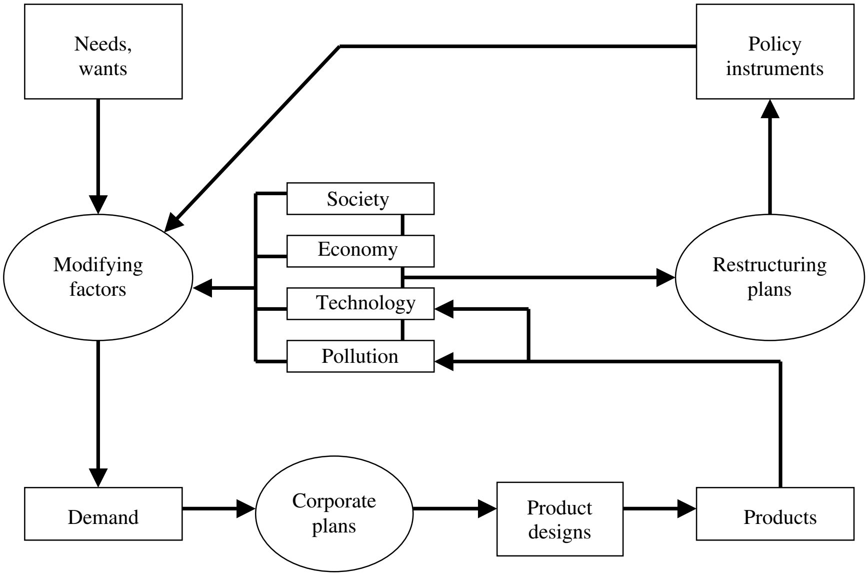

Figure 1.2. The relationship between the needs and wants of modern society and the environmental impacts that are likely to result.

ends with nocent environmental impacts. We are therefore faced with the technology-environment paradox: technology permits us to lead healthier, more productive, and more enjoyable lives, yet its actions threaten the planet. Cannot society achieve the technological accomplishments it desires without simultaneously degrading the world in which we live? Why must technological institutions operate the way they do? These are the central questions addressed in this book.

1.2 TRADING ENERGY FOR RESOURCES

Modern technology involves the acquisition of materials and their transformation into desirable products. Acquisition is typically accomplished by heroic technology, such as drilling an oil well from a platform embedded on the sea floor, or mining metal ores from shafts sunk deep into mountain rock. Once acquired, only a few materials such as rock aggregate for roadbeds can be used as is. Much more often, the material must be transformed—oil into plastics or metal ore into copper pipe and zinc castings.

Resource extraction and transformation requires energy—lots of it. Energy is used to open mine shafts, to drill the rock, to bring the ore to the surface, to crush it, to smelt and refine the metal minerals, and to fashion the resulting metal into products, or to pump crude oil, refine it, fractionate the products, and form plastic parts. The actual processes require energy to break the chemical forces bonding the material in its original form, and to generate new chemical bonds that render the material useful.

Ultimately, all technology is involved in this trade: to have available the materials needed to provide the products of modern industry we must invest energy to acquire resources, and use energy to put those resources in suitable form. If we desire the materials, we must pay the energy price.

1.3 THE “POTENTIAL TO POLLUTE”

Industrial processes, especially those involved in cleaving chemical bonds and reforming them in desired ways, are rarely benign. These processes often require strong acids, strong bases, or other aggressive chemicals. The use of these chemicals requires in turn that the chemicals be manufactured, transported, stored, and used, and that after use the residues be dealt with appropriately. Most of these activities are carefully and thoughtfully performed, and little or no direct environmental consequences occur. Nonetheless, the potential for problems is always present: technological processes have the “potential to pollute (PTP)”.

The PTP for a specific process or process sequence is heavily influenced by two factors: the hazard potential of the materials involved, and the quantities of materials used. Consider the generic process shown in Figure 1.3. Materials enter from the left

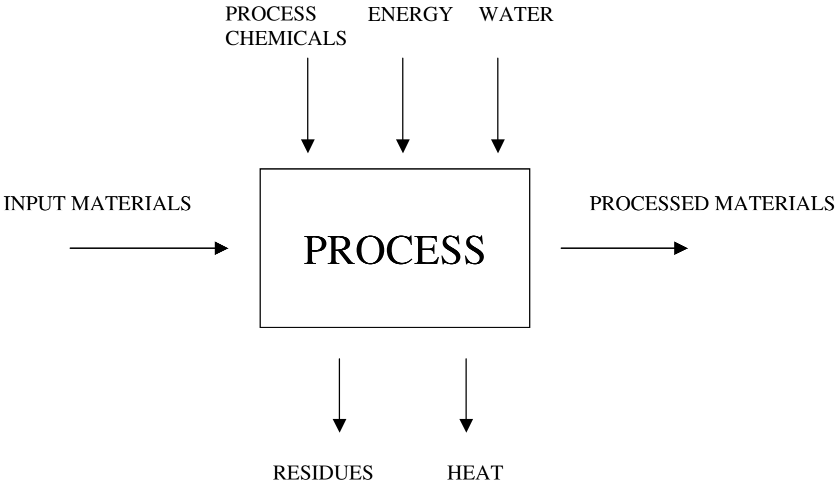

Figure 1.3. A generic diagram of an industrial process.

and top and leave from the right and bottom of the diagram. Because all processes use energy, and none are completely successful at utilizing every molecule that enters the process, heat and residues are inevitable. The challenge to technology is to minimize those to the extent possible, while achieving maximum efficiency in the creation of the desired product or products.

An additional difficulty is that purification or cleaning steps are frequently required if resources are to be satisfactorily made available. In these processes, any undesired material that is extracted from the resource being purified must itself be properly treated. At that stage, the residue is often a minor constituent of an inorganic or organic solvent stream of washwater. It is possible to capture, treat, and dispose of such materials, but monetary and energy costs are often high.

Finally, it must be recognized that technology produces, by design, a number of problematic materials. A manufacturer of pesticides, for example, purposely generates large quantities of bioactive material. A pharmaceutical company manufacturing chemotherapy drugs does the same. The hazards involved in the manufacture and use of such products are widely recognized and mostly well handled. Nevertheless, the potential for environmental difficulty is always present.

1.4 THE INDUSTRIAL FOOD WEB

It is often useful to frame issues of technology and environment on an industrial sector basis. A sector is a distinct part of the economy whose members share several

Table 1.1. Industrial Sectors Discussed in This Book

Fossil Fuel Extraction and Processing
Power Generation
Metal Ore Extraction and Processing
Inorganic Minerals and Chemicals
Petrochemicals
Agriculture
Food Processing
Textiles and Leathers
Sand and Glass
Fabricated Metal Products
Fabricated Plastic Products
Electronics
Synthetic Organic Chemicals
Assembled Products
Forest Products and Printing
Packaging and Shipping
Industrial, Residential, and Infrastructure Construction
The Remanufacturing and Recycling Industry
Advanced Materials

common attributes:

- Similar operations, processes, or practices
- Similar environmental challenges and potential impacts
- Similar compliance issues

Sectors can be broadly defined, as in agriculture or electronics, or narrowly defined, as in corn production or computer manufacture. In this book we will tend to use broad definitions, and will discuss the sectors shown in Table 1.1.

Sectors are often treated as independent entities, especially for economic purposes. In practice, however, they are highly interdependent, with the products of one sector serving as inputs to one or more others. The result is a sort of food web reminiscent of a biological ecosystem. Figure 1.4 shows the sectors and their primary linkages, though we have omitted many of the less important interactions in the interest of clarity.

Because of the structure of the industrial food web, changes in the use of resources by one sector have a tendency to ripple through many others. The wide acceptance of plastics, for example, resulted in increased material flows in the petroleum extraction and petrochemical sectors and decreased flows in metal mining, smelting, refining, and fabrication.

As a general rule, moving from left to right on Figure 1.4 results in lower energy use and lower emission rates per unit of product. These tendencies are related in large part to the quantities of impure and extraneous material that must be dealt with in the early stage sectors, and the extensive physical and chemical transformations that

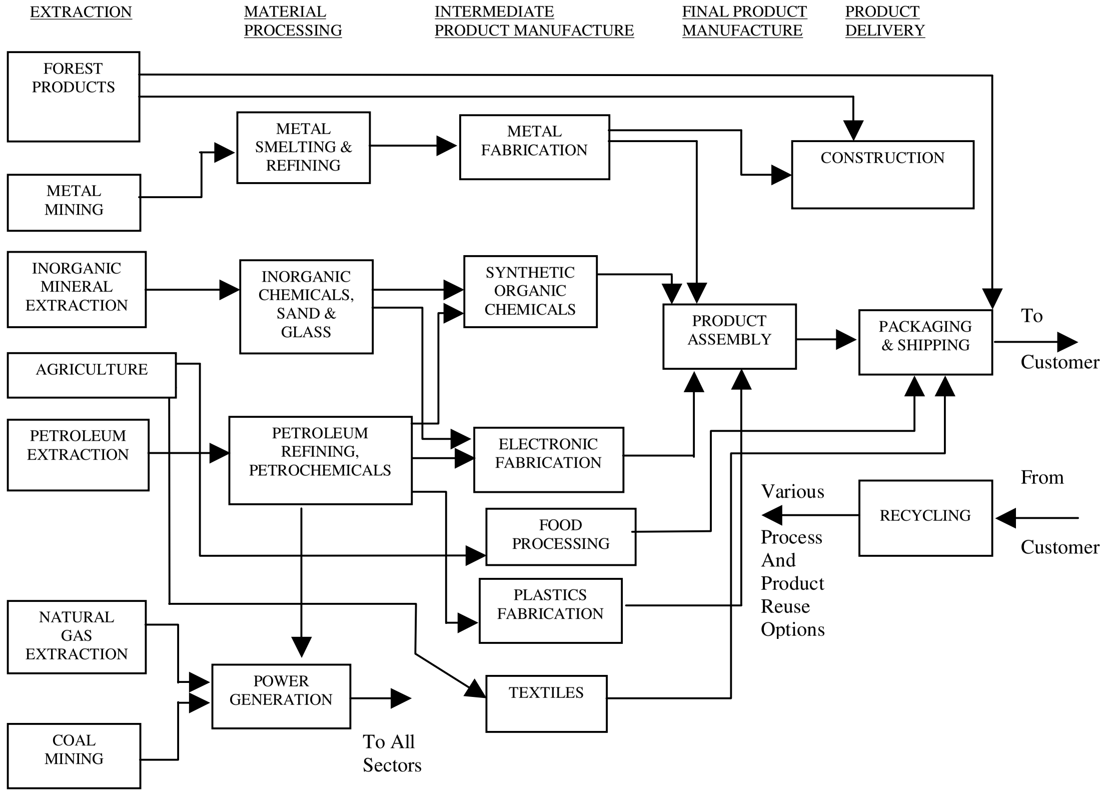

Figure 1.4. The industrial sectors treated in this book and the interrelationships among them. Electrical power, the output of the power generation sector, is utilized to a greater or lesser degree by all other sectors.

are required. Sectors later in the sequence may perform more intricate operations, but generally do so by working with starting materials much closer in form to the final product. This circumstance does not imply a difference in technological sophistication in the sectors; there are low-technology companies here and there, but no low-technology sectors in the modern industrial world.

The central message of Figure 1.4 is that industry functions as a system, not as many unconstrained individual entities. The desire for a computer thus implies the issuance of production orders to nearly every industrial sector. If we wish industry to be environmentally superior, we must optimize the entire system, not some of its pieces.

1.5 ENVISIONING POTENTIAL FUTURES

1.5.1 Trends of Interest

Sectors and their environmental performance are not static, in part because their technologies evolve, their product lines change, and the relationship between the individual firms, their customers, and their environmental interactions are constantly being reconfigured under internal and external stimuli. For each of the sectors we discuss in this book, we have attempted to understand and describe likely or possible trends related to products and processes. Where appropriate, we have also evaluated regulatory and societal trends that may influence the technology-environment relationship.

1.5.2 Future Scenarios

It is, of course, impossible to predict the future with anything approaching perfect accuracy. Nonetheless, there is great value in constructing descriptions of possible futures and evaluating the consequences, should something like those descriptions of the future actually come about. In this book we employ three descriptions, termed scenarios, to evaluate and discuss possible futures for the different industrial sectors. The time scale we have in mind is two to three decades—far enough into the future to provide a bit of distance from today's practices, but not so far that the opinions of today's industrial futurists will have little credibility or relevance. These scenarios, chosen to represent a wide range of possibilities, are as follows:

- *Trend world.* This scenario envisions a future that follows from "business as usual" practices. Its features can be adequately predicted by extrapolating today's trends. Economic growth and consumer demand would drive increased consumption of goods and services in industrialized countries. Industry would continue to improve its environmental performance in response to government regulation and/or social pressure. At the same time, economic and technical feasibility would be important determinants of industry's actions towards the environment, and strong incentives to develop fundamentally superior environmental practices would not be in place. In the developing world, environmental practices would continue to reflect lower standards or would be constrained by technical and economic factors. While some developing country economies would be able to attract and support industries using the most advanced production methods and associated environmental controls, many would continue to be havens for "dirty" industries.

- *Green world.* This scenario envisions a future in which strong adherence to superior environmental performance and sustainable development shapes and constrains corporate activity. Environmental impact would become a key factor in the design, manufacture, and use of products. Technological innovation, government incentives, and consumer demand would all support the adoption of cleaner production methods, decreased consumption of non-renewable resources, and increased reuse and recycling. The industrialized countries would help industries in the developing world adopt state-of-the-art production technologies that would minimize environmental impacts.
- *Brown world.* This scenario envisions a future that would follow from economic development unhindered by concern for environmental impact or sustainability. Government actions and social pressures would not limit the use of nonrenewable resources nor would they impose significant environmental performance standards on industry. Industrial companies would design products and use manufacturing processes that maximize short-term economic gains, regardless of environmental impact. Consumers would value cost and convenience over environmental consequences when they buy products. Industrial activity in developing countries would not aspire to the environmental standards now in place in industrialized countries. Resource extraction and consumption would be governed solely by economic factors, not by environmental considerations.

The green world and brown world scenarios do not assume particular conditions of economic growth or technological development. Economic growth under each scenario may be robust or not. The difference rests more on how technological choices are made within a given economic context than on absolute economic growth rates. The choice of how technologies are used (to further environmental ends or not) is more critical than the rate of technological change in determining which of these scenarios may come about. Of course, the consequences of technological development, economic growth, and the equity with which the gains from each are distributed may differ a great deal between the two worlds.

We do not suggest or infer that any of these options are predictions. They allow us, however, to imagine worlds in which the environmental performance of industries of all kinds follows radically different paths. If the results of these exercises *are not* significantly different from an environmental standpoint, that result permits us wide flexibility in our technological development. If the results *are* significantly different, they are likely to be of even more interest, since they thereby suggest that technological development will need to be planned extremely carefully if it is to be carried out without causing significant environmental harm.

Scenarios provide us with approaches that look past today's performance to that of the future. We as a society need to do a better job of environmental performance in today's technological world—no question. At least as important, however, is looking to the future, realizing that the technological visions of today will dictate the industry-environment interactions of the future. Optimizing and minimizing those interactions—the subject of this book—is a crucial component in planetary sustainability.

1.6 THE ORGANIZATION OF THIS BOOK

This book is organized as shown in Figure 1.5. The first two chapters introduce the interactions between technology and the environment, and the key topics to be explored to bring rigor to technology-environment evaluations. The next five chapters present in some detail four approaches that can be used to evaluate facility environmental performance. Chapter three describes and compares two regulatory

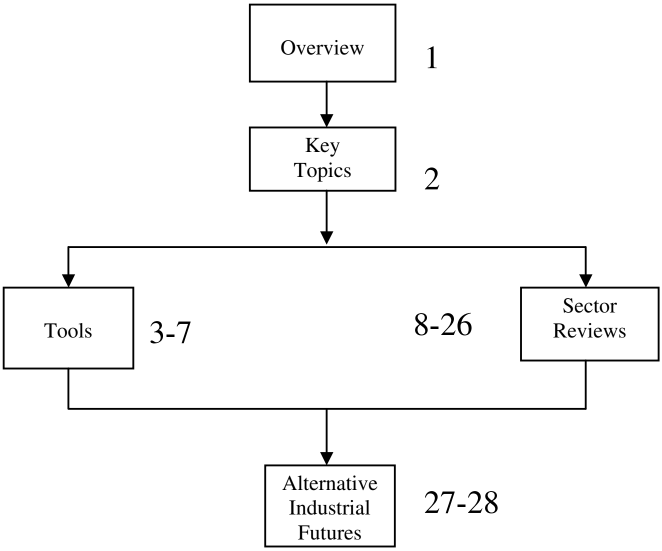

Figure 1.5. The sequence of topics and chapters in this book.

approaches, while chapters four and five introduce key principles and tools, pollution prevention and life cycle assessment, that are used by industrial facilities to move beyond compliance with regulation. Chapters six and seven develop the sustainability assessment tools used for the industry sector analyses in this book, which include consideration of energy and water use, materials throughput, and hazard analysis. In chapters eight through twenty-six, we treat each major industrial sector in a separate chapter, describing its typical operations and key environmental impacts, performing a sustainability assessment and identifying possible trends. The book concludes with two cross-cutting chapters. The first assesses trends in the several sectors and predicts the industrial sector sequence at the midpoint of the 21st century. The second addresses implementation—how organizations, individuals, and groups of organizations can work toward improved corporate environmental performance. A number of appendices provide assessment guidelines and present examples of several types of evaluations of the environmental performance of industrial facilities.

The preface outlines the use of the book as a course text for graduate students, but many other readers will find the book valuable. Those working in industry as engineers, managers, or environmental specialists will find much of interest in the sector chapters that deal with their industry, or those that deal with upstream or downstream industrial activities. Similarly, policy-makers and students of organizations concerned about the greening of industry will learn about sector-specific opportunities and threats. While the industry sector chapters seek to describe the technological sequence of production, they are written to be understandable to those without technical backgrounds. The recommended approach for all readers is to read the first two chapters to understand the overall approach of the book, select topics from chapters three through five that are of particular interest, and then read chapters six and seven to understand the sustainability assessment tool used in subsequent sector chapters. Readers should choose which sector chapters among chapters eight through twenty-six are of greatest interest, then conclude with the final two chapters.

FURTHER READING

Hammond, A., *Which World? Scenarios for the 21st Century*, Washington, DC: Island Press, 1998.

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Chapter 2

Key Topics and Approaches in Greening the Industrial Facility

Industrial activity varies from coal mining to electronics, from forestry to automobile manufacture. Despite the dramatic differences among these sectors, there are many similarities among the environmentally related attributes and concerns, especially in a qualitative sense. This chapter discusses the common topics that will recur as the individual sectors themselves are presented in chapters eight through twenty-six.

2.1 TECHNOLOGY'S USE OF ENERGY

Energy consumption occurs not only in industry itself, but also in public and (especially) private transportation, and in residential and commercial uses. In the U.S., buildings, transpiration, and industry each use roughly one-third of the energy that is consumed, as seen in Figure 2.1. As demands have increased for a higher quality of life, energy use has accelerated markedly.

Although technology is a heavy user of energy, the industrial sectors are quite diverse in this regard. In particular, the energy required to perform "heavy industry" functions reflects the requirement of those sectors to move large quantities of material, to heat material to high temperatures, and to apply high pressures. Thus, metal mining and processing, pulp and paper, chemicals, petroleum refining, and building materials are dominant industrial energy consumers.

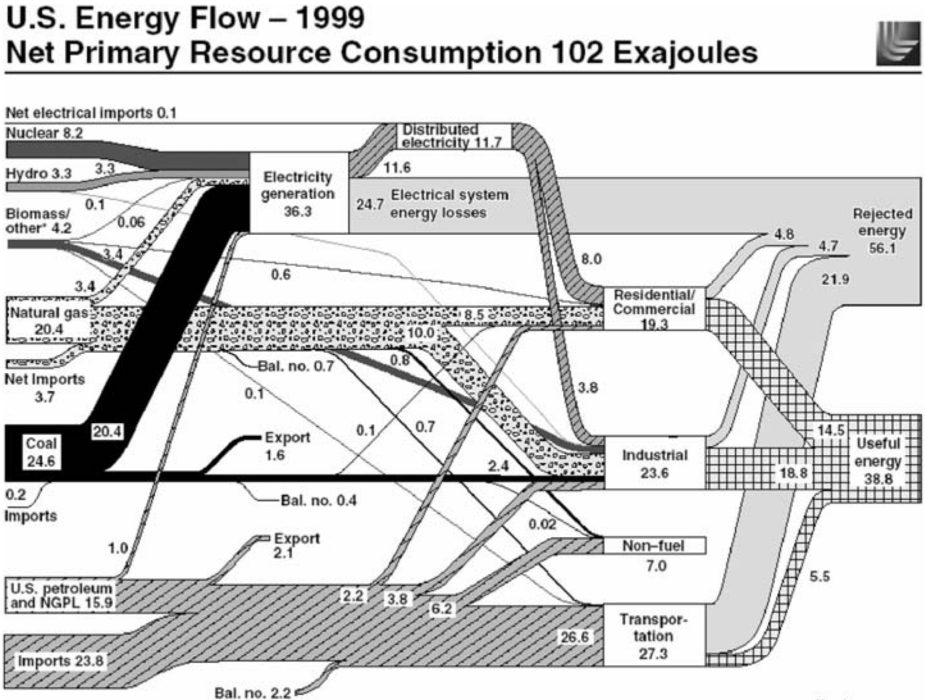
2.2 TECHNOLOGY'S USE OF WATER

Water may ultimately turn out to be the resource that most limits the way in which industrial activity, broadly defined, can evolve. As seen in Table 2.1, roughly

Table 2.1. Global Uses of Water, circa 1990

Activity	Water Consumption (km^3 per yr)
Agriculture	1870
Industry	90
Domestic	50
Other	275
Total	2285

Source: S. L. Postel, G. C. Daily, and P. R. Ehrlich, Human appropriation of renewable fresh water, *Science, 271*, 785–788, 1996.


U.S. Energy Flow – 1999
Net Primary Resource Consumption 102 Exajoules

Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 1999*
*Biomass/other includes wood and waste, geothermal, solar, and wind.

March 2001
Lawrence Livermore
National Laboratory

Figure 2.1. Sources and uses of energy in the United States in 1999. The units are Exajoules (10^{18} Joules). Reproduced from http://www-energy.llnl.gov/99Flow.html, accessed Aug. 7, 2001.

80 percent of global water use is for crop irrigation by the agricultural sector. All other industries consume about 10 percent of the total. The distribution of use in the United States is quite different: cooling water for electrical power production amounts to 39 percent of all use, and agriculture uses another 42 percent.

The dependence of agriculture on water is obvious from these data; that sector is so important to water budgets that it is broken out separately in nearly every assessment. While data on broader distributions of water use across industrial sectors are rare, agriculture is the dominant sector, with human uses, chemical manufacture, forest products, power generation, textiles, and pulp & paper, all using significant, but much lower, amounts of water. Most other industrial sectors are much less consumptive overall.

Water is the supreme example of a local resource. Unlike metals, minerals, or fuels, water is seldom transported long distances. As a consequence, geographical regions where water is scarce are not good places to locate water-hungry industry. This is particularly true of regions where populations are growing rapidly, as the water demand for domestic and agricultural uses will place increasing constraints on that available for industry in those regions.

2.3 TECHNOLOGY'S USE OF MATERIALS

A well-established historic relationship is that an improved standard of living brings with it an increase in the use of materials. That history for the United States in the twentieth century is shown in Figure 2.2. The population during the century increased by about a factor of 3, whereas the total materials use increased by about a factor of 10. Most of the materials groups showed reasonably steady gains during that period except for agriculture, which has been a relatively stable user of materials since about 1940.

We will note later that the tendency of modern products to perform equivalent functions while using smaller amounts of materials may act as a control against increased materials use. A powerful counterforce, however, is the large proportion of the world's population that desires improvement in its standard of living and thus can be expected to increase its rate of materials use. Table 2.2 speaks to that situation by listing the 1990 world production and U.S. consumption of a number of different commodities. Also shown in the table are the levels of production that would be needed were the world's population to use materials at the same per capita level as do Americans. In many cases, increases in production of factors of 4–6 would be required. Should such levels of production occur, they would obviously exacerbate any current perturbations of natural budgets. Hence, a future based on present American levels of consumption appears unrealistic for the planet on a long-term basis. There can be no simpler expression of how difficult it will be to achieve sustainable development than the factors shown in the last column of Table 2.2.

Table 2.2. Materials Consumption Rates and Possible Projections

Commodity	US Consumption	World Production	Conceptual World Consumption Need	Factor of Increase
Plastic	25.0	78.3	530.0	6.8
Synthetic fibers	3.9	13.2	82.7	6.3
Aluminum	5.3	17.8	111.5	6.3
Phosphate rock	4.4	15.7	93.3	5.9
Copper	2.2	8.8	46.0	5.2
Salt	40.6	202.3	860.7	4.3
Potash	5.5	28.3	115.5	4.1
Sand & gravel	24.8	133.1	525.3	4.0
Iron & steel	99.9	593.7	2117.9	3.6
Nitrogen	18.0	107.9	381.0	3.5
Cement	81.3	1251.1	1723.1	1.4

Source: Adapted from *Minerals Today*, p. 17, Washington, DC: U.S. Bureau of Mines, April 1993. All consumption rates are expressed in Tg/yr.

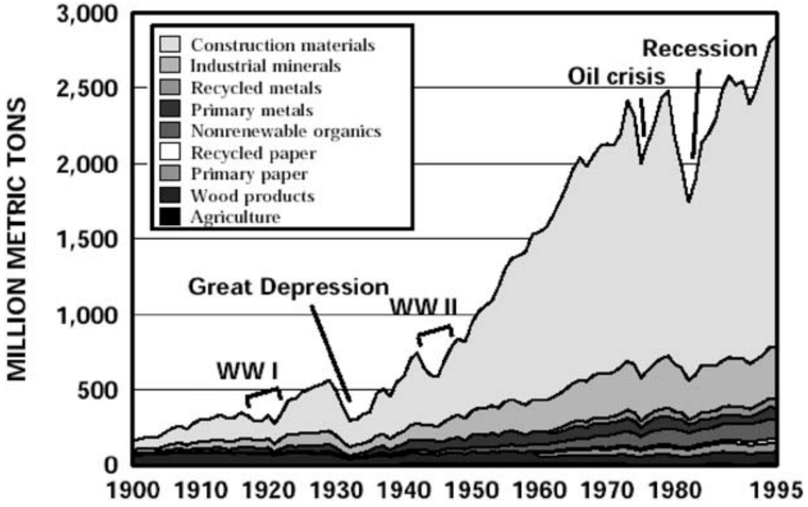


Figure 2.2. The consumption of materials in the United States, 1900–1995. (U.S. Geological Survey.)

2.4 COMMON INDUSTRIAL PROCESSES

In attempting to put the impact of industrial technology into perspective, it is helpful to note that a sequence of actions govern resource utilization. As seen in Figure 2.3, the sequence begins with the extraction of the resource and continues

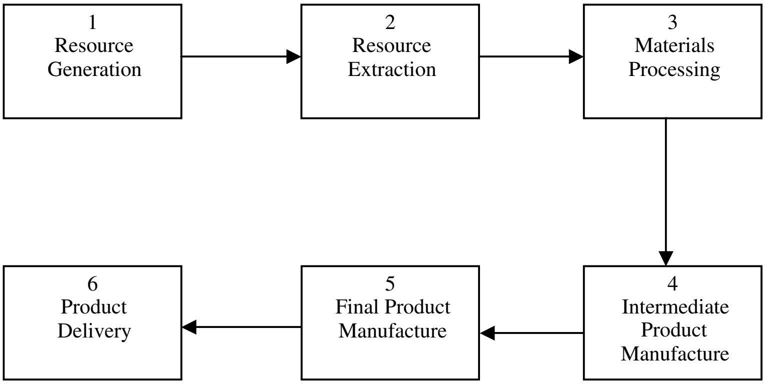


Figure 2.3. The technological sequence from resource to product. The numbers indicate the sequence stages.

with its processing. The processed material is the input to intermediate and final product manufacture. The sequence concludes with product delivery. In some cases, aquaculture or forestry, for example, a resource generation stage precedes extraction.

To carry out this sequence of activities, twelve types of processes are employed. Some are confined to a single sequence stage, while others may be employed in more than one. The process types are as follows:

Resource Generation The process of generating a valued resource, generally confined to agricultural and aquacultural activities.

Extraction The removal for use of a resource from its natural repository.

Beneficiation A process largely employed in extractive metallurgy and extractive mineralogy in which an ore, either metallic or nonmetallic, is concentrated in preparation for further processing.

Cleavage of Chemical Bonds It is uncommon for nature to provide a resource in the chemical form most desirable for use. More commonly, the initial form is a mixture of materials, often tightly bonded together (a mixture of metal oxides, for example). If a desired resource is to be used, the chemical bonds joining it to its reservoir partners must be cleaved. Bond cleavage requires the use of energy, the amount of energy needed being dependent on the strength of the bonds themselves.

Purification The degree of purification needed for a material that is to be used in an industrial process varies widely. Purity is hardly considered at all for gravel used in concrete, but is paramount in fashioning high-strength metals or potent pharmaceutical products. Many forms of purification are used: heating to eject trace contaminants, washing to rinse contaminants off, solvent treatment to extract them. A key realization is that impurities removed from an industrial material do not disappear, but are transferred to solvents, or wastewater streams, or sludge. Ultimately, the impurities themselves must be industrially utilized or discarded; either route has potential environmental impacts.

Formation of Chemical Bonds If a product is a chemical compound (steel, which is an alloy of iron with other elements, for example) rather than a pure element (iron, for example), a chemical reaction step is generally involved in making it available for use. This reaction may require energy or it may generate energy. The process usually results in one or more byproducts as well as the primary product.

Lubrication The activities involved in forming products from materials often require that the materials be lubricated to make them more amenable to processing or to carry away excess heat. The lubricant inevitably becomes an unwanted residue after the completion of the process for which it was needed.

Shaping Creating the desired physical form of the material. Shaping often involves the removal of excess material by grinding, trimming, or smoothing.

Cleaning Cleaning of material is commonly necessary prior to joining or surface treating operations. Any residues that are removed are then contained in the cleaning solution, and must be industrially utilized or discarded (with potential environmental impacts).

Joining Joining is a process used to fasten two or more materials together. It involves the formation of new chemical bonds at the interface between the materials. The materials may be bonded directly to each other (as in welding) or to an adhesive (as in gluing).

Surface Treatment It is common for materials and products to receive some form of surface treatment prior to shipment to the customer. Anticorrosive coatings, paint, polymer coatings, platings, and the formation of surface oxides are examples. Surface treatment processes often produce coating residues (paint overspray, degraded plating baths, etc.) that must be industrially utilized or discarded.

Packaging A very high percentage of materials and products are packaged for shipment to the customer. The choice of packaging materials and packaging techniques can result in large amounts of hard-to-recycle residues if not carefully chosen.

Transportation The transportation of material occurs between each technological stage. Given the substantial environmental effects of transportation (smog generation, energy consumption, etc.), it is important to minimize transportation as much as possible.

The types of processes described above are related to technological stages in Table 2.3. Some process types relate to a single stage, others to several. Since different

Table 2.3. The Types of Industrial Processes and Their Associated Technological Stages

Technological Stage*	Type of Process
1	Resource generation
2	Extraction
3	Beneficiation
3,4	Cleavage of chemical bonds
3,4,5	Purification
3,4,5	Formation of chemical bonds
4,5	Lubrication
4,5	Shaping
4,5	Cleaning
4,5	Joining
4,5	Surface treatment
6	Packaging
1,6	Transportation

*The technological stages are indicated in Figure 2.3.

industrial sectors tend to occupy different technological stages, this table provides an initial framework for evaluating the potential environmental interactions of a particular sector.

2.5 GREEN CHEMISTRY AND GREEN ENGINEERING

Many of the potential environmental impacts that can result from an industrial process are related to chemical reactions that take place within a facility. In response to this challenge, the field of *green chemistry* has developed rapidly since about 1995. Green chemistry is founded on principles that reduce or eliminate the use or generation of hazardous substances in the design, manufacture, and use of chemicals. A selected set of green chemistry principles appears in Table 2.4. While the goal of green chemistry is simple, its implementation can be quite complex, and often calls for highly advanced methods and practices.

A broader perspective, but one that springs from the same motivation, is the field of *green engineering*, which seeks to provide a framework for the design of new materials, products, processes, and systems that are benign to human health and the environment. A set of principles for green engineering has also been generated; a selected grouping of them constitutes Table 2.5. Unlike green chemistry, which is targeted largely to the chemical and pharmaceutical industries, green engineering is applicable to any industrial sector engaged in design and manufacturing.

Table 2.4. Selected Principles of Green Chemistry

1. It is better to prevent waste than to treat or clean up waste after it is formed.
2. Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.
3. Wherever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment.
4. Chemical products should be designed to preserve efficacy of function while reducing toxicity.
5. The use of auxiliary substances (e.g., solvents, separation agents, etc.) should be made unnecessary wherever possible and innocuous when used.
6. Energy requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure.
7. A raw material or feedstock should be renewable rather than depleting wherever technically and economically practicable.
8. Chemical products should be designed so that at the end of their function they do not persist in the environment, but break down into innocuous degradation products.
9. Substances and the form of a substance used in a chemical process should be chosen so as to minimize the potential for chemical accidents, including release, explosions, and fires.

Source: Adapted from Anastas, P. T., and J. C. Warner, *Green Chemistry: Theory and Practice*, Oxford, UK: Oxford University Press, 1998.

Table 2.5. Selected Principles of Green Engineering

1. Designers need to strive to ensure that all materials and energy inputs and outputs are as inherently non-hazardous as possible.
2. It is better to prevent waste than to treat or clean up waste after it is formed.
3. Separation and purification operations should be designed to minimize energy consumption and materials use.
4. Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.
5. Targeted durability, not immortality, should be a design goal.
6. Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.
7. Material diversity in multicomponent products should be minimized to promote disassembly and value retention.
8. Integrate local materials and energy flows into the design process.
9. Products, processes, and systems should be designed for performance in a commercial "afterlife".
10. Material and energy inputs should be renewable rather than depleting.

Source: Adapted from Anastas, P. T., and J. B. Zimmerman, Design through the 12 principles of green engineering, *Environmental Science & Technology*, *37*, 94A–101A, 2003.

2.6 TOOLS FOR IMPROVING ENVIRONMENTAL PERFORMANCE

Environmentalists worry quite properly about the impacts of industrial activity on the planet, yet they do not always make the connection between the demands of society and the means that industry must take to respond to those demands. Accordingly, the book aims to set out those basic interactions, major industrial sector by major industrial sector. For each one, we attempt to provide the following information:

- The principal operations of the sector.
- How those operations are accomplished.
- The flows of resources into and from the sector.
- The related environmental impacts of concern.
- A review of relevant historical trends.
- The potential for technological evolution.

The knitting together of sector activities produces the products on which society depends. This is perhaps no better illustrated then in the case of the automobile. The manufacture of the automobile involves nearly all the sectors discussed in this book. Without those sectors we would have no automobiles, nor washing machines, nor computers. However, we can doubtless do a better job of the technology-environment interaction. In figuring out how, the perspectives of the various sectors' potential to pollute will be the key information we explore in subsequent chapters.

Although the several industrial sectors perform very different tasks, there are several sector-independent tools that can be used to effect environmental performance improvement. They are as follows:

- *Regulatory compliance*. The foundation for any environmentally-responsible facility is compliance with regulatory requirements or agreements dealing with emissions to air, water, and soil, and with any other necessary environmental performance and reporting responsibilities. This topic is discussed in Chapter 3.
- *Pollution prevention*. Environmentally superior facilities do not waste energy or water, or discharge chemicals to the environment where prevention is possible, whether regulated or not. The topic and techniques of pollution prevention are presented in Chapter 4.
- *Life-Cycle Assessment*. This tool extends the scope of environmental performance beyond the facility boundaries, to encompass all stages of the product or process from resource extraction through end of life. Chapter 5 contains this discussion.
- *Sustainability Assessments*. The components of the ΣWESH tool that is used for sustainability assessments is described in Chapter 6, and the tool itself is presented in Chapter 7. The ΣWESH tool is used to assess the attributes of an industrial sector or facility as they relate to sustainability. It is the broadest in scope of the approaches, addressing the subjects of energy and water use in the context of local availability, input materials in the context of their global abundance, and all materials in terms of their biohazards.

Although in principle the tools listed above could be applied at either facility or sectoral level, for the most part they are most appropriate when used to evaluate individual facilities rather than sectors as a whole. This is because regulations differ from geographical region to geographical region and country to country, opportunities

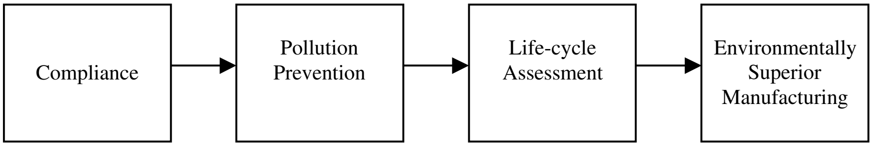


Figure 2.4. The evolutionary sequence in environmentally-superior manufacturing.

for pollution prevention from facility to facility, life-cycle assessments from process to process, sustainability from watershed to watershed. In the chapters that follow, we will comment on the most likely concerns addressable by the four tools across each of the sectors, but it is in the application of these tools to individual facilities that their capabilities will be fully realized.

To a great degree, the four assessment tools are sequential, as seen in Figure 2.4. Nearly all industrial facilities have completed a compliance audit and continue to comply with its recommendations. Many, but fewer, have worked hard at pollution prevention. Still fewer routinely use life-cycle assessment to evaluate their products and processes, and true sustainability evaluations are rare. These situations occur in large part because of lack of knowledge—training on all but compliance has historically been in short supply. This book is, in part, an attempt to help rectify this information deficit.

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Part II

Approaches and Tools for Industrial Environmental Management

Chapter 3

The Starting Point

Compliance with Regulations and Agreements

3.1 MOTIVATION FOR REGULATIONS

The foundation for any environmental activity at an industrial facility includes compliance with relevant local, state, national and internatinonal regulation, and adherence to voluntary environmental standards. Individual industrial facilities can be evaluated on the basis of their regulatory compliance. An example of a report that does so is given in Appendix A, and the motivations for and implementation of environmental regulation is discussed here.

Environmental regulation exists to explicitly address the potential conflict between ecosystem health and human activity. While the products of industry are typically seen as enhancing quality of life, the by-products of industrial activity can threaten environmental integrity and human health. Most governments use environmental regulation to control industrial pollution, manage natural resource use, and preserve habitats.

The control of industrial pollution is motivated by a need to protect the health of humans and environmental systems. Pollutants in the air or water can have immediate detrimental effects. For example, toxic chemicals in a stream can kill fish and other aquatic life, and smog can cause breathing problems in people. Pollution control is also necessary to guard against long term, cumulative effects of exposure to chemicals. Cancer, birth defects, or permanent damage to organ systems can result when people are repeatedly exposed to certain pollutants.

We now know that pollution can have an indirect but even longer term impact on humans and non-human organisms because it can fundamentally alter the earth's environmental systems. For example, a class of chemicals known as ozone-depleting substances (ODSs) destroys the ozone layer that protects the earth from ultraviolet radiation. The release of carbon dioxide and other global warming gases is changing global climate patterns. Regulation aimed at controlling industrial pollution is designed to minimize both the immediate and longer term effects of exposing humans and environmental systems to these pollutants.

Regulation is also used to preserve natural habitats and manage resource extraction and use. This is motivated by a need to both conserve resources for future use (or deplete them at a rate that allows them to regenerate) and balance competing demands for land use.

3.2 SETTING REGULATORY GOALS

While the exact way in which a country enacts its environmental policy varies, commonly governments establish regulations to control the impact of industrial activity on the environment. First, a health or environmental problem must be identified. This may be relatively obvious, like Cleveland's Cuyahoga River fire of 1969, or a brown haze over an urban area, or it may be much harder to identify, like the effects of synthetic chemicals on the human endocrine system. In any case, an attempt is made to define the problem scientifically and to draw connections between it and possible causes. Once a connection is made between a problem and a specific activity, a decision may be made to restrict that activity. The issue then becomes one of determining how and at what level to impose restrictions.

In the case of pollution control, it is necessary at this stage to establish a target level below which the health and ecosystem effects are considered acceptable. This might take the form of an air quality standard for a geographic region, or a water quality standard for a body of water. This type of target specifies a desirable level of environmental quality but it does not provide detailed targets for individual sources of pollution.

Once environmental quality targets are set based on health and environmental considerations, they must be translated into specific guidelines for industry. This may be done by creating discharge standards or imposing requirements for the use of certain control technologies. The standards applicable to an individual industrial facility are typically contained in one or more permits. If industrial facilities operate within their permit limits, environmental quality targets should be met. Adjustments are made either to permit requirements or to environmental quality targets when the desired results are not achieved, or when new information on environmental impacts becomes available.

The actual mechanics of developing guidelines for industry, imposing them, and enforcing them differs from country to country. In the U.S., the approach taken is primarily regulatory. Congress passes laws that establish relatively broad goals for environmental protection. The Environmental Protection Agency (EPA) is authorized to put these laws to work by creating more specific regulation. For example, the Clean Air Act is passed by Congress, but the EPA determines (after hearing public comments) the actual target levels for, say, sulfur dioxide emissions. The EPA also establishes the specific emissions guidelines and targets for industry sectors.

In the Netherlands, the approach is quite different. Environmental quality targets are established by government but specific pollution targets for industry are negotiated between industry sectors and government authorities. Industry sectors enter agreements, known as "covenants," with government bodies. A covenant specifies emissions reduction targets, and timeframes for achieving them, but leaves the decision about how to obtain emissions reduction up to industry. Covenants do not replace environmental legislation, but they do establish a consensual process between government and industry as the primary tool in environmental management.

The U.S. and Dutch systems are discussed in more detail in the sections that follow.

3.3 THE UNITED STATES: AN EXAMPLE OF A PRIMARILY REGULATORY APPROACH

The U.S. regulatory framework for environmental protection, developed after the formation of the federal Environmental Protection Agency (EPA) in 1970, has several distinct features. First, the core of environmental regulation is founded on a "command and control" approach. The EPA sets detailed requirements for industry and ensures these requirements are met by inspecting facilities and punishing offenders with civil, or even criminal, penalties. Regulation issued under this command and control approach is prescriptive. It either specifies pollution control equipment (known as Best Available Technology) that must be used by facilities in a given industry or it defines maximum permissible emissions levels for particular pollutants. To comply with this type of regulation, many companies focus on the installation and operation of "end-of-pipe" pollution control equipment. Little incentive exists within a command and control regulatory framework to improve production processes so they produce less waste.

A second key characteristic of U.S. environmental regulation is that it treats industrial emissions to different media separately. In other words, distinct legislation, permits, and enforcement actions are used to manage emissions to air, water and land. Rather than treat the manufacturing facility as a unit and examine its overall environmental impact, media-segmented regulation encourages environmental managers to compartmentalize their efforts, possibly shifting pollution from one medium to another.

These features—an adversarial command-and-control regulatory climate, an emphasis on technological end-of-pipe emissions controls rather than process redesign, and a media-segmented approach—remain important elements of the U.S. regulatory framework for environmental protection, despite some new programs and experiments that offer industry greater flexibility. The major legislative acts that comprise this framework are described below, followed by a review of some of the new approaches.

3.3.1 Clean Air Act (CAA)

The Clean Air Act of 1970 regulates air emissions from stationary and mobile sources. This law authorizes the EPA to establish National Ambient Air Quality Standards (NAAQS) to protect public health and the environment. A geographic area that does not meet the air quality standards for at least one of six "criteria" pollutants (smog, particulate matter, carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and lead) is classified as a "non-attainment" area. The Clean Air Act is typically enforced by the departments of environmental quality at the state level. States can set more stringent air quality standards if they choose, but they cannot set less stringent standards than those stipulated as a consequence of the CAA.

Major amendments were made to the Clean Air Act in 1990. A national permit system was established so that major industrial sources of air emissions must obtain a permit that specifies which pollutants are being released, how much may be released, what steps are being taken to reduce pollution, and how releases will be monitored. The 1990 Clean Air Act Amendments also create categories of severity of non-attainment that are used to set priorities and deadlines for clean-up. States manage these clean-up efforts through the permitting process. As a result, industrial facilities may face different air emissions limits in different regions of the country and these limits may change over time.

In addition to limiting the release of criteria pollutants, the Clean Air Act restricts the release of air toxics or hazardous air pollutants (HAPs). The 1990 Amendments name 189 chemicals that are classified as HAPs. Sources that release any of these chemicals are expected to use what is termed the "Maximum Available Control Technology" (MACT) to reduce emissions.

The 1990 amendments also address large-scale problems such as acid rain, ground-level ozone, and stratospheric ozone depletion that were unaddressed or insufficiently addressed in the 1970 CAA. One program to control acid rain makes use of a novel market-based approach that allows power plants to buy, sell or trade sulfur dioxide emissions allowances.

Compliance with the federal Clean Air Act, as enforced by state agencies, is a central task for any industrial facility that generates criteria pollutants from combustion or process emissions and/or generates hazardous air pollutants as process by-products.

3.3.2 Clean Water Act (CWA)

The Federal Water Pollution Control Act, commonly known as the Clean Water Act, of 1977 regulates discharges of pollutants to waters of the United States. Pollutants fall into three categories according to the CWA: "priority" pollutants are 126 listed toxic substances, "conventional" pollutants (like biological oxygen demand (BOD), total suspended solids (TSS), fecal coliform, and oil) are not directly toxic but affect water quality, and "non-conventional" pollutants fit neither of the other two categories.

A source that discharges water directly to navigable waters must obtain a NPDES (National Pollutant Discharge Elimination System) permit. The permit describes industry-specific, technology-based, or water-quality-based limits on releases, and establishes monitoring and reporting requirements. As with the Clean Air Act, the EPA delegates to the states the duties of granting permits for, administering, and enforcing the Clean Water Act. States follow the guidelines established by the EPA but can set more stringent discharge limits or water quality standards. As a result, industrial facilities located in different geographies will face different discharge requirements.

The Clean Water Act also regulates the indirect release of industrial pollutants to water. An industrial facility that releases storm water containing pollutants must obtain a NPDES permit for storm water discharge. Facilities are also required to pretreat water that is sent to municipal wastewater treatment plants, otherwise known as publicly owned treatment works (POTW). By enforcing pretreatment standards for industrial users, the POTW protects its own system from damage that could result from large quantities of toxic or hazardous chemicals. Although the EPA establishes "categorical" pretreatment standards on an industry basis, POTWs also develop "local" standards based on the profile of their users and the POTW's effluent standards. Again, the particular limits an industrial facility will face depends on local conditions.

3.3.3 Resource Conservation and Recovery Act (RCRA)

The 1976 Resource Conservation and Recovery Act (RCRA) governs the handling and disposal of hazardous waste as well as the management of solid waste. The regulation authorizes the EPA to establish and oversee a "cradle-to-grave" system for managing hazardous waste. Industrial facilities are required to comply with RCRA standards for the generation, handling, transportation, treatment, storage and disposal of hazardous waste. RCRA lays out several categories of hazardous waste, including commercial chemical products, wastes from specific industries, and wastes that are ignitable, corrosive, reactive, or toxic.

A permit must be acquired by any facility that generates or handles hazardous waste, and a stringent set of record keeping, labeling, and reporting requirements must be adhered to. Certain categories of waste, like solvents, heavy metals, electroplating wastes, and acids are subject to Land Disposal Restrictions (LDRs) and cannot be disposed of until they have been treated by a hazardous waste vendor. As with other federal environmental legislation, administration and enforcement of RCRA is largely carried out by the states.

The 1984 Hazardous and Solid Waste Amendments of RCRA strengthened the act by increasing EPA's enforcement authority, setting more stringent standards for hazardous waste management, and adding a program governing underground storage tanks.

3.3.4 Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, commonly known as Superfund, provides a fund to clean up uncontrolled or abandoned hazardous waste sites contaminated because of former industrial activity, spills, or accidents. The act authorizes EPA to force the parties responsible for the contamination to clean it up, or to pay the Superfund for the costs incurred by EPA in the course of a clean-up. The act also sets up a process for prioritizing sites for clean-up.

CERCLA differs in two important ways from other environmental legislation. First, it addresses past environmental damage rather than the mitigation of current pollution. Second, it puts the EPA into a new role as a manager and coordinator of environmental clean-up, as well as maintaining its traditional role as regulator. The involvement of industry in Superfund regulation is also different. In searching for responsible parties, the EPA can hold a single major party responsible for all clean-up costs at a given site, even if the party contributed a fraction of the total pollution. That party can then pursue other contributors in the courts and try to extract their share of the damages. Because the process of cleaning up a contaminated site can involve significant legal activity, Superfund is regarded as potentially one of the most costly pieces of environmental legislation for industry. The average cost of a Superfund site clean-up (not including the cost of litigation) has been estimated at $30 million. Some estimates put the costs of litigation nearly equal to the cost of the clean-up itself. One message that CERCLA sends to industry is to invest in pollution control today to avoid costly clean-up tomorrow.

CERCLA also establishes a procedure for reporting the release of hazardous substances. A report of a release triggers a response by the EPA and state or federal emergency response authorities.

CERCLA was revised and reauthorized by the Superfund Amendments and Reauthorization Act (SARA) of 1986. SARA also created a free-standing law, discussed below, to improve community awareness of chemical and environmental hazards and establish community emergency response capabilities.

3.3.5 Emergency Planning and Community Right-to-Know Act (EPCRA)

The Emergency Planning and Community Right-to-Know Act (EPCRA, also known as SARA Title III) was created as part of the Superfund Amendments and Reauthorization Act (SARA) of 1986. EPCRA requires that each state develop a State Emergency Response Commission (SERC) and appoint Local Emergency Planning Committees (LEPC). Each of these types of committees are comprised of emergency responders (firefighters, health officials), government officials, media representatives, community groups, and representatives of industrial facilities.

Any industrial facility that stores or manages chemicals is responsible for informing the SERC and LEPC if it has greater than a reportable quantity of specified hazardous chemicals on site. If this is the case, the facility must appoint an emergency response coordinator and it must provide local officials (fire department and local government) with information to be used in the case of a spill or release.

A second significant aspect of EPCRA is that it introduces into federal environmental regulation a provision for making information on chemical use and release publicly available. Each year, manufacturing facilities must report on their releases and transfers of some 600+ chemicals. These detailed reports include the chemical name and the quantity released to various media (air, water, POTW, land) or transferred off-site (e.g., for hazardous waste treatment or recycling). The reports are made available to the public as the Toxic Release Inventory (TRI). Although EPCRA formally establishes only a reporting requirement, the transparency of the TRI has had a powerful influence on the environmental management actions of some manufacturing companies. Seeing, perhaps for the first time, how many tons of chemical waste a facility releases can give managers an incentive to reduce waste and a clear baseline from which to pursue emissions reduction activities (see Text Box 3.1). Furthermore, the fact that TRI data are readily available on-line and in print means that concerned community members and advocacy groups can learn exactly what is being released from a facility or group of facilities, and can track changes in releases over time.

Text Box 3.1

Facing Up to the Numbers: One Company's Response to Emissions Reporting

When former Monsanto CEO Richard Mahoney saw his company's TRI (Toxic Release Inventory) data for 1987, the first year it was reported, he was alarmed by the sheer quantity of chemicals emitted. He declared that Monsanto would reduce its toxic air emissions by 90 percent within five years, a commitment that became the first "Monsanto Pledge." Employees groups around the world worked to figure out how to meet the reduction goal, making tough local decisions including closing down some production units. While Mahoney observed that setting a goal for a 50 percent reduction would have been "good enough," the challenge of a seemingly impossible goal galvanized employees and signaled that Monsanto was serious about its environmental commitment. In 1993 Monsanto announced that it had met its aggressive goal; Monsanto's pledge and the transparency of reporting that TRI afforded challenged many other companies to take similar steps to significantly reduce toxic air emissions.

Source: Mahoney, Richard. 1996. "Beyond Empowerment: Relevant Ad Hockery." The CEO Series Issue No. 1. Center for the Study of American Business. Washington University, St. Louis.

By forcing industry to become more open with the public about emergency plans and chemical release information, EPCRA perhaps has a more profound impact on environmental practices than do the more traditional command and control statutes that set limits on emissions. Manufacturing companies whose facilities were already in compliance with environmental legislation have begun to set goals to reduce annual TRI emissions, meaning their employees must search for ways to reduce or prevent pollution below compliance levels. This kind of activity is discussed more fully in the next chapter on pollution prevention.

3.3.6 Other Federal Legislation Relevant to Industrial Environmental Practice

In addition to the major acts discussed above, a host of other legislation exists that affects how industrial facilities operate with respect to the environment. The Toxic Substances Control Act (TSCA) does not govern the release or disposal of toxic substances but it does influence how such substances are manufactured and used. Any new chemical that is not listed in TSCA's inventory must go through a premanufacture notice (PMN) process before it can be manufactured or imported. The PMN must identify the chemical and provide available data on its health and environmental effects. If these data are insufficient, the EPA may restrict the use of the chemical. In practice, the majority of chemicals that are approved for use by TSCA have limited environmental and health information because of the difficulty of establishing the effect of a single chemical on a complex organism. TSCA also gives the EPA the authority to ban, require labeling, or limit the use of chemicals that have been determined to pose unreasonable risks. Examples of chemicals regulated through TSCA are PCBs (polychlorinated biphenyls), CFCs (chlorofluorocarbons), and asbestos.

The Endangered Species Act of 1973 provides for the conservation of threatened and endangered plants and animals and their habitats. The list of endangered species is maintained by the U.S. Fish and Wildlife Service (FWS) of the Department of the Interior. As of 1995, 632 species were listed as endangered and 190 as threatened. Any person can petition the FWS to list a species as endangered, or to prevent an activity, like logging or mining, that might endanger a species. While the Endangered Species Act is not of direct concern to many manufacturing companies, it can be a very important factor for those involved in extractive industries or logging.

Another regulation that affects the actions of some industrial operations is the Oil Pollution Act (OPA) of 1990. The OPA establishes a fund to be used to finance the clean-up of oil spills if the responsible party is unable to do so. It also requires that oil storage facilities and transportation vessels establish and provide to the government emergency response plans for dealing with large oil spills.

Of primary interest to the agriculture sector, and also industries that own large areas of land (e.g., utility companies), is the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) of 1972. FIFRA stipulates that all pesticides be registered with the EPA once it has been established that they will not cause unreasonable environmental harm if used as directed. In addition, FIFRA requires that users of pesticides be certified and registered.

The National Environmental Policy Act (NEPA) of 1969 was one of the first pieces of legislation to establish a framework for environmental protection. NEPA's requirements apply to the federal government and call for proper consideration to be given to environmental impacts before any major activity (e.g., building a highway or airport) is undertaken. All federal agencies are required to do environmental assessments (EAs) and Environmental Impact Statements (EISs) as a result of NEPA. Any mining or logging activity that will take place on federally-owned lands is subject to the these requirements, and an EIS must be prepared that describes the impacts (not just discharge-related impacts) of the proposed project and alternatives.

The Pollution Prevention Act of 1990 is directed at both government and industry. It does not mandate specific pollution prevention activities but it does establish pollution prevention as the national environmental protection policy, outlining a hierarchy of approaches.

3.3.7 State Regulations

National law related to the environment sets the minimum level of regulated performance for a product or facility. States are free to enact more restrictive legislation if they deem it appropriate. The most active state in this regard has been California, which tends to set more restrictive emissions regulations for vehicles than does the national government, as well as to regulate emissions of a variety of consumer products such as paints and solvents. These actions obviously influence the design of products, and thus are of vital concern to product designers.

For the purposes of this book, regulations directed at individual facilities by the states are more relevant than those relating to products. Perhaps the most interesting and demanding of the state-mandated facility requirements are the materials accounting regulations of Massachusetts and New Jersey. The New Jersey legislation (that of Massachusetts is similar, but with a somewhat different approach) offers a reasonably complete picture for each material used in a facility. It covers facilities making at least 25,000 pounds (55 Mg) or using at least 10,000 pounds (22 Mg) of a particular material per year. (This amounted to about 600 facilities in 1998). The following data are reported annually on a chemical-by-chemical basis:

Chemical Use Information:

- The amount brought onto the plant site
- The amount in inventory at the beginning and end of the year
- The amount produced on site
- The amount consumed in production
- The amount leaving the site as or in a product

Chemical Waste Information:

- The amount of waste generated before recycling, treatment, or disposal
- Releases to air, water, and land
- Off-site transfers to recycling, treatment, and disposal

Because all manufacturing facilities in New Jersey are reporting this information, it can be aggregated to form statewide indicators of environmental performance. An example is pictured in Figure 3.1, which shows that non-product output generated by New Jersey facilities showed a downward trend from 1991 to 1993. It is likely that the new reporting requirements played a significant role in this decline. Performance since 1993 has been virtually stable, suggesting that new strategies may be required if further improvements are to be made.

The information required by Massachusetts and New Jersey represents an expansion of the information provided by individual facilities under the Toxic Release Inventory. It measures the total quantity of materials in commerce and their efficiency of use. In addition, it permits the analyst or any other interested party to conduct a mass analysis, and determine whether reported inputs equal reported outputs.

3.3.8 The Enforcement of U.S. Environmental Regulations

As mentioned earlier, state agencies administer and enforce federal environmental regulation in most states, and they are responsible for performing several distinct monitoring and enforcement activities. First, they ensure a new facility or process can meet the requirements of its various permits. This is known as initial compliance. Failure to meet initial compliance results in either a fine to the owner of the facility or a denial of permission to operate until the permit requirements are met.

Second, state agencies monitor facilities for continuing compliance—is the facility still operating within its permits? Most states actually rely on self-monitoring by industrial facilities of their water and air emissions. While facilities may have permits that stipulate hourly or daily emission limits, state authorities typically perform measurements only a few times per year to audit a given facility. When a facility is found to have violated its operating permit the penalty can take a range of forms, from a “slap on the wrist” to criminal prosecution. In most cases, the facility is required to pay a fine that is designed to reflect the cost savings it may have incurred by being out of compliance plus an extra penalty for punishment. Critics of the system observe that fines are generally small relative to a facility’s income and that fines are typically only levied when a facility’s owner refuses to address a violation or is uncooperative.

A final monitoring task that falls to the state agencies is the measurement of ambient environmental standards. This type of monitoring does not concern itself with particular sources of discharge but instead focuses on the overall quality of water and air in a region. It is through ambient monitoring that states are able to track progress against environmental quality targets. Ambient monitoring can also be used

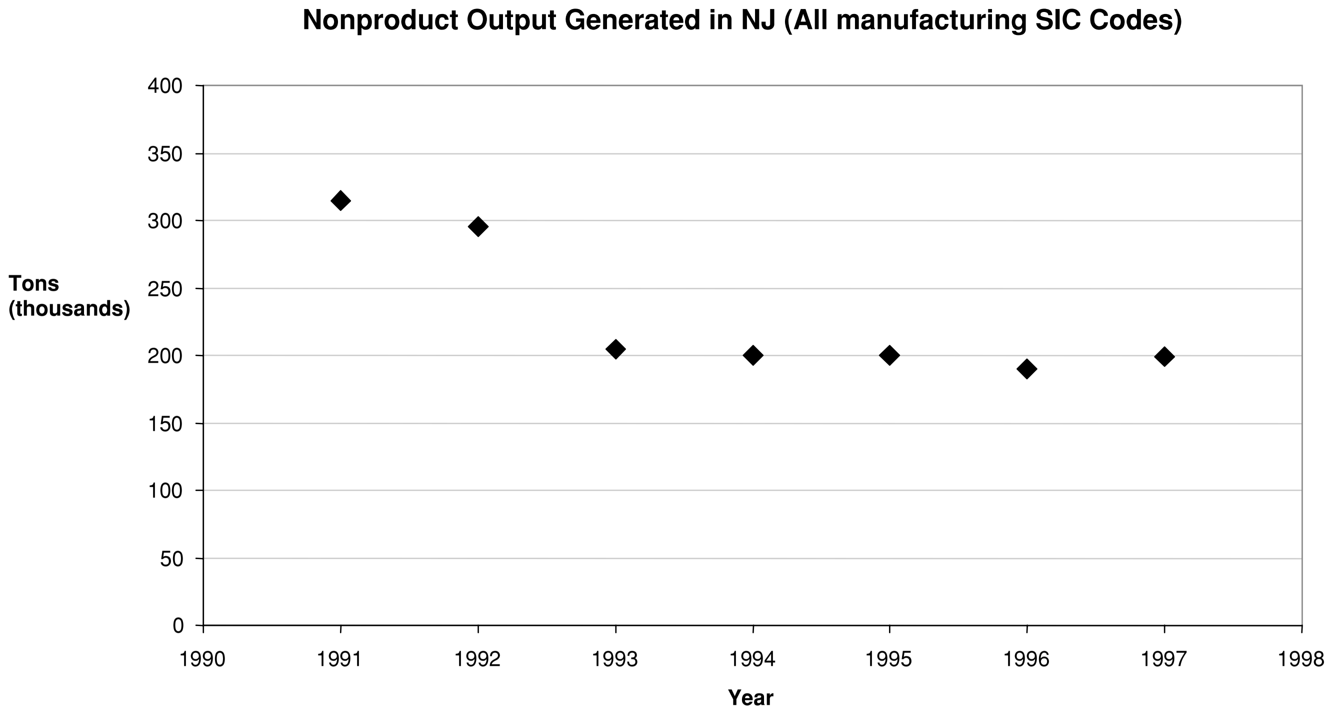

Figure 3.1. The quantity of non-product output generated by New Jersey manufacturing facilities between 1991 and 1997. (*Source:* New Jersey Department of Environmental Protection, September, 2002.)

to guide changes in permit levels. For example, due to population growth and increased industrial activity, many urban areas are experiencing either a decline in (or a lack of improvement in) air quality. Measurements are used to classify a region's severity of non-attainment of the National Ambient Air Quality Standards (NAAQS) established by the Clean Air Act. Based on these measurements, new air emissions limits can be set for individual facilities operating within an urban region.

3.3.9 *Voluntary Programs and Negotiated Agreements*

In the last decade or so, the EPA has initiated several new programs that fall outside the command and control regulatory model. These programs are designed to encourage and reward environmentally responsible activity that goes beyond what is required by regulation. These programs fall into two categories: voluntary programs and negotiated agreements.

Voluntary programs are developed by government agencies around a specific goal, say toxic emission reduction or energy conservation, and companies are recruited to participate. The companies in turn receive public recognition and technical assistance. One of the best known voluntary programs established by the EPA is the 33/50 program. The intention of 33/50 was to reduce emissions of 17 toxic chemicals by 33% by 1992 and 50% by 1995, from a 1988 baseline. 1,300 companies (representing 6,000 facilities) joined the program and collectively met the goals a year early. Other voluntary programs run by the EPA include Energy Star (to minimize energy used by buildings and consumer appliances), Waste Wise (to promote waste reduction and recycling), and Climate Wise (to reduce greenhouse gas emissions). Participants in these voluntary programs are still subject to all of the standard environmental regulation.

Negotiated industry-government agreements differ from voluntary programs because they are developed jointly through cooperation between government and an individual company or industry sector. Negotiated agreements are sometimes used to address a well-defined environmental issue associated with one industry sector (see Text Box 3.2) and may in these cases preempt or prevent future regulation. A Memorandum of Understanding (MOU) signed by the EPA and each participating company lays out the intention of the agreement, its goals, and what each party is responsible for. The EPA may commit to provide technical assistance to the companies while the companies commit to perform research and develop environmentally superior manufacturing processes or technologies. The MOU may or may not contain specific performance goals and deadlines.

A new program centered on negotiated agreements was launched by the EPA in the mid-1990's. Known as Project XL, this program is fundamentally different from others because it seeks new ways of accomplishing traditional environmental goals and can provide regulatory relief to participating companies. Prior to Project XL, a company's participation in one of EPA's voluntary programs had no bearing on its environmental permits or compliance record. Project XL changes this by granting

Text Box 3.2

Reducing Greenhouse Gas Emissions from the Aluminum Industry: A Negotiated Industry-Government Agreement

The Voluntary Aluminum Industry Partnership (VAIP) between the U.S. Aluminum industry and the EPA is one example of a negotiated industry-government agreement. The goal of the agreement was to reduce emissions of perfluorocarbons (PFCs) from aluminum smelting by 45 percent by 2000 (relative to a 1990 baseline). PFCs are potent greenhouse gases. Their production as a by-product of aluminum smelting operations is actually indicative of process inefficiencies. In the course of developing and implementing technologies to reduce PFC emissions, the aluminum smelting industry should also improve the efficiency of aluminum production.

Source: Voluntary Aluminum Industry Partnership. EPA website. http://www.epa.gov/highgwp1/vaip/

participants greater regulatory flexibility in return for a promise to deliver superior environmental performance. For example, a company might be granted a permit that removes some of the onerous reporting requirements as long as its emissions are lower than they would have been under a traditional permitting scheme. The idea behind Project XL is that it will allow companies with strong environmental records more freedom to choose how to tackle particular environmental issues, enabling them to manage their environmental impact more cost-effectively. Project XL projects are negotiated between individual companies and the EPA, meaning that each one is unique. Furthermore, projects are being treated as experimental so it is too early to tell whether this voluntary approach will take hold more broadly and replace traditional command and control regulatory approaches.

3.4 THE NETHERLANDS: AN EXAMPLE OF A PRIMARILY CONSENSUAL APPROACH

While negotiated agreements between industry and government are a relatively peripheral component of the U.S. approach to industrial environmental management, they are now the core of the Dutch approach. In the 1980's, the Netherlands recognized several problems with its approach to environmental regulation: environmental quality was not improving and in many cases was deteriorating, a large number of ministries had responsibility for environmental protection which created a confusing and inconsistent set of policies, and industry was faced with a complex permitting process that was inefficient to implement and difficult to enforce. Furthermore, the consideration of environmental effects on separate media (air, water and land) sometimes led to passing a problem from one media to another rather than solving it. The Dutch government decided that extensive reform was needed to create an integrated environmental policy and an integrated regulatory and administrative framework in which it would reside.

The resulting system is fundamentally different from that operating in most industrialized countries because it is founded on the assumption that environmental protection is a shared responsibility. Government devolves much of the responsibility for environmental protection onto other members of society. While the government is still responsible for setting the broad environmental targets (e.g., overall emissions reduction goals for CO_2), industry is responsible for developing and implementing effective and efficient measures to help reach these targets (e.g., specific technology or product changes that will reduce CO_2 emissions). Other actors, like the agriculture, transportation, construction, and energy sectors, and the public, are also assigned specific responsibilities and the Dutch system has clear environmental measures and targets for each of these groups.

A National Environmental Policy Plan (NEPP) is generated every four years. The first NEPP was issued in 1989 with a broad goal of achieving environmental sustainability for the country in one generation, or by 2010. Each plan establishes detailed environmental quality indicators and targets in a number of areas, or environmental "themes." For example, in the euthrophication theme, quality standards are set for surface and ground waters and a ten-year goal for 50% reduction in phosphate and nitrate emissions is established. The nine themes are:

- Climate change (global warming and ozone depletion)
- Acidification (acid deposition on soil, surface water and buildings)
- Eutrophication (excessive nutrient build-up in surface water)
- Dispersion of toxic and hazardous substances
- Land contamination (including soil and aquatic systems)
- Waste disposal (waste processing, prevention, reuse and recycling)
- Local nuisance (disturbances caused by noise, odor and local air pollution)
- Water depletion (habitat change or depletion of water supply)
- Resource dissipation (sustainable use of renewable and nonrenewable resources and energy)

Target groups must develop plans to achieve the goals established for each theme. It is recognized that target groups contribute differently to each environmental theme. The target groups responsible are: agriculture, traffic and transport, industry and refineries, energy companies, the construction industry, consumers and retail trade, waste processing companies, and actors in the water cycle.

The industry target group is further broken down into the ten sectors that contribute most heavily to pollution in the Netherlands: primary metals, chemicals, printing, dairy products, metalworking and electrical engineering, textiles and carpeting, paper and cardboard, meat, rubber and synthetic materials, and cement mortar and cement products. Each of these sectors has negotiated covenants with the Dutch government. The exact nature of the covenants differs for different sectors. For example, the base metals sector has an agreement that sets targets for emissions reductions, energy efficiency, noise control, and clean-up of contaminated soil. Each company then creates its own Company Environmental Plan (CEP) that translates the sector's targets into implementation actions at the plant level. The CEP must be approved by government authorities and must cover a period of at least four years. Once a plan is approved, it forms the basis for issuing a permit. It is important to note that the covenant approach, although consensual and designed to give companies operating flexibility, is not a replacement for regulation or permits. If a company does not abide by its CEP, the government has recourse to apply legal limits and penalties.

Although the Netherlands has a history of consensual decision-making and cooperation between industry and government, the negotiation of covenants for environmental protection did not prove easy. In practice, the integrated approach still relied on the involvement of government officials from many different ministries (e.g., the Ministry for Spatial Planning and Environment, the Ministry for Transport and Public Works, and others) and from many different levels of government (local, regional, and national). Negotiations could last for 18 months or longer as industry representatives and government representatives moved towards a common plan for the sector. At times the positions of different government bodies were at odds with each other. Over time these issues were resolved. More than 100 covenants have now been negotiated; they deal not only with emissions reduction but also with product quality and energy conservation.

Several conditions were important to the successful adoption of the covenant approach to environmental management. First, there was the political will to make a radical change in regulatory philosophy and administration. This translated into political pressure on industry to go along with this change. Second, there was a process to define clear and achievable environmental quality indicators and targets that were relevant to all target groups. This gave both industry and government a way to establish a baseline and measure progress. The fact that targets are long term (most of those set in the 1980's or 1990's were for 2000 or 2010) makes it possible for industry to plan activities and capital investments over a reasonable time frame. Third, mutual gains were possible using a covenant approach. The government gained a more integrated and effective policy framework, while industry gained the flexibility to make environmental decisions that make sense for individual sectors and companies. Finally, the consensual approach operated because there was always a threat of sanctions. The government retained legal instruments to use if a company did not negotiate a covenant or comply with its environmental plan.

The results of the Dutch approach, more than a decade after the first NEPP was issued, are now coming clear. Target groups are by and large meeting their goals set for 2000 and 2010. Successes for industry include the reduction of waste disposal by 60% and an increase in waste recycling by 70%. Environmental quality indicators are favorable in most areas, with the exception of carbon dioxide emissions. The "decoupling" of pollution production and economic output has been achieved (except in the case of CO_2 and NO_x emissions), as economic growth has accompanied declines in pollution levels. The third and fourth NEPP, issued in 1998 and 2001 respectively, call for greater attention to achieving long-term sustainability through changes in lifestyle and consumption patterns. While continuing to address persistent environmental problems, NEPP 4 focuses on quality of life in both the Netherlands and abroad and tries to link environmental policy more directly to the concerns of individual citizens.

3.5 INTERNATIONAL AND INDUSTRY-GENERATED APPROACHES

National policies for environmental protection are not the only frameworks that guide industrial environmental management practice. In this section, international agreements that influence a company's environmental practices or a nation's environmental policies are described. A relatively new approach—industry-generated voluntary schemes—is also discussed.

3.5.1 International Agreements

Two broad categories of international agreements influence industry's actions towards the environment. The first category includes international environmental agreements negotiated between governments with the explicit purpose of protecting species or habitats, or restricting the transport and release of hazardous materials. Examples include the 1987 Montreal Protocol that phases out the production of ozone depleting substances, the Convention on International Trade in Endangered Species (CITES), the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, and the Kyoto Protocol to the United Nations Framework Convention on Climate Change. Despite the fact that some of these agreements are yet to be ratified by participating nations, their mere existence has drawn attention to critical international environmental issues. For example, the Kyoto Protocol calls for the reduction of emissions of global warming gases by developed countries below 1990 levels by 2008. Some companies are taking the issue seriously enough that they are reducing their own emissions even though the agreement may never enter into force (see Text Box 3.3).

Text Box 3.3

Taking Action on Global Warming: BP's Internal Emissions Trading Scheme

British Petroleum (BP) was one of the first companies to publicly acknowledge that the risks of climate change were serious enough to warrant action. In 1998 BP committed to a 10 percent reduction of its greenhouse gas emissions from 1990 levels. One mechanism BP used to meet this goal was an internal global emissions trading scheme that operated between 1999 and 2001. Under such schemes, emitters (individual facilities in BP's case, companies, or even countries) buy and sell rights to emit pollutants; those able to reduce emissions for the lowest cost can sell reductions to other entities. By establishing a market for emissions, trading schemes are seen as ways to bring down the overall cost of achieving a certain net emissions reduction. Although BP has met its internal goal it remains supportive of market mechanisms for emissions reduction, including the U.K. government's Emissions Trading Scheme (ETS).

Source: Pew Center on Global Climate Change. Company Profiles. http://www.pewclimate.org/companies_leading_the_way_belc/company_profiles/

The second broad category of international agreements that affect industrial environmental practice are trade agreements. The major framework for addressing international trade is the World Trade Organization (WTO). This body exists to promote free trade among member countries and it prohibits any country from developing a domestic policy that would discriminate against certain trading partners but not others. This principle sometimes comes into conflict with the international environmental agreements just mentioned, and it is criticized as stripping a nation of its sovereignty to develop and enforce stringent environmental standards. For example, the U.S. sought to ban the importation of shrimp from countries that failed to protect endangered sea turtles from entrapment in fishing nets. Thailand, India, and Malaysia argued that the U.S. ban on shrimp was a restriction on free trade and in 1998 the WTO ruled in their favor.

Regional blocs also influence environmental policy within their boundaries. The European Union has harmonized environmental standards across member countries and created a European Environmental Agency. Regulations have been passed on eco-labeling, packaging waste, vehicle end-of-life, emissions standards and carbon taxation. Any member state may impose more stringent environmental standards as long as they do not unduly restrict trade between member states. The North American Free Trade Agreement (NAFTA) includes provisions for environmental cooperation between its members—the U.S., Canada, and Mexico. It notes that each country should determine its own level of environmental protection and its own environmental policies, but that a country can not use environmental regulations to restrict trade unless there is a legitimate reason.

While it is true that environmental standards and the monitoring and enforcement of regulation can vary widely between different countries, particularly between developed and developing countries, industries with foreign operations are increasingly under pressure to harmonize their own practices globally. Some of this pressure comes from public objection to some highly visible incidents of neglect for the environment and indigenous peoples. Other pressure comes from within the manufacturing community itself as companies increasingly adopt voluntary international standards (e.g., ISO 14001), described more fully below.

3.5.2 Industry-Generated Approaches

A discussion of the environmental constraints faced by industry would not be complete without addressing the recent rise in non-regulatory programs for environmental protection. These programs, initiated by industry without the participation of government, take two forms: industry-generated commitments, and management system standards. While some programs are confined to single industries and single countries, others are applicable to any organization operating in any geography.

Industry-generated commitments are unilateral initiatives developed by a single company or an industry association. The company or group of companies makes a public declaration of environmental goals they plan to meet or new practices they plan to implement. Typically these actions are beyond what is required for compliance with environmental legislation, but they may be motivated by new or anticipated regulation.

Unilateral commitments made by industry associations, as opposed to individual companies, generally do not contain performance goals but establish codes of management practice that members must follow. While the chemical industry was one of the first to establish a set of unilateral commitments for environment, health and safety practice (see Text Box 3.4), initiatives of this type are now seen in industries as diverse as textile manufacturing, petroleum extraction and refining, automobile manufacturing, and forestry, paper and printing.

In recent years, there has been growing attention paid to the development of environmental management systems (EMSs) and their use to improve environmental performance. An EMS is simply a system for evaluating environmental practice, making changes, and responding to the outcomes. Founded on the idea of continual improvement and similar to the total quality management (TQM) approach, an EMS is an organizational tool, not a set of performance metrics or standards. The assumption is, however, that a company operating with an EMS is more likely to identify opportunities for improvement in environmental practice than one who is not, and will consequently have superior environmental performance.

Text Box 3.4

Responsible Care®: A Voluntary Commitment by Chemical Manufacturers

In 1986 the Chemical Manufacturers Association (now the American Chemistry Council, or ACC) developed Responsible Care®, a set of codes that guide environmental, health, and safety practices. As a condition of membership in the ACC chemical companies must commit to the Responsible Care® codes and implement its practices. The six codes govern pollution prevention, community awareness and emergency response, process safety, distribution, employee health and safety, and product stewardship. Each code stipulates management systems and operational practices that companies must implement. Criticized for not ensuring that members were actually implementing the Responsible Care® codes, the ACC started performing third-party verifications of members' Responsible Care® programs. Also, while it still does not set blanket performance goals, the ACC now requires each member company to set at least one performance goal relating to Responsible Care.®

Source: American Chemistry Council. http://www.responsiblecare-us.com

The International Organization for Standardization (ISO) has developed a voluntary standard (known as ISO 14001) for environmental management systems. Companies can obtain ISO 14001 certification if their EMS meets the standards. ISO 14001 certification is granted through a third-party verification. As of 2000, more than 40,000 organizations worldwide had been ISO 14001 certified. The countries with the largest number of certified organizations were Japan (with more than 9000), the U.K. and Germany. Organizations can chose to pursue the standard without seeking third-party verification. Because of this, there may be a great many more companies operating ISO 14001-compatible management systems than are reflected in the numbers of those certified.

ISO 14001 has important implications for firms in all industries. Some large manufacturers, such as automakers, now require that each of their thousands of suppliers be certified to ISO 14001. Also, governments of some countries, particularly those in Asia, have considered requiring that multinational companies operating in their borders be ISO 14001 certified. Several European banks and insurance companies will give preferential treatment to organizations with ISO 14001 certification. It may be that certification to ISO 14001 becomes a basic requirement of doing business. While it is not an international "law," or even a performance standard, ISO 14001 has the potential to promote further consideration of environmental impacts by companies operating anywhere in the world.

3.6 CONCLUSION

According to economic theory, environmental quality, as a public good, will not be maintained or protected adequately in the absence of regulation. Pollution is seen as an economic "externality"; there is no market associated with its production. Regulation steps in to force companies who do create pollution to "internalize the externality" by putting a price on its production. In a handful of cases, including the SO_2 emissions trading scheme in the U.S. Clean Air Act, a unit of pollution is literally assigned a price. In most cases, however, the cost of producing pollution takes the form of a fine, the threat of removal of a permit to operate, or the threat of criminal charges.

In the last few decades, complying with environmental regulation has increasingly become a "taken for granted" aspect of operating for most companies, rather than a cost of doing business. Environmental compliance does more for companies than just forestall costs imposed by regulation. It sends signals to regulatory authorities, communities, shareholders and employees that a company takes its responsibility to reduce environmental impact seriously. While the benefits of this "good neighbor" reputation may be hard to quantify, they probably include a less adversarial relationship with regulatory authorities, greater trust from the community in which facilities are operated (or communities in which new facilities will be sited), and enhanced employee morale and commitment. In financial terms, companies with a good compliance record may be rewarded in the market place as shareholders and lenders see good environmental management as an important component of lowering business risk. Regulation like the U.S. Superfund law made it abundantly clear that industrial operations are held liable for past environmental damage, not just for accidents and spills. Companies also seek to reduce future liability and investing in environmental control technologies that meet regulatory requirements is one way to do this.

In this manner, regulation sets both a legal and a normative standard for behavior. All companies are required by law to meet the requirements of their permits. In addition, many companies seek to instill a "beyond compliance" mind-set in their employees that encourages continuous improvement in environmental performance. Regulation, at least in theory, sets the environmental quality goals that are most critical to continued human and ecosystem health.

In practice, a regulatory system likely does not capture all issues of importance and will emphasize some over others. The U.S. system of environmental regulation focuses almost exclusively on the control of hazards in the environment; it generally does not address the consumption of scarce resources, energy, or water. Table 3.1 compares the focus of U.S. federal environmental regulations and the scheme used in this book (ΣWESH) to analyze environmental impact. Environmental regulation in the Netherlands, organized around nine broad themes, is much more inclusive. Covenants with industry address product environmental performance and energy consumption, as well as hazardous emissions.

Table 3.1. Federal Environmental Legislation Related to the Water, Energy, Scarcity and Hazard (ΣWESH) Framework for Environmental Impact Analysis

Legislation	Water	Energy	Scarcity	Hazard	Other
Clean Air Act				X	
Clean Water Act	X*			X	
RCRA				X	
CERCLA (Superfund)				X	
EPCRA (SARA Title III)				X	
TSCA				X	
Endangered Species Act				X	
Oil Pollution Act				X	
FIFRA				X	
NEPA				X	
Pollution Prevention Act					X

*The Clean Water Act governs water quality of facility effluent and does not address water consumption.

Regulation is also a relatively static tool for environmental protection. Once environmental quality standards are set and specific industry goals created, change occurs only after a lengthy process of debate and negotiation. Incorporating new scientific findings or the development of new technology into regulation is a slow process. It almost certainly occurs more easily and quickly under a consensual system like that used in the Netherlands because industry covenants are renewed every four years and are narrowly focused on a group of companies that shares common processes and technologies. The U.S. system has been criticized as too static and too inflexible for the changing state of manufacturing technology.

While regulation will continue to create the basis for industrial environmental practice, it is likely that the development of regulation and the issuance of permits will be more and more a process of negotiation between industry and government. Voluntary programs—both government-initiated and industry-generated—are bound to become more important in channeling industry's environmental practices, but are unlikely to replace regulation. Governments will continue to play a role in setting the standards for environmental quality, and developing some way to ensure that these standards are met.

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Chapter 4

The Next Step

Pollution Prevention

4.1 INTRODUCTION

In the 1970's, when industry's primary environmental management approach was to comply with regulation, little attention was paid to the source of pollution. The emphasis was placed almost entirely on the back end of the production process, or "end-of-pipe," and the treatment of emissions before they were released to the environment. This started to change in the 1980's as businesses began to see pollution as waste, a mark of the inefficient use of resources, and a costly one at that. Attention turned to reducing the production of pollution at its source. A pioneer of this approach, 3M, started its Pollution Prevention Pays (3P) program in 1975. Employees with daily experience of the manufacturing processes were encouraged to propose projects that would reduce the production of pollution. The success of the 3P program was measured not just in how many pounds of pollutant emissions were avoided (1 billion pounds between 1975 and 1992) but also in the money saved (over $500 million) as a result. Many other companies followed 3M's example and, according to one recent survey, pollution prevention (often designated P2) is now an important element of the overall environmental compliance strategy of the great majority (more than 85%) of manufacturing companies.

A pollution prevention (P2) approach differs from traditional environmental compliance practices in several fundamental ways. First, the core organizing principle for pollution prevention is one of efficiency. The goal of pollution prevention is to minimize the use of, and optimize the reuse or recycling of, hazardous materials. Pollution prevention is not guided, as regulatory limits are, by the single goal of achieving environmental quality standards. Rather, it seeks the end-state of improved environmental quality by paying attention to how materials are used during the manufacturing process itself.

Text Box 4.1

The American Chemical Council's Responsible Care® Program: Using P2 to Go Beyond Regulation

The most formal and oldest P2 program is Responsible Care®, a 1988 initiative of the U.S. Chemical Manufacturers Association (now the American Chemistry Council). Developed to respond to public concerns about the manufacture and use of chemicals, the program has proven to be good for business as well as the environment, and has been replicated by a variety of national and international chemical organizations worldwide.

Ten principles comprise the core of the program:

- Recognize and respond to community concerns
- Develop and produce chemicals that are safe to make, transport, use, and dispose of
- Make health, safety, and environmental matters priorities in planning products and processes
- Promptly report chemical hazards to officials, workers, customers, and the public, and recommend corrective measures
- Counsel customers on safe use, transportation, and disposal of chemicals
- Operate plants in a way that protects the environment, health, and safety of employees and the public
- Support research on the health, safety, and environmental effects of chemical products, processes, and waste materials
- Work with others to resolve problems from past handling and disposal of hazardous substances
- Work with government and others to create responsible laws, regulations, and standards to safeguard the community, workplace, and environment
- Offer to assist others who produce, handle, use, transport, or dispose of chemicals

The principles are implemented by Codes of Management Practice, dealing with pollution prevention, process safety, product stewardship, community awareness and emergency response, distribution (i.e., the shipment of chemicals), and employee health and safety. In many cases, performance relative to these codes is evaluated by third-party groups that include unaffiliated experts and local citizens.

Member companies of the Responsible Care® program have made impressive environmental progress. Since 1988, emissions have been reduced by 58%, even while production has increased by 18%. Reportable injuries have decreased by about 30%. More than 300 community panels have been created to promote consultation.

No manufacturing process, particularly one involving hazardous materials, high temperatures, and high pressures, is likely to be perfect, but the Responsible Care® program has done much to move the chemical industry, in the U.S. and elsewhere, toward a strong P2 commitment.

Second, by drawing attention to the pollutants themselves, pollution prevention can encourage a more systemic examination of a production process than traditional media-segmented regulation does. If efforts are made to prevent pollution of any form, it is less likely a reduction in emissions to one medium will result in increased emissions to another medium.

Third, pollution prevention is highly process dependent. An approach that works for one facility will not necessarily work for another facility in the same industry. While regulation stipulates emissions standards or control technology requirements for whole industries, pollution prevention solutions are best developed by those most familiar with the production process at individual facilities. This means that pollution prevention approaches, while they may require more effort to develop, are also more closely matched to the dynamic nature of manufacturing.

Finally, pollution prevention approaches typically require capital investment on the part of the manufacturer, but a monetary return on investment is expected due to lower materials costs, lower waste handling costs, or lower energy consumption. Compliance with regulation, on the other hand, is often seen as costly and the returns that accrue are reputational or risk-reducing, not monetary. In fact, the emphasis on environmental and economic "win-win" solutions is evident in the names given to early pollution prevention efforts like 3M's Pollution Prevention Pays or Dow's Waste Reduction Always Pays (WRAP) programs.

These are notable differences between regulation and pollution prevention, but they do not suggest that the two approaches are incompatible. In fact, they should probably be seen as complementary. Some forms of regulation, like that which significantly increases the cost of generating and disposing of hazardous waste, can encourage companies to pursue pollution prevention. In the U.S., the detailed regulatory requirements for handling and disposing of hazardous waste make reduction in the quantity of waste generated an attractive, and cost-saving, alternative. One way of complying with environmental regulatory limits is to run an operation that minimizes emissions of regulated substances. Pollution prevention can be seen as one tool industry can use to meet regulatory requirements, and at the same time it can be seen as a tool to go beyond regulatory requirements and optimize the production process with consideration of environmental impacts.

4.2 WHAT IS POLLUTION PREVENTION?

The objective of pollution prevention (also termed *cleaner production*) is to reduce impacts or risk of impacts to employees, local communities, and the environment at large by identifying a problem or potential problem, locating its source within the manufacturing process, and changing the source so as to reduce or eliminate the problem.

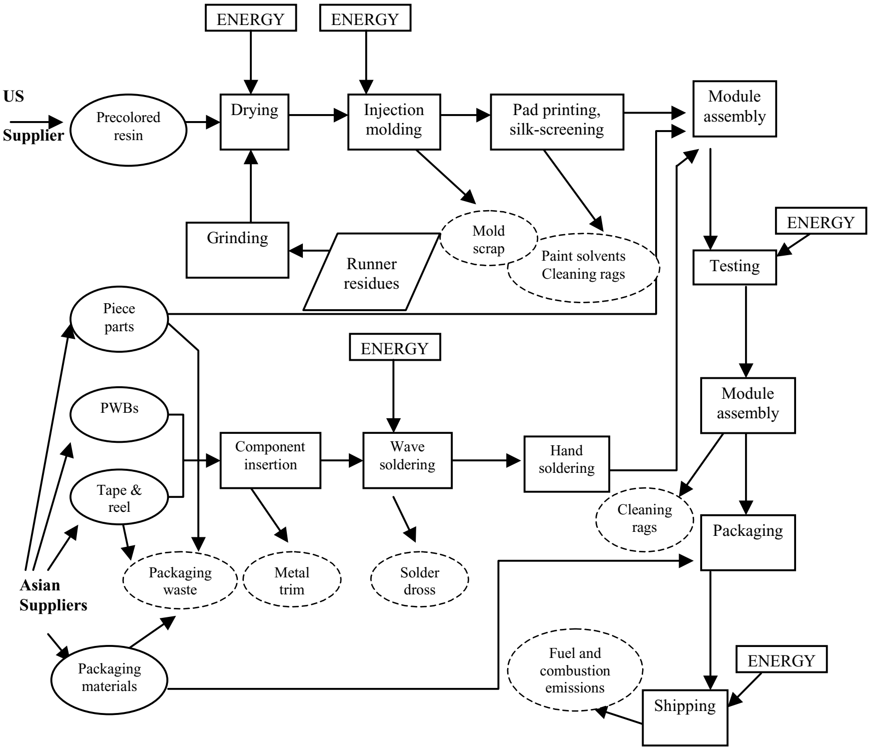

Figure 4.1. A process characterization map for the manufacture of a desktop telephone. (Courtesy of Lucent Technologies.)

Process evaluation in P2 deals with sequence flow, the consumption of materials, energy, water, and other resources, the manufacture of desired products, and the identification and quantification of residues. An example flow chart or "map" for this *process characterization* is shown in Figure 4.1. No attempt is made at this stage to quantify any of the flows. The more complete the process characterization diagram, the easier the subsequent assessment will be.

P2 techniques for dealing with issues identified by process characterization include:

1. *Process modification*—changing a process to minimize or eliminate waste generation
2. *Technology modification*—changing manufacturing technology to minimize or eliminate waste generation
3. *Good housekeeping*—changing routine maintenance or operation routines to minimize or eliminate waste generation

4. *Input substitution*—changing process materials to minimize quantity or potential risk of generated waste
5. *On-site reuse*—recycling residues within the facility
6. *Off-site reuse*—recycling residues away from the original facility

The health and environmental risks from different flow streams and processes are, of course, far from equivalent. For example, a detailed study of petrochemical intermediate industry showed that only a small number of compounds were responsible for most of the potential toxicity. The results of that study, shown in Figure 4.2, demonstrate that toluene diisocyanate, phosgene, and methylene diamine are obvious targets for P2 efforts.

David Allen, of the University of Texas, has pointed out that P2 can be addressed at different spatial scales. At the microscale, or molecular level, chemical synthesis pathways and other material fabrication procedures can be redesigned to reduce waste

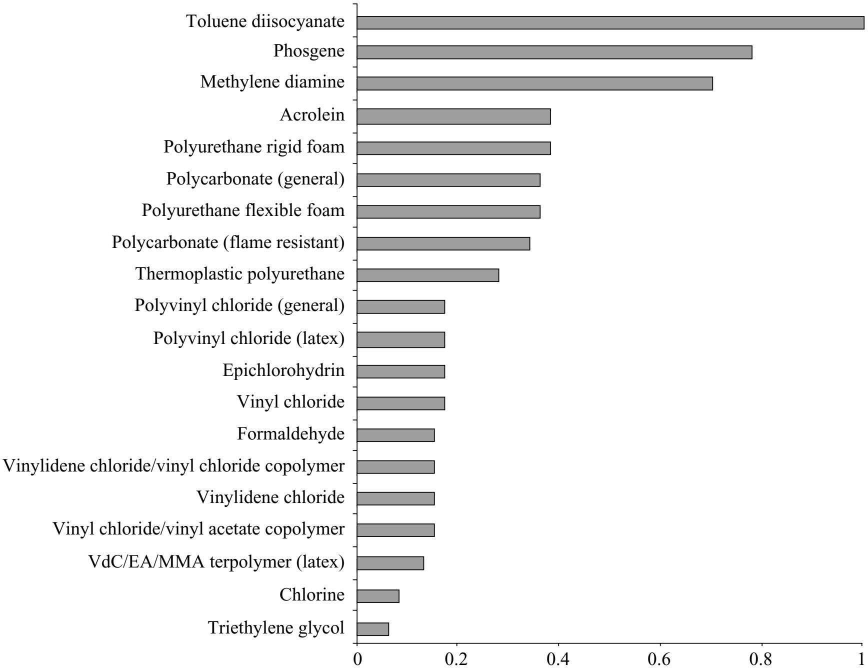

Figure 4.2. Compounds that are major contributors to the overall potential toxicity of the chemical intermediates industry. (Adapted from S. Fathi-Afshar and J. C. Yang, Design the optimal structure of the petrochemical industry for minimum cost and least gross toxicity of chemical production, *Chemical Engineering Science, 40*, 781–797, 1985.)

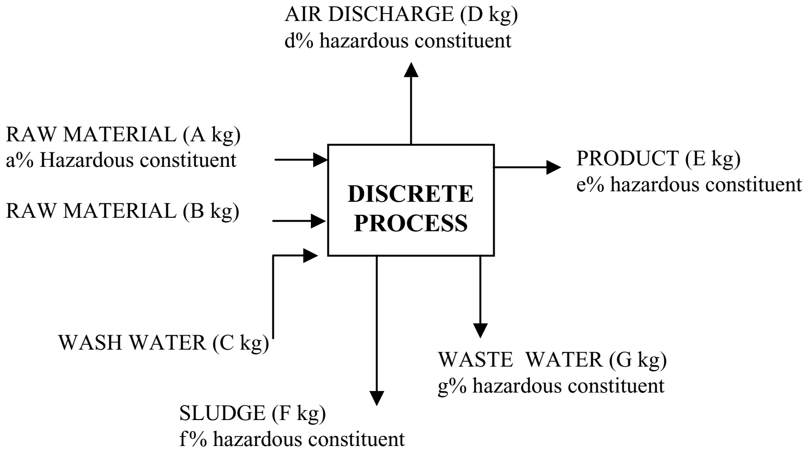

Figure 4.3. A material-centered process analysis directed toward the use, retention, and residue production of a hazardous constituent. (D. G. Willis, Pollution prevention plans—A practical approach, *Pollution Prevention Review*, 347–351, Autumn, 1991. Reprinted by permission of John Wiley & Sons, Inc.)

and lower process toxicity. At the process line level, or mesoscale, design considerations include adjustments in temperature, pressure, processing time, and the like, with energy and water use, by-product generation, and inherent process losses as foci. Activities at the mesoscale level are those most commonly termed P2. Finally, the macroscale, at the sector or intersectoral level, can be addressed through industrial ecology perspectives in which byproducts find uses outside the facility in which they are generated. Microscale P2 activities are generally possible only where chemicals are being synthesized; mesoscale and macroscale P2 can be undertaken anywhere chemicals or other materials are being used.

Once a chemical or process of interest has been identified, *materials accounting* can be employed to determine the best avenues for action. For a single process, the result would be a diagram of the form of Figure 4.3. Here the quantities of the target species are listed and compared.

With the target identified and its flows determined, reduction or elimination are approached in a multi-step manner:

- Redesign the process to substitute low toxicity materials for those that are highly toxic, or to generate high toxicity materials on-site as needed
- Minimize process residues
- Reuse process residues
- Redesign the process so that unwanted residue streams become streams of useful byproducts

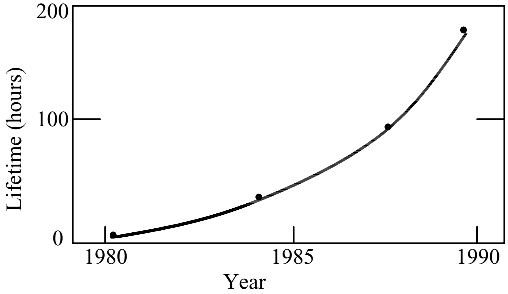

Figure 4.4. The extension in lifetime of a peroxide solution used in the manufacturing of electronic components. (Courtesy of E. Eckroth, AT&T Microelectronics.)

In the case of a process already existing or newly begun, a *waste audit* is generally useful. The approach is to study *all* waste flows from the facility to determine which can be decreased, and how. Industrial solvents, cleaning solutions, and etchants are often good places to begin. An approach that has proven beneficial in a number of cases is the regeneration of chemical solutions, which can often be accomplished by filtration, changes to relax purity requirements, the addition of stabilizers, redesign of process equipment, and so on. An example of the improvement that can be achieved is shown in Figure 4.4. A peroxide bath, initially used once and discarded, was gradually redesigned over a period of years until the chemical solution was replaced only every week. The reduction in cost and decrease in liquid residues that resulted were very large.

A further lifetime-extension technique for solutions is that of recuperative rinsing. This is most often used where parts are sprayed or immersed to clean them after electroplating or surface finishing. Subsequently, the rinse water containing process chemicals can be returned to the process tank to replace fluid lost during evaporation rather than being discarded. Recuperative rinsing can be successful where a high degree of solution monitoring and control is used.

Pollution prevention thus includes a wide variety of practices that contribute to reducing the generation of hazardous substances. Projects may also seek to maximize the efficiency with which water and energy are used, and to minimize overall water and energy loss rates. These actions are seen as complementary to those directed toward routine emissions to air, water, and soil, or to leaks or accidents. One of the simplest operational definitions of P2 is that it is "very good housekeeping."

A pollution prevention hierarchy has been established and is widely adopted by companies engaged in pollution prevention and organizations that promote it. The hierarchy is shown in Figure 4.5. The base of the pyramid shows the most environmentally favorable practice, while the tip of the pyramid shows the least environmentally favorable one. Most desirable is the reduction of the generation of waste. If this is not possible, material should be reused in a similar or related process. If reuse is not

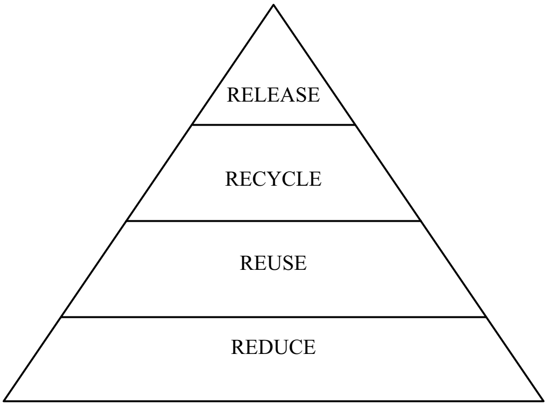

Figure 4.5. The Pollution Prevention hierarchy.

possible, the material should be recycled. Recycling differs from reuse because recycling usually involves the transformation of the material from one form to another, requiring the input of energy. Reuse (say, of a process chemical) requires little or no transformation. If no other options are available for dealing with a material, it should be disposed of or released to the environment only as a last resort.

In practice, the pollution prevention hierarchy should be used as a guide and actual choices made on a case-by-case basis. For example, there may be situations when the disposal of a relatively non-hazardous material is environmentally superior to a complex recycling operation that requires the use of a great deal of water or energy. If the idea of pollution prevention is taken to include more than just the reduction of chemical emissions, and accounts for the consumption of raw materials, water and energy, the solution should balance the environmental impacts associated with each. In many cases, companies have found that toxic emissions reduction goes hand in hand with reduced materials consumption, and more efficient use of water and energy.

Pollution prevention approaches differ from some other approaches that seek to reduce the impact of industrial processes on the environment. Pollution prevention typically focuses on a single manufacturing process or factory and does not necessarily optimize material consumption or waste generation across a chain of interconnected industrial activities. In contrast, industrial ecology calls on manufacturers to view others as elements of their ecosystem and to use the waste from one facility as feedstock for another facility. Pollution prevention is primarily aimed at finding ways to reduce the production of waste, rather than looking for productive uses for it.

Pollution prevention approaches are focused more on process than on product. They tend to look at ways to modify existing processes instead of looking for ways to fundamentally redesign a process or product. A product-focused environmental strategy may differ from pollution prevention by encouraging different patterns of product use, lengthening product life, or requiring end-of-life recycling. All of these involve expanding the scope of pollution prevention beyond the factory fence line.

4.3 IMPLEMENTING POLLUTION PREVENTION

A pollution prevention project at an industrial facility typically consists of a number of steps. First, information is gathered about the materials used and wastes generated. The quantity of a material purchased, how it is used in one or more processes, and how it is converted into waste material or product is all of interest during this step. Useful data can be gathered from raw material inventory records, process flow diagrams, operating logs, production schedules, hazardous waste reports, and emissions records. Some measure of the relative risk of various materials and emissions is essential to prioritize which materials should be the focus of pollution prevention efforts.

Once a particular material or process has been selected for a pollution prevention project, a number of analytical tools are available for use. A materials accounting or mass balance approach can be taken to identify the type and quantity of a material at each stage in a process. Input and output quantities are measured directly or indirectly and a flow diagram constructed. Total cost accounting (TCA) can be used as a complement to materials accounting. In TCA, the full cost of material purchase, handling, use, treatment, and disposal is evaluated. This total cost can be used to compare the cost of the current practices with alternatives. Life-cycle analysis (LCA) is also a tool used for some pollution prevention projects. A life-cycle analysis is focused on a single product and it evaluates data on the materials used, as well as energy and water consumed, through all stages of a product's life, from raw material extraction to final disposal.

Ideally, a pollution prevention project would identify several alternatives and generate the materials, environmental impact, and cost data needed to choose between them. Implementing the chosen project may involve engineering changes to alter a process or equipment, procedural and operating changes to alter how a material is used, materials substitution, or all three.

Once implemented, materials and cost audits may be performed to measure the success of a pollution prevention project. Measuring outcomes and making adjustments based on them is an important element of the total quality management (TQM) approach, which is a basis for much of the thinking behind pollution prevention. The ideas of continual improvement and employee involvement, also central to TQM, have also been integrated into many organizations' pollution prevention programs.

Industrial facilities can be evaluated on the basis of their performance relative to pollution prevention. An example of a report that does so is given in Appendix C.

Text Box 4.2

The Payback for Reduced Energy Consumption

A particularly successful energy conservation program to date was initiated by the Louisiana Division of the Dow Chemical Company in 1982. Many of the improvements embodied techniques useful industry-wide, such as heavy insulation on pipes carrying hot fluids, cleaning heat exchanger surfaces often to improve heat transfer efficiency, and employing point-of-use fluid heaters where storage or long pipelines create the potential for heat loss. The company's energy contest results are summarized below.

	1982	1984	1986	1988	1990	1992
Winning Projects	27	38	60	94	115	109
Avg. Return on Investment	173%	208%	106%	182%	122%	305%

The data are from K.E. Nelson, Practical techniques for saving energy and reducing waste, *Industrial Ecology and Global Change*, R. Socolow, C. Andrews, F. Berkhout, and V. Thomas, Eds., Cambridge U.K.: Cambridge Univ. Press, 1994.

4.4 ENVIRONMENTAL SUPPLY CHAIN MANAGEMENT

In the 1920s, the Ford Motor Company came close to being "fully integrated": it owned and supplied itself with iron ore, lumber, glass, and most of the other materials needed to make an automobile. Few corporations today even approach such a model. Rather, they are an intermediate or final player in a supply chain—an intricate and vital relationship between suppliers and those supplied.

An unrealistically simple three-stage supply chain is pictured in Figure 4.6. It is obvious that a component manufacturer has many suppliers, but is itself a supplier to an integrated product manufacturer. The final product seen by the customer thus becomes a composite of decisions made and actions taken at many levels in this chain.

Many large corporations interact with thousands of suppliers, and coherent management of these relationships is as important as it is complex. It is common practice for corporations to audit the capabilities and performance of their suppliers on many fronts: incoming product quality, financial management, long-term stability, and so forth, an activity termed *supply chain management* (SCM). Increasingly, corporations are auditing their suppliers' environmental performance as well, looking at such topics as regulatory compliance, existence of an environmental management system, and commitment to environmental process improvement. This activity, an extension of SCM, is *environmental supply chain management* (ESCM).

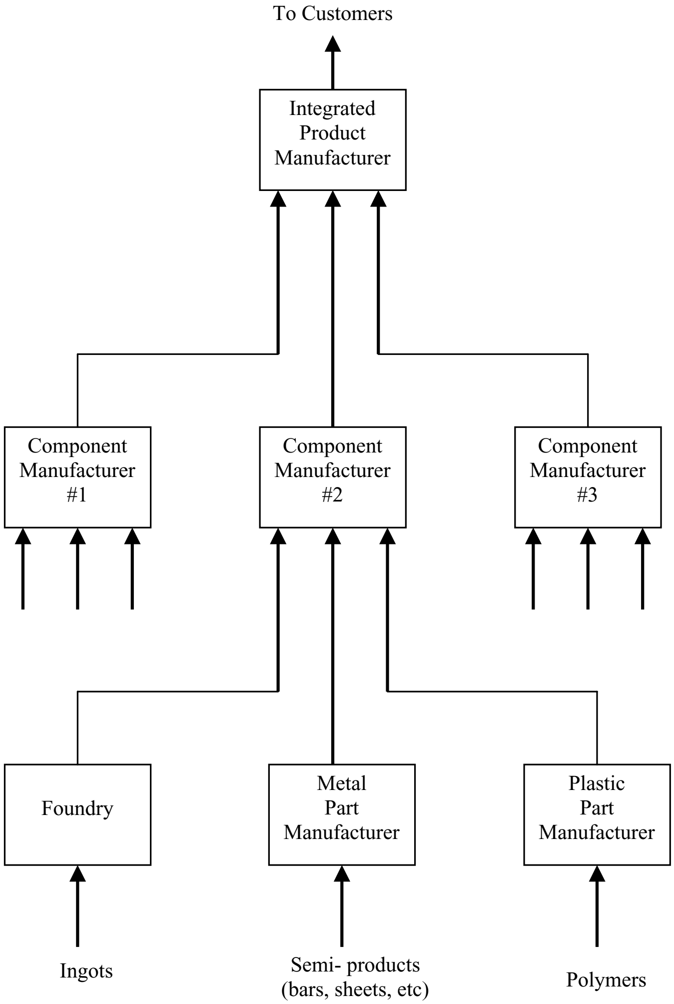

Figure 4.6. A simplified supply chain diagram for a manufacturer of an integrated product such as a vehicle. A typical supply chain might include tens or hundreds of suppliers, each having many more inputs than those shown here.

The reason for corporations to practice ESCM are many, some obvious, some not. Perhaps the initial motivation for corporations building final products (e.g., aircraft, computers, refrigerators) was the realization that the materials content of components dictated the materials content of final products, and that (especially in international supply chains) different materials regulations and practices could result in strong negative impacts on the final assembler. A second premise for change is environmental activism: large firms do not want to be publicly associated with polluting suppliers, even if the components being supplied are satisfactory. Finally, there is increasing evidence that good environmental performance is a sign of a well-managed company, the kind of supplier one would like to deal with.

ESCM began in the early 1990s with vendor questionnaires. These documents, to be completed by potential suppliers, covered both technical and managerial issues. Although useful, this approach proved problematic because the completion of a host of related but different questionnaires placed a heavy load on suppliers, and the interpretation of the responses a heavy load on those supplied. As a result, it has become increasingly common for ESCM to be included as a component of the SCM audit, usually in the form of an on-site visit.

In addition to questionnaires or audits, environmentally-related initiatives by purchasing departments play an important role in ESCM. Corporate purchasing departments audit what they buy, not how what they buy is made. They can and do specify such things as materials that cannot be included (e.g., CFCs, mercury switches) and how shipments should be packaged and delivered (e.g., recyclable or reusable containers).

Relationships between corporations and their suppliers often take the form of mentor relationships, in which information is shared and all participants act as part of a team. Ongoing dialogues, sometimes day-to-day, clarify issues that arise and decisions that influence both suppliers and supplied. This is particularly important at times of change and new product development.

It might seem that ESCM is unrealistically burdensome on suppliers. If the relationships are truly collaborative, however, there are many benefits to be had. These include:

- Learning new information from customers performing audits.
- Demonstrating a high degree of environmental performance to customers.
- Becoming positioned to attract new customers because of demonstrated performance.

Finally, of course, since nearly every corporation is both customer and supplier, involvement in a customer's ESCM teaches one how to repeat the process with one's own suppliers.

4.5 WHERE POLLUTION PREVENTION FITS

Pollution prevention is an approach that encourages a certain way of thinking about industrial pollution, but it is not a substitute for regulation or other approaches. It complements existing regulation, because it is seen by many manufacturing companies as a cost-effective way to meet or exceed regulatory requirements. The need for regulation remains, however, to govern the disposal or emission of wastes that cannot be reduced at the source.

Pollution prevention has found its place within other frameworks for environmental protection. Industry-generated voluntary commitments typically require members to adopt pollution prevention as one approach to environmental management. Regulation, like the U.S. Pollution Prevention Act, can encourage companies to adopt pollution prevention as a goal and implement practices consistent with it. While the Pollution Prevention Act does not create new regulatory requirements for companies, it does establish programs for technical assistance and funding for the promotion of source reduction techniques. Environmental management systems like those meeting ISO 14001 criteria are capable of generating the data on which pollution prevention decisions can be made.

FURTHER READING

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Chapter 5

Facility Assessment from the Life-Cycle Perspective

5.1 THE LIFE CYCLE CONCEPT

A recent innovation in the study of the interactions between industry and the environment is life-cycle assessment: the evaluation of the relevant environmental implications of a material, process, or product across its life span from creation to waste or, preferably, to re-creation in the same or another useful form. The Society of Environmental Toxicology and Chemistry defines the life-cycle assessment process as follows:

> "The life-cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material usage and environmental releases, to assess the impact of those energy and material uses and releases on the environment, and to evaluate and implement opportunities to effect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing of raw materials; manufacturing, transportation, and distribution; use/re-use/maintenance; recycling; and final disposal."

5.2 LIFE-CYCLE ASSESSMENT OF PRODUCTS

It is feasible for life-cycle assessment (LCA) to be applied to a facility in any industrial sector. It has most often been used thus far for manufacturing facilities, especially those assembling final products such as computers or appliances. These manufacturers are in a unique position. They are not the resource extractor, digging or drilling whatever raw materials have a market; they are not materials processors, forming the powders, crystals, or liquids desired by the component or product assembler; and they are not marketers, making available to customers whatever is desired. While those sectors

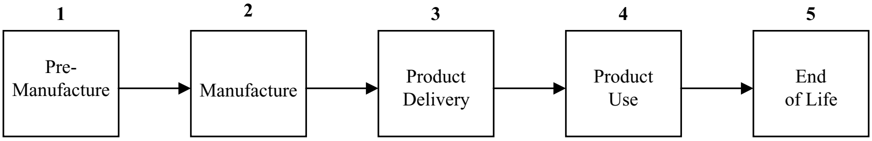


Figure 5.1. The life-cycle stages of a product.

can exercise some influence, they do not have the freedom of the manufacturer, whose sole constraint is to produce a desirable, salable product. In doing so, the manufacturer can choose to make an automobile body from sheet steel, composites, aluminum, or plastic, or a telephone transmission system from coaxial cable, optical fiber, microwave, submarine cable, or satellite systems. Cost, manufacturability, and consumer acceptance limit the choice, of course, but do not determine materials selection or assembly techniques per se. Thus, the designer's role in the manufacturing industry is central.

A life-cycle assessment must explicitly treat the entire life cycle of a product. For a typical manufactured product, there are five life-cycle stages, as shown in Figure 5.1.

- Stage 1, *Premanufacturing,* treats impacts on the environment as a consequence of the actions needed to extract materials from their natural reservoirs, transport them to processing facilities, purify or separate them by such operations as ore smelting and petroleum refining, and transport them to the manufacturing facility. Where components are sourced from outside suppliers, this life stage might also incorporate assessment of the impacts arising from component manufacture.
- Stage 2, *Manufacturing*, consists of the actual industrial processes involved in product creation.
- Stage 3, *Product delivery*, includes the manufacture of the packaging material, its transport to the manufacturing facility, residues generated during the packaging process, transportation of the finished and packaged product to the customer, and (where applicable) product installation.
- Stage 4, *Product use*, includes impacts from consumables (if any) or maintenance materials (if any) that are expended during customer use. For some products, such as machinery or vehicles, periodic maintenance is sufficiently important that it is treated as a separate life stage coincident with the product use life stage.
- In Stage 5, *End of life*, a product no longer satisfactory because of obsolescence, component degradation, or changed business or personal decisions is refurbished, recycled, or discarded.

The life-cycle assessment consists of evaluating the implications of each of these life stages, for all relevant environmental concerns. Guidelines and protocols for doing so are given in Appendix D.

5.3 LIFE-CYCLE ASSESSMENT OF PROCESSES

The environmental assessment of processes across their life span is particularly important, since processes often remain in place for decades once they are developed, and designs for new products often depend on the continuing existence of those processes. Detrimental environmental impacts of processes are thus locked in for much longer times than is the case with the design and manufacture of individual products.

As with products, the process LCA needs to address all relevant environmental concerns, but the life cycle stages are different. Unlike product life stages, which are sequential, process life stages have only three epochs (Figure 5.2): resource provisioning and process implementation occur simultaneously, primary process operation and complementary process operation occur simultaneously as well, and refurbishment, recycling, and disposal is the end-of-life stage. The characteristics of these life stages are described below.

Stage 1a: *Resource Provisioning.* The first stage in the life cycle of any process is the provisioning of the materials used to produce the consumable resources used throughout the life of the process being assessed. One consideration is the source of the materials,

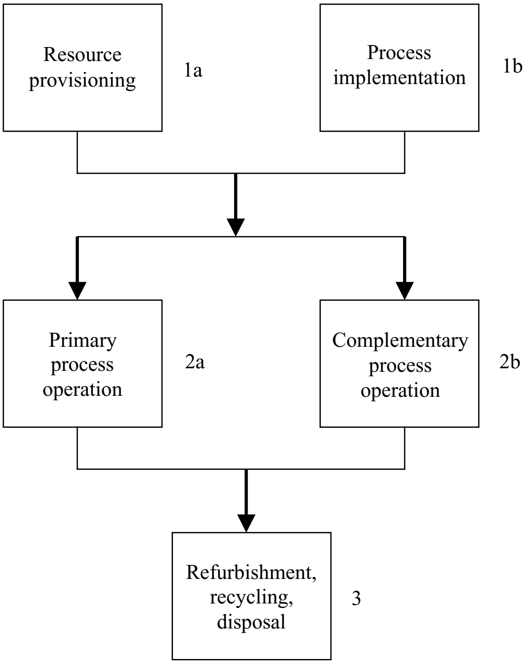


Figure 5.2. The life-cycle stages of a process.

which in many cases will be extracted from their natural reservoirs. Where possible, however, recycled materials are nearly always preferable to virgin materials. The second consideration is the methods used to prepare the materials for use in the process. Regardless of the source of a metal sheet to be formed into a component, for example, the forming and cleaning of the sheet and the packaging of the component should be done in an environmentally responsible manner. Supplier operations are thus a topic for evaluation as the process is being developed and, later, as it is being used.

Stage 1b: *Process Implementation.* Coincident with resource provisioning is process implementation, which treats the environmental impacts that result from the activities necessary to make the process happen. These principally involve the manufacture and installation of the process equipment, and installing other resources that are required such as piping, conveyer belts, exhaust ducts, and the like. This life stage has a strong commonality with the approach to evaluating a product.

Stage 2a: *Primary Process Operation.* A process should be designed to be environmentally responsible in operation. Such a process would ideally limit the use of toxic materials, minimize the consumption of energy, avoid or minimize the generation of solid, liquid, or gaseous residues, and ensure that any residues that are produced can be used elsewhere in the economy. Effort should be directed toward designing processes whose secondary products are salable to others or usable in other processes within the same facility. In particular, the generation of residues whose toxicity renders their recycling or disposal difficult should be avoided. Since successful processes can become widespread throughout a manufacturing sector, they should be designed to perform well under a variety of conditions.

Stage 2b: *Complementary Process Operation.* It is often the case that several manufacturing processes form a symbiotic relationship, each assuming and depending upon the existence of others. Thus, a comprehensive process evaluation needs to consider not only the environmental attributes of the primary process itself, but also those of the complementary processes that precede and follow. For example, a welding process generally requires a preceding metal cleaning step, which traditionally required the use of ozone-depleting chlorofluorocarbons. Similarly, a soldering process generally requires a post-cleaning to remove the corrosive solder flux. Changes in any element of this system–flux, solder, or solvent–usually require changes to the others as well if the entire system is to continue to perform satisfactorily.

Stage 3: *Refurbishment, Recycling, Disposal.* All process equipment will eventually become obsolete, and must therefore be designed so as to optimize disassembly and reuse, either of modules (the preferable option) or materials. In this sense, process equipment is subject to the same considerations and recommended activities that apply to any product–use of easily disconnected hardware, identification marking of plastics, and so on.

Guidelines and protocols for the streamlined life-cycle assessment of an industrial process are given in Appendix E.

5.4 LIFE-CYCLE ASSESSMENT OF INDUSTRIAL FACILITIES

Just as products and processes can be made in environmentally responsible ways, so also can industrial facilities be designed, built, operated, renovated, and recycled in an environmentally responsible manner. However, buildings have characteristics sufficiently different from products and processes that facility LCA must be approached from a somewhat different framework. Among the obvious differences are that (1) the geographical location of a building has a strong influence on its design and construction (climate influences the degree to which heating and air conditioning are incorporated, for example), (2) it is common for the use of a building to change several times during its life span, (3) the end-of-life stage for a building is typically generations into the future, making it difficult to predict what materials recovery facilities may be desirable and what activities may be possible and (4) very often, the use phase is predominant (i.e., 50 years of energy consumption). Any assessment approach should ideally be applicable to all varieties of facilities. Table 5.1 lists several examples of facilities and identifies their products and processes.

All of these aspects of a building's relationship to the wider world are important, but the list is incomplete without the inclusion of the impacts of the activities carried on within the building during its useful life. For an industrial facility, for example, one needs to evaluate not only the structure itself but also the products that are manufactured within it, the processes that are used in that manufacture, and the ways in which other activities within the building are performed. Clearly a building cannot be truly green if the products, processes, and related operations associated with it are not.

Given the life-cycle perspective, the assessment of the environmental responsibility of a facility can be defined to involve five stages or activities as shown in Figure 5.3.

Stage 1: *Site Development, Facility Development, and Infrastructure.* A significant factor in the degree of environmental responsibility of a facility is the site that is selected and the way in which that site is developed. If the facility is an extractive or materials processing operation (oil refining, ore smelting, and so on), the facility's geographical location will

***Table** 5.1.* Product and Process Characteristics of Typical Industrial Facilities

Facility	Product	Process
Ore smelter	Metal ingots	Smelting and refining of ores
Chemical works	Chemicals	Processing of chemical feedstocks
Appliance mfr.	Washing machines	Assemble products from components
Recycler	Components, materials	Disassemble and reprocess obsolete goods

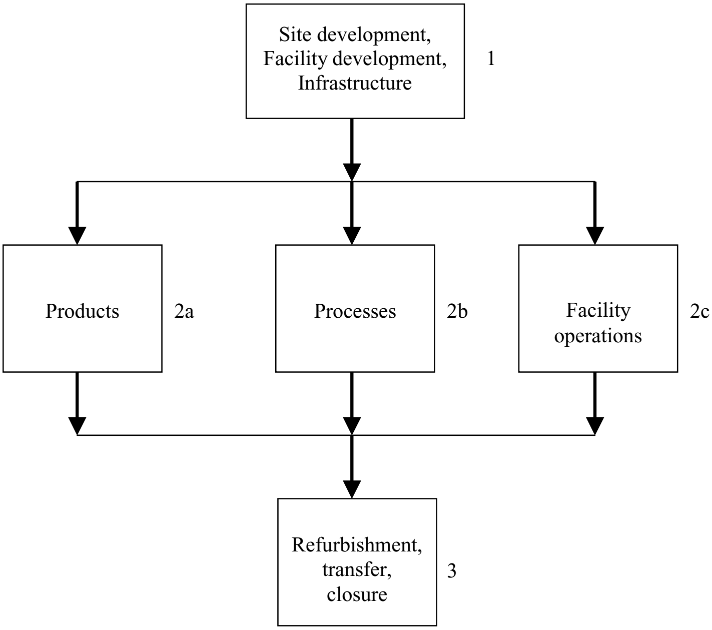


Figure 5.3. The life-cycle stages of a facility.

generally be constrained by the need to be near the resource. A manufacturing facility usually requires access to good transportation and a suitable work force, but may be otherwise unconstrained. Many types of facilities can be located virtually anywhere.

Manufacturing plants have traditionally been in or near urban areas. Such locations often have suitable buildings available and have the advantages of drawing on a geographically concentrated work force and of using existing transportation and utility infrastructures. It may also be possible to add new operations to existing facilities, thereby avoiding any of the regulatory intricacies of establishing a wholly new plant site. A promising recent development is the trend toward cooperative agreements between governments and industries for the reuse of these "brownfield" sites.

For facilities of any kind built on land previously undeveloped as industrial or commercial sites, ecological impacts on regional biodiversity may result, and we can anticipate added air emissions from new transportation and utility infrastructures. These effects can be minimized by working with existing infrastructures and developing the site with the maximum area left in natural form. Nonetheless, given the ready availability of commercial buildings and facilities in many cities and countries, such "greenfield" choices are hard to justify from an environmental perspective.

An activity that generally receives little attention is the disposal of construction debris. It has been estimated that as much as 25% by weight of all material brought to a building construction site is eventually consigned to the landfill, and approximately 20% of the waste flow to landfills is construction debris. Some of this debris is probably difficult to avoid—broken or defective materials, for example—but much of it could be reduced by an enhanced focus on manufacturing and building to standard dimensions, minimizing packaging, and promoting material reuse on site.

Stage 2a: *Principal Business Activity—Products.* Tangible products are items manufactured within the facility for sale to customers. Their LCA aspects are discussed above.

Stage 2b: *Principal Business Activity—Processes.* Processes are the techniques, materials, and equipment used in the creation of products. Their LCA aspects are discussed above.

Stage 2c: *Facility Operations.* The impact of any facility on the environment during its active life is heavily weighted by transportation issues. As with many other aspects of industrial activities, trade-offs are involved. For example, just-in-time delivery of components and modules has been hailed as a cost-effective and efficient boon for manufacturing. Nonetheless, it has been estimated that the largest contribution to the emissions that generate Tokyo smog comes from trucks making just-in-time deliveries. The corporations delivering and those receiving these components and modules bear some degree of responsibility for those emissions. It is sometimes possible to reduce transport demands by improved scheduling and coordination, perhaps in concert with nearby industrial partners or by siting facilities near to principal suppliers. Options may also exist for encouraging ride sharing, telecommuting, and other activities that reduce overall emissions from employee vehicles.

Material entering or leaving a facility also offers opportunities for useful action. To the extent that the material is related to products, it is captured by product assessments. Facilities receive and disperse much nonproduct material, however: food for employee cafeterias, office supplies, restroom supplies, and maintenance items such as lubricants, fertilizer, and road salt, to name just a few. A facility should have a structured program to evaluate each incoming and outgoing materials stream and to tailor it, as well as its packaging, in environmentally-responsible directions. Obviously, the most environmentally preferable products should be chosen in performing each function.

Facility energy use also requires careful scrutiny, as opportunities for improvement are always present. An example is industrial lighting systems, which are estimated to be responsible for between 5–10% of air pollution emissions overall. Another major energy consumer is the heating, ventilating, and air-conditioning systems. Office machines and computers in office buildings can also use significant amounts of energy. The environmental impacts chargeable to energy use generally occur elsewhere—emission of CO_2 from fossil fuel power plants, for example—but are no less real for not happening right at the facility.

Stage 3: *Facility Refurbishment, Transfer, and Closure.* Just as environmentally-responsible products are increasingly being designed for "product life extension," so facilities should be. Buildings and other structures contain substantial amounts of material with significant levels of embodied energy, and the (especially local) environmental disruption involved in the construction of new buildings and their related infrastructure is substantial. Clearly a facility must be designed to be easily refurbished for new uses, to be transferred to new owners and operators with a minimum of alteration, and, if it must be closed, to permit recovery of materials, fixtures, and other components for reuse or recycling.

Guidelines and protocols for the streamlined life-cycle assessment of an industrial facility are given in appendix F.

5.5 THE MATRIX ASSESSMENT APPROACH

A comprehensive life-cycle assessment attempts to identify and quantify all aspects of the industry-environment interaction. Techniques and data bases for doing so have appeared in various forms, most as software packages and most requiring considerable effort and expense to utilize. While the goals of such exercises are generally useful, the details of the methods continue to be debated, and the lack of efficiency of the existing approaches has led to the development of a number of qualitative and semi-quantitative "streamlined" systems as alternatives. It is a streamlined life-cycle assessment (SLCA) approach that we present here.

The SLCA approach that we recommend has as its central feature a 5 × 5 assessment matrix, one dimension of which is the life-cycle stage and the other of which is environmental concern (Table 5.2). The topics treated by the matrix are those discussed in the previous sections of this chapter. In use, the assessor studies the activities at each life stage and the potential environmental impacts, and assigns to each element

Table 5.2. The Streamlined Life-Cycle Assessment Environmental Matrix

	Environmental Concern				
Life Stage*	Ecology/ Materials	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues
1, 1a, 1	1,1	1,2	1,3	1,4	1,5
2, 1b, 2a	2,1	2,2	2,3	2,4	2,5
3, 2a, 2b	3,1	3,2	3,3	3,4	3,5
4, 2b, 2c	4,1	4,2	4,3	4,4	4,5
5, 3, 3	5,1	5,2	5,3	5,4	5,5

*The first number refers to the life stages of products, the second of processes, the third of facilities (see Figs. 5.1, 5.2, and 5.3). The remaining numbers in the table are matrix element designations.

of the matrix an integer rating from 0 (highest impact, a very negative evaluation) to 4 (lowest impact, an exemplary evaluation). In essence, the assessor provides a figure of merit to represent the estimated result of a more formal life-cycle assessment (LCA) inventory analysis and impact analysis. She or he is guided in this task by experience, a design and manufacturing survey, appropriate checklists, and other information. Unlike some forms of SLCA that attempt to be quantitative but selective, the process described here is purposely semi-quantitative and utilitarian.

In arriving at an individual matrix element assessment, or in offering advice to designers seeking to improve the rating of a particular matrix element, the assessor can refer for guidance to underlying sets of checklists and protocols, examples of which appear in Appendices D, E, and F.

Once an evaluation has been made for each matrix element, the rating is computed as the sum of the matrix element values:

$$R = \Sigma_{i,} \Sigma_j M_{i,j}$$

Because there are 25 matrix elements, a maximum product rating is 100.

Although the assignment of integer ratings seems quite subjective, experiments have been performed in which comparative assessments of products are made by several different industrial and environmental engineers. When provided with checklists and protocols, overall product ratings differ by less than about 15 percent among groups of four assessors.

5.6 ASSESSING THE AUTOMOBILE AND ITS MANUFACTURE

As a detailed example of how SLCA is accomplished in practice, the automobile and its manufacture provide a widely-known and widely-studied example. Automobiles have both manufacturing and in-use impacts on the environment, in contrast to many other products such as furniture or roofing materials. The greatest impacts result from the combustion of gasoline and the release of tailpipe emissions during the driving cycle. However, there are other aspects of the product that affect the environment, such as the dissipative use of oil and other lubricants, the discarding of tires and other spent parts, and the ultimate retirement of the vehicle. To assess these factors, our SLCA example is performed on a generic automobile of the 1990s, its manufacturing processes, and the facility in which they are housed. Some of the relevant characteristics are given in Table 5.3.

5.6.1 SLCA of the Product

The basic automotive manufacturing process has changed little over the years but much has been done to improve its environmental responsibility. One potentially high-impact area is the paint shop, where various chemical are used to clean the parts and volatile organic emissions are generated during the painting process. There is now

Table 5.3. Salient Characteristics of Products, Processes, and Facilities for the Generic Automobile and Manufacturing Plant of the 1990s

Characteristic	Typical Attribute
PRODUCT: The Automobile	
Material content (kg):	
Plastics	101
Aluminum	68
Metals	1047
Rubber	61
Fluids	81
Other	76
Total Weight: (kg)	1434
Fuel Efficiency (miles/gallon)	27
Exhaust Catalyst	Yes
Air Conditioning	HFC-134a
PROCESS: Auto Manufacture	
Energy use	Substantial
Painting	Aqueous low-volatile
Recycling	Extensive
Process hardware	
Welding	Ubiquitous
Conveyer belts	Numerous
Complementary processes	
Metal cleaning	Aqueous detergents
FACILITY: Auto Manufacturing Plant	
Site	"Greenfield"
Worker transport	Private auto
Heating	Natural gas
Lighting	High-eff. fluorescent
A/C Fluid	CFC-12
Grounds	Natural areas
Building mtls.	Concrete, composites
Recycling	Yes
Closure	Reuse-adaptable

greater emphasis on treatment and recovery of wastewater from the paint shop and the switch from low-solids to high-solids paint has done much to reduce the amount of material emitted. With respect to material fabrication there is currently better utilization of material (partially due to better analytical techniques for designing component parts) and a greater emphasis on reusing scraps and trimmings from the various fabrication processes. Finally, the productivity of the entire manufacturing process has been improved, substantially less energy and time being required to produce each automobile.

The product delivery stage of the automobile's life cycle is benign relative to the vast majority of products sold today, since automobiles are delivered with negligible packaging material. Nonetheless, some environmental burden is associated with the transport of a large, heavy product.

Significant progress has been made in automobile efficiency and reliability but automotive use continues to have a very high negative impact on the environment. The increase in fuel efficiency and more effective conditioning of exhaust gases accounts for the 1990s automobile achieving higher ratings but clearly there is still room for improvement.

Most modern automobiles are recycled (some 95% currently enter the recycling system), and from these approximately 75% by weight is recovered for used parts or returned to the secondary metals market. There is a viable used parts market and most cars are stripped of reusable parts before they are discarded. Improvements in recovery technology have made it easier and more profitable to separate the automobile into its component materials.

In contrast to vehicles of earlier eras, at least two aspects of modern automobile design and construction are regressive from the standpoint of their environmental implications. One is the increased diversity of materials used, mainly the increased use of plastics. The second aspect is the increased use of welding in the manufacturing process. In the vehicles of the mid-20th century, a body-on-frame construction was used. This approach was later switched to a unibody construction technique in which the body panels are integrated with the chassis. Unibody construction requires about four times as much welding as does body-on-frame construction, plus substantially increased use of adhesives. The result is a vehicle that is stronger, safer and uses less structural material, but is much less easy to disassemble.

We will not describe the evaluation of each SLCA matrix element in detail, but provide the ratings and a brief justification in Table 5.4. The overall product rating for the 1990s vehicle is 68, probably much better than that of earlier vehicle, but still leaving plenty of room for improvement.

5.6.2 SLCA *of the Process*

The assessment for automobile manufacturing processes is begun by treating life stage 1a, that of resource provisioning, guided by the matrix element checklists. An obvious difference between mid-century and contemporary vehicles is that almost no recycled materials were used in the former, and substantial amounts are used in the latter. This has impacts on three environmental stresses: energy use (less is needed to recycle material than to mine and process virgin material), solid residues (no rock overburden results from the use of recycled materials, and gaseous residues (modest emissions result from materials reprocessing as opposed to the initial smelting process). The provisioning of particularly toxic or otherwise undesirable materials are not involved in either era, nor are liquid residues a significant problem.

Table 5.4. Product Matrix Element Assessment for the Generic 1990s Automobile

Element Designation	Element Value and Explanation
Premanufacturing	
Matls. choice (1,1)	3 (Few toxics are used; much recycled material is used)
Energy use (1,2)	3 (Virgin material shipping is energy-intensive)
Solid residue (1,3)	3 (Metal mining generates solid waste)
Liq. residue (1,4)	3 (Resource extraction generates moderate amounts of liquid waste)
Gas residue (1,5)	3 (Ore processing generates moderate amounts of gaseous waste)
Product Manufacture	
Matls. choice (2,1)	3 (Good materials choices, except for lead solder waste)
Energy use (2,2)	2 (Energy use during manufacture is fairly high)
Solid residue (2,3)	3 (Some metal scrap and packaging scrap produced)
Liq. residue (2,4)	3 (Some liquid residues from cleaning and painting)
Gas residue (2,5)	3 (Small amounts of volatile hydrocarbons emitted)
Packaging and Transportation	
Matls. choice (3,1)	3 (Sparse, recyclable materials used during packaging and shipping)
Energy use (3,2)	3 (Long-distance land and sea shipping is energy-intensive)
Solid residue (3,3)	3 (Packaging during shipment could be further minimized)
Liq. residue (3,4)	4 (Negligible amounts of liquids are generated by packaging and shipping)
Gas residue (3,5)	3 (Moderate fluxes of GHGs produced during shipment)
Customer Use	
Matls. choice (4,1)	1 (Petroleum is a resource in limited supply)
Energy use (4,2)	2 (Fossil fuel energy use is large)
Solid residue (4,3)	2 (Modest residues of tires, defective or obsolete parts)
Liq. residue (4,4)	3 (Fluid systems are somewhat dissipative)
Gas residue (4,5)	2 (CO_2, lead [in some locales])
Refurbishment/Recycling/Disposal	
Matls. choice (5,1)	3 (Most materials recyclable, but not sodium azide)
Energy use (5,2)	2 (Moderate energy use required to disassemble and recycle materials)
Solid residue (5,3)	3 (Some components are difficult to recycle)
Liq. residue (5,4)	3 (Liquid residues from recycling are minimal)
Gas residue (5,5)	2 (Recycling involves some open burning of residues)

Life stage 1b is primary process implementation, in which the manufacture of the process equipment is evaluated. Energy use is a significant consideration here.

Primary process operation in automobile manufacturing evolves rapidly. Among the improvements made by the 1990s are the elimination of most metal plating operations except for zinc anticorrosion treatment of body panels. Casting sand disposal and significant use of energy and organic solvents remain as challenges.

Complementary process operation is a continuing environmental concern as well. Metal trimming and smoothing has not changed greatly over the years, but process energy use is decreasing fairly rapidly, and metal trimmings and filings are better contained. A major improvement in metal cleaning is the transition from CFCs to organics, in many cases to aqueous cleaners, and in some cases to no cleaning at all.

Table 5.5. Process Matrix Element Assessment for Generic 1990s Automobile Manufacture

Element Designation	Element Value and Explanation
Resource Provisioning	
Matls. selec. (1,1)	4 (No significant concerns)
Energy use (1,2)	2 (Partially recycled materials)
Solid residue (1,3)	2 (Moderate mining residues)
Liq. residue (1,4)	4 (No significant concerns)
Gas residue (1,5)	3 (Smelting emissions are modest)
Process Implementation	
Matls. selec. (2,1)	3 (Nontoxic cleaning solvents)
Energy use (2,2)	2 (Variable speed motors, other conservation)
Solid residue (2,3)	2 (Moderate packaging residues)
Liq. residue (2,4)	4 (No significant concerns)
Gas residue (2,5)	3 (Modest gaseous emissions)
Primary Process Operation	
Matls. selec. (3,1)	2 (Organic solvents)
Energy use (3,2)	2 (Significant energy use)
Solid residue (3,3)	1 (Casting sand)
Liq. residue (3,4)	3 (Most wastewater recycled)
Gas residue (3,5)	3 (Most VOC emissions captured)
Complementary Process Operation	
Matls. selec. (4,1)	3 (Nontoxic solvents)
Energy use (4,2)	3 (Modest energy for trimming and smoothing)
Solid residue (4,3)	3 (Modest metal trimmings)
Liq. residue (4,4)	2 (Recycling of contaminated solvent)
Gas residue (4,5)	3 (Minimal volatile emissions)
Refurbishment/Recycling/Disposal	
Matls. selec. (5,1)	4 (Most materials recyclable)
Energy use (5,2)	1 (High energy use in metals recovery)
Solid residue (5,3)	3 (Only modest design for disassembly)
Liq. residue (5,4)	4 (No significant concerns)
Gas residue (5,5)	4 (No significant concerns)

The completed process matrix appears in Table 5.5. The overall rating for the 1990s vehicle manufacturing process is 70. This is much better than that for earlier eras, but again leaves plenty of room for improvement.

5.6.3 SLCA of the Facility

While it is fairly straightforward to picture and describe typical automobiles of different eras, and the processes by which they were made, there has historically been a wide variation in the types of manufacturing sites and their development. The generic facility of the 1990s that we evaluate is built on a site new to commercial development: a "greenfield." Instead of modification or reconstruction of an existing building, natural land areas are developed, together with the necessary infrastructure of roads, power lines, water and sewer services, and so forth. The structure is primarily concrete, but a wide variety of materials is used. Because the site is not near public transportation, private automobiles are used by employees to go to and from work. Heating is provided by natural gas, and modern air conditioning units with the potentially-ozone-depleting refrigerant CFC-12 is used. In keeping with more enlightened modern practice, a substantial fraction of the grounds is maintained in a natural condition, and fertilizer and pesticide use is minimized.

A central aspect of the facility assessment is, of course, that of the environmental responsibility of the products made within it. For this stage, the previous assessment of the generic automobile of the 1990s is used. For incorporation into the facilities assessment, the integer ratings for each of these impacts are summed over all five life stages, and then divided by five to put the rating on the same scale with the other facilities stages considered. For example, from Table 5.4, the five customer use ratings for the 1990s automobile were 1, 2, 2, 3, and 2. Their sum is 10, and the sum divided by 5 is 2.0, which is entered into the ratings. The process is diagrammed in Figure 5.4.

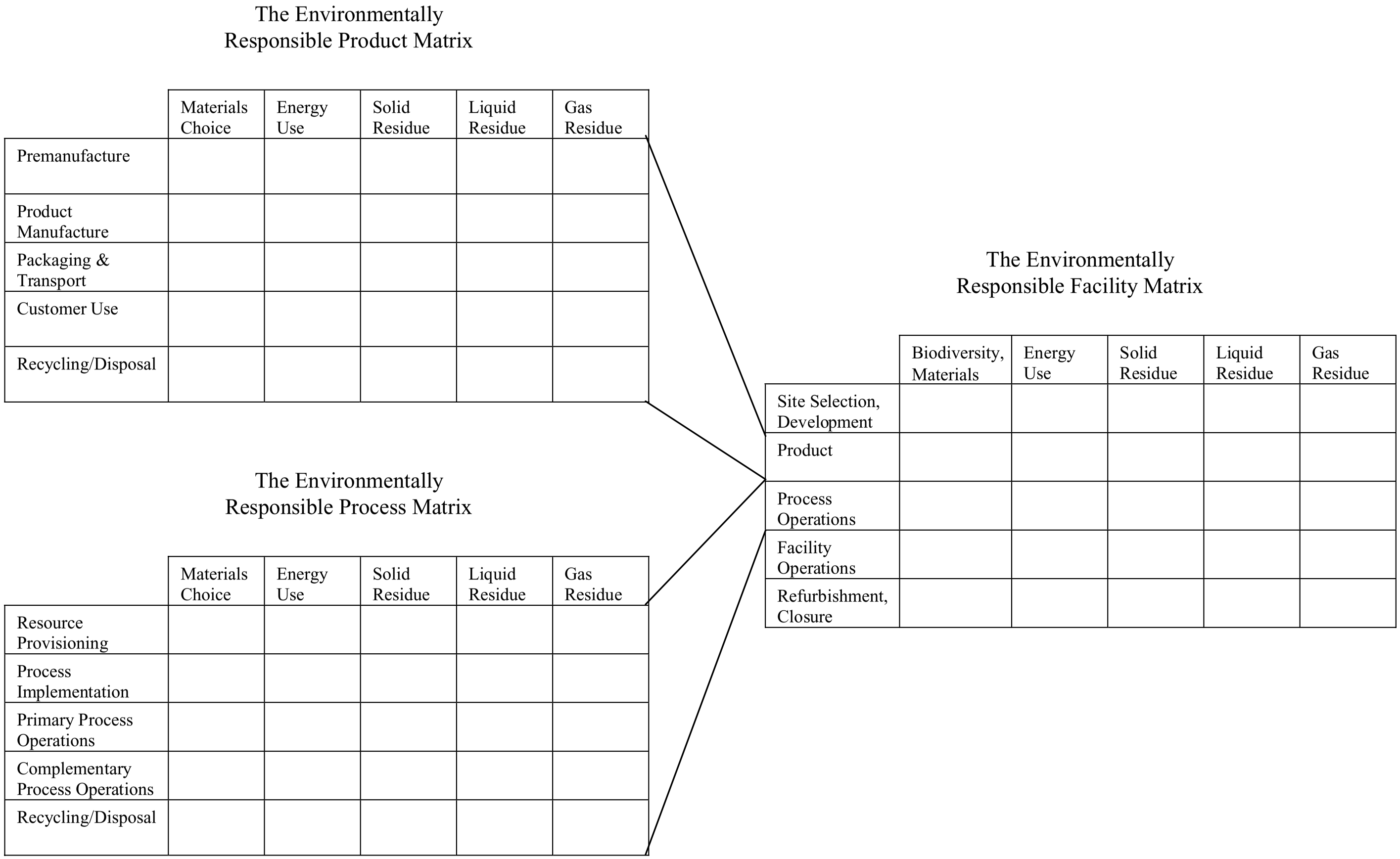
The third activity stage is processes, for which the rating scores of the previous process assessment are utilized in the same way as those for products.

The matrix element rankings for the generic 1990s automobile manufacturing facility (as opposed to its products or processes), and explanations for the rankings, are given in Table 5.6. In Table 5.7, we collect the information from Tables 5.4 through 5.6 to generate the overall ranking of 64.2. The life stage that is particularly egregious is that of site selection and preparation. Energy use and solid residue generation receive the lowest ratings of the environmental concerns.

Two approaches to facility-environment interaction that are sometimes advocated are green building design reviews and facility audits. The emphasis in the former is on life stage 1 (site and facility development) and the energy-related aspects of life stage 2c (facility operations). In the latter, the emphasis is on life stages 2a and 2b (product and process operations), with less attention given to life stage 2c (facility refurbishment or closure). Green building design rarely considers life stage 3, and facility audits universally ignore the final life stage.

Utilizing green building design reviews and facility audits for buildings is reminiscent of the traditional government division of environmental monitoring and control into air, water, and waste. In each approach, practitioners tend to think only about their area of expertise, and the system as a whole seldom approaches optimization. Facility evaluation and the improvement of facility environmental performance is made difficult by the long time scales involved and by the different parties involved at different phases of the process, but it is clear that optimization can only be approached if the evaluation is carried out from a systems perspective, ideally that of life-cycle assessment.

Industrial facilities can be evaluated on the basis of their life-cycle performance. An example of a report that does so for environmental concerns is given in Appendix H.



The Environmentally Responsible Product Matrix

	Materials Choice	Energy Use	Solid Residue	Liquid Residue	Gas Residue
Premanufacture					
Product Manufacture					
Packaging & Transport					
Customer Use					
Recycling/Disposal					

The Environmentally Responsible Process Matrix

	Materials Choice	Energy Use	Solid Residue	Liquid Residue	Gas Residue
Resource Provisioning					
Process Implementation					
Primary Process Operations					
Complementary Process Operations					
Recycling/Disposal					

The Environmentally Responsible Facility Matrix

	Biodiversity, Materials	Energy Use	Solid Residue	Liquid Residue	Gas Residue
Site Selection, Development					
Product					
Process Operations					
Facility Operations					
Refurbishment, Closure					

Figure 5.4. The interrelationships among product, process, and facility matrices for a streamlined comprehensive life-cycle assessment.

Table 5.6. Facility Matrix Element Assessment for a Generic 1990s Automobile Manufacturing Facility

Element Designation	Element Value and Explanation
Site Selection, Development, and Infrastructure	
Biodiversity (1,1)	1 (Greenfield site, large biotic impacts)
Energy use (1,2)	0 (Complete new energy infrastructure)
Solid residue (1,3)	1 (Abundant solid residues in site prep)
Liq. residue (1,4)	3 (Modest liquid residues in site prep)
Gas residue (1,5)	3 (Modest gaseous residues in site prep)
Ratings: Facility Operations	
Biodiversity (4,1)	3 (Natural areas, no pesticides)
Energy use (4,2)	3 (Modest energy use in operations)
Solid residue (4,3)	3 (Extensive waste minimization and recycling)
Liq. residue (4,4)	3 (Extensive liquid residue treatment)
Gas residue (4,5)	3 (Efficient gaseous residue controls)
Refurbishment/Transfer/Closure	
Biodiversity (5,1)	3 (Little ecological impact when reused)
Energy use (5,2)	3 (Modest energy use when reused)
Solid residue (5,3)	3 (Extensive reuse–low demolition probability)
Liq. residue (5,4)	3 (Minor liquid residues when reused)
Gas residue (5,5)	3 (Minor gaseous residues when reused)

Table 5.7. Combined SLCA Assessment for the Generic 1990s Automobile and its Manufacturing Facility

	Environmental Concern					
Life Stage	Biodiversity, Materials	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues	Total
Site Selection, development	1.0	0.0	1.0	3.0	3.0	8.0/20
Principal business activity–Products	2.6	2.4	2.8	3.2	2.6	13.6/20
Principal business activity–Processes	2.6	2.0	2.2	2.8	3.0	12.6/20
Facility operations	3.0	3.0	3.0	3.0	3.0	15.0/20
Refurbishment, transfer, and closure	3.0	3.0	3.0	3.0	3.0	15.0/20
Total	12.2/20	10.4/20	12.0/20	15.0/20	14.6/20	64.2/100

5.7 FACILITY HEALTH AND SAFETY PERFORMANCE

Health and safety aspects of industrial operations are not, strictly speaking, part of an environmental evaluation. However, in most corporations the organization responsible for overseeing environmental performance oversees health and safety (HS)

Table 5.8. The Streamlined Life-Cycle Assessment Health and Safety Matrix

	Health and Safety Concern				
Life Stage	Physical Hazard	Chemical Hazard	Shock Hazard	Noise Hazard	Ergonomic Hazard
1	1,1*	1,2	1,3	1,4	1,5
2	2,1	2,2	2,3	2,4	2,5
3	3,1	3,2	3,3	3,4	3,5
4	4,1	4,2	4,3	4,4,	4,5
5	5,1	5,2	5,3	5,4	5,5

*The pairs of numbers are matrix element designations.

performance as well. It is therefore useful to develop analytical approaches that can be used for HS evaluation.

It turns out that the streamlined life-cycle approach is well suited to a review of the HS attributes of a product or process. We retain the same life stages as used above, so the HS matrix for a product will have as life stages premanufacturing, manufacturing, product delivery, product use (perhaps with a separate life stage for field maintenance), and end of life. The HS concerns are different, of course, from the environmental ones. We recommend five concerns, as follows: physical hazards, chemical hazards, shock hazards, noise hazards, and ergonomic hazards. The resulting HS matrix is pictured in Table 5.8.

Elements of the HS matrix are evaluated in ordinal fashion from 0 to 4, just as with the environmental matrices. Guidelines and protocols for doing so are given in Appendix G.

5.8 CORPORATE USE OF COMPREHENSIVE LCAs

Corporations and individuals have traditionally been regarded as good citizens if they follow rules of behavior established by their societies, i.e., if they comply with regulations. This reactive approach is now giving way to a proactive one. Processes were the first target of attention–emissions and energy use, for example, and pollution prevention has been the common and beneficial response. Products were next, as their environmentally-related attributes were assessed and improved. Facilities are the third facet to receive attention. As techniques for comprehensive assessment undergo further development, product, process, and facility LCAs and SLCAs will become an increasingly important aspect of corporate environmental responsibility.

FURTHER READING

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Hocking, M. B., *Modern Chemical Technology and Emission Control*, Berlin: Springer-Verlag, 1985.

Rocky Mountain Institute, *Green Development: Integrating Ecology and Real Estate*, New York: John Wiley & Sons, 1998.

Todd, J. A., and M. A. Curran, Eds., *Streamlined Life-Cycle Assessment: A Final Report from the SETAC North American Streamlined LCA Workgroup*, Society of Environmental Toxicology and Chemistry, http://www.setac.org/lca.html.

Chapter 6

Sustainability-Related Performance

The broadest and most forward looking of the evaluation tools for facilities deal with aspects of sustainability. The goal is to retain transparency and efficiency of assessment while addressing issues across the range of time and space scales. The use of resources—materials of all kinds, water, and energy—is thus incorporated. Human and ecosystem hazard is included as well. As with the tools in the previous chapters, the use of the sustainability assessment approach described here will not solve all problems, nor is every facet necessarily fully supported by environmental science and environmental data sets. Nonetheless, conscientious use of the approach will enable improved understanding of and marked improvement in the environmental performance of a facility or corporation.

6.1 ORDINAL EVALUATION

The potential to pollute for a specific process or process sequence is heavily influenced by two factors: the hazard potential of the materials involved, and the quantities of those materials that are used. Consider the generic process shown in Figure 1.3. Materials, energy, and water enter from the left and top and products and residues leave from the right and bottom of the diagram. Assume that for each material the rate of use (the "throughput") is known, as is its environmental impact potential (the degree of concern regarding such issues as human or ecosystem toxicity, process energy and water requirements, materials scarcity, degradation of air, water, or soil, etc.). A simple but useful evaluation system can be established by using an ordinal rather than a cardinal approach. To do so, we create two three-level sets of "bins"—one set for throughput magnitude, one set for hazard potential. In each set, the three bins are designated High, Moderate, and Low. Materials may be assigned to the appropriate

Table 6.1. Throughput—Impact Binning of Materials in a Generic Industrial Process

Material	Throughput Magnitude	Environ. Impact Potential
A	H	L
B	H	M
C	M	H
D	M	M
E	L	H
F	L	M

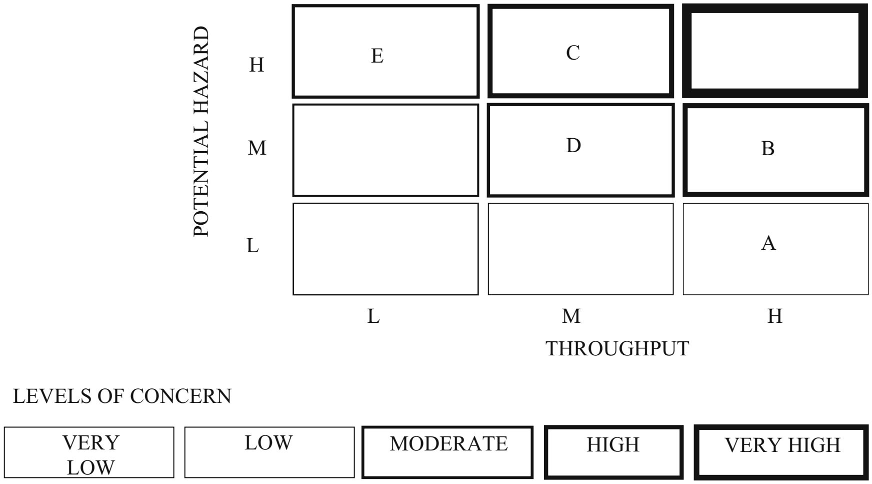

Figure 6.1. The throughput-potential hazard (TPH) matrix. Regions of different levels of concern are shown by the outline key. The letters refer to the materials of table 6.1.

bins based on their inherent properties and rates of use. (The exact formalism for doing so is discussed below.)

As an example, suppose that a process takes an input material A and generates a material B. This is done through the use of reactant C, and byproduct D, residue E, and emission F result. Assume that the binning of the materials is as given in Table 6.1. Once the materials are binned, they can be displayed on a Throughput-Potential Hazard Matrix, as in Figure 6.1. One can quickly see in this example that there are no materials of extremely high concern related to the process, but a *high* level of concern is warranted for output material B (high throughput, moderate hazard) and reactant C (moderate throughput, high hazard). Similar approaches can be taken to the rates of use of water, energy, and scarce materials, as explained below. Overall, the formulation is not rigorous, but is very helpful in comparative evaluations and in directing attention to aspects of processes where significant sustainability-related improvements may be possible.

6.2 MATERIAL THROUGHPUT

In evaluating a process constituent on the basis of throughput, either for an entire industrial sector or for an individual corporation or facility, the actual quantity of material is a valuable measure, but certainly not the complete story. Also relevant, and consistent with our qualitative approach, are the *relative* flows of the several constituents. We choose to divide the constituents into three "bins": high throughput (H), moderate throughput (M), and low throughput (L). In the evaluation of throughput, for process inputs and for material product outputs (a product is anything that is sold for use, not necessarily the principal target product), the binning is accomplished as follows:

- H: Resource constituent flow >10% by weight of total facility or process line input constituent flows
- M: Resource constituent flow 1–10% by weight of total facility or process line input constituent flows
- L: Resource constituent flow <1% by weight of total facility or process line input constituent flows

From the example given in the introduction, binning on the above basis would be applied to constituents A and C and product B. Binning would also be applied to byproducts if those byproducts were sold rather than discarded. Limiting the evaluation to virgin resource flows allows a facility to improve its ranking by incorporating larger fractions of recycled content into its incoming material streams.

The relative magnitudes of emissions of various kinds are also important to assess. They are often small fractions of the total input flows, however, so a separate binning process is appropriate. Thus, residue E and emission F (and byproduct D if discarded rather than sold) are binned as follows:

- H: Constituent flow equal to or greater than 1% by weight of total facility input constituent flows
- M: Constituent flow less than 1% by weight of total facility input constituent flows
- L: Constituent flow much less than 1% by weight of total facility input constituent flows

This approach establishes the throughput level for each constituent of significance, and the process of binning can generally be accomplished by knowledgeable employees or consultants without the need for measurement.

6.3 HAZARD POTENTIAL

Assessing potential environmental hazards, even qualitatively, is the most problematic step in the prioritizing process. Among the difficulties that might be noted are the following:

- Hazard potential covers an enormous range. Human carcinogenic potential, for example, spans some six orders of magnitude.
- Contributions to quite different impacts must be compared and prioritized: global climate change, habitat disruption, vegetative toxicity, and aesthetic degradation, to name a few.
- The spatial scales and time scales for the impacts can be very different, the former extending from scales of a few meters to the entire planet, the latter from perhaps an hour to several centuries.

All of these complexities suggest that it will be useful to begin with an overall framework. The framework we choose proceeds in three steps. The first is the ranking of major environmental concerns. Their relative significance can be established on the basis of the following criteria:

- The spatial scale of the impact (large scales being worse than small)
- The severity of the hazard, i.e., the product of the damage potential of a material, how much material is involved, and how numerous is the exposed population (highly hazardous substances being of more concern than less highly hazardous substances)
- The degree of exposure (well-sequestered substances being of less concern than readily mobilized substances)
- The penalty for being wrong (longer remediation or reversibility times being of more concern than shorter times)

These general criteria are perhaps too anthropocentric as stated, but are nonetheless a reasonable starting point for distinguishing highly important concerns from those less important. Using them, common local, regional, and global environmental concerns can be grouped as shown in Table 6.2. The exact wording and relative positioning of these concerns is not critical for the present purpose; what is important is that all actions of industrial society that have potentially significant environmental implications relate in some way to the list.

Of the seven "crucial environmental concerns," three are global in scope and have very long time scales for amelioration: global climate change, loss of biodiversity, and ozone depletion. The fourth and fifth critical concerns relate to damage to human or ecosystem organisms by toxic, carcinogenic, or mutagenic agents. The sixth critical concern is the availability and quality of water, a concern that embraces the magnitude of water use as well as discharges of harmful residues to surface or ocean waters. The

Table 6.2. Significant Environmental Concerns*

Crucial environmental concerns
- Global climate change
- Human organism damage
- Ecosystem organism damage
- Water availability and quality‡
- Loss of biodiversity
- Stratospheric ozone depletion
- Depletion of fossil fuel resources‡

Important Environmental Concerns
- Photochemical Smog
- Acid deposition
- Depletion of non-fuel resources‡
- Aesthetic degradation

Less Important Environmental Concerns
- Thermal pollution
- Odor
- Radionuclides
- Landfill exhaustion

*Adapted from T. E. Graedel, The grand objectives: A framework for prioritized grouping of environmental concerns in life-cycle assessment, *Journal of Industrial Ecology, 1*(2), 51–64, 1997. Within groupings, the order of concerns is arbitrary.
‡These topics are not treated in the throughput-potential hazard matrix analysis.

seventh is the rate of depletion of fossil fuel resources, vital to many human activities over the next century, at least. The last four also introduce consideration of spatial inhomogeneity, since they play out differently in different geographical locations.

Four additional concerns are regarded as highly important, but not as crucial as the first seven. The first two of these, acid deposition and (in some instances) smog, are regional scale impacts occurring in many parts of the world and closely related to fossil fuel combustion and other industrial activities. Aesthetic degradation, the third highly important concern, incorporates "quality of life" issues such as visibility, the action of airborne corrodants on statuary and buildings, and the dispersal of solid and liquid residues. The final concern, depletion of non-fossil fuel resources, is one of the motivations for current efforts to recycle materials and minimize their use.

Finally, four concerns are related as less important than those in the first two groupings, but still worthy of being called out for attention: radionuclides, odor, thermal pollution and depletion of landfill space. The justification for inclusion in this grouping is that the effects, while sometimes quite serious, tend to be local or of short time duration or both, when compared with the concerns in the first two groups.

It is appropriate to comment briefly on the selections of the "crucial concerns." Of those seven, five are called out by the U.S. EPA Science Advisory Board and by most

Table 6.3. Binning Potential Environmental Hazards

Concern Level	Potential Impact	Potential Hazard
H	H	H
H	M	M
H	L	L
M	H	M
M	M	M
M	L	L
L	H	L
L	M	L
L	L	L

detailed approaches to life-cycle assessment. The availability and quality of water is already a major concern in some areas of the world, and will likely become more so as populations and urbanization continue to increase over the next half-century. The concern for fossil fuel resources is obvious, as most of the energy-consuming activities of modern society are dependent on fossil fuels and their supporting infrastructures, and a long transition period will be required to implement any broad replacement of fossil fuels by other energy sources.

In the case of potential hazards, the major input and output materials of a process must be determined, and then evaluated individually. To bin a particular constituent in an industrial process, the first step is to identify the related environmental concern in the list below. The "crucial," "highly important," and "less important" groupings are identified with H, M, and L bins, and that information is retained for future use. In the second step of this process, the potential impact of the constituent in question is evaluated from the perspective of the concern in question, again on an H, M, L basis. (How this is done is described in detail below.) Finally, in step three, the overall potential hazard for the constituent is specified as shown in Table 6.3. For example, consider the emission of three halogenated components: CFC-12, HCFC-22, and HFC-134a. All are implicated in stratospheric ozone depletion, a crucial concern. The concern group is therefore H. The potential impact (discussed below) is H for CFC-12, M for HCFC-22, and L for HFC-134a. The resulting potential hazard ratings are thus H, M, L, respectively. As a second example, consider the emission of the smog-forming compounds propylene and ethane. The potential impact for the compounds is H and L (see below), but since smog has an environmental concern of M, the resulting potential hazard ratings are M and L.

6.3.1 Potential Impact Binning for Global Climate Change

Global warming gases (GHG) are gases that are efficient absorbers of infrared radiation. This radiation is emitted from the surface of the heated Earth, and its escape to outer space permits the planet to maintain a stable surface temperature. If a portion of that radiation is absorbed by GHGs, the temperature will stabilize at a higher level, thus warming the planet.

Climate is naturally quite variable and the oceans absorb some degree of heat from the atmosphere. As a consequence, although there is general scientific agreement concerning the greenhouse warming process, an unambiguous indication of human-related warming has not yet been conclusively established. Nonetheless, many corporations regard reducing GHG emissions as a sound business strategy as well as a sound environmental one.

The potential of a gas x to contribute to global climate change is measured on a per-molecule basis by the *global warming potential* (GWP), defined approximately as

$$\mathrm{GWP_x} = \frac{\text{Time-integrated radiative absorption due to x}}{\text{Time-integrated radiative absorption due to CO}_2}$$

A selection of GWPs, computed by detailed atmospheric computer models, is given in Table 6.4.

Global warming potentials are referenced to that for the moderately-absorbing gas carbon dioxide. They range from 0 (for molecules that do not absorb infrared radiation) to 1 (for CO_2) to more than 20,000 (for long-lived, highly-absorbing gases such as SF_6). We assign the following potential impact ratings:

H $\mathrm{GWP} > 100$
M $1 \leq \mathrm{GWP} \leq 100$
L $\mathrm{GWP} < 1$

Table 6.4. Selected Global Warming Potentials and Ozone Depletion Potentials*

Molecule	GWP (100 yr)	ODP
CO_2	1	0
CH_4	11	0
N_2O	270	0
CFC-11	4500	1
CFC-12	7100	0.95
HCFC-22	4200	0.05
HFC-134a	3100	0
CF_4	6500	0
SF_6	23900	0

*Nearly all molecules not appearing in this table (some halogens excepted) have GWP = 0 and ODP = 0.

6.3.2 *Potential Impact Binning for Human Organism Damage*

Human organism damage is an ensemble term that includes toxicity (causing prompt illness or death), carcinogenicity (causing cancer), and mutagenicity (causing birth defects). It refers to effects of these types caused by specific chemicals, rather than by general activities such as site development.

Many emittants are included in the list of chemicals in the U.S. Toxic Release Inventory (TRI). The human organism damage of these chemicals has been ranked on a 0-100 scale by the organization Environmental Defense, and is available on the worldwide web at www.scorecard.com. We adopt the Human Health Risk Screening Score (HHRSS) as our rating indicator, and assign ratings as follows:

H $\text{HHRSS} > 75\%$
M $25\% \leq \text{HHRSS} \leq 75\%$
L $\text{HHRSS} < 25\%$

where HHRSS refers to the mean value of the range specified on the web site. Details about this approach appear in the appendix to this chapter.

6.3.3 *Potential Impact Binning for Ecosystem Organism Damage*

Ecosystem organism damage is an ensemble term that includes toxicity (causing prompt illness or death), carcinogenicity (causing cancer), and mutagenicity (causing birth defects). It refers to effects of these types caused by specific chemicals, rather than by general activities such as site development.

Many emittants are included in the list of chemicals in the U.S. Toxic Release Inventory (TRI). As with human organism damage, the ecosystem organism damage of these chemicals has been ranked on a 0-100 scale by the organization Environmental Defense. We adopt the Ecological Risk Screening Score (ERSS) as our rating indicator, and assign ratings as follows:

H $\text{ERSS} > 75\%$
M $25\% \leq \text{ERSS} \leq 75\%$
L $\text{ERSS} < 25\%$

where ERSS refers to the mean value of the range specified by EDF. Details appear in the appendix to this chapter.

6.3.4 *Potential Impact Binning for Loss of Biodiversity*

Losses of biodiversity result from the disruption or destruction of habitat areas. Several features are of interest. One is the amount of land disrupted, since concerns are larger the more land is involved, other factors being equal. A second is the character of the land, more sensitive regions being of more concern. A third is whether the industrial activity represents a continuation of use of disrupted land or a new disruption. Some

Table 6.5. Binning Biodiversity Impact

Land Amount Binning	Land Type Binning	Biodiversity Impact Rating
H	H	H
H	M	M
H	L	L
M	H	M
M	M	L
M	L	L
L	H	L
L	M	L
L	L	L

disruption always occurs when humans make use of the land, but the distinctions among slight, modest, and extensive disruption can probably be made by most honest observers. In the case of sensitive areas, we define those as the following: (1) undisrupted wetland; (2) undisrupted marshland; (3) land with native, well-established vegetation; (4) land which is the habitat of endangered or threatened species.

Given the definition, we now bin land amounts as follows:

H	>10 ha
M	1–10 ha
L	<1 ha

We bin the land types as follows:

H	Major new disruption of sensitive land
M	Modest new disruption of sensitive land
L	Slight new disruption to sensitive land or no significant change to a previous disruption.

The biodiversity impact rating is then assigned from Table 6.5.

6.3.5 *Stratospheric Ozone Depletion*

Ozone-depleting chemicals (ODC) are those whose daughter fragments react with and deplete stratospheric ozone (O_3). These gases all contain one or more halogen atoms (F,Cl,Br) that are liberated by the energetic radiation present in the stratosphere. The simplified depletion chemistry, with chlorine as the example, is

$$\begin{array}{l}
\mathrm{ODC} \xrightarrow{\text{STRATOSPHERIC RADIATION}} \mathrm{Cl} \\
\mathrm{Cl} + \mathrm{O_3} \longrightarrow \mathrm{ClO} + \mathrm{O_2} \\
\mathrm{ClO} + \mathrm{O_3} \longrightarrow \mathrm{Cl} + 2\mathrm{O_2} \\
\hline
2\mathrm{O_3} \longrightarrow 3\mathrm{O_2}
\end{array}$$

The sequence uses Cl (the chlorine free radical) as a catalyst, since it is left unchanged from an overall perspective. On average, a single halogen free radical repeats this destruction cycle several thousand times before being scavenged by an alternative chemical reaction.

The potential of different gases to contribute to ozone depletion is measured on a per-molecule basis by the *ozone-depletion potential* (ODP), defined approximately as

$$\mathrm{ODP_x} = \frac{\text{Time-integrated global } \mathrm{O_3} \text{ loss due to x}}{\text{Time-integrated global } \mathrm{O_3} \text{ loss due to CFC-11}}$$

A selection of ODPs, computed by detailed atmospheric computer models, is given in Table 6.4. Ozone-depletion potentials range from 1 (for the gas CFC-11 [$CFCl_3$]) to less than 0.05 (for hydrogen-substituted CFCs such as HCFC-22 [$CHClF_2$]) to zero (for nonhalogenated gases and highly reactive halogenated gases). We assign the following potential impact ratings:

H $\mathrm{ODP} > 0.1$
M $0.0 < \mathrm{ODP} \leq 0.1$
L $\mathrm{ODP} = 0$

6.3.6 Potential Impact Binning for Photochemical Smog

The degree to which the various volatile organic carbon (VOC) molecules enhance smog formation depends on how readily they react with the atmospheric hydroxyl radical (OH) or (less frequently) the ozone molecule (O_3). The rate constants for many VOC molecules with OH and O_3 have been established by laboratory studies; a sample for some of the more common VOC molecules is given in Table 6.6; data for many additional VOCs are given in the Atkinson et al. (1999) paper cited in the Further Reading section of this chapter.

Table 6.6. Rate Constants for Selected VOC Molecules

Molecule	OH Rate Constant*	O_3 Rate Constant*
CH_4	6.3×10^{-15}	
C_2H_4	8.8×10^{-12}	1.7×10^{-18}
C_3H_6		1.1×10^{-17}
HCHO	1.0×10^{-11}	
CH_3COOH	8.0×10^{-13}	
Toluene	6.2×10^{-12}	
Isoprene	1.8×10^{-11}	

*Units are $\mathrm{cm^3/(molecule\text{-}s)}$

We assign a potential impact rating as follows, in accordance with the U.S. EPA division of molecules into "high reactivity," "moderate reactivity," and "low reactivity":

H $k_{OH} > 1 \times 10^{-12}$ or $k_{O_3} > 1 \times 10^{-17}$
M $1 \times 10^{-14} \leq k_{OH} \leq 1 \times 10^{-12}$ or $1 \times 10^{-18} \leq k_{O_3} \leq 1 \times 10^{-17}$
L $k_{OH} < 1 \times 10^{-14}$ or $k_{O_3} < 1 \times 10^{-18}$

6.3.7 Acid Deposition

Acid deposition is the process in which precipitation that has become acidified falls onto Earth's surface and reacts with the surface environment. Depending on the degree of acidity and the character of the surface, the result can be damage to vegetation, acidification of surface waters, and the corrosion of exposed metals.

The atmospheric acids or acid precursors include the following: sulfur dioxide (SO_2), nitrogen dioxide (NO_2), hydrogen chloride (HCl), formic acid (HCOOH), acetic acid (CH_3COOH), and carbon dioxide (CO_2). Of these six, the first three are strong acids, the next two of moderate acidity, and the last a weak acid. Accordingly, we assign the following potential impact ratings:

H SO_2, NO_2, HCl
M HCOOH, CH_3COOH
L CO_2

6.3.8 Aesthetic Degradation

Aesthetic degradation is not something that can be quantified, nor is it a topic on which reasonable people will always agree. It is clearly of importance to many, nonetheless, who find that the subject mirrors former U.S. Supreme Court Justice Potter Stewart's famous remark about pornography: "I may not be able to define it, but I know it when I see it."

As addressed here, aesthetic degradation need not refer to emissions harmful to human or other organisms; their implications are captured elsewhere in this analysis. It could, however, refer to any of the following:

- Emissions that are within regulatory constraints and not known to be harmful but are nevertheless unsightly.
- Structures that are viewed as inherently unsightly (e.g., wind farms)
- Structures that intrude on landscapes or seascapes valued for their natural beauty.

Aesthetics appear, in most cases, not to be directly related to throughput, nor can we devise an unbiased way by which to measure level of hazard. As a result, we are unable to include aesthetic degradation within our analysis of the environmental performance of a facility.

6.3.9 Thermal Pollution

Thermal pollution occurs when an industrial facility extracts water from an ocean, river, lake or groundwater system, uses it as part of an industrial process, and returns it to nature at a higher temperature than that at which it was acquired. The potential consequence is damage to aquatic organisms. Thermal pollution most commonly occurs as a consequence of the once-through use of water for cooling.

Throughput for thermal pollution is defined on the basis of the industrial sector being evaluated, since average water use is strongly related to sector. For example, a pulp and paper mill is clearly more water-intensive than are most product assembly operations. No matter what the specific performance of the mill, it is highly probable that it has a higher water use intensity due to its nature than facilities in many other sectors. Therefore, we assign throughput for thermal pollution as determined in Table 6.7.

The degree of hazard for thermal pollution is strongly related to the difference in temperature between intake water and discharged water. We assign the following potential impact ratings:

H $\Delta T > 5°C$
M $2.5 \leq \Delta T \leq 5°C$
L $\Delta T < 2.5°C$

Table 6.7. Water Usage by Industrial Sector

Sector	Water Use
Fossil Fuel Extraction and Processing	H
Power Generation	H
Metal Ore Extraction and Processing	H
Inorganic Minerals and Chemicals	M
Petrochemicals	M
Agriculture	H
Textiles and Leather	M
Sand and Glass	M
Fabricated Metal Products	L
Fabricated Plastic Products	L
Electronics	L
Synthetic Organic Chemicals	H
Assembled Products	L
Forest Products and Printing	H
Packaging and Shipping	L
Construction	L
Recycling	L

6.3.10 Odor

Despite years of research, the reasons why a certain molecule is odorous and why it produces the sensation that it does remains incompletely understood. It is clear, of course, that a molecule capable of producing the sensation of odor must make its way to the olfactory receptors of the nose and produce a signal that can be transmitted to the brain by a sensory neuron. Many attempts have been made to relate odor sensations to selected molecular properties such as shape or chemical bonding properties, and certain molecules have been identified as particularly odoriferous. It is common knowledge, for example, that reduced compounds of sulfur and nitrogen (e.g., hydrogen sulfide, trimethylamine, etc.) tend to have extremely high odor sensitivities.

Once a molecule is recognized as being odorous, regardless of what psychophysical processes are involved, the response to it may be quantitatively investigated. The principal factor important to odor intensity is the olfactory threshold concentration C_t, the concentration at which a molecule is not only detectable but is definable as representative of the odor being studied. The range of C_t values is very wide, indicating that certain molecules are detected with extreme sensitivity by the nose, while others must be present at very high concentrations to be noticeable at all. For example, an experimental study tested 101 petrochemicals with an odor panel and found that the concentration "at which 50% of the panel defined the odor as being representative of the odor being studied" ranged from 300 parts per trillion (ethyl acrylate) to 500 parts per million (ethylene oxide). This represents a range of more than six orders of magnitude in C_t.

A selection of C_t values is given in Table 6.8 for odorants commonly associated with industrial processes. We assign a potential impact rating as follows:

H $C_t < 50$ ppbv
M 50 ppbv $> C_t <$ 1000 ppbv
L $C_t >$ 1000 ppbv

Table 6.8. Selected Olfactory Threshold Values

Molecule	Molecular Formula	Threshold (ppbv)*
Acetone	CH_3COCH_3	500,000
Hydrogen sulfide	H_2S	30
Limonene		10
Methyl mercaptan	CH_3SH	0.02
Phenol		5900
Styrene		730
Toluene		2000
Xylene		1000

*ppbv = parts per billion per volume (i.e., 1 part in 10^9).
The data are from Leffingwell and Associates, at http://www.leffingwell.com/odorthre.htm, accessed August 20, 2002. At this site, and through web searching with "odor threshold" and the compound name, many more data are available.

Table 6.9. Throughput-Hazard-Scarcity Binning of Materials in a Generic Industrial Facility

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
A	H	–	L	M
B	H	Ecosystem	M	H
C	M	Climate	H	L
D	M	Smog	M	L
E	L	Human	H	L

Because different people find different odors attractive or unattractive, we take no account of the character of the odor.

6.3.11 *Radionuclides*

Radionuclides are generally the subject of extensive regulatory oversight and control. Accordingly, they are captured by the facility compliance evaluation of chapter 3 and are not included in the sustainability evaluation.

6.3.12 *Landfill Exhaustion*

This topic is one that is difficult to evaluate either quantitatively or qualitatively, since landfill availability and capacity are not generally the province of a single corporation or facility. If there are serious concerns, those concerns will lead to regulatory requirements. The topic is thus captured by the facility compliance evaluation, not here.

6.3.13 *The Throughput-Potential Hazard Matrix*

The construction of the throughput-potential hazard (TPH) matrix involves a hazard evaluation for each constituent or emittant with a high enough throughput to be considered significant. For example, assume that the environmental impacts of Table 6.1 were potential hazards specified on the basis of the framework discussed above. Table 6.1 can then be rewritten as Table 6.9, where for illustration the primary reason for the hazard potential binning (i.e., the hazard basis) is indicated.

6.4 USE OF MATERIALS

A well-established historic relationship is that an improved standard of living brings with it an increase in the use of materials. Recall that the United States in the twentieth century had a population that increased during the century by about a factor of 3, whereas the total materials use increased by about a factor of 10.

Most of the materials groups showed reasonably steady gains during that period except for agriculture, which has been a relatively stable user of materials since about 1940.

A first approximation to the effective abundance of a natural nonrenewable resource can be derived by examination of the total amount of the resource currently thought to be present (the *reserve base*, RB) and the rate at which it is being utilized. If the reserve base is divided by the annual virgin resource consumption rate (CR), the result is the *depletion time* (t_D), i.e., the number of years left until the resource is exhausted:

$$t_D = RB/CR$$

It is true that the resource bases are constantly being enhanced by new discoveries and by the development of improved extractive techniques. However, it is equally true that the global rates of increase in population and standard of living, and the additional resource use thereby demanded, may well more than balance resource base enhancement. In addition, environmental limitations on development may make it more difficult or impossible to use resources even if we know where they are and how to recover them.

The possibility that some common resources may become quite scarce in the foreseeable future suggests that industrial sectors that rely on those resources may need to explore alternative materials or alternative approaches to accomplishing their function. An initial evaluation of scarcity might be that nonrenewable resources with $t_D < 40$ years be regarded with substantial concern, those with $40 \leq t_D \leq 100$ years with some concern, and those with $t_D > 100$ years with little concern. Potential scarcity applies to input materials only, of course, not outputs or releases.

Materials are binned on the basis of scarcity as follows:

H (high scarcity)	$t_D < 40$ yr
M (moderate scarcity)	$t_D = 40$–100 yr
L (low scarcity)	$t_D > 100$ yr

Table 6.10 lists depletion time categories for many common materials.

In the case of materials scarcity evaluation, the throughput is determined slightly differently than for hazard. We continue to divide the constituents into three "bins": high throughput (H), moderate throughput (M), and low throughput (L), but we assess only the virgin resource used, not the total resource used. This encourages the use of recycled content in products and process chemicals. Thus, for the scarcity matrix the throughput binning is accomplished as follows:

- H: virgin resource constituent flow >10% by weight of total facility or process line input constituent flows
- M: virgin resource constituent flow 1–10% by weight of total facility or process line input constituent flows
- L: virgin resource constituent flow <1% by weight of total facility or process line input constituent flows

***Table* 6.10.** Depletion Time Categories for Common Materials*

Materials with $t_D < 40$ *yr (the "H" bin)*

Arsenic, barium, bismuth, cadmium, copper, diamond, gold, graphite, indium, lead, manganese, mercury, peat, silver, strontium, thallium, tin, uranium, zinc

Materials with $t_D = 40\text{–}100$ *yr (the "M" bin)*

Antimony, cobalt, fluorine, molebdenum, natural gas, nickel, oil, phosphate/phosphorus, rhenium, selenium, tantalum, tungsten, vermiculite (source of light-weight aggregate), zirconium

Materials with $t_D > 100$ *yr (the "L" bin)*

Aluminum, boron, carbon, chromium, columbium, coal, cerium, dysprosium, erbium, europium, gadolinium, holmium, hydrogen, iodine, iridium, iron, lanthanum, lithium, lutetium, magnesium, neodymium, nitrogen, osmium, oxygen, palladium, platinum, potash, praseodymium, promethium, rhodium, ruthenium, samarium, scandium, silicon, soda ash, sodium sulfate, sulfur, terbium, titanium, thulium, vanadium, ytterbium, yttrium

*The data are from S. E. Kesler, *Mineral Resources, Economics, and the Environment*, New York: Macmillan, 1994. The exception is sulfur, a trace constituent of coal and oil, which is now recovered from power plant stack gases and hence is not under supply pressure.

Text Box 6.1

Recognizing the Use of Recycled Material in the Sustainability Evaluation

If recycled material is used in an industrial process, that use does not create an impact on resource scarcity; this approach needs to be recognized in our evaluation. As an example, assume that a factory makes electrical equipment using the following set of material inputs from virgin resources:

75,000	kg steel	Throughput: H
12,000	kg copper	Throughput: H
5,000	kg brass	Throughput: M
4,000	kg thermoset plastic	Throughput: M
1,100	kg powder paint	Throughput: M
1,100	kg cardboard packaging	Throughput: M

Now assume that the same facility works with its suppliers to use 50% recycled content in the steel, copper, and packaging. The revised throughput ratings are:

37,500	kg virgin steel	Throughput: H
6,000	kg virgin copper	Throughput: M
5,000	kg virgin brass	Throughput: M
4,000	kg virgin thermoset plastic	Throughput: M
1,100	kg virgin powder paint	Throughput: M
550	kg cardboard packaging	Throughput: L

In this example, the use of recycled materials has changed the binning on copper and packaging, though not on the steel.

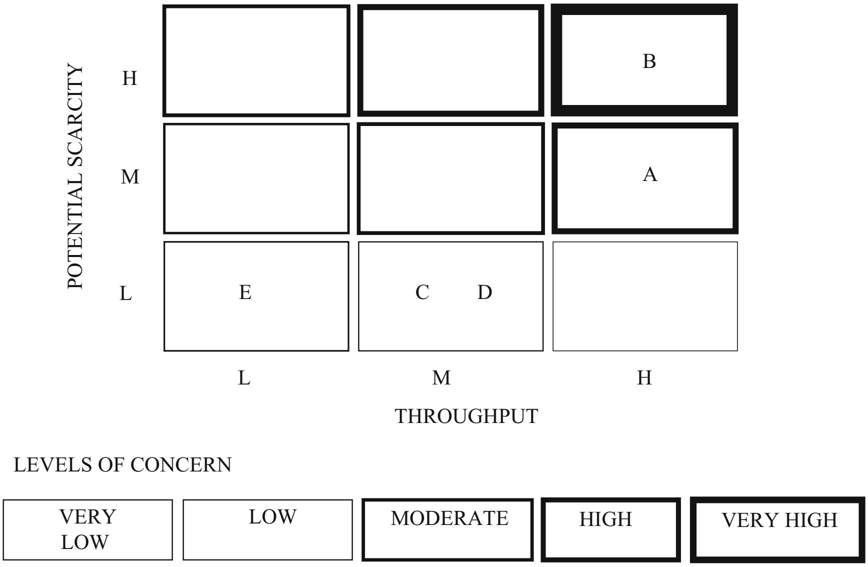

Figure 6.2. The throughput-potential scarcity (TPS) matrix resulting from the data in table 6.7.

For the relative magnitude of emissions, the adjustments to the hazard throughput approach are similar:

- H: Virgin material constituent flow equal to or greater than 1% by weight of total facility input constituent flows
- M: Virgin material constituent flow less than 1% by weight of total facility input constituent flows
- L: Virgin material constituent flow much less than 1% by weight of total facility input constituent flows

Given a method to rank constituents on a scarcity basis, and having established throughput classification, a throughput-potential scarcity (TPS) matrix can now be constructed. For illustration, assume that an analysis of the generic industrial facility of table 6.9, which uses only virgin materials, has produced the scarcity binnings shown there. The resultant TPS matrix plot is shown in Figure 6.2.

6.5 USE OF WATER

Water may ultimately turn out to be the resource that most limits the way in which industrial activity, broadly defined, can evolve. Unlike wood or other renewable resources, the total average quantity of water available to humans is fixed. What is not fixed, however, is any constancy in rate of supply, since droughts, floods, and average water flows are all relatively common experiences. Because industrial sectors all use water, some much more than others, industrial location, type, and efficiency are important factors in water budgets.

Recall from Table 2.1 that of global water use is for crop irrigation by the agricultural sector. All other industries consume about 80% additional. The distribution of use in the United States is quite different: cooling water for electrical power production amounts to nearly 40% of all use. Other industrial sectors that depend very heavily on abundant water supplies are agriculture, pulp and paper (in the manufacture of wood pulp), metal smelting and refining, inorganic chemical processing, and petrochemicals.

The use of water by industry varies widely on different continents. Asia, which emphasizes rice grown in paddy fields, uses much more water for irrigation than is the case anywhere else. North America, which utilizes water heavily for power plant cooling and pulp manufacture, uses more water than elsewhere for non-agricultural purposes. Around the world, the water budget is a balance between what nature provides and how efficiently human activities use the water that is provided.

A major environmental concern in a number of parts of the world, and one that may become increasingly important as populations increase and urban areas become larger and more complex, is the geographical nature of water availability. Because some regions of the world are more water-rich than others, water use tends to be a locationally-based metric, since a water-using process in Norway would almost certainly be of little concern, whereas the same process in water-starved Ethiopia would likely be a major problem. Figure 6.3 shows per capita supply and use to availability ratios associated with various scenarios ranging from water surplus to scarcity.

The quality of the water returned to the environment following use is every bit as important as the quantity used. The ideal situation is that the usefulness of any water that is returned does not compromise further human or ecosystem use. This aspect is generally captured by the human and ecosystem hazard evaluation discussed above.

The approach to use within a particular facility (the water performance) is ideally evaluated with respect to other facilities or corporations in the same industrial sector, since the sectors differ widely in water use. The use must be considered as well with respect to the vulnerability of the available water resources. These two parameters then form the performance-water concern (PWC) matrix for water. In practice, this information is hardly ever directly available at the facility or corporate level, so we adopt somewhat more general but still informative methods.

6.5.1 Water Concern

The water concern binning should comprise components that address issues that are beyond the control of the facility: the availability of water and the water usage of the industrial sector.

Supply per capita (m^3)	**Use-Availability Ratio (%)**			
	<40	**40 - 60**	**60 - 80**	**>80**
<1,000	☆☆	☆☆☆	☆☆☆☆	☆☆☆☆
1001–2000	☆☆	☆☆☆	☆☆☆☆	☆☆☆☆
2,001–10,000	☆	☆☆	☆☆☆	☆☆☆☆
>10,000	☆	☆	☆☆	☆☆☆☆

☆ **Water Surplus**
☆☆ **Marginally Vulnerable**
☆☆☆ **Water Stress**
☆☆☆☆ **Water Scarcity**

Figure 6.3. A four-level ranking for the water vulnerability of individual countries. (Reproduced with permission from S. Kulshreshtha, *World Water Resources and Regional Vulnerability: Impact of Future Changes*, Report RR-93-10, Laxenburg, Austria: International Institute of Applied Systems Analysis, 124 pp., 1993.)

National Concern

Although national water concern is not the only factor in facility water evaluation, it is still an important determiner in the concern over water. Table 6.11 provides a binning for the level of national water concern.

Regional Concern

In addition to national water concern, regional water concern should be taken into consideration. Transportation of water between regions is generally prohibitively expensive. Therefore, an evaluation of the regional water supply more accurately depicts the water concern felt by a specific location. In order to determine the level of concern, the average annual precipitation should be used to compare the area where

Table 6.11. Water Resources Vulnerability Status for Countries of the World*

Water surplus (the "L" bin)

Afghanistan
Albania
Angola
Argentina
Austria
Bangladesh
Benin
Bhutan
Bolivia
Botswana
Brazil
Bulgaria
Burkina Faso
Burundi
Cambodia
Cameroon
Canada
CAR
Chad
Chile
China
Colombia
Comoros
Congo
Costa Rica
CSFR
Cuba
Denmark
Djibouti
Dom. Republic
Ecuador
El Salvador
Equatorial Guinea
Ethiopia
Finland
France
Gabon
Gambia
Ghana
Greece
Guatemala
Guinea
Guinea Bissau
Guyana
Haiti
Honduras
Hungary
Iceland
Indonesia
Ireland
Italy
Ivory Coast
Jamaica
Kenya
Laos
Lesotho
Liberia
Luxembourg
Malawi
Malaysia
Mali
Mauritania
Mexico
Mongolia
Mozambique
Myanmar
Nepal
Netherlands
New Zealand
Nicaragua
Niger
Nigeria
Panama
Paraguay
Philippines
Portugal
Romania
Rwanda
Senegal
Sierra Leone
Somalia
Spain
Sri Lanka
Sudan
Suriname
Swaziland
Sweden
Switzerland
Tanzania
Togo
Trinidad
Turkey
Uganda
Uruguay
USA
Venezuela
Vietnam
Yugoslavia
Zaire
Zambia
Zimbabwe

Marginal supply (the "M" bin)

Algeria
Australia
Barbados
Cape Verde
Germany
India
Korea (PR)
Korea (R)
Lebanon
Madagascar
Mauritius
Morocco
Oman
Pakistan
Poland
Singapore
South Africa
Thailand

Water scarcity (the "H" bin)

Bahrain
Belgium
Cyprus
Egypt
Iran
Iraq
Israel
Jordan
Kuwait
Libya
Malta
Peru
Qatar
Saudi Arabia
Syria
Tunisia
UAE
United Kingdom
Yemen (PR)
Yemen (R)

*The classifications are from S. N. Kulshreshtha, *World Water Resources and Regional Vulnerability: Impact of Future Changes*, Report RR-93-10, Laxenburg, AU: Intl. Inst. for Applied Systems Analysis, 124 pp., 1993. Australia and New Zealand have been added. His categories of "stress" and "scarcity" are here combined into the category "scarcity".

the facility is located to other areas within the country. This allows for a refinement of the overall national concern bin.

For example, in the US, data on yearly precipitation is available from the National Oceanic and Atmospheric Administration (NOAA). A map showing yearly rainfall is available on the website: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/regional_monitoring/us_12-month_precip.html. From this map, it can be seen that US annual rainfall ranges from about two to 80 inches per year. Therefore, in the US, total rainfall scarcity will be binned as:

High:	less than 75 cm annual precipitation
Medium:	between 75 and 150 cm annual precipitation
Low:	above 150 cm annual precipitation

This analysis differentiates between climatic zones of a large nation like the US. This captures the rationale that a facility located in Phoenix faces more concern about water supply than does one in Connecticut. In addition, it is a simple and reasonable indicator for regional water availability. Values for this binning can easily be obtained from the NOAA precipitation map.

The establishment of the threshold levels for the bins based upon dividing the annual precipitation range roughly into thirds is somewhat arbitrary. These levels may need to be adjusted in countries with different rainfall ranges from the US. In addition, precipitation does not represent total water availability. However, as no measurement of groundwater levels is readily available, annual precipitation is a reasonable proxy for regional water availability.

Sectoral Concern

In addition to the amount of water available at a given location, the amount of water used by the type of facility is an important determinant in the water concern. As for thermal pollution, we assign this rating on a sectoral basis, as determined in Table 6.7.

This approach normalizes water concern for companies within the same industry. It also appropriately raises the concern of water-intensive industries, relative to less water-intensive ones. However, it may be difficult to categorize some companies into this set of sectors. As this list is very general, some facilities may be unjustly punished for what others in the same sector do. For example, a facility highly specialized within a sector may not perform the water-intensive operations of the sector.

Binning

Water concern is binned by averaging the bin of the three components: national, regional, and sectoral concern. As each of these components is equally important, they are weighted equally. A simple way to find this bin is to assign numeric values to the three bin levels: H = 1, M = 2, L = 3. The scores from the three component

Table 6.12. Water Concern Binning in the US (national, regional, sectoral)

Component Bins	Average	Component Bins	Average	Component Bins	Average
LHH	M	LHM	M	LHL	M
LMH	M	LMM	M	LML	L
LLH	M	LLM	L	LLL	L

metrics are then averaged, and standard rounding procedures used to determine the bin assignment:

High:	less than 1.5
Medium:	1.5 to 2.5
Low:	2.5 or greater

Table 6.12 shows the range of possible scores for facilities in the US, where national concern is Low.

6.5.2 Water Performance

Water performance is difficult to evaluate because the treatment methods and trends differ between facilities. Evaluations of water performance must be based on whatever information is available for a facility but we outline some of the data that is desirable.

The water performance binning system is also divided into three component metrics, and looks at issues occurring within the facility that are consequently controllable by the facility.

Baseline Comparison

As previously described, normalized baseline comparisons are very important in determining the performance of a facility. Therefore, the first component of water performance is the trend in water usage normalized to some production factor. Specifically, the one-year trend in water use will be used to determine the comparison performance bin:

High:	reduction in normalized water usage by more than 5%
Medium:	constant normalized water usage within 5%
Low:	increase in normalized water usage by more than 5%

The one-year trend was chosen because it is much more likely that data will be available for the previous year than for several years prior. In addition, since this analysis is aimed at analyzing current performance, a one-year trend is thought to be more appropriate than a multi-year one. While the specifications and frequency of processes may vary year to year without signifying a change in efficiency, the variation in usage efficacy is more likely to be significant, and that is what is captured by the normalized comparisons.

Using a normalized trend metric to bin performance is enormously important. This metric allows for an overview of the company's water usage performance, yet does not penalize a facility for increased production. Rather, it rewards the facility for decreasing water usage relative to a proxy for production. Another benefit of this system is that rough estimates for the data necessary for this analysis can often be fairly easily obtained from discussions with key personnel.

Waste Water Treatment

In addition to water usage, wastewater treatment is a key portion of water performance. Recognizing that different levels of treatment may be appropriate for different waste water conditions, both the level of wastewater treatment and the waste water quality averaged across wastewater streams are factored into this component:

High: tertiary treatment or above secondary wastewater quality
Medium: secondary treatment or above primary quality
Low: primary treatment only or less than primary quality
Adjustment: decrease the bin one level for significant NPDES permit violations

The data regarding violations can be found on databases such as at http://www.rtk.net.

This component allows the evaluator to differentiate qualities of wastewater between different plants. In addition to reducing the amount of water used, a facility with a high level of awareness of its water performance should have a fairly effective wastewater treatment plan.

This metric allows for the possibility of wastewater that does not need to be treated, since it addresses both effluent quality and level of treatment. For example, it is easy to imagine that non-contact cooling water, which is formally regarded as wastewater, may not require tertiary treatment to achieve high quality. In addition, the adjustment factor allows consideration of permitted levels of effluent release by incorporating reference to NPDES permits.

Water Reuse

The third component of the water performance binning is the amount of process water that is reused. In order to bin this factor, the evaluator should determine how much of the water stream is cycled for reuse, in the facility or at another location:

High: greater than 10% reuse
Medium: 1–10% reuse
Low: less than 1% reuse

This factor allows for consideration of reuse programs. In addition, it captures symbiotic exchanges or cascading reuse of water. It also allows for systematic

Table 6.13. Water Performance Binning

Trend-Wastewater-Reuse	Bin	Trend-Wastewater-Reuse	Bin	Trend-Wastewater-Reuse	Bin
HHH	H	MHH	H	LHH	H
HHM	H	MHM	M	LHM	M
HHL	M	MHL	M	LHL	M
HMH	H	MMH	M	LMH	M
HMM	M	MMM	M	LMM	M
HML	M	MML	M	LML	L
HLH	M	MLH	M	LLH	M
HLM	M	MLM	M	LLM	L
HLL	M	MLL	L	LLL	L

incorporation of information which otherwise would be arbitrarily averaged into water performance evaluation.

Binning

Water performance is binned by averaging the bin of the three components: baseline comparison, wastewater treatment, and water reuse. As each of these components is equally important, they should be weighted equally. Table 6.13 shows the possible distribution of bins. The score for water performance is obtained by the same approach as for water concern. For each component of water performance, assign points based on H = 1, M = 2, and L = 3. Average the scores and bin water use as follows:

High	less than 1.5
Medium	1.5 to 2.5
Low	2.5 or greater

The performance-water concern (PWC) matrix plot for a hypothetical water-inefficient facility located in a water-stressed region is shown in Figure 6.4.

6.6 USE OF ENERGY

We have said earlier that industry is a heavy user of energy, consuming roughly one-third of all energy in the U.S. The industrial sectors are quite diverse in this regard, however, so it is worthwhile to examine energy use sector by sector. The energy required to perform "heavy industry" functions reflects the requirement of those sectors to move large quantities of material, to heat material to high temperatures, and to apply high pressures. Thus, mining, smelting, refining, and petroleum processing are dominant industrial energy consumers. Other important sectors are the production of chemicals, the primary metals industry, and the paper and paper products industry.

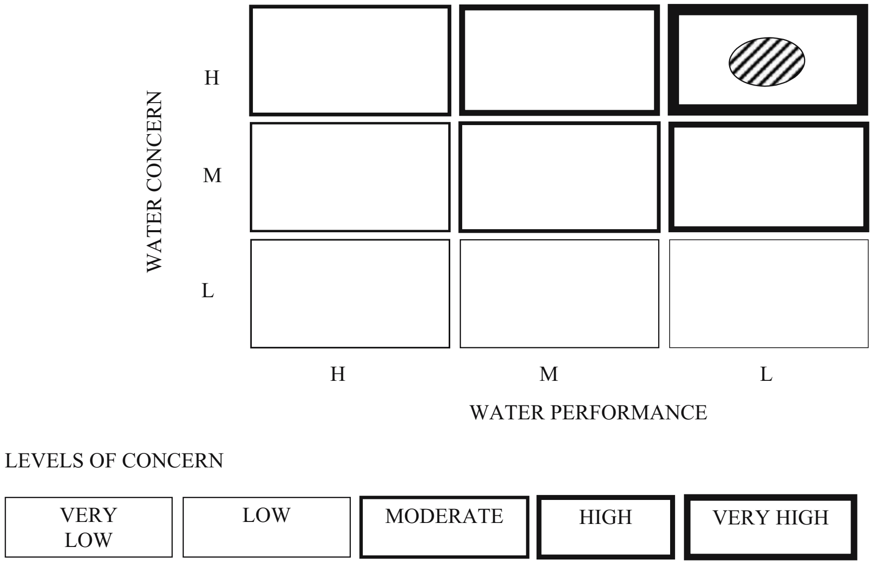

Figure 6.4. The performance-water concern (PWC) matrix plot for a hypothetical water-inefficient facility located in a water-stressed region.

The use of energy is a major environmental concern because of its role in greenhouse gas emissions, acid rain generation, and various other environmental impacts. A related concern is energy scarcity. As with water, energy use can be considered either a global consideration or a local one. Obviously, so long as energy in the form of fossil fuels is readily transportable and affordable, energy scarcity in any location on the planet is closely tied to global resources. In the longer term, however, a potential peaking of oil and natural gas supplies suggests that more attention needs to be paid to renewable energy supplies, and those supplies are far more localized than are fossil fuels. Accordingly, it seems useful for facilities, corporations, or regions to evaluate environmental performance in part on the potential for locally-generated energy.

As with water, the ideal evaluation of energy use with a particular facility would be comparison with other facilities or corporations in the same industrial sector. The use would be considered as well with respect to the vulnerability of the available energy resources. These two parameters then form the Performance-Energy Concern (PEC) Matrix.

6.6.1 Energy Concern

As with water concern, energy concern comprises three component metrics: national, regional, and sectoral, addressing issues that are beyond the control of the facility for the most part.

National Concern

The national determination used in the previous process for water will be retained as a valuable component of energy use concern. The importance of national energy vulnerability is clear, and arguably drives much of the national agenda. A conservative approach to energy consumption is to treat the resources as one does water—to attempt to live within the indigenous supply. A vulnerable country from an energy standpoint is thus one that imports substantial amounts of fossil fuels to meet its energy requirements.

Energy statistics for all countries in the world are maintained by the International Energy Agency, which tabulates total energy production (χ) and net energy imports (η). The quotient of these two parameters can be defined as the *energy vulnerability* γ,

$$\gamma = \eta / \chi$$

since it measures to proportion of energy that is supplied from imported stocks. A country that is producing energy that exactly matches its rate of use will have $\gamma = 1$. If it is importing energy to supplement indigenous sources, γ will be positive. Conversely, if it is exporting excess production of fossil fuels, γ will be negative.

As an arbitrary standard, 25% deviation from energy production and use that exactly balance will be regarded as significant. Thus, a 25% oversupply relative to use is designated *low vulnerability* and a 25% undersupply relative to use is designated *high vulnerability*. Mathematically,

H (High vulnerability): $\gamma > 0.25$
M (Moderate vulnerability): $-0.25 \leq \gamma \leq 0.25$
L (Low vulnerability): $\gamma < -0.25$

For the countries of the world, national energy vulnerability ratings are given in Table 6.14.

Regional Concern

The regional energy supply can be based on regional energy resource or generating capacity supply. However, neither of these metrics were deemed appropriate for this analysis. Since energy resource supplies, currently primarily fossil fuels, are easily and economically transportable, the regional energy resource supply is adequately described by the national energy vulnerability. As new generation capacity can be profitably built in many locations, it will also not be included in this analysis.

Instead, the regional energy concern a facility may have is likely to be based on the price of energy, which does vary by region and fuel type. Therefore, the regional concern will compare the price paid (per million BTU, for example) in the region

Table 6.14. Energy Resource Vulnerability Status for Countries of the World

Energy surplus (the "L" bin)

Algeria
Angola
Argentina
Australia
Bolivia
Brunei
Cameroon
Canada
Colombia
Congo
Ecuador
Egypt
Gabon
Indonesia
Iran
Iraq
Kazakhstan
Kuwait
Libya
Malaysia
Mexico
Nigeria
Norway
Oman
Paraguay
Qatar
Russia
Saudi Arabia
South Africa
Syria
Trinidad
Turkmenistan
United Arab Emirates
Yemen

Marginal supply (the "M" bin)

Albania
Azerbaijan
Bahrain
Bangladesh
Benin
China
Czech Republic
Denmark
Ethiopia
Ghana
Guatemala
Haiti
India
Ivory Coast
Kenya
North Korea
Mozambique
Myanmar
Nepal
Netherlands
New Zealand
Peru
Poland
Sudan
Tanzania
Tunisia
United Kingdom
United States
Uzbekistan
Vietnam
Zambia
Zimbabwe

Energy scarcity (the "H" bin)

Armenia
Austria
Belarus
Belgium
Bosnia-Herzegovina
Brazil
Bulgaria
Chile
Costa Rica
Croatia
Cuba
Cyprus
Dominican Republic
El Salvador
Estonia
Finland
France
Georgia
Germany
Gibralter
Honduras
Hong Kong
Hungary
Iceland
Ireland
Israel
Italy
Jamaica
Japan
Jordan
Korea
Kyrgyzstan
Latvia
Lebanon
Lithuania
Luxembourg
Macedonia
Malta
Moldava
Morocco
Nicaragua
Pakistan
Panama
Philippines
Portugal
Romania
Senegal
Singapore
Slovakia
Slovenia
Spain
Sri Lanka
Sweden
Switzerland
Tajikistan
Thailand
Turkey
Ukraine
Uruguay
Yugoslavia

(state, province, etc.) with the national average:

High: greater than 10% above the national average
Medium: within 10% of the national average
Low: greater than 10% below the national average

Price data for the US can be found from the Energy Information Administration of the Department of Energy at http://www.eia.doe.gov/pub/state.prices/pdf/rank.pdf. Other countries have similar data sources. As the price of energy can vary widely between regions, the relative energy price is an important piece of a facility's energy concern. This metric measures the relative stress that the price of energy imposes on facilities in various locations.

Sectoral Concern

Similar to water usage, the amount of energy used by the type of facility is an important determinant in the energy concern. Therefore, the third factor to determine the energy concern is the facility's sectoral energy use, as determined in Table 6.15.

As for water usage, this approach normalizes energy concern for companies within the same industry. It also appropriately raises the concern of industries that require more energy, relative to less energy-intensive ones. Since this list is very general, it may be difficult to classify some companies into this set of sectors, and some facilities may be unjustly punished for what others in the same sector do, as a facility highly

Table 6.15. Energy Usage by Sector

Sectors	Energy Use
Fossil Fuel Extraction and Processing	H
Power Generation	—
Metal Ore Extraction and Processing	H
Inorganic Minerals and Chemicals	M
Petrochemicals	H
Agriculture	M
Textiles and Leather	M
Sand and Glass	H
Fabricated Metal Products	M
Fabricated Plastic Products	M
Electronics	L
Synthetic Organic Chemicals	H
Assembled Products	L
Forest Products and Printing	H
Packaging and Shipping	M
Construction	L
Recycling	L

Table 6.16. Energy Concern Binning in the US (national, regional, sectoral)

Component Bins	Average	Component Bins	Average	Component Bins	Average
MHH	H	MHM	M	MHL	M
MMH	M	MMM	M	MML	M
MLH	M	MLM	M	MLL	L

specialized within a sector may not perform the energy-intensive operations of the sector.

Binning

These three factors, national, regional, and sectoral, should be equally averaged into the overall concern bin. This will follow the same binning schedule as the water concern binning does. As the United States is in the Medium national bin, the scoring is depicted in Table 6.16.

6.6.2 Energy Performance

Baseline Comparison

A normalized usage trend comparison is an important reflection of the efficiency of energy usage at the facility. Therefore, a comparison similar the one used for water performance is a component of energy performance. Specifically, the one-year trend in energy use normalized to some production factor will be used to determine the comparison performance bin:

High:	reduction in normalized energy usage by more than 5%
Medium:	constant normalized energy usage within 5%
Low:	increase in normalized energy usage by more than 5%

The reasons for selecting the one-year trend are the same as for water performance. Energy conservation is a hallmark of strong energy performance. However, it is not only the absolute amount of energy used, but also amount relative to facility activity, that is important. Using a normalized energy factor provides a means of taking variations in production into account.

Energy Source

Many industrial facilities do produce their own energy, often through use of boilers. Therefore, it is appropriate to evaluate such facilities based on the resource used to provide their energy. Energy sources are scored based on fuel type:

1 point: Coal and oil
2 points: Gas and nuclear
3 points: Hydroelectric and hydrocarbon-derived hydrogen
4 points: Non-hydroelectric renewables, including non-hydrocarbon derived hydrogen

The scores for the various fuels are multiplied by the relative proportion of that fuel from which facility energy is derived. This score is used to bin the energy source performance:

High: greater than or equal to 2.5
Medium: between 1.5 and 2.5
Low: less than 1.5

For example, a facility that uses one third coal, one third gas, and one third solar energy would be scored as follows:

$$(1/3)^*1 + (1/3)^*2 + (1/3)^*4 = 2.3$$

which corresponds to a Medium bin.

Many facilities do not produce any, much less all, of their own energy supplies. In that case, information about the region's energy fuels should be obtained, and the same scoring and binning procedures should be used based on the proportion of the various fuels consumed within the region. For the United States, this information is provided by the Energy Information Agency at http://www.eia.doe.gov/cneaf/electricity/st_profiles/toc.html.

For a facility that both produces and purchases energy, the larger source should be reflected in the score. For most facilities, this means the score is based on the region's energy generation. While this system refers back to conditions beyond the control of the facility, it is important to capture this impact from fuel type.

Technology

A facility with high energy performance should be one that it utilizing modern, perhaps advanced, technologies to reduce both energy use and impacts from fuel production. Therefore, energy technology performance is binned as follows:

High: Strong use of energy conservation and control technologies beyond compliance with state and federal regulations
Medium: Demonstrated use of conservation and control technologies
Low: No energy conservation or compliance with regulations

Without a list of standard technologies or programs, this metric does remain subjective, and can only be based on the information presented to the evaluator, which itself is limited and biased by the informant at the facility.

Table 6.17. Energy Performance binning

Trend-Source-Tech	Bin	Trend-Source-Tech	Bin	Trend-Source-Tech	Bin
HHH	H	MHH	H	LHH	H
HHM	H	MHM	M	LHM	M
HHL	M	MHL	M	LHL	M
HMH	H	MMH	M	LMH	M
HMM	M	MMM	M	LMM	M
HML	M	MML	M	LML	L
HLH	M	MLH	M	LLH	M
HLM	M	MLM	M	LLM	L
HLL	M	MLL	L	LLL	L

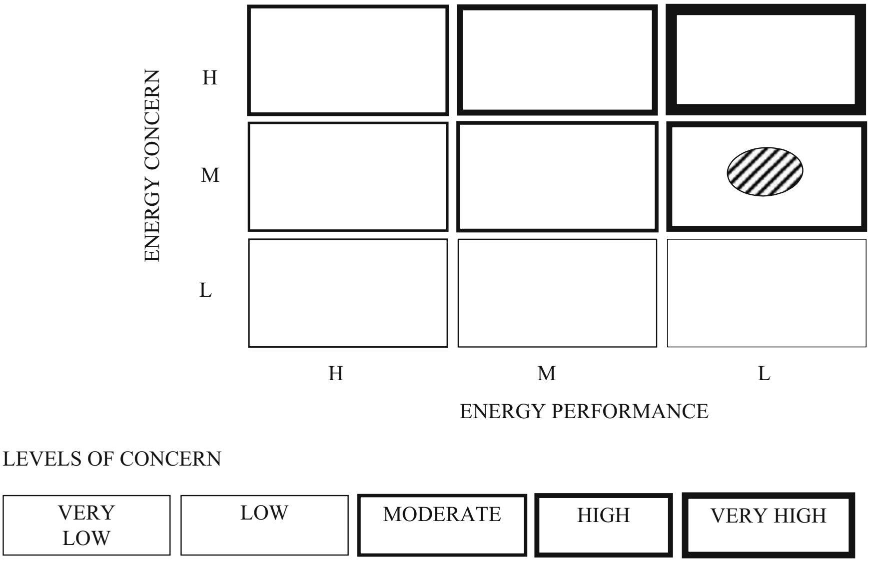

Figure 6.5. The performance-energy concern (PEC) matrix plot for a hypothetical energy-inefficient facility located in a region with moderate local energy supplies.

Binning

The energy performance will be scored in a manner analogous to the water performance. Table 6.17 shows the distribution of energy performance scores.

The performance-energy concern (PEC) matrix plot for a hypothetical energy-inefficient facility located in a region with moderate local energy supplies is shown in Figure 6.5.

6.7 MOVING THE SYMBOLS ON THE MATRIX PLOTS

A goal of our efforts in this book is, of course, to provide tools that can be used to thoroughly but efficiently assess environmental performance and get insights into potential environmental improvement. Improvement would be indicated, in part, by position changes in the symbols on the matrix displays, the normal goal being to move any symbol in the upper right region of the matrix toward the left and down. Let us recall the matrices pictured earlier in this chapter and examine the potential for improvement.

First, the situation with potential water scarcity, as shown in Figure 6.6(a). In theory, at least, one can imagine the water icon moving to the left on the matrix by implementing operating changes that decrease water use or otherwise improve water performance, such as changing from intensive water washing for the leaching of minerals to a bacterial process. Moving vertically on the matrix is not possible at the existing location, however, because the vertical location depends on local supply, not on details of the industrial process that uses the water.

Next, consider potential energy scarcity (Figure 6.6(b)). In theory, at least, one can imagine the energy icon moving to the left on the matrix by implementing operating changes that decrease energy use, such as changing to a more energy-efficient refining process. This can also be accomplished by changing to an energy supply with a longer depletion time, especially renewables. Moving vertically cannot be accomplished unless the facility is moved to a location with a lower energy concern.

Third, consider potential materials scarcity (Figure 6.6(c)). There are two different situations here. In the case of an extrinsic material like a process chemical, the associated symbol could move to the left on the matrix by increasing process efficiency for that chemical and thus decreasing throughput. If the chemical is an intrinsic material, however (such as the product itself), throughput cannot change, because the intrinsic material is the goal of the process. Moving vertically on the matrix is not possible for a given intrinsic material, because the potential scarcity of materials cannot be changed. In the case of an extrinsic material, however, the symbol could be replaced by one for another material that has a lower potential scarcity rating but similar process efficacy.

Finally, consider the situation with potential hazard (Figure 6.6 (d)). Again the intrinsic or extrinsic nature of the materials is of interest. Short of a replacement of one material by another, no vertical movement is possible in either case. If the chemical is an intrinsic material, throughput again cannot change, nor can hazard. In the case of an extrinsic material, however, symbol movement could be accomplished by the replacement of one material that has a lower potential hazard rating but similar efficacy, which would amount to vertical symbol movement, or by utilizing a more efficient but equally hazardous material, which would lower throughput, or by both strategies together.

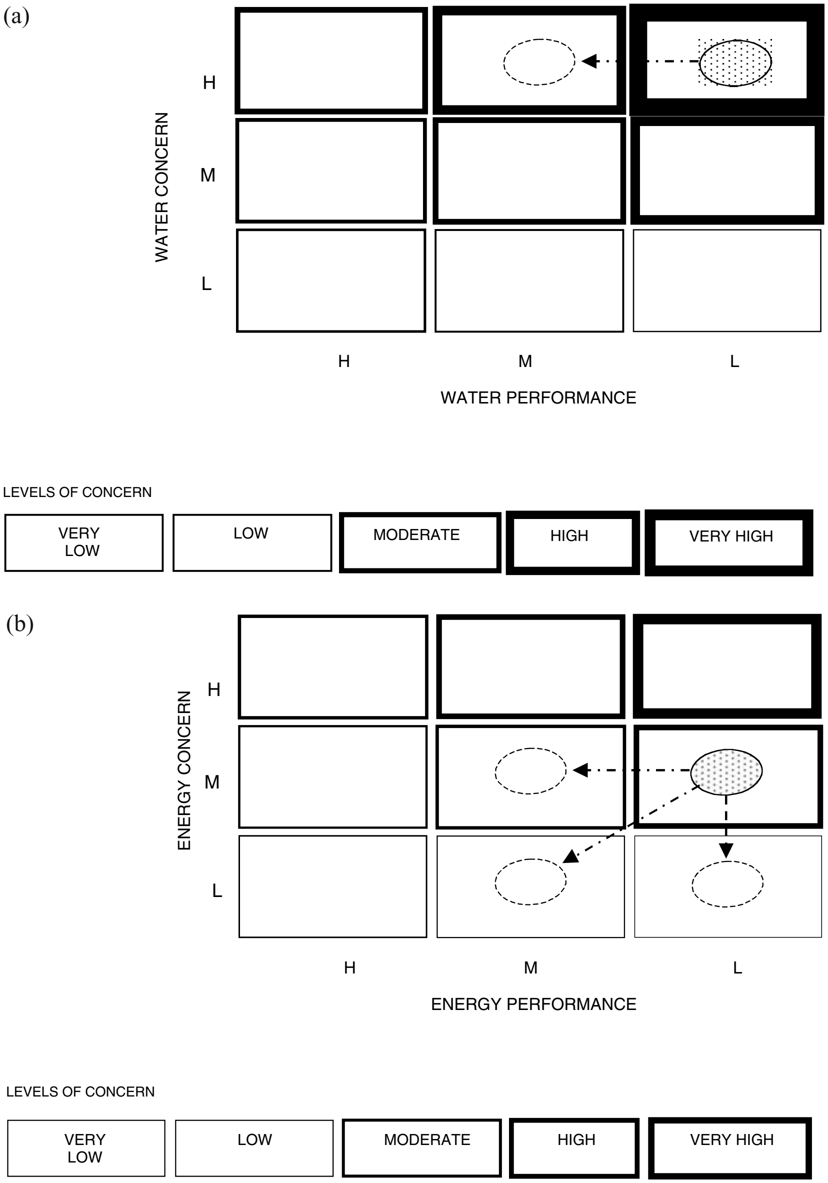

Figure 6.6. Paths of possible improvement in industry-environment interactions as seen on the matrix diagrams. (a) water; (b) energy; (c) scarcity, an intrinsic material being indicated by stippling, an extrinsic material by crosshatching; (d) hazard, notation as for part (c).

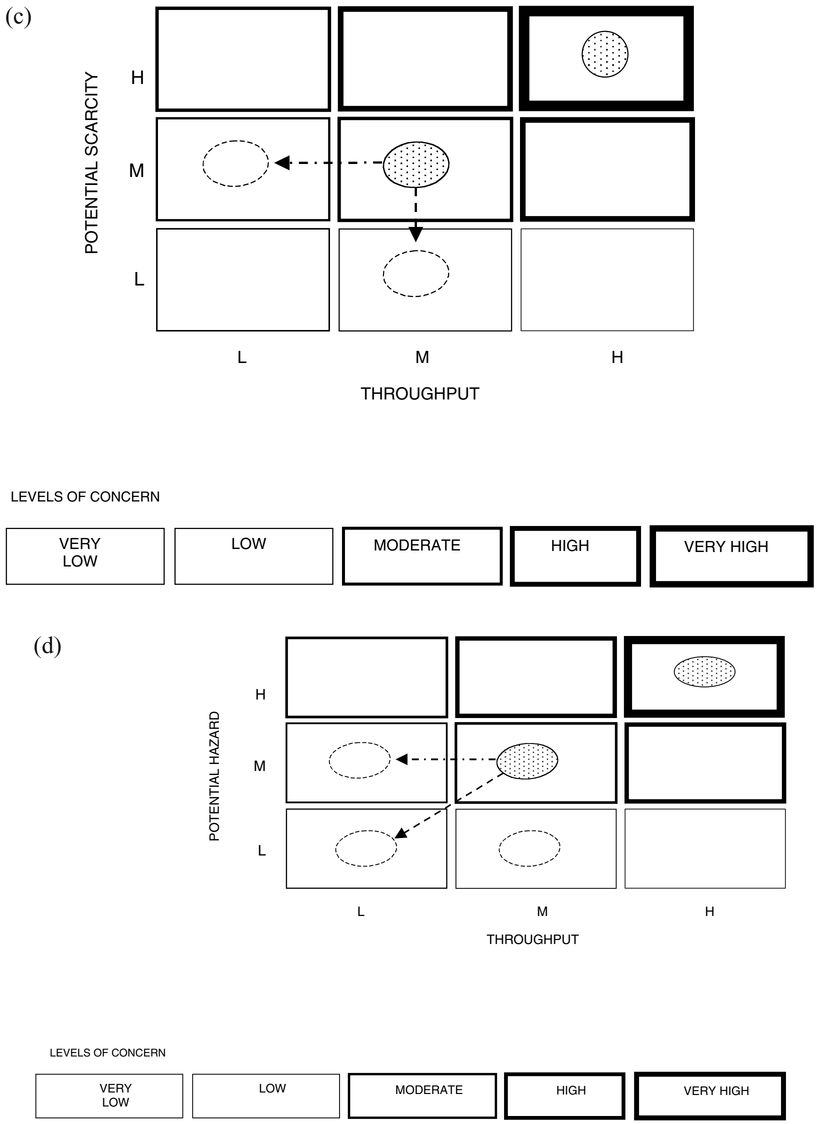

Figure 6.6. (Continued)

Note, therefore, that the matrix assessment techniques are ways to study the potential for environmental improvement by an entire industrial sector or by an individual corporation or facility. The approach and tools for accomplishing that improvement constitute part of the field of industrial ecology.

6.8 SUMMARY

Given a topic as complex as impacts on the environment, one in which both science and human values play complementary roles, and one in which all the desired information on impacts has yet to be acquired (especially in many local and regional situations), there is no completely satisfactory way in which to assess the environmental performance of industrial facilities, corporations, or sectors. This is particularly true when viewed from the perspective of sustainability. Even were there a perfect technique, requirements for efficiency and transparency would be difficult to achieve. In this chapter, a semi-qualitative approach to such challenges is presented. The matrix approach is easy to understand, easy for those who are not environmental professionals to use, efficient to complete, and presentation of the results readily communicates the information. Even with its imperfections, its use can move industrial facilities much closer to environmental superiority.

FURTHER READING

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Davis, G. A., M. Swanson, and S. Jones. *Comparative Evaluation of Chemical Ranking and Scoring Methodologies*, EPA Order No. 3N-3545-NAEX, University of Tennessee, April 7, 1994.

Graedel, T. E. *Streamlined Life-Cycle Assessment*, Upper Saddle River, NJ: Prentice Hall, 310 pp., 1998.

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Owens, J. W., Water resources in life-cycle impact assessment: Considerations in choosing category indicators, *Journal of Industrial Ecology, 5*(2), 37–54, 2001.

Appendix to Chapter 6
Using the Environmental Defense Scorecard Web Site

The assessment procedure outlined in this chapter uses the chemical evaluation procedure developed by the organization Environmental Defense. The detailed way in which this is done is as follows:

1. Develop a list of the principal chemicals entering and leaving a particular facility.
2. Go to the Scorecard web site: www.scorecard.org/chemical-profiles/
3. Insert the name of a chemical on your list (the name serves as a key word).

4. Select the precise chemical you wish to evaluate from the list that will result. This will produce a Chemical Profile.
5. On the Chemical Profile screen, scroll down to Hazard Rankings and click on the one line hazard description immediately beneath.
6. Several rankings will result; not all will appear for all chemicals. For potential human organism damage, select the midpoint of the more severe of Human Health Effects Score (UTN) or Human Health Risk Screening Score (WMPT).
7. For potential ecosystem organism damage, select the midpoint of the more severe of Ecological Effects Score (UTN) or Ecological Risk Screening Score (WMPT).
8. Repeat for the other chemicals on your list. If Scorecard has no data for one or more of the chemicals, note that fact in your evaluation. It may be possible for you to approximate a ranking based on chemical similarity; that too should be noted.

Chapter 7

Sustainability Assessments

7.1 THE ΣWESH PLOT

Imagine stacking the four assessment matrices developed in Chapter 6 so that we can visualize them as a unit. Were we to do so, we would have four matrices with a common resource utilization (throughput or resource performance) axis and second axis that relates to environmental concern. How might these be integrated? Consider an individual matrix element, and divide it into quarters. If either the energy or water symbols appear in that element in their parent matrix, they are plotted as shown in Figure 7.1. For scarcity and hazard, we enter names or symbols for all entries appearing on the parent matrices.

If a summary matrix made up of such elements is placed atop the other four matrices, we arrive at the display shown in Figure 7.2. It consists of the summary (Σ) matrix, the water (W) matrix, the energy (E) matrix, the scarcity (S) matrix, and the hazard (H) matrix, and is thus referred to as the ΣWESH plot (pronounced "swesh").

What insight is provided by the ΣWESH plot? An initial advantage is that it forces the analyst to consider all four potential impact areas—hazard, scarcity, water, energy—not just one or two. A second is that the summary matrix relates resource utilization to total environmental impact. In the example shown here, the high-throughput components of the process carry with them a number of impacts of high concern.

ΣWESH plots provide information to at least three constituencies. One is the environmental policy community, which gains perspective on the most important areas of environmental concern in each industrial sector, and thus on what policy instruments might be most valuable. A second constituency is industrial trade associations, which can consider their inherent environmental challenges and potential responses. For each of these constituencies, considerations and planning exercises can be applied at

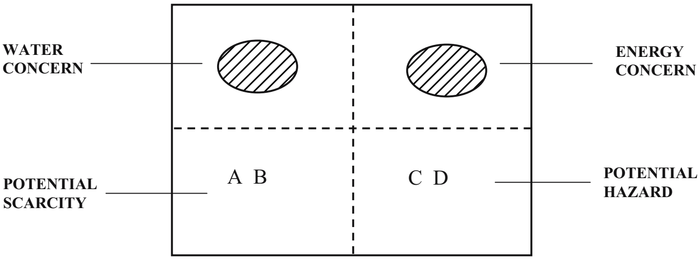

Figure 7.1. The design of a sustainability-related matrix element.

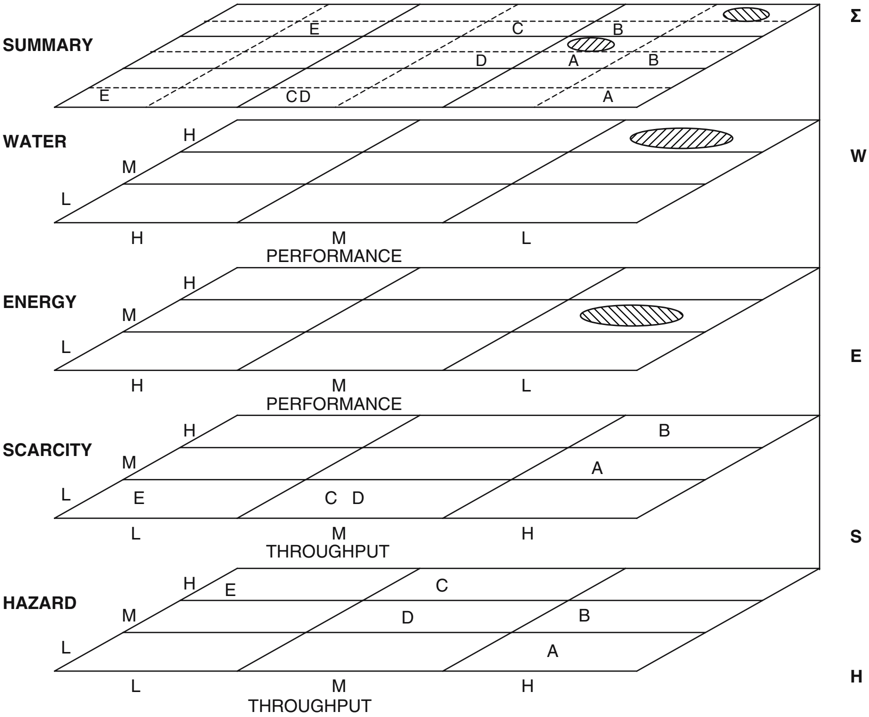

Figure 7.2. The ΣWESH plot for a hypothetical facility, drawing on figures from Chapter 6.

any of several spatial levels—regional, continental, or global—and over a variety of time periods from a few years into the future to decades hence. Perhaps the most important use of ΣWESH plots is their application to the third constituency: an individual facility. In a comprehensive way, the ΣWESH plot points out the areas where the greatest environmental improvement potential is located.

7.2 QUANTIFYING THE ΣWESH PLOT

The creation of a scoring system for the ΣWESH assessment has two principle benefits. First, the assessment can be used as a single-number index of environmental sustainability. Second, the assessment scores can be used for various comparisons, including cross-sectional analysis, time-series analysis, and management planning. This section describes the scoring method developed for the ΣWESH assessment. It also shows how the method is used to evaluate performance and as a basis for recommending improvements.

The scoring method for the ΣWESH assessment is based on a scale of 0 to 100. This approach has the strength of offering a simple, bounded scale that is similar to the familiar percent scale. The scored ΣWESH offers the advantage of comparison among different facilities as well as comparison of the same facilities prior to and following improvements. The drawback of this approach is that it suggests an absolute measurement of sustainability, whereas the ΣWESH assessment is actually a relative indicator of sustainability. That is, a facility scoring 100 points is not sustainable by some systematic accounting method. A high scoring facility simply meets the requirements of the ΣWESH assessment methodology for sustainability.

The four levels of the ΣWESH assessment are given equal weight and are worth 25 points each. The water and energy levels are scored in a similar manner. There are two alternative approaches. In the first, a score is assigned on the basis of the location of the water and energy symbols on the respective matrices. A facility has more control over its performance with respect to water and energy than it does over the regional concern for water and energy. Therefore, more scoring weight is assigned to facility performance than concern. High performance and low concern give a maximum of 25 points, while low performance and high concern give a minimum of 0 points. For a low concern level, medium performance receives 15 points and low performance receives 10 points. Increasing the level of concern for these performances subtracts 5 points for each level of concern. Figure 7.3 shows the points assigned for each bin.

In the second approach, a slightly more complex but probably a preferable indicator is arrived at. The six evaluations each for energy and water are assigned zero points for low sustainability, one point for medium sustainability, and two points for high sustainability. The point scores are then added, and the total converted to the 25-point scale by

$$\text{Score} = 25(\text{point total}/12)$$

The scarcity and hazard levels are also scored in a manner similar to the first of the alternatives for energy and water. Points are awarded for using materials of low concern and decreasing throughput for materials of higher concern. Each bin is given a weight shown in Figure 7.4. These weights are assigned to give the highest impact for materials of high concern and high throughput with decreasing weight for decreasing concern and throughput. No weight is given to materials of low concern because the best a facility can do is to use all materials of low concern.

		PERFORMANCE		
		H	M	L
CONCERN	H	15	5	0
	M	20	10	5
	L	25	15	10

***Figure** 7.3.* Scoring by bin for water and energy levels of the ΣWESH assessment.

		THROUGHPUT		
		L	M	H
CONCERN	H	2	3	4
	M	1	2	3
	L	0	0	0

***Figure** 7.4.* Weighting by bin for scarcity and hazard levels of the ΣWESH assessment.

Four calculations must be done to obtain the score for each of the scarcity and hazard levels:

1. Bin score = number of materials in bin × bin weight
2. Aggregate score = sum of all 9 bin scores

3. Maximum score = number of materials in all bins × 4
4. Level score = 25 × (1− (Aggregate score/Maximum score))

By inspection, the formula for the score of each level gives a maximum of 25 if all materials are of low concern, and a minimum score of 0 if all materials are of high concern and high throughput.

This method of scoring the scarcity and hazard levels of ΣWESH has the advantage of providing a continuous range of scores. It weights concern and throughput evenly as both aspects have equal potential to be changed at a facility.

Summing the scores for each of the four levels yields a score for the ΣWESH assessment in the range of 0 to 100. This score can be used as a single-number index for the environmental sustainability of a facility.

Individual facilities can be evaluated on the basis of their environmental sustainability performance. Techniques for doing so are presented in Appendix I, and an example facility report is given in Appendix J.

7.3 A ΣWESH PLOT EXAMPLE

As an example of ΣWESH analysis, we consider a hypothetical electronics manufacturing facility in an arid region of central China. The facility makes extensive use of water, and incorporates modest levels of water reuse and waste water treatment. Energy from the regional authority is from coal-fired power plants. Precipitation in the region averages 60 cm/year. The baseline water and energy performance of the facility is low.

Table 7.1 provides the ordinal analysis for the facility's use of water and energy. The information source for each evaluation are shown in the table. As was noted in Chapter 6, some of the items included in the evaluation are under the direct control of the facility, while others are under national control or relate to the supply of resources by nature.

A partial list of material inputs and outputs and their magnitudes for the facility is given in Table 7.2. Also indicated in the table are sources of information needed to perform the hazard evaluation. The results from the use of those sources is given in Table 7.3. Most of this will be self-explanatory, but the results for acetic acid should be pointed out. Acetic acid has two possible hazard bases: smog and human organism damage. Both were assessed, and the latter found to be the more severe, so that is the hazard ranking that was used.

The final evaluation is for materials scarcity, for which only the input materials from Table 7.2 are used. The resulting evaluations, drawn from Table 6.10, are given in Table 7.4. Note that the actual material evaluated is not necessarily the exact input material, since the material component of highest potential concern (e.g., the fluorine in hydrofluoric acid, but not the hydrogen) is the one addressed.

***Table** 7.1.* Energy and Water Use Evaluation for a Hypothetical Electronics Manufacturing Facility in Central China

Topic	Information Source	Evaluation
Energy:		
National energy vulnerability	Table 6.14	M
Regional energy concern	Regional data	M
Sectoral energy concern	Table 6.15	L
Baseline energy performance	Facility data	L
Energy source	Facility data	L
Energy technology	Facility information	M
Water:		
National water concern	Table 6.11	L
Regional water concern	Regional data	H
Sectoral water concern	Table 6.7	L
Baseline water performance	Facility data	L
Waste water treatment	Facility data	M
Water reuse	Facility data	M
Ordinal rankings (Tables 6.12, 6.13, 6.16, 6.17)		
Energy concern		M
Energy performance		L
Water concern		M
Water performance		M

***Table** 7.2.* Sources for Hazard Evaluation for a Hypothetical Electronics Manufacturing Facility in Central China

	Throughput*	Hazard Basis	Environmental Concern	Potential Input
Inputs (partial):				
Silicon wafers	86	None	NA	NA
Copper	5	Ecosystem	Table 6.2	Scorecard
Acetic acid	5	Smog	Table 6.2	Table 6.6
		Human	Table 6.2	Scorecard
Hydrofluoric acid	3	Human	Table 6.2	Scorecard
Phosphine	0.1	Human	Table 6.2	Scorecard
Outputs (partial):				
Electronic chips	0.8	None	NA	NA
Acid residues	8	Ecosystem	Table 6.2	Scorecard
Solid residues	91	Ecosystem	Table 6.2	Scorecard

*Percentage of total process line flows.

The ΣWESH plot that results from the composite evaluation is pictured in Figure 7.5. There are no entries in the upper right corner of the summary matrix, the most important area for immediate concern. However, the overall environmental record of the facility could benefit from increased attention to energy performance, water performance, and reduced use and increased recycling of acid residues.

Table 7.3. Hazard Evaluation for a Hypothetical Electronics Manufacturing Facility in Central China

	Throughput	Environmental Concern	Potential Input	Potential Hazard
Inputs (partial):				
Silicon Wafers	H	L	L	L
Copper	L	H	M	M
Acetic acid (smog)	L	M	M	M
(human organism)	L	H	H	H
Hydrofluoric acid	L	H	M	M
Phosphine	L	H	H	H
Outputs (partial):				
Electronic chips	M	L	L	L
Acid residues	H	H	M	M
Solid residues	H	H	L	L

Table 7.4. Scarcity Evaluation for a Hypothetical Electronics Manufacturing Facility in Central China

Input Material	Material Assessed	Scarcity
Silicon Wafers	Silicon	L
Copper	Copper	H
Acetic acid	Carbon	L
Hydrofluoric acid	Fluorine	M
Phosphine	Phosphorus	M

The numerical score for the facility's sustainability performance is calculated as discussed above. The results are:

Energy: $25 \times \{(1 + 1 + 0 + 0 + 0 + 1)/12\} = 6.3$
Water: $25 \times \{(0 + 2 + 0 + 0 + 1 + 1)/12\} = 8.3$
Hazard: $25 \times \{1 - ([1 \times 3 + 2 \times 1 + 2 \times 2 + 3 \times 0]/[8 \times 4])\} = 18.0$
Scarcity: $25 \times \{1 - ([2 \times 1 + 1 \times 2 + 2 \times 0]/[5 \times 4])\} = 20.0$
ΣWESH score $= 6.3 + 8.3 + 18.0 + 20.0 = 52.6$

7.4 THE SUSTAINABILITY ROADMAP

Sustainability scores are not necessarily static over the long term, even if no changes are made to a facility and its operations. Rather, it is realistic to anticipate that the score of an unchanging facility will decrease with time as new environmental challenges emerge or existing ones intensify. For example, some resources may become increasingly scarce (moving to different depletion time bins on Table 6.10), or shifts

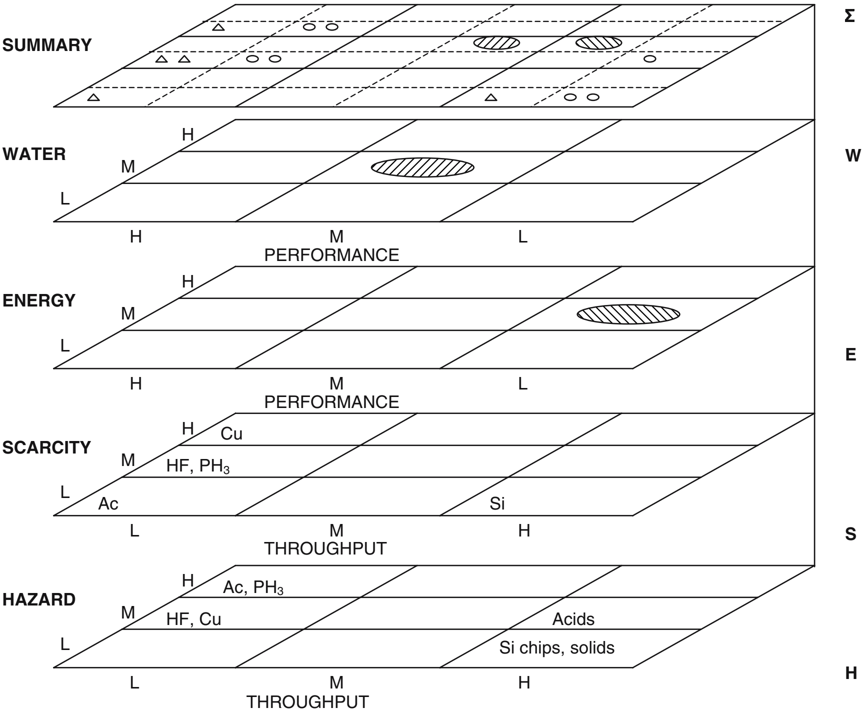

Figure *7.5.* The ΣWESH plot for a hypothetical electronics manufacturing facility in central China.

in climate may affect amounts of precipitation (the regional water concern metric). It is thus important to be proactive, and make plans for improving one's sustainability performance, not merely for standing still.

The sustainability journey begins at the starting point (the ΣWESH plot for the current situation), and ends (at least for planning purposes) at a ΣWESH plot as close to ideal as appears possible. Once such an assessment has been accomplished, the next step is to designate targets for each of the sustainability-related categories. This is most conveniently done from the perspective of the ΣWESH matrices themselves. As shown in Figure 7.6, the ideal result would be one in which

- Water performance was high
- Energy concern was low and energy performance high
- All materials used in facility processes, either intrinsic or extrinsic, were of low potential scarcity
- All material inputs and all non-product outputs were of low potential hazard.

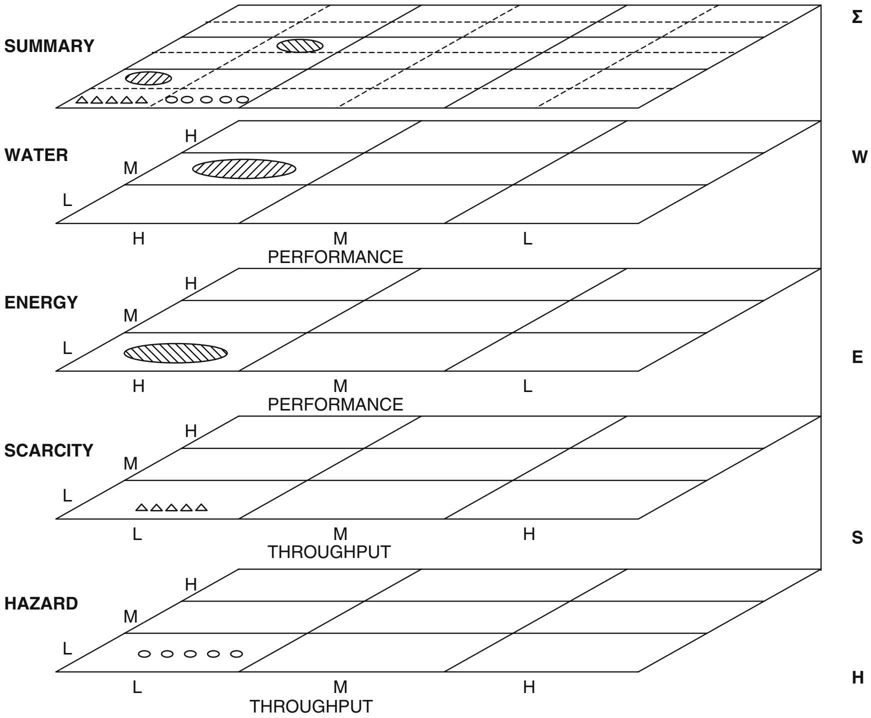

Figure 7.6. The ideal ΣWESH plot. The features on the plot are discussed in the text.

The target for water is two-faceted, being based on both supply and performance. The basic supply is not controllable by a manufacturing corporation, but by nature. Water concern is thus a fixed row of the matrix. Water performance is, however, a corporate function. The ideal target is a rate of consumption less than or equal to the sustainable allocation.

The ideal energy target is also two-faceted. Energy concern is determined on a country level, and is thus a fixed row of the matrix. The ideal energy performance involves minimal energy use and a transition to renewable sources, if made possible by the local energy infrastructure.

The target for the scarcity matrix is a simple one—to utilize only materials for which the potential scarcity is low. This is a technology-limited requirement. In many cases a transition to such materials will be difficult; in some cases there may be no known way to achieve the transition, at least given the technological knowledge of the day.

The hazard matrix target is similar to that of the scarcity matrix—materials should appear only in the low potential hazard row. In the case of inputs, this is a technologically-limited requirement. For outputs, a transition to zero emissions eliminates them from consideration.

The sustainability roadmap specifies the route from start to finish. It includes rates of speed, barriers to progress, and periodic reviews and updates. In actuality, the roadmap applies to several simultaneous journeys—one for water, one for energy, several for transitions related to individual materials. Although each of the four matrices has the same potential score, it should be recognized that scoring improvement should not be followed slavishly. For example, a facility using very little water should not devote a large amount of effort to improving its water score, but address changes that will have maximum environmental improvement. Overall, the roadmap is a recipe for achieving ultimate corporate environmental superiority.

7.4.1 Barrier Identification

A common situation is the use of a material in a product or process for which no substitute appears to be available, and where the material is scarce or hazardous or both. In some cases the barrier is real, with contemporary technology indeed providing no alternative. In others, the availability of an alternative may require enhanced engineering investments. Sometimes a good alternative exists, but at an unfavorable price. It is important to distinguish these cases for all materials of interest. True barriers cannot be the subject of transition planning, though their existence should be reconfirmed periodically. For apparent barriers, however, efforts can be made to invest in research, perhaps cooperatively with others, to attempt to provide a detour around the barrier.

7.4.2 The Transition Function

A transition function is a mathematical description of the chosen transition path from the starting point to the ending point. The simplest is the linear function of Figure 7.7a. In cases where this function is adopted, the corporation plans to make a uniform transition over the chosen time span. In the absence of strong reasons to adopt another type of function, a linear approach to transition is a good choice. It has the virtues of requiring at least a modest commitment right from the start, and is easily understood and monitored.

A convex transition function (Figure 7.7b) is generally a poor choice, since it promises little effort over the short term—it avoids seriously addressing the problem. In some cases, as where a technological alternative is anticipated but the time scale is uncertain, such a functional choice may be necessary, but it is to be avoided unless absolutely necessary.

A concave transition function (Figure 7.7c) is a laudable choice if it can be made. It promises a transition that will be rapid, and a commitment that will be substantial and immediate. Roadmaps to sustainability should include as many concave transition functions as possible.

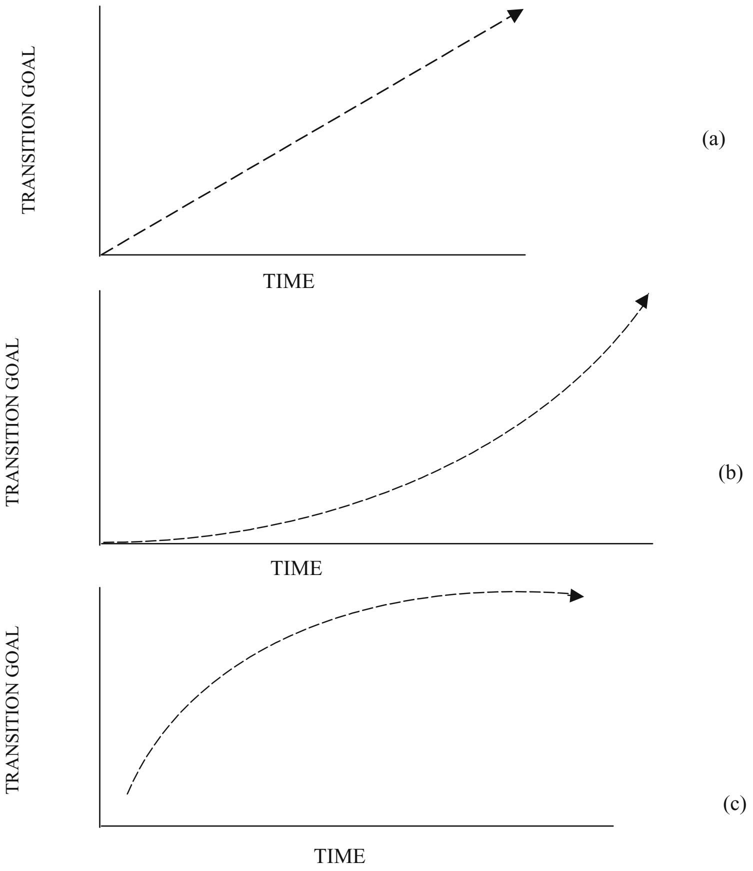

***Figure* 7.7.** Types of transition functions. (a) linear, (b) convex, (c) concave.

Transition functions are not limited to the types shown in Figure 7.7, but in practice there is seldom information to prescribe more complex functions. Whatever the function, its choice requires corporate decision-making from a long-term perspective, and provides a plan where performance can readily be monitored over time.

7.4.3 Periodic Updates to the Roadmap

A sustainability roadmap must be a dynamic planning tool, not a static one. The reason for this is that many of the factors that go into the roadmap have the potential to change over time—barriers are unexpectedly eliminated by technological advances, new regulations or taxes encourage some approaches and discourage others, the available energy source mix changes, and so forth. An astute corporation will therefore review and update its sustainability roadmap at regular intervals. Five years is probably the maximum interval for reviews; two years is much better.

7.5 THE ABSOLUTE NATURE OF SUSTAINABILITY

A crucially important property of *sustainability* is that the concept is an absolute, as are *pregnant* and *unique*, to use two common examples. A sustainable world is not one that is slightly more environmentally responsible than it was yesterday. Rather, in John Ehrenfeld's words, it is a world that assures that all who live today and in the future will be able to satisfy their needs and human aspirations. The imperative is clear. Our implementation of it is necessarily less clear, because we have imperfect knowledge of the world, its functioning, its resources, our technological prospects, and ourselves. In the past several chapters, however, we have described a series of analytical approaches and actions by which firms can operate in an increasingly sustainable manner. They will never be perfect at doing so, but much will be gained by the attempts.

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Part III

Industrial Sector Analysis

Chapter 8

Fossil Fuel Extraction and Processing

8.1 OVERVIEW

Fossil fuels (coal, petroleum, natural gas) are formed, as their name suggests, from the decay and alteration of deeply buried organic matter, mostly woody plants. These processes occur over millions of years, so Earth's fossil fuel resources are, for all practical purposes, nonrenewable.

On the industrial sequence diagram, Fig. 8.1, the extraction of fossil fuels occurs at the earliest stage after resource generation itself. Coal and natural gas are used almost entirely for the production of electrical power, as described in Chapter 9. Petroleum is also dominantly used for the generation of electrical or motive power, but about 3% of its annual flow is used as starting material ("feedstock") for a very wide variety of petrochemicals, as described in Chapter 12.

The use of fossil fuels dominates humanity's energy budget. As seen in Table 8.1, petroleum is the largest current energy source. In 1990 it accounted for 33% of the world's primary energy consumption. (*Primary energy* is the energy embodied in resources as they exist in nature; it is not possible for a variety of technical and thermodynamic reasons to recover all of it.) Extracted coal and natural gas contributed 24% and 18% of the global total, respectively. Biomass, mostly used locally for heating and cooling, generated about 15% of the total. Nuclear power and hydropower accounted for about 5% each.

The table shows that *final energy* (the energy actually supplied to the point of final use) was slightly less than three-fourths of the primary energy in the extracted fuels ($^{279}/_{385}$). Of the final energy amount, nearly a third ($^{86}/_{279}$) was used industrially. It is this 86 EJ/yr that represent the total energy consumption discussed in the subsequent chapters of this book.

***Table* 8.1.** Global Energy Consumption in 1990 by Energy Source and by Sector, in EJ/yr*

	Coal	Oil	Gas	Nuclear	Hydro	Electricity	Heat	Biomass	Total
Primary	91	128	71	19	21	–	–	55	385
Final	36	106	41	–	–	35	8	53	279
Industry	25	15	22	–	–	17	4	3	86
Transport	1	59	0	–	–	1	0	0	61
Others	10	18	18	–	–	17	4	50	117
Feedstocks	0	14	1	–	–	–	–	0	15

* *Data Source*: N. Nakicenovic et al., Energy primer, in *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change*, R. T. Watson, M. C. Zinyowera, and R. H. Moss, Eds., pp. 75–92, Cambridge, UK: Cambridge University Press, 1996.

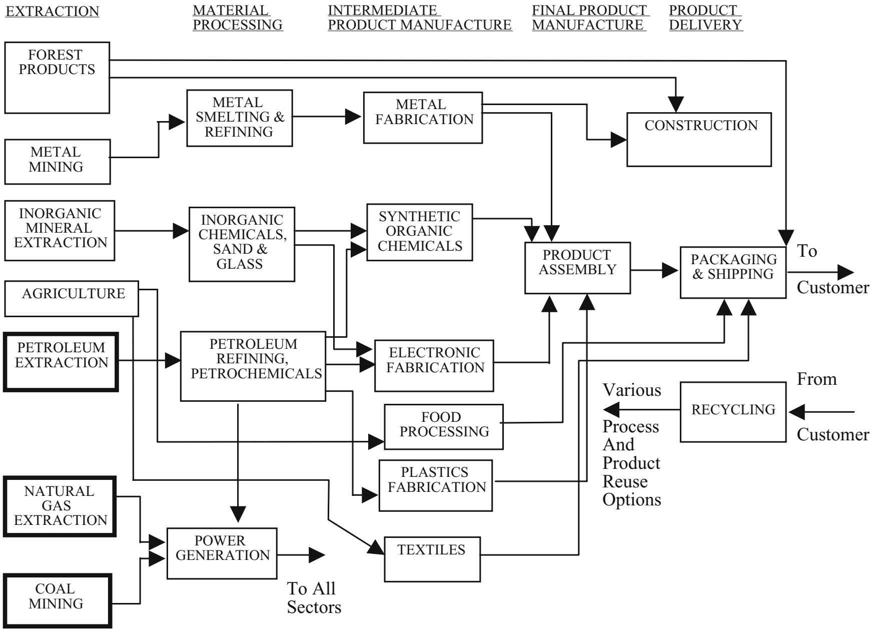

Figure 8.1. The technological sequence diagram for the fossil fuels sector. The industry sector itself is indicated by heavy outlining.

8.2 PHYSICAL AND CHEMICAL OPERATIONS

8.2.1 Coal

Historically, coal has been extracted by underground mining, in which shafts are drilled into the coal deposit, passages are opened off the shafts, the coal is explosively extracted from the seams in which it occurs, and the resulting fragments brought to the surface by mine railroads or hoists. Some coal is still extracted in this way, but most is now acquired by *open-pit mining* (*strip mining*) in which the rock, soil, and vegetation overlying the coal deposit are removed. The coal is then recovered by drilling, blasting, or cutting into it with specially designed mining equipment. In either mining technique, the coal fragments that come out of the mine are further broken down into suitable-sized lumps by comminution (crushing and grinding processes).

The quantities of coal required by the global power industry to generate the energy shown in Table 8.1 is very large—some 5.2 Pg in 1996. In the U.S., coal accounts for about 40% of the monetary value of all mined materials (metal ores accounting for another 40%, minerals and aggregate for the remaining 20%).

8.2.2 Petroleum

8.2.2.1 Extraction

The petroleum extraction process begins with the drilling and development of a well into an underground or undersea petroleum reservoir. The petroleum is removed to the surface by pumping, injection of fluids into surrounding reservoirs to force the petroleum into the well, or by other means. The petroleum that is recovered (also called *crude oil*) may be pumped directly to a nearby refinery or it may be transported by pipeline or seagoing tanker to a distant refinery. Petroleum transport is a major industry in its own right. Pipelines as large as 125 cm in diameter move most petroleum that is refined on the same continent where it is extracted. Petroleum refined on other continents is transported by ocean tanker—some 9 billion barrels per year in 1995.

8.2.2.2 Refining

United States refineries are capable of processing more than 15 million barrels of crude oil per day. At the refinery, the crude oil is heated and then distilled into a number of components, including fuel products (87 percent), non-fuel products (5 percent), and petrochemical feedstocks (3 percent). Fuel products mainly consist of motor gasoline, distillate fuel oil (diesel fuel, heating oil, and industrial oil), jet fuels, fuel coke, kerosene, liquefied petroleum gases (i.e., propane), and refinery fuels. Non-fuel products include asphalt, road oil, bitumen, lubricants, and waxes. Petrochemical feedstocks include many different types of chemicals, including ethane, benzene, and xylene to name just a few. These products of the refining activity are shipped for distribution to the transportation system (gasoline, diesel fuel), the power generation sector (heavier fuels), and the highway infrastructure-manufacturing sector (bitumen).

8.2.3 Natural Gas

Natural gas is generated by the same type of organic matter decay that produces petroleum, and is often found as a volume of gas trapped between a subterranean pool of liquid petroleum and an impervious capping rock layer. The gas and oil are then extracted as part of a common oil and gas field development process. Alternatively, gas can occur relatively independently of oil, and its recovery and transport can then be approached independently. In either case, recovered gas is piped to liquefaction plants, and the gas transported by pipelines or ocean tankers and distributed in liquid form.

Methane (CH_4) constitutes roughly 85% of a typical natural gas. Larger molecules such as ethane (C_2H_6) and propane (C_3H_8) contribute of order 10% and 3%, respectively, a variety of other hydrocarbon gases constituting the remainder. In some gas fields, substantial amounts of carbon dioxide or helium are present and must be dealt with separately. (Natural gas is the only commercial source of helium, a rare gas used for specialized industrial application.)

8.3 THE SECTOR'S USE OF RESOURCES

8.3.1 Energy

Fossil fuels are extracted because of their energy content, but it takes a significant amount of energy to achieve that extraction. Petroleum and coal production consumed more energy than any other U.S. sector in 1985. Today, the refining industry remains the largest single industrial user, consuming over 20 percent of all manufacturing energy.

The extraction and refining industries are actively seeking to reduce energy consumption by improving efficiency. However, the nature of the processes is such that they are almost unavoidably energy intensive. Furthermore, as fuel comes from increasingly hard to reach areas, energy consumed during the extraction process will only increase. Additionally, as lower quality sources are tapped, refining will become more energy intensive with the emergence of such fuel sources as heavy crude, tar sands, and shale oils.

8.3.2 Materials

Globally, fossil fuels are being consumed at extremely high rates. The stability of supplies in the long term is a hotly debated topic, with many factions presenting different scenarios. A generally accepted approximate order-of-magnitude perspective is provided by calculating for each resource the depletion time, as discussed in Chapter 6. The results are given in Table 8.2; they show that the supply of coal appears ample for several centuries, but that supplies of petroleum and natural gas may be growing short by the middle of the century.

It is true, as is often pointed out, that the stated reserves of oil and gas are probably underestimated, but it is also true that global consumption of energy continues to rise,

***Table* 8.2.** Worldwide Fossil Fuel Use and Reserves*

Fuel	Consumption	Reserves	Depletion Time (yr)
Coal	4.8 Pg	1.0 Eg	204
Oil	2.8×10^{10} barrels	1.05×10^{12} barrels	41
Natural gas	2.5×10^{12} cubic meters	1.6×10^{14} cubic meters	61

**Data Source*: *BP Statistical Review of World Energy*, www.bp.com/centers/energy/downloads/index.asp, accessed August 15, 2003.

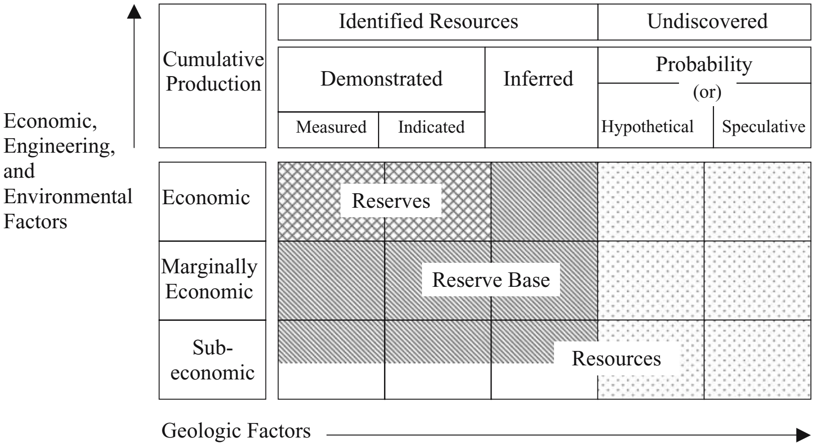

Figure 8.2. The McKelvey box. The model charts economic feasibility and geologic assurance of extractable resources. (Reprinted from McKelvey, V. E., 1967, Mineral resource estimates and public policy, *American Scientist, 60*, 32–40.)

and the increase is mostly at the expense of petroleum and gas. Furthermore, much of the readily extracted fraction of the fuels has been or soon will be recovered. Strong arguments have been made that petroleum production is likely to peak around the year 2010 and decline thereafter, with resulting shortages and price increases.

One tool that can be used to understand the relationship between resources and reserves is the McKelvey box (Figure 8.2). This plots geological assurance of a resource against economic feasibility. The reserve base is defined as concentrations of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such forms that economic extraction is potentially feasible. The geologic dimension is divided into identified and undiscovered resources. Reserves are identified resources that are presently economically recoverable. Undiscovered resources are quantities expected to exist under analogous geologic conditions. The boundaries between reserves, resources, and occurrences are defined by current or expected profitability of exploitation.

Technologic improvements are continuously pushing resources into the reserve category by advancing knowledge and lowering extraction costs. On the economic feasibility axis, "other occurrences" are not considered to have immediate economic potential, but over the long term, technological progress may upgrade significant portions to resources.

Today, only about 35 percent of the oil in place is recovered by conventional production methods. With enhanced recovery methods, this rate could be increased to as much as 65 percent of the original oil in place in a reservoir, although the additional oil would be obtained at higher extraction costs. The use of enhanced recovery methods for fossil fuel reserves in abandoned fields and new developments could thus increase conventional resource supplies, moving them into the resources section of the McKelvey box.

The material flows in the fossil fuels industry can be simply categorized. In the case of coal, about 5% is used for coking (i.e., to produce coke, an essential ingredient in the manufacture of steel [see Chapter 10]); the rest is consumed in the generation of electric power, producing large amounts of carbon dioxide. Natural gas requires little processing; it is extracted, transmitted, and mostly burned for energy. The crude oil sequence is more complex. Refining the crude oil consumes some 7% of the oil itself. The resulting products are almost entirely used for transportation and heating, both of which are combustion applications.

8.4 POTENTIAL ENVIRONMENTAL CONCERNS

8.4.1 Solids

Most coal is extracted by open-pit mining, in which the *overburden* (the material atop the coal) is displaced, the coal removed, and the overburden replaced. The same treatment is accorded pyrite (FeS_2) and other common impurities in the coal. Since material has been removed from the ground, the resulting landform is typically shallower than it was originally, but the solid residues can, in principle, be completely redeposited in approximately their original locations. Residues from underground mining are treated similarly.

Petroleum and natural gas drilling produces very little solid byproducts, and are of little concern in this regard.

8.4.2 Liquids

A major potential problem at coal mines containing substantial amounts of pyrite impurities is acid mine drainage resulting from the chemical reaction of precipitation on pyrite. (We discuss this topic in more detail in Chapter 10.) Pyrite is also a problem when coal is combusted, since the resulting gas is the acid rain precursor

Text Box 8.1

The Threat of Toxic Chemical Releases from Refineries

The seven most common Toxic Release Inventory (TRI) chemicals released by refineries in 1996 were ammonia, methanol, toluene, total xylenes, propylene, methyl ethyl ketone, and methyl-tert-butyl ether (MTBE). MTBE is an additive that was originally mixed with gasoline to improve fuel efficiency of cars. The compound was recently deemed highly carcinogenic, and is currently being phased out of the refining process in California and many other states. Unfortunately, MTBE is also highly soluble, and when released to ground water, has the potential to spread very large distances in short time periods, posing a significant threat to drinking water sources.

sulfur dioxide (SO_2). To reduce the sulfur content of coal, washing and leaching with various chemicals is common. The result, of course, is sulfate-containing wash water that requires proper disposal in order to avoid acid-related environmental impacts.

In oil extraction, water often is pumped to the surface along with the oil. There it must be separated, treated, and pumped back down into a deep formation. Any that is lost in the process has the potential to degrade local water supplies. In the case of petroleum, spills and leakages have historically had significant ecosystem impacts where they have occurred, but vigorous preventive actions have significantly reduced the rate of such accidents. Nonetheless, the risk of spills remains high, and can have irreparable ecosystem consequences.

Petroleum refining produces 180 million tons of waste annually, and has the highest pollution abatement costs as percent of sales (nearly 4 percent) of almost any major industry. In 1995, 8 percent of on-sight releases were to water, 5 percent to on-site underground injection, and 4 percent to off-site release. Due to the highly toxic nature of many of the chemicals released by refineries, and the extremely expensive ground water contamination investigations and treatments, pollution prevention has become a priority of the refinery industry.

8.4.3 Gases

A significant potential concern associated with petroleum refining is the release of gaseous residues. Roughly eighty percent of petroleum refinery releases are to the air. Refineries are designed to manufacture a small number of highly useful products, but, as Figure 8.3 illustrates, a number of byproducts inevitably occur. These may be generated at flows of one ten-thousandth or less of the principal product flows, yet are smog-formers and often toxic. They require that refineries practice close control of even very minor residue streams.

Table 8.3. Sources of Methane*

Energy industry	110 Tg/yr
All anthropogenic sources	330 Tg/yr
Natural and anthropogenic sources	576 Tg/yr

*J. T. Houghton, et al., Eds., *Climate Change 2001: The Scientific Basis*, Cambridge, UK: Cambridge University Press, p. 250, 2001.

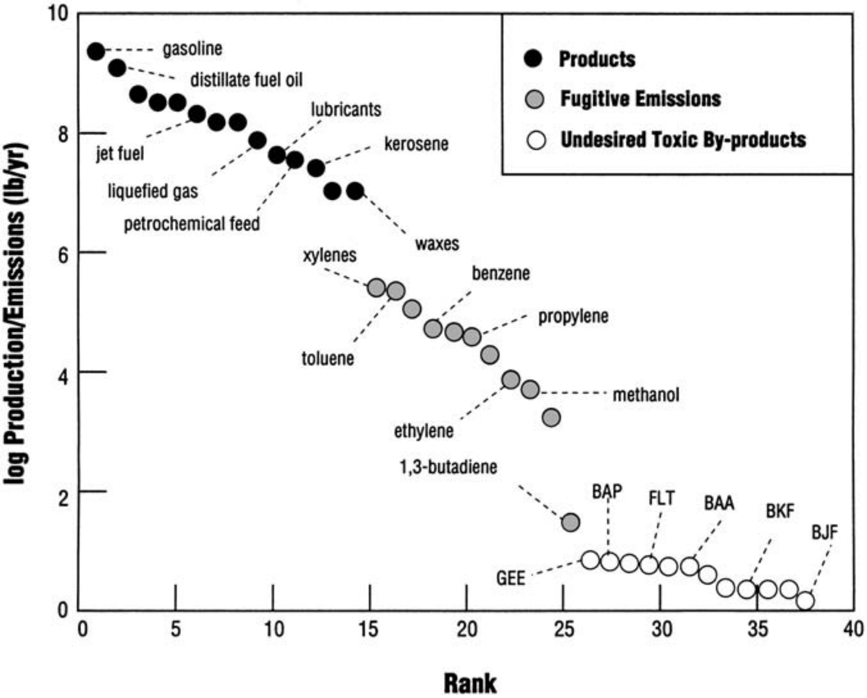

Figure 8.3. The typical spectrum of products from a modern petroleum refinery. (*Source:* S. K. Friedlander, The two faces of technology: Changing perspectives in design for environment, pp. 217–227 in *The Greening of Industrial Ecosystems*, B. R. Allenby and D. J. Richards, Eds. Copyright 1994 by National Academy Press, Washington, D.C.)

A specific concern of the fossil fuel sector relates to the escape of methane, a greenhouse gas, as part of extraction, processing, and distribution operations. In the case of coal, the methane exists as a gas in coal seams and is liberated (unless captured) as the coal is mined. In the extraction and transport of natural gas from gas and gas-petroleum deposits, the volatile methane has a propensity to escape as well. As shown in Table 8.3, these emissions represent approximately 20% of the global total methane sources, and about a third of anthropogenic methane sources.

Text Box 8.2

Capturing and Sequestering CO_2 During Natural Gas Extraction

Statoil, Norway's national oil and gas company, extracts natural gas from the Sleipner gas field below the North Sea between Norway and Scotland. Unlike much of the world's natural gas, which contains small amounts of carbon dioxide, the North Sea gas contains about 9% CO_2. Because CO_2 is one of the principal global warming gases, Statoil has begun to capture the CO_2.

In the process developed for the Sleipner field, the CO_2 is selectively absorbed by a mixture of amines in 20m absorption towers. It is then separated from the amine in a regeneration facility. The extracted CO_2 is compressed and injected into a water-filled sandstone reservoir 100m below the sea bed, where it is expected to remain indefinitely. In addition to pumping more than one million metric tons of CO_2 below the ocean floor each year instead of releasing it to the atmosphere, the Sleipner project will serve as a test bed for other large fossil fuel and power facilities that may wish to adopt similar CO_2 capture and storage strategies.

Two other gases that occur in varying amounts in petroleum and natural gas are carbon dioxide (CO_2) and hydrogen sulfide (H_2S). Both are abundant, so scarcity is not an issue, but both are environmentally problematic. Carbon dioxide contributes to climate change and hydrogen sulfide, the "rotten egg" gas, has a high inhalation toxicity. In most contemporary extraction operations, H_2S is captured and the sulfur marketed, while CO_2 is allowed to escape.

8.4.4 Habitat Disruption and Destruction

Fossil fuel extraction has the potential for major impacts on natural habitats. Strip mining of coal totally destroys the local habitat, of course, and it is generally difficult to recreate a habitat after the completion of mining. In the case of oil and gas extraction, much of the drilling and refining activity occurs in sensitive environments—wetlands, coastal regions, and the like. In such environments it is vital to minimize the footprint of any facilities that are developed, as well as the emissions from those facilities.

8.4.5 Sustainability Assessment

The Process, Activities, and Potential Emittants table for the fossil fuels sector appears as Table 8.4. The materials involved in the sector are analyzed in Table 8.5 on a low-medium-high basis both for the magnitude of their throughput and their hazard potential. The results are plotted as a TPH matrix in Figure 8.4.

Table 8.4. Processes, Activities, and Potential Emittants for the Fossil Fuel Extraction and Processing Sector

Process Type	Sector Activities	Potential Emittants
Extraction	Mining, drilling	CH_4
Beneficiation	Crushing, grinding	Dust particles
Cleaving bonds	Petroleum refining	VOCs
Transportation	Petroleum shipping	Oil spills

Table 8.5. Throughput-Hazard-Scarcity Binning of Materials in the Fossil Fuel Extraction and Processing Sector

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
Coal	H	–	L	L
Petroleum	H	–	L	M
Natural gas	H	–	L	M
Overburden	H	Habitat	M	–
Methane	M	Climate	M	–
Carbon dioxide	M	Climate	H	–
Hydrogen sulfide	L	Human	H	–
Refinery byproducts	L	Human	H	–

As the figure demonstrates, there is a high degree of concern related to several byproducts of the extraction and transport of petroleum, coal, and natural gas. Moderate concern is registered for methane, a greenhouse gas, and for overburden, because of its significant disruption of habitat. To the degree that hazardous gases are captured the concerns are allayed, but in the absence of good extraction or processing controls some concerns are warranted. Overburden generated by the strip-mining operations also has a high potential for acid drainage if not carefully controlled.

Scarcity concerns are listed in Table 8.5 and plotted in the TPS matrix on Figure 8.4. There are mid-level concerns for both oil and natural gas, because they have depletion times of around half a century. Unlike the resources being extracted and processed by the fossil fuels sector, byproducts such as methane and refinery gases are not evaluated from a scarcity standpoint, since they are not "mined."

Recall from Chapter 2 that the fossil fuel sector was a large user of energy and a moderate user of water when compared with other sectors. From a sectoral standpoint, therefore, the PWC and PEC matrices can be prepared as shown in Figure 8.5, where the appropriate concern row has been stippled. Water performance and energy performance are characteristics of individual facilities, not of sectors, so they cannot be assessed on a sectoral basis. In the case of facilities, energy concern and water concern relate to local *supplies*. For sectors, the rankings refer to sectoral *use*.

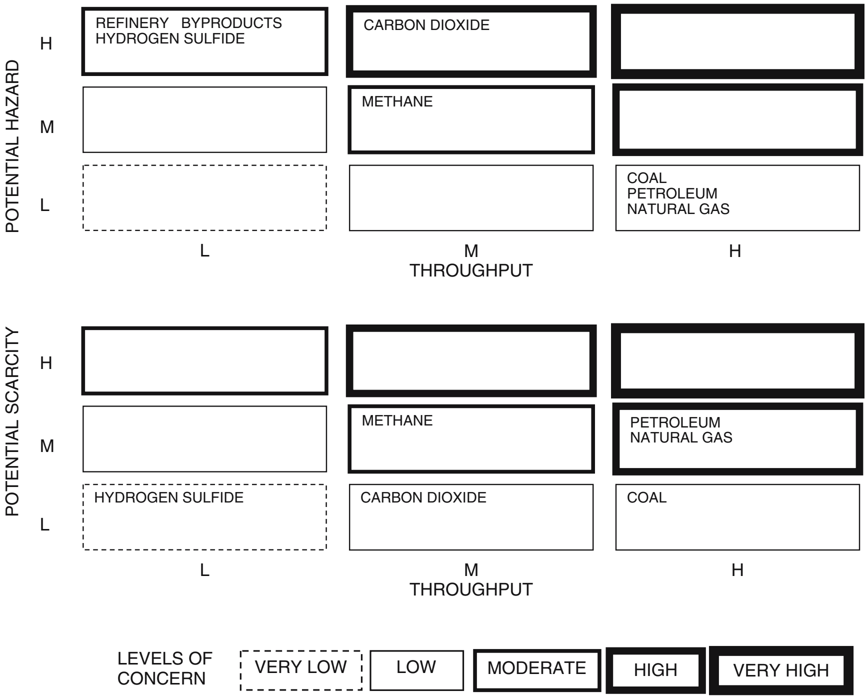

Figure 8.4. The throughput-potential hazard matrix (top panel) and the throughput-potential scarcity matrix (bottom panel) for the fossil fuels sector.

In Figure 8.6, the four matrices are used to construct a sectoral ΣWESH plot. Overall, there are no "very high" concerns. A number of "high" concern areas exist, however: energy and water use, CO_2 emission, overburden generation, and petroleum and natural gas scarcity. Actions to move any of these to lower concern levels would improve the environmental performance of the fossil fuel sector.

8.5 SECTOR PROSPECTS

8.5.1 Trends

Trends for the fossil fuel sector have been divided into extraction trends and refining trends, reflecting the two main industries within this sector. Regulation and societal trends significant to this sector are then discussed.

8.5.1.1 Extraction Trends

As reserves of fossil fuels in their current forms decline, petroleum companies are looking to produce fuel from unconventional resources. Vast amounts of

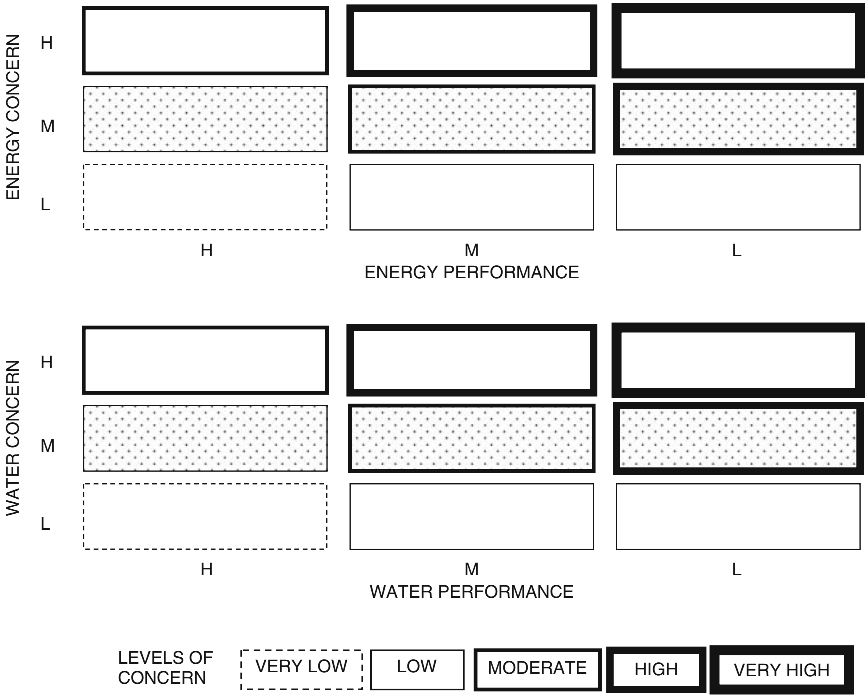

Figure 8.5. The performance-energy concern matrix (top panel) and performance-water concern matrix (bottom panel) for the fossil fuels sector.

unconventional oil occur as oil shale, heavy crude oil, and tar sands. Oil shale is a sedimentary rock rich in organic matter, and can be used directly as a fuel in power plants or processed to produce synthetic petroleum products. Heavy crude oil is a high-viscosity crude oil that is formed by the degradation of conventional oil in shallow reserves. Currently, about 8 percent of world oil production comes from heavy crude oil. Tar sands are sands or sandstones that contain a large portion of tarry hydrocarbons with a very high viscosity. Extracting tar sands requires unconventional methods such as mining with bucket-wheel excavators or in truck and shovel operations.

Unconventional natural gas exists as coalbed methane, tight formation gas, and gas hydrates. Coalbed methane occurs primarily in high-rank coal seams from where it can migrate into the surrounding rock strata. This can be a byproduct of coal mining, or a coal deposit can be tapped for methane exclusively. Tight formation gas is a natural gas trapped in low-permeability bedrock, and requires massive hydraulic fracturing to extract. Gas hydrates are frozen ice-like deposits that probably cover a significant portion of the ocean floor. This could potentially be an enormous source of methane, but many questions currently exist as to the technical and economic feasibility of tapping these resources.

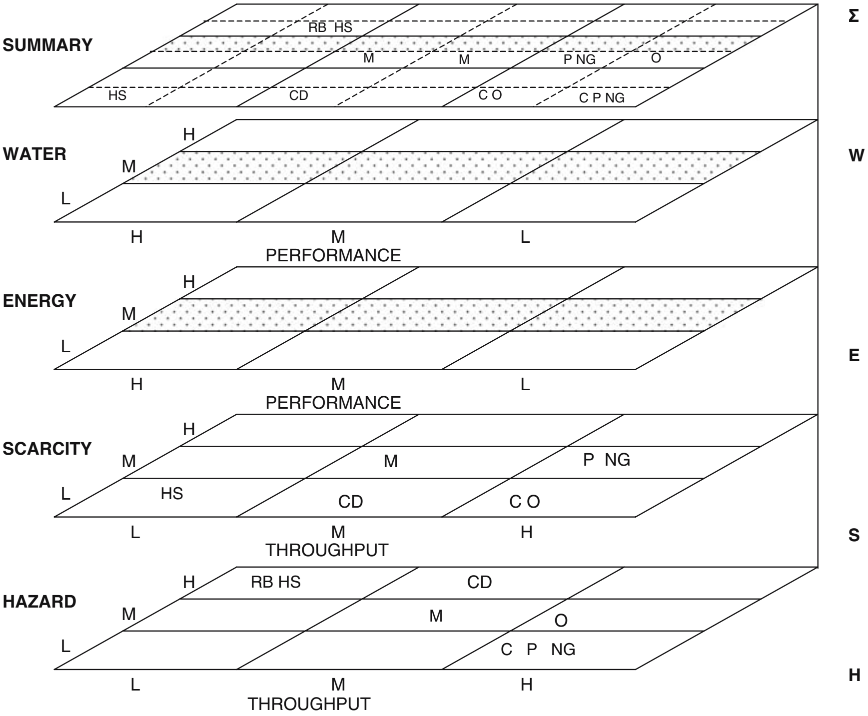

Figure 8.6. The ΣWESH plot for the fossil fuels sector. Abbreviations refer to the materials in Figure 8.4.

Due to the huge resources of coal throughout the world, and the relatively cheap extraction methods, unconventional coal sources have not been researched thoroughly. Despite the benefits that expanded resources provide, there are paramount environmental risks associated with these potential reserves as illustrated in Text Box 8.3.

Extraction technologies for conventional fossil fuels are rapidly shifting towards methods that attempt to preserve environmental integrity. Both energy savings and water pollution decreases are provided by downhole separation of oil and water, i.e., separating the liquids at the bottom of the well, re-injecting the water into a rock formation at the same level, and pumping only the oil to the surface. This relatively new separation technology is being increasingly applied.

Another advance is the sensitive detection and capture of methane leaking from coal mines or natural gas deposits. Because of methane's global warming potential, its recovery is now a focus of fossil fuel extraction activities.

Over the next few decades, it is likely that this sector will see significant change in two major facets of the way in which resources are extracted: (1) the locations of resource reservoirs and their relative richness and extractability will be much more

Text Box 8.3

Environmental Risks of Tapping Unconventional Reserves

Although current reserve supplies of conventional oil and gas appear to be nearing depletion, the existence of untapped unconventional fuels buffers fears of complete fossil fuel exhaustion. However, these unconventional fuels carry significant environmental costs, both in the solid and liquid wastes produced during their extraction and in the continued release of carbon dioxide to the atmosphere during their use.

Because the unconventional oils and gases are harder to extract and less pure than conventional fossils, their extraction has the potential to generate significantly higher solid, liquid, and gaseous wastes, many of which are toxic both to human health and ecosystems. The example of tar sand mining, conversion, and upgrading to synthetic crude oil illustrates these detrimental environmental impacts. During the open pit mining process, toxic heavy metals are released that need to be contained, cleaned, and disposed of in an environmentally benign manner. In the separation of synthetic crude oil from tar sands, a hot water process is used to extract the oil from sand. This process is extremely energy intensive and requires large quantities of water that must be treated before release. The liquid tailings from tar sand separation, which are contaminated with organic and inorganic compounds, can seriously damage nearby aquatic ecosystems. Spent tar sand is put in specially designed storage areas to avoid acid drainage or used to refill the open pit cavity. The quantity of solid mass is substantial, raising concerns of widespread land degradation.

The use of alternative fossil fuel sources, as opposed to renewable energy sources, as a replacement for depleted fossil fuel reserves will do nothing to reduce CO_2 emissions. If anything, CO_2 emissions will increase as these less concentrated forms of energy are tapped.

The long-term availability of fossil fuel reserves will likely become more an issue of the degree to which future societies want to balance environmental and economic tradeoffs, than a question of resource existence.

precisely deduced in a non-invasive fashion before any extraction occurs, and (2) the extraction processes will be much less intrusive and environmentally stressful than is now the case.

Natural reservoirs for coal, oil, and gas are never uniform, but vary in richness, depth, extent, and many other parameters. Traditional extraction methods have tended to be haphazard, leaving portions of reservoirs incompletely drained and others untouched (Figure 8.7). Advanced detection and mapping technologies, including 3-D seismic interpretation, crosswell seismic tomography, and quantitative well log analysis can be expected to permit bypassed or incompletely exploited reservoirs to be delineated.

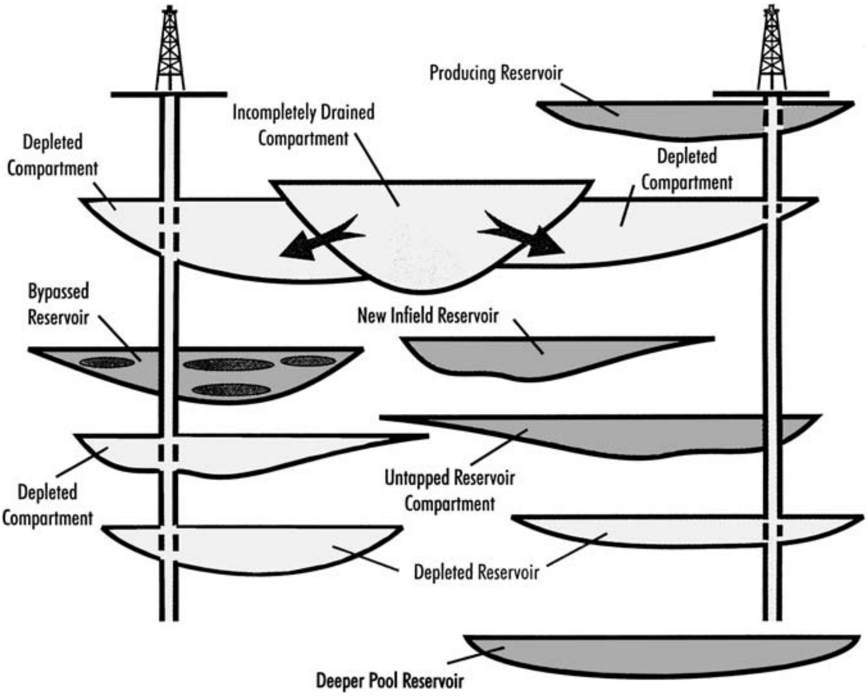

Figure 8.7. A schematic diagram of a typical oil or gas extraction field, showing bypassed and untapped reservoirs and incompletely drained compartments. (Reprinted from U.S. Department of Energy, *Oil and Gas RD&D Programs*, Report DOE/FE-0386, Washington, D.C., 1999.)

Once delineated, fossil fuel extraction in the future will likely take advantage of new drilling methods to minimize environmental damage. Various forms of microdrilling (e.g., see Figure 8.8) will be able to produce the same amount of resources with smaller, cheaper, more benign hardware.

8.5.1.2 Refining Trends

As a major energy user, this sector has substantial incentive to increase energy efficiency. Four routes are available: the introduction of more efficient equipment, the use of improved catalysts, enhanced heat recovery, and improved process control. The biggest potential for gains is in the coking operation of coal, and in the refining of crude oil.

Enhanced energy efficiency will significantly reduce the quantity of greenhouse gas air emissions. The potential for improvement is substantial, given the enormous quantities of CO_2 emitted to the atmosphere during the refining process. Heat transfer,

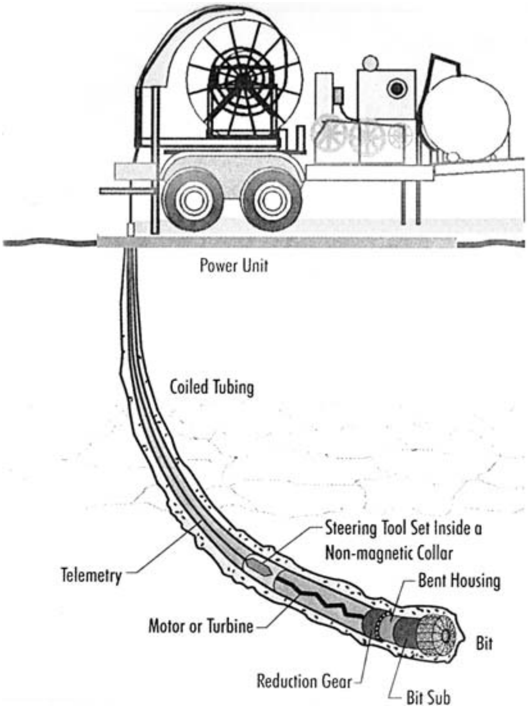

Figure 8.8. A schematic diagram of an experimental rig for microdrilling of oil and gas. The device occupies only about 5% of the space of a typical rig while minimizing cost substantially. (Reprinted from U.S. Department of Energy, *Oil and Gas RD&D Programs*, Report DOE/FE-0386, Washington, D.C., 1999.)

fluid flow, kinetics, and feed stock compatibility are all aspects of refining that can be optimized. Additionally, the refining process releases large amounts of waste heat and steam. Finding ways to generate electricity from this waste heat will shrink the petroleum industry's footprint.

Pollution prevention in the petroleum industry will play a key role in minimizing the production of wastes, reducing emissions, and developing more effective technologies for in-situ remediation of unintentional releases. The refining industry is currently examining various methods to improve long-term chemical and energy efficiency. For example, bioscience is a concept that is gaining momentum. This technology has the capability of enhancing the petroleum fermentation process by biologically activating catalysts. Applications range from improved desulfurization, denitrogenation, and demetallation of the petroleum crude stock without the need to use high-pressurized hydrogen, which requires large amounts of energy and money. These applications decrease SO_2, NOx, and heavy metal particulate matter releases to the atmosphere during the refining process, thus lowering air pollutants from refining.

8.5.1.3 Regulation and Societal Trends

The extraction and transportation of fossil fuels has been responsible for some serious and well-publicized cases of environmental degradation. Oil spills are perhaps one of the most dramatic events that focus public attention on the environmental costs of fossil fuel use. Regulation tends to respond to societal pressure. For example, the U.S. Oil Pollution Act (OPA) of 1990 streamlined and strengthened the EPA's ability to prevent and respond to catastrophic oil spills. The OPA requires oil storage facilities and vessels to submit to the federal government plans detailing how they will respond to large discharges. It also requires the development of Area Contingency Plans to prepare and plan for oil spill response on a regional scale. It is not coincidental that the OPA was developed and passed in the wake of the 1989 Exxon Valdez spill off the coast of Alaska. It is likely that new regulations governing fossil fuel extraction and transportation will be developed in response to societal concern over the disruption of sensitive ecosystems; the environmental consequences of fossil fuels in use are less dramatic and hence may be harder to regulate.

8.5.2 Possible Future Scenarios

The possible future scenarios for the fossil fuel sector depend heavily on the choices society makes regarding continued fossil fuel consumption. The World Energy Council has devised three potential energy scenarios, which are outlined in Chapter 9. These three scenarios present the different paths that a global society can take by choosing to consume different amounts or forms of primary energy.

8.5.2.1 Trend World

In this scenario, the fossil fuels sector would continue to extract and refine conventional fuel forms, with a gradual shift toward tapping the unconventional resources when doing so becomes economically feasible. Renewable and non-polluting (i.e., nuclear) energy sources, described in further detail in Chapter 9, will also compete with fossil fuels, both conventional and unconventional, as renewable technologies improve to permit this industry to compete at a large scale.

8.5.2.2 Green World

A truly sustainable global energy system would require the phasing out of all fossil fuels, and the substitution of renewable energy sources. This is idealistic, and certainly not economically feasible in the near term. However, with appropriately guided policy, technology advancement, and information dissemination, progress may occur within a quarter century in this sector. First, combustion will become increasingly controlled, and CO_2 is likely to be largely captured and sequestered. Second, extraction technologies will improve so that land degradation and habitat destruction are minimized. Third, as awareness of the benefits of non-fossil fuel sources develops, it will accelerate the global acceptance of these fuels by about the middle of the century.

8.5.2.3 Brown World

The most environmentally insensitive path would involve the continued production of fossil fuels and the rapid development of unconventional fuel extraction technologies. In this scenario, developing nations would follow the industrialized nations in becoming heavily dependant on fossil fuels, rather than building non-renewable energy infrastructure. This path would be void of domestic and intergovernmental policies aimed at addressing the major environmental concerns associated with fossil fuel use.

For the Brown World scenario to actually develop, the fossil fuel sector would have to be supported by favorable regulation and incentives because certain renewable energy technologies (namely biomass and wind) are rapidly becoming economically feasible. It is unlikely that the worst-case Brown path could actually develop, given some of the awareness in most nations regarding the significant dangers of continued fossil fuel dependence. A challenge is to convince *all* countries, ranging from the most powerful to the least developed, of the significant consequences of heavy petroleum usage.

FURTHER READING

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Chapter 9

Power Generation

9.1 OVERVIEW

Given the critical importance of energy to industrial activity, it is not surprising that whole industries have been created for the purpose of producing and distributing energy as a product in itself. The most common source of energy in human history has been that chemically stored in fuels such as wood and coal. Before the nineteenth century, energy was both distributed and stored in fuel form and converted to useful energy only after reaching its point of use. For example, heat energy was almost always produced by burning fuels near where the energy was to be used. Moving heat energy for any meaningful distance by transporting some heated medium entails significant losses unless expensive insulated containment is used. Similarly, mechanical or motive energy was usually produced (often by burning fuels) very near the site it was to be used. And, whether useful energy was produced by burning fuels or by capturing energy from moving fluids (water or wind), the conversion process itself involved considerable equipment, effort, skill, attention, and concern for safety.

The introduction of the large-scale production of electricity late in the nineteenth century made it possible to transport energy for long distances in electrical form and to make it available to ultimate consumers almost instantly, at any time, and in virtually any quantity. While the equipment needed by the consumer to convert electricity to heat, light, or mechanical energy may be considerable, it is usually compact, clean, and convenient to operate. Even though electricity production is generally inefficient (see section 9.2.3), the low cost of electricity-driven equipment and the high cost of on-site primary energy conversion have traditionally made the economics of using electricity highly favorable. With such advantages, the world's electric power generation and distribution system has become thoroughly integrated with industrial production everywhere. Figure 9.1, shows the inputs to the power generation sector, but omits electricity inputs to all other sectors on the diagram, in the interest of clarity.

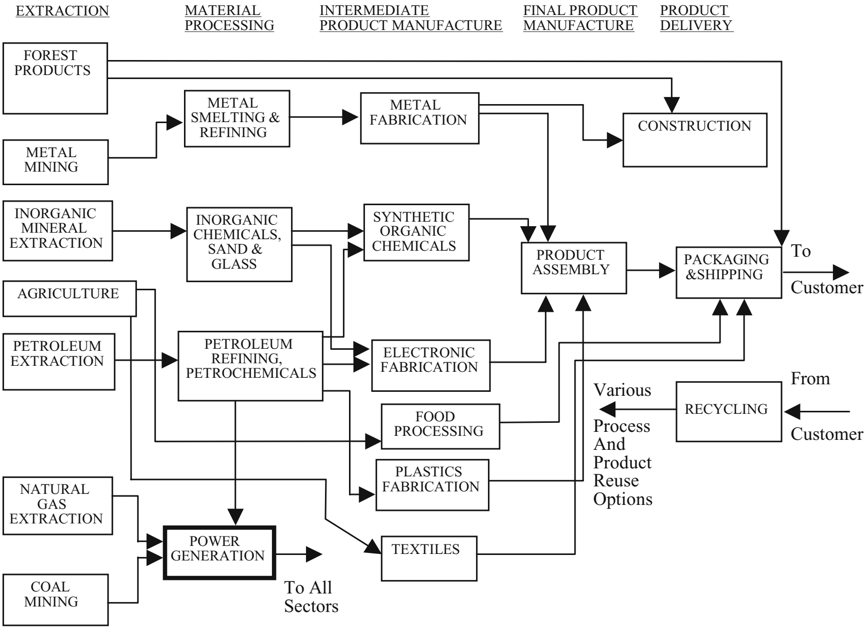

Figure 9.1. The technological sequence diagram for the power generation sector. The industry sector itself is indicted by heavy outlining.

9.2 PHYSICAL AND CHEMICAL OPERATIONS

Today, most electricity is generated by burning fossil fuels (coal, oil, or natural gas) to produce steam that is then used to drive a steam engine that, in turn, rotates the shaft of an electric generator. Significant amounts of electricity are also produced by harnessing the kinetic energy of water or wind, the radiation energy of sunlight, or the nuclear energy of uranium and these are described in section 9.3.2. In this section we focus on fossil-fuel-fired power plants which remain the predominant source of electric power, accounting for roughly 64% of the global total electricity production.

9.2.1 *Overall Process Characteristics*

Figure 9.2 is a schematic representation of a typical fossil-fuel-fired steam power plant. In such a plant, fuels are burned in a combination furnace and boiler wherein the heat released by combustion (at temperatures of roughly 1300 to 1900 degrees Celsius) converts water into high-pressure steam. The steam leaving the boiler is piped to a steam turbine that is turned by the action of steam impinging on turbine blades; the steam turbine rapidly rotates an electric generator. After the steam leaves the

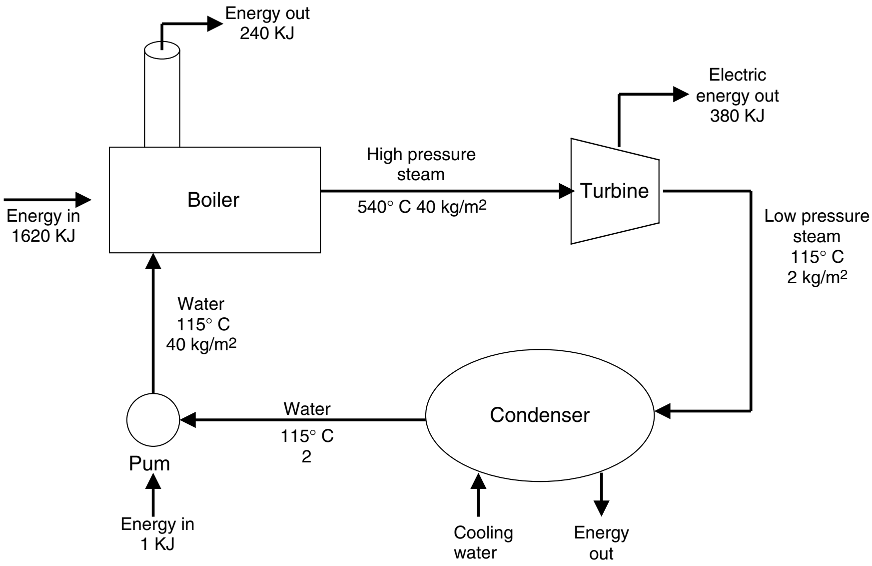

Figure 9.2. Schematic diagram of a fossil-fuel steam power plant.

turbine, it is reconverted into water in a condenser, which usually is cooled itself by large volumes of cooling water. Electricity produced by the generator is immediately "stepped up" to voltages in excess of 100,000 volts and enters the electric transmission and distribution system, where, along the way, it is subsequently "stepped down" in stages until finally being delivered to end users at between one hundred and a few hundred volts.

9.2.2 Combustion Chemistry

Petroleum fuels are made up almost entirely of hydrocarbons, compounds of carbon and hydrogen having a generalized chemical formula of C_nH_m. Coal is made up mostly of carbon, although some coals also contain significant amounts of hydrocarbons. Natural gas is made up mostly of methane (CH_4), but often with significant quantities of ethane (C_2H_6) and sometimes propane (C_3H_8).

The combustion of carbon (from coal, from example) with oxygen (O_2) produces carbon dioxide (CO_2) and, of course, heat.

$$\text{C (coal)} + \text{O}_2 \text{ (from air)} \longrightarrow \text{CO}_2 + \text{thermal energy} \tag{9.1}$$

In addition to heat, the combustion of hydrocarbons (from any of the fossil fuels) with oxygen produces carbon dioxide and water (H_2O), in proportions and quantities that depend on the makeup of the hydrocarbon molecule:

$$C_nH_m + (n + 1/4m)O_2 \longrightarrow nCO_2 + 1/2mH_2O + \text{thermal energy} \tag{9.2}$$

For methane, for example,

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O + \text{thermal energy.} \tag{9.3}$$

9.2.3 Process Efficiency

Although no conversion from a primary energy source to electricity is perfectly efficient, processes involving the burning of fuel to make electricity are especially inefficient, and in many respects unavoidably so. Most of that inefficiency is a result of the thermal and mechanical process of converting the primary energy source into electricity, with a very large fraction of the input energy being rejected as waste heat. At least two methods for improving the overall efficiency of thermal power plants have gained prominence in the last few decades—namely, combined-cycle technology and cogeneration. Both are methods that capture and put into productive use large portions of the rejected heat related to the inefficiencies discussed above.

The combined-cycle plant burns a fossil fuel—usually natural gas—in a gas turbine as shown in the upper part of Figure 9.3. One of the characteristics of a gas turbine is that the combustion-product gases are still extremely hot at the gas-turbine

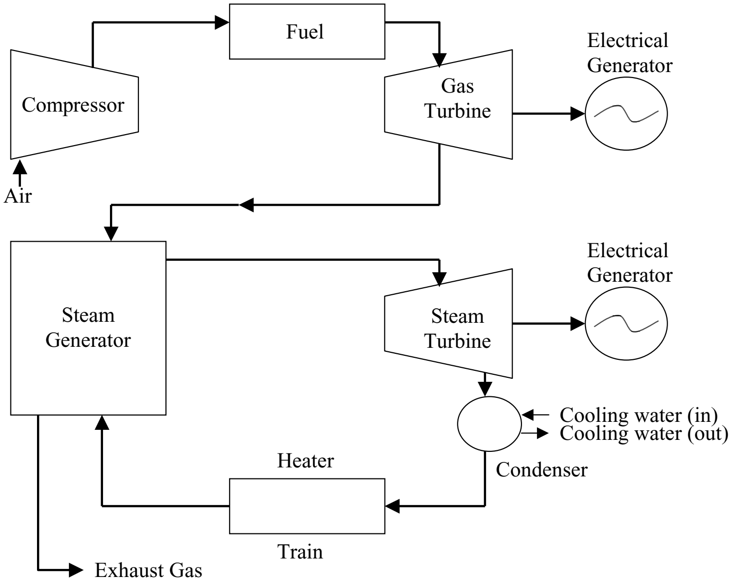

Figure 9.3. Schematic diagram of combined-cycle power plant.

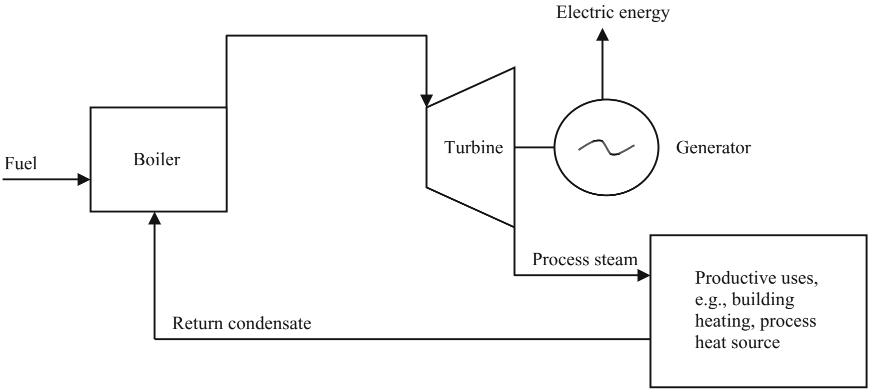

Figure 9.4. Cogeneration plant schematic diagram.

exit. Rather than being discarded at the outlet of the turbine, the gases are directed into a steam generator (i.e., a boiler) where their remaining high temperatures are used to make steam. That steam is then directed to a steam turbine, just as in a conventional steam power plant (see the lower part of Figure 9.3). The combustion products in a combined-cycle plant are essentially used twice to squeeze as much thermal energy from them as possible by "piggy backing" one power plant on another. Combined-cycle power plants that achieve efficiencies in excess of 55 percent are in commercial operation.

Cogeneration also makes use of the energy rejected from a power plant, usually by directing to some productive application the steam from the discharge of a steam turbine (see Figure 9.4). Combining cogeneration with a combined-cycle gas turbine plant can produce very high overall efficiencies. Systems with overall efficiencies on the order of 80 percent are presently in operation.

9.3 THE SECTOR'S USE OF RESOURCES

Overwhelmingly, the largest component of materials required for the generation of electric power in a typical fuel-burning power plant is the cooling water needed to remove waste heat from the process. The second largest material input is the fuel needed for the process, and the exclusive purpose of the fuel is to provide energy rather than material content.

9.3.1 Energy

As Table 9.1 shows, fossil fuels are used to produce 64 percent of the world's electricity. The predominant fossil fuel used in electricity generation is coal, which

Table 9.1. World Net Electricity Generation by Type, 2001

Energy Source	Amount Generated (Billion KWh)	Percentage of Total
Conventional thermal (coal, oil, or gas fuel)	9486	64%
Nuclear	2515	17%
Hydroelectric	2565	17%
Other renewables*	245	2%
Totals	14813	100%

*Other renewables include solar, geothermal, wind, wood and waste.
Source: International Energy Annual, 2002. accessed at: http://www.eia.doe.gov/emeu/iea/elec.html

in the U.S. is used to produce about 50 percent of all electric power. Natural gas is the next most prevalent fossil fuel, accounting for 13 percent of all electric power produced in the U.S. in 2002, and oil is used much less, accounting for only 2 percent of the total. Globally, both hydropower and nuclear power are important sources of electricity production, each contributing 17 percent of the total. Other renewable sources, which include solar, geothermal, wind, wood and waste, are used to generate only 2 percent of the world's electricity.

Local price and availability are key determinants of the sources one will find being used in individual countries. For example, more than 90 percent of the electricity produced in Brazil is hydroelectricity, which is to be expected in a country with such high rainfall amounts and extensive mountainous topography. Oil and natural gas are major sources in oil-producing countries such as Saudi Arabia, and coal is the major source in China, which has abundant coal reserves and limited money to use for importing oil or natural gas. On average, the proportion of nuclear energy sources in industrialized countries is almost 8 times what it is in the developing economies.

9.3.1.1 *Fossil Fuels*

Coals vary by wide ranges of heat content, water content, chemical makeup, impurities, and residual-ash content. In addition to elemental carbon, coal contains water, hydrocarbons, other organic compounds, sulfur compounds, and organometallic compounds and minerals, including those bearing such troublesome heavy metals as lead, mercury, and nickel. Coal requires considerably more equipment and procedures for fuel handling and preparation and for plant pollution control than either of the two other fossil fuels.

Ordinarily, fuel oil is the form of petroleum burned in electric power plants. Fuel oil is one of the "heavier" refined products into which crude oil is divided in an oil refinery. (Other refined products—not usually burned to make electricity—include gasoline, kerosene, jet fuel, lubricating oils, and asphalt.). Fuel oil also varies to some degree in heat content, water content, and impurities such as sulfur and heavy metals, but generally not as much as coal because, as a refined product, its properties can be more easily tailored. Fuel oil also requires suitable handling, storage, and pollution-control equipment although it contains fewer impurities than coal.

Natural gas has few components other than methane and ethane and virtually no impurities. Furnaces and boilers that burn fuel oil are often designed to burn natural gas as well to allow the burning of whichever of these fuels may be cheaper at the time. Although suitable equipment for handling and storing natural gas is required at a power plant, needed pollution control equipment is less extensive than that for coal or oil.

9.3.2 Energy Sources other than Fossil Fuels

9.3.2.1 Hydropower

Hydropower was an important source of energy long before modern times and the era of electricity production. Stream-side waterwheels have for centuries directly powered grist mills and factories by capturing energy from moving water. Dams were used to raise the operative water level and maximize the amount of energy available at a waterwheel site. In more recent times, hydropower has become an extremely important source for electric generation. Today, hydropower is the source for 17 percent of all the electricity produced worldwide. Hydropower provides more than half the electricity generated in Canada, Brazil (and most other Latin American countries), Austria, Norway, Switzerland, New Zealand, and Vietnam.

9.3.2.2 Nuclear

Nuclear power is the newest of the prominent present-day technologies for generating electricity commercially; it hardly existed before 1970. Since that date, it has reached the point of generating 17 percent of the world's electricity. A nuclear power plant operates in much the same way as the fossil-fuel plant illustrated in Figure 9.2. However, rather than heat energy being produced by the combustion of fossil fuels, the source of heat in a nuclear plant is a controlled nuclear reaction inside fuel rods filled with uranium fuel pellets. That heat is used to boil water and produce steam much as in the fossil-fuel plant. Nuclear power generates more than half the electric power produced in Belgium and France and over one third of the electric power in South Korea.

9.3.2.3 Biomass

Bioenergy from biomass comes either directly from the land, as dedicated energy crops, or is a residue that is generated in the processing of crops for food or other products such as pulp and paper. Another important contribution is from post consumer residue streams such as construction and demolition wood, pallets used in transportation, and the clean fraction of municipal solid waste (MSW). Most biomass in industrialized countries is converted into electricity and process heat in cogeneration systems at industrial sites or at municipal district heating facilities. Biomass energy has the potential to be produced and converted efficiently and cost-competitively into electricity. It is argued that if biomass is to become a major fuel in the world, as is being proposed in future energy scenarios, then residues will not suffice and energy plantations may need to supply 80 percent of the future feedstock. Such levels of land use for bioenergy raises the issue of intensified competition with other important land uses, especially food production, in tropical and developing countries.

9.3.2.4 Wind

Wind has considerable potential as a global clean energy source, being both widely available and producing no pollution during power generation. The cost of generating electricity from wind is falling as economies of scale begin to take hold. Nonetheless, significant challenges exist, with the siting of wind turbines being the most significant. Densely populated countries have pushed for offshore projects which increases costs. In some cases, the best wind locations are not in close proximity to populations with the greatest energy needs, as in the U.S. Midwest, making such sites impractical due to the high cost of transmission over long distances.

9.3.2.5 Geothermal

Geothermal energy arises from the ancient heat remaining in Earth's mantle by means of tectonic friction, convection, and from the decay of radioactive elements that occur naturally in all rocks. The amount of geothermal energy is enormous, with estimates that just 1 percent of the heat contained in the uppermost 10 kilometers of Earth's crust is equivalent to 500 times the energy contained in all of Earth's oil and gas resources. However, this heat is very unevenly distributed, seldom concentrated, and often present at depths too great to be exploited industrially and economically.

Geothermal systems that are exploitable occur in geologically active high temperature fields. Technologies for tapping hydrothermal reservoirs include drilling into the reservoirs, piping the steam or hot water to the surface, and using the heat directly or converting the heat into electricity. Developing countries with relatively limited electrical consumption but with good geothermal prospects stand to benefit most from the exploitation of geothermal systems. In industrialized countries where installed electrical capacity is already very high, geothermal energy is unlikely to contribute much to the total.

9.3.2.6 Solar

Two basic categories of technologies convert sunlight into useful forms of energy: solar photovoltaic (PV) and solar thermal systems. PV modules convert sunlight directly into electricity. Solar thermal systems use focused solar radiation to produce steam, which is then used to turn a turbine. The net conversion efficiency of solar electric power systems is typically 10 to 15 percent. As such, substantial areas are required to capture and convert significant amounts of solar energy to fulfill energy needs, especially in industrialized countries where the load demand is great. Additionally, the latitudinal location of solar systems affect the potential power generating capacity, as regions far from the equator experience less iridescence (power intensity) of sunlight than areas closer to Earth's equator. Although solar technologies do not cause emissions during operation, they do cause emissions during manufacture, a life-cycle impact that should be realized. Experts anticipate that the percentage of power provided from solar energy will continue to increase, but can never become more than a modest fraction of the total.

9.4 POTENTIAL ENVIRONMENTAL CONCERNS

In this section, we focus attention on the environmental concerns associated with the generation of electricity using fossil fuels and present a brief discussion of wastes from nuclear plants. In addition to thermal pollution, fossil-fuel-fired plants create three classes of polluting materials—air emissions, solid waste, and waste water. Some of those materials are produced directly and continuously by the combustion of fuel. Others are associated with fuel handling and plant maintenance and operation. In the paragraphs below, we discuss the key pollutants in each of the three classes.

9.4.1 Air Emissions

Six important pollutants ordinarily leave the combustion furnace of a power plant mixed in with effluent gases: nitrogen oxides (NOx), SO_2, carbon monoxide (CO), unburned organic compounds, ash particles, and carbon dioxide (CO_2). Emissions of CO_2 are by far the largest of any of these combustion products, and with growing concerns about climate change, CO_2 is now becoming classed as a pollutant. Nitrogen oxides and SO_2 are sources of acid rain. Table 9.2 shows the relative amounts of pollutants that result from using different fossil fuels, based on actual 1995 U.S. utility operation.

Table 9.2. Relative Production Rates of Air Pollutants from Different Fossil Fuels

Fuel	SO_2 (grams/kWh)	NOx (grams/kWh)	CO_2 (grams/kWh)
Coal	6.2	3.6	962
Oil	4.8	1.4	758
Natural gas	nil	1.6	680

Nitrogen oxides are produced to some extent in the high-temperature burning of any fossil fuel. These compounds are, for the most part, the result of the “combustion” of the elemental nitrogen present in the air that has provided oxygen for overall combustion:

$$N_2 \text{ (in air)} + xO_2 \text{ (in air)} \xrightarrow[\text{high temperature}]{} 2NOx \qquad (9.4)$$

Because the production of NOx is the result of high furnace temperatures and because high furnace temperatures enhance the efficiency of the power plant, avoiding NOx production is inherently problematic. Nitrogen oxides can be removed from combustion products by scrubbers or converted to less harmful compounds by chemical or catalytic means. It even appears that NOx production can be prevented to a very large extent by using recently developed catalytic-burner technologies.

Sulfur dioxide is produced by the combustion of the many forms of organic sulfur compounds—and, to some extent, elemental sulfur—found to varying degrees in both coal and fuel oil, but not in natural gas. The amount of SO_2 produced depends almost entirely on the concentration of sulfur compounds in the original fuel—which can be as much as 2.5 to 4 percent in some high-sulfur coals and 2 to 3 percent in some petroleum fuels. Largely because of the requirements of environmental regulations, sulfur is removed either by blending a chemical sorbent into the original fuel before burning or by passing the furnace effluent gases through a flue-gas desulfurization (FGD) device, which removes 90 to 95 percent of the original SO_2. Lime or limestone is often used as the absorbing agent in both the furnace process and the FGD process. The calcium sulfate (gypsum) that results from such an FGD process must be either sold or discarded.

Text Box 9.1

Reusing Ash in Japan

When coal is burned to produce energy, coal ash is among the inevitable results. The material has moderate hazard potential, as it typically contains heavy metals that were originally contained in the coal. Rather than discarding coal ash, many countries have developed programs to encourage its reuse.

One large reuse program has been established along the Japanese coast, producing “ashcrete,” a concrete with high coal ash content. The goal of the program is to construct artificial sea mounts in deep waters around Japan in order to create new fishing grounds. It has been estimated that a 1 GW coal-fired power plant would produce over 10 Tg of ash in 30 years, enough to produce 18 km of artificial linear sea mount 30 km high and 120 m wide at the base.

Source: L. L. Sloss, *Trends in the Use of Coal Ash*, Report CCC/22, London: IEA Coal Research, 1999.

Carbon monoxide and unburned organic compounds are both the result of incomplete combustion in the furnace, either because of inadequate oxygen or because of temperatures being too low. Once again, we see a situation in which the reduction of pollutant production would mitigate against some other environmentally desirable outcome. In this case, reducing the production of CO and burning more organic compounds would call either for increasing the flow of oxygen (which draws in more nitrogen that, in turn, would carry heat out of the furnace with it) or for increasing the combustion temperature (which would tend to increase the production of NOx).

Ash is a solid, though finely powdered, combustion product made up mostly of oxides of silicon, aluminum, iron, and calcium as well as smaller amounts of other metal oxides. It is produced in relatively large amounts by burning coal, in lesser amounts when burning fuel oil, and not at all when burning natural gas. Most of the ash falls to the bottom of the furnace during and after combustion—the "bottom ash"—and is disposed of as a solid waste. Some, however, is caught up in the combustion gases as they leave the furnace—the "fly ash". Almost all modern coal- and oil-burning plants now use equipment to remove fly ash from power-plant effluent gases, with the most common types of such equipment being electrostatic precipitators, fabric filters ("bag houses"), and mechanical collectors, such as cyclones.

9.4.2 Liquid Waste Streams

There are a number of streams internal to power plants that carry wastes or some other potential pollutants. Almost all of these involve water as the medium. Some of the streams have come into direct contact with fuels or the combustion wastes described above. These streams are called "contact" waste streams. Water from virtually all these liquid waste streams requires treatment before being released into the environment, and often even before being transferred to municipal waste treatment facilities.

9.4.3 Wastes From Nuclear Power Plants

Because nuclear power plants do not use a combustion process to produce heat energy, these plants produce none of the air emissions, solid combustion wastes, or contact liquid waste streams described above for fossil-fuel-fired power plants. Importantly, nuclear power plants do not produce CO_2, one of the most vexing of the greenhouse gases. They do, however, have their own, very similar forms of non-contact liquid waste streams.

The wastes from nuclear power operations that are of greatest importance in a discussion of environmental impacts are radioactive wastes. The two key categories of radioactive nuclear plant wastes ("radwastes") are: (1) wastes associated with day-to-day operations and maintenance and (2) the "spent" nuclear fuel that is effectively depleted as power plant fuel and must be removed and disposed of. Day-to-day operational wastes have relatively low levels of radioactivity and are called low-level radwastes, while spent nuclear fuel is highly radioactive.

Nuclear power plants are designed such that ordinary, day-to-day operations result in the release of only extremely small amounts of radioactivity, amounts that are, in general, less than the radiation plant workers and the public continually receive from such sources as medical x-rays and cosmic radiation that penetrates the atmosphere. Such low levels of radioactive release are achieved by the manner in which operational radwastes are collected, treated, and disposed of. For example, air and other plant gases that become radioactive—usually by containing radioactive particles—are collected and filtered or scrubbed inside the plant to prevent radioactivity being released as these gases leave the plant. Liquid streams that contain radioactive materials—such as reactor and steam-generator blowdown, wastes from cleaning equipment in radioactive areas, and even liquids from floor drains—are collected and cleaned by filtering and treatment with ion-exchange processes to remove such materials. The clean-up processes for both gaseous and liquid waste streams ordinarily convert collected radioactive materials into either a solid form or a highly concentrated liquid form that can be solidified by mixing with cement and disposed of in solid form.

Spent nuclear fuel, of course, must be handled with extreme care and, for that reason, its handling—and particularly the safety of its permanent disposal—has become the most critically important issue affecting the continued use of this energy source. Methods for safe, permanent disposal, while arguably feasible, have not been universally accepted, and most spent nuclear fuel is held in some form of temporary storage. While the physical volume of such materials is quite low, a more appropriate measure of the throughput of spent fuel is the radioactivity of the material, which is extremely high. Efforts continue to gain acceptance for safe disposal methods, though the process is highly politicized and may go on for many years to come.

9.4.4 Habitat and Land-Use Concerns

Electric power facilities typically use significant amounts of land, both for generating and transmission purposes. A typical fossil-fuel power plant, for example, would be situated on 20 to 60 hectares. A typical nuclear plant is usually allocated considerably more—200 to 300 hectares.

Because of the need to be near sources of large volumes of cooling water, power plants are most often located adjacent to large, natural bodies of water, which almost always represent wetlands, marshes, and other habitats for aquatic flora and fauna. The potential for erosion and for toxic and thermal pollution, therefore, has important implications for the location, design, and operations of such facilities.

Transmission lines, the purpose of which is to transport generated power to concentrations of end users (called "load centers"), also have significant potential impacts. When built above ground, these power lines—usually characterized by three heavy cables suspended from tall metal or concrete towers—are located within dedicated rights-of-way having widths ranging from 30 to 80 meters and lengths of tens or even hundreds of kilometers. Thus, substantial land areas can be appropriated for power transmission, with notable areal and lineal impacts on local habitats. In addition, the need to control vegetation in transmission rights-of-way sometimes leads to the use of herbicides, although mechanical vegetation-control methods are becoming the norm.

9.4.5 Sustainability Assessment

The concerns for potential environmental impacts that are raised by the several input streams and waste streams from power generating plants depend upon the amount of material present in the stream and the harm that could be done if that material were released. The materials are analyzed in Table 9.3 for the magnitude of their throughput and their hazard and scarcity potentials. The TPH matrix in Figure 9.5 indicates that carbon dioxide is the material of most concern in the power generation sector. Several other materials are also of high concern: nuclear fuel, sulfur dioxide, particulate matter, and bottom ash. The TPS matrix of Figure 9.5 duplicates that of the fossil fuel extractants of Chapter 8; there are moderate scarcity potentials for all but coal.

Power generation creates energy rather than consuming it, so the sector has no PEC matrix. Because so much water is used in power plant cooling, however, water concern on the PWC matrix is high (Figure 9.6).

The sector ΣWESH plot (Figure 9.7) demonstrates that water use and CO_2 emissions are of highest concern. Several input or byproduct materials are of only slightly less concern.

Table 9.3. Throughput-Hazard-Scarcity Binning of Materials in the Power Generation Sector

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
Coal	H	–	L	L
Petroleum	H	–	L	M
Natural gas	H	–	L	M
Nuclear fuel	M	Human	H	M
CO_2	H	Climate	H	–
Bottom ash	H	Ecosystem	M	–
SO_2	M	Acid rain	H	–
NO_X	M	Smog	M	–
Heavy metals	L	Human	M	–
Scrubber sludge	M	Ecosystem	M	–
CO	L	Human	M	–
Particulate matter	M	Human	H	–

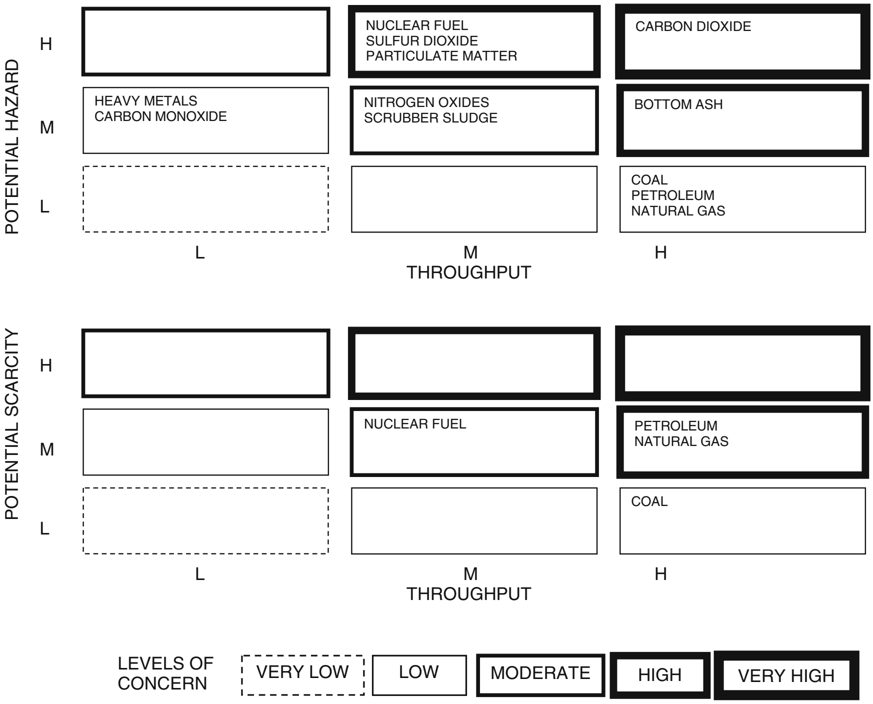

Figure 9.5. Throughput-potential hazard matrix (top panel) and throughput-potential scarcity matrix (bottom panel) for the electric power generation sector.

9.5 SECTOR PROSPECTS

Among the many aspects of industrial activity, electricity may be, directly and indirectly, one of the most pervasive sources of environmental impact. Electricity is used in virtually every step of every industrial process, and the damage to ecological habitat at the time of fuel extraction and the production of toxic and climate-altering pollutants at the time of electricity production are potentially enormous. The highly disparate, fluid, and independent nature and short-term economic focus of industrial organizations make it difficult to arrange the usually large investments needed for demand reductions and for the utilization of cleaner sources.

Much is being done to overcome these obstacles and to harness the many opportunities available to reduce the impact of electricity generation on the environment. Some of these opportunities for reduced consumption and cleaner sources are at hand; others are in the early stages of development, and many have somewhat speculative futures.

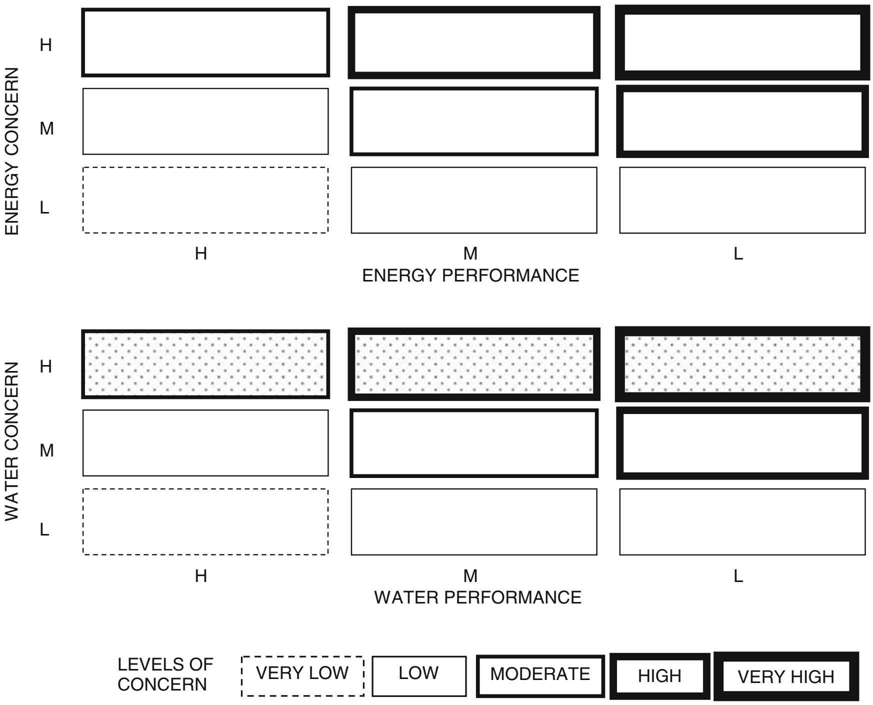

Figure 9.6. The performance-energy concern matrix (top panel) and performance-water concern matrix (bottom panel) for the electric power generation sector.

The environmental impact of electricity production can be lowered by addressing supply-side and demand-side potential solutions. Supply-side improvements include reducing the amount of fuel needed to produce a given amount of electricity (i.e., improving efficiency), and using cleaner production technologies. Demand-side improvements can result from reducing the overall amount of electricity consumed (and thereby produced).

9.5.1 Supply-Side Trends

9.5.1.1 Fuel Cells

As an advanced energy conversion device, fuel cells are attractive because of their efficiency, and because they do not produce toxic combustion products such as NOx and carbon monoxide. Fuel cells for vehicle and stationary applications may be a key enabling technology for the transition from a fossil-fuel based energy system to one that is dominated by renewable energy sources. Fuels cells run on stored or

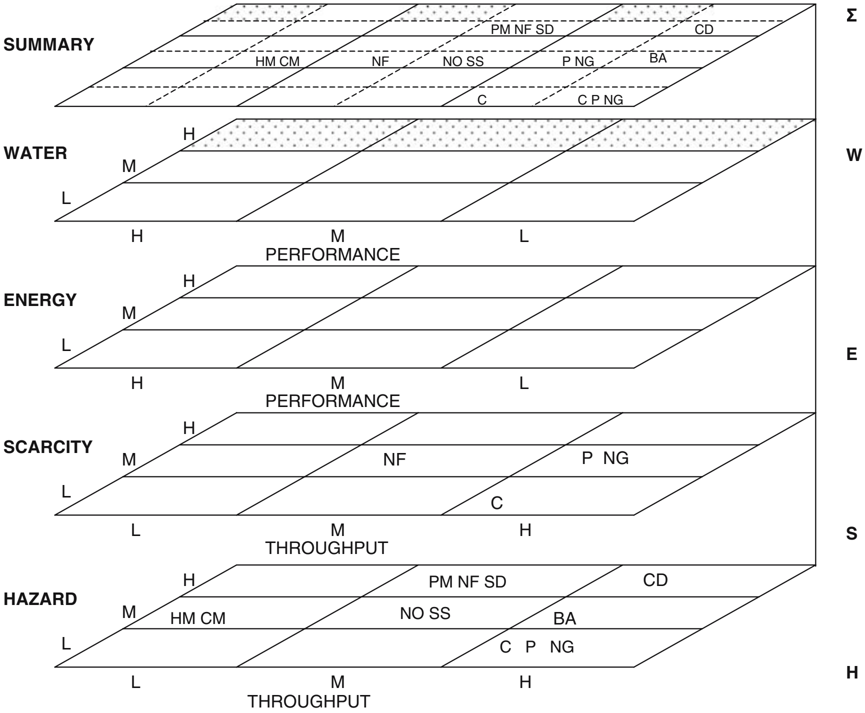

Figure 9.7. The ΣWESH plot for the electric power generation sector. Abbreviations refer to the materials in Figure 9.5.

manufactured hydrogen to produce power. The efficiency of fuel cells is today about 50 percent, but as the technology improves, much higher efficiency levels will probably be attainable. The primary obstacle to rapid expansion of fuel cell application is cost, presently about three times that of conventional, high-efficiency, fossil-fuel-burning technology. Even at that rate, in cases where small amounts of electricity are needed in locations quite removed from conventional power grids—in remote villages of developing countries, for example—fuel cells may well be the favored choice.

9.5.1.2 Cleaner Sources

On a worldwide basis, renewable energy sources are used for about 19 percent of all electricity produced. By far the most prevalent form of renewable energy sources are hydroelectric sources. Growth in the use of renewable energy sources is expected to keep pace with the overall growth in global energy consumption, estimated to be 2 percent per year through 2020. About half the growth in renewable utilization

Text Box 9.2

Wind Power in Canada

In Canada, the province of Ontario's first commercial wind farm began operations in 2002. Located on the shore of Lake Huron, the wind farm consists of five 1.8 MW wind turbines and is capable of generating enough electricity to power 3,000 homes. Each wind turbine is 117 meters tall, roughly the roof height of Toronto's SkyDome stadium. The turbines start to produce electricity when wind speeds reach 14 kilometers per hour and reach full power when winds reach 56 kilometers per hour. Some sources estimate the up to 20 percent of Canada's electricity demand could be provided by wind power, although the development of wind power relies on the selection of sites with suitable wind profiles and access to transmission facilities.

Source: Huron Wind. http://www.huronwind.com/huronwind/default.asp

will come from hydroelectricity development, and almost all of that will occur in the developing world because most of the cost-effectively exploitable water resources in the developed world have already been harnessed. Concern about climate change and regulatory and voluntary pressures to cut greenhouse gas emissions levels may provide a significant opportunity for even greater growth in the use of renewables.

Wind power is a technology that has overcome a great many obstacles to become one of the most promising of the renewable sources of electricity. The use of wind generation will, nonetheless, be limited by the number of locations having appropriate wind regimes, but will grow from its small present level at about the same pace as the average of other non-hydro renewables.

Even among conventional generating methods, electricity will probably be generated with less pollution. Owing to stricter limits on pollution and the availability of effective new control technologies, the emissions of sulfur dioxide and NO_x from conventional generation are projected to fall even while electricity generation is growing.

9.5.1.3 Production Efficiency

Technology is already available that would significantly improve the efficiency of power generation, that is, reducing the amount of fuel that must be consumed to generate a given amount of electricity. Combined-cycle gas turbines—having efficiencies as high as 55 to 60 percent, as discussed above—are presently in operation in large generating stations. Advances are continually being made that provide high efficiencies in smaller installations as well, making it more and more feasible to use these high-efficiency generators in individual industrial plants, commercial developments, and small, remote residential communities. Although these installations are cost effective, obstacles to their dominance include the slow replacement rate of power-generation capital equipment and concerns about regional over-reliance on natural gas.

9.5.2 Demand-Side Trends

9.5.2.1 Electricity Conservation and Load Management

In large part because of government programs aimed at developing and implementing effective ways to use electricity more efficiently at the point of consumption, the technologies for doing so are readily available. These take the form of, for example, better insulated and solar-heated buildings, more efficient lighting systems and residential appliances, greater application of cogeneration, and higher efficiency industrial electric motors. It has been estimated that the application of new technologies could reduce electricity consumption in the residential sector by 10 to 30 percent by the year 2020. While new technologies will be important in determining the extent to which consumer efficiency is improved, progress will depend mostly on the advances made in shaping institutional and financial systems favorable to that progress.

9.5.2.2 Deregulation

The electricity industry in many parts of the world is currently undergoing deregulation. Single monopoly control of electricity generation, transmission, and distribution is being transformed into a system where providers compete to provide generation capacity. The system allows large industrial users and even consumers to choose who generates the power they consume. If demand for cleaner or higher efficiency alternatives is sufficient, deregulation may allow for the growth of environmentally favorable or renewable power sources.

9.5.3 Possible Future Scenarios

Future technological progress will almost certainly provide us with dramatic improvements in consumer efficiency and generating efficiency and with cleaner generation methods. Whether this progress will overcome the present large environmental impacts of this sector is highly uncertain. Nonetheless, tools to mitigate such degradation may be very powerful.

The Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC) modeled three long-term global energy scenarios to the year 2100 (Figure 9.8). The scenarios all project different global energy consumption patterns based on technological improvements, economic development, and social policy progress with respect to alternative power, particularly in the developing world. They provide for improved energy efficiencies and environmental compatibility, and thus for

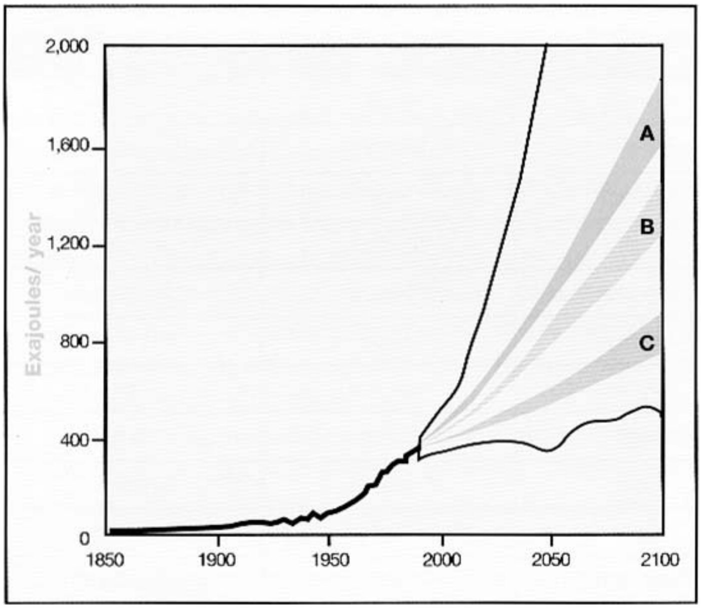

Figure 9.8. Energy consumption in the 21st century under various development scenarios. The extremes of published scenarios are indicated by the narrow lines. Scenarios A, B, and C are discussed in the text. (*Source:* World Energy Council, http://www.worldenergy.org/wec-geis/edc/scenario.asp)

associated growth in both the quantity and quality of energy services. Across all three cases, the structure of final energy develops in the same way and energy intensities improve steadily. To facilitate comparisons, all scenarios share the same demographic assumption that global population grows to 10 billion by 2050 and to nearly 12 billion by 2100.

9.5.3.1 *Trend World*

Scenario A of Figure 9.8 represents a business-as-usual trend of current energy consumption, where energy supply remains dominated by fossil fuels, hydroelectricity, and a renewed contribution from "Generation III and IV" nuclear power. There is a moderate rate of growth of non-hydro renewables such as wind power. Oil and natural gas supplies dwindle by mid-century, and coal becomes more important. Because of the widespread use of fossil fuels, the capture and sequestration of carbon dioxide is actively pursued. Nonetheless, CO_2 emissions are sufficient to cause progressive climate change, and the attendant impacts are substantial. Scenario B is a more modest version of Scenario A, with slower technological development and diffusion of energy generation.

9.5.3.2 Green World

Scenario C is ecologically driven, and very challenging. It incorporates unprecedented progressive international cooperation and challenging environmental and energy taxes to simultaneously protect the environment and transfer wealth from the developed to the developing world to enhance economic equity. Simultaneously, a major transformation of energy generation from fossil fuels to renewables is carried out. During the transition period, CO_2 sequestration is extensive. Coal is used, but full implementation of clean coal technology is achieved. Oil and gas are saved for specialized technological uses. This approach leads to lower energy use, but high overall growth, especially in the developing world.

9.5.3.3 Brown World

In the brown world scenario, an emphasis on inexpensive power encourages extensive use of fossil fuels. Supplies of oil and natural gas are extensively drawn down by 2030–2040, and coal is used extensively. Because of minimal investments in CO_2 capture and sequestration, atmospheric CO_2 concentrations climb rapidly, triggering major changes in weather and climate by mid-century.

FURTHER READING

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Chapter 10

Metal Ore Extraction and Processing

10.1 OVERVIEW

The industrial sequence diagram for the metal ore extraction and processing sector is shown in Figure 10.1. This sector is one of several involved in the earliest stages of the industrial materials cycle. The sector activities comprise the following: physical extraction of metal ores (mineral aggregates from which metals can be recovered) from their natural reservoirs, concentration of the desired metal by minimizing associated but unwanted ore constituents, separation of the metal atoms from the compounds in which they occur, and purification of the resulting metals.

10.2 PHYSICAL AND CHEMICAL OPERATIONS

10.2.1 The Extraction Process

In modern metal ore extraction, the most common technique is *open-pit mining*. In much the same manner as open-pit coal extraction, soils and vegetation are first removed from the mine site. Bulk ore is then extracted by blasting charges to loosen the bedrock. For less dense geological formations, special saws and drills can be used to remove the ore from the formation. The ore is then transferred to processing stations, described below. Massive industrial machinery is often used to extract and transfer the ore from the earth. As with coal mining, open-pit mining is usually cheaper and safer than the alternatives, but is less desirable from an environmental standpoint in that it generates more waste and may use more energy.

The historical (and usual) option to open-pit ore mining is *underground mining*, in which shafts are sunk into the ore deposit, passages opened off the shaft, and the ore then broken up and brought to the surface. This process is typical for vein deposits,

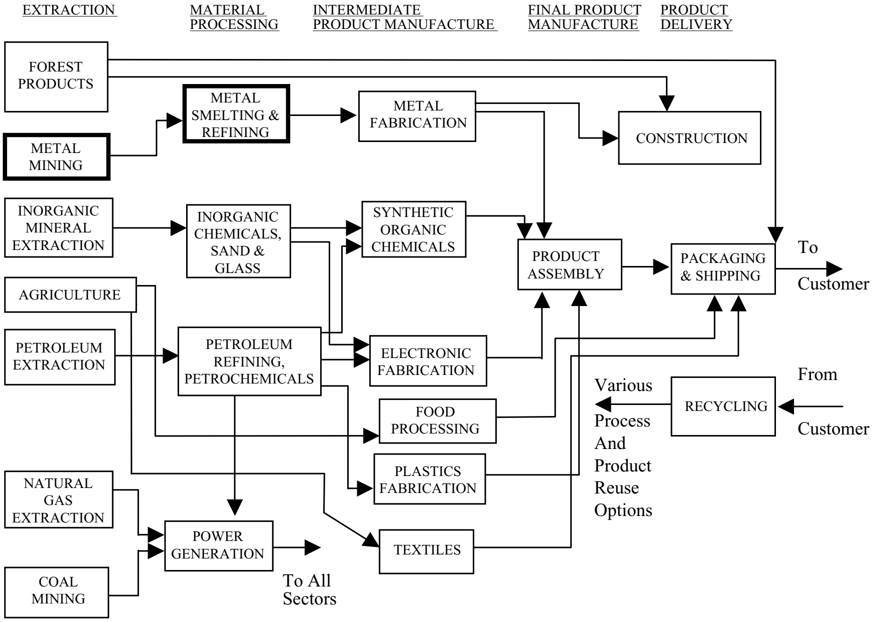

Figure 10.1. The technological sequence diagram for the metal ore extraction and processing industries. The industry sector itself is indicated by heavy outlining.

where a continuous but localized metals-rich ore vein can be followed great distances through the earth. Underground mining is often the more cost-effective option in formations where a few metals-rich veins or regions occur; open-pit mining may be the preferable method when a more expansive body of less-rich, but more voluminous, ore exists. Since the overburden is left in place during underground mining, it does not have to be dealt with, and local vegetation and habitat suffers minimal disruption. Expense and safety are often compromised, however.

The third option is *fluid mining*, in which a leaching solution is injected into drill holes to dissolve metals, and then recovered and the metal separated from the solution. This approach is not common for most of the widely-used industrial metals (e.g., iron, copper, zinc), but is much more widespread with gold and sometimes with silver.

10.2.2 Beneficiation

Beneficiation immediately follows extraction. The goal of beneficiation is to convert the ore into a more uniform size and higher grade than the raw material that comes from the earth after extraction. The beneficiation process typically involves two steps. The first step is *comminution* (a term synonymous with *milling*), in which the lumps of mined ore are reduced in size by crushing and grinding processes. The usual target size is similar to the grain size of the mineral being recovered (roughly a millimeter), so several stages of size reduction are usually involved. Various preliminary purification processes may then be performed, in which metal ores are separated from unwanted materials on the basis of differential magnetic, density (the flotation process), or chemical properties. The desired ores are then commonly reduced in size by *sintering*, in which they are heated to temperatures as high as 1300°C to agglomerate and weld the particles together. Metals can then be recovered from the sintered ore, as described below.

10.2.3 Recovering the Metal from the Ore

With few exceptions, pure metals are not found in nature. Rather, they are nearly always present in either oxide or sulfide forms, shown in Table 10.1. In order to recover the metal from the ore, the bonds between the metal atoms and the sulfur or oxygen atoms must be broken, the sulfur or oxygen discarded, and the resulting metal purified. Very high temperatures are typically required to accomplish these processes.

After the ore has gone through beneficiation, metals can either be separated at a smelting facility close to the mine itself, or the beneficiated ore can be transported (usually by rail or barge) to a central location for metals recovery.

The first step in the recovery process for most metals is *smelting*, in which the ore is heated to liquefy the mineral, the chalcocide (the oxygen or sulfur) extracted in gaseous or other form, and the resulting metal skimmed off (drossed) or poured off and formed into solid bricks (ingots). Since the target metal is usually present in the *beneficiated* ore in concentrations significantly less than a few percent, a very large amount of material must be heated up and processed, and most of the accompanying material discarded.

Smelting is followed by *refining*, in which the impure ingots are reheated with various additives that scavenge impurities. The resulting slag, or waste, is skimmed off or otherwise removed, leaving the purified metal. Depending on the purity desired, several stages of refining or other purification processes may be employed.

Table 10.1. Common Forms of Metal Minerals

Metal	Mineral	Mineral Name
Aluminum	Al_2O_3	Bauxite
Copper	Cu_2S	Chalcocite
Iron	Fe_2O_3	Hematite
Lead	PbS	Galena
Silver	Ag_2S	Argentite
Zinc	ZnS	Sphalerite

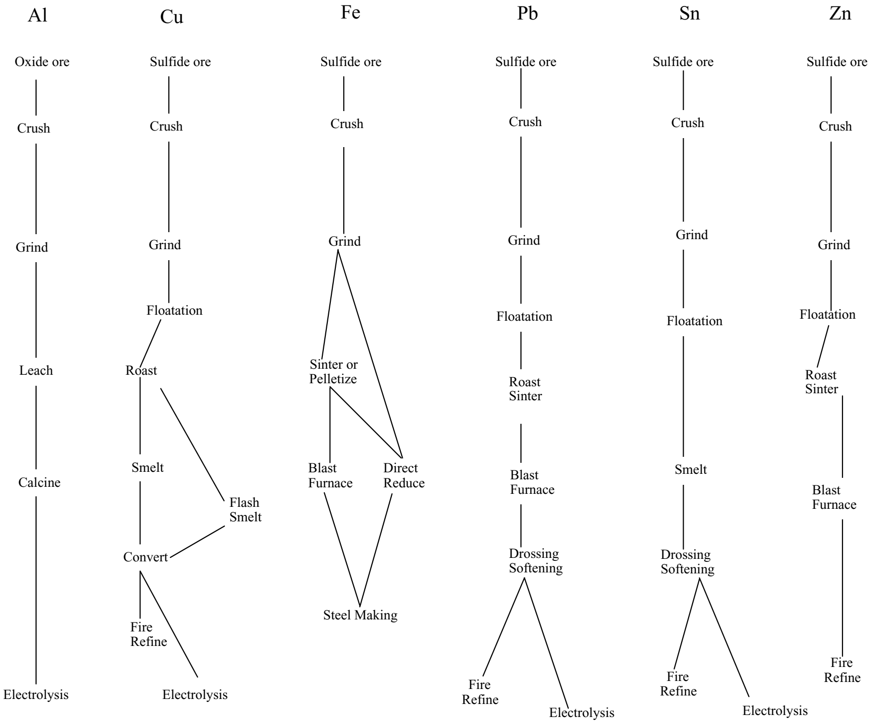

Figure 10.2. Sequences of extraction and refining for the common industrial metals. (Adapted from C. Bodsworth, *The Extraction and Refining of Metals*, Boca Raton, FL: CRC Press, 1994.)

10.2.4 Processing Sequences for the Common Industrial Metals

With some variations, almost all of the common industrial metals undergo the steps outlined above as they proceed through their transition from being part of Earth's crust to being employed as a constituent in our modern technological society. The sequences are shown in broad outline in Figure 10.2.

In the case of iron, by far the most widely mined and used of the metals, the most common process is rather different from those for other ores. It begins, as shown in Figure 10.3, with the injection of iron ore pellets, crushed limestone, and coke into a blast furnace. The coke provides the fuel for the furnace and the limestone reacts with and removes unwanted ore constituents. The molten iron that is produced is combined with other materials to generate a mixture appropriate for the type of steel desired (steel is an alloy of other constituents with iron). The *mild steels*, used for most structural and engineering purposes, contain 0.15 to 0.25 percent carbon. *High carbon steels* contain 0.6–0.7 percent carbon, and are used for more demanding applications. Specialty steels contain precise amounts of additives other than carbon.

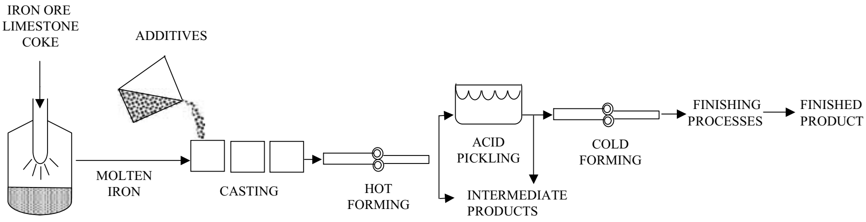

Figure 10.3. The transformation of iron ore into steel products. (a) Processing of iron ore. (b) Manufacture of steel ingots.

The most common are stainless steels, with several percent each of chromium and nickel, and high-strength steels which incorporate magnesium, silicon, tungsten, and or vanadium. The right side of Figure 10.3 outlines the casting, forming, and finishing process sequence. Some of the products, such as welded pipe, are used directly by customers. Others are provided to metal fabricators (Chapter 17), who manufacture more complex products.

The primary steel industry underwent a transition in the 1990s from using mainly blast furnace procedures to using the electric arc furnace (EAF). Steel production using EAFs is scrap-based. With the growth in use of EAFs, a great deal of ore-based steel production was shut down. This shift from ore-based to scrap-based steel has increased the recycling value of scrap steel and has decreased iron extraction pressures.

Text Box 10.1

American Scrap Metal Feeds China's Growing Steel Industry

America's scrap metal is helping to feed China's building boom. Imported scrap steel and copper is being used to build skyscrapers, factories, and telecommunications infrastructure throughout China. Reflecting a sharp rise in demand for scrap metal, the price of scrap steel soared in the first months of 2004, reaching more than $300 per ton in March, roughly double the price at the end of 2003, and up significantly from the price of $77 commanded in the beginning of 2001. Exports of scrap steel from the U.S. almost doubled between 2000 and 2004, with 30 percent of it going to China. The fraction of U.S. scrap steel exported to China remains low compared to that consumed domestically; the U.S. still consumes about seven times the amount shipped to China, although the quantity has fallen in recent years. As long as the cost of producing metal from scrap remains lower that that of producing it from ore, the scrap metal trade will remain strong.

Source: Pollack, A. and Bradsher, K. 2004. "China's need for metal keeps U.S. scrap dealers scrounging." New York Times. March 13, 2004.

The most significant difference between ferrous and non-ferrous processing (iron and steels are the *ferrous* metals, others are termed *non-ferrous*) is that the latter commonly undergo *electrolysis* as the final purification step. An electrolytic process is one in which an electric current is passed through a molten solution, and the solution constituents are differentially collected on the electrodes on the basis of their electrical charge.

The process for aluminum illustrates several characteristics of non-ferrous processes. After the ore is crushed and ground to suitable size, it still contains 10–30 percent of impurities, chiefly iron oxide. The impurities are largely removed by *leaching* the ore, i.e., by dissolving either the target material or the impurities in a chemical solution. In the case of aluminum, the solution is of sodium hydroxide (NaOH), a highly caustic chemical, and the $Al(OH)_3$ is converted to soluble $AlO \cdot ONa$. This solution is then separated from the impurities and cooled to precipitate $Al(OH)_3$. The $Al(OH)_3$ is then heated to 1200°C, upon which it is transformed to alumina (Al_2O_3), a process termed *calcining.* Finally, the alumina is dissolved in molten cryolite (Na_3AlF) at 1000°C and a large amount of electrical power applied (Figure 10.4). The dissolved aluminum ions pick up electrons at the cathode and are transformed into elemental aluminum, which sinks through the cryolite and is extracted from the bottom of the electrolytic cell.

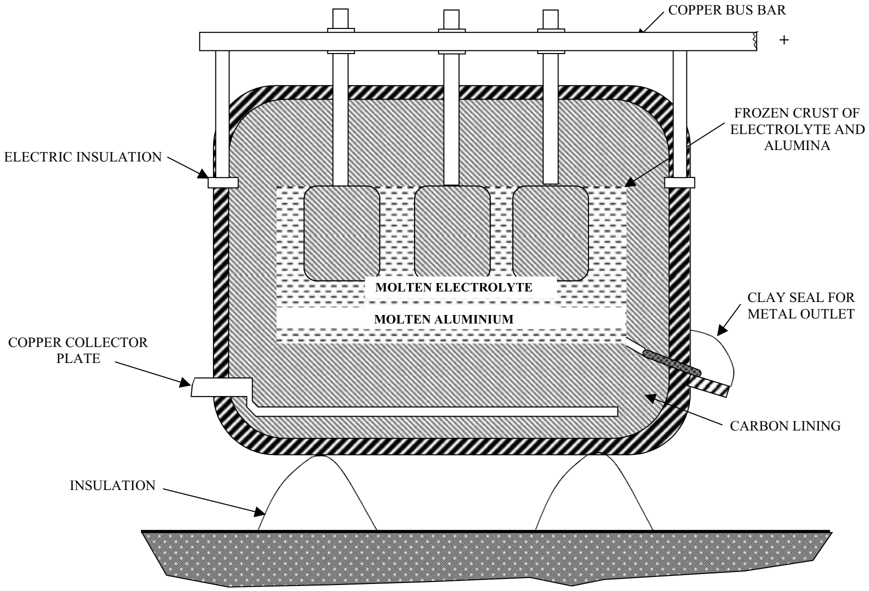

Figure 10.4. The electrolytic cell used in the production of aluminum. (Reprinted with permission from R. N. Shreve, *The Chemical Process Industries*, 2nd ed., New York: McGraw-Hill, 1956.)

Although other non-ferrous metals have lower melting points than aluminum, and can therefore be processed at somewhat lower temperatures, the same process steps tend to be used: crushing, grinding, concentration by flotation or other means, smelting, refining, and electrolytic purification. Temperatures of several hundred to a thousand degrees Celsius are typically required.

A further complication is that geological processes often deposit chemically-similar metals together. Thus, arsenic is often found in copper ores, cadmium in zinc ores, and so forth. Beneficiation, smelting, and refining must therefore deal with several metals at once, from both processing and residue standpoints.

10.3 THE SECTOR'S USE OF RESOURCES

10.3.1 Energy

The extraction and processing of metals are very energy-intensive processes, particularly in the comminution, smelting, and refining stages. In 1992, the U.S. mining industry used 8.1×10^{16} J for the extractive processing of nonferrous metals and 6.1×10^{17} J for excavating and hauling. As an industrial sector, metal ore extraction and processing ranks third in energy use behind fossil fuel extraction and the chemical industry.

Because of intrinsic differences in bond strength, melting temperatures, and other properties, the metals differ substantially in the amount of energy required to produce the same amount of material. This "embedded energy" has been analyzed by Manfred Schuckert of the University of Stuttgart. His research has resulted in quantifying the typical amount of energy needed to produce a certain amount of the target metal. As Figure 10.5 demonstrates, this amount can vary dramatically. Titanium, which has a very high melting point and is relatively difficult to purify, has an *embedded energy* of more than 260 MJ/kg. Lead, which has a very low melting point and is relatively easy to purify, has an embedded energy of only 20 MJ/kg. The concept of embedded energy is particularly important from a recycling standpoint. If we discard a kilogram of titanium, for example, we not only discard a material that we might be able to reuse, we also, in effect, discard the product of the fossil fuels that generated 260 MJ of energy. Every discard of a processed material thus has impacts on the energy cycle as well as on the cycle of the material itself.

10.3.2 Materials

Mass flows in the U.S. iron and steel industry are very large and have several characteristics worth noting. First, the amount of material that emerges from the blast furnace step is typically less than the amount lost to the environment in all forms—gases, water, slag, etc. Second, scrap input to the furnaces is large; in the case of iron production the scrap input is greater than that of virgin metal. Third, large

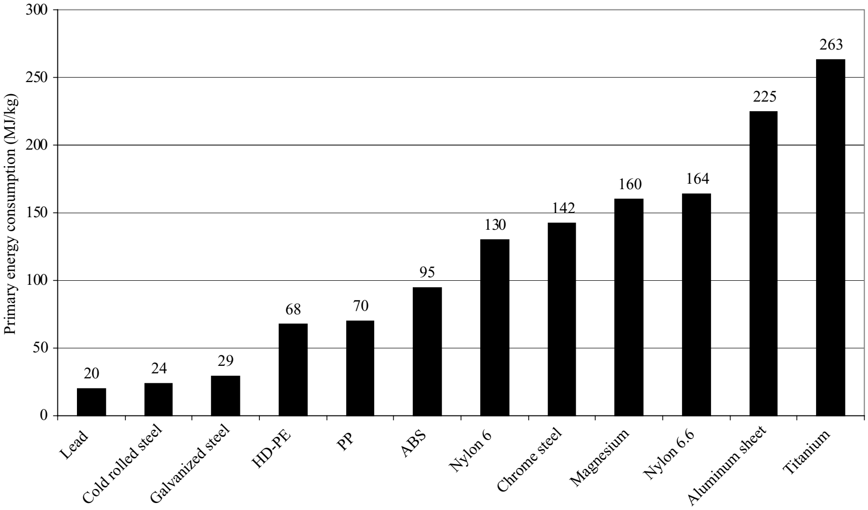

Figure 10.5. The energy embedded in metals by their manufacture. (Adapted from M. Schuckert, *Proc. 3rd Intl. Conf. on Ecomaterials*, Tokyo: Society of Non-Traditional Technology, pp. 325–329, 1997.)

Table 10.2. Depletion Times for the Common Industrial Metals

				Depletion Time (Years)	
Metal	Usage	Reserves	Reserve Base	t_D [Res] (yr)	t_D[Res Base] (yr)
Aluminum	105 Pg/yr	23 Eg	28 Eg	220	270
Copper	8.9 Pg/yr	310 Pg	590 Pg	35	66
Iron	850 Tg/yr	150 Pg	230 Pg	180	270
Lead	3.2 Pg/yr	63 Pg	130 Pg	20	41
Silver	14 Tg/yr	280 Tg	420 Tg	21	30
Tin	200 Tg/yr	8 Pg	10 Pg	40	50
Zinc	7.4 Pg/yr	140 Pg	330 Pg	19	45

*Abstracted from S. E. Kesler, *Mineral Resources, Economics and the Environment*, New York: Macmillan, pp. 347–359, 1994.

quantities of carbon dioxide are generated, making this sector a significant contributor to the global climate change problem.

As was done in Chapter 9 for fossil fuel resources, estimates of depletion times for metal resources can be calculated. The results appear in Table 10.2 where we have purposely performed the calculation using both the reserve base and the reserves. In the cases of aluminum and iron, the reservoirs of suitable minerals appear sufficient for centuries to come. For the other metals, however, reserves are much less abundant; all

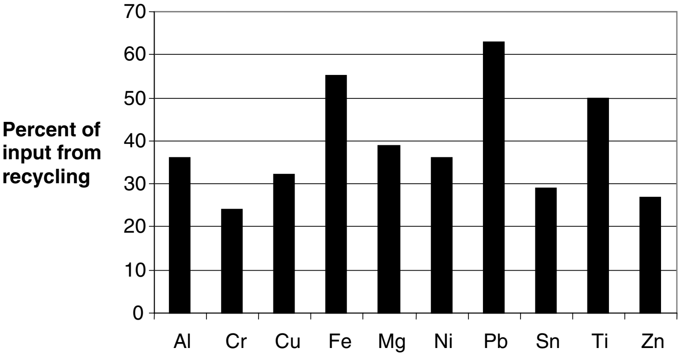

Figure 10.6. Recycled metals as a percent of total supply. (*Data source:* U.S. Geological Survey, Resources–Metals, http://minerals.usgs.gov/minerals/pubs/commodity/recycle/recymyb01.pdf, accessed August 30, 2003.)

those listed being less than 50 years on the basis of known reserves. The utilization of the currently uneconomical reserve bases of the metals would extend those depletion times by perhaps a factor of 1.5, but it appears prudent to begin thinking about vigorous conservation measures for those resources with very short depletion times such as lead, silver, and zinc.

One way in which depletion times can be lengthened is by procuring some of the needed materials though recycling rather than from virgin ores. For some metals, as shown in Figure 10.6, a significant percentage of the supply is being provided in this way. The feasibility with which metals can be recycled varies widely with the ease of recovery after first use and the suitability of reprocessing technologies, but recycling percentages continue to increase for most materials.

For the United States, the consumption, recycling, and dominant uses of the major metals are indicated in Table 10.3. It is notable that iron is both used and recycled at much higher rates than the other metals. Also of significance are the low recycling rates of both zinc and copper in comparison to the relatively low projected depletion times for these metals.

10.3.3 Process Chemicals and Ore Residues

The metal extraction process involves chemical steps as well as physical ones, and the chemicals used tend to be very aggressive. Those of greatest environmental concern are employed in leaching impurities from the ore. Perhaps the most problematic is cyanide (a solution of either KCN or NaCN), used for leaching gold from gold-bearing ores and in some lead and zinc mining processes. In a typical application, the ore is immersed in the leaching solution for periods of up to several months, after which the solution must be recovered and chemically treated if environmental damage is not to occur.

Table 10.3. Annual Flows and Major Uses of Industrial Metals in the United States (1996)

Metal	Annual Use (Tg)	Amt. Recycled (Tg)	Major Uses
Aluminum	6.3	3.1	Transportation-32% Packaging-28% Buildings-15%
Copper	2.8	0.4	Buildings-40% Electrical-25% Transportation-13%
Iron	9300	3300	Buildings-70% Infrastructure-12% Transportation-11%
Lead	1.4	1.0	Batteries-84% Paints, glass-5% Ammunition-5%
Silver	0.22	0.20	Photography-50% Electrical-20% Jewelry-10%
Tin			Solder 41% Chemicals 14% Plating 21%
Zinc	1.5	0.4	Galvanizing-55% Alloy products-31%

Source: Minerals Yearbook, U.S. Geological Survey, Washington, D.C., 1997.

Other hazardous leaching chemicals include sodium hydroxide and a variety of strong mineral acids. The byproduct of the leaching and beneficiation is *tailings*, a slurry that is typically half-liquid, half-solid, and contains extraneous crushed rock, trace metals, and residues of the chemical leaching process. In modern mining, tailings are stored in lined holding ponds; traditional practice had been to simply discard them into the nearest body of water.

Overall, the residues generated by this sector are quite high, second only to the chemical industry. Most of the material is concentration wastes (ore residues plus process chemical residues). The residues from iron and steel processing are largely ore impurities, while those from nonferrous metals processing contain substantial quantities of process chemicals or their products.

10.3.4 Water

Water use in this sector is high, as a significant amount of early-stage ore processing involves crushing of the rock followed by gravitational separation in flowing water.

Water-based separation technology tends to be inexpensive and reasonably effective, but it also implicitly degrades the local water discharge streams. The recycling and reuse of water in this sector have advanced greatly in recent years, and water use is of lesser concern thas was formerly the case.

10.4 POTENTIAL ENVIRONMENTAL CONCERNS

The metal ore extraction and processing sector has a number of potential environmental interactions. Of the top 20 chemicals or chemical groups reported under the U.S. Toxic Release Inventory for 1998, five are metal-related: zinc compounds (#2 in terms of releases and transfers), manganese compounds (#9), copper compounds (#14), chromium compounds (#18), and lead compounds (#20).

10.4.1 Solids

The principal reason that this sector uses so much energy and generates such a large quantity of solid residue is that the typical concentration of target metals in the ores is rather low. The remaining essentially valueless rocks and minerals, termed gangue, must be extracted with the target metal, separated from it, and then returned to the ground in an environmentally sound manner. The sheer quantities of material involved make this difficult. As Table 10.4 demonstrates, of the ore mined worldwide in 1991, only about 15 percent was utilized and the rest was discarded. The situation is even more dramatic in the case of gold, where each gram of gold requires blasting and processing about 120 kg of rock—a cube nearly a meter on each side. Overall, the generation of waste rock and smelting residues makes metal mining the industry with consistently the largest rate of release of problematic solid residues.

Table 10.4. Global Materials Flows Associated with Major Minerals, 2000

Mineral	Ore (Tg)	Average Grade (%)	Residues (Tg)
Copper	1580	0.91	1565
Iron	1410	40.0	564
Lead	124	2.5	120
Aluminum	104	23.0	71
Nickel	52	2.5	51
Others	925	8.1	850
Total	4195		3221

Source: After J. E. Young, *Mining the Earth*, Worldwide Technical Paper 109. Washington, DC: Worldwatch Institute, 1992. Some data are from U.S. Geological Survey, *Mineral Yearbook*, Washington, D.C., 2000.

10.4.2 Liquids

Liquids are major residue problems in metal ore extraction and processing. Three categories can be distinguished: mine water, sludge, process chemicals, and tailings.

Mine water is water pumped out of mines to permit ore extraction or remove water that arises from precipitation during mining activities. This water is likely to be acidic and to contain high concentrations of hazardous metals. The acidity arises from reactions of water and oxygen with sulfide ores. For pyrite, for example, the overall reaction can be expressed as:

$$2FeS_2 + 2H_2O + 7O_2 \rightarrow 2FeSO_4 + 2H_2SO_4$$

The reaction is mediated by bacteria. Mine water can be pumped to treatment ponds where it is treated and neutralized, but many older facilities do not have this capability in place.

Slurries of gangue, metals, and leaching chemicals are customarily stored in above-ground impoundments and gradually dried to form sludge. This hardened or semi-hardened sludge is generally redeposited back into the exhausted mine cavities. Alternatively, the slurries in their liquid form may be injected directly into exhausted underground mines.

Although process chemicals are used in closed-batch leaching systems, the significant environmental concern is from leaks in the baths. One famous example is that of cyanide, which has escaped the closed bath system in many instances. The cyanide can be transported through surface water systems and have immense deleterious effects on downstream aquatic ecosystems, and in some cases has migrated through ground water aquifers, threatening human drinking water supplies.

Mine tailings pose significant environmental problems years after mining operations terminate. Tailings from heavy metals and coal (Chapter 8) extraction often contain high quantities of toxic heavy metals and acid-forming minerals. Tailings can also contain chemical agents used to process the ores, such as cyanide or sulfuric acid. Tailings are usually stored above ground in containment areas or ponds (and in an increasing number of underground operations they are pumped as backfill into the excavated space from which they were mined). If improperly secured, contaminants in mine waste can leach out into surface and groundwater causing serious pollution.

Unlike the environmental impacts of many industries, which stop when industrial activities stop, liquid mining residues continue to be generated long after mining ceases. Acid mine drainage (AMD) and the drainage of surface and ground water containing toxic metals remain continuing problems in many regions of the world. AMD is likely the mining industry's greatest environmental problem and its greatest liability, especially to waterways. An acid-generating mine has the potential for long-term, devastating impacts on rivers, streams and aquatic life, becoming in effect a perpetual source of pollution. Text box 10.2 illustrates the harmful repercussions of AMD at the Britannia Mine in British Columbia. In addition to being an ecological concern, AMD has proven to be a significant financial liability. For example, in Canada, there are an estimated 351 millions tons of waste rock from mining, 510 million tons of sulfide tailings, and more than 55 million tons of other mining sources which have the potential to cause AMD. Cleanup at existing acid-generating mines in Canada will cost the mining companies and the government between $2 billion and $5 billion.

Text Box 10.2

Damage from Acid Mind Drainage in British Columbia, Canada

The former Britannia Mine, located 50 km north of Vancouver near Squamish, B.C., was once the largest copper producer in the British Empire. Discovered in the late 1800's, it was operated from 1905 to 1963 by the Britannia Mining and Smelting Company Ltd., and from 1963 to 1974 by the Anaconda Mining Company. In total, approximately 48,000,000 tons of ore were mined from seven ore bodies for copper, silver, zinc, and gold. The mine's mill building is located in the town of Britannia Beach, which sits directly on Howe Sound. The mine extends approximately 6 kilometers westward into the Coastal Mountain Range.

Environment Canada has called the mine "the worst single source of metal pollution on the North American continent." The abandoned mine's AMD currently threatens the health of Howe Sound. Every day, millions of liters of contaminated water from the mine flow into the ocean inlet via Britannia Creek and a large underwater outflow pipe. The resultant effluent is highly acidic, with a pH between 2 and 4, and it carries a whole suite of dissolved metals into Britannia Creek and Howe Sound. These metals include iron, aluminum, cadmium, zinc and copper. During the spring snowmelt, more than a ton of copper, zinc and cadmium can be flushed from the mine's 160km of tunnels and enter Howe Sound in a single day.

In 1996, residents claimed that life in the creek was damaged, and that the mine's toxic water has had a similar effect on aquatic life near the town of Britannia Beach. Surface waters from Britannia Creek are highly toxic to young salmon. When chinook salmon smolts were held in cages near Britannia Creek, they all died in less than 48 hours, whereas at Porteau Cove, a site on Howe Sound that is not impacted by AMD, almost all of the young salmon remained healthy. Studies have shown that the mine effluent is harmful to mussels, brine shrimp and salmon; copper concentrations in Britannia Bay surface waters are well in excess of the toxic level for most marine organisms. By May 1997, it was reported that the only sign of life in Britannia Creek was some algae on rocks.

In April 2001, the first clean-up plan for the Britannia Mine was unveiled. Initial costs of remediation are on the order of $40 million US.

Source: Environmental Mining Council of British Columbia. (http://www.miningwatch.org/emcbc/index.htm)

10.4.3 Gases and Particles

The most significant atmospheric impact of ore extraction is the generation of fugitive windblown dust. Specific sources include ore crushing, conveyance of crushed ore, loading bins, blasting, mine and motor vehicle traffic, use of hauling roads, waste rock piles, windblown tailings, and disturbed areas. Always an annoyance, the dust can be hazardous if it contains arsenic, lead, radionuclides, or other problematic materials. Particulate matter is an environmental concern because it can contaminate air. It can also deposit dust in surface water, causing sedimentation and turbidity.

During smelting, the biggest concern is with the sulfur in the ore. Traditionally, the resulting SO_2 was simply vented to the atmosphere. In modern facilities it is likely to be captured by limestone scrubbing to form gypsum. The gypsum can be used as construction filler or in wallboard manufacture if geographical proximity makes these uses financially attractive.

During the refining step, the gaseous emissions of most concern are probably the saturated fluorocarbons (CF_4 and others) from the electrolytic refining of aluminum. (The saturated fluorocarbons are potent greenhouse gases.) Vigorous efforts are underway to reduce these emissions.

10.4.4 Land Use and Habitat Destruction

By its very nature, mining can cause large disturbances to the land. The large amounts of land required for metal ore extraction, particularly strip mining, result in significant deforestation and habitat destruction. Not only can there be direct terrestrial and aquatic ecological impacts from mining, but the manipulation of topography and releases of particulates and chemicals can all have indirect impacts on various habitats.

Sedimentation and erosion due to mining activities pose serious problems. The extent of erosion and sedimentation depends on various factors, including the degree to which the surface has been disturbed, the prevalence of a vegetative cover, the type of soil, the slope length, and the degree of slope. Disturbed areas with little or no vegetative cover, soils high in silt, or a steep slope are the areas most likely to erode. Erosion and sedimentation affect surface water and wetlands more than any other media. Erosion can also adversely affect soil organisms, vegetation, and revegetation efforts because it results in the movement of soil, including topsoil and nutrients, from one location to another.

Mining subsidence is also an environmental concern. Subsidence is the surface impact of the collapse of overlying strata into mined-out voids. Subsidence may manifest itself in the form of sinkholes or troughs. Sinkholes are usually associated with the collapse of a portion of a mine. Sinkholes or depressions interrupt surface water drainage patterns, affecting ponds, streams, and wetlands. Reducing the withdrawal of groundwater through specific practices such as recycling mine water can reduce the potential for subsidence. The threat and extent of subsidence is related to the method of mining employed. In many instances, traditional room and pillar methods of underground mining leave enough material in place to avoid subsidence. However, high volume extraction techniques, such as pillar retreat and longwall mining, result in a strong likelihood of subsidence. Preventing subsidence involves leaving support mechanisms (e.g., pillars) in place after completing the mining operation or backfilling with waste rock.

A final land use concern from mining is aesthetic degradation of mined landscapes. Aesthetics involve the general visual environment, including the overall scenery and unique topographical characteristics. Since most mining operations result in large land disturbances, aesthetic impacts can be significant. Recontouring the land to reduce unnatural anomalies, backfilling holes, revegetating, and promoting wildlife habitats can all improve the aesthetics of mining operations.

10.4.5 Sustainability Assessment

The potential emittants resulting from processes in this industrial sector are given in Table 10.5, and the potential hazards are collected and evaluated in Table 10.6. Only the usual engineering metals are included, and those only if they are the principal target constituent of the ore. The highest concern is for mine water, tailings, lead, and mineral acids. The potential hazard from dissipated copper and silver, sulfur dioxide, slags, and discarded overburden is also high. The results appear in the throughput-potential hazard diagram of Figure 10.7.

The resource scarcity concerns in this sector are also diagrammed in Figure 10.7. Of particular note are four metals with rather short depletion times: copper, gold, silver, and zinc.

This sector uses very large amounts of both energy and water. As a result, the PEC and PWC matrices both have the "high concern" row called out for special attention in Figure 10.8.

Table 10.5. Processes, Activities, and Potential Emittants for the Metal Ore Extraction and Processing Sector

Process Type	Sector Activities	Potential Emittants
Extraction	Mining	Mine water
	Stripping	Overburden, habitat loss
Beneficiation	Crushing, grinding	Windblown dust
	Floatation	Toxic tailings
	Leaching	Toxic tailings
Cleaving bonds	Smelting	SO_2, H_2SO_4
Purification	Refining	Slags, CF_4

Table 10.6. Throughput-Hazard-Scarcity Binning of Materials in the Metal Ore Extraction and Processing Sector

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
Site preparation	M	Ecosystem	M	–
Overburden	H	Ecosystem	M	–
Aluminum	H	–	L	L
Copper	H	Ecosystem	M	H
Gold	H	–	L	H
Iron	H	–	L	L
Lead	H	Human	H	H
Nickel	H	–	L	M
Silver	H	Ecosystem	M	H
Zinc	H	–	L	H
Mineral acids	H	Ecosystem	H	L
Mine water	H	Ecosystem	H	–
Windblown dust	M	–	L	–
Tailings	H	Ecosystem	H	–
Slags	M	Ecosystem	H	–
SO_2	M	Acid rain	H	–
CF_4	L	Climate change	H	–

The sector ΣWESH plot in Figure 10.9 is dramatic in its concentration of entries to the right of the diagram, and especially to the upper right. It is obvious that the potential for poor environmental performance in this sector is great, and that continued efforts to reduce the magnitudes of inputs and losses will pay great dividends.

10.5 SECTOR PROSPECTS

10.5.1 Trends

Trends for the metal ore extraction and processing sector have been divided into extraction and mine site trends and processing trends, reflecting the two main operations within this industry. Regulation and societal trends significant to this sector are also discussed.

10.5.1.1 Extraction and Mine Site Trends

The increasing use of high technology during both exploration and extraction processes is an active trend for the mining industry.

A major effort is the development of techniques for non-invasive exploration using remote sensing, advanced data processing, and computer modeling techniques that more accurately locate and map areas of minable resources. To the degree that

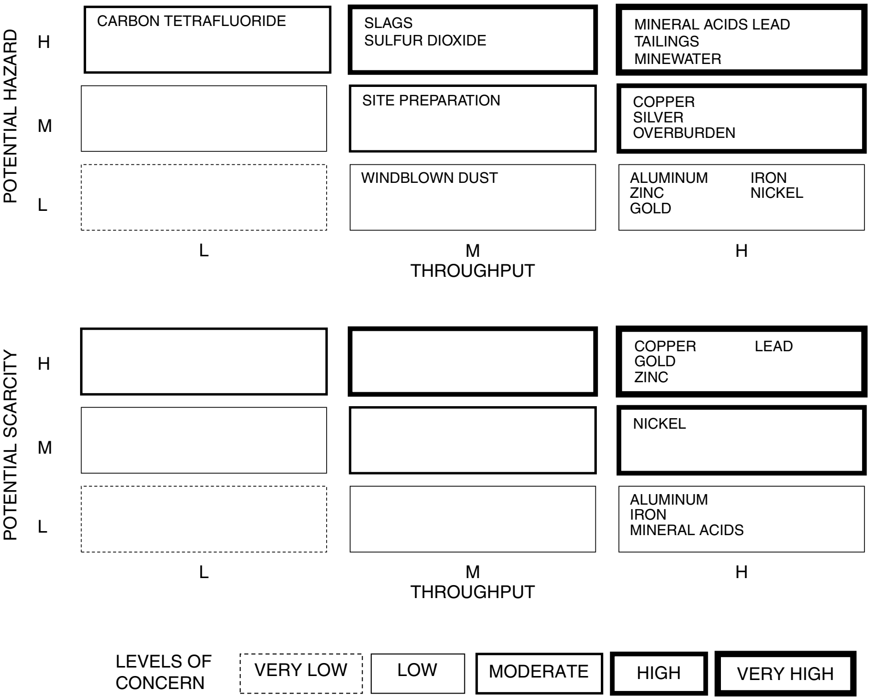

Figure 10.7. The throughput-potential hazard matrix (top panel) and throughput-potential scarcity matrix (bottom panel) for the metal ore extraction and processing sector.

this is successful, it could minimize the drilling of test holes and, by mining higher-grade ores, the generation of overburden. One example is the development of real-time mineral content sensors for all minerals. This would minimize the energy-intensive and laborious processes of collecting samples (surficially and sub-surficially) and analyzing them. Another more distant example is the creation of new sensors operating from space, high altitudes, low altitudes, above ground, and below the ground surface to characterize mineral occurrences. Techniques like this would reduce the need for blind drilling and exploration.

Once a mine has been opened, a second potential new technology can be envisioned. Known as near-face beneficiation, this is conceived as the development of processes by which ore removed from the mine face (i.e., the exposed rock in the strip mine or shaft) could be beneficiated and perhaps further processed within the mine itself rather than by the removal of the entire rock volume from the mine to a designated processing area. The challenge will be to develop physical and chemical separation processes that can be carried out efficiently in rather small spaces, while maintaining the desired level of product purity and worker safety. Given the enormous

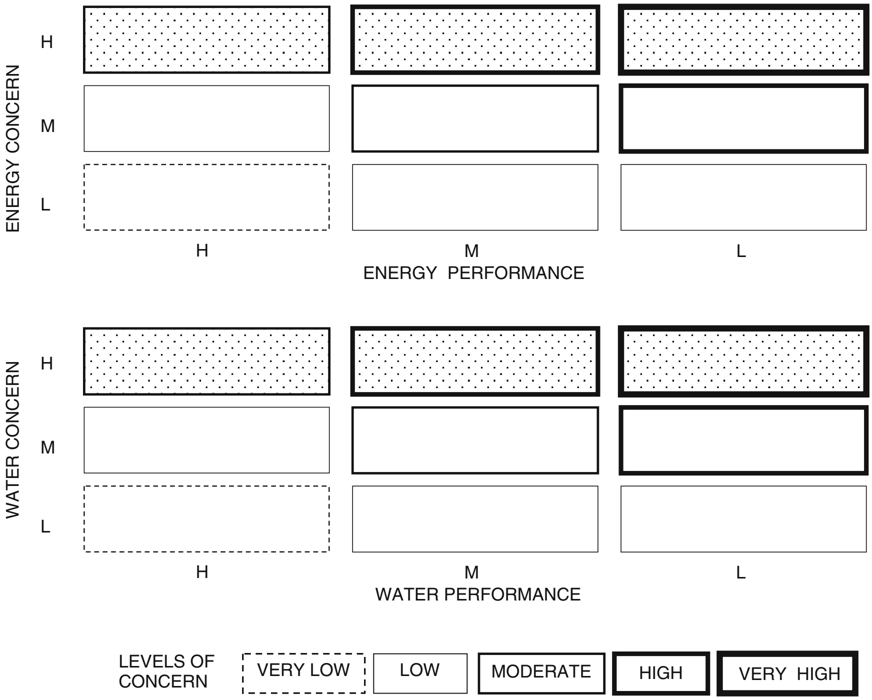

Figure 10.8. The energy performance-energy concern matrix (top panel) and water performance-water concern matrix (bottom panel) for the metal ore extraction and processing sector. The stippled rows reflect typical levels of sector consumption.

amounts of overburden involved, the environmental improvement potential for near-face beneficiation is high.

Research is underway in the mining engineering field to develop robot miners—robots directed by sophisticated navigational and chemical sensors—that could tunnel into promising ore bodies and efficiently extract rich metal ore from small veins and thin seams of high-quality material. The extraction process itself might make use of biological extraction, aspects of which are currently used for above-ground ore processing. Similar approaches could then be applied to underwater mining of manganese nodules and other marine and freshwater subsurface resources.

10.5.1.2 *Processing Trends*

A major effort is being made to reduce the amount of energy used in metals refining. Current levels are between two and three times the predicted thermodynamic minima, and comprise more than 3 percent of total industrial energy use. Better

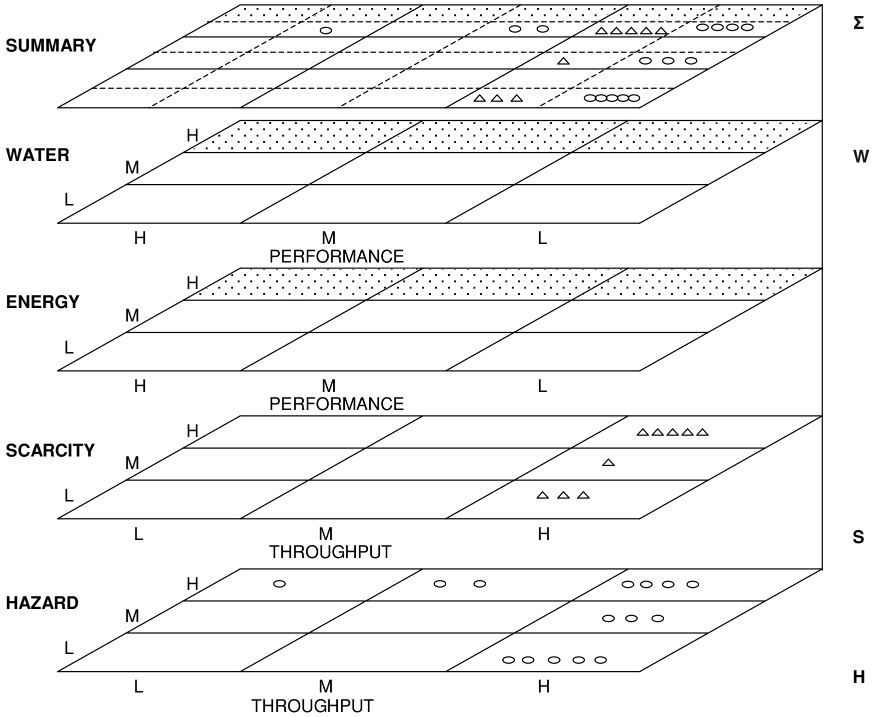

Figure 10.9. The ΣWESH plot for the metal ore extraction and processing sector. The squares and circles refer to the materials in Figure 10.7.

energy housekeeping and the gradual phase-in of more efficient equipment will make noticeable improvements. As long as low-grade ore is mined and metal is melted, however, the energy requirements will continue to be substantial.

In smelting and refining, the long-term goal is for zero or near-zero emissions. Two factors strongly influence achievement of this goal. The first is that downstream emissions reflect the purity of the material provided by the upstream processes. If the products of extraction can be made purer, slag and other unwanted byproducts of smelting and refining will be decreased. The second consideration is that many metals occur as sulfides in the ore (Table 10.1). If near-zero emissions are to be achieved in smelting, the sulfur must be trapped; it cannot be avoided, as it is part of the feed stock material.

Technology under development will help reduce emissions of carbon dioxide and other greenhouse gases from aluminum smelting. Today, primary aluminum processing typically involves a carbon anode with molten cryolite as the electrolyte and molten aluminum acting as the cathode in an electrolytic cell. When electric energy is added and the carbon anode consumed, the raw alumina (Al_2O_3) is converted to aluminum plus CO_2. Additional variability in the process causes the emissions of perfluorocarbons, which are greenhouse gases. Development of inert cathode and anode technology for *electrowinning* of aluminum in primary electrolysis cells is the subject of ongoing research. This technology would significantly decrease emissions of gases that contribute to global climate change.

Two process trends specific to the iron and steel manufacturing industry are of interest. First, the sintering process of ironmaking has the capacity to recycle and recover iron-bearing waste oxides that are generated from ironmaking and steelmaking facilities. It has an added benefit of producing a material that replaces iron pellets with recycled and iron-bearing secondary material, and also adds stability to blast furnace operation. Some blast furnaces in Japan operate on virtually 100% sinter feed. This emphasis on recycling and recovery will likely become a more common trend in the ironmaking industry. It should be noted that other environmental concerns from sintering, primarily water and air effluents, pose significant environmental concerns. These environmental concerns and high overall capital and operating costs have led to declining use of traditional sinter plants. This has afforded the emergence of other waste oxide agglomeration processes that serve as a substitute for sintering.

Second, the steel industry is starting to use natural gas to reduce iron ore to produce Direct Reduced Iron (DRI). As direct reduction plants are not built on the same, enormous scale as blast furnaces, their investment costs are lower, and they have been mainly constructed in developing countries where natural gas is relatively inexpensive. Recently, however, even in developed countries, direct reduction plants are drawing more and more attention as a way to provide a stable supply source of both pure and scrap iron. This process is environmentally superior because it recycles the used gas for a second combustion, making the energy consumption more efficient and less polluting than traditional blast furnace processes.

10.5.1.3 *Social and Regulatory Trends*

In the U.S., since the passage of the Resource Conservation and Recovery Act (RCRA) in 1976, Congress, the mining industry and the Environmental Protection Agency (EPA) have maintained that waste products generated by the mining industry do not warrant hazardous waste regulation. At sites where hazardous substances may have been released due to mining operations, the Comprehensive Environmental Response, Compensation and Liability Act (better known as Superfund) sometimes comes into play. It provides for emergency response cleanup and determination of liability for hazardous substances released into the environment, including releases from inactive waste disposal sites.

As significant problems like acid mine drainage and land and habitat impacts can persist far beyond the long life of a mine, it is likely that there will be increased social and regulatory pressure brought to bear on mining operations to avoid and reduce such impacts.

Text Box 10.3

Curbing Greenhouse Gas Emissions from Iceland's Steel Industry

The silicon used in silicon-bearing steels is produced in a reaction that can be described as

$$SiO_2 + 2C \rightarrow Si + 2CO$$

Similarly, a side chain reaction in aluminum production is

$$Al_2O_3 + 3C \rightarrow 2Al + 3CO$$

The toxic CO gas is traditionally converted to CO_2 (a greenhouse gas) by adding ambient air.

To minimize Iceland's CO_2 emissions, researchers from the University of Iceland are working with local industry to produce methanol (CH_3OH) from the CO and from hydroelectrically-generated hydrogen:

$$CO + 2H_2 \rightarrow CH_3OH$$

The methanol that is produced can be used as fuel for Iceland's transport and fishing industries, and CO_2 emissions from methanol-fueled vehicles are about half those of an equivalent gasoline-fueled vehicle. Thus, if the approach is fully implemented, it appears possible to reduce the country's CO_2 emissions by between one-third and one-half.

Source: B. Arneson and T. Il. Sigfusson, Converting CO_2 emissions and hydrogen into methanol vehicle fuel, *JOM, 51*(5), 46–47, 1999.

10.5.2 Possible Future Scenarios

10.5.2.1 Trend World

In this scenario, virgin material would be extracted from lower and lower grades of ore as overall reserve quality decreases. However, pressure would continue to be placed on mining companies to reduce and mitigate environmental damage. Recycling will likely become more and more prevalent as virgin supplies become more costly to extract and process.

The potential to pollute is clearly large in the metal ore extraction and processing sector, and will continue to be so in the future, under this scenario. The demand for metal products, however, will continue unabated. Substantial supplies of metals will be needed to support the evolution of a technological society. Even those metals that are needed in small quantity may be essential for certain functions. Examples include the alloying elements in high-strength steels and the platinum-group metals used as catalysts in many industrial chemical reactions.

10.5.2.2 Green World

In this scenario, improved environmental technologies will continue to be developed for the metal mining sector. Among them will be improved chemical management of tailings, the development of non-toxic reagents for some leaching processes, and the use of wetlands systems for treating acid mine drainage.

A sharp decrease in the mining of metal ores will occur because of the declining economic feasibility of extraction and the rising costs associated with adequate mitigation of environmental impacts. Metals will continue to be important materials in industry and commerce, but they will increasingly be derived from scrap metal. New technologies will be developed to enable the recovery of metals from complex products, and infrastructure will be put in place to collect used products containing metals.

10.5.2.3 Brown World

In this scenario, the response to declining high-grade ore reserves will involve intensification of mining activities to extract lower-grade ore. To acquire the same amount of metal, more ore will be mined and more overburden, gangue, and tailings will result. The area of land required to extract the lower grade ore will increase, likely infringing upon previous untouched ecological habitats across the globe. Energy efficiency measures will not improve during extraction, resulting in increased greenhouse gas emissions from this process.

The ore processing trend in this scenario continues to resort to high energy consumption and low utilization rates of recycled materials, such as are used in the EAF. With expanded production of low-quality ore, the energy requirements of processing will likely increase as well.

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Chapter 11

Inorganic Minerals and Chemicals

11.1 OVERVIEW

A small number of inorganic minerals extracted from the ground form the basis for much of modern technology. The most important of these minerals, what we might term the "crucial seven", are given in Table 11.1; they feature non-metal cations (positive ions) common in Earth's crust (calcium, sodium, sulfur, titanium) and anions (negative ions) present or readily formed in Earth's bodies of water (carbonate, chloride, phosphate). These materials, which have been known and used since ancient times, are relatively abundant, relatively easy to extract, and capable of being transformed into a somewhat larger family of more reactive chemicals. Of this group, only rutile is used without chemical change, and it nonetheless must be purified before use.

The technological sequence diagram for the inorganic minerals and chemicals sectors is given in Figure 11.1. While the first step is the extraction of the inorganic materials mentioned above, the important next step is generally the production of reactive inorganic intermediates, the most common of which are given in Table 11.2. Several of these latter materials are used directly as fertilizers by the agricultural sector (see Chapter 13), which begins to give some sense of the large relative size of that activity. Nearly all of the rest are what the chemical industry terms "starting materials"; their primary fate is to serve as reactants in the formation of a very large variety of inorganic and organic products (see Chapters 12 and 18).

11.2 PHYSICAL AND CHEMICAL OPERATIONS

The inorganic minerals are, for the most part, collected from deposits on or near the surface, i.e., they are strip-mined. This form of mining is efficient and relatively

Table 11.1. The Most Important Nonmetallic Minerals

Common Name	Chem. Formula	Common Uses
Flowers of sulfur	S	Synthesis of sulfuric acid, rubber vulcanization
Limestone	$CaCO_3$	Synthesis of lime
Phosphate rock	$Ca_3(PO_4)_2$	Synthesis of fertilizer
Potash	K_2CO_3	Synthesis of fertilizer
Rutile	TiO_2	Paint pigment
Salt	NaCl	Synthesis of chlorine and hydrochloric acid
Soda ash	Na_2CO_3	Synthesis of caustic soda

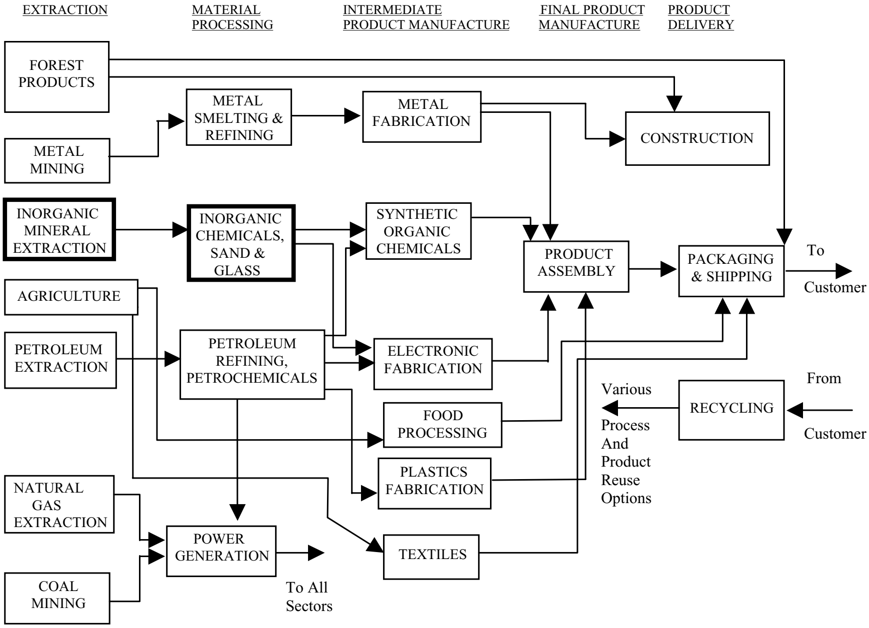

Figure 11.1. The technological sequence diagram for the inorganic minerals and chemicals industries. The industry sector itself is indicated by heavy outlining.

inexpensive, and large quantities of these materials are extracted. The invariable next step is that of beneficiation, since the mineral deposits are never perfectly pure. This generates material that can be used as the basis for synthesizing other chemicals. ("Synthesis" is the creation of a substance by one or more chemical reactions.) The synthesized chemicals are also never pure, and a subsequent purification step is required.

Table 11.2. The Most Important Synthesized Inorganic Chemicals

Common Name	Chemical Formula	State	Common Uses
Ammonia	NH_3	Gas	Reactant, fertilizer
Ammonium nitrate	NH_4NO_3	Solid	Fertilizer
Ammonium sulfate	$(NH_4)_2SO_4$	Solid	Fertilizer
Carbon dioxide	CO_2	Gas	Solvent, refrigerant
Caustic soda	$NaOH$	Liquid	Reactant, acid neutralizer
Chlorine	Cl_2	Gas	Reactant
Hydrochloric acid	HCl	Liquid	Reactant
Hydrogen	H_2	Gas	Reactant
Lime	$CaO/Ca(OH)_2$	Solid	Reactant
Nitric acid	HNO_3	Liquid	Reactant
Nitrogen	N_2	Gas	Reactant
Oxygen	O_2	Gas	Reactant
Phosphoric acid	H_3PO_4	Liquid	Reactant
Sulfuric acid	H_2SO_4	Liquid	Reactant
Superphosphate	$CaH_4(PO_4)_2$	Solid	Fertilizer

The use of water and energy and the generation of residues can be demonstrated by examining the principal chemical reactions linking the minerals to the synthesized products. The details of the chemistry are the subject of entire texts, and many alternate synthesis routes exist, but the concept can be illustrated by example reactions. In what follows, the usual requirements for high temperatures and pressures and the presence of catalysts is not indicated, nor are the reactions chemically balanced (since in practice there are often a number of reactions involved).

Sulfur to sulfuric acid:

$$S \rightarrow SO_2 \rightarrow SO_3 \rightarrow H_2SO_4$$

Limestone to lime:

$$CaCO_3 \rightarrow Ca(OH)_2 + CO_2$$

Air to oxygen and nitrogen:

$$\text{Air} \rightarrow O_2 + N_2$$

Propane (a petrochemical feedstock) to hydrogen:

$$C_3H_8 \rightarrow H_2 + CO$$

Salt to chlorine, caustic soda, and hydrochloric acid:

$$NaCl \rightarrow NaOH + Cl_2$$

$$NaCl + H_2SO_4 \rightarrow HCl + NaHSO_4$$

Coke to carbon dioxide:

$$\text{Coke} + O_2 \rightarrow CO_2$$

Soda ash to caustic soda:

$$Na_2CO_3 + Ca(OH)_2 \rightarrow NaOH + CaCO_3$$

Phosphate rock to phosphoric acid and superphosphate:

$$Ca_3(PO_4)_2 + SiO_2 \rightarrow H_3PO_4$$

$$Ca_3(PO_4)_2 + H_2SO_4 \rightarrow CaH_4(PO_4)_2 + CaSO_4$$

Nitrogen and hydrogen to ammonia:

$$N_2 + H_2 \rightarrow NH_3$$

Ammonia to nitric acid:

$$NH_3 + O_2 \rightarrow HNO_3 + H_2O$$

Ammonia and nitric acid to ammonium nitrate:

$$NH_3 + HNO_3 \rightarrow NH_4NO_3$$

Ammonia and sulfuric acid to ammonium sulfate:

$$NH_3 + H_2SO_4 \rightarrow (NH_4)_2SO_4$$

These reactions, so simple in appearance on paper, are great technological challenges in practice. Most of them are carried out at high temperatures and pressures, and in the presence of catalysts (materials that allow or accelerate a reaction without being transformed themselves), for the following reasons:

- To overcome the energy barrier to the reaction
- To increase the rate of the reaction
- To induce the reaction to go further toward completion (i.e., to increase the fraction of products relative to that of reactants)

11.3 THE SECTOR'S USE OF RESOURCES

11.3.1 Energy

The minerals and inorganic chemicals sector ranks next to petrochemicals and coal production as the most energy intensive. Minerals extraction itself is, of course, quite energy intensive because of the very large amounts of materials to be moved.

Text Box 11.1

Reducing the Energy Demand of Chlor-Alkali Production

Chlor-alkali plants use substantial amounts of energy to separate the sodium and chlorine atoms in common salt and recombine them as chlorine gas (Cl_2) and caustic soda (NaOH), both vital materials in many industrial chemical processes. The process can be written as

$$2NaCl + 2H_2O \xrightarrow{\text{electricity}} 2NaOH + Cl_2 + H_2.$$

The Italian company DeNora S.p.A. has recently studied the feasibility of using stationary fuel cells to provide some of the power for this process. The concept is that the hydrogen gas from the process will be fed to the fuel cells, which will use that fuel to generate power that is fed back to run the electrolytic process. The bank of fuel cells is computer controlled to optimize the interaction between power generation and power use. The system is entering service and is expected to provide up to 20% of the total energy required to operate the chlor-alkali facility.

Source: D. T. Mah, J. W. Weidner, and S. Motupally, Report on the electrochemical industries for the year 1998, *Journal of the Electrochemical Society, 146*, 3924–3947, 1999.

Additionally, the high temperatures and pressures under which many of the chemically transformed products of the sector are produced require large injections of energy. Although energy efficiency can nearly always be improved, the mass flows and transformations by which the sector is defined set the very substantial minimum rate of energy consumption.

11.3.2 Materials

After energy materials, construction materials, and agriculture, the inorganic chemical sector ranks highest in materials mobilization, at least in the United States (see figure 11.2). This is largely a consequence of its position near the start of the industrial sequence, and of the percentage of total sector flows dedicated to the production of fertilizer. One of the initial stages is the synthesis of ammonia. It is sometimes used directly as a fertilizer, but more often employed as the starting material for nitrate fertilizers (through urea and nitric acid). Phosphorus fertilizers form the second major component. They originate in phosphate rock (note the very large overburden and concentration wastes). The phosphate rock is then converted to superphosphate by reaction with sulfuric acid, which is itself produced from elemental sulfur. The gypsum that also results from the reaction sequence to produce superphosphate is the main ingredient in wallboard, and is used in the construction industry.

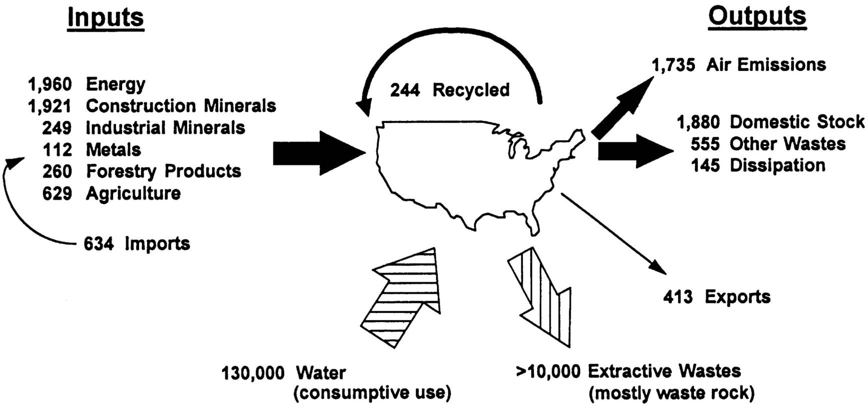

Figure 11.2. The estimated flows of materials through the U.S. economy, circa 1990. The values are in Tg. (Reproduced with permission from I. K. Wernick and J. H. Ausubel, National materials flows and the environment, *Annual Review of Energy and the Environment, 20*, 463–492, © 1995 by Annual Reviews, www.annualreviews.org)

Scarcity is not a significant problem in the inorganic minerals and chemicals sector. Supplies of these materials are ample, none having depletion times of less than several hundred years.

11.3.3 Process Chemicals

As shown in Section 11.2 most chemical reactions produce byproducts as well as products. In addition, they take place in solvents (generally water for the inorganic chemicals). The byproducts and solvents are often of little value, and may be disposed of as waste. The typical manufacturing process for an inorganic chemical generates 2–5 kg of residues for every kg of product.

11.3.4 Water

Industrial chemical extraction and reaction processes are big users of water, ranking in the top half-dozen industrial sectors in water use. Within the extractive industries in the United States, fossil fuel mining requires the most water, with mineral mining next. Even higher rates of use occur in what is termed the chemical sector (which includes not only inorganic mineral processing but also the synthetic organic chemical sector discussed in Chapter 18). The chemical sector is, in fact, the biggest water user after agriculture.

11.4 POTENTIAL ENVIRONMENTAL CONCERNS

The chemical sector processes very large quantities of material and generates very large amounts of residues. Of the top 20 chemicals reported under the Toxic Release Inventory in the U.S., five are inorganic: ammonia (#3 in terms of releases and transfers), nitrate compounds (#4), chlorine (#10), hydrochloric acid (#11), and phosphoric acid (#12). Inorganic chemical processing residues have several principal fates, the most common of which is injection into underground storage reservoirs such as inactive mines. Some 70% of residues meet that fate, the remainder being largely relegated to surface impoundments.

11.4.1 Solids

The inorganic minerals and chemicals sector is far ahead of all other sectors in the generation of production-related waste, though the quantities have been substantially reduced in recent years. Much of this material is disposed of as sludge; it typically has a very high liquid water content.

11.4.2 Liquids

Liquid residues, especially hazardous ones, are tracked extensively by regulatory agencies. The minerals and inorganic chemicals sector tends to manufacture byproducts that are detrimental to the environment if released.

11.4.3 Gases

Gaseous emissions are a significant problem for the inorganic chemicals sector. Carbon monoxide and volatile organic carbon compounds (VOCs) are the most common emittants to the air.

11.4.4 Sustainability Assessment

The potential emittants, activities, and hazards resulting from processes in this industrial sector are given in Table 11.3, and the materials binned for throughput, potential hazard, and potential scarcity in Table 11.4. The TPH matrix appears in Figure 11.3. It generally shows that the inorganic minerals have low to negligible hazard potential, since as common constituents of Earth's crust they tend not to be biologically harmful. For the chemicals synthesized from the minerals, the fertilizers are also not harmful (in fact, are designed to be beneficial to vegetation). The reactants, however, tend to be hazardous precisely because they are designed to be reactive. Of extreme potential hazard are the strong acids and bases. Of only slightly less concern,

Table 11.3. Processes, Activities, and Potential Emittants for the Mineral Extraction and Processing Sector

Process Type	Sector Activities	Potential Emittants
Extraction	Mining	Overburden, habitat loss
Beneficiation	Crushing, grinding	Windblown dust
Cleaving bonds	Chemical reactions	CO_2, CO, NH_3
Purification	Washing	Acid residues
Forming bonds	Chemical reactions	VOCs, sludge, HCl

Table 11.4. Throughput–Hazard Binning of Materials in the Mineral Extraction and Processing Sector

Material	Throughput Magnitude	Hazard Potential
Flowers of sulfur	H	L
Limestone	H	L
Phosphate rock	H	L
Potash	H	L
Rutile	M	L
Salt	H	L
Soda ash	H	L
Ammonia	H	H
Ammonium nitrate	H	M
Ammonium sulfate	M	L
Carbon dioxide	M	L
Caustic soda	H	H
Chlorine	M	H
Hydrochloric acid	H	H
Hydrogen	M	H
Lime	H	L
Nitric acid	H	H
Nitrogen	M	L
Oxygen	M	L
Phosphoric acid	H	H
Sulfuric acid	H	H
Superphosphate	H	L

because of their throughput magnitudes, are the industrial gases H_2 and Cl_2. Unlike some of the organic materials we will discuss in Chapter 18, non-metallic inorganics manifest their hazardous nature on contact with biological receptors; they have little or no long-term effects.

The THS matrix is also given in Figure 11.3. The only significant concern is for sulfur and its derivatives, since sulfur has a depletion time of less than 40 years.

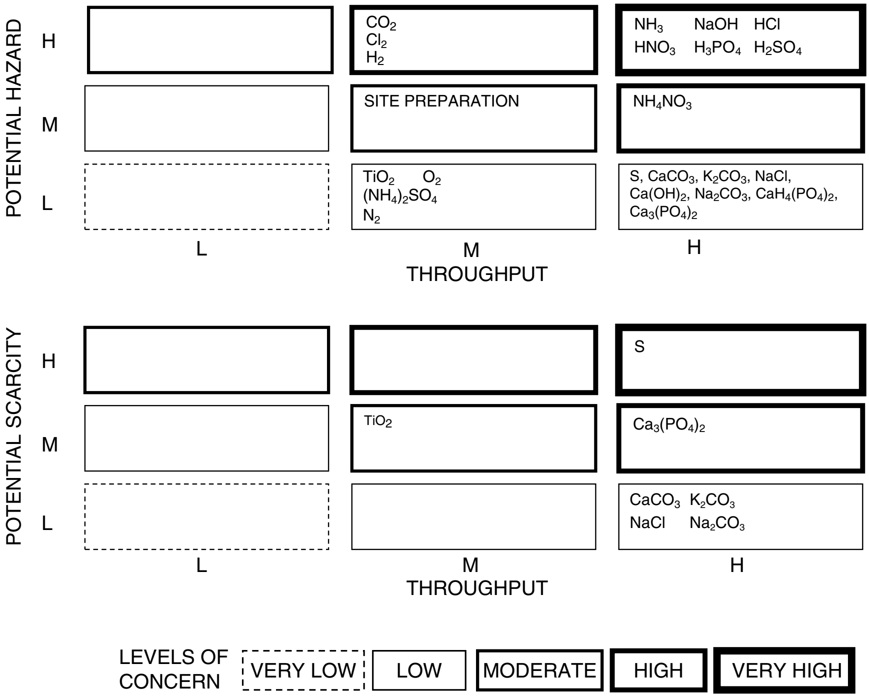

Figure 11.3. The throughput-potential hazard matrix (top panel) and the throughput-potential scarcity matrix (bottom panel) for the inorganic minerals and chemicals sector.

This sector uses substantial amounts of energy and water, but less than that used by several other sectors. Accordingly, the PEC and PWC matrices both have the "moderate concern" row highlighted, as shown in Figure 11.4.

The sector ΣWESH plot in Figure 11.5 indicates that the major environmental concerns are related to the strong acids and bases that are principal sector products. Throughput reduction or hazard decrease is thus probably not possible, and the sector should concentrate its efforts on ensuring that losses to the environment from the processes that generate these products are minimal.

11.5 SECTOR PROSPECTS

11.5.1 Trends

A certainty in this sector is that the rate of production of its principal products will remain near the present rate or grow somewhat over time. With the global

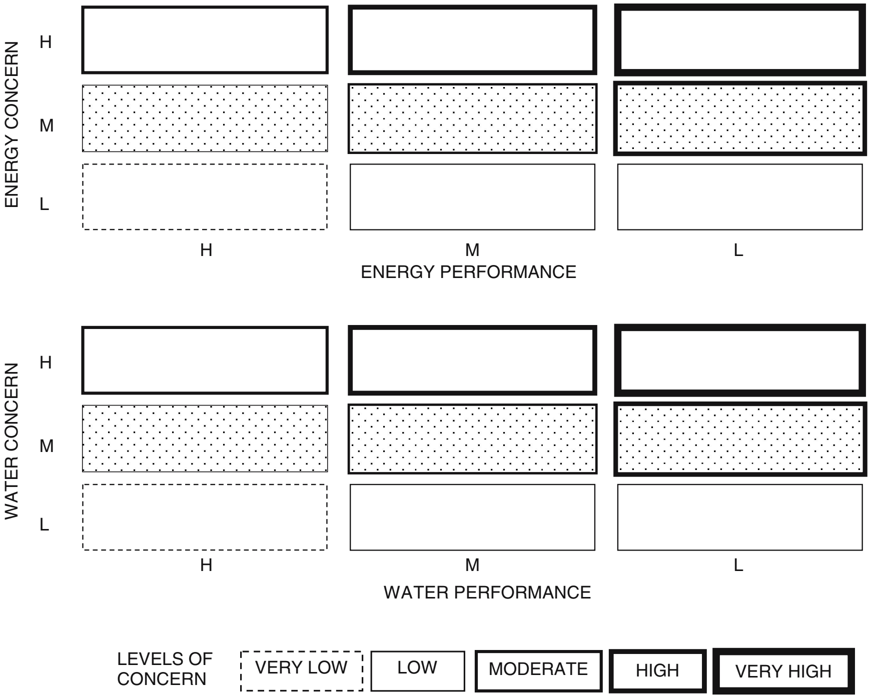

Figure 11.4. The performance-energy concern matrix (top panel) and the performance-water concern matrix (bottom panel) for the inorganic materials and chemicals sector.

population increasing and people demanding more and better food, there will be strong incentives for high rates of fertilizer use. The mineral acids play important roles in fertilizer manufacture and in the production of numerous specialty materials. Use of industrial gases (O_2, N_2, CO_2) is increasingly important to high efficiency, high purity industrial processes.

A number of the synthesis reactions in this sector do not go to completion or generate low-value byproducts, thus making the sector a major waste generator. It is likely that improved catalyst selection and enhanced process control will alter this picture. Yield gains should result from the application of increasingly higher levels of technology to this sector.

This sector deals with basic feedstock materials, the starting agents for processes and products that influence most of the later-stage industrial sectors. Unlike metals, for example, they are mostly dissipated in use, as with fertilizers, or transformed into other products, as with sulfur and salt. Accordingly, there is little prospect for recovery and recycling.

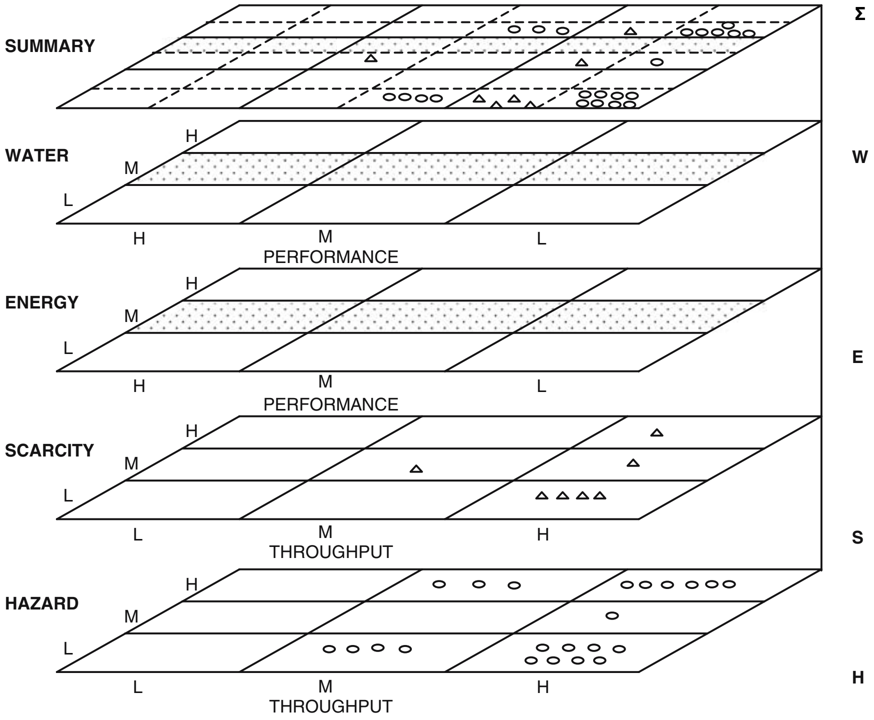

Figure 11.5. The ΣWESH plot for the inorganic materials and chemicals sector. The squares and circles represent the materials in Figure 11.3.

11.5.2 *Scenarios*

11.5.2.1 *Trend World*

The current trend for this sector is for the same products to continue to be manufactured, in ever larger quantities. Modest increases will be made in energy and water efficiency as processes are progressively better controlled. Environmental regulations will result in modest decreases in emissions to air, water, and soil.

11.5.2.2 *Green World*

In this scenario, highly efficient agriculture with controlled fertilization decreases the need for large volumes of fertilizers. As a result, the products of this sector become more like lower-volume specialty chemicals. Extraction sites undergo extensive reclamation. Byproducts are designed for commercial use rather than being discarded. Rates of energy and water use near their theoretical limits.

11.5.2.3 Brown World

This scenario is one in which high levels of demand for traditional inorganic chemicals results in large-scale open pit mining. Byproducts are largely discarded. Little effort is made to reclaim and restore extraction sites. Energy and water are used in profligate fashion.

FURTHER READING

Hocking, M. B., *Modern Chemical Technology and Emission Control*, Berlin: Springer-Verlag, 460 pp., 1985.

U.S. Department of Energy, *Technology Vision for the U.S. Chemical Industry*, http://www.oit.doe.gov/chemicals/pdfs/chemvision2020.pdf, 1999.

Chapter 12

Petrochemicals

12.1 OVERVIEW

Petrochemicals are organic materials obtained from petroleum (Figure 12.1). The class of materials known as petrochemicals is not simply characterized. Originally, a petrochemical was a generally pure, hydrocarbon compound that could be separated out of petroleum—for example, ethylene and benzene. Now, petrochemicals are more broadly defined to include organic compounds—such as ethyl alcohol and styrene—that can be directly derived from petroleum by one or two steps of chemical processing of products directly obtained from petroleum refining.

Most petroleum products are used as fuels and as lubricants. A petroleum product for those purposes is usually an aggregation of several of the hydrocarbon compounds found in crude oil. Such aggregations—called "fractions"—each contain mostly hydrocarbon compounds with roughly similar boiling points. Even then, a fraction may consist of hundreds or even thousands of individual hydrocarbon compounds. A petrochemical is a single chemical compound, and the primary difference between a petroleum fraction and a petrochemical is that the petrochemical has been so thoroughly separated from other components of a petroleum fraction that it is considered pure, or essentially so.

Petrochemicals are important feedstocks for the production of more complex organic chemicals such as plastics (Chapter 18), detergents, solvents, and pharmaceuticals (Chapter 20). The demand for petrochemical feedstocks is large enough, in fact, that the quantities available directly from petroleum refining are sometimes inadequate and are often supplemented by: (a) chemically altering other abundant petrochemical compounds taken from petroleum and (b) deriving them from coal either by simple separation or by chemical treatment of compounds taken from coal. Benzene, phenol, and acetylene, for example, are directly available from coal. Nevertheless, only about 3% of crude oil is used for petrochemicals—the rest goes to make gasoline, diesel fuel,

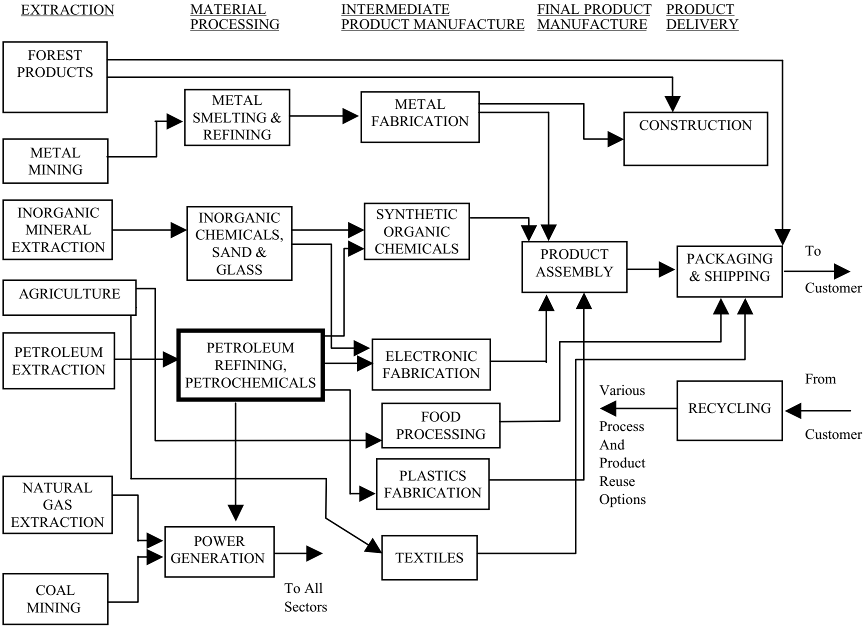

Figure 12.1. The technological sequence diagram for the petrochemical industry. The sector is indicated by heavy outlining.

aviation fuel, various grades of fuel oil, and asphalt. The fate of all those fuels is to be burned for their energy content, in the process being lost forever.

Table 12.1 provides important examples of petrochemicals that are commonly obtained by separating them directly from petroleum. All of the compounds listed in table 12.1 having four or fewer carbon atoms in each molecule (i. e., the carbon number) are gases at "room temperature". Butadiene, for example, boils at about 10 degrees Celsius. Those having carbon numbers of five or more are colorless liquids at room temperature. Such petrochemicals are quite volatile and, in the presence of air, are highly flammable and even highly explosive. In general, the higher the carbon number, the higher the boiling point.

Tables 12.2 and 12.3 list secondary petrochemicals that are commonly derived from the primary petrochemicals methane and ethylene and typical uses for such products. Figures 12.2, 12.3, and 12.4 indicate, in flowchart form, the large number of petrochemical products typically made from methane, ethylene, and such aromatics as benzene, toluene, xylene, and ethylbenzene. Note that a number of processes involve the use of inorganic chemicals (bromine, hydrogen chloride, sulfuric acid, etc.) produced by the inorganic minerals and chemicals sector (Chapter 11).

***Table** 12.1.* Hydrocarbon Petrochemicals Obtained Directly From Petroleum

	Hydrocarbon Type		
Carbon Number	Saturated	Unsaturated	Aromatic
1	Methane		
2	Ethane	Ethylene Acetylene	
3	Propane	Propylene	
4	Butanes	n-Butenes Isobutene Butadiene	
5	Pentanes	Isopentenes (Isoamylenes) Isoprene	
6	Hexanes Cyclohexane	Methylpentenes	Benzene
7		Mixed heptenes	Toluene
8			Xylenes Ethylbenzene Styrene
9			Cumene

***Table** 12.2.* Petrochemicals From Methane And Their Uses

Basic Derivatives	Uses
Carbon black	Rubber compounding Printing ink Paint
Methanol	Formaldehyde synthesis Methyl ester synthesis Amine synthesis Solvent synthesis
Acetylene	Vinyl chloride synthesis Vinyl acetate synthesis Chloroprene (neoprene) synthesis Chloroethylene synthesis Acrylonitrile synthesis

Given that approximately three percent of the crude oil input at most refineries is typically converted to petrochemicals, and that roughly 5.5 billion barrels of petroleum are refined in the U.S. each year, U.S. refineries produce at least 24 Tg of petrochemicals annually. The actual amount is likely to be much higher, however. For example, in 1996, about 110 Gg of ethylene were produced in the U.S., and,

***Table** 12.3.* Petrochemicals From Ethylene And Their Uses

Basic Derivatives	Uses
Ethylene oxide	Ethylene glycol synthesis Ethanolamine synthesis Nonionic detergent synthesis
Ethyl alcohol	Acetaldehyde synthesis Solvent synthesis Ethylacetate synthesis
Styrene	Polystyrene synthesis Styrene-butadiene rubber synthesis
Ethylene dichloride	Vinyl chloride synthesis

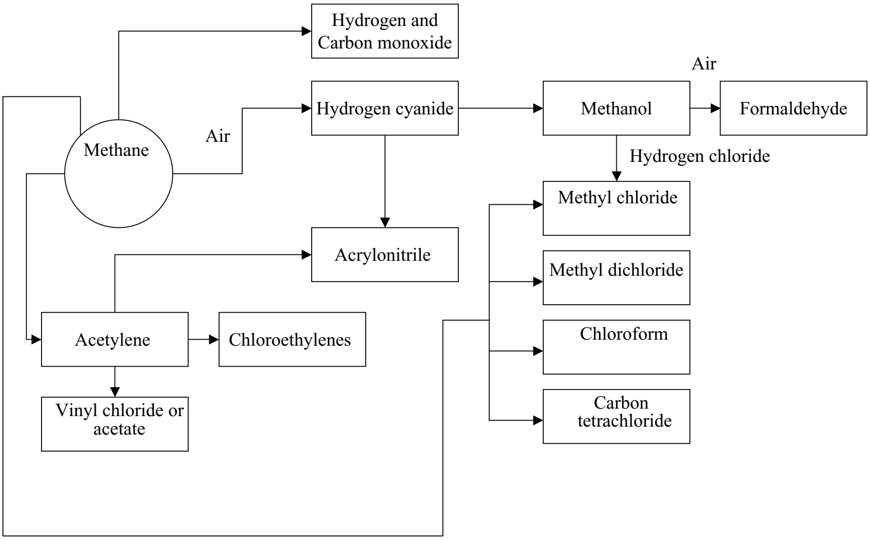

***Figure** 12.2.* Conversion of methane into petrochemical products.

while more ethylene is manufactured than any other single petrochemical, there are many others. For instance, about 55 Gg of propylene and about 35 Gg of benzene were produced in the U. S. in 1996. The total amount of those three high-volume petrochemicals—about 200 Gg—is quite consistent with the total amount of plastics, synthetic rubber, and synthetic fibers produced in the U. S. that year.

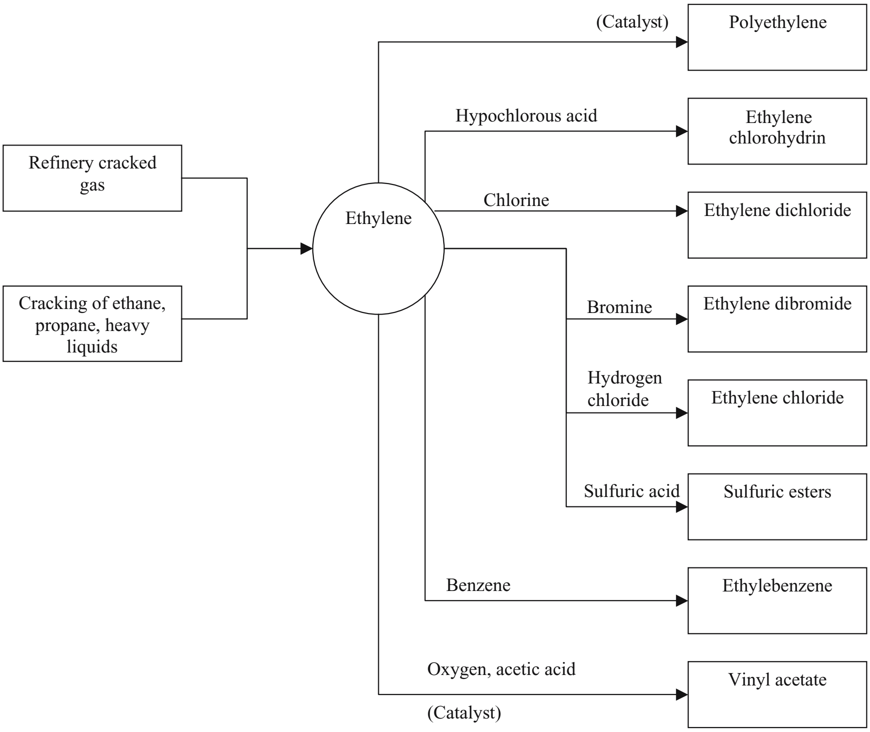

Figure 12.3. Conversion of ethylene into petrochemical products.

12.2 PHYSICAL AND CHEMICAL OPERATIONS

Petrochemical manufacture is almost exclusively a matter of chemical reaction processes and separation operations. Even when feedstocks for a chemical reaction process contain only one chemical compound, several compounds may be produced, so that the desired product must be separated from its byproducts. In fact, because few reactions go to completion, the output stream from a chemical reaction process will usually contain unreacted feedstock along with reaction products and byproducts, so that the desired product must also be separated from remaining feedstock material (which is then recycled as feedstock into the reaction vessel).

For petrochemicals, the most common separation operation is accomplished in a distillation column: a vertically oriented, cylindrical vessel containing glass or ceramic "packing" (e.g., glass beads). The material to be distilled is introduced as a liquid midway in the height of the column. Liquid reaching the bottom is drawn out, heated up, and reintroduced into the bottom of the column where it evaporates, with much of

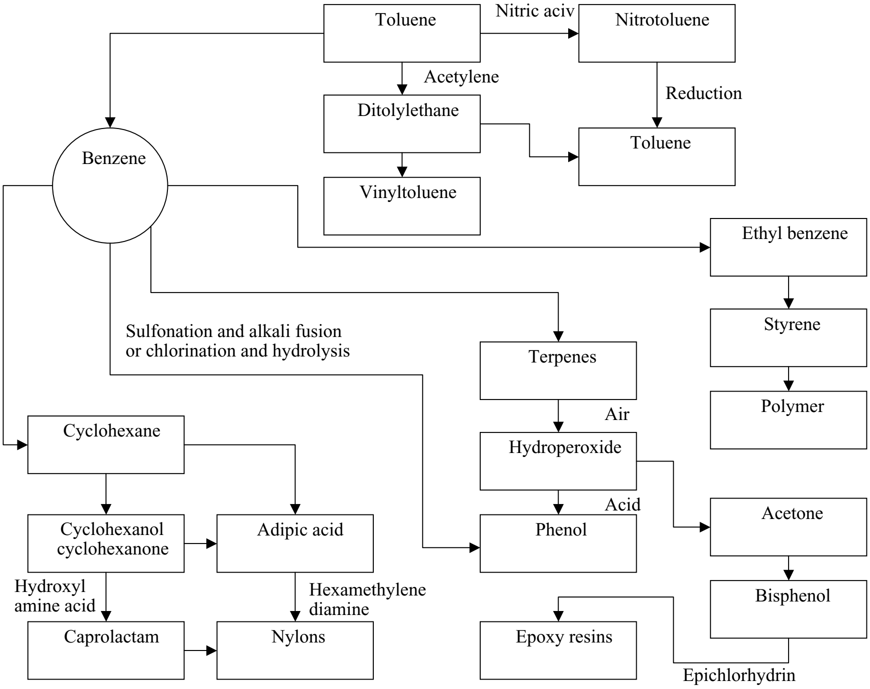

Figure 12.4. Conversion of various aromatic compounds into petrochemical products.

the vapor rising up through the column and coming into intimate contact with liquids coming down the column. At the top of the column, vapor is drawn out, cooled and condensed, and reintroduced into the top of the column where it falls down through the column, coming into intimate contact with rising vapors. During stabilized operation, the material at the top of the column will be very rich in those compounds with low boiling points (the "lighter" compounds), and the material at the bottom will be similarly very rich in those compounds with high boiling points (the "heavier" compounds). Separated product is taken from the top—the "lighter" product—and from the bottom—the "heavier" product. Further separation of either product, if needed, is accomplished by piping it to another distillation column. Separation is quite energy intensive. In distillation, for example, each of the product streams is only a small part of the materials being recycled back into the top and into the bottom of the column. The recycled streams are continually and repeatedly vaporized and condensed, all of which requires the transfer of energy, with the extreme energy losses one would expect from such repeated transfers.

Because there are so many different petrochemicals, there are many different reactions that are used to produce them. There are, however, a few common reaction types involved in the manufacture of the bulk of the petrochemicals produced: *cracking,* *reforming, and alkylation.* All three are aimed at producing petrochemicals that are suitable for use as building blocks for more complex organic compounds.

Cracking is the process of breaking apart hydrocarbons with high carbon numbers to obtain lower carbon number molecules. Ethylene—which has two carbons in each molecule—is an extraordinarily important building block for other organic compounds, and large quantities of ethylene are produced by cracking hydrocarbons with higher carbon numbers. For example, when propane (with a carbon number of three) is heated to about 850 degrees Celsius in the presence of steam, it breaks down into propylene, ethylene, methane, and hydrogen:

$$2CH_3CH_2CH_3 \longrightarrow CH_3CHCH_2 + CH_2CH_2 + CH_4 + H_2$$

Note that to obtain pure ethylene, that product must be separated from the by-products propylene, methane, and hydrogen as well as from the condensed steam and any unreacted propane, a separation that is ordinarily done with a series of distillation steps. Large quantities of ethylene are used in the manufacture of polyethylene and polyvinyl chloride, both very common plastics.

Reforming is also used to improve the suitability of petrochemical building blocks that are to be subsequently used to manufacture more complicated organic chemicals. Reforming is most often accomplished at high temperatures with catalysts such as platinum or rhenium and involves leaving the carbon number of feedstock compounds unchanged but creating ringed compounds—e.g., benzene—and compounds with fewer hydrogen atoms. One common example of a reforming reaction is the production of benzene from hexane, both of which have carbon numbers of six:

$$CH_3CH_2CH_2CH_2CH_2CH_3 \longrightarrow C_6H_6 + 4H_2$$

Alkylation reactions are of many types, one of which involves reacting an olefin—such as ethylene—with benzene to make a large combined building block for subsequent organic-chemical production. One frequently used alkylation reaction is the production of ethylbenzene by combining ethylene and benzene at moderately high temperatures and sometimes at elevated pressures in the presence of any of several effective catalysts:

$$CH_2CH_2 + C_6H_6 \longrightarrow CH_3CH_2C_6H_5$$

Note that, although only one product is made, the reaction generally is not 100% complete, and ethylbenzene must be separated—again, by distillation—from unreacted ethylene and benzene. Ethylbenzene is the key ingredient in the production of polystyrene and other styrene polymers.

Catalysis is crucial to the operations of the petrochemical industry; it is the process by which chemical reactions are either accelerated or inhibited by bringing the reactants into contact with a substance (the catalyst) that is not changed during the reaction. It has been estimated that 90% of current chemical processes rely on catalysis-based synthesis.

12.3 THE SECTOR'S USE OF RESOURCES

The petrochemicals sector is a significant consumer of energy and water resources. On the other hand, the sector is probably an "economical" consumer of petroleum-based raw materials, that is, it uses nearly the same volume of raw materials as it produces in the targeted product, with little by-product that cannot be recycled as feedstock for other petrochemical or petroleum-refining processes.

Petrochemicals have relatively high energy content, which is one of the reasons that they are suitable to be used as feedstocks for manufacturing larger, more complicated organic molecules. But the energy required for their manufacture goes far beyond the need to raise the products' energy content. As can be seen from the above descriptions of common petrochemical reactions, a great deal of heat is required to provide the temperatures needed for the reactions, and similarly a large amount of heat is needed in separation operations. As we saw in electric power generation in Chapter 9, the Second Law of Thermodynamics interferes somewhat with the ability to recycle heat. There are ways to reduce the waste of heat in petrochemical production, but they are rarely the most obvious and convenient.

The production of petrochemicals is often merely an ancillary feature of the production of fuels and other organic chemicals, so that it is extremely difficult to determine the amount of water use that should be attributed to petrochemicals by themselves. However, the petroleum and related industries in China consumed about 3 billion cubic meters of water in 1985. If we were to allocate that consumption to petrochemical production on the basis of the fraction of crude petroleum converted to petrochemicals, we would estimate that the production of 110 Gg of petrochemicals requires roughly 100 million cubic meters (or 480 Gg) of water, and, thus, that 4 to 5 kilograms of water are needed in the production of one kilogram of a petrochemical.

Fortunately, the by-products of petrochemical production are almost always usable as feedstocks in other organic chemical processes or—given their flammability and energy content—as high-value fuels. Further, petrochemical manufacturing facilities are often located where maximum use can be readily made of these alternative applications. Thus, it may easily be argued that petrochemicals make the most efficient use of feedstock of any manufactured product.

12.4 POTENTIAL ENVIRONMENTAL CONCERNS

The production of petrochemicals suffers many of the same forms of pollution potential as does petroleum refining. At least three classes of compounds are involved—those that are characteristic of the petroleum feedstocks and petrochemical products themselves, those that result from the chemical processes involved in manufacturing petrochemicals, and those that result from the combustion of fuels that are necessary to supply the large amounts of heat needed for petrochemical production.

Petroleum and petrochemical feedstocks and products are themselves the sources of significant potential pollutants, partly because of impurities that must be separated out—e.g., sulfides and mercaptans—and partly because most of the reactants themselves are hazardous and otherwise undesirable if released—e.g., volatile organic compounds (VOCs). Many of the reactions involved in the chemical conversions require corrosive reagents and potentially hazardous catalysts that must be properly contained when spent. Many of the reactions require steam, the condensate of which is rich in many of the compounds involved in the feedstocks and the reactions. Additionally, the combustion of fuels for the heat needed in making petrochemicals produces the same pollutants we see whenever there is fossil-fuel combustion for any reason—carbon monoxide, sulfur dioxide, nitrogen oxides, and particulates.

Virtually all petrochemical plants anticipate such releases and provide equipment and practices to prevent and mitigate them. These work well as long as these provisions are designed and operated properly and as long as the magnitudes of the releases are within the bounds anticipated. Still, as EPA's Toxic Release Inventory reports, some level of emissions continues from petroleum refining and organic chemical manufacturing facilities, presenting an ongoing challenge to determine the hazard and risk and to reduce outputs.

12.4.1 Air Emissions

Releases into the air from petrochemical plants include fugitive emissions from the feedstocks, stack gases from burning fuels for process heat, and emissions from chemical reactors and separation equipment. Fugitive emissions are potentially a problem throughout a petrochemical plant because of the usually elevated pressures involved in the processes, the often corrosive and erosive nature of chemicals at high temperature, and the exceedingly complex network of valves, pipe joints, pumps, pressure-relief valves, reactor vessels, holding tanks, and flanges, all of which present opportunities for leakage. In addition, gaseous emissions are potentially a problem during the loading and unloading of materials onto and from trucks, rail cars, and barges.

12.4.2 Releases to Water and Liquid Wastes

There are several ways in which water streams can become polluted during petrochemical production. First, process water that has come into contact with reactants, impurities, reagents, and products will contain small quantities of these compounds. Steam might be used to promote a chemical reaction and its condensate would be contaminated in this way. Cooling water can become polluted if hydrocarbons or other compounds leak into it as it passes through process equipment. Similarly water used

Table 12.4. Processes, Activities, and Potential Emittants for the Petrochemicals Sector

Process Type	Sector Activities	Potential Emittants
Chemical conversions	Process feeds, catalysts, reagents, steam	Spent catalysts, acids, and caustics; VOCs; organics in condensates
Feedstock preparation	Scrubbing and extraction	Sulfides and mercaptans in wash streams
Product separation	Distillation and extraction	VOCs, spent extraction streams, organics in extraction streams
Process heat	Fossil fuel combustion	SO_2, CO, NO_x, particulates

to wash the interior of process equipment during periodic maintenance activities will pick up contaminants. Finally, spilled hydrocarbons or reagents can flow into storm sewage.

12.4.3 *Solid Wastes*

Many of the wastes from petrochemical plants are collected in solid form—e.g., spent catalysts, filters, and carbon/resins. A large number of the materials that would otherwise be emitted into the air or released into water are captured and handled as solid wastes—e.g., particulates from stack gases, catalyst particles from process water, and sludges from waste-water treatment.

12.4.4 *Sustainability Assessment*

The materials that might be released from petrochemical manufacturing facilities are summarized in Table 12.4, and these materials are displayed in terms of throughput, potential hazard, and potential scarcity in Table 12.5. The throughput-potential hazard matrix is shown in Figure 12.5, as is the throughput-potential scarcity matrix. The former demonstrates that many of the petrochemical products, as well as the unwanted byproducts, are hazardous to living organisms. The basic reason is that organisms have not evolved defenses against many of these chemical species, as they are unlike those found in nature. Several of the emittants not directly related to the petrochemicals, especially the acid gases, are potentially hazardous as well. Their throughput is not large, however.

Because the only material that enters the petrochemical process is petroleum, it is the only material that appears on the TPS matrix.

This sector uses very large amounts of energy and moderate amounts of water, as shown in the PEC and PWC matrices of Figure 12.6.

Table 12.5. Throughput-Hazard Binning of Materials in the Petrochemicals Sector

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
Petroleum	H	Human	L	M
Petrochemicals	H	Human	H	M
Byproducts	H	Human	H	–
VOCs (to air)	L	Smog	M	–
VOCs (in water)	L	Ecosystem	M	–
Spent reactants (catalysts, acids, and caustics)	M	Ecosystem	M	–
Sulfides and mercaptans	L	–	L	–
Spent extraction streams (e.g., ethylene glycol)	L	–	L	–
SO_2, NO_x	L	Acid rain	H	–
CO, particulate matter	L	Human	M	–

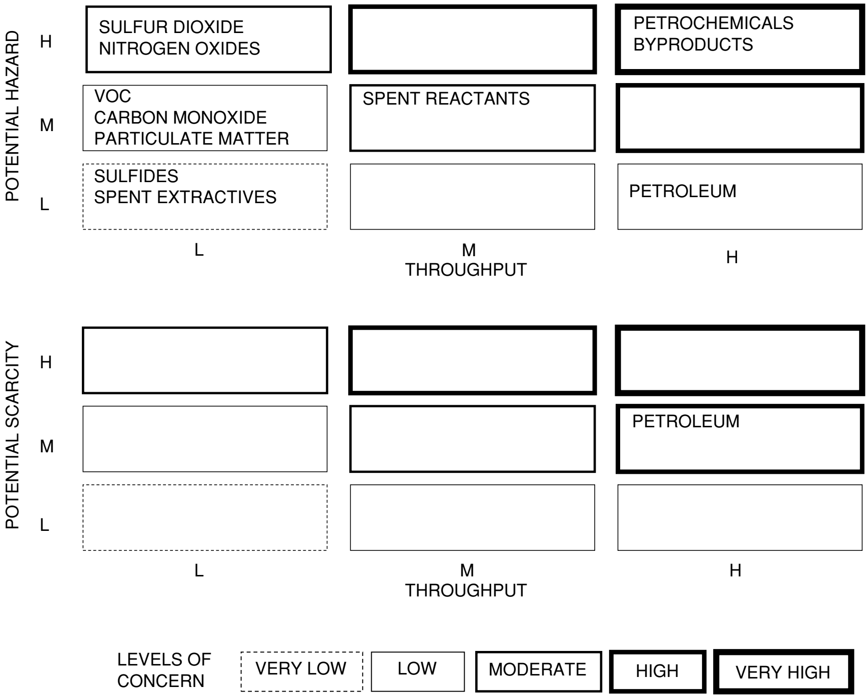

Figure 12.5. Throughput-potential hazard matrix (top panel) and throughput-potential scarcity (bottom panel) for the petrochemical sector.

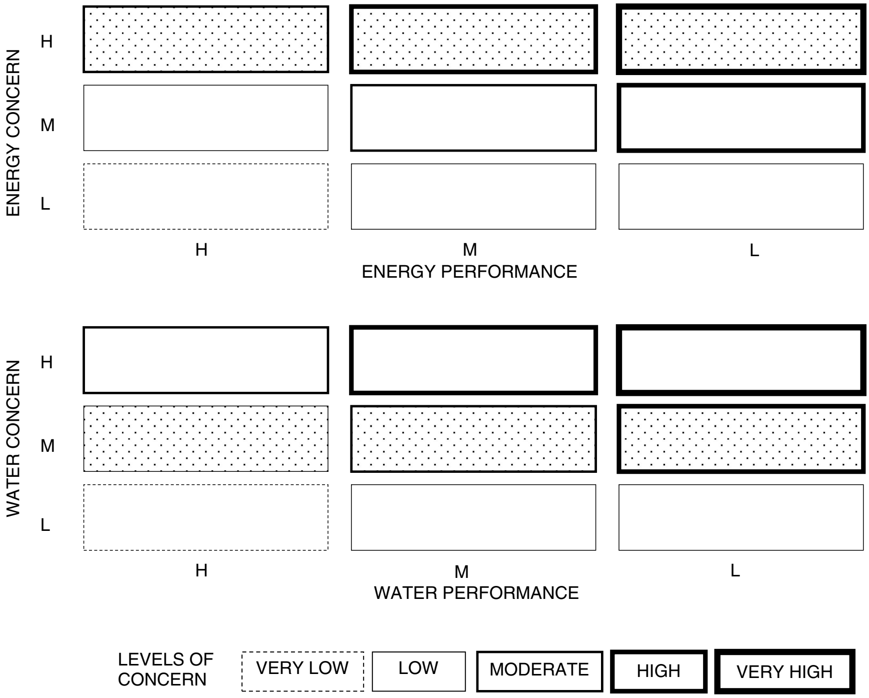

Figure 12.6. Performance-energy concern matrix (top panel) and performance-water concern matrix (bottom panel) for the petrochemical sector.

The sector ΣWESH plot appears in Figure 12.7. The upper right corner of the summary diagram suggests that sector attention needs to be particularly focused on energy reduction, product containment, and byproduct minimization.

12.5 SECTOR PROSPECTS

12.5.1 Trends

Process, as opposed to product, trends are expected to be most significant in the petrochemicals sector. Because the products of this sector are typically feedstocks for other industries, such as the synthetic organic chemicals and plastics industries, they will likely only change as a result of a change in demand. The process trends will come about as technological changes result in more efficient means to manufacture a given product.

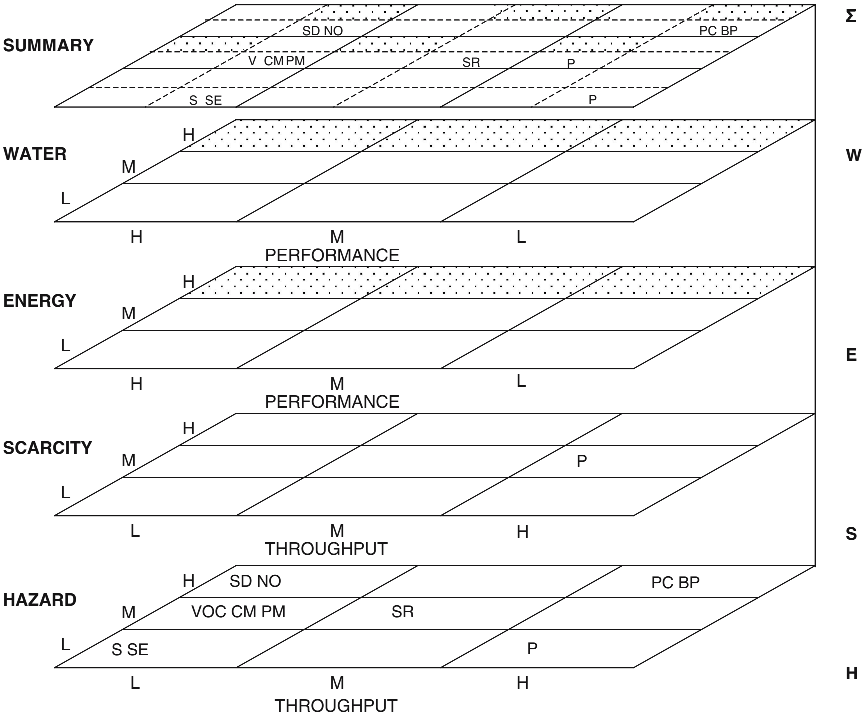

***Figure** 12.7.* The ΣWESH plot for the petrochemical sector. Abbreviations refer to the materials in Figure 12.5.

12.5.1.1 Process Trends

The petrochemicals sector is very efficient in its use of input materials. Its energy use is extremely high, however, and improving energy efficiency is now a focus of many manufacturers in this sector.

Analytical approaches for process monitoring and control are rapidly becoming available and they function over wide ranges of temperature, pressure, and chemical environments. This permits real-time, continuous monitoring and adjustment of chemical reaction processes, thereby improving yields and decreasing waste. This trend will accelerate.

It is likely that research in energy efficiency will lead to alternative synthesis routes for some of the most common petrochemical products. In a recent example, a University of Minnesota team developed a process to synthesize ethylene from ethane at greater than 70% conversion using a platinum-tin catalyst and added hydrogen. (The current steam-cracking process is a large energy user and has only about 60%

conversion efficiency.) The result will probably lead to smaller, more energy-efficient processing facilities.

Another likely prospect is the use of alternative feedstock materials in order to avoid long-term dependence on petroleum. Whether one should continue to term such a sector Petrochemicals is not obvious; we might instead adopt such names as Starter Chemicals or Building Block Chemicals. In any case, new feedstocks are on the horizon. Among the possibilities are recycled materials from various sources and the use of biomaterials. Already soy and corn oils are being used as feedstock in the manufacture of adhesives and plastics.

Over time the chemical industry will be centered on biological feedstocks and will depend heavily on biocatalysis, in which reactions are influenced by enzymes and other natural molecules. Challenges will exist in achieving desired rates of product isolation and product specificity, and biotechnological approaches will be advantageous only if they enable multiple synthetic steps to be accomplished in a single process stage.

12.5.1.2 Product Trends

An active area in product development is the use of computer modeling to design new chemical products, to choose optimum methods and sequences for synthesis, and to minimize environmental attributes of their manufacture. The result is much more rapid development of new products, and possibly improved environmental performance.

It is likely that the chemical industry will increasingly become a materials science industry, one in which new materials are designed and brought to market not by teams of chemists, but by teams involving chemists, biologists, physicists, and materials scientists. Interdisciplinarity will become the hallmark of this materials industry.

12.5.2 Scenarios

12.5.2.1 Trend World

In this scenario, the petrochemical industry will make incremental improvements to its current operations. Energy efficiency will gradually improve as better process control enables more precise monitoring of reaction conditions and product generation rates. Fugitive emissions will be increasingly well controlled as air quality regulations continue to provide incentives to minimize VOC releases. Some effort will be given to developing processes with new feedstocks.

12.5.2.2 Green World

In this scenario, biomaterials replace petroleum as the feedstock for generating building block chemicals. Alternative synthesis routes and starting materials allow for substantial reductions in energy and water use. Emissions of all kinds are near-zero, with extensive catalyst recovery and reuse and with uses established for feedstock impurities. The efficiency of the sector and the importance of its products make it a central element in the global transition to better lifestyles with minimal environmental impact.

12.5.2.3 Brown World

The third scenario is one in which the sector retains its single-minded concentration on petroleum feedstocks. Throughput rates are the overriding motivator, so rates of energy and water use are deemed unimportant. The expense of preventing fugitive emissions is too high to encourage lower emissions. The eventual depletion of petroleum supplies gradually results in the demise of this sector.

FURTHER READING

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Chapter 13

Agriculture

13.1 OVERVIEW

Agriculture is the science, art and/or practice of cultivating the soil, producing crops, raising livestock, and in varying degrees, preparing and marketing the resulting products. In environmental terms, it is the manipulation and modification of the biophysical environment to produce desired plants and animals for food, fiber, fuel, and raw materials. Most familiar are the activities that comprise field cropping, especially field-grown food crops. Agriculture also includes livestock, the crops grown to feed livestock, orchards and industrial crops (cotton, rubber, oils, starch, etc.), horticulture (the husbandry of mixed group of plants near a dwelling), and swidden agriculture (field-forest rotation in subsistence economies). To some extent, the framework presented in this chapter also applies to aquaculture.

Agriculture involves the appropriation of solar energy through photosynthesis. That energy and the related sources of energy that are of value for human existence are either captured directly from the original crop (as with raw vegetables and grains), processed into prepared foods (e.g., grain into bread), or fed to livestock which are then slaughtered and eaten or used for industrial purposes. Agriculture is also the major source of protein in the human diet (along with that obtained through fishing and hunting).

For other industries described in this book, the production of output involves mechanical, electrical, or chemical processes. In agriculture the creation of the basic product is obviously biological. After the plants or animals are harvested, however, the processing of them involves purification and manufacture into products of interest to the final consumer. These latter stages involve a host of nonbiological industrial processes as well as some further use of biological processes (e.g., fermentation).

13.2 PHYSICAL AND CHEMICAL OPERATIONS

The core process in agriculture, photosynthesis, transforms light energy into chemical energy in the form of simple sugars.

$$6CO_2 + 6H_2O \xrightarrow{\text{sunlight}} C_6H_{12}O_6 + 6O_2$$

The energy stored in the sugar molecule is released by living organisms through the process of respiration:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O$$

The production of proteins from amino acids and ultimately from nitrogen-bearing (and often sulfur-bearing) compounds is also a key biological process. Proteins are made of long chains of linked polypeptides which are, in turn, made up of amino acids. Proteins are essential in the animal diet and are found in and synthesized by all living organisms. They play a key role in a wide variety of physiological processes. The biochemistry of protein cannot be represented in a characteristic chemical equation in the same simple fashion as photosynthesis and respiration.

13.2.1 Process Stages

Figure 13.1 shows the technological sequence for agriculture. As indicated in the diagram, usable products are generated throughout the stages of the product life cycle: directly from harvest, after a basic level of purification, or after extensive alteration and combination, as in highly processed and packaged foods. This simplified diagram does not show the innumerable stages that are actually present in agriculture's technological sequence, nor does it show the large number of loops for re-use of residues.

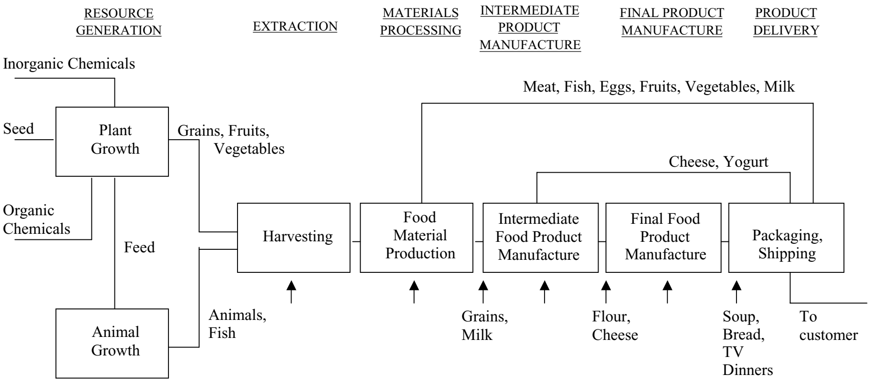


Figure 13.1. The technological sequence diagram for the agricultural sector.

For example, manures are used as fertilizer and residues from food processing are fed to livestock.

13.2.2 Descriptions and Diagrams

Agricultural outputs are highly diverse. As Table 13.1 shows, the variety of foods, fibers and other products obtained from cultivated plants and raised animals is quite

Table 13.1(a). Main Crop Plants

Crop Category	Examples
Cereals	Corn, rice, wheat, oats, barley, millet
Pulses	Bean, pea, peanut, soybean
Forage crops	grass, clover, alfalfa
Roots and tubers	Potato, cassava, sweet potato, turnips
Leafy crops	Lettuce, cabbage, spinach
Fruits	Orange, lemon, peach, apple, strawberry
Oil crops	Palm, peanut, olive, cottonseed, linseed, sunflower
Nuts	Almond, filbert, pecans
Sugar crops	Sugar Cane, sugar beet
Beverage, spices, etc.	Coffee, tea, cocoa, grape, perfumes, peppers
Fiber crops	Flax, jute, hemp, sisal, cotton
Fuel crops	Corn (ethanol) wood

Table 13.1(b). Main Agricultural Animals

Type of Animal	Examples
Mammals	Horse Ass Mule Camel Cattle Buffalo Sheep Goat Pig
Birds	Chicken Duck Goose Turkey
Cold-blooded vertebrates	Fish
Invertebrates	Bees Silk moth

large. The boundaries of the agricultural industry are subject to differing definition so the quantitative assessments of resource use and impact are often incommensurate. Comparative assessments—over time, cross-nationally and between sectors—are especially vulnerable to misinterpretation.

Table 13.2 translates the inventory of world agricultural production prepared by the United Nations Food and Agriculture Organization into calories and proteins; entries in portions of the table are sorted from most eaten to least eaten. The table shows five classes of products. Class 1 includes crops such as wheat that are generally eaten by people. Animal products comprise Class 2. Class 3 is coarse or feed grains. Other agricultural products commonly used for non-food or non-feed purposes make

Table 13.2. Inventory of World Agricultural Production of Calories and Protein and Consumption by Draft Animals, 1990

Product	Production (kt)	Energy (cal/100 g)	Protein (%)	Energy (cal in trillions)	Protein (kt)
Class 1					
Wheat	601,723	401	14	2,413	84,162
Rice	521,703	354	9	1,847	46,953
Veg., melon	450,986	19	1	85	4,669
Fruit ex melon	344,875	43	1	150	2,811
Potatoes	268,107	61	2	165	4,547
Cassava	150,768	352	1	530	897
Sweet potatoes	125,124	92	1	115	1,709
Sugar	123,401	373	0	460	0
Pulses	58,846	340	22	200	13,117
Rye	40,042	343	14	137	5,606
Rapeseed	24,416	403	34	98	8,320
Ground nuts	23,410	411	19	96	4,440
Sunflower	22,682	403	34	91	7,729
Yams	20,966	87	2	18	379
Copra (coconut)	5,476	661	7	36	394
Taro	5,173	82	2	4	82
Tree nuts	4,379	138	5	6	198
Roots other	3,971	92	1	4	54
Cocoa beans	2,528	265	17	7	437
Sesame	2,399	403	34	10	817
Olive oil	1,573	883	0	14	0
Honey	1,172	304	0	4	4
Safflower	917	403	34	4	312
Class 2					
Milk	537,844	65	4	349	18,836
Meat	176,629	219	15	387	26,222
Fish	99,535	24	25	24	24,585
Eggs	37,056	145	11	54	4,252

(Continued)

Table 13.2. (Continued)

Product	Production (kt)	Energy (cal/100 g)	Protein (%)	Energy (cal in trillions)	Protein (kt)
Class 3					
Corn	479,340	391	10	1,874	47,934
Barley	181,946	408	13	742	23,653
Soybeans	108,134	403	34	435	36,847
Sorghum	56,677	393	11	223	6,234
Oats	42,799	428	13	183	5,564
Cotton seed	33,930	403	34	137	11,562
Millet	29,896	335	12	100	3,569
Class 4					
Cotton lint	18,477	213	16	39	2,955
Palm oils	11,163	883	0	99	0
Hides	8,648	219	15	19	1,284
Tobacco	7,076	308	12	22	876
Coffee green	6,282	58	0	4	30
Fiber other	5,391	213	16	11	862
Rubber	4,992	213	0	11	0
Wool	3,071	219	15	7	456
Linseed	2,821	403	34	11	961
Tea made	2,533	308	12	8	314
Castorbeans	1,340	403	34	5	457
Hops dry	112	308	12	0	14
Silk	86	219	15	0	13
Tung oil	79	883	0	1	0
Hempseed	20	403	34	0	7
Class 5					
Buffaloes	139,236	10,000	454	508	23,073
Horses	61,164	10,000	454	223	10,135
Asses	43,862	7,000	272	112	4,361
Camels	19,509	10,000	454	71	3,233
Mules	14,775	10,000	454	54	2,448
Sums				**12,209**	**448,373**

Source: P. E. Waggoner, *How Much Land Can Ten Billion People Spare for Nature?*, Ames, IA: Council for Agricultural Science and Technology, 64 pp., 1994.

up Class 4 and calories and protein consumed by draft animals make up Class 5. In general, one expects the more severe environmental problems to be related to the table entries high up (i.e., of higher throughput) within their respective classes.

13.3 THE SECTOR'S USE OF RESOURCES

Agricultural output is generated through the growing of crops and raising of livestock. Like forestry, but unlike many manufacturing industries, the basic resources are not mined from geological sinks (as with metals or petrochemicals), but are instead cultivated from renewable biological sources. Nonetheless, biophysical resources are necessary for agricultural production. The required inputs to agriculture are diverse and include:

- land, including appropriately fertile soil
- energy, including sunlight for crops and fuel for machinery
- water
- fertilizer to provide missing or consumed nutrients for plant growth
- feed for livestock, including feedcrops, by-products and residues, and forage obtained through grazing
- pesticides, including insecticides, herbicides, and fungicides
- seed/parents—both crops and livestock require a biological parent
- physical (capital) stock—including buildings, farm equipment, and draught animals

The use of land, energy, water, fertilizer and pesticides as inputs are reviewed here.

13.3.1 Land

For nearly all forms of agriculture, with the possible exception of hydroponics and greenhouse-house grown crops, land is critical resource and one of the defining inputs of this sector.

As an input, the central questions surrounding land use and agriculture revolve around the sufficiency of land of appropriate quality for agricultural production and the impact of competing uses. Robert Malthus's famous 1798 discussion of resource scarcity focused on land use. He argued that population increased geometrically and agricultural output increased arithmetically because increased production would require the cultivation of land with declining marginal productivity. There is less contemporary concern about the availability of arable (farmable) land because of improvements in agricultural productivity. Instead, concern has shifted to the competition between non-agricultural uses of land (housing developments, shopping centers, etc.) and farming. Figure 13.2 shows the major changes in world land use over time, with the gradual conversion of forest land to cropland being obvious. Table 13.3 shows the proportion of land under cultivation for major crops in the U.S. in 1996.

The land required for agriculture is clearly a function of derived demand for agricultural output—what and how much society chooses to consume (and therefore, in part, a function of population). It is also, however, a function of technology and productivity, that is, the land needed for agriculture depends in part on how much output can be produced per unit area. The output per unit of land results from both the choices of crops and agricultural approaches and from the productivity and success of the farmer.

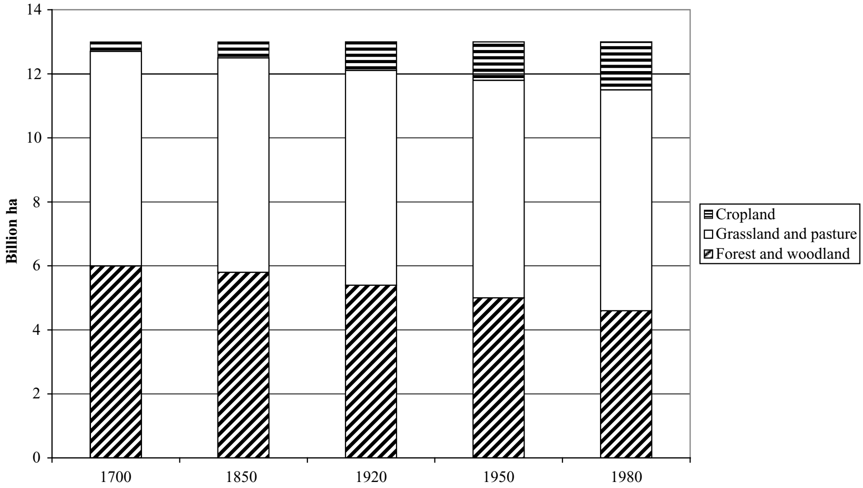


Figure 13.2. Changes between 1700 and 1980 in the use of the world's 13 billion hectares of land. (Reprinted with permission from P. Waggoner, *How Much Land Can Ten Billion People Spare for Nature?*, Ames IA: Council for Agricultural Science and Technology, 1994.)

13.3.2 Energy

Agriculture can be viewed as an energy-conversion process where human, fossil and solar energy are converted into food, fiber and related products. Energy is used throughout the agricultural product life cycle. The capture of the product of solar energy is relatively unproblematic in environmental terms—solar energy is a renewable source and non-polluting source of energy. Some researchers worry that as requirements for food and other agricultural outputs increase, the amount of land required for the cultivation of crops—to capture this energy through photosynthesis—will approach the limits of arable land on the planet. In this sense, the discussion of agricultural energy use intersects with that of agricultural land use.

Livestock production and consumption are another topic of debate relevant to energy and agriculture. When animals consume plants and convert it to flesh, between 19 and 188 megajoules (MJ) of feed energy is required to produce 1 MJ of animal protein energy. This is the oft-cited reason why the production of animal protein is so much less efficient than that of plant protein and why many argue for a vegetarian diet as a means of reducing environmental and resource burdens.

Energy in the form of fuel and electricity are needed in all stages of agriculture in a more familiar industrial sense as well. Energy use in agriculture is often classified as direct or indirect. In the former category are fuels used on farms to power machinery for planting and harvesting. In some regions, the direct energy for irrigation, typically

Table 13.3. Area Utilized for Selected Crops, 1996

Selected Crops Harvested	Area	Proportion of Total
Principal crops harvested:	**1,000 acres**	**Percent**
Corn for grain	73,147	22.4
Sorghum for grain	11,901	3.6
Oats	2,687	.8
Barley	6,787	2.1
Total (feed grains)	**94,522**	**29.0**
All wheat	62,850	19.3
Rice	2,799	.9
Rye	347	.1
Total (food grains)	**65,996**	**20.2**
Soybeans for beans	63,409	19.4
Peanuts for nuts	1,392	.4
Sunflower	2,499	.8
Dry edible beans	1,718	.5
Sugarbeets	1,323	.4
Sugarcane	845	.3
Potatoes	1,425	.4
Tobacco	734	.2
Cotton	12,833	3.9
All hay	61,029	18.7
Corn silage	5,395	1.7
Sorghum silage	371	.1
Total (all principal crops)	**313,491**	**96.1**
Citrus fruits	1,104	.3
Noncitrus fruits	1,934	.6
Tree nuts	671	.2
Principal vegetables and melons for the fresh market	1,821	.6
Principal vegetables for processing	1,476	.5
Other crops	**5,577**	**1.7**
Estimated total of crops harvested in 1996, including double-cropping	**326,074**	**100.0**

Source: USDA Economic Research Service, *Agricultural Resources and Environmental Indicators, 1996–1997*, Handbook 716, Washington, DC, 1997.

in the form of electricity used to operate pumps, is significant. Indirect energy is consumed off-farm in the manufacture of fertilizers, pesticides, equipment and other inputs. In processing agricultural products, energy is used to power equipment and fuel is used to provide steam, hot water, process heat and for the transport of agricultural products, intermediates and final goods.

Total energy use, excluding electricity, for the U.S. agricultural sector peaked in 1978 and has fallen by about one quarter since then. Driven by the oil shocks of the 1970, on-farm use of petroleum-based fuels has become more efficient and declined in absolute terms. The energy used to produce fertilizers and pesticides has declined only slightly. On a global basis, agricultural energy use is increasing rapidly as mechanization begins to take hold in developing countries.

13.3.3 Materials: Fertilizer

In areas where land is plentiful, increased food production comes from expansion of the land devoted to farming and through the mining of existing nutrients in the soil. As demand for agricultural products increases, nutrient replacement is required to maintain or increase yields. Historically, and in some less developed economies, manure and other forms of waste are the source of these replacement nutrients. Generally, because of transportation costs, use of animals wastes as fertilizer is economically feasible only if on-farm or nearby sources exist. In the US some 90 percent of manure does not leave the farm where it is generated and, as a result, it is used on relatively few acres. According to the U.S. Department of Agriculture, such wastes have provided between 9 and 24 percent of total nutrients available in U.S. agriculture in recent years. In contrast, because manufactured fertilizers provide low-cost nutrients, they have largely replaced recycled wastes.

Commercial fertilizers (see Chapter 11) are the predominant source of nutrients for plant growth in developed country agriculture, with manures as a much smaller source. Fertilizers principally provide macronutrients—nitrogen, phosphorus and potassium (NPK)—but also boron, copper, iron, manganese, and zinc. Other substances are added to soils to adjust pH or other soil contents (e.g., lime, calcium, magnesium, sulfur).

Commercial fertilizer use depends on a mix of technical and socio-economic factors including soil, climate, feasible technology, weather, crop mix, crop rotations, government programs, and commodity and fertilizer prices. Figure 13.3 shows the large role that commercial fertilizers play. In general, fertilizer use has varied with the amount of planted acreage because the application rates and percentage of acres treated has remained less variable than cultivated acreage in the U.S.

13.3.4 Process Chemicals: Pesticides

Pesticide use is among the most controversial of inputs to agricultural production and one that has played a key role in increasing output. Agriculture and storage of agricultural products account for about three quarters of pesticide use in more developed countries. Two thirds of the approximately $7.5 billion dollars spent in the US on agricultural pesticides is for herbicides (57 percent by weight in 1995) with the remainder for insecticides (12 percent by weight), fungicides (8 percent by weight) and other pesticide products such as soil fumigants (23 percent by weight).

In the U.S., synthetic pesticide use grew rapidly in the post World War II period and peaked in the early 1980s. It declined in the subsequent decade but increased and fluctuated in the 1990s.

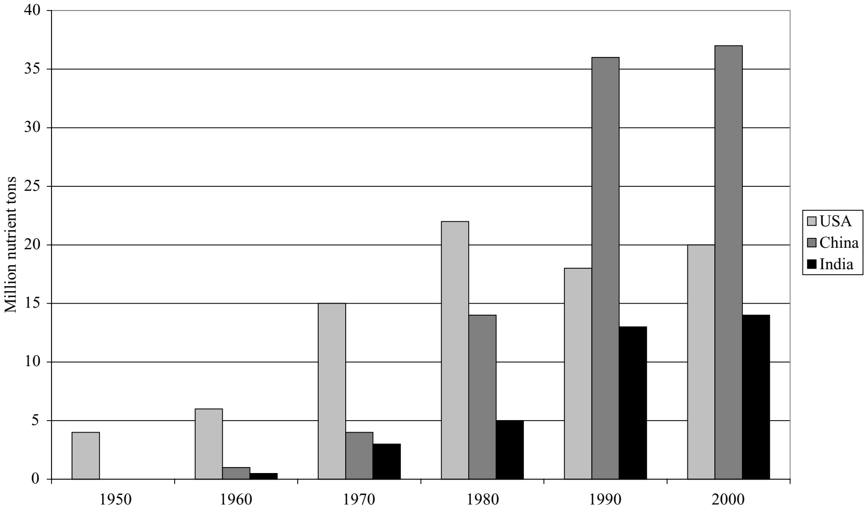
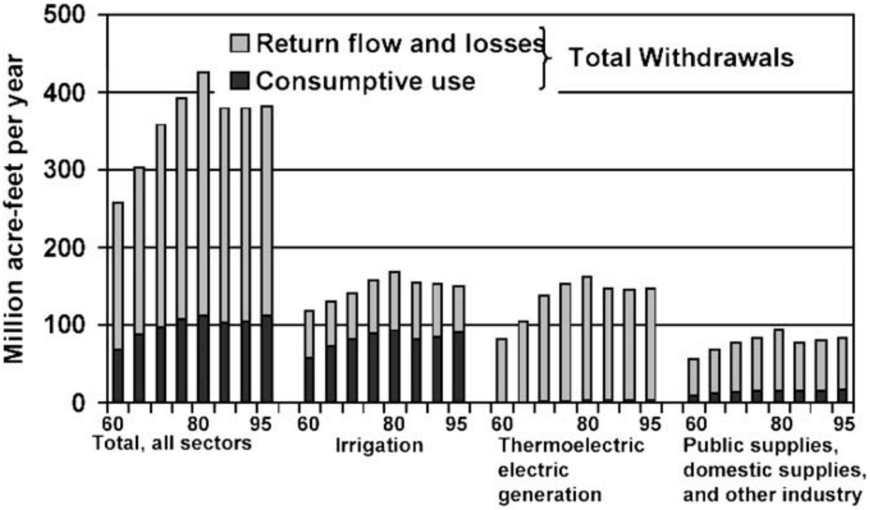


Figure 13.3. Commercial fertilizer use in China, India, and the U.S., 1950–2000. Data sources: Worldwatch Institute, www.worldwatch.org/mag/1996/96schi.html, and Fertilizer Association of India, www.fadinap.org/india/consumption-n.htm., both accessed November, 2002.

13.3.5 Water

Water is a conspicuous and critical input to agriculture. At the biological level, it is required for photosynthesis. Many field crops rely on rainfall, but irrigation plays a key role in many regions and for many types of agricultural output. Increasingly, demand for water for municipal and "in-stream" uses (non-consumptive flows for recreation, maintenance of riparian habitat and other environmental uses) compete with agricultural needs. Figure 13.4 shows water withdrawals and consumptive uses in the US over the past three decades.

The abundance of water in many countries belies significant regional variation in water resources. Historically, expansion of available water supply—dam construction, groundwater pumping and interbasin conveyance—provided the means of meeting increased water demand in areas of water scarcity. The satisfaction of future needs, however, will need to come through reallocation of existing supplies because of lack of suitable project sites, reduced funding, and increased environmental concern. This is likely to result in the reduction of water available for agriculture. Growth in nonagricultural needs, particularly in areas with limited potential to increase water supply, may be met with relatively small reductions in irrigation at the national level, but potentially large adjustments in local and regional patterns of irrigation.



Source: USDA, ERS, based on Solley et al., 1998

Figure 13.4. Water withdrawals and consumptive uses in the U.S., 1960–1990. (Reprinted from U.S. Department of Agriculture, *Agricultural Resource and Environmental Indicators, 1996–1997, Handbook 716*. Washington, D.C., 1997.)

13.4 POTENTIAL ENVIRONMENTAL CONCERNS

The framework used elsewhere in this book to assess the environmental threats posed by an industry—where the gaseous, liquid and solid releases are assessed as to their potential to causes environmental damage—is only partly applicable to agriculture. Agriculture *does* generate releases of environmental importance, but other environmental problems are either easier to discuss in other terms or do not relate to releases per se. We start with the releases and then turn to a variety of other impacts including impacts of agricultural activity on water quality, soil, biodiversity, and product quality.

13.4.1 Solids

A wide variety of solid nonproduct output is generated in agriculture including manures, litter (soiled bedding), "mortality" (dead livestock), crop residues, and processing residues. Most such wastes are recycled as fertilizer or animal feed. The amount of a particular waste that is actually reused in this fashion depends not only on the character of the wastes, but also the proximity of the potential user. The wastes typically have a low value to bulk ratio making extensive transport uneconomic.

13.4.1.1 Manures and Litters

Manure from the raising of livestock is a significant problem in contemporary agriculture. As poultry, pork, and cattle and dairy operations have centralized to achieve economies of scale, the generation of manure has outstripped the capacity of nearby fields to make use of it as a fertilizer. As noted above, transportation costs often limit the shipment of manure to other locales that might find it useful.

The primary environmental threat from manures is release of excess nitrogen from soil whose assimilative capacity has been outstripped. The excess nitrogen can result in eutrophication, the aging of a body of water. The excess nutrients cause accelerated growth of algae which die and decompose depleting the water of oxygen which in turn causes the death of fish. Excessive nutrients have also been tied to disruptive blooms of microorganisms such as *Pfiesteria piscicida* which affect the health of fish and potentially that of humans who consume them.

Soiled animal bedding, especially chicken litter in the poultry industry, also presents a waste management challenge, roughly similar in character to that of manures, in that the primary threats are nutrient overloading and spread of pathogens.

13.4.1.2 Crop Residues

Crop residues or field stubble are the materials left in the field after the harvest of the economically valuable portion of a crop. Frequently, the residues are left on the field to decay and recycle nutrients and improve soil structure. The amount of crop residue to be managed varies widely by crop type with crops such as corn, grain sorghum and wheat having significant residues and forage crops and vegetables having less residue requiring management. Wheat and rice straw are often burned in the field, but air pollution concerns have increasingly limited this approach to residue management. Off-site management, such as use as animal bedding, animal feed, fuel, or as industrial raw materials (as with pulp and paper manufacture), is used for some residues.

13.4.1.3 Mortality

A predictable portion of animal herds and poultry flocks die from diseases and other causes in the course of rearing. The carcasses must be disposed of, both to take off the resulting solid waste and to avoid infection of the remaining herd/flock. The carcasses can be collected for rendering, converted by a variety of means to animal feed, composted, incinerated or landfilled.

13.4.2 Liquids/Water Quality

While there are a variety of liquid releases from agricultural activities including spent irrigation water, manures in liquid form and wastewater from food processing facilities, water-related impacts are better described in terms of the water quality (i.e., the impacts on receiving bodies).

Agricultural activity generates a variety of releases that affect both surface water (rivers, streams, lakes and ponds, and estuaries and coastal waters) and groundwater. Liquid releases from agricultural activities are less like the familiar industrial effluent flowing from a pipe into a watercourse. More typically, they are diffuse non-point sources of pollution to surface and groundwater. The releases and the associated impacts include:

- sediments—which reduce the useful life of reservoirs, clog ditches and irrigation canals, block navigation channels, and increase dredging costs.
- salts—from irrigation return flows can harm aquatic wildlife, increase the need for drinking water treatment, and reduce crop yields.
- nutrients—nitrogen and phosphorus from synthetic fertilizer and manures accelerate algal production which in turn can cause a variety of problems including clogged pipelines, fishkills and reduced recreational opportunities.
- pesticides—pesticides move into water much as nutrients do (run-off, run-in and leaching) as well as through atmospheric deposition. They can harm freshwater and marine organisms and pose health risks to humans.

13.4.3 Gases

Greenhouse gases are the major air pollutants in agriculture. As noted above, field burning, with the associated air pollution, especially particulates, is used as a means of managing some crop residues.

Methane (CH_4) is released from the digestion of ruminants (cows and other livestock that chew their cud) and from the decomposition of manure and from rice paddies. Methane releases from livestock digestion are the most significant agricultural source. The potential for management of digestive releases is not large; it is limited to changes in feed and changes in the productivity of livestock rearing (more meat or milk per animal can lower the aggregate of releases by lowering the number of animals needed). Releases from manures arise primarily from anaerobic fermentation of manure in liquid management systems such as slurry and lagoon systems. Such systems are likely to become more prevalent as ways to control nutrient overload from field application of manure, and they also hold out the potential for increased capture of the methane for fuel use.

13.4.4 Biodiversity

Agricultural production affects biodiversity at several scales. It converts what are, in some cases, natural ecosystems to farmland. In many places this conversion did not occur in modern times, but in others, the contemporary conversion of hayfield and pasture to cropland continues to affect species diversity.

Through choices of crops, varieties and strains, agriculture homogenizes the genetic character of plants and animals grown. The resulting narrowing of the genetic base can make plants and animals more vulnerable to pests and disease.

Choices about cultivation, field size, and land use also affect the biodiversity of nonproduct species especially birds, small mammals, and game species. Game species are of economic and recreational value and nongame species can be of aesthetic importance (as with songbirds) or contribute to pest management. Finally, the biodiversity of soil microbes, insects and other species directly integral to the productivity of farmland is affected by the use of fertilizer, pesticides and other inputs.

A recent, highly-publicized concern related to biodiversity is the use of genetically-modified organisms (GMOs); these are seeds that have been genetically engineered to add, subtract, or enhance specific traits in the plant. The most common of the GMOs are corn and soybeans resistant to herbicides or capable of producing an insect-toxic protein. The related environmental concern is that the altered genomes may jump to other plant varieties, including non-cultivars, producing unpredictable but detrimental effects. The potential benefits include reduced environmental impact from pesticides, increased yield, improved soil conservation, and the use of bio-based materials as chemical factories functioning in lieu of today's petrochemical and synthetic organic chemical sectors.

13.4.5 Sustainability Assessment

The processes, activities, and potential hazards for the agricultural sector are given in Table 13.4. The input and output materials are binned for throughput, potential hazard, and potential scarcity in Table 13.5. The TPH matrix appears in Figure 13.5. Land use for agriculture is regarded as being of potentially extreme concern because of potential ecosystem impacts, and the generation of sediment is regarded as of high

Table 13.4. Processes, Activities, and Potential Emittants for the Agriculture Sector

Process Type	Sector Activities	Potential Emittants
Resource generation	Planting, fertilizing	Pesticides, sediments, salts, CH_4, nutrients
Land maintenance	Burning	VOCs
Purification	Washing	Degraded water, food processing wastes, manures
Packaging	Food packaging	Packaging material residues
Transportation	Food delivery	All packaging materials, gaseous emissions from delivery vehicles

Table 13.5. Throughput–Hazard–Scarcity Binning of Impacts in the Agriculture Sector

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
Agriculture inputs				
Land	H	Habitat	H	H
Seed	M	–	L	L
Animal parents	M	–	L	L
Fertilizer	H	–	L	L
Pesticides	L	Ecosystem	H	M
Packaging	M	–	L	M
Agriculture outputs				
Food grains	L	–	L	–
Feed grains	H	Human	M	–
Animal food products	H	Animal	M	–
Animal feed products	H	Animal	M	–
Non-food products	M	Ecosystem	H	–
Sediment	H	Ecosystem	M	–
Salt	M	Ecosystem	M	–
Nutrients	M	Ecosystem	M	–
Non-product outputs				
Processing water	H	Ecosystem	H	–
Air pollution	M	Smog	M	–

concern for the same reason. Several of the products or byproducts of agriculture are also of high concern because of potential hazard to organisms.

The throughput-potential scarcity matrix also appears in Figure 13.5. There is an extremely high concern related to land use, as arable land is desired for a wide variety of different uses. There is moderate concern for packaging materials derived from petroleum feedstocks because of the mid-range depletion time for oil.

The PEC and PWC matrices for this sector are given in Figure 13.6. As discussed in Chapter 2, water use in agriculture is larger by far than that of any other sector. Energy use, while substantial, is in the mid-range of that of all industrial sectors.

The sector ΣWESH plot appears in Figure 13.7. The dominant concerns are for land scarcity and the impact of land use, and the very high rate of water use. Other concerns, though significant, appear much less crucial to long-term sustainability.

13.5 SECTOR PROSPECTS

Agricultural practice insofar as it affects environmental quality is likely to be shaped by input scarcity, pressures for increased output and concerns over the impacts of agricultural activity on human and ecological health. Two other key developments,

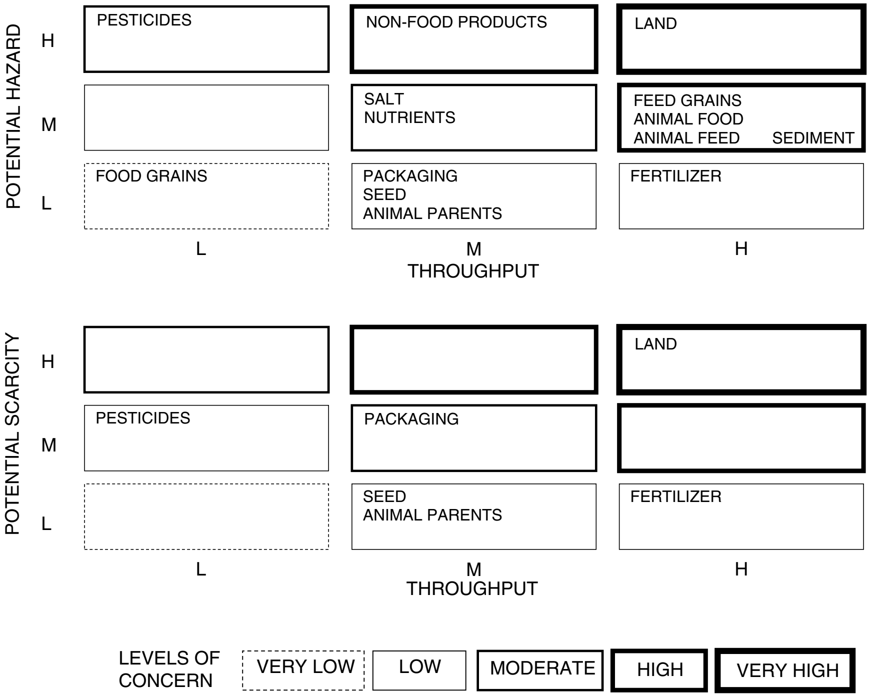


Figure 13.5. The throughput-potential hazard matrix (top panel) and throughput-potential scarcity matrix (bottom panel) for the agricultural sector.

agricultural biotechnology and precision agriculture, driven in part by the other concerns, are likely to have a substantial effect on agriculture. A third factor relates to institutional innovation that would be needed for agriculture to approach sustainability over the long term. The desirable initiatives are likely to include increased public participation in agriculture and land use decisions, and flexible and collaborative approaches to property rights and distortionary fiscal policies. The institutional challenges may ultimately be more difficult to surmount than those related to resources or the environment.

13.5.1 Trends

As the population of the planet continues to grow, particularly in developing countries, the need for increased production of food and other agricultural products will increase. United Nations calculations indicate that population growth adds about 85 million people per year mostly in developing countries. This in turn entails some combination of (1) more intensive agriculture (i.e., more output per unit

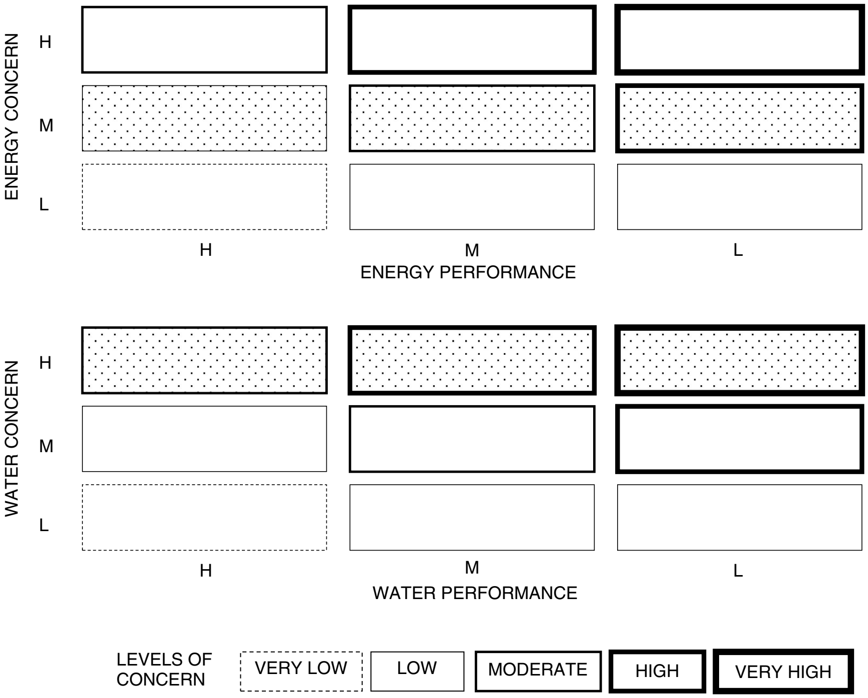


Figure 13.6. The performance-energy concern matrix (top panel) and performance-water concern matrix (bottom panel) for the agricultural sector.

of land cultivated and typically more inputs used per unit output) (2) more land in cultivation, (3) more efficient agriculture (i.e., more output per unit input), (4) less waste throughout the food production and consumption chain or (5) lowered consumption. The actual manner in which increased demand for food is met is obviously difficult to predict, but the impact of biotechnology on the first and third strategies is likely going to be significant. Less waste and lowered consumption are important but outside of the scope of this book. The tension between increasing land under cultivation and increasing yields on existing farmland is an old one and is being revisited in contemporary debates over the benefits of agricultural biotechnology and organic farming.

13.5.1.1 Mounting Resource Pressure

Scarcity of inputs, especially of fresh water, is likely to become a key factor in many regions, independent of increasing demand for food. As population grows, demand for nonagricultural water use grows, creating competition with agriculture

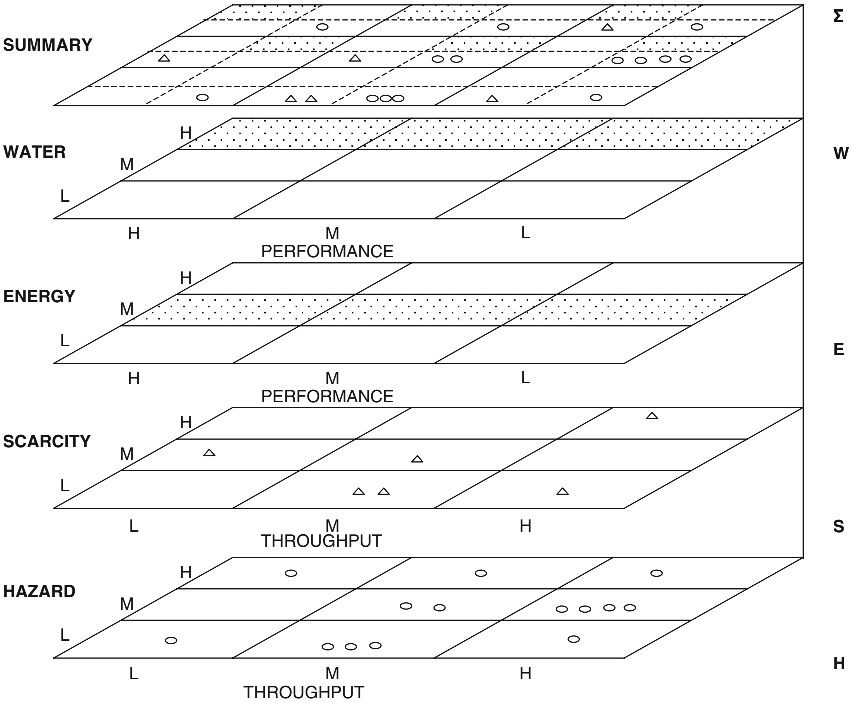


Figure 13.7. The ΣWESH plot for the agricultural sector. The symbols refer to the materials on Figure 13.5.

for this key input. The other input likely to be scarce in some regions is arable land. Here too the competition for this resource is driven both by growing agricultural needs and by nonagricultural activities.

To the extent that current practices in agriculture degrade the land (e.g., salinization, depletion of nutrients, accumulations of toxic substances, soil erosion), some land will be unavailable for growing food in the future. This both limits the supply of land and prompts regulation that can shape this industry. In addition, societal concerns over environmental effects in general, regardless of their impact on agricultural productivity (e.g., pesticides in drinking water, etc.), can also prompt such regulation.

13.5.1.2 Agricultural Production Trends

A trend that appears to be gathering momentum is the increase in precision/intensive agriculture, in which water is supplied only where and when needed, soil may not be required, fish and other aquatic species can be intensively farm-raised, and so forth. To the extent that these new approaches continue to gain adherents, the agricultural sector may look very different in a decade or two.

A second trend moves away from intensification of agricultural production through the the application of new technology and instead relies on ancient methods such as multi-cropping, crop rotation, and use of biological controls to reduce the use of synthetic pesticides and fertilizers (see Text Box 13.1). Organic farming is growing rapidly as a form of production in the developed world and standards are being developed for producers to adhere to. For example, the U.S. Department of Agriculture's National Organic Program requires that certified producers avoid use of any prohibited material (synthetic pesticides, growth hormones, etc.) for three years prior to harvest, maintain or improve the soil through methods like crop rotations, cover crops and composting, use organic seeds, seedlings and planting stock, raise animals on organic pasture under humane conditions and refrain from the use of synthetic growth hormones or antibiotics in animals. Concern over food safety and over agricultural impacts to the environment have stimulated an increase in demand for organic and environmentally favorable agricultural methods. Organic food is currently the fastest growing segment of the consumer food market, and the continued use of these production methods depends on sustained consumer demand as well as the ability of this sector to meet rising demand for output.

Text Box 13.1

Multi-Cropping Boosts Agricultural Yield in China

The loss of agricultural crops to pests and diseases each year is very large—as much as 50 percent of potential yield for some crops in some locations. The traditional defense against these losses has been the application of pesticides, herbicides, and fungicides, all of which are costly and may result in ecosystem degradation.

A recently recognized alternative has been to move from planting a single crop to planting two or three in adjacent plots. If one plant type is susceptible to disease, this approach makes it more difficult for the disease to spread. In addition, if multi-cropping is applied on a regional scale, it will tend to inhibit disease on the same scale.

This theory was tested in 1999 in the Yunnan Province of China, where farmers alternated rows of sticky rice (highly valuable but quite susceptible to disease) with standard rice (less valuable but more resistant). The result was almost total elimination of rice blast fungus, a disease that costs Asian farmers the equivalent of several billion U.S. dollars of losses each year. With this demonstration of the benefits of diversity, applications are being pursued for prairies, rainforests, and other agricultural systems.

Source: C. K. Yoon, Simple method found to increase crop yields vastly, *New York Times*, F1-F2, August 22, 2000.

13.5.2 Scenarios

13.5.2.1 Trend World

A continuation of current trends in the agricultural sector represents a contest between gradually improving technology and rapidly escalating needs. Through improved efficiency in the use of water and energy, global agriculture can be expected to produce ever larger quantities of food. Population and the food needs and preferences of an increasingly affluent world, however, continue to escalate demands on the industry. In a trend world, smarter farming, increasingly organic in nature, will gradually decrease dependence on fertilizers and pesticides. Concurrently, climate change will cause transitions in crop health, resilience, yield, and the geographical distribution of agriculture. If trends hold, the more affluent parts of the world will increasingly feed themselves well, while the poorer regions will face great food challenges.

13.5.2.2 Green World

In a green world for agriculture, the world's population will be fed a nourishing diet. This will come about through a combination of technological, political, and cultural advances. On the technological side, precision agricultural techniques will be used to optimize the use of water and land. Genetically modified organisms, properly safeguarded, will increase crop yields and resistance to disease. Research and its results will be transferred efficiently to the less developed world. Worldwide, diets will evolve into a central dependence on fruits and grains, and lesser components of meat and fish.

13.5.2.3 Brown World

In a brown world for agriculture, attempts to control pests and pathogens will be overwhelmed by evolving resistance to pesticides and the transfer of organisms by international travel and trade. Concurrently, the loss of arable land to rapidly growing cities and to recreational uses will decrease total agricultural land. The reallocation of water from irrigation to residential and commercial use will be extensive. Rapid climate shifts will create new areas of drought and flood. The result of all these pressures will be a significant global loss in agricultural production and an increase in rates of starvation.

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Chapter 14

Food Processing

14.1 OVERVIEW

The food processing industry transforms the products of agriculture into the foods and drinks we consume daily. The industry is relatively diverse, dealing with some products that need minimal processing, such as fresh fruits and vegetables, and others that require substantial secondary processing to create a final product, such as dry cereal or baked goods. Figure 14.1 shows the technological sequence for the sector.

The subsectors of the food processing industry include those that produce:

- meat, poultry, and seafood
- fruits and vegetables
- dairy products
- vegetable oils
- sugar
- soft drinks
- beer (brewed beverages)
- wine and spirits
- baked goods
- confectionaries
- snack foods
- pastas and other starches

The food processing industry has an interesting structure that is determined partly by the geographical distribution of its raw materials, the products of agriculture. In the European Union, 92% of food and drink processors are small or medium sized companies. Some processors are located in rural areas while others are more industrial in scale, e.g., large sugar plants. Some processors, like olive oil producers, have a highly seasonal production cycle that is determined by the harvest, while others, like dairy processors, have a more stable production cycle. Perishable items, like fruits and

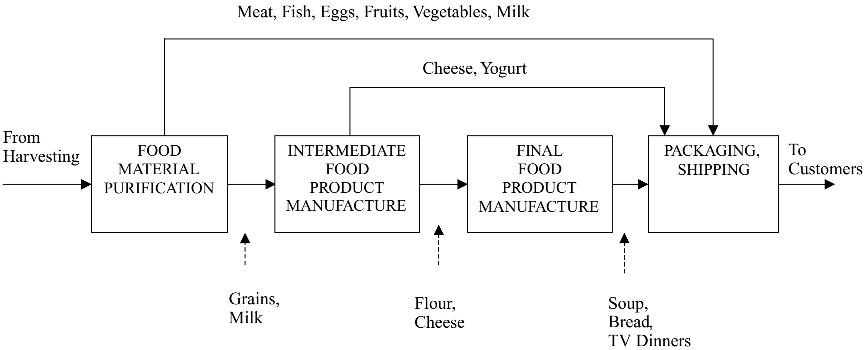

Figure 14.1. The technological sequence diagram for the food processing industry.

vegetables, tend to be processed and packed near their source, whereas other products, like soft drinks, are produced closer to population centers and sources of water.

Advances in the processing and packaging of perishable foods have extended the shelf life and improved the transportability of some foods, allowing for wider geographic distribution and possible consolidation or relocation of plants. The industry in the U.S., which is responsible for 26% of the worldwide production of processed food, has become dominated by a handful of large, highly diversified companies. The 20 largest U.S. food processors have higher total sales than the next 80 combined, and than the subsequent 400 combined. There are currently about 17,000 food manufacturing facilities in the U.S., down from 34,000 in 1947. The European Union is home to 26,000 food and drink manufacturers.

The food processing industry is a heavily regulated industry, with regulatory scrutiny focused primarily on the quality and safety of the products delivered to the consumer rather than on environmental aspects of production. In recent years, however, the industry has made progress in improving environmental performance through waste minimization (which also increases production efficiency). Solutions that simultaneously address the quality and safety of the products and the environmental performance of the production process will be particularly attractive to this industry.

14.2 PHYSICAL AND CHEMICAL OPERATIONS

14.2.1 Physical Operations

Many of the operations used in processing foods and drinks are physical in nature. Raw materials are received, sorted, cleaned, cut, blended, ground, formed, or mechanically separated before they are either packaged or sent for further processing or heat

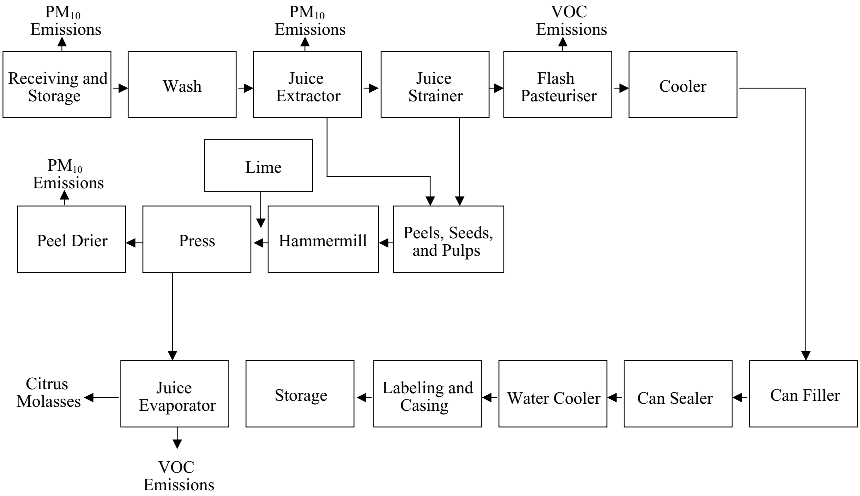

Figure 14.2. A typical flow chart of fruit and vegetable processing. (*Source:* U.S. Environmental Protection Agency, *Compilation of Air Pollution Emission Factors*, AP-42, Fifth Edition, Research Triangle Park, NC, 1995.)

treatment. The production of canned juices, for example, consists of the following steps illustrated in Figure 14.2: washing, extracting, straining, container filling, container sealing, cooling, labeling, casing, and storing for shipment. Where vegetables are concerned, peeling, coring, cutting, cooking, and heat sterilizing are included in the process.

The production of soybean oil is slightly more complex, with a number of physical processes used to prepare the beans for the subsequent extraction of the oil. Figure 14.3 shows the typical steps in preparation and extraction. The beans enter a mill on conveyor belts and are weighed, cleaned of metal using magnets, and passed through a roller for "cracking" into several pieces. The hulls are removed from the cracked beans by aspiration, and the cracked beans are heated slightly prior to being pressed through a cylindrical roll which forms them into flakes. The oil is extracted from the flakes by washing them in a hexane solvent. The solvent is then evaporated from the oil and the flakes and steam is used to desolventise the oil further. Residual hexane is removed using mineral oil scrubbers. The oil is then stored for further processing or packaging.

14.2.2 Chemical and Biological Operations

Chemical and biological operations play an important role in the manufacture of many foods and beverages, including bread, cheese, yogurt, beer, wine, and meats.

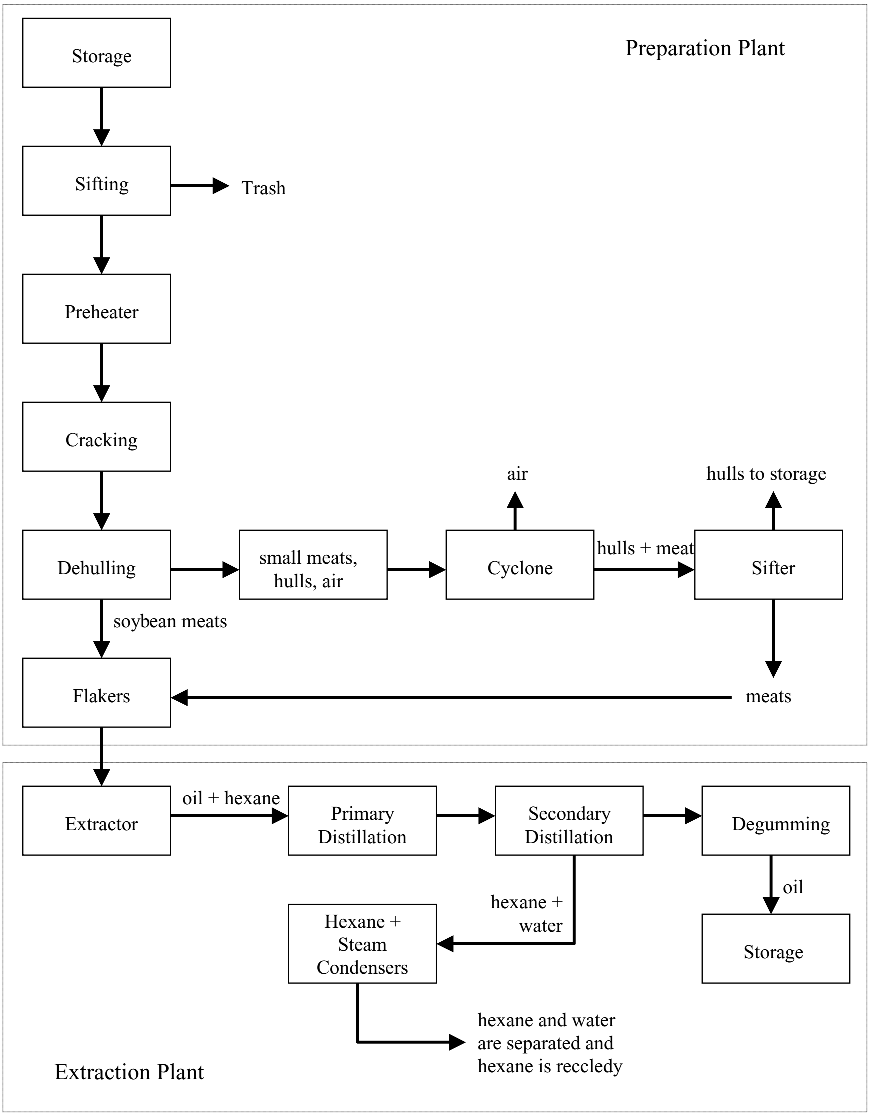

Figure 14.3. Process steps in the preparation of oil from soybeans. (*Source:* National Pollutant Inventory Emission Estimation Technique Manual for the Vegetable Oil Processing Industry. Environment Australia. 1999. http://www.npi.gov.au/handbooks/approved_handbooks/pubs/fvegoil.pdf, accessed August 30, 2003.)

Fermentation is used to alter the texture, preserve, or produce certain flavors and aromas in foods and beverages, while curing is used to preserve and alter the flavor of meats.

Fermentation involves the controlled used of biological organisms to break down the sugars in food into either alcohol or lactic acid. To produce beer or wine, yeast is used to break down sugars and produce ethanol and carbon dioxide, as shown in the equation.

$$C_6H_{12}O_6 \longrightarrow 2C_2H_5OH + 2CO_2$$

Breadmaking uses yeast fermentation to leaven the bread (i.e., to generate carbon dioxide to cause the bread to rise) and the ethanol in this case is released to the air.

Cheese and yogurt are produced using various bacterial cultures to break down the lactose in milk and produce lactic acid. Different bacteria give different tastes and aromas, and the conditions under which these cultures are used must be carefully controlled to prevent contamination or spoilage. Fermentation processes also require close regulation of temperature and may require extended periods of storage at specific temperatures, resulting in energy and cooling water consumption.

Meat is cured by adding common salt (NaCl) and a source of nitrite from a curing salt (including $NaNO_3$, $NaNO_2$, KNO_3, or KNO_2). A pigment in the meat reacts with nitrite to give the meat a certain color. The presence of the salt and nitrite in the meat inhibits the growth of organisms and increases its shelf-life.

A final type of operation that is starting to be employed in the food processing industry is irradiation. Low-dose radiation applied to foods can kill pathogens like *E. coli* and salmonella, and hence increase shelf-life of the products. It can also inhibit ripening or sprouting in fruits and vegetables. Foods that are irradiated must be labeled as such in the U.S., a factor that may inhibit the use of this technique as the public is wary of consuming irradiated products. If public perception changes, the irradiation of foods could become more widespread over the next decade or so.

Food safety and purification are central concerns in this sector. As a result, much of the water used in the industry is drinking-water quality. This requirement tends to be in opposition to the desire to reduce energy and water use for environmental reasons.

14.3 THE SECTOR'S USE OF RESOURCES

14.3.1 Energy

The food processing industry is not as energy intensive as the heavy industries, like mining, metal processing, and chemicals. However, the industry ranks relatively high (fifth) on the use of energy by all industrial sectors. The food processing sector uses 5.9% of the total energy consumed by U.S. industry for fuel uses. Similarly, in

Table 14.1. Consumption of Energy by Food Processing Industry Sub-Sectors (German Food Processing Industry)

Rank	Sub-Sector in Food Industry	Energy Consumption (MWh/yr)
1	Manufacture of sugar	212109
2	Manufacture of crude oils and fats	177898
3	Manufacture of starches and starch products	158918
4	Manufacture of refined oils and fats	70862
5	Processing of tea and coffee	35370
6	Manufacture of malt	29889
7	Processing and preserving of potatoes	27372
8	Manufacture of homogenized food preparations and dietetic food	24939
9	Operation of dairies and cheese making (without ice cream)	22323
10	Manufacture of ice cream	19477

Source: Integrated Pollution Prevention and Control. Draft Reference Document on Best Available Techniques in the Food, Drink, and Milk Industry. Draft April 2002. European Commission. http://eippcb.jrc.es/pages/FActivities.htm

Germany, the food processing industry uses 6.7% of the total energy consumed by industry, and ranks as the fifth largest energy-consuming sector.

Some subsectors of the food and beverage industry are much more energy intensive than others. For example, the manufacture of sugar involves the use of steam and direct heat for evaporation (sugar beets are 75% water). Sugar manufacture ranks highest in energy consumption of the sub-sectors of the German food industry, as shown in Table 14.1. Other subsectors that rely on heating, cooling, freezing, or the storage and transportation of bulky raw and processed products are also relatively heavy consumers of energy. For example, 77% of the electricity used for the transportation and storage of frozen vegetables is consumed by compressors.

14.3.2 Water

The food and beverage industry has historically been a large consumer of water. Water is used as a primary ingredient (e.g., in the manufacture of beverages), as well as to clean ingredients and equipment, to transport raw materials in a plant, and for heating and cooling. Data for Germany show that the food and drink industry uses about 5% of the total water consumed by industrial sources, but it uses about 30% of all drinking water consumed by industrial sources. Overall, almost two-thirds of the water used by the industry is of drinking-water quality and some subsectors, like soft drink, beer, and dairy manufacture, use drinking water almost exclusively.

The amount of water used for some practices, like washing and rinsing, may be set by regulation. For example, the U.S. Department of Agriculture (USDA) defines

Table 14.2. Typical Rates of Water Use for Food Processing

Sub-Sector	Rate of Water Use (Gal/ton Product)
Fruits and Vegetables	
Green beans	12,000–17,000
Peaches and pears	3,600–4,800
Other fruits and vegetables	960–8,400
Food and beverage	
Beer	2,400–3,840
Bread	480–960
Meat packing	3,600–4,800
Milk products	2,400–4,800
Whiskey	14,400–19,200

Source: Clean Technologies in U.S. Industries: Focus on Food Processing, www.p2pays.org/ref/09/08853.htm, accessed August 30, 2003.

minimum standards for the amount of water needed to clean poultry products. Table 14.2 shows some typical rates of water use for different subsectors of the industry. While water will always be an important resource for the food and beverage industry, there is scope for conservation and reuse, especially in its non-ingredient uses.

14.3.3 Materials and Process Chemicals

The raw materials used in the food and drink industry are primarily products of agriculture. Some subsectors, like fruits and vegetables, rely directly on agricultural products, while others, like breadmaking, rely on intermediate products that have been derived from agricultural products. The abundance or scarcity of these raw materials, or ingredients, is determined by the output of the agricultural sector discussed in Chapter 13.

Consumer preference will also, to some degree, dictate the supply of raw materials used in the food and beverage industry. In recent years, for example, sub-sectors of the food industry have developed product lines to serve consumers who wish to avoid consuming foods containing genetically modified organisms (GMOs). At the same time, agricultural biotechnology companies are developing techniques to improve the productivity or alter the properties of seeds and crops, potentially changing both the quantity and quality of the raw materials provided to the food processing industry.

Whether and how extensively agricultural biotechnology will change the supply of raw materials to the food processing industry remains to be seen. A complex set of issues surrounding consumer preference, government regulation, technology, and international trade are involved. U.S. consumers seem generally more receptive to agricultural biotechnology than are their counterparts in Europe and Japan. U.S. farmers have adopted the technology most widely; 70% of the biotech crops planted worldwide are planted in the U.S. On the other hand, major food processors and retailers, including McDonalds and Frito-Lay, have declared that they will not use ingredients produced using biotechnology. Regardless of the rate of change in the industry in terms of adopting or abandoning agricultural biotechnology, fundamental scarcity of raw materials seems unlikely to pose a major problem for the food and beverage industry. Scarcity of agricultural products is typically a question of distribution rather than quantity.

14.3.4 The Biomass Metabolism of the Food System

It is instructive to examine the overall food system from the perspective of its resource utilization efficiency. An overview of the flows, expressed in energy units, is given in Figure 14.4. One obvious and rather startling feature of the data is that of the

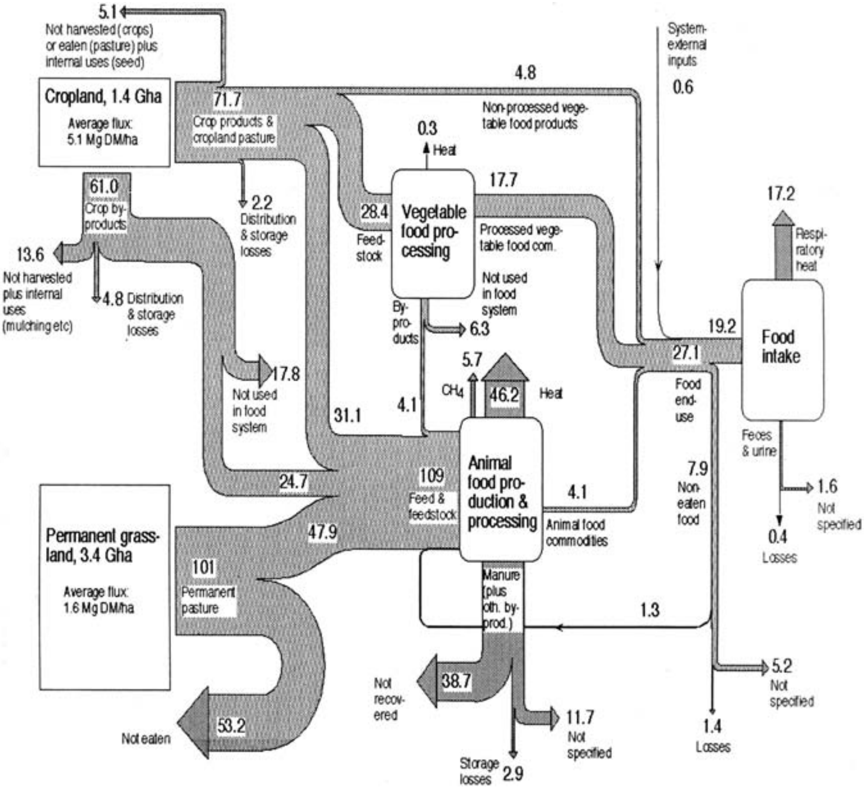

Figure 14.4. Biomass flows in the global food system in 1992–1994. The units are exajoules of gross energy per year. Source: Chalmers and Göteborg University, *Research Report from Physical Resource Theory, 1995–2001*, Göteborg, Sweden, 2002.

234 units of biomass leaving the land, only 19 are finally delivered as food intake—about 8%. The difference in efficiency between the animal and vegetable food systems is also dramatically apparent. The animal food system accounts for nearly 70% of total biomass appropriation, but it constitutes only 13% of the human diet. Overall, this diagram indicates that there are many opportunities for efficiency improvement in the food processing sector.

14.4 POTENTIAL ENVIRONMENTAL CONCERNS

Table 14.3 gives an overview of the types of releases to air, water and land that are generated by selected operations used in the food and beverage manufacturing industry.

14.4.1 Releases to Land

Solid wastes released by the food processing industry consist largely of organic waste derived from food waste such as trimmings and peelings. While they are typically very high in nitrogen and phosphorous, these organic wastes are not of very high volume relative to the waste generated by other industrial sectors. Some organic wastes are reused as components of fertilizer or animal feed. However, much of the solid waste from food processing is disposed of by conventional means, to landfill, by incineration, or by composting.

A second source of solid waste is the packaging of foods and beverages. This includes both end-consumer packaging, and the packaging used to handle and transport the products within a plant and to retail locations. Use of reusable plastic totes in a plant, or substitution of packaging materials for more environmentally favorable ones are examples of attention to this solid waste issue. Some packages are used almost exclusively by this industry; 95% of all steel cans produced are used by the food and beverage industry, for example.

14.4.2 Releases to Water

Just as the food processing industry is a large consumer of water, it is a large producer of wastewater. Cleaning of the raw materials is the biggest user of water in the industry. The quality of wastewater emitted is of as much, or more, concern than the quantity. Wastewater from food processing is unique among industrial wastewater in that it is relatively low in metals and inorganics, but very high in organic contaminants.

Food processing waste water is highly variable, but it is typically very high in biochemical oxygen demand (BOD) and chemical oxygen demand (COD). A high BOD level is associated with high levels of dissolved and/or suspended solids, minerals,

Table 14.3. Environmental Releases from Food and Beverage Processing Operations

	Environmental Release to		
Operation	Air	Water	Land
Raw Material Preparation			
Material handling, unpacking, storage	None	None	Organic waste
Sorting, grading, trimming, destemming	Odor, particulates	Soluble organic matter, TSS	Organic waste, inorganic waste (e.g., soil)
Size Reduction, Mixing, Forming			
Cutting, mincing, etc.	None	Soluble organic matter, TSS, Oils/fats	Organic waste, Oils/fats
Mixing, blending	Odor, particulates, organics	Soluble organic matter, TSS, Oils/fats	Organic waste
Separation Techniques			
Extraction	Odor, organics	Soluble organic matter, TSS	Organic waste, solvent
Filtration	Few	Soluble organic matter, TSS, Oils/fats	Organic waste, inorganic waste
Distillation	Odor, Organics, CO_2	Soluble organic matter, TSS	Organic waste
Product Processing Techniques			
Fermentation	Odor, CO_2	Soluble organic matter, TSS	Organic waste
Brining, curing	None	Soluble organic matter, TSS, dissolved solids	Organic waste
Carbonation	CO_2	None	None
Heat Processing			
Baking	Odor, particulates, organics, CO_2	Soluble organic matter, TSS, Oils/fats	Organic waste
Frying	Odor, organics	Soluble organic matter, TSS, Oils/fats, Acid/alkali	Organic waste, Oils/fats
Processing by Removal of Heat			
Freezing	CO_2, NH_3	None	None
Packing, filling, storage under gas	Particulates	Soluble organic matter, TSS	Organic waste, packaging from process operations
Utility processes			
Cleaning/sanitization	None	Soluble organic matter, TSS, Oils/fats, Acid/alkali, Nitrate, Nitrite, Ammonia, Phosphate	None
Demineralization of process water	None	Soluble organic matter, TSS, Acid/alkali, Nitrate, Nitrite, Ammonia, Phosphate	Organic waste, inorganic waste

TSS = Total suspended solids.

Source: Integrated Pollution Prevention and Control. Draft Reference Document on Best Available Techniques in the Food, Drink, and Milk Industry. Draft April 2002. European Commission. http://eippcb.jrc.es/pages/FActivities.htm and organic nutrients containing nitrogen and phosphorus. Wastewaters with high BOD cannot be released directly to an aquatic environment or POTW (publicly owned treatment works) and will typically be pretreated to lower the BOD. The pH of food processing wastewater can also vary a great deal depending on the natural pH of the raw material, and the process steps used (e.g., dairy operations can produce acid waste streams). Wastewater from the fruit and vegetable subsector may contain residual pesticides, while that from the meat subsector will contain fats and oils.

A final component of the wastewater that is of concern in this industry is pathogens. Such organisms may be present in the water used to clean and process meats, poultry and seafood. Chlorine is typically used to disinfect the wastewaters prior to their discharge, but alternative techniques using UV light or ozone as disinfectants are starting to be used to reduce the use of chlorine.

14.4.3 Releases to Air

Air emissions from the food processing industry contain few hazardous compounds. The release of volatile organic compounds (VOCs, involved in smog production) is common, however. Air emissions from brewery operations are among the more significant among the industry's subsectors, and they largely consist of CO_2, ethanol, particulates, and by-products of combustion. Odors can be a significant concern from many food processing plants, but they are difficult to control by regulation and are typically treated as a nuisance rather than an environmental concern. Many food processing plants have some form of odor controls in place.

14.4.4 Sustainability Assessment

The potential emittants from food and beverage operations are shown in Table 14.4 and the materials binned for throughput, potential hazard, and potential scarcity in Table 14.5. The TPH matrix is shown in Figure 14.5. The only emission of high concern is wastewater, and this is typically treated to reduce BOD and other constituents of concern (e.g., pathogens). The TPS matrix is shown in the lower half of Figure 14.5, and it shows no areas of high concern.

Both water and energy use are of moderate concern in the food processing industry, and the matrices are shown in Figure 14.6. The ΣWESH plot, Figure 14.7, calls attention to several issues, especially wastewater BOD.

14.5 SECTOR PROSPECTS

Practices in the food and beverage industry are quite closely governed by regulation which provides both constraints and opportunities for changes that minimize environmental impact. While food and beverage processing facilities are subject to

Table 14.4. Processes, Activities, and Potential Emittants from the Food and Beverage Manufacturing Sector

Process Type	Sector Activities	Potential Emittants
Purification	Rinsing, sorting, disinfecting (including equipment)	Organic solid waste, inorganic solid waste (e.g., soil), wastewater, chlorine
Cleaving bonds	Cutting, fermentation	Organic solid waste, wastewater, oils/fats, CO_2, odor
Combining	Mixing, blending	Organic solid waste, wastewater, odor, particulates
Forming bonds	Baking, cooking	CO_2, particulates, by-products of combustion, oils/fats, wastewater, organic solid waste
Packaging	Food and beverage packaging	Packaging materials
Transportation	Food and beverage distribution	Packaging materials, organic solid waste, gaseous emissions from delivery vehicles

Table 14.5. Throughput-Hazard-Scarcity Binning of Impacts in the Food and Beverage Manufacturing Sector

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
Agricultural raw materials	H	–	L	M
Process chemicals or microbes (e.g., salt, yeast)	L	–	L	L
Packaging materials	H	–	L	M
Pathological organisms	L	Ecosystem	H	–
Wastewater BOD	H	Ecosystem	H	–
Organic solid waste	H	Ecosystem	L	–
CO_2	L	Climate	L	–
Particulates	L	Human	L	–
Odors	M	Aesthetic	L	–
Packaging residues	M	Landfill	L	–

environmental regulation, they must also adhere strictly to regulations that ensure food safety and quality. In the U.S., two federal agencies are responsible for food safety. The FDA (Food and Drug Administration) is responsible for alcoholic beverages under 7% alcohol level, dairy products, and seafood products, while the USDA (U.S. Department of Agriculture) is responsible for fruits, vegetables, meat, poultry and eggs. These bodies enforce quality, safety and wholesomeness standards by inspecting food and beverage production at all stages. Some regulations restrict the measures that could be taken to reduce environmental impacts of the operations. For example, standards set by the USDA for the minimum quantity of water needed to clean poultry products suggest that it would be unsafe and unhygienic to reduce water consumption in this area for environmental reasons. Environmental impact reductions can be made in other areas of the process, such as the reuse of water for utility (e.g., heating, cooling) operations.

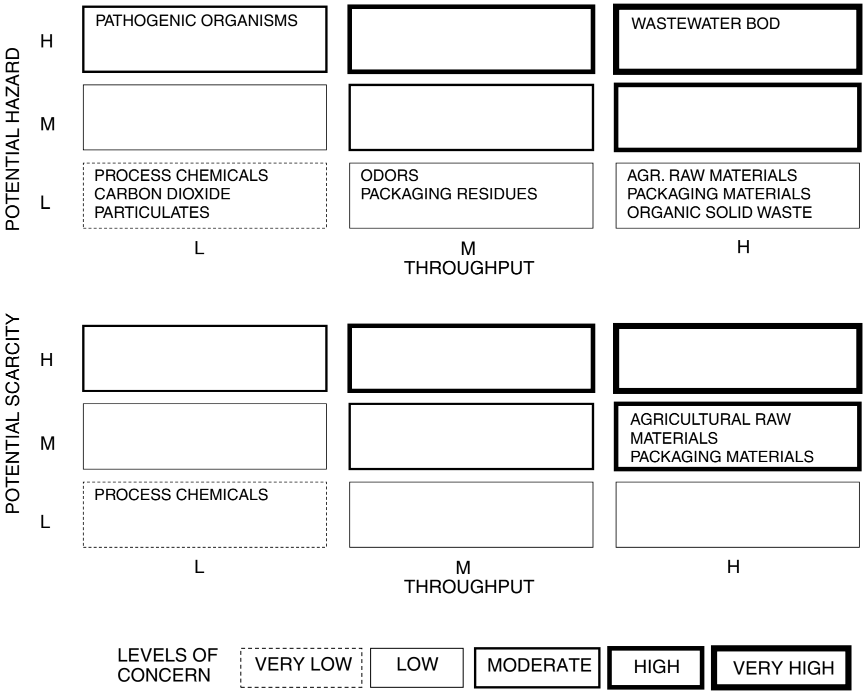

Figure 14.5. The TPH matrix, above, and TPS matrix, below, for the food processing industry.

A new rule, made fully effective in 2000, strengthens the procedures used to detect, reduce and prevent microbial infection in U.S. meat processing facilities. The Hazard Analysis and Critical Control Point (HACCP) regulations require the use of scientific testing to measure levels of pathogens and bacteria, replacing a traditional system that inspected the final product on the basis of sight and smell. The HACCP regulations also require processing facilities to write and adhere to a set of sanitation standard operating procedures (SSOPs). Implementing these new procedures may provide opportunities for plants to investigate their environmental impacts, especially as the simultaneous strengthening of the Clean Water Act (CWA) requires U.S. food processors to meet more stringent standards for wastewater discharge.

Processors in Europe are subject to a comprehensive framework of European Commission Directives that govern food safety, hygiene, composition, labeling, nutrition, organic production, and other issues. Both "horizontal measures" that apply across food categories, and "vertical measures" that apply to specific commodities across all processing stages, are in place.

Pollution prevention has recently become prominent in the food processing industry, with particular focus on reducing water use, and improving packaging to

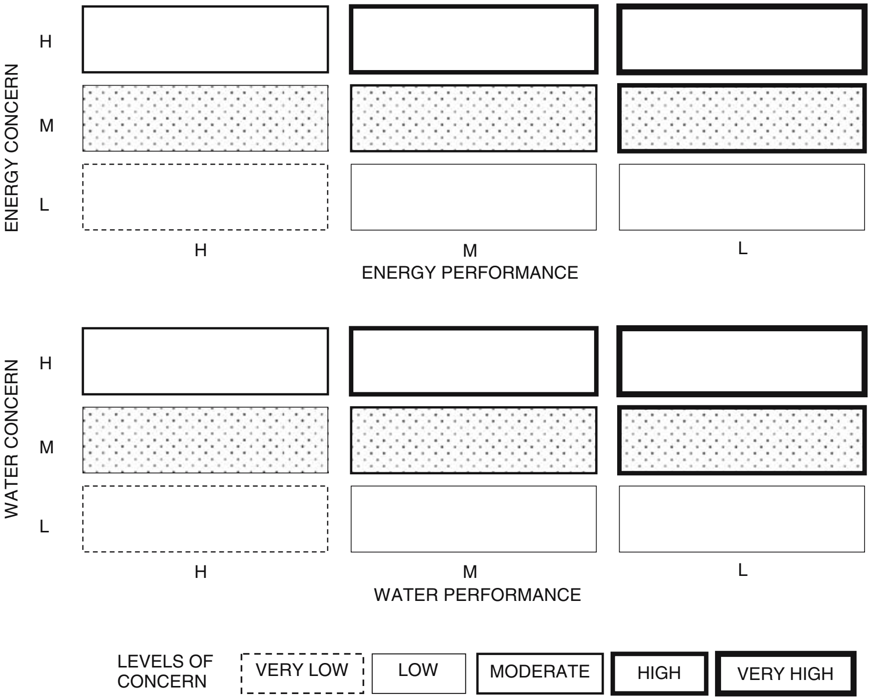

Figure 14.6. The performance-energy concern matrix (top panel) and performance-water concern matrix (bottom panel) for the food processing sector.

reduce environmental impacts. Food processing operations in Europe are subject to the European Union's IPPC (Integrated Pollution Prevention and Control) Directive, which requires that certain industrial facilities be issued permits that are based on the use of Best Available Technologies (BAT) to achieve pollution prevention. Consistent with this approach, the European IPPC Bureau produces reference documents on BATs and encourages their use by member states as they issue permits to facilities. This approach is likely to speed the adoption of pollution prevention methods in Europe, many of which fall into the general categories of waste minimization through good housekeeping and operational improvements, recycling and reusing water, process redesign to prevent emissions, and energy efficiency.

14.5.1 Process Trends

One important process trend is increased attention to the reduction, reuse and recycling of non-ingredient water. Advanced wastewater treatment processes—beyond biological treatment—including membrane filtration (reverse osmosis), disinfection

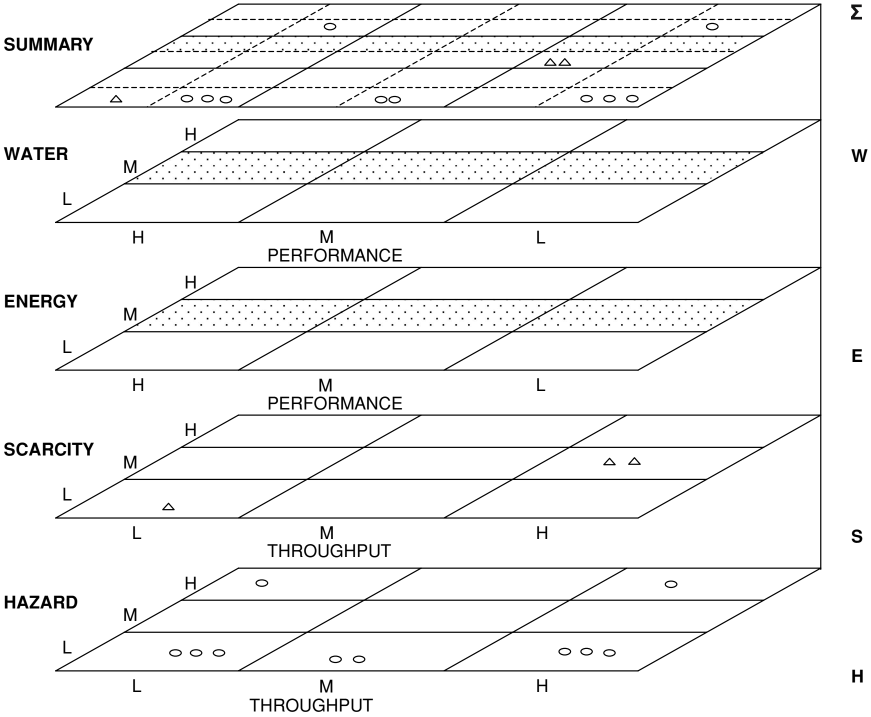

Figure 14.7. The ΣWESH plot for the food processing industry. The symbols refer to the materials on Figure 14.5.

(ozone and UV replacing chlorine), and charge separation. The goal of advanced wastewater treatment is to remove particular constituents—e.g., pathogens, suspended solids, nitrogen, and phosphorous, and to dramatically reduce the rate of water withdrawal.

Improved sensors and automated process control will lead to finer control of temperature, pH, humidity, flow rates and contamination levels. This can result in greater efficiency in energy and water use, and lower waste production dues to decreased spoilage.

As long as regulations allow, process waste from food processing may be used as feedstock or product in the agricultural sector. For example, animal feed may be produced from process byproducts, or fertilizer from other waste. Such actions both reduce costs and reduce the amount of material going to landfills.

Finally, there is a trend toward the practice of food irradiation to extend shelf-life and kill pathogens. Irradiation decreases the amount of water needed for rinsing and cleaning, but can be a controversial practice because it employs low-level radioactive isotopes. Its future will depend on public perception and regulation.

14.5.2 Product Trends

There are two competing trends in product packaging. First, consumers want more convenient, more ready-to-use, transportable foods, which implies more packaging (and waste) and second, environmentally conscious consumers want packaging reduced or materials to be recyclable. It is possible that both of these desires will be satisfied by use of biodegradable and even edible food packaging, although the applications for such packages are limited.

The reduction of in-plant packaging will come about from increased use of reusable containers and totes, or those made from recycled materials. Such containers often lower costs for food processors and distributors.

Food products themselves are likely to be more "processed" as consumers demand things that are ready to eat (e.g., salads rather than lettuces, or complete meals in a package). This implies increased "manufacturing" (cooking, assembly, etc.) as a part of the food processing industry, rather than just packaging and distribution.

Finally, consumer pressures exist for use or non-use of certain product ingredients—e.g., food with or without genetically modified organisms, organic foods, food from threatened species, etc. Food distributors and retailers are responding to this demand by committing to label or not to carry foods made using genetically modified organisms. For example, in response to consumer backlash about Monsanto's use of GM seeds, major supermarket chains in Europe (Tesco, Sainsburys and others) pledged that they would not carry goods made from such seeds. These pressures inevitably influence farmers' selections of the crops they plant, and hence the available supply of raw materials to the food processing industry.

14.5.3 Possible Future Scenarios

Trend World

The trend world for the food processing sector is a world of gradually increasing efficiency in manufacturing, packaging, and distribution. Energy and water will be used with gradually improving attention to conservation (and reuse where possible). Better refrigeration and management will decrease food wastage. Escalating pressures for more convenient foods will result in increased packaging per unit of food, however, and an accompanying increase in the costs of shipment and storage will be realized.

Green World

In an environmentally superior world, emphasis will be placed on locally derived foods to the degree possible, cutting transport and packaging challenges substantially. Spoilage will be reduced to very low levels by improved control of processing and refrigeration, and by the safe irradiation of a number of food products. Packaging will be reduced, and may be either biodegradable or edible. The world will grow enough food for all its citizens, and will process, package, and distribute it so that hunger is no longer a problem, even in relatively poor countries.

Brown World

In a brown world, scarcity of energy and water in many parts of the world will increase the rate of spoilage of whatever food is available. Food distribution will be hampered by a shortage of transportation fuels, and at the same time the increasing desire for convenience will make locally-sourced food less viable. Continued problems with food safety will raise its cost and force tradeoffs with environmental goals. Rapid climate changes will have resulted in rapidly changing mixes of available food products, and processing facilities and machinery have been unable to adjust in an efficient manner.

FURTHER READING

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Chapter 15

Textiles and Leathers

15.1 OVERVIEW

The textiles and leather sector prepares natural and manmade materials for use in clothing, carpets, furniture manufacture, interior decoration, and related industries. In the case of textiles, natural and manmade fibers are spun into yarns and threads, woven or knit into fabrics, and dyed and finished into final products. In the case of leathers (the largest industrial sector based on a byproduct), the epidermis and hair are removed from animal hides, tannins or chromium salts applied as preservatives, and dyes and waxes used to achieve the final products.

The sector sequence diagram is shown in Figure 15.1. The preceding sectors are agriculture for cotton and wool, petrochemicals for synthetic fibers (polyester, nylon, acrylic, and others), and forest products for cellulosics (rayon, acetate, and others). Cotton and synthetic fibers dominate fiber production and use, as Table 15.1 demonstrates. The textiles and leathers sector is categorized as an intermediate manufacturing stage, the products moving to final manufacture as clothing, furniture coverings, and auto seat covers.

15.2 PHYSICAL AND CHEMICAL OPERATIONS

15.2.1 Textiles

The fibers from which textiles are made originate from three sources: natural fibers (cotton, wool, etc.), cellulosic fibers (acetate, rayon, etc.) made by reacting chemicals with wood pulp, and synthetic fibers (polyesters, nylon, acrylics, etc.) which are synthesized from petrochemical feedstocks. The process is shown in Figure 15.2. For natural and cellulosic fibers, cleaning and texturing preparation steps begin the process. Once the fibers are relatively uniform, they are spun into yarn by twisting several fibers together in a high-speed spindle.

Table 15.1. Global Production of Textile Fibers (Tg)

	1993	1994	1995	1996	1997
Cotton	17.0	18.7	20.0	19.5	19.7
Wool	2.7	2.7	2.7	2.6	2.5
Synthetics	16.0	17.7	18.4	19.7	21.7
Cellulosics	2.3	2.3	2.5	2.3	2.3

Source: M. S. Reisch, U.S., European fiber producers regroup, *Chemical & Engineering News*, pp. 12–14, August 31, 1998.

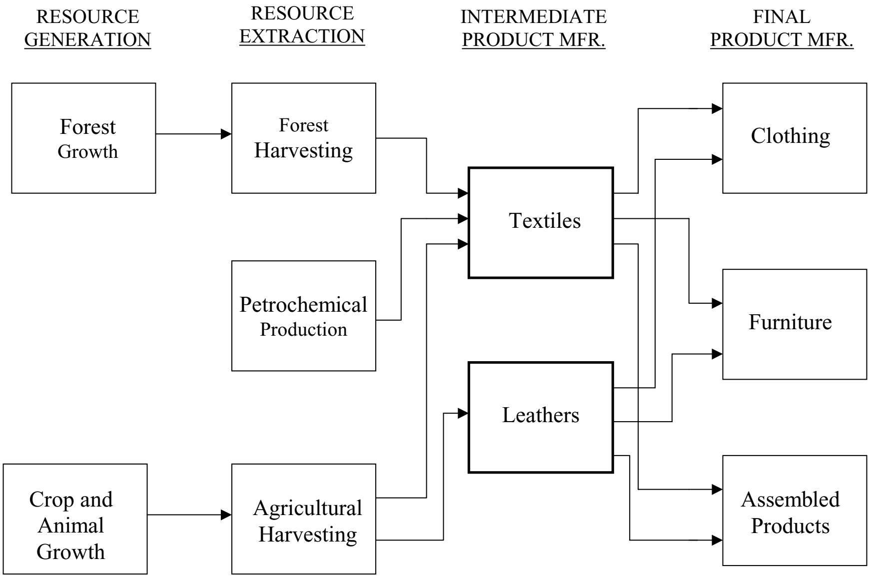

Figure 15.1. The technological sequence diagram for the textiles and leathers industries.

The most common technique for manufacturing fabric is weaving, in which one set of yarns is interlaced with another set oriented crosswise on a loom. Before weaving, the yarn is passed through a sizing solution (usually starch, a polysaccharide derived from plants) to protect it from snagging or abrasion. The alternative fabric manufacture technique is knitting, in which the yarn threads are interlocked.

Wet processing stages follow fabric formation, shown in Figure 15.3. These steps are those with the potential to pollute. They begin with several preparation steps, the most important for our purposes being desizing (using hot-water washes with or

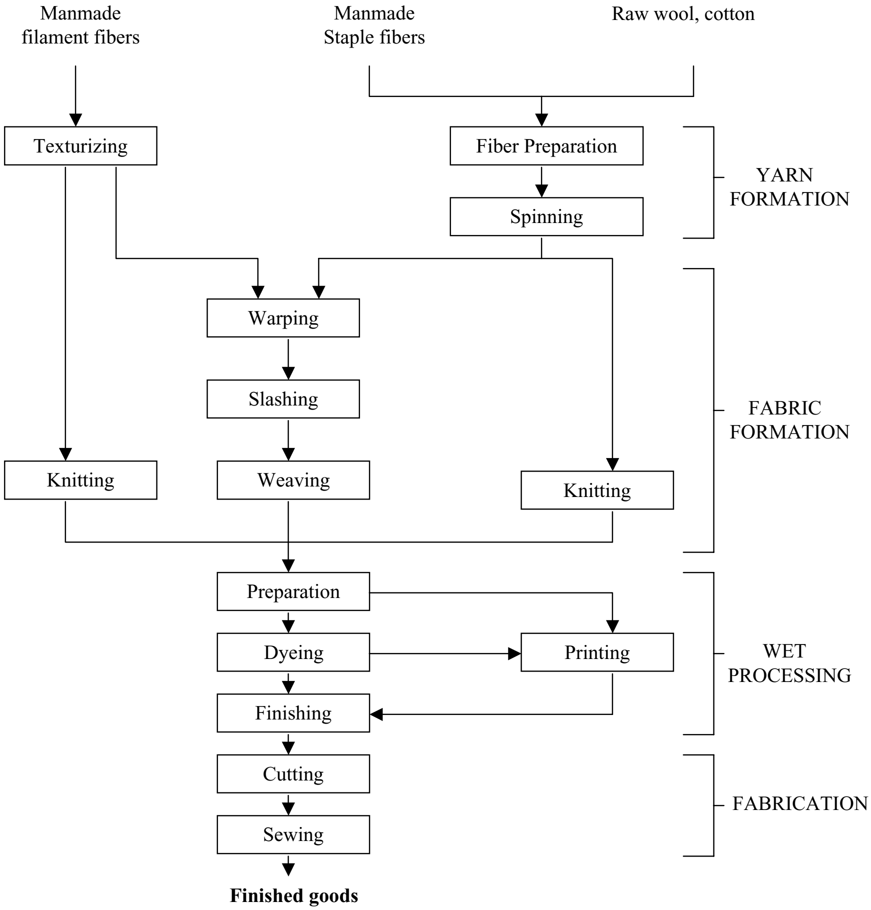

Figure 15.2. The flow chart for typical textiles manufacture. (Adapted from *Profile of the Textile Industry*, EPA 310-R-97-009, Washington, D.C.: Environmental Protection Agency, 1997.)

without enzymes to remove sizing materials) and scouring (using alkaline solutions to remove impurities).

Dyeing is a necessary but problematic wet processing step. There are a number of dye classes, chosen on the basis of the fibers being dyed, the colorfastness desired, and the colors available (see Table 15.2). Since bright colors and high fiber affinities are desirable, typical dyes contain metals, sulfides, and other constituents potentially hazardous to ecosystems.

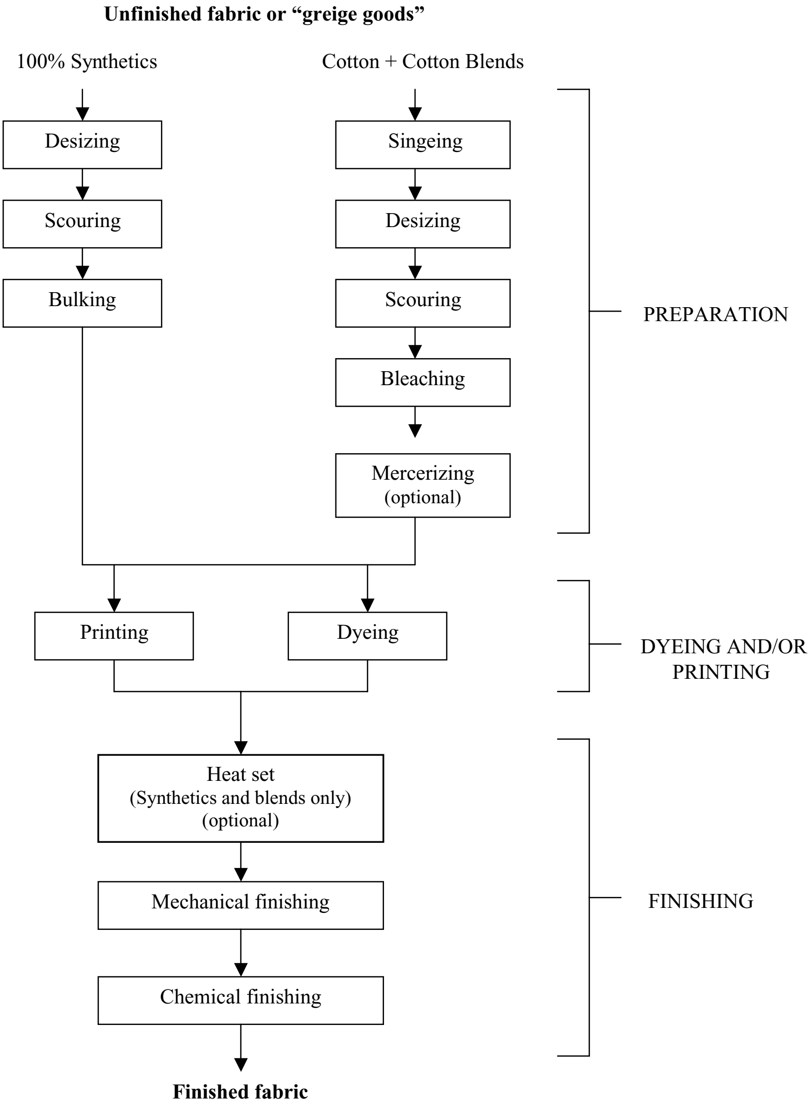

Figure 15.3. A detailed flow chart for the wet processing steps utilized in textile manufacture. (Reprinted from *Profile of the Textile Industry*, EPA 310-R-97-009, Washington, D.C.: Environmental Protection Agency, 1997.)

Table 15.2. Major Dye Classes and Related Fibers*

Dye Class	Description	Fibers Treated
Acid	Water-soluble anionics	Wool, nylon
Basic	Water-soluble cationics	Acrylic, polyester
Direct	Water-soluble anionics	Cotton, rayon
Disperse	Not water-soluble	Polyester, acetate
Reactive	Water-soluble reactive ionics	Cotton
Sulfur	Sulfur-containing organics	Cotton

*Adapted from U.S. Environmental Protection Agency, *Profile of the Textile Industry*, Report EPA-310-R-97-009, Washington, D.C. 1997.

A variety of finishing steps complete the fabric manufacturing process. These may include chemical treatments to provide stain resistance and mechanical treatments to optimize fabric structure and appearance.

15.2.2 Leathers

As with textiles, the manufacturing processes for leather have undergone little change for millennia. As shown in Figure 15.4, the sequence begins with the removal

Text Box 15.1

Designing Environmentally Favorable Textiles

In 1993, architect William McDonough was asked by Design Tex, Inc. to design a new collection of fabrics. Knowing that the processes and ingredients used in textile manufacture can be environmentally problematic, he and chemist Michael Braungart redesigned the entire approach to fabric manufacture. The first goal was to create a recyclable product, which meant that natural fibers would be required. Experimentation eventually produced a fabric from ramie (a plant similar to linen) and wool. In addition to being compostable, the fabric transports moisture away from the skin, thus increasing comfort. A bigger challenge was the textile dyes, which McDonough and Braungart decided should be free of mutagens, carcinogens, bioaccumulative and persistent toxins, heavy metals, and endocrine disrupters. Working with the Ciba-Geigy chemical firm, they developed a set of sixteen dyes that were certified by the German EPEA to meet all the chemical criteria and also produced vivid colors. The resulting fabrics are now available for office furniture applications, and are thought to constitute the most environmentally "intelligent" product produced on a commercial scale.

Source: Environmentally Intelligent Textiles, Report DT 052495, McDonough Braungart Design Chemistry, Charlottesville, VA, 1995.

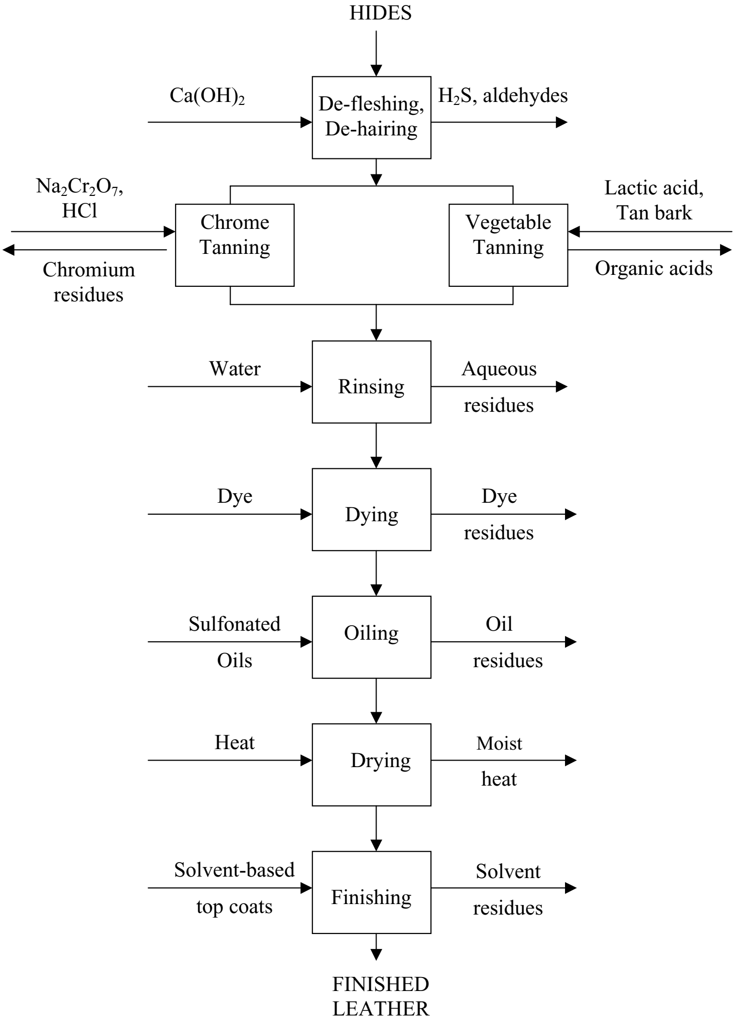

Figure 15.4. The flow chart for typical leather manufacture.

of residual hair and flesh from the animal hides. They are then "tanned" to strengthen and soften them by combining the tanning solution molecules with the hide fibers. The traditional method, vegetable tanning, uses tannins derived from plant species. Chrome tanning, the alternative, uses chromium salts; it produces a stronger product and works more quickly, but can produce substantial environmental impacts.

Text Box 15.2

From Chromate to Berries: Vegetable-Based Leather Tanning

A long-standing environmental challenge for the leather industry has been the discharge of chromate-rich liquid from tanning operations. Although the softest and longest-lasting leathers have traditionally been made by chromate tanning processes, the Eagle Ottawa Leather Company of Grand Haven, Michigan decided in the early 1990s to develop a satisfactory vegetable tanning alternative. After numerous attempts, they developed a process that utilizes an extract made of Peruvian berries. Unlike most other vegetable tanning approaches, the product does not tend to crack when exposed to intense heat or cold, a vital characteristic since Eagle Ottawa is the largest supplier of leather to U.S. automobile manufacturers. In 1998, the first vehicles with Eagle Ottawa's new leather appeared in showrooms. The benefits relate to more than the manufacturing life stages of the leather: unlike chromate-tanned leathers, the new Eagle Ottawa product meets anticipated European recycling laws for automotive components and accessories.

Source: D. Neil, Leather for the car: A rising tide of hides, *New York Times*, section 12, Aug. 23, 1998.

Following tanning, the hides are rinsed and then dyed. Then various-colored dyes are used in various combinations on different types of hides. Oils are then used to make the leather soft, and various finishing coatings are added to complete the process.

15.3 THE SECTOR'S USE OF RESOURCES

Relative to other sectors, moderate amounts of water and energy are used by textile and leather industries. The natural starting materials—cotton, wool, animal hides—are renewable and abundant. Synthetic fibers are ultimately derived from petrochemicals, but the amounts are not major fractions of petrochemical output. The processing chemicals tend to be abundant as well, as befits an industrial sector with a very long and technologically modest history.

15.4 POTENTIAL ENVIRONMENTAL CONCERNS

15.4.1 Solid Residues

Solid residues are of minimal concern in the textile and leather sector. Perhaps the most significant but not very important solid residue source is overstocked clothing disposed of from warehouses; this easily outweighs mill scrap.

15.4.2 Liquid Residues

In principle, this sector has the potential to generate large amounts of problematic liquid residues: acids, alkalis, chromates, dyes, etc. In practice, the concentrations of these constituents in wastewater are typically quite low. The major concern is for sizing and desizing residues, which can produce high levels of biological oxygen demand if not carefully controlled.

15.4.3 Gaseous Residues

Gaseous releases are a major potential concern for this sector. In the U.S. in 2001, three chemicals dominated the gaseous emissions. Methyl ethyl ketone and toluene, those with the largest emission rates, are volatilized from solvent coating operations. Methanol, the third largest, is emitted as a consequence of using poly (vinyl alcohol) in synthetic sizing operations. All of these emittants, grouped under the heading of volatile organic carbon (VOC) compounds, are potential smog formers.

15.4.4 Sustainability Assessment

The potential emittants resulting from processes in this industrial sector are given in Table 15.3, and the materials binned for throughput, potential hazard, and potential scarcity in Table 15.4. The TPH matrix appears in Figure 15.5. There are no very high concerns, but chrome tanning and dyes rate high concern. The TPS matrix, also in Figure 15.5, shows only synthetic fibers originating from petroleum as significant.

***Table** 15.3.* Processes, Activities, and Potential Emittants for the Textiles and Leathers Sector

	Textiles	
Cleaving bonds	De-sizing	Enzymes, sugars
Purification	Rinsing	Aqueous residues
	Scouring	NaOH
	Bleaching	Peroxide residues
Forming bonds	Sizing	Starch, poly(vinyl alcohol)
Surface treatment	Dyeing, printing	Dye residues
	Leathers	
Cleaving bonds	De-fleshing, de-hairing	H_2S, aldehydes
Surface treatment	Chrome tanning	Chromium residues
	Vegetable tanning	Organic residues
	Dyeing	Dye residues
	Oiling	Oil residues
	Finishing	Organic solvent residues
Purification	Rinsing	Aqueous residues

Table 15.4. Throughput-Hazard-Scarcity Binning of Materials in the Textiles and Leather Sector

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
Cotton	H	–	L	L
Wool	L	–	L	L
Synthetic fibers	H	–	L	M
Cellulosics	L	–	L	L
Leather	M	–	L	L
Dyes	M	Ecosystem	H	M
Solvents	M	Ecosystem	M	M
Salts	M	–	L	L
Chrome tanning solution	M	Ecosystem	H	L
Vegetable tanning solution	L	–	L	L
Wastewater BOD	M	Ecosystem	M	–
Dye effluent	M	Aesthetic	M	–
Oil residues	L	–	L	–
VOC	M	Smog	M	–

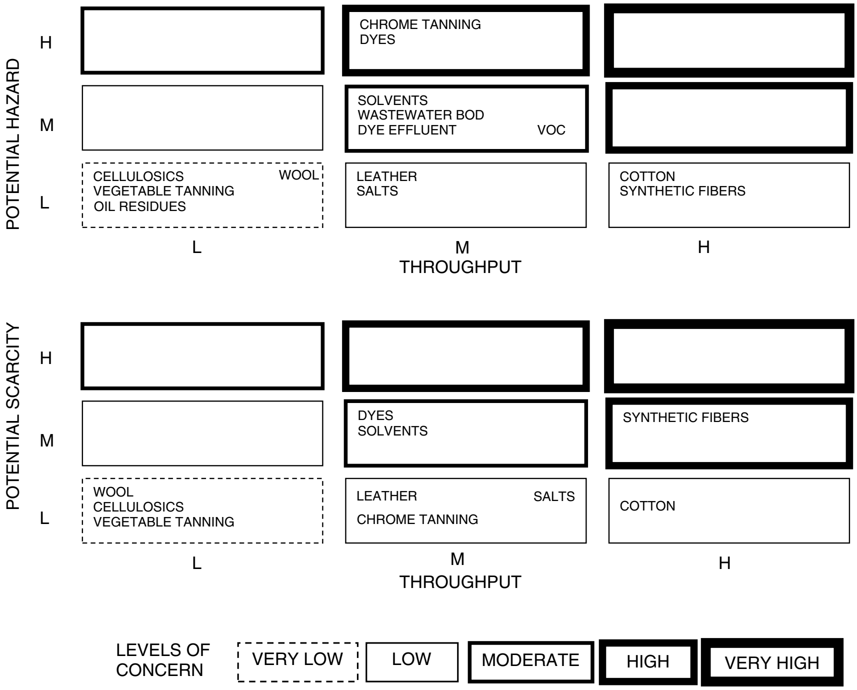

Figure 15.5. The throughput-potential hazard matrix (top panel) and the throughput-potential scarcity matrix (bottom panel) for the textiles and leathers sector.

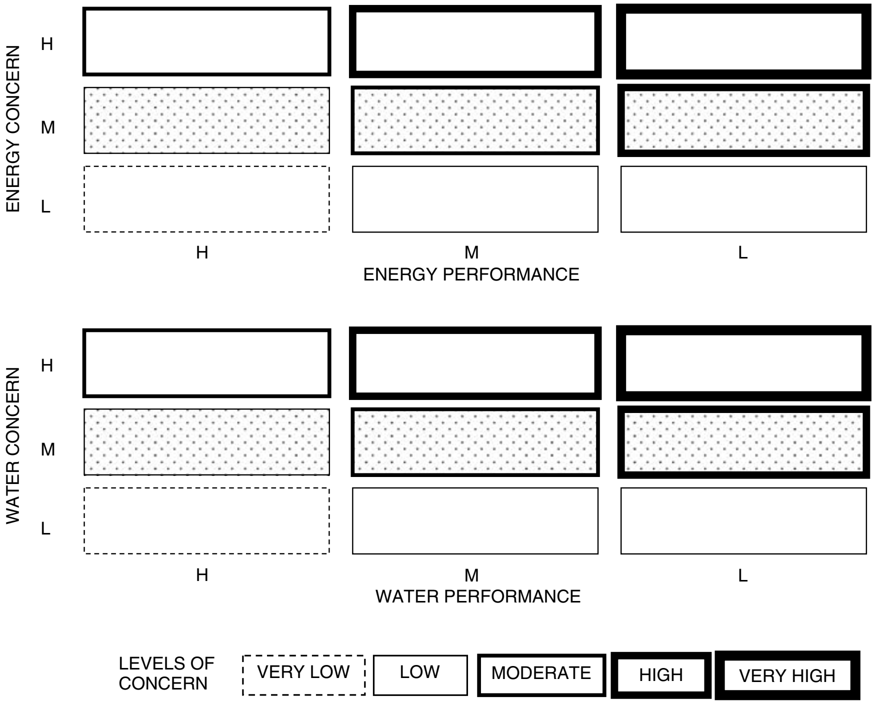

Figure 15.6. The performance-energy concern matrix (top panel) and performance-water concern matrix (bottom panel) for the textiles and leathers sector. The stippled rows reflect typical levels of sector consumption.

As mentioned above, the sector energy and water use rates fall in the moderate category, as shown in Figure 15.6.

The ΣWESH plot for the sector is given in Figure 15.7; it contains several entries worthy of attention, but none of significantly high concern.

15.5 SECTOR PROSPECTS

15.5.1 Trends

In concert with nearly every other industrial sector, the textiles and leathers sector is vigorously adopting pollution prevention approaches to its technology. The first fruits of these efforts will be more efficient use of energy, decreased water consumption, and increased water recycling. The rates of use of problematic chemicals in sizing, dyeing, and coating will be reduced. Efforts are also underway to reduce the quantities of solid waste that are generated including cardboard and pallets.

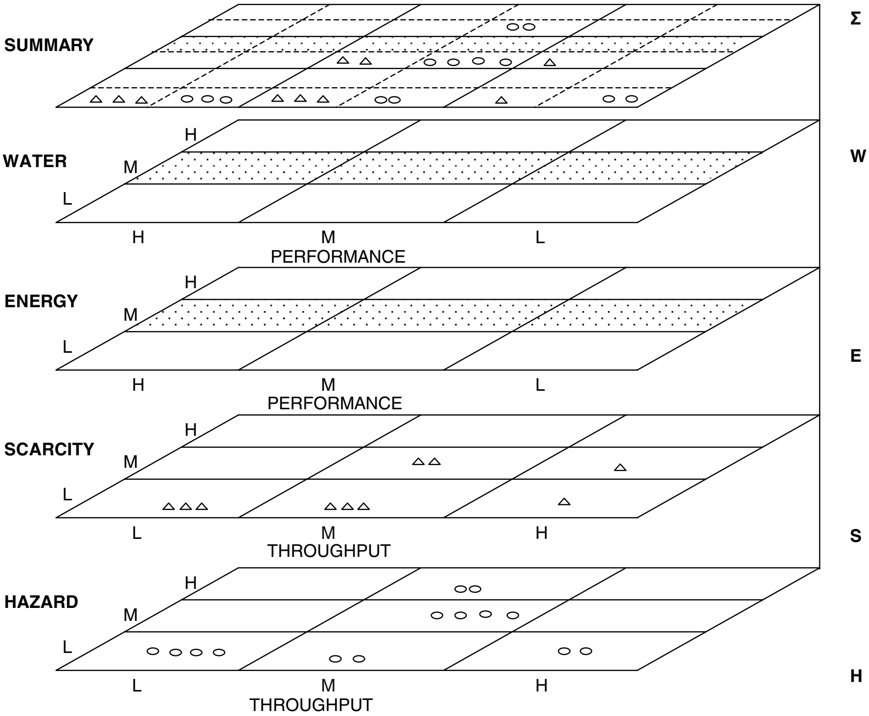

Figure 15.7. The ΣWESH plot for the textiles and leathers sector. The squares and circles refer to the materials of Figure 15.5.

These potential changes, all desirable, are quantitative in nature—they reduce the magnitudes of resource use but do not significantly change manufacturing processes. In particular, they do relatively little for the rather large airborne emissions of volatile organic compounds (VOCs).

A transformational change for this sector would be the generation and use of high-quality uniform fibers from renewable sources. The most likely way in which such a transformation could be achieved is through the use of biotechnology. It is reasonable to anticipate that improved plant and animal fibers, more uniform hides, and more consistent cellulosics will result from such efforts.

A second transformational change which is likely is the extensive use of computer-aided control of processing machines. Such approaches are relatively primitive at present, but have the potential to perform precision metering and monitoring of process fluids, real-time detection of defects in knitting or printing, and precision laser cutting of garments and other products. Much of this technology is available now, but capital requirements pose a startup barrier in many cases.

The most rapidly evolving part of the textile sector, still largely in the experimental phase, involves the manufacture of clothing and fabrics with added properties, many aided by electronics. The general approach is to add to fabrics metal atoms, wires, or electronic components. The application can be as simple as antibacterial properties introduced by silver particles, or as complex as shirts designed to monitor a patient's vital signs and communicate trouble by a wireless phone. Other product ideas include jackets capable of playing MP3 music files and carpets that can detect intruders and fires. Not all of these ideas will prove feasible, but some are likely to.

15.5.2 Scenarios

Trend World

In a trend world, decreased water use per unit of product will be particularly noticeable in the textiles and leather sector. The hazardous dyes and coatings used in the sector will be gradually phased out as improved alternatives are developed. Improved equipment will decrease wastage, a useful change since most residues from textile and leather processing require hazardous waste disposal. Modest progress will be made in reducing the rates of emission to the atmosphere of VOCs.

Green World

In a green world, the extensive use of high-technology manufacturing will result in high levels of energy efficiency, much improved water efficiency, and the virtual elimination of VOC emissions. In addition, the clothing industry will make a transition to textiles produced through safe biotechnology. In this new era, clothing may be capable of actively or passively providing a host of new characteristics:

- Thermo-regulating clothing may be made with microcapsules that store heat energy by melting at warm temperatures and release heat by crystallizing at cooler temperatures.
- Odor-neutralizing clothing could contains capsules that release the appropriate chemical when the fabric is rubbed.
- Shirts may be made partly from ceramic fibers that block solar infrared and ultraviolet radiation.

These and other functions will complicate clothing manufacture, cleaning, and recycling, but these functions will be addressed from an environmental standpoint in a green world.

Brown World

In a brown world for textiles and leathers, high cost and unwillingness to invest will prevent the industry from transitioning away from hazardous dyes and coatings, and from the chromate tanning of leather. As a consequence, the factories will continue to be major polluters of the environment. The substantial capital requirements of new equipment will prevent the industry from achieving gains in energy or water efficiency as well. These problems, especially acute in the less developed countries, will result in an industrial sector that exacts a heavy environmental penalty in order to continue to operate.

FURTHER READING

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U.S. Environmental Protection Agency, *Best Management Practices for Pollution Prevention in the Textile Industry*, Report EPA/625/R-96/004, Washington, D.C., 1996.

U.S. Environmental Protection Agency, *Profile of the Plastic Resin and Man-made Fiber Industry*, Report EPA 310-R-97-006, Washington, D.C., 1997.

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Chapter 16

Sand and Glass

16.1 OVERVIEW

The sand and glass industry is one of the world's oldest. Its raw materials are among the most environmentally benign of those used in the entire industrial sector, and processing is largely limited to heating the materials under carefully controlled conditions. The result is products with great utility and often with great visual appeal.

This industry sector follows inorganic chemicals on the sector sequence diagram as shown in Figure 16.1. What is termed "industrial sand" (to distinguish it from the chemically heterogeneous sand and gravel used in construction) has three major uses: the manufacture of glass (about 50 percent), as foundry sand (about 30 percent) and as abrasives and fillers (about 20 percent). In all of these, the basic material is silica (silicon dioxide, SiO_2).

Extremely fine-grained crystalline silica (grain sizes 0.1–10 μm) is a particularly useful abrasive because (1) it has high hardness, and (2) its grain structure does not contain edges and corners. These properties make it suitable for use in toothpastes, industrial soaps, and polishing compounds. It is also widely employed as a filler material in paints, plastics, and rubbers. In all these uses, processing is limited to size separation and purification.

Foundry sand is mostly used for the casting of steel components in the motor vehicle industry. This process is discussed in Chapter 17.

The largest use of industrial sand, and the use with the highest potential environmental impacts, is the manufacture of glass. Glass is an amorphous (i.e., noncrystalline) undercooled liquid of extremely high viscosity, having all the appearances of a solid. There are four major segments of the glass industry:

- Specialty glass (kitchenware, TV tubes, light bulbs, fiber optics, etc.)
- Fiberglass (insulation for buildings and fibers for reinforcement)
- Container glass (bottles, jars, etc.)
- Flat glass (windows, mirrors, computer displays, auto glass, etc.)

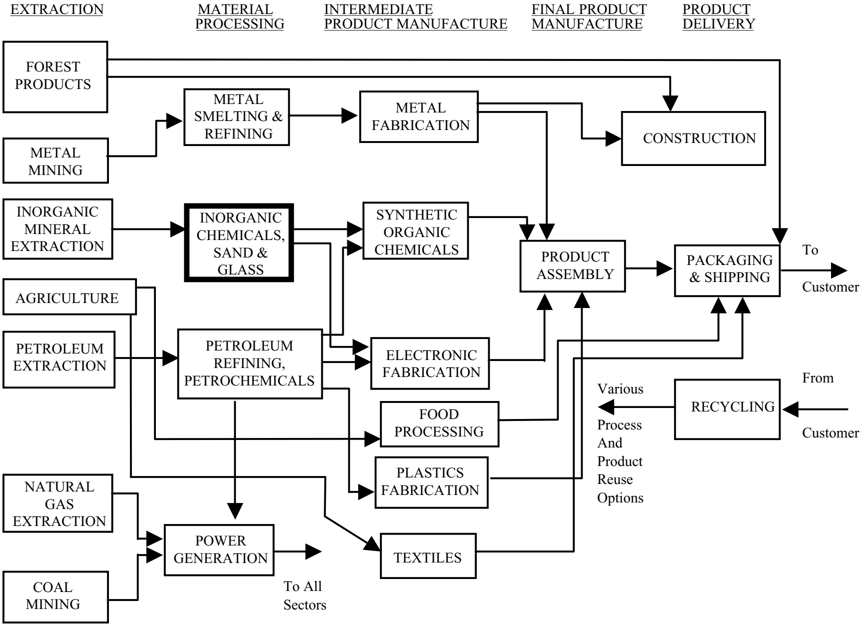

Figure 16.1. The technological sequence diagram for the sand and glass sector. The industry sector itself is indicated by heavy outlining.

The proportions of these segments of the total glass market have varied somewhat during the years, but about 50 percent of the total mass produced is flat glass, another roughly 30 percent is container glass, and the remainder is split roughly equally between specialty glass and fiberglass.

16.2 PHYSICAL AND CHEMICAL OPERATIONS

16.2.1 Composition

There are many different types of glass, each with its own chemical composition (see Table 16.1). In all cases, however, the dominant material is silica. It makes a good glass by itself, but the melting point is very high (~1725°C) and the liquid glass is extremely viscous. Soda (sodium carbonate, Na_2CO_3) is therefore added to reduce the melting temperature to a more convenient level. However, the resulting glass is not suitable for general use; it even dissolves in water. Limestone (calcium carbonate) is therefore also included to increase the ruggedness of the product. Lead oxide can be substituted for limestone to produce glasses of high optical quality, or boron oxide to give a Pyrex?-type glass that withstands rapid temperature changes. Glass is colored

Table 16.1. Typical Final Compositions of Commercial Glasses

Constituent	Weight Percent
Silica (SiO_2)	70
Lime (CaO), from limestone ($CaCO_3$), or PbO or B_2O_3	5–15
Sodium oxide (Na_2O), from soda (Na_2CO_3)	15
Metal oxides (Al_2O_3, K_2O, etc.)	5–10

by adding various metallic oxides. Flat glass may be coated with metallic oxides to give it different properties, like improved reflecting or insulating properties.

16.2.2 *The Glassmaking Process*

Most glass, with the exception of optical fiber, is manufactured, using the following five common steps:

(1) Combine the raw ingredients
(2) Heat to ~1500–1600°C to melt
(3) Form the glass into the desired shape
(4) Cool slowly to the vitreous state (this is termed the *annealing* process), rolling or blowing as needed
(5) Finish the product by mechanical or chemical polishing

Unsatisfactory material can be crushed and returned to the melting furnace. The process is shown in Figure 16.2.

The key reactions in glassmaking involve the formation of complexes of silica with sodium oxide and with calcium oxide:

$$Na_2CO_3 + \alpha\, SiO_2 \xrightarrow{\Delta} Na_2O \cdot \alpha\, SiO_2 + CO_2$$

$$CaCO_3 + \beta\, SiO_2 \xrightarrow{\Delta} CaO \cdot \beta\, SiO_2 + CO_2$$

In each reaction, heat is added and the carbon dioxide is lost to the atmosphere.

These reactions occur in a melting furnace. The size and type of furnace used depends on the quality and quantity of glass being manufactured. Small pot furnaces containing up to two tons of glass are used for specialty or small-volume applications, while the large furnaces used by container or flat glass manufacturers can melt hundreds of tons of glass per day. Glass furnaces are fired by the combustion of gas or oil. Oxy-fuel furnaces, those that burn fuel in an oxygen-only environment, are replacing traditional furnaces in some sectors of the industry. Oxy-fuel furnaces significantly reduce the production and emission of oxides of nitrogen (NOx) that are the by-product of combustion in a traditional furnace. In some cases, electrodes are placed in the molten glass to provide an auxiliary source of heat.

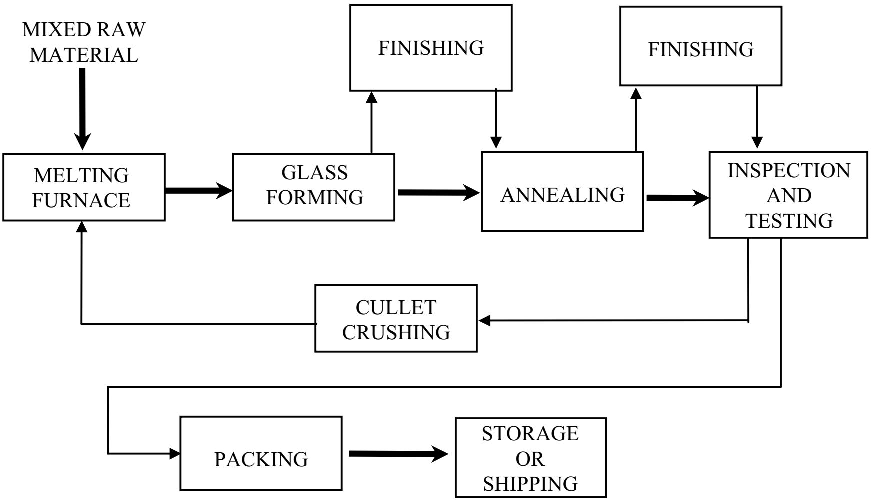

Figure 16.2. A typical process for manufacturing glass. (U.S. Environmental Protection Agency, *Profile of the Stone, Clay, Glass, and Concrete Industry*, Report EPA 310-R-95-017, Washington, DC, 1995.)

16.2.2.1 The Forming of Container Glass

In the modern manufacture of glass containers, shown in Figure 16.3, a glob of molten glass is poured into a mold and a large pocket formed in it by pressurized air. The resulting material, following cooling, is transferred to a second mold and reheated. A second pressurized blow then forms the glass into the final product. Careful control of temperature is obviously very important. A similar approach is used for the manufacture of light bulbs.

Once formed, the glass products are gradually cooled or annealed in a long oven called a lehr. Annealing reduces the internal stresses that could cause cracking if the glass was rapidly cooled.

16.2.2.2 The Forming of Flat Glass

To make flat glass, shown in Figure 16.4, molten glass is fed as a continuous sheet from the furnace onto a bath of molten tin. The glass floats, as it is less dense. It then travels down to an annealing lehr for gradual cooling. Most flat glass used in architectural and other applications is made using this technique. Float glass manufacturing produces good quality glass with thicknesses of about 2–3 mm. Thinner, higher quality flat glass, like that used for laptop computer displays, is produced using a downdrawn process. In this case, a glass sheet, about 0.6–0.7 mm thick, is drawn

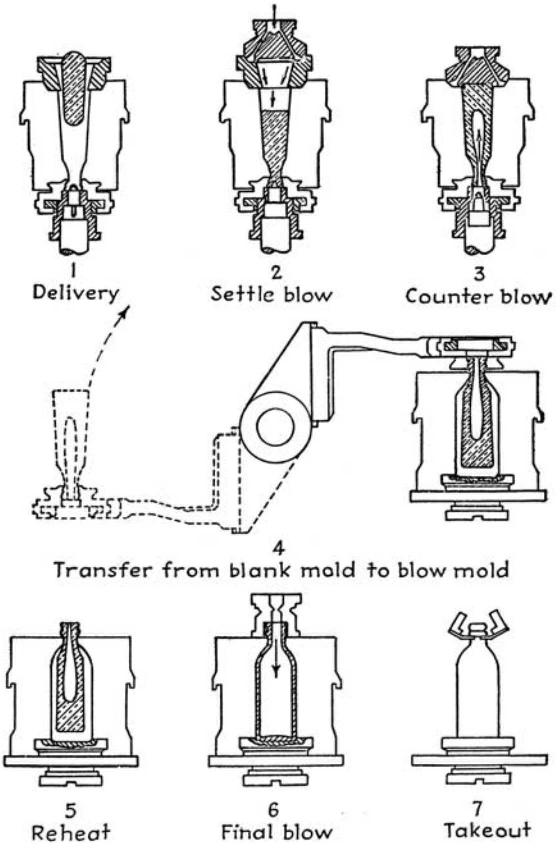

Figure 16.3. The steps involved in the manufacture of a glass bottle. The glass is indicated by the alternating solid and dashed lines. (Reprinted with permission from R. N. Shreve, *The Chemical Process Industries*, 2nd Ed., New York: McGraw-Hill, 1956.)

vertically down from a reservoir of molten glass. The composition of glass used for this application is slightly different from that of float glass because of the different optical properties desired.

16.2.2.3 The Forming of Fiberglass

The composition of fiberglass is slightly different from that of container or flat glass as it contains more boron (from boric acid added to the initial mixture). Melting is usually enhanced by using electrodes in the molten glass bath. In some cases, the melting is entirely electric. In a "cold top" melter, raw materials are sprinkled on the

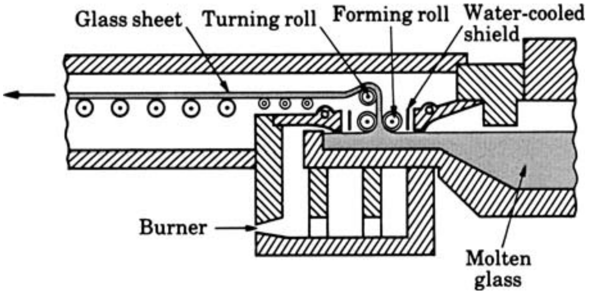

Figure 16.4. A flow diagram for the manufacture of flat glass. (Reprinted with permission from R. N. Shreve, *The Chemical Process Industries*, 2nd Ed., New York: McGraw-Hill, 1956.)

surface of a bath, molten glass is drawn off the bottom, and the heat is supplied by electrodes in the middle.

The forming of glass fiber depends on the type of fiber being made. Very thin glass fiber, or "wool" is created by spinning molten glass in a rotating cylinder. As the glass is forced against the edges of the cylinder and through small holes in the cylinder wall, it forms thin strands that are broken into small pieces by an air stream. The majority of fiberglass is formed in this manner.

Glass fibers are also used as reinforcement or for fire resistance and are incorporated into other materials. These fibers are manufactured by pulling the molten glass through a platinum bushing and then either winding or chopping the fibers to the desired lengths.

16.2.3 Glass Finishing

After manufacture, all glass is finished and polished before shipment. Finishing involves the necessary cutting, drilling and grinding to shape the final product appropriately. Frosting and etching with dilute hydrofluoric acid may be performed to produce the desired surface finish. The polishing may be accomplished either chemically or mechanically. Polishing with an acid (either hydrofluoric acid or sulfuric acid) can change the strength or durability of the glass. The final finishing step is typically an aqueous or organic solvent wash to remove surface debris.

The addition of coatings is important to produce the desired properties for flat glass and fiber glass. Flat glass that will be used in residential or commercial buildings can be coated to alter its insulating properties. Coatings can also be applied to make glass anti-reflective (used for computer monitors) or electrically conductive (for photovoltaics). Coatings are applied to glass sheets by either chemical vapor deposition (CVD) or vacuum sputtering. In each case, the coating material is usually a metal oxide and the precursor either an organometallic compound or inorganic metal compound. Only about 20–30% of the material ends up in the coating, the rest is captured in gaseous form for treatment. Glass fibers are also coated to give them the appropriate properties to adhere to the material into which they are incorporated. These coatings are sprayed on in liquid form.

16.2.4 The Manufacture of Optical Fiber

Optical fiber is manufactured using completely different techniques from those used to manufacture other glass products. Instead of starting with solid raw materials and melting them, the process involves starting with liquid raw materials, vaporizing them, and collecting them on a target. The liquid starting material is typically silicon tetrachloride. Once vaporized and mixed with oxygen in a flame burner, the liquid forms small (10–20 micron size) silicon dioxide particles that are collected on a target rod. The material is heated and chlorine gas introduced to drive out any moisture. Following this, the material is heated to a higher temperature so the particles fuse together and consolidate into a single rod, or preform, about 5 cm in diameter. In order to obtain the right optical properties for transmitting information, the preform is manufactured in two steps. An inner core is manufactured with a small amount of germanium tetrachloride added to the silicon tetrachloride starting material, and then an outer cladding layer made with silicon tetrachloride is added. The fiber, with a final diameter of about 125 microns, is created by drawing out the double-layered preform at high temperature. The fiber is then coated with polymer layers to protect it from impact and abrasion.

Optical fibers are a very small fraction of the glass market when measured in terms of tons of product, but they are a significant and growing segment that is crucial to the deployment of optical communications technology. Only about 45 grams of glass is used in one mile of optical fiber, but the market is growing at a rate of 20 to 30% per year.

16.3 THE SECTOR'S USE OF RESOURCES

16.3.1 Energy

In the use of energy by major industrial sectors in the United States, the combined sectors of stone, clay, and glass rank sixth, just below food products. This rate of energy use reflects the requirement of heating the glass ingredients to very high temperatures and continuing to add enough heat during product manufacture to keep the material molten for extended periods. Other process components consume large amounts of energy as well, an example being the requirement for a molten tin bath in the production of flat glass.

The consumption of energy for melting varies with the quantity and quality of glass being manufactured. Energy consumption by manufacturers of optical fiber is relatively low because of the small volume of glass being produced. The manufacture of specialty glasses like TV displays or optical elements consume high amounts of energy. Energy consumption falls as the fraction of waste glass, or cullet, included in the starting material is increased. For a ten percent increase in the quantity of cullet used, the total energy required for melting decreases by two to three percent because it is easier to melt cullet than to melt raw starting materials. Currently glass manufacturers use about 30% cullet in a batch of glass.

16.3.2 Water

Water is used in glass manufacture for cooling and for final washing. On a relative sectoral basis, the quantities are rated as moderate. Much of the wastewater is recycled internally.

16.3.3 Materials and Process Chemicals

The principal materials used to manufacture glass are among the most abundant resources on the planet, and the least toxic. The starting materials for optical fibers are an exception; silicon tetrachloride are germanium tetrachloride are extremely hazardous and must be used under carefully controlled conditions. Additives and coatings used to give glass particular characteristics can be toxic, or be derived from harmful precursors. Process chemicals are used in glass manufacturing only to a modest degree, principally for etching and cleaning. Some of these materials, such as hydrofluoric and sulfuric acid, are chemically aggressive.

16.4 POTENTIAL ENVIRONMENTAL CONCERNS

16.4.1 Resource Use and Releases

The use of energy by the sand and glass sector is the biggest environmental concern related to manufacturing; it is among the highest of all the sectors, and is obviously a significant factor in industry's production of greenhouse gases.

The sector is tenth in the US in the production of chemicals in total production-related waste. Much of this material consists of dilute mineral acids used in etching and cleaning processes; it can effectively be treated on-site, so little is transferred off-site for treatment or released to the environment. As a result, the sector ranks relatively low in its releases.

The application of coatings is responsible for the majority of the non-combustion-related air emissions from the flat glass manufacturing process. Since the deposition of coatings is only 20 to 30 percent efficient, a large fraction of the precursor materials and by-products (including acid gases and organic materials) must be collected for treatment. Occasionally by-products can be condensed and reused. Regardless of their fate, the throughput of these materials is quite low because coatings are so small a fraction—usually only a few thousand angstroms in thickness—of the final product.

16.4.2 Recycling

A significant concern relates to the weight-to-value ratio for glass products, especially glass containers that will have short service lifetimes. For these products, transportation impacts (use of fossil fuels, generation of vehicle emissions, etc.) are very high per container. Furthermore, the relatively low value of glass and difficulties in reuse (especially for colored glass) have impeded recycling. Among the potential uses of ground recycled glass (termed "cullet") are

- Reused as containers
- Made into fiberglass
- Made into "glasphalt" (a road surface produce made from a mixture of asphalt and ground glass)
- Made into abrasives
- Made into reflective paint beads

In all of these cases, local economics come heavily into play, and efficient collection, transportation, and processing are minimum conditions for successful glass reuse. In Japan, for example, total cullet reuse is substantial, but the rate of disposal remains high, even in this geographically concentrated and behaviorally responsible society. In the U.S., about two-thirds of all cullet is landfilled or stockpiled, representing 14.2 million tons of waste annually. This waste stream makes up 6.7 percent (by weight) of municipal solid waste. Ninety percent of this waste glass is comprised of beverage and food containers which, by the nature of their use, end up widely distributed. Education and improved recycling infrastructure make a difference, however. The rate of recycling of glass containers is currently 35 percent, compared to about 20 percent in 1988.

16.4.3 Sustainability Assessment

The potential emittants, activities, and hazards resulting from processes in the sand and glass sector are given in Table 16.2, and the materials binned for throughput, potential hazard, and potential scarcity in Table 16.3.

Table 16.2. Processes, Activities, and Potential Emittants for the Sand and Glass Sector

Process Type	Sector Activities	Potential Emittants
Bond breaking	Glass melting, fusing	CO_2
Shaping	Mechanical finishing	Glass dust
Surface treatment	Etching, chemical finishing	Acids, etchants
Cleaning	Residue removal	Wastewater

Table 16.3. Throughput-Hazard-Scarcity Binning in the Sand and Glass Sector

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
Silica	H	–	L	L
Soda	H	–	L	L
Limestone	H	–	L	L
Lead oxide	M	Human toxicity	M	H
Acids, etchants	M	Ecosystem toxicity	M	L
Cleaning solutions	M	–	L	L

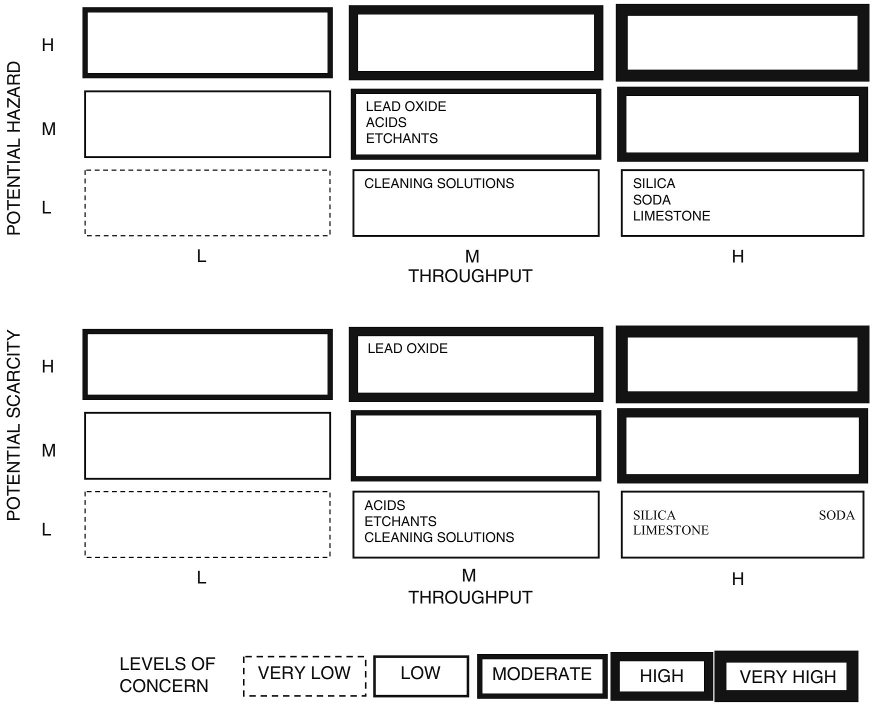

Figure 16.5. The throughput-potential hazard matrix (top panel) and throughput-potential scarcity matrix (bottom panel) for the sand and glass sector.

The TPH matrix appears in Figure 16.5. It indicates moderate concern regarding the use of lead oxide in leaded glass (not because of the toxicity of the products, but because the mining and processing of lead by upstream industries is required). The use of acids and etchants are also of moderate concern; their bioimpacts are potentially significant, but their throughput is moderate and they tend to be well controlled. The other materials used in the sector have high throughput but low hazard, and are of minimal concern.

The TPS matrix is also given in Figure 16.5. Here the only significant concern is with lead oxide, based on the relatively short depletion time for lead resources (recall Table 6.7).

The PEC and PWC matrices for this sector are given in Figure 16.6. The sand and glass sector is a major user of energy, primarily in the process of liquefying the raw materials for glass. Water use is also significant, ranking in the moderate category.

The ΣWESH plot for the sand and glass sector appears in Figure 16.7. The rates of energy and water use by the sector are the most important concerns.

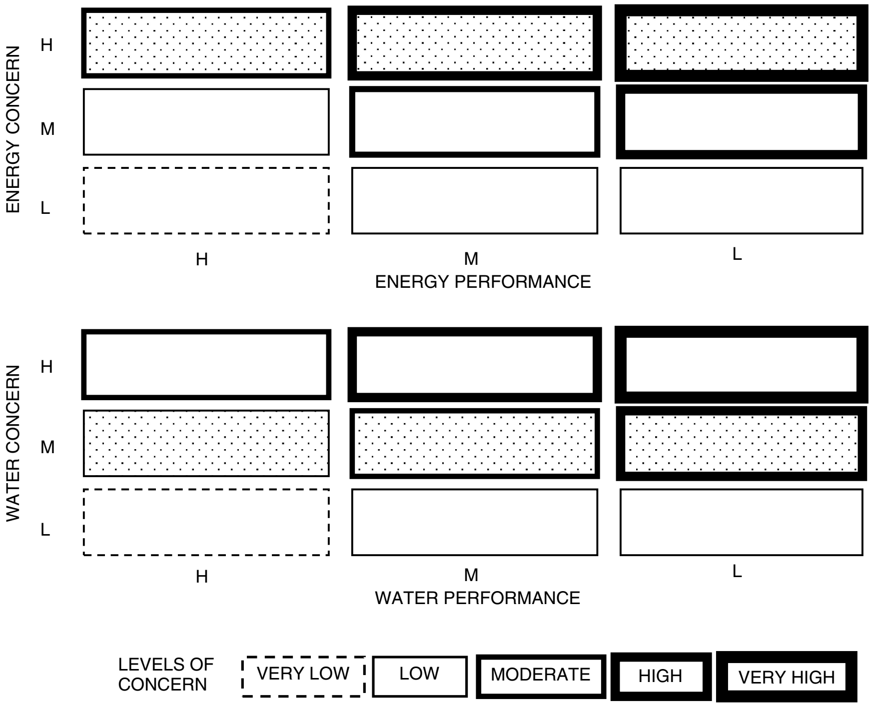

Figure 16.6. The energy performance-energy concern matrix (top panel) and water performance-water concern matrix (bottom panel) for the sand and glass sector.

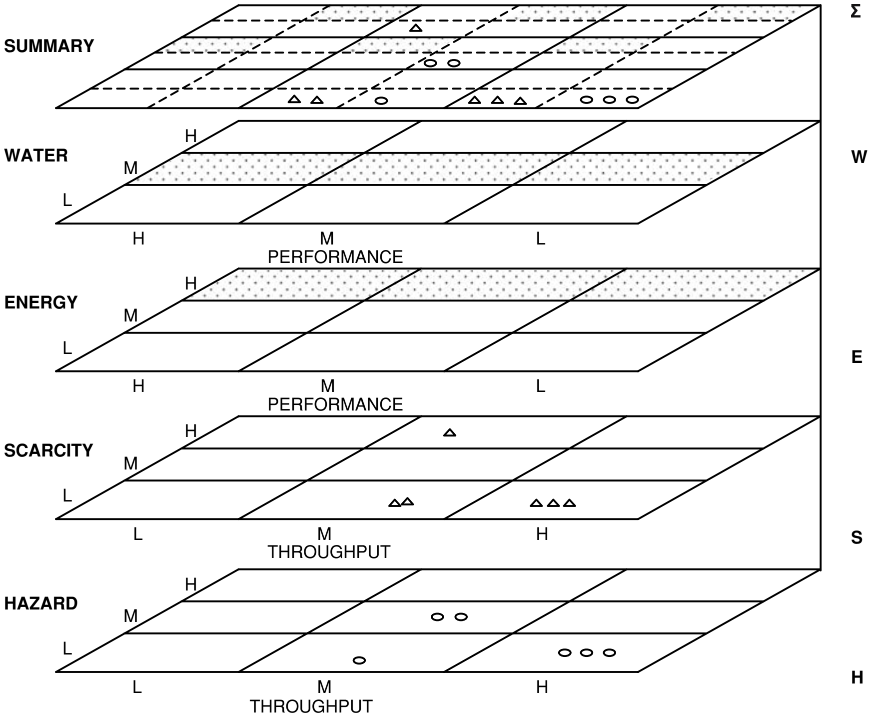

Figure 16.7. The ΣWESH plot for the sand and glass sector. The squares and triangles refer to the materials of Figure 16.5.

16.5 SECTOR PROSPECTS

16.5.1 Process Trends

16.5.1.1 Energy Efficiency

In theory it requires 2.6×10^6 J/kg to melt glass. In practice, glass manufacturing facilities use about three to four times this amount of energy per ton of glass produced. While it would be impossible to reduce energy consumption to the theoretical minimum, there are many opportunities to reduce it from its current level. Improvements in refractory materials, changes in the composition or preparation of raw materials, development of new melting technologies, improvements in yield, and better process control and optimization may contribute to energy efficiency improvements of 20–30% over the next decade or two.

The key drivers of energy efficiency are both economic and environmental. Process energy represents 15% of the cost of manufacturing glass. Any reductions in energy consumed per ton of glass drive down the cost of manufacturing, making the product more cost-competitive. From an environmental standpoint, reducing energy consumption makes sense in an industry that relies heavily on fossil fuel sources of energy.

16.5.1.2 Air Emissions

A second trend in the glass manufacturing industry is for reduced emissions of the acid gas precursors NO and NO_2. These species are formed when air is heated to high temperatures, as occurs in glass manufacture using traditional air-fuel furnaces. The new oxy-fuel furnaces, which burn fuel in an oxygen rather than air environment, can reduce NO_x emissions by 75 percent. The use of oxy-fuel furnaces is already widespread in some subsectors of the industry. They are used almost exclusively by fiberglass manufacturers, are used widely in container glass manufacturing, and are just starting to be used by flat glass manufacturers. Over the next decade or more, the replacement of air-fuel furnaces with oxy-fuel furnaces will continue particularly in the flat glass segment where this process has been slower to take hold. The rate of adoption of oxy-fuel technology depends on the lifetime of furnaces and the local regulatory air emissions requirements. The large furnaces used by flat glass manufacturers typically last for 10–12 years and it makes little economic sense to rebuild a furnace before the end of its useful life.

16.5.1.3 Pre-Consumer Recycling

Increased attention is being given to the degree to which cullet generated during the manufacturing process can be used on-site. This depends on the details of product and process design, but it seems likely that the industry will approach complete recycling of pre-consumer waste glass. Apart from reducing solid waste volumes, including cullet in the raw materials can reduce the energy consumed per ton of glass produced.

16.5.2 Product Trends

16.5.2.1 Post-Consumer Recycling

It is not unlikely, though far from certain, that increasing amounts of post-consumer glass products will be recovered and recycled in the future, as landfill space runs short in some regions and as environmental laws and policies continue to encourage recycling. Because 90% of the glass that is currently sent to landfill consists of beverage and food containers, the economics of collection, transportation and sorting will play a crucial role in determining whether significant changes in recycling rates occur.

Regulations may influence the recycling of other specialty glass products. For example, product take-back laws for electronic products are now being introduced in

Text Box 16.1

Separating Waste Glass for Recycling

Although cullet (waste glass) can, in theory, be used as feedstock for glass manufacturing, about two-thirds of all cullet is landfilled or stockpiled because it is contaminated with ceramics, and hand-sorting the two materials is slow and expensive. A process developed by Alpine Technology addresses this issue. Cullet is loaded thinly on a conveyer belt and conveyed past a light and light sensor. Pieces of glass allow the light to pass through, but pieces of ceramic do not. If a ceramic piece is sensed, it is separated from the glass fragments by a high-pressure air jet. The process is more than 90 percent accurate, and projections are that it has the potential to reduce the fraction of cullet being landfilled from 65 to 70 percent to about 2 percent, while increasing efficiency and lowering costs in glass manufacture.

Source: Office of Industrial Technologies, *Advanced Optical Ceramic Sortation Technology*, U.S. Dept. of Energy (undated).

Europe. The glass lcd displays used in laptop computers often contain small quantities of arsenic. The recycling of these products then raises environmental concerns. In this case, it is likely that the take-back legislation will force manufacturers to adopt arsenic-free manufacturing techniques so that the products can be more easily recycled.

16.5.2.2 Higher Value-Added Products

The glass manufacturing industry will seek to increase the value-added of its products not necessarily by changing the fundamental materials or processes used, but by enhancing the products for specialty uses. One significant growth area for flat glass manufacturers is in the design and manufacture of glass coatings. It is now possible to use passive coatings that make window glass equivalent in terms of heat transfer to a solid wall. The use of active coatings that can adjust to changing weather conditions and optimize building energy efficiency is a likely development. Other types of coatings are now being developed to make self-cleaning glass. The environmental impact (typically increased air emissions) resulting from the manufacture of these coatings is weighed against the energy savings these coatings can produce through use on commercial and residential windows.

Other high value-added glass products include optical fiber and other components of optical communications systems. While it will remain relatively small in terms of glass tonnage, this segment is growing rapidly. Its manufacturing techniques and its environmental impacts resemble those of electronics manufacturing because of the types of precursors used and the relatively large volume of process chemicals used to make a small volume of product.

16.5.2.3 Alternative Materials

The glass manufacturing industry faces competition from other materials. The largest segment of the glass industry, containers, is under heavy pressure from plastics which are lighter to transport and more resistant to breakage. Plastic components may also become feasible alternatives to traditional flat glass products, like auto windshields or video display panels.

Glass may also be used increasingly in composite materials. Fiberglass reinforced plastics, for example, offer a variety of desirable material properties that neither glass nor plastic on its own may deliver. The manufacture of these new materials will employ at least some subset of the manufacturing techniques currently used.

16.5.3 Scenarios

Trend World

The glass manufacturing sector will continue to use manufacturing processes largely similar to those used today, but it will pursue incremental improvements in melting technologies. These improvements will likely increase energy efficiency and process control. Research and development effort will be directed towards the development of high-value specialty products like coatings that can improve the characteristics of glass for a particular application.

A growing segment of the sector will be involved in producing optical components for communication and computing. It will operate at the interface of glass and electronics manufacturing, bearing little resemblance to the traditional glass manufacturing furnace operations. The environmental implications of such processes will also differ from those of traditional glass manufacturing. Instead of using sand as a raw material, these new products will be made using more exotic silicon-containing materials whose environmental and human health impacts may be unknown. The degree of control now used in electronics manufacturing will need to be used in this new segment.

Green World

Glass production in a green world would involve radically new melting technology that significantly decreases energy consumption and its environmental impact. Capital investment in technologies currently only at the research and development stage will have made commercially viable alternatives available. Recycling rates in a green world will be high, both during manufacturing and post-consumption. This shift will have come about through a combination of providing new infrastructure for collection of waste glass, new technology for sorting and reusing waste glass, and changing consumer's practices. Substitution of glass with environmentally superior plastics (e.g., produced from renewable plant sources, recyclable or biodegradable) will occur in some segments (e.g., container glass) where the environmental impact over the product's life cycle is reduced.

In a green world, the manufacture of optical components for computing and telecommunication will be achieved with environmentally-conscious process design. Although the use of hazardous materials will be impossible to avoid, they will be used in limited quantities and treated appropriately.

Brown World

In a brown world glass manufacture will be wasteful of energy and air emissions from the combustion of fossil fuels will be significant. New glass functionality will be achieved through the use of coatings and the addition of small quantities of problematic chemicals, with little regard to ultimate recyclability. Rate of recycling will be low, with a large fraction of waste glass that could otherwise be recycled and reused going to landfill.

FURTHER READING

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Chapter 17

Fabricated Metal Products

17.1 OVERVIEW

The fabricated metal products sector follows the metal ore extraction and processing sector (Chapter 10), as shown in Figure 17.1. Fabricated metals are components of most finished products present in our technological society. In the U.S., metal castings are used to produce 90 percent of all manufactured durable goods and nearly all manufacturing machinery. The sector also manufactures a wide variety of metal-based products, such as metal ductwork, hardware, electrical components, and automotive parts.

There are three principal steps in the normal work flow for fabricated metal products, shown in Figure 17.2. In the first step, fabrication, metal mill products, such as sheet, tube, or rod enter the fabricating facility. There they undergo a variety of cutting and/or forming processes, which are described below. Alternatively, a metal ingot or metal scraps are heated until molten and then poured into a mold to produce the desired product.

The second step is invariably a cleaning stage, in which solvents of various kinds are used to remove extraneous metal scraps, dirt, and sand, and prepare the metal for further cutting, forming, or joining, or for finishing. In the final step, finishing, the product receives some type of surface treatment, generally for both aesthetic and anticorrosive reasons.

A composite list of common manufacturing processes that may be encountered is given in Table 17.1. Some of these processes have been in existence throughout human history, others represent the state of the art of modern technology.

17.2 PHYSICAL AND CHEMICAL OPERATIONS

17.2.1 Metal Casting

Metal casting is the process of heating metal until it is molten, pouring the molten metal into a mold, and letting the metal harden into the desired shape. The

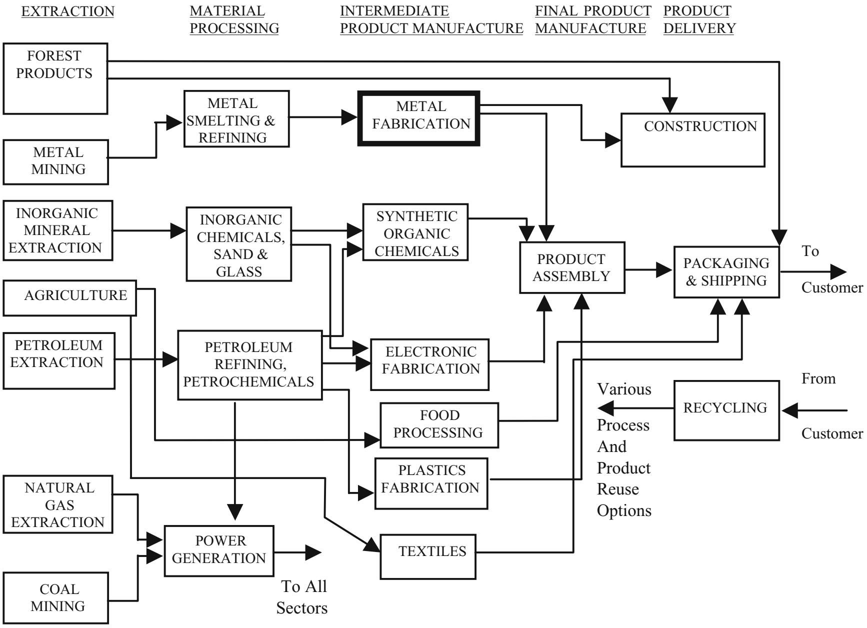

***Figure** 17.1.* The technological sequence diagram for the metallurgical and manufacturing industries. The industry sector itself is indicated by heavy outlining.

process is illustrated in Figure 17.3, where several features of metal casting deserve comment. The first is that the metal fills not only the mold cavity, but also channels (termed sprues, runners, and risers) that allow the metal to reach the cavity from outside the mold. The second is that the mold must be capable of being separated into two or more pieces in order to extract the casting. The third is that the metal, when cooled, must be readily separable from the mold material. The fourth is that the extraneous metal channel material must be removed from the casting by trimming and/or smoothing.

The common mold material for molten steel is sand, held together by an organic binder. The mold cavity is formed in the sand around a model, which is then removed before casting. This is the sand casting process. Alternatively, one can employ the lost wax process, in which the model is made of wax which vaporizes (i.e., is lost) upon the injection of the molten metal into the mold. In all cases any impurities in the metal tend to collect as a glassy mass termed slag; the slag must be discarded.

A great simplification occurs in the case of aluminum (and some other metals), since the metal melting point is lower than that of steel. Here, a steel mold (a die) may be used in place of sand. The advantages are that the cycle time is more rapid in die casting than in sand casting, the resulting products are more uniform, and the die is longer-lasting. The tendency of poured metal to adhere to a metal die is greater

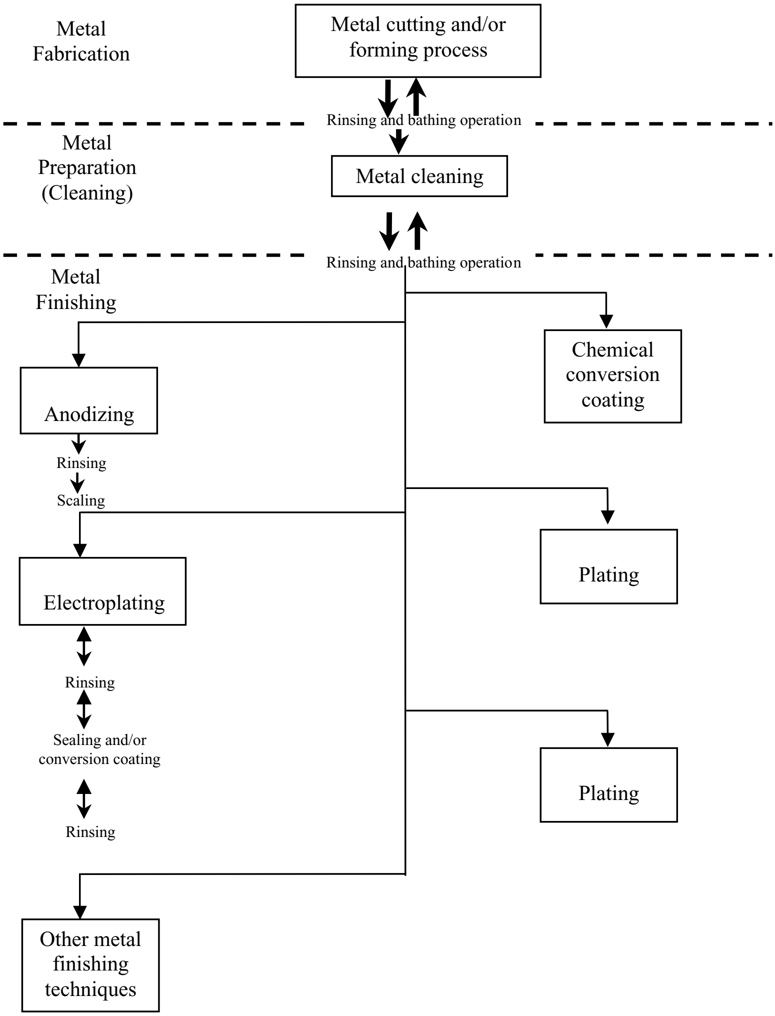

***Figure** 17.2.* Manufacturing processes for fabricated metal products. (Reproduced from U.S. Environmental Protection Agency, *Profile of the Fabricated Metal Products Industry*, EPA 310-R-95-007, Washington, D.C., 1995.)

than to a sand die, however, and an organic mold-release agent is generally applied to the inner surface of the die after each casting.

17.2.2 Shaping

In shaping processes, a variety of physical means are employed to modify the shape or size of a piece of metal. The simplest, forging, is a version of casting in which the

***Table** 17.1.* Processes, Activities, and Potential Emittants for the Fabricated Metal Products Sector

Process Type	Sector Activities	Potential Emittants
Forming bonds	Metalcasting	Scrap metal, casting sand, VOC
Lubrication	Cutting oils use	Oily wastewater
Shaping	Forming, cutting, trimming	Scrap metal, VOC
Cleaning	Solvents, acids, alkalis, emulsifying agents	Waste acids, wastewater with metal ions, VOC
Surface treatment	Plating, anodizing, coating	Plating solutions, wastewater with metal ions, VOC

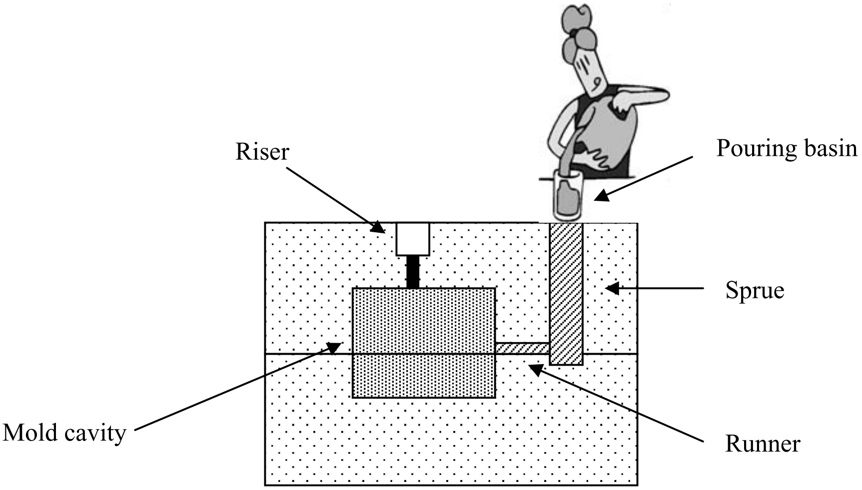

***Figure** 17.3.* A typical metalcasting process showing a mold being filled.

metal workpiece is pressed into a new shape while in solid form. The process generally results in extraneous material (flash) that must be removed later in the manufacturing process.

Shearing is the removal of the edge of a piece of metal by the rapid impaction of two high-strength shear blades to the top and bottom of the metal piece. The sheared edges are roughened and burred, and require subsequent grinding and polishing. The unwanted material is recycled.

A variation of shearing is punching, in which a piece of the desired shape is punched from the interior of a larger metal plate or strip. The desired part may be either that which is punched out or that which remains; the undesired part is recycled. As with sheared parts, punched parts require subsequent smoothing.

Deep drawing is similar to punching except that the workpiece is shaped rather than being cut. The process requires that the workpiece be malleable enough to be reformed without fracturing. In many cases deep drawing can be accomplished without the production of any scrap material.

17.2.3 Machining

Various forms of more precise machining follow casting or shaping. Drilling inserts holes in metal parts, reaming smooths the holes after drilling, and milling cuts grooves and shapes into the metal. All machining processes generate metal shavings, which can be recycled.

17.2.4 Joining

Metal fabrication products that incorporate several pieces comprising similar or dissimilar materials undergo one or more joining processes. The simplest process is the use of fasteners of various kinds: clips, screws, bolts, rivets, etc. Not only is the use of fasteners straightforward, the process can readily be reversed by fastener removal.

A joining process less subject to reversal is the use of adhesives—glues, epoxies, etc. Adhesives frequently join dissimilar materials and are especially effective if the materials are porous. Depending on the adhesive, the process may or may not be reversible. The ability of many adhesives to bind indiscriminately renders them potentially hazardous.

The most rugged methods of joining involve melting a metal that serves the adhesive function when it cools. Soldering is the joining of metal by an alloy of tin and lead made molten by heating to about 160^oC. The strongest joints are produced by welding, in which the metal pieces to be joined and a filler rod of similar material are oil heated above the common melting point (about 750^oC for most steels). The subsequent cooled metal forms a single integrated material. Soldering requires energy to melt the tin-lead alloy, and welding requires much more.

17.2.5 Finishing

Most metal products are given some kind of surface treatment or treatments, both to improve their appearance and to protect them from corrosion. A common step is plating, in which a thin layer of metal is deposited upon the surface of a dissimilar metal. The plating process is generally an electrochemical one, carried out in an appropriate chemical solution. Common plating elements are zinc upon steel (galvanizing), chromium upon steel, and gold upon silver. Plating solutions are often cyanides or other aggressive chemicals, and used plating solutions generally contain high metal ion concentrations. The proper disposal or reuse of plating solutions is a continuing challenge to the metal fabrication industry.

In place of or in addition to plating, chromate coatings or other surface treatments are frequently applied to metal products, usually for corrosion prevention, as a base for further paint or rubber bonding, and to offer abrasion resistance.

17.2.6 Complementary Processes

Most metal working processes are followed by one or more complementary processes: trimming, grinding, and smoothing. In the first, excess material remaining from casting or forming processes is cut away. The remaining part is then ground, polished, or otherwise smoothed. All of these steps produce metal fragments and metal dust, much of which has hazardous properties if not handled properly.

Many of the metal working processes that involve cutting (shearing, reaming, milling, grinding) use a moderate viscosity oil to lubricate the cutting edges and to carry excess heat away from the workpiece. Cutting oils by the very nature of the processes in which they are involved contain metal shavings, and proper recycling or disposal is required.

Another very common complementary process is metal cleaning, especially for the purpose of removing cutting oils prior to surface treatment. The cleaning fluid inevitably acquires metal shavings as it cleans, and it too requires proper recycling or disposal.

17.3 THE SECTOR'S USE OF RESOURCES

17.3.1 Energy

The metal fabrication industry is a substantial user of energy. Casting is sometimes considered part of the primary metals sector, and sometimes part of the fabricated metals sector. Casting is the most energy-consuming activity in metal fabrication, because of the heat required to melt the metal.

From Chapter 10 (see Figure 10.5) it was shown that the amount of energy needed to produce a fixed quantity of different metals varies substantially, largely as a result of differences in melting points. The same factor is obviously at work in the metal casting industry—casting a titanium component will require much more energy than casting the same component from steel.

17.3.2 Materials

Most material used in this sector comes directly from metal mills in the form of sheet, tube, wire, or rods. More than 90 percent of mill stock is iron or its alloys.

Its purity and physical properties depend on the application for which it is intended. About 10 percent of the sector's material goes into metal casting, where the flow of metals is about 85 percent iron and steel, 11 percent aluminum, and 4 percent all other metals. Most of the metal used for castings is from recycled material.

All processes of this sector utilize process chemicals, solvents, or lubricants, and generate waste heat and unwanted chemical residues, as shown in Figure 17.4.

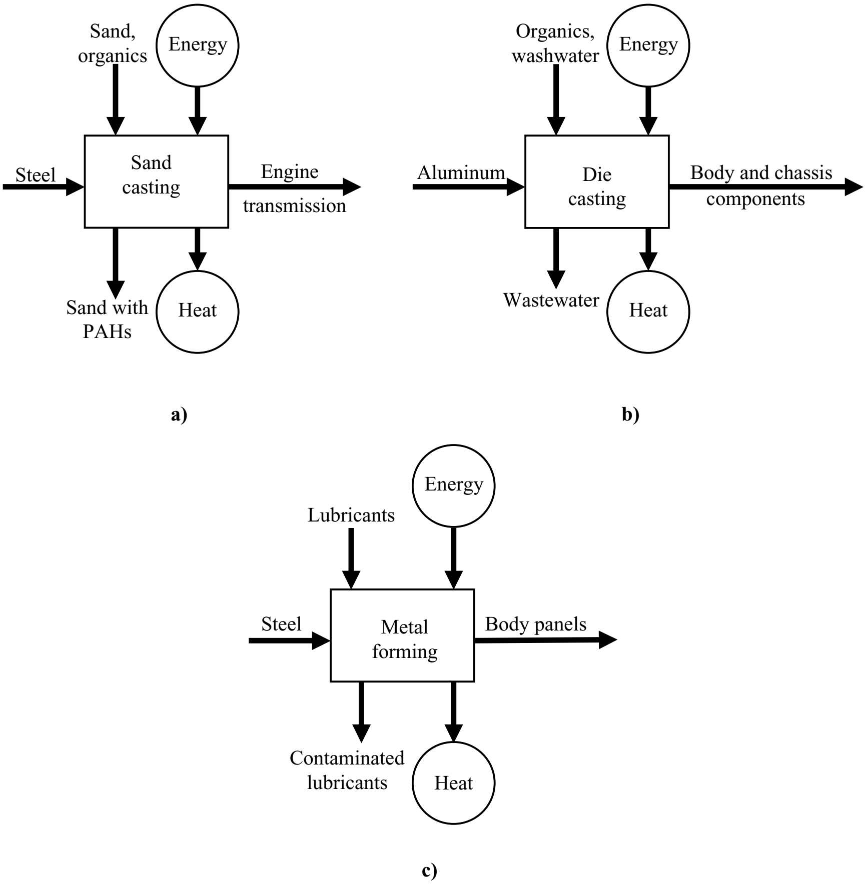

Figure 17.4. Representations of flows of materials, energy, and components for processes used in metal fabrication: (a) Sand casting, (b) Die casting, (c) Metal forming, (d) Trimming and smoothing, (e) Metal cleaning, and (f) Metal plating. Components enter the process from the left and leave from the right. Process materials enter from the top and waste products leave from the bottom. The flows shown are intended to be illustrative, not comprehensive.

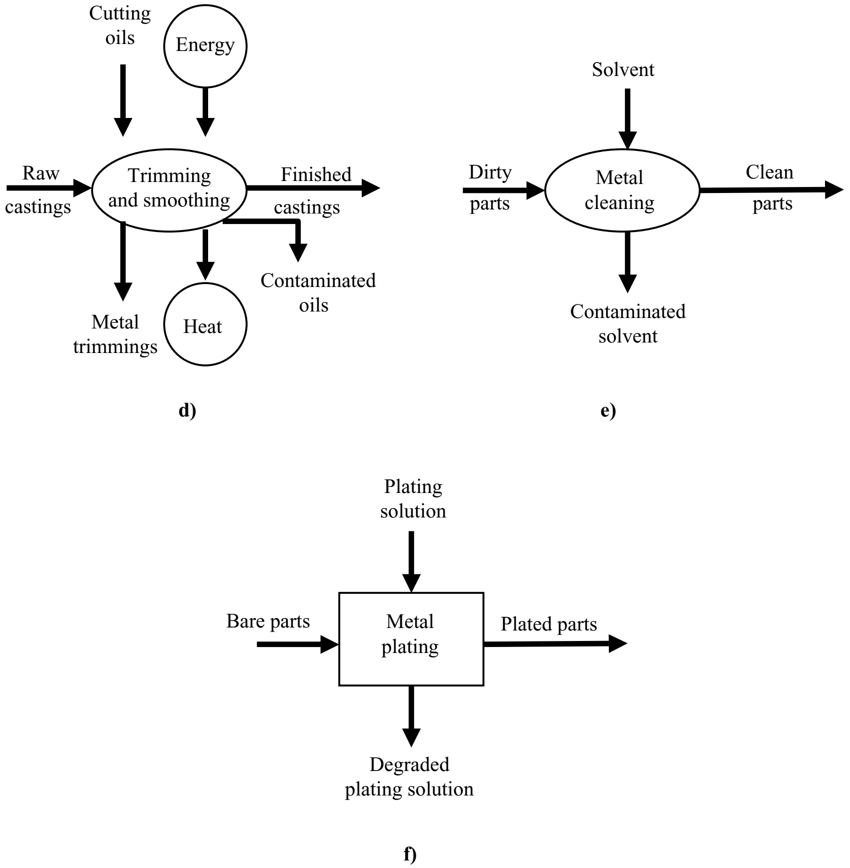

***Figure** 17.4.* (Continued)

17.3.3 Water

The metal fabrication sector uses less than 5 Tg of water per year, much less than many of the other industrial sectors. Water is used for cooling in the cast molding process, and as a solvent base for plating and finishing procedures.

17.4 POTENTIAL ENVIRONMENTAL CONCERNS

17.4.1 Solid Residues

The largest volume solid residue from this sector is discarded casting sand. The sand must be sprayed with VOCs in order to prevent it from sticking to the casting.

The eventual result is that the sand becomes too oily to flow properly and must be replaced. By that time, the VOCs have become transformed by heat into potential carcinogens, and hazardous waste disposal is required.

Metal fabrication inevitably results in metal cuttings and shavings, a second potential solid residue problem. Cuttings and shavings are generally recycled if care is taken to keep the metals separate from each other. The industry recycles 15 to 20 million tons of scrap annually in the U.S., generating an estimated $3.5 billion in cost savings over using virgin metals.

17.4.2 Liquid Residues

A major liquid phase concern in metal fabrication is the plating solutions, which have traditionally utilized cyanide, a deadly poison. Extensive treatment of exhausted plating solutions prior to discharge is required.

A second liquid residue flow, generally the largest, is contaminated wastewater from metal cleaning processes. The water is likely to contain cutting oil residues and metal shaving, and must be extensively treated prior to discharge.

The third liquid residue is cutting oil that has become broken down and contaminated with use. Specialty collectors and processors, who also deal with such industries as motor vehicle repair shops, generally recycle this oil.

17.4.3 Gaseous Residues

The principal gaseous residues from the operations of this sector are the volatile emissions from surface coating and casting processes. These VOCs are a concern because they are involved in photochemical smog formation. Surface coating and coating application process changes in the past decade have minimized these problems considerably. For casting, the emissions of concern relate to the organic binders for the sand. When hot metal is poured into the molds, the binders vaporize to form aromatic toxics such as toluene and phenol.

17.4.4 Sustainability Assessment

The potential emittants resulting from processes in this industrial sector are given in Table 17.1, and the materials binned for throughput, potential hazard, and potential scarcity in Table 17.2. The TPH matrix appears in Figure 17.5. It indicates high concern for casting sand and more moderate concern for other materials. The TPS matrix is also given in Figure 17.5. Here the most serious potential concern is the sector's extensive use of copper and its alloys, given the depletion time for copper of 35 years.

The results of the matrix assessment suggest that the substitution of more abundant materials in place of copper might be advisable, and that attention be given as well to alternatives for the present use of mold release agents on casting sand.

Table 17.2. Throughput-Hazard Binning of Materials in the Fabricated Metal Products Sector

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
Ferrous metals	H	–	L	L
Aluminum	H	–	L	L
Copper and alloys	M	Ecosystem	M	H
Zinc plating solution	L	Ecosystem	M	H
Nickel plating solution	L	Ecosystem	M	M
Chromium plating solution	L	Ecosystem	H	L
Cutting oils	M	Human	M	M
Cleaning solutions	M	Human	M	L
Casting sand	H	Human	M	L
VOC	M	Smog	M	–
Slag	M	Ecosystem	M	–

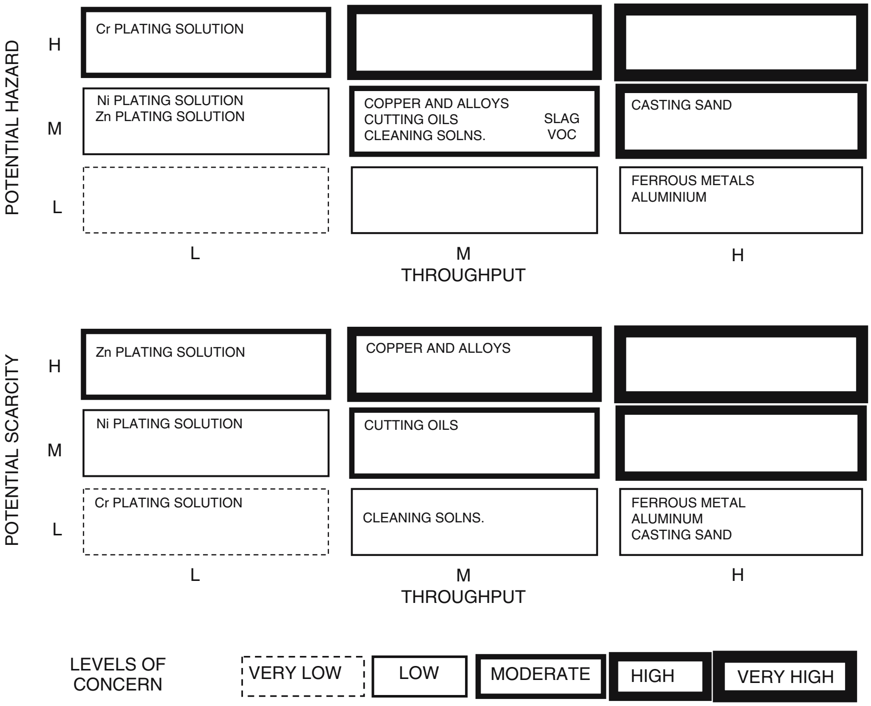

Figure 17.5. The throughput-potential hazard matrix (top panel) and the throughput-potential scarcity matrix (bottom panel) for the fabricated metal products sector.

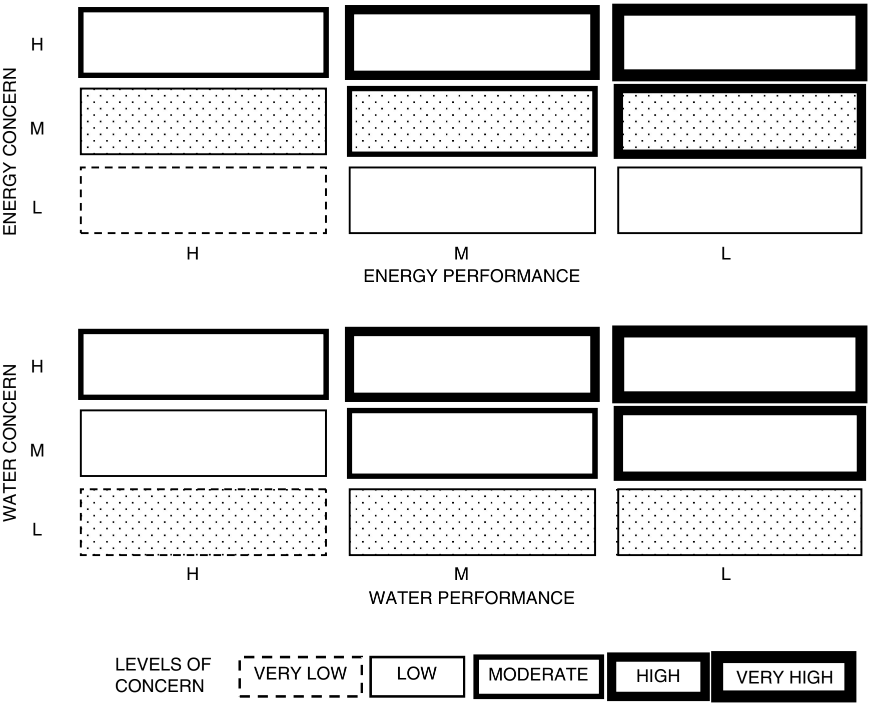

Figure 17.6. The performance-energy concern matrix (top panel) and the performance-water concern matrix (bottom panel) for the fabricated metal products sector.

The PEC and PWC matrices for the sector appear in Figure 17.6. The sector ranks in the moderate concern category in terms of energy use, and in the low concern category in terms of water use.

The ΣWESH plot for the metal fabrication sector is shown in Figure 17.7. The upper right corner of the summary matrix is empty, indicating that the sector does not raise critical concerns. A number of lesser but still important concerns are called out for attention.

17.5 SECTOR PROSPECTS

17.5.1 Trends

Trends for the fabricated metal products sector have been divided into fabrication trends, which deal with physical operations of metal and metal alloy shaping, and finishing trends, which target innovations in the plating and coating stage of

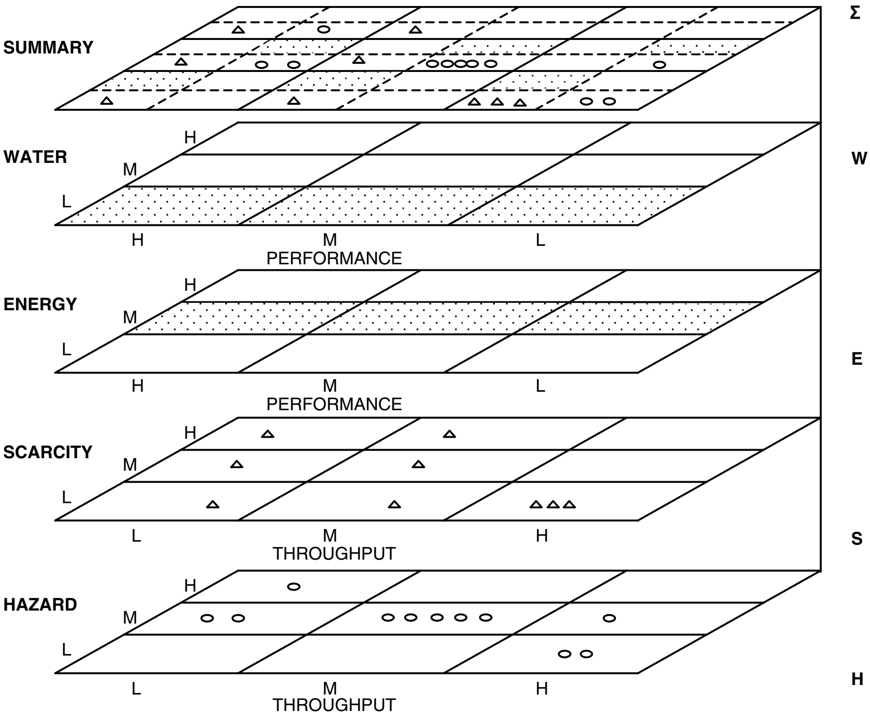

***Figure** 17.7.* The ΣWESH plot for the fabricated metal products sector. The squares and circles refer to the materials in Figure 17.5.

metallurgy. Product trends are not addressed in this chapter, since most environmental concerns are inherent to the metalworking process, rather than the products they produce. Finished metal products generally are sent to the assembled products sector, addressed in Chapter 21.

17.5.1.1 Fabrication Trends

The types of metals used in the metal fabrication sector are likely to be altered to eliminate the more toxic heavy metals. Work is underway to develop non-toxic alloys, thus eliminating the need to handle and process toxic metals. A special target is the elimination of lead from bronzes. Alternative alloy materials will decrease the toxic release rates for the metal fabrication industry.

A trend of the metalcasting segment of the sector is to achieve truly "net shape" casting, in which trimming, smoothing, and other material removal steps are not required before a casting is ready for use. This would significantly reduce the amount of scrap generated from the casting process, ultimately achieving higher process efficiencies. The thermodynamics and fluid flow of molten metal into and through molds are generally poorly understood. Small variations in internal surfaces, mold materials, initial temperatures and cooling rates, internal geometry, and the molten metal's specific properties can all have a significant effect on the end product. A better understanding of these factors will help achieve the goal of net shape casting, and will thereby decrease the volume of cast product wastes (rejects and excess materials). By reducing wastes, energy consumed for the overall process can be reduced. Complete realization of this goal will require substantial progress in controlling the casting process, but it may at least be possible to approach the goal over time.

Shaping, machining, and joining processes are increasingly computer-controlled. Research in tool making that incorporates defect-free and dimensional control of castings, as well as advanced sensing and modeling capabilities all add to the precision of the overall metal fabrication process. The result is that grinding and other mechanical steps will be eliminated or minimized, along with the (often toxic) residues that result.

Another possible fabrication trend is the extensive re-use of foundry sand, now the largest solid waste stream in the sector. Achieving this goal will require developing environmentally benign, dimensionally-stable molding materials, as well as die release agents that do not adhere to the dies and thus require cleaning and replenishment with each cycle. It is uncertain whether these breakthroughs will occur, due to the high capital costs associated with the sand reclamation process. If these technologies become more affordable, there will be significant cost savings to be achieved from re-use of spent sand, including both disposal costs as well as costs for new foundry sand. Some foundries depend on expensive, low-expansion sand, and these facilities could benefit greatly from re-use. As research and development of this field improves, foundry sand should be able to undergo re-use at most metal fabrication facilities. Alternatively, it may be possible to replace the use of sand with permanent molds of foam or metal.

A final trend in this sector is the reuse of sulfur dioxide (SO_2) in the casting process. SO_2 is used as a catalyst in the formation of certain types of molds. The present method uses the SO_2 once and then discards it by purging the mold with dry air or nitrogen. The effluent has to be scrubbed before it is released, resulting in high pollution control costs. A new process is being designed where the SO_2 is contained in a closed loop, thus eliminating waste.

17.5.1.2 Plating and Coating Trends

Major progress is being made in minimizing hazards from plating solutions. In the most advanced plating shops, toxic plating compounds are gradually being phased out as acceptable alternative solutions are discovered and developed. In some cases, alternative surface coatings are being employed in place of potentially toxic plated metals. A major environmental problem in the metal fabrication sector—the

Text Box 17.1

The Search for Environmentally Favorable Plating Solutions

The plating of one metal upon another is a widely-used process in the metal fabrication industry in order to provide improved appearance or corrosion protection. Plating is environmentally problematic, however, particularly because of the use of cyanide solutions. In a typical operation to plate copper and steel, for example, copper cyanide solution is used in an electrolyte process:

$$\mathrm{Cu(CN)_2} \rightarrow \mathrm{Cu^{2+}} + 2\mathrm{CN^-} + \text{steel} \rightarrow \text{Cu/steel} + 2\mathrm{CN^-}$$

Cyanide solutions traditionally have proven very effective in producing well-plated parts, but the toxic cyanide must be carefully handled and neutralization steps added following plating.

Lawrence Livermore National Laboratory has worked for several years to develop alternatives to cyanide plating and to plating metals that themselves raise toxicity concerns. For copper, they demonstrated that a copper pyrophosphate ($Cu_2P_2O_7$) process was as effective as the copper cyanide approach. In another effort, chromium plating was replaced with nickel-tungsten-boron plating, thus avoiding the hazardous hexavalent chromium. In both cases, product quality was maintained and potential hazard was sharply reduced.

Source: J. Dini and C. Steffani, Plating shop moves to finish off waste, *Science & Technology Review*, pp. 28–29, May, 1996.

generation of acidic liquid residues containing hazardous metals—is being addressed with modern filtration methods involving dialysis with acid-resistant membranes. It is likely that this approach will reduce both the volume and the toxicity of the waste stream.

Another initiative is the development of substitutes for the cyanide plating baths that have long been one of the industry's principal processes. When cyanide solutions become acidic, they liberate cyanide gas (obviously a problem for the workers), and when cyanide solutions are released to the environment they are hazardous to ecosystems. It is likely that cyanide plating will be completely replaced by alternative plating approaches over the next decade or two.

A final overall trend for the sector is the complete elimination of waste streams. While probably unrealistic, such a vision gives impetus to efforts to use benign materials, develop loss-free processes, and minimize cleaning and finishing practices. Over the longer term, new composite materials are likely to replace metal fabricated materials in a number of applications. In the future, the sector may be somewhat smaller and more concentrated on specialty products.

17.5.2 Possible Future Scenarios

17.5.2.1 Trend World

In this scenario, no radical process or innovation changes will occur. Most of the trends described in the preceding section carry intrinsic economic and environmental benefits in that they aim to achieve process efficiency. To the extent that they are attractive from a cost or productivity standpoint, these fabrication, plating, and coating trends will be adopted.

17.5.2.2 Green World

A green world for the fabricated metals sector involves constant adaptation of the most efficient technologies available. Information sharing and technology transfers would be the norm so that efficient techniques could be shared throughout both the developing and developed world. Materials usage would make a transition to only non-toxic, recycled metals. Net-shaping would be the norm in state-of-the-art facilities; otherwise scrap recycling would recirculate all waste metals. The finishing process would eliminate the use of cyanide and other toxic solutions, and efforts would be made to close the plating solution loop so that water throughput volumes would be near zero.

17.5.2.3 Brown World

In this scenario, the fabricated metal sector would operate much as it does today but would not adopt new technologies to improve efficiency or environmental performance. Toxic materials would continue to be used widely, and scrap recycling would not improve, resulting in release of many toxic metals to landfills and the environment. Finishing liquids would continue to use cyanide and other harmful solutions. There would be little recycling at the plating or coating stages.

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Chapter 18

Fabricated Plastic Products

18.1 OVERVIEW

Plastics are some of the most important and widely used materials in the industrialized world. Defined as solid, synthetic, organic polymer materials, plastics are easily formed into almost any shape desired. They have a wide range of physical properties—strength, rigidity, opacity, color, toughness, hardness, ductility, heat tolerance, thermal and electrical conductivity, etc.—and can thus be used in a variety of products and applications. The properties of plastics are so diverse that they can be and are substituted for metals—in which case they are called "engineered materials"—and, when formed into fibers, substitute for natural fibers like silk and wool. Overall, plastics are so useful that their production has roughly quadrupled since 1970, while the production of metals has less than doubled over the same time period.

Plastic products are created by the molding, forming, and shaping of solid or liquid resins. Two types of resins are used in the manufacture of plastics—thermoplastics and thermosets. Thermoplastic resins can be heated and formed repeatedly, but thermoset resins, once heated and formed, cannot be remelted. The process of melting a thermoset resin irreversibly alters the internal linkages of the polymers, making it difficult to recycle products made from the thermoset plastic. In contrast, thermoplastics are generally suitable for recycling.

In the U.S., thermoplastics account for 90 percent of the resin produced and thermosets for the remaining 10 percent. Common thermoplastics include polyethylene, polyvinyl chloride (PVC), polypropylene, and polystyrene. Thermosets include polyesters and polyurethanes. In Europe, the most common use for thermoplastics is as packaging materials which comprises 37 percent of all plastics use. The most common use of thermosets in Europe is for building and construction; 19 percent of all plastics used are employed in this way. Table 18.1 presents data on typical European plastics applications.

Table 18.1. Production and Applications of Plastics*

Resin Type	2000 Production (Teragrams)	Typical Applications
Epoxy	0.4	Circuit boards, adhesives
Amino	2.6	Countertops, small-appliance housings
Thermoset polyesters	0.6	Boats, luggage, chairs, auto bodies
Low-density polyethylene	7.6	Bottles, trash cans, toys, packaging materials
High-density polyethylene	5.0	Machinery parts, canoes, sleds, belts
Polypropylene	7.1	Wire insulation, pipes, drinking cups
Polystyrene	3.1	Disposable containers, packaging
Acrylonitrile-butadiene-styrene	0.7	Pipes, helmets, tool handles, telephones, luggage
Polyvinyl chloride	5.8	Food wrap, pipes, windshields
Thermoplastic polyesters	0.5	Gears, bottles, films

*The data are for Western Europe in 2000, as provided by the Association of Plastics Manufacturers in Europe (www.apme.org/media/public_documents/20020419_163332/2002_2000.pdf).

While some plastics were manufactured in the 19th century, most of the technology for producing the wide array of modern plastics was developed in the middle of the 20th century as a major component of the petrochemical industry (see the sector sequence diagram of Figure 18.1). The production and use of plastics has increased dramatically since the early days of their availability. In the past decade, the growth of the plastics sector in both the U.S. and Europe has exceeded the growth of the metals sector by a factor of about three.

The many monomers that are available for making polymers and the multitude of ways they can be joined together create an almost infinite number of possibilities for the properties of plastics, especially with regard to such qualities as strength, elasticity, and rigidity. Indeed, almost any set of performance specifications can be met by selecting among two dozen or so types of plastics.

It is this versatility that makes plastics increasingly attractive as manufacturing materials, and, plastics are, thereby, good substitutes for other materials. For example, a rod made of one of the stronger plastics would have only 25 to 30 percent of the tensile strength of an aluminum rod of equal cross section. Yet, because those plastics are generally so much lighter than aluminum, rods of equal weight would perform very similarly and make it possible to consider substituting plastic for aluminum.

18.2 PHYSICAL AND CHEMICAL OPERATIONS

The three general categories of operations involved in the manufacture of plastics products are: (1) the manufacture of polymer resins; (2) the incorporation of additives into the resins to provide certain performance characteristics; and (3) the formation of the desired product through the shaping of melted resin.

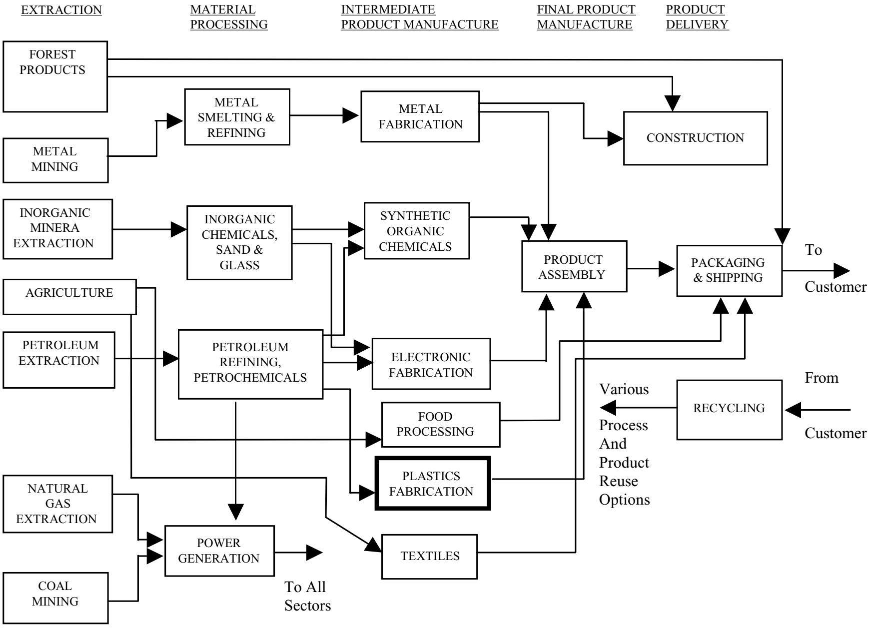

Figure 18.1. The position of the plastics industry within the sector sequence diagram. The industry sector itself is indicated by heavy outlining.

18.2.1 *Manufacture of Resins*

Some common resins can be made in several different ways, but the chemical reactions used involve, at a minimum, placing monomer material—e.g., ethylene—in a reaction vessel and allowing time for that material to combine into polymers—e.g., polyethylene. Common polymers and their monomer precursors are shown in Figure 18.2. Usually a catalyst is added with the monomer material to speed the reaction, and the reactor vessel is pressurized to increase the fraction of monomer material that is transformed to polymer. In one frequently used method for producing polyethylene, pressures of 600 to 3,000 atmospheres are used. Even then, a polymerization reaction rarely goes to completion. The material coming out of the reactor must be separated into a polymer product stream and a stream of monomer and catalyst to be recycled to the input of the reactor vessel.

Sometimes, in order to control the viscosity of materials in the reactor vessel and to facilitate the removal of heat from these ordinarily exothermic reactions, the monomer material is dissolved in a solvent before being mixed with catalyst and placed in the reactor vessel. This method is called "solution polymerization." A method similar to solution polymerization is "suspension polymerization." In this method, droplets of

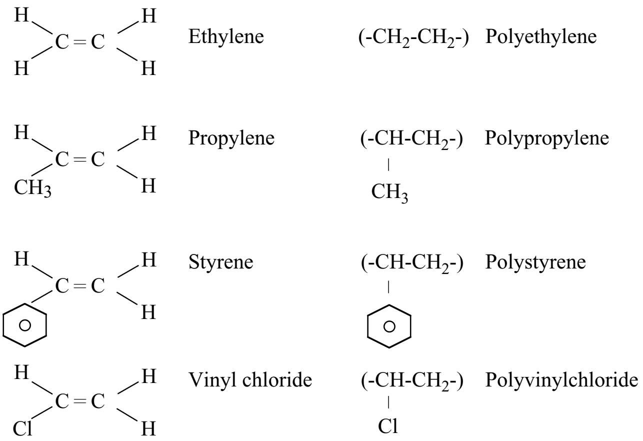

***Figure** 18.2.* Makeup of some common polymers.

monomer material are suspended in a liquid that does not dissolve the monomer, but that does control the viscosity and facilitate heat removal from the reaction stream. In both solution and suspension polymerization reactions, the polymer may be produced as a solid, in which case the reactor product stream is a slurry of polymer.

After solution or suspension polymerization, the solvent and unreacted monomer must be removed from the polymer product. This is done through a combination of heating, flashing (lowering pressure to volatize the solvent and monomers), thin-film evaporation, and vacuum stripping. In cases where the reaction mixture contains heavy solvents or liquids, it may be filtered or centrifuged. In all cases, the resin pellets are dried as a final step in the recovery operation.

When only monomer materials, catalysts, and necessary reactant materials are involved in a reaction, the reaction is called "bulk polymerization." Note that, in a bulk polymerization, separation of the polymer product from other materials coming out of the reactor vessel is less complex than it is for solution or suspension polymerization.

Table 18.2 shows the reaction types used in the manufacture of several common plastics and the solvents and suspension agents used.

The manufacture of plastic resins, particularly commodity resins like polyvinyl chloride, polyethylene, polypropylene, and polystyrene, is often performed by synthetic organic chemical manufacturers. Resin pellets are packaged and shipped to plastics manufacturers who perform the forming and finishing operations.

18.2.2 Incorporation of Additives

The use of additives is essential to the manufacture of robust plastics. Without additives, plastics might deteriorate during processing or use, lose strength and

Table 18.2. Reactions, Solvents, and Suspension Agents Used to Make Common Plastics

Polymer	Reaction Type	Solvent or Suspension Agent
High-density polyethylene (HDPE)	Solution, suspension	Isobutane, hexane
Low-density polyethylene (LDPE)	Bulk, suspension	Hydrocarbons
Linear low-density polyethylene (LLDPE)	Solution	Octene, butene, or hexene
Polypropylene	Bulk, solution, suspension	Hexane, heptane, liquid propylene
Polystyrene	Bulk, solution, suspension	Styrene, ethylbenzene
Polyvinyl chloride (PVC)	Suspension	Water
Nylon	Bulk	–
Polyethylene terephthalate (PET)	Bulk	–

Table 18.3. Chemical Additives in Plastics Processing

Additive Type and Purpose	Common Examples
Lubricants: ease mold ejection, finishing	Stearic acid, fatty acid esters
Anti-oxidants: prevent oxidation breakdown	Alkylated phenols, amines, organic phosphites
Anti-stats: dissipate static electricity	Quaternary ammonium compounds, amines
Blowing/foaming agents: make foam plastics	Azodicarbonamide
Colorants: color product material	Titanium oxide, iron oxides, anthraquinones
Flame retardants: resist burning	Antimony trioxide, chlorinated paraffins
Heat stabilizers: prevent heat degradation	Lead, barium-cadmium, tin, calcium-zinc
Catalysts: assist thermoset reactions	MEK, benzoyl, alkyl peroxides
Plasticizers: soften, enhance pliability	Adipates, azelates, trimellitates
Ultraviolet stabilizers: resist light degradation	Benzophenones, benzotriazoles, carbon black
Impact modifier: improve stress resistance	Acrylonitrile-butadiene-styrene (ABS)

elasticity, become discolored, or take on electrostatic charges. In addition, additives are used to provide specific combinations of quality and performance characteristics in a plastic product; they can alter the color, strength, density, plasticity, heat tolerance, and flame resistance of a part.

Table 18.3 lists several common types of additives, their usual purposes, and some examples of each. Roughly 15 billion pounds of additives are used each year in the U.S. plastics industry. This represents about 14 pounds of additives for each 100 pounds of plastic produced.

Some polymer pellets are produced with additives already mixed in. More commonly, additives and pellets are mixed by a plastics manufacturer prior to the forming operations. In some cases, additives can be applied to a plastic part as a finishing step.

18.2.3 Forming and Shaping Plastics Products

The forming and shaping of plastic products uses operations similar to those used to make and finish metal products. Several of the more common methods are described below. Note that a melted thermoplastic must be cooled to make the formed product suitably rigid. For a thermoset, it is the heating and melting process itself that triggers the final polymerization reactions that produce a rigid plastic product even before cooling. For that reason, the forming of thermoset products must be very carefully controlled to avoid premature polymerization and hardening in processing equipment.

18.2.3.1 Extrusion

In extrusion, resin pellets are fed into the hopper of a screw-type extruder. As they fall into the machine, a turning screw captures the pellets and conveys them into a zone where the friction of the movement and building pressure combines with added heat to melt the pellets. The action of the screw forces the melted resin through a die. Extruded material is then air- or water-cooled. This continuous operation can produce such products as solid rods, pipe, and tubing.

18.2.3.2 Injection Molding

Injection molding is similar to extrusion, except that instead of producing a continuous product the screw injects measured quantities of melted resin into a mold. After the mold is filled, it is cooled to harden the product and subsequently opened to eject the formed part. The injection molding sequence is illustrated in figure 18.3. A typical injection molding cycle lasts roughly ten seconds. Injection molding can produce pre-colored, complex parts that in many cases require no secondary finishing operations. A great many parts for machines, appliances, and automobiles, many of them high-precision items, are made by injection molding.

18.2.3.3 Blow Molding

Blow molding is a variation of the extrusion process that is used to make plastic beverage bottles and thin films for such products as food wrap and plastic bags. As illustrated in Figure 18.4a, plastic bottles are made by first extruding a tube of softened plastic onto an air tube. The tube of softened plastic is then inserted into a bottle mold and blown up, cooled, and ejected to form the bottle.

To make thin-film products using blow molding, plastic material is extruded as a thin-walled tube, which is then blown up and expanded into even thinner material with air. (See Figure 18.4b) Once cooled by the blowing air, the material can be tailored and joined as necessary to make the intended product.

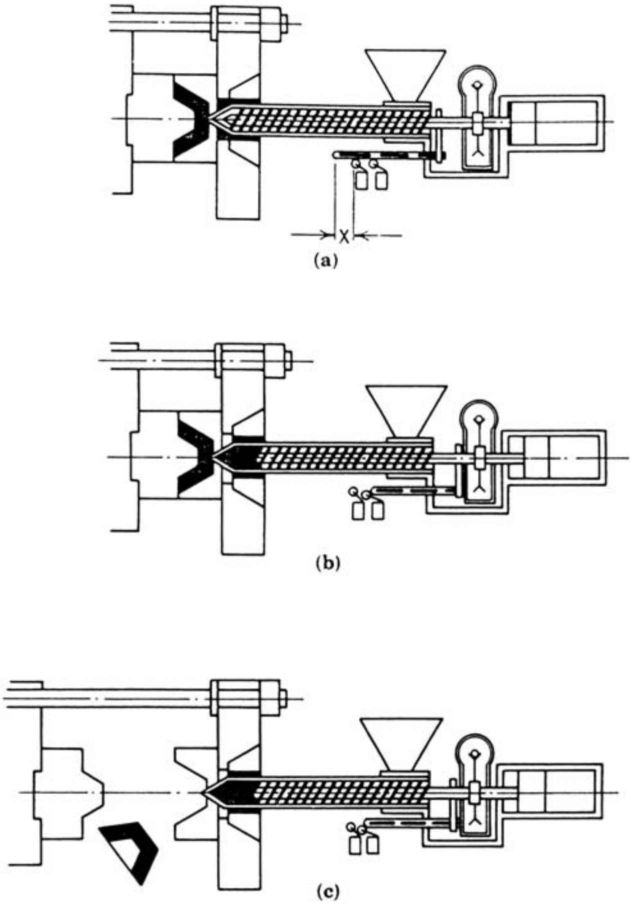

Figure 18.3. Schematic illustration of injection molding. (a) The mold is closed. Polymer resin fills the hopper and is transported to the mold and liquified by a heated screw drive. (b) The mold is filled with molten plastic. (c) After the plastic solidifies, the mold is opened and the molded part ejected. (Reproduced by permission from N. M. Bikales, Ed. 1971. Molding of Plastics. John Wiley & Sons.)

18.3 THE SECTOR'S USE OF RESOURCES

The production of plastic products is a major consumer of neither energy nor water, but it is a significant, though reasonably efficient, consumer of petrochemical raw materials.

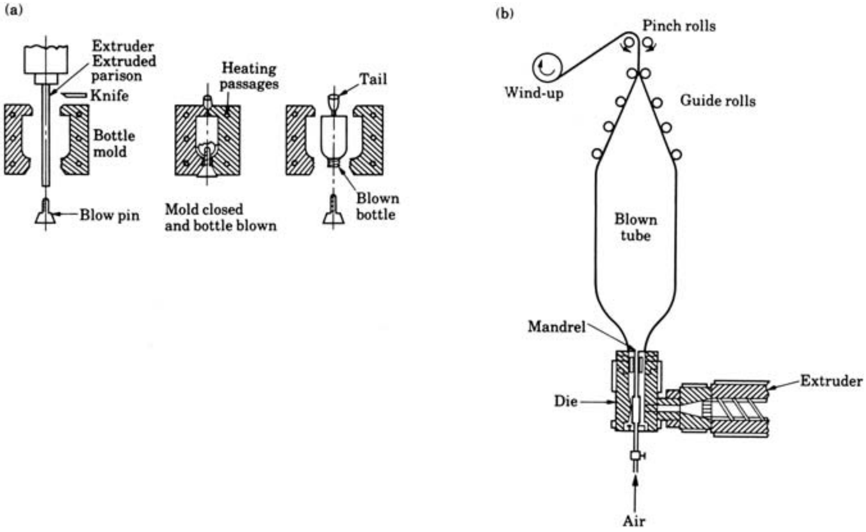

Figure 18.4. (a) Schematic illustration of the blow-molding process for making plastic bottles. (b) Schematic illustration of the blow-molding process for making thin-film products. (Reproduced by permission from D. C. Wiley and J. H. Briston. 1979. Polymer Technology. Chemical Publishing Co., Inc.)

Because most polymerization reactions are exothermic, the production of polymer resins requires only moderate amounts of energy, roughly 25 MJ/kg of resin product. The manufacturing of final plastic products from polymer resins—e.g., with injection molding—requires even less energy, roughly 7 MJ/kg of formed products.

Large quantities of water are not needed for the production of resins or the forming of finished products either. Water is used for heat removal from polymerization reactions and occasionally as a reaction solvent, but it can be easily recycled in either case. The only significant requirement for water in the forming of plastic products is for the cooling of molds and formed products, for washing molded products, and for lubricating product finishing operations. Again, water used for such purposes can easily be recycled after conventional treatment.

The predominant raw material needed for the manufacture of plastic products is monomer material, usually from petrochemical processing. Polymerization reactions generally produce only the desired polymer, with little byproduct and with any unreacted monomer being recycled. Therefore, these reactions are reasonably efficient users of raw materials. Even with the losses of material associated with molding wastes—e.g., sprues and finishing wastes—the overall efficiency of raw material use in the manufacturing of plastics products is high, especially when compared with a process like synthetic organic chemical manufacturing.

18.4 POTENTIAL ENVIRONMENTAL CONCERNS

The primary sources of pollutants in the manufacture of plastic products are releases of raw materials, catalysts, and solvents in polymerization processes and releases of additives during plastic forming, use, and end-of-life.

18.4.1 Air Emissions

During polymerization processes, air emissions may result from volatilized monomer material—e.g., butadiene—and organic solvents—e.g., ethylbenzene. Both are volatile organic compounds (VOCs). VOCs and Hazardous Air Pollutants (HAPs) are also emitted during plastic forming, especially when thermoset resins are being used.

The application of high heat and pressure during the molding and forming processes can result in fugitive emissions from additives. Some additives contain chemicals that are hazardous in very small quantities, such as lead and cadmium. In the U.S., over seventy percent of the chemical and metal ion releases to the environment from this manufacturing sector are air emissions.

Most of the heat energy needed for this manufacturing sector is produced by the burning of natural gas, which in turn produces small amounts of carbon monoxide and nitrogen oxides.

Air emissions can also result at the end of a plastic product's life. Incineration of plastic waste, particularly popular in Europe and Japan, can release toxic chemicals into the air. These chemicals are usually derived from the additives that are contained in plastics. In the European Union, chlorinated flame retardant additives have long been banned because they can form dioxins upon incineration, and restrictions are now being placed on the use of brominated flame retardant additives.

18.4.2 Releases To Water

Water is used in polymer processing as a reaction solvent, for product cooling and cleaning, and in lubricating product finishing operations. In all those uses, water comes into contact with reactants, catalysts, additives, resins, grease, and cleaning agents, and, unless steps are taken to remove them, water effluents could contain small quantities of several hazardous organic chemicals, among them bis(2-ethylhexyl) phthalate, phenol, zinc, di-n-butyl phthalate, and dimethyl phthalate.

The unintentional release of resin pellets to the environment as a result of spills during shipping and handling can result in contamination of runoff water. Although the pellets are inert, they can be harmful if ingested by marine birds and animals. The discovery of pellets in storm water runoff would prompt regulatory action, hence manufacturers are careful to contain resin pellets and minimize spills.

18.4.3 Solid Wastes

There are three primary sources of solid waste generated during plastics manufacturing—unsatisfactory polymer product, spilled resin pellets, and mold sprues and other materials removed during final product finishing. Ordinarily, most of these materials are collected for solid-waste disposal because they would result in inferior product quality if recycled.

The more important solid waste issue associated with plastics manufacture is the disposal of plastic products at the end of life. It is estimated that in more highly-developed countries plastics constitute between 14 and 21 percent (by volume) of the municipal solid waste stream. Although some consumer products like milk jugs and soft drink bottles are recycled on a large scale, less than one percent of all plastic products are recycled. Plastics degrade very slowly in landfills and, if improperly disposed of, may pose a hazard to marine ecosystems. The additives used in plastics can leach into the environment as a product degrades. Some of these additives contain highly toxic chemicals. Plastics are the source of 28 percent of the cadmium and two percent of the lead found in municipal solid waste landfills in the U.S.

18.4.4 Sustainability Assessment

The materials that have the potential to be released from facilities involved in the production of plastic products are summarized in Table 18.4, and these materials are presented in terms of throughput, potential hazard, and potential scarcity in Table 18.5. The throughput-potential hazard matrix and the throughput-potential scarcity matrix are shown in Figure 18.5.

The manufacture of plastics is among the most efficient of industrial operations. The starting materials are mostly only slightly hazardous (vinyl chloride being an exception). As a result, the TPH matrix is relatively benign. From a scarcity standpoint, the petroleum feedstock and its derivatives (solvents, additives, lubricants) have moderate potential scarcity.

The PEC and PWC matrices appear in Figure 18.6. This sector has low relative water use and moderate energy use.

Table 18.4. Processes, Activities, and Potential Emittants for the Fabricated Plastic Products Sector

Process Type	Sector Activities	Potential Emittants
Resin production	Polymerization reactions	Monomers, solvents, off-spec resins, catalysts
Additives	Blending	Volatilized/spilled additives
Final product fabrication	Molding, finishing	Volatilized/leached additives, cleaning/lubricating agents
Process heat	Natural gas combustion	CO, NOx

Table 18.5. Throughput-Hazard-Scarcity Binning of Materials in the Fabricated Plastic Products Sector

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
Monomer material	H	Human	M	M
Catalysts	L	Human	M	L
Solvents	L	Human	M	M
Additives	L	Human	M	M
Cleaning/lubricating agents	L	–	L	M
Polymer product	H	–	L	–
CO, NO_x	L	Smog	M, H	–
VOC	L	Smog	M	–

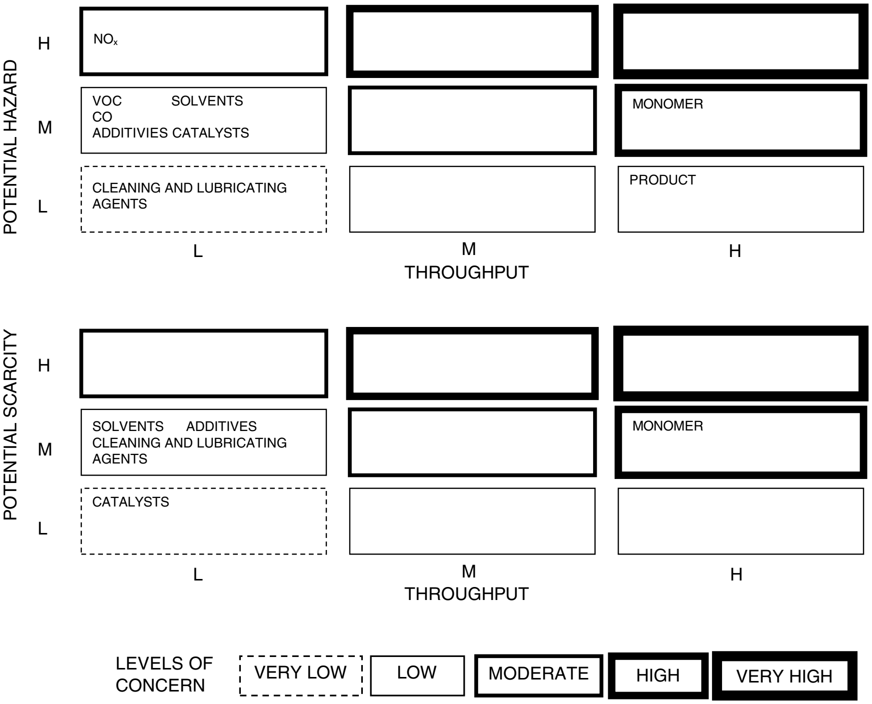

Figure 18.5. Throughput-potential hazard matrix (top panel) and throughput-potential scarcity matrix (bottom panel) for the fabricated plastic products sector.

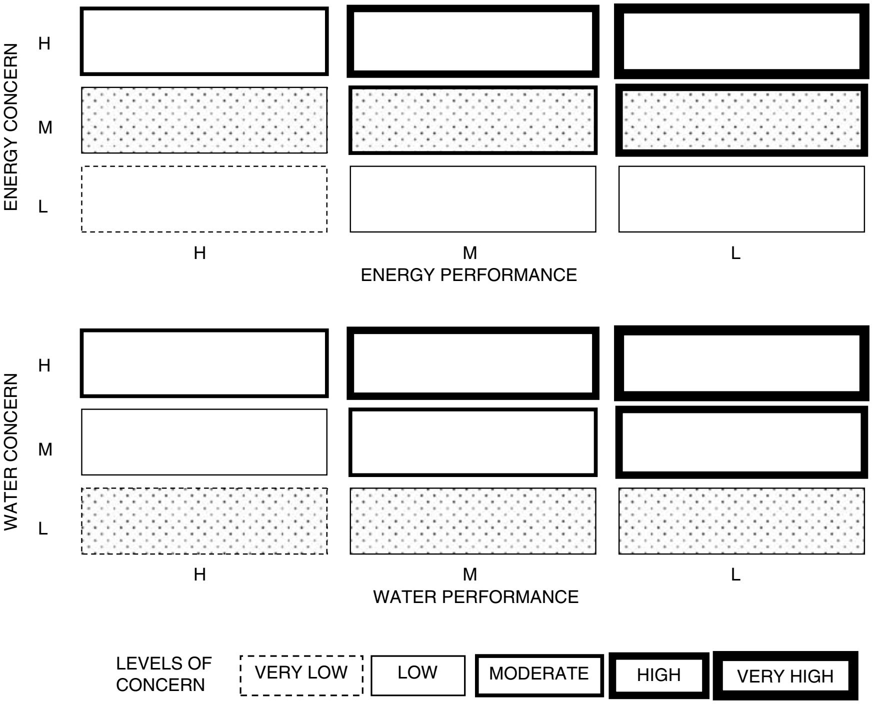

Figure 18.6. The performance-energy concern matrix (top panel) and performance-water concern matrix (bottom panel) for the fabricated plastic products sector.

The sector ΣWESH plot is given in Figure 18.7. Aside from concern over energy use and feedstock supply, there are no items to call out for special attention.

18.5 SECTOR PROSPECTS

18.5.1 Process Trends

The methods used to shape and form plastic products will likely remain similar to those used today, but the starting materials for plastics manufacture may change. As fossil fuels become scarcer, biological materials may replace them as the raw material for plastics manufacture. Already, PHA (polyhydroxyalkanoate), a plastic derived from corn, is being used as a biologically-derived, biodegradable alternative to polystyrene. Thermosetting matrixes for plastic composite materials have been made from soybean oil and used to make vehicle panels. Corn and soy are inexpensive enough to begin competing with petroleum as feedstock materials. Genetic engineering of the

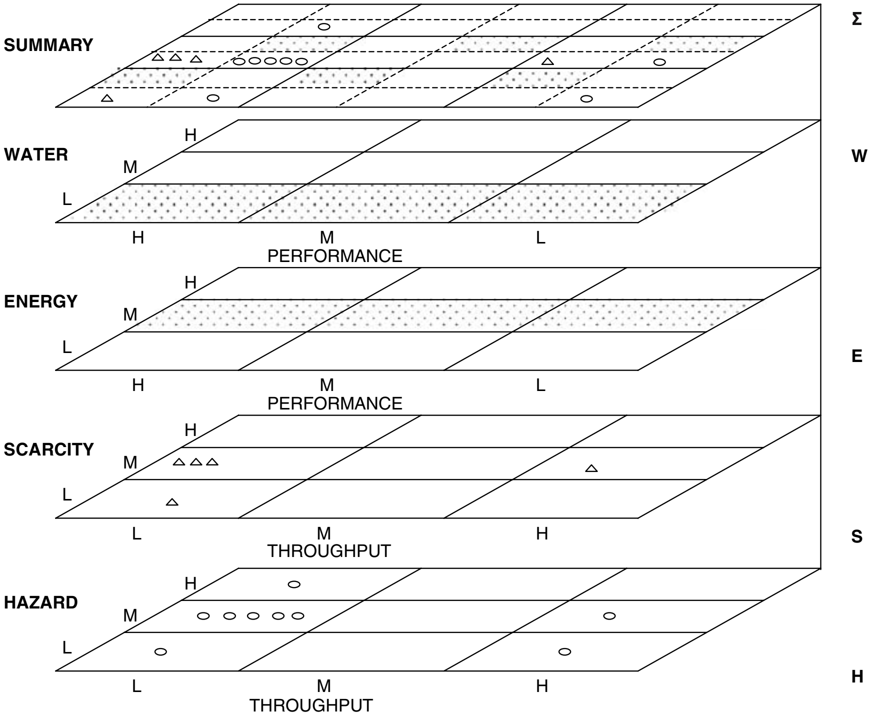

Figure 18.7. The ΣWESH plot for the fabricated plastic products sector. The squares and circles represent the materials in figure 18.5.

plants may be used to control the type of oil produced and hence tailor it to specific applications.

The potential environmental benefits of using biological materials to produce plastic resins include reducing dependence on fossil fuels, using the plants as a sink for CO_2 during their growth phase, and enabling the manufacture of biodegradable plastics. On the other hand, the manufacture of plastics using biological materials remains dependant on petroleum for energy and fertilizer. One study has shown that producing PHA from corn uses more electricity and water than is used in the conventional manufacture of plastics. According to this study, production of a pound of polystyrene requires 2.26 pounds of petroleum, while production of a pound of PHA requires 2.39 pounds of fossil fuel resources.

A second broad process trend will be increased attention to the design of plastic products for recyclability. Plastic components used in vehicles or computers can be recovered and remanufactured efficiently only if the types of plastics and additives are compatible. Auto makers, for example, are starting to reduce the number of different plastics used in a single vehicle to enable recycling. The ability to recycle thermoset plastics (which are largely unrecyclable) would greatly enhance their environmental performance. Progress on this front is expected in the coming decades. Already, thermoset plastics that break down when exposed to ultraviolet light have been developed.

18.5.2 Product Trends

In general, plastics will continue to substitute for other materials like wood and metal where their lighter weight and durability make them attractive. Developments in product design will likely result in the same or superior functionality at even lower weight. For example, the Association of Plastics Manufacturers in Europe reports that technological innovation in the past decade has resulted in savings of nearly 30 percent by weight for a major portion of the plastics packaging market. Reducing weight results in fuel savings when plastic products or packages are transported. When plastic panels are used for automobiles, the lighter weight results in greater fuel efficiency.

Biodegradable plastics will continue to be developed and likely find niche applications. For example, biodegradable plastics may be attractive for short life-time products like food packaging but less attractive for long life-time products like vehicle panels. PHA made from corn is one example of a biodegradable plastic that could be used to make beverage cups or utensils.

Text Box 18.1

Towards a Plastic Vehicle?

Every pound of vehicle weight is important from a sustainability standpoint, as gasoline must be burned in order to carry it around for ten years or so. Automakers are thus eager to employ plastics in place of metals, but only where safety and appearance are not compromised. For this market GE Plastics has developed a series of engineering materials, the latest of which—the W-4 polymer—is intended for use in automotive body panels, bumpers, and other exterior components. A variety of pigments can be incorporated into the products during the molding process, giving a painted look that withstands the elements.

Polymers that are highly colored are difficult to recycle, because the pigment cannot be readily removed. The environmental benefits of a lighter vehicle far outweigh a more difficult recycling situation, however.

Source: A. H. Tullo, Polymer makers bridge the gap, *Chemical & Engineering News*, pp. 21–24, May 22, 2000.

The wide spectrum of properties, relatively light weight, and reasonable cost has resulted in rapidly increasing rates of use of polymers and plastics for many applications. In Western Europe, annual per capita plastic use reached 90 kg, up from only 65 kg a decade earlier. Continued growth, through perhaps not at this rate, is expected for the foreseeable future. New types of plastics will continue to be developed for new applications, and plastics will continue to displace traditional materials like wood and metal.

Plastic matrix composites will become increasingly prevalent (for more on composites, see chapter 26). These materials may use biologically derived material for both the plastic matrix and the reinforcing fibers. Fibers from crops like sisal, flax, kenaf, hemp, and switch grass are successfully replacing glass fibers in plastic matrix composites. Plant fibers bind well to soy-based resins, creating a material that performs as well as petroleum-based plastic composites. Plastic composites reinforced with plant fibers may one day replace wood in construction applications or metal in vehicle applications.

18.5.3 Social and Regulatory Trends

The types of additives used in plastics will likely change in response to consumer and regulatory demands. Recent concern over the human health effects of some plasticizers (e.g., diethylhexyl phthalate (DEHP) and diisononyl phthalate (DINP)) used in vinyl has resulted in some manufacturers switching to using phthalate-free plastics for toys and medical uses. Heat stabilizers are another class of additives that have negative environmental consequences because they usually contain lead or cadmium. Alternatives, such as calcium/zinc mixtures will likely replace these traditional materials, particularly in Europe where use of lead is still predominant. The use of brominated flame retardants (BFRs) is discouraged by voluntary labeling programs in Europe and particular BFRs are restricted by the electrical and electronics equipment waste directive (WEEE) developed by the European Union. When plastics containing BFRs are incinerated, harmful dioxins and furans can be released. There is much uncertainty, however, over which particular BFRs are harmful and whether these will still be used in the electronics industry.

Pressure for increased recycling is likely to mount. In some cases, governments are mandating that plastic packaging or plastic products be recovered and reused or recycled at the end of life. For example, the German Packaging Ordinance requires distributors and manufacturers to take back transport packaging after it is used. Significant barriers to increased recycling of post-consumer plastic exist. Because of the great variety of plastics and the variety of additives used, products must be sorted carefully in order to be recycled into a single resin type. Alternatively, mixed resins of lower quality may be made from mixtures of recycled plastic. The historically low cost of new plastic resins makes it economically unattractive for plastics manufacturers to invest heavily in technologies to collect, sort and recover post-consumer plastics. Significant increases in the production and use of recycled plastic therefore depends on providing incentives to develop new separation technologies and/or to increase the market for mixed-resin material.

18.5.4 Scenarios

Trend World

In this first scenario, the plastics industry will continue to operate much as is does today, using petroleum as feedstock to produce a wide variety of products. Recycling will continue and probably increase somewhat, but will ultimately be limited by the need for better infrastructure to support collection and sorting of post-consumer material. As long as the price of plastic resins remains low, there will be little economic incentive for manufacturers to increase their use of recycled plastic. Pressure for change is likely to come from regulations governing the end-of-life of products like automobiles and electronics. These regulations will force manufacturers to design products for disassembly, reuse, and recycling, which may mean reducing the variety of plastics used in a single part.

Green World

In a green world, plant-based materials will replace petroleum as the starting material for at least some plastic products. This switch may be made due to scarcity of petroleum or due to demonstrated reduction in environmental consequences of plastics manufactured from bio-materials. Composite materials may increasingly use light-weight, renewable fibers derived from plant crops instead of using glass fibers or wood filler. Two trends will be discernable within the plastics manufacturing industry: first, the use of biodegradable plastics for packaging and other short-term uses, and second, the design of other plastic products for easy recycling or reuse. In this scenario, the use of harmful additives would be rapidly phased out and alternatives developed.

Brown World

In the final scenario, the plastics industry would not reduce its environmental impact through recycling, producing biodegradable products, or reducing its use of harmful additives. If petroleum is abundant and prices remain low, the traditional production of plastics will continue and will be driven by a market that rewards convenience, durability and disposability. Incentives to recycle plastics will be almost non-existent and concern about the environmental impacts of plastics disposal or incineration will not have a voice.

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Chapter 19

Electronics

19.1 OVERVIEW

The electronics sector produces both consumer products and components for more complex assembled products. Figure 19.1 shows the position of the electronics sector in the overall sector sequence. The electronics sector incorporates three quite distinct processes—the manufacture of integrated circuits ("chips"), the manufacture of printed wiring boards, and the assembly of chips and other components on printed wiring boards to give finished electronic modules. Those modules may be assembled by the electronics sector itself into computers, cell phones, and the like, or sold to the assembled products sector (Chapter 21) to be incorporated in "smart" products such as microwave ovens, machine tools, or airplanes.

We are increasingly familiar as individuals with consumer electronics products, such as hand-held organizers and DVD players. However, consumer electronic products account for less than five percent of the market for electronics, with computers dominating the market and communications applications and industrial electronics taking up much of the remainder.

The electronics industry is probably the most rapidly evolving of any industrial sector, with the possible exception of biotechnology. Gordon Moore, a founder of Intel Corporation, first observed that the density of transistors on chips doubled about every two years, resulting in rapid increases in the power and performance of the chips and the products they are used in. "Moore's Law," as it has come to be known, is shown graphically in Figure 19.2. In accordance with Moore's Law, microprocessor chips that hold a billion transistors will soon be manufactured. The rapid evolution of what constitutes state-of-the-art in this sector clearly has implications for both manufacturing processes and final products; new manufacturing processes are continually under development, product cycles are short, and product obsolescence frequent.

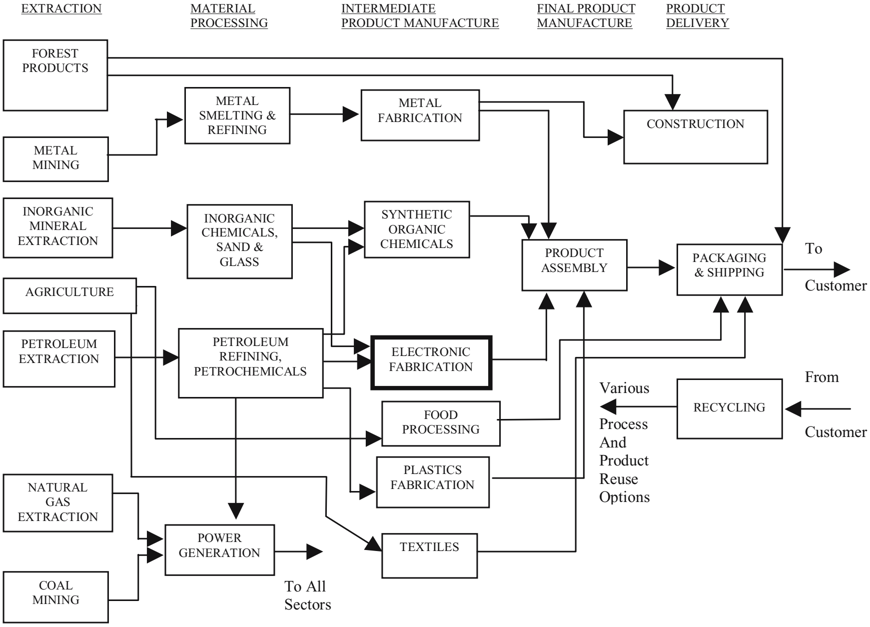


Figure 19.1. The technological sequence diagram for the electronics industries. The industry sector itself is indicated by heavy outlining.

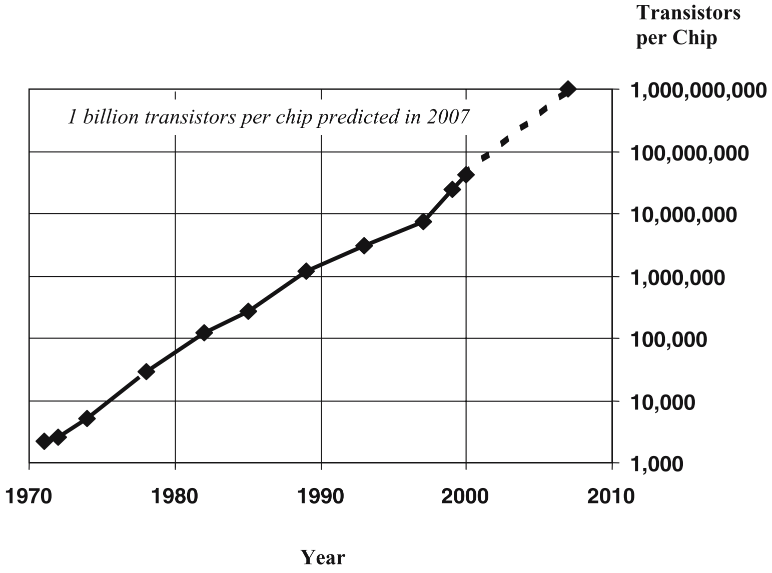


Figure 19.2. The number of transistors per chip for microprocessors and dynamic random access memories (DRAMs) as a function of year of introduction.

19.2 PHYSICAL AND CHEMICAL OPERATIONS

There are four distinct steps involved in electronic product manufacture, each with many substeps. They are as follows:

- Manufacture of the integrated circuit (the "chip")
- Manufacture of the printed wiring board (PWB).
- Mounting of chips and components on the PWB to form an electronic circuit pack.
- Assembly of circuit packs and other components to make the finished product.

19.2.1 Integrated Circuit Manufacture

The manufacture of an integrated circuit is a remarkable technological achievement. In an area smaller than a fingernail are created hundreds of millions of electrical components, connected by wires more than 1,000 times thinner than a human hair. A typical process is shown in Figure 19.3. To begin, the surface of a thin wafer of silicon is oxidized (step 1). A mask with desired cutouts is then placed over the oxidized silicon and the oxide stripped away by chemical action in the cutout areas (patterning and etching, step 2). Atoms are then implanted in selected regions by ion bombardment and moved to the appropriate depth through diffusion (implant and diffusion, step 3) and more of the oxide stripped away (step 4). Continuing in this manner, regions of high and low conductivity are constructed so as to form multiple planar transistors.

Interconnections between transistors are fabricated by depositing patterned metal conducting layers. Several metal layers, separated by insulating material, are used to make all the connections both between transistors and to the chip's external contact

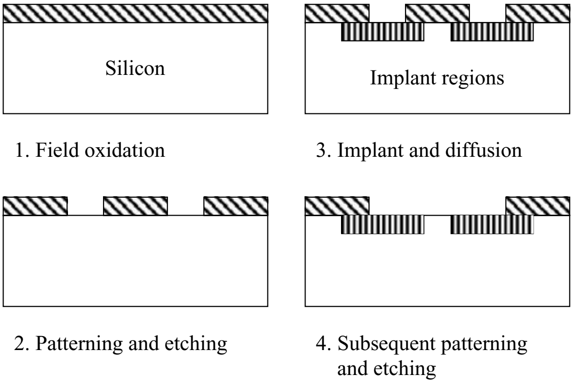
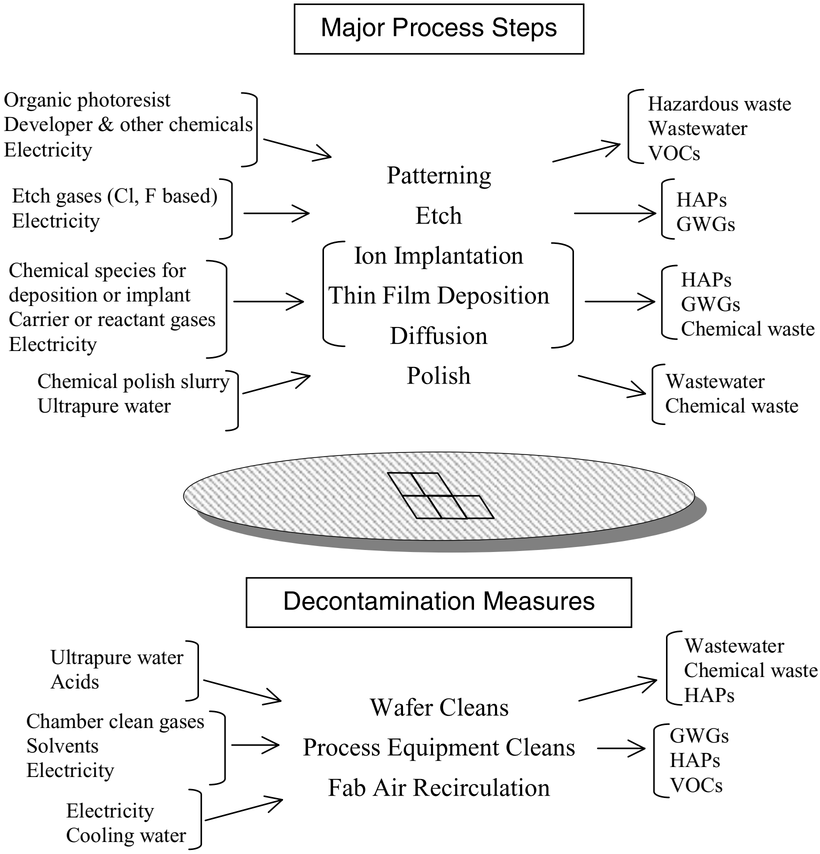


Figure 19.3. The steps involved in the manufacture of an integrated circuit.



Note:

HAPs = Hazardous Air Pollutants
GWGs = Global Warming Gases
VOCs = Volatile Organic Compounds
Wastewater needs on-site treatment to neutralize acids/bases.
Chemical waste may include hazardous and/or non-hazardous solid waste.

Figure 19.4. Environmental impacts of key steps involved in chip manufacture. Flows from the left hand side are key chemicals and resources; flows towards the right hand side are emissions and waste.

points. The fabrication of metal and insulating layers is done using similar basic steps to those used in transistor fabrication: patterning, material deposition, and material etch.

These basic steps may be repeated hundreds of times to fabricate the chips on a single wafer. Many of the steps involve toxic process chemicals, and the techniques used to clean the wafers between steps and ensure an ultra-clean manufacturing environment are heavy users of water, energy and chemicals. The flows of resources and hazardous chemicals into and out of the various process steps are shown in Figure 19.4.

19.2.2 Printed Wiring Board Manufacture

Printed wiring boards are the mounting and interconnection platforms for integrated circuits and other electrical components that cannot be fabricated as part of the circuits. The boards are made of a thermoset plastic laminate, usually a fiberglass and epoxy composite into which mounting holes are drilled. Copper is then deposited onto the board in a desired pattern, any excess removed, and a solder coating (an alloy of tin and lead) applied in order to affix parts at a later stage. The copper conductors that result are much larger than those on an integrated circuit—typically one or two millimeters in width. The sequence produces substantial amounts of copper plating solution and cleaning solvent residues.

19.2.3 Electronic Circuit Board Assembly

The final operation in the electronics industry is the assembly of a circuit board from the printed wiring board, integrated circuits, and other components—batteries, heavy-duty resistors and capacitors, resonators, and so forth. In the usual case, the board will have integrated circuits on its top, affixed to the board by blobs of solder between the encapsulated circuits and the solder-coated copper conductors on the board. Also atop the board, but affixed by wires running through holes in the board and soldered beneath, are bulkier, heavier components. The fastening is done in two stages. In the first, the integrated circuits and other surface-mounted components are set in place and the board is then heated to barely melt ("reflow") the solder. Through-parts insertion then occurs, and the board is passed over a bath of molten solder, the solder adhering to the through-hole wires. Post-solder bath cleaning may be required after the soldering steps and before the connector is added to permit the board to be connected to the outside world.

The process chemicals involved in this sequence are restricted to solder and cleaning solutions.

19.3 THE SECTOR'S USE OF RESOURCES

19.3.1 Energy

Electronics manufacturing is not a large user of energy overall, as the process steps are relatively efficient and the amount of material relatively small. Interestingly, in integrated circuit manufacture the largest single portion of energy is consumed in filtering the air for the clean room in which the manufacturing steps take place. Clean room air must be one million times cleaner than normal room air to protect the chips from dust particles that could destroy them. The manufacture of the printed wiring board consumes more energy than the integrated circuit and display manufacturing combined. All of these are dwarfed, however, by the energy consumed by electronics products during use. It is estimated that about 80 percent of the lifetime energy consumption of a computer is expended during use; only 2.5 percent is used for manufacturing the integrated circuits. Because they are so numerous and are in service for extended periods, an estimated 5 percent of all generated energy in the more developed countries goes to power electronic devices (some 500 PJ for the world's 140 million PCs in 1993).

19.3.2 Materials

Although the absolute magnitudes of materials use by the electronics industry are not particularly large relative to other industrial sectors, the electronics industry makes use of a large fraction of the periodic table (see Figure 19.5), since microcircuit

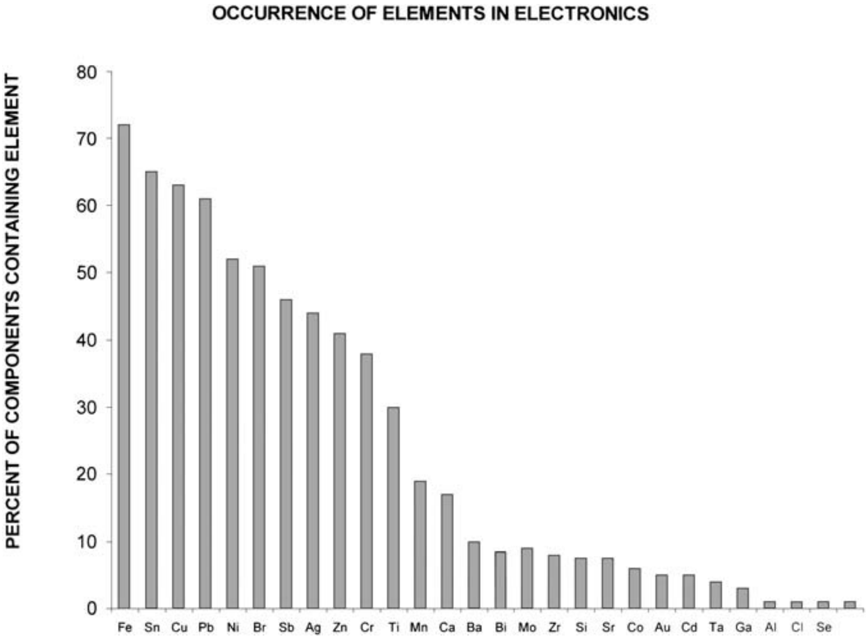


Figure 19.5. Elements used in modern electronics, expressed as the percent of electronic components containing a particular element.

operations are so sensitive to the physical properties of its materials. As a result, the industry is linked indirectly to virtually every subsector of the extractive and refining industries. Among the materials used are 350 Gg of PC-board material and 10 Gg of molding compounds.

19.3.3 Process Chemicals

Many steps in the manufacturing processes of the electronics industry involve the use of etchants and other aggressive chemicals. We have mentioned above the use of strong oxide and reactive gases in the creation of integrated circuits, of copper plating solutions in printed wiring board manufacture, and of tin-lead solder in electronic circuit board assembly. All of these processes have numerous cleaning steps involving aqueous and nonaqueous detergents.

If the manufacture of components produced by suppliers is considered, the list of problematic chemicals expands significantly, as indicated in Figure 19.6. Overall, the electronics sector employs many potentially hazardous chemicals in accomplishing its manufacturing goals. The quantities of materials are relatively small

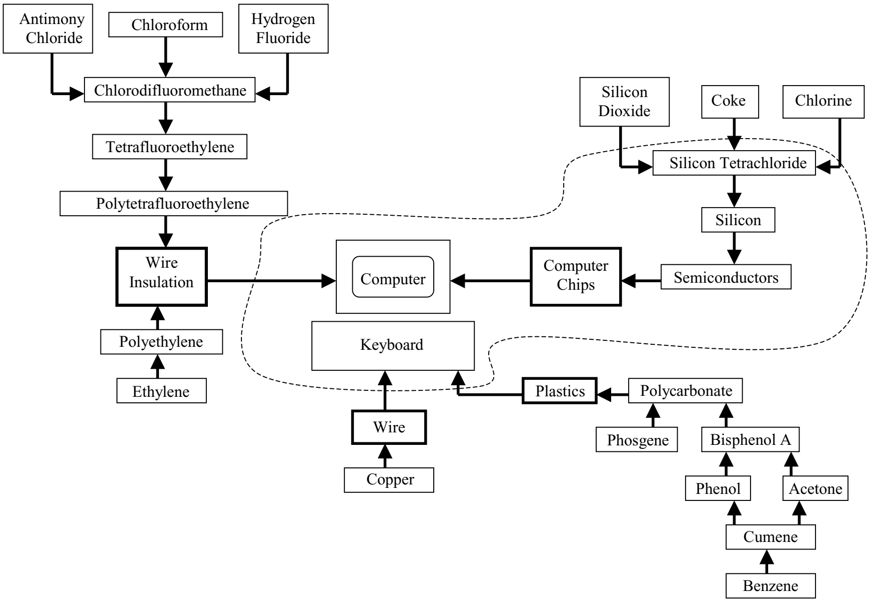


Figure 19.6. Chemical use mapping for the manufacture of a modern computer. The portion of the diagram normally attributed to the electronics sector is indicated by the dashed line. (Adapted from Microelectronics and Computer Technology Corporation, *Electronics Industry Environmental Roadmap*, Austin, TX, 1994.)

and the degree of control extensive, but the very diversity and toxicity of the materials remains a constant challenge. In the manufacture of integrated circuits in particular, the quantity of process material used far exceeds the quantity of material incorporated into the final product. The weight of waste process materials can exceed the weight of the chip itself by a factor of several thousand; the weight of hazardous chemical waste generated can exceed the weight of a chip by a factor of several hundred. Because its manufacturing processes are constantly evolving, new process chemicals with little available environmental hazard data may be used by this sector.

19.3.4 Water

Overall, the electronics sector is not a major water user relative to other sectors. Nonetheless, the frequent washings required in the manufacture of integrated circuits and printed wiring boards result in large water usage relative to the amount of product generated. Depending on the exact manufacturing sequence involved, the electronics sector may typically use around 1000 g of water for every gram of final product. In the manufacture of a typical workstation computer, the packaging of integrated circuits within plastic shells and the manufacture of cathode-ray tube displays requires extremely small amounts of water in comparison to integrated circuit and printed wiring board manufacture.

19.4 POTENTIAL ENVIRONMENTAL CONCERNS

19.4.1 Solids

Solid residues from the electronics sector do not have high hazard potential. However, since many electronic products have high obsolescence rates, the solid waste generated at the end of life is of concern. The lifetimes of personal computers is shrinking and it is predicted that about 65 million will become obsolete each year. When disposed of in landfill, the lead from solder on printed wiring boards and contained in cathode ray tubes (for computer displays) is hazardous.

19.4.2 Liquids

The liquid emission of most concern from the electronics industry has historically been from copper plating and solder plating operations. In recent years, these have been aggressively controlled. Organic residues of various types from integrated circuit manufacture are also potential hazards and their emission must be tightly controlled.

19.4.3 Gases

The gas emissions of most concern from integrated circuit manufacture are perfluorocarbons (PFCs) which are used to etch silicon wafers and clean process equipment. PFCs, including C_2F_6, C_3F_8, and CF_4 are greenhouse gases with very high global warming potentials. The electronics industry is attempting to develop alternatives to the use of PFCs and to curb PFC emissions. Several other gases used in the industry—arsine (AsH_3), phosphine (PH_3), hydrogen fluoride (HF), and hydrogen chloride (HCl)—are highly hazardous to living organisms, but their use has traditionally been controlled very carefully for this reason.

19.4.4 Sustainability Assessment

The processes, activities, and potential emittants for the electronics sector are given in Table 19.1. The materials are binned for throughput, potential hazard, and potential scarcity in Table 19.2. The TPH matrix appears in Figure 19.7. It indicates no items of more than moderate concern except for the lead in solder. The TPS matrix is also given in Figure 19.7; it shows that significant scarcity concerns apply for copper and solder (where the last reflects gradually dwindling amounts of both tin and lead), as well as for the circuit board composite materials that are derived from petrochemicals. A major environmental focus for the sector should therefore be reduction in the rates of use (and especially the rates of discard) of Cu, Pb, and Sn.

Not appearing as a consequence of the matrix analyses, but nevertheless important, are efforts to reduce the generation of solid waste per unit of product. This ratio is typically in the range 100–1000/1, and deserves extensive and continuing reduction efforts.

As indicated earlier, the typical water and energy use for the electronics sector is rather low in comparison with other industrial sectors and is shown as low concern in Figure 19.8. The water and energy use per unit of product is high, however, and is a focus of industry efforts.

Table 19.1. Processes, Activities, and Potential Emittants for the Electronics Sector

Process Type	Sector Activities	Potential Emittants
Forming bonds	Copper plating	Copper ions
	Solder plating	Lead ions
	Soldering	Solder residues
Shaping	Etching	CF_4, AsH_3, PH_3
	Stripping	HF, HCl
Cleaning	IC washing	Organic residues

Table 19.2. Throughput-Hazard-Scarcity Binning of Materials in the Electronics Sector

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
Silicon	M	–	L	L
Copper	M	Human	M	H
Solder	M	Human	H	H
Composites	H	–	L	M
Plastic package	L	–	L	M
Organics	L	Human	H	M
Copper residues	M	Human	M	–
Lead residues	M	Human	M	–
HF	L	Human	H	–
HCl	L	Human	M	–
CF_4	L	Human	H	–
AsH_3	L	Human	H	–
PH_3	L	Human	H	–
Organic residues	M	Human	M	–

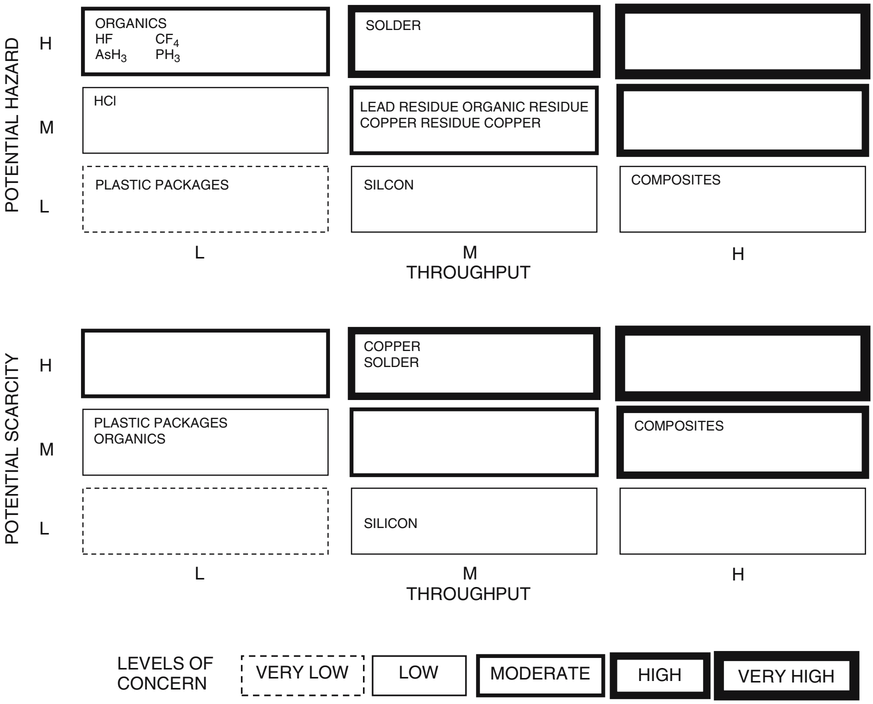


Figure 19.7. The throughput-potential hazard matrix (top panel) and throughput-potential scarcity matrix (bottom panel) for the electronics sector.

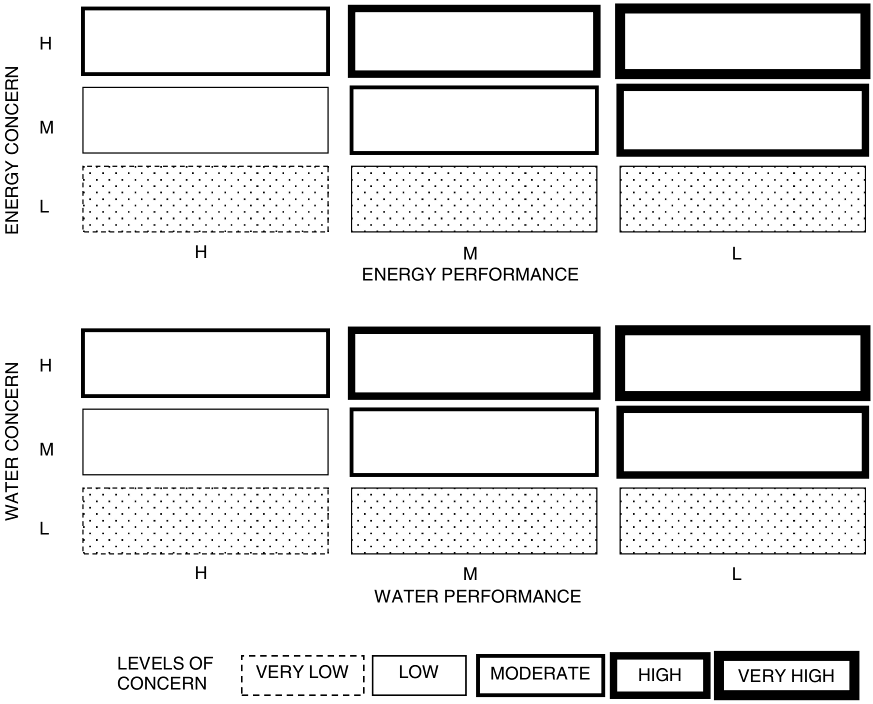


Figure 19.8. The energy concern matrix (top panel) and the water concern matrix (bottom panel) for the electronics sector.

The sector ΣWESH plot is given in Figure 19.9. With the exception of scarcity concerns related to copper and solder, little is called out as highly important from both a throughput and impact standpoint.

19.5 SECTOR PROSPECTS

19.5.1 Trends

19.5.1.1 Process Trends

Process changes that will improve the environmental performance of each aspect of electronics manufacturing are currently underway or on the horizon.

Integrated circuit manufacturers are continuing to reduce water consumption by optimizing wafer rinsing techniques and recycling process water. The ultra-pure water used in the manufacturing process must be very carefully purified for reuse in rinsing or process applications, but it can readily be reused in cooling towers or for irrigation.

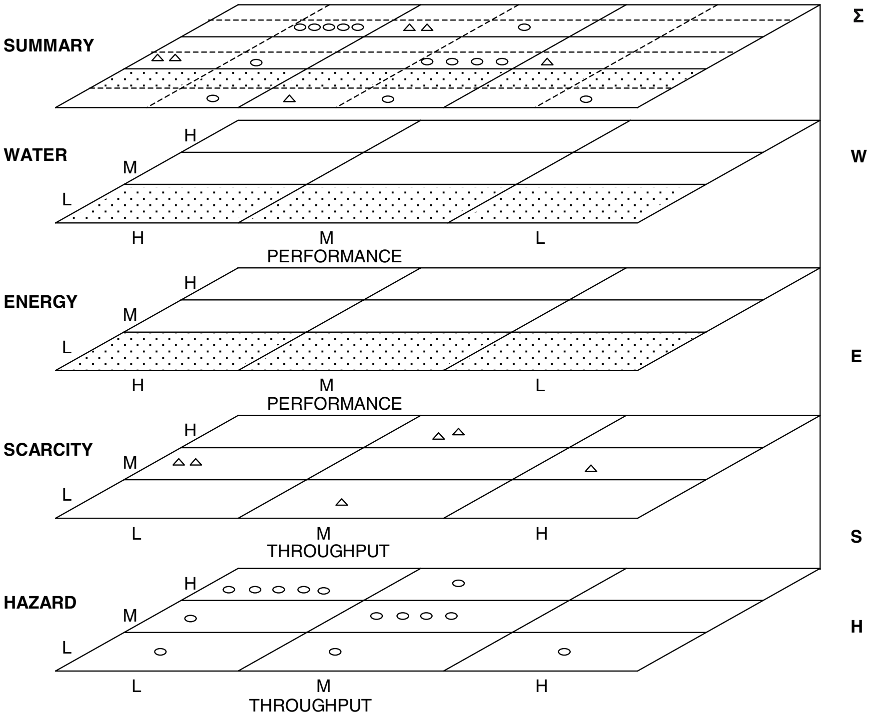


Figure 19.9. The ΣWESH plot for the electronics sector. The squares and circles are related to the materials in Figure 19.7.

Integrated circuit manufacturers are now starting to pay increased attention to energy efficiency as the clean room air filters and process equipment are major consumers of energy.

The materials and processes used to fabricate integrated circuits will continue to change as the conductor linewidth (the smallest integrated circuit dimension) shrinks further. Copper has replaced aluminum as the interconnect material because it is a better conductor and enables faster propagation of signals within the chip. Manufacturers have installed systems to recover copper from wastewater as very low levels of copper can be harmful to aquatic ecosystems. Other new materials, like new insulators, will be needed as circuit structures become ever smaller. The use and disposal of these new materials will need to be carefully monitored to ensure they do not pose environmental hazard.

The major thrust in the manufacture of printed wiring boards is the elimination of lead-containing solder. This is driven partly by the European Union's directive on electronics waste (WEEE) that bans the use of lead in electronic equipment after 2008. The tin-lead solder currently used has attractive thermal properties and is highly reliable, but concern over possible contamination of groundwater from improperly disposed products has resulted in a search for lead-free alternatives. One material recommended by the National Electronics Manufacturing Initiative (NEMI) is a tin/silver/copper alloy to be used in reflow applications.

New techniques may be adopted for the manufacture of PWBs that would enable the size of the boards to be shrunk, an essential goal if cell phones and handheld devices are to be made considerably more powerful. One technology uses microvias, solid conducting channels, instead of plated copper holes, to conduct electricity across the board. Microvia technology would produce less waste and use less water because the drilling operation is eliminated. Components that have typically taken up valuable space on boards, like capacitors, resistors and inductors, are now being shrunk and integrated into boards, reducing the size and weight of boards and the number of soldered components.

Assembly of electronic products will increasingly be done with end-of-life fate in mind. Both the European Union and Japan have developed or are developing regulations that govern the recycling of electronic products. Historically, chips and boards contained enough precious and base metal (e.g., gold, palladium, copper, and lead) to make recycling economically attractive. Housings made of steel were also economical to recycle. As the volume of precious metals used in components has decreased (e.g., chips are no longer gold-backed) and engineering thermoplastics have become the predominant material used in housings, the recycling of electronic products has become less economically viable. With new regulations in force, manufacturers are starting to design products that can be effectively recycled. This involves changes like eliminating the use of brominated flame retardants (which can form dioxins and furans when incinerated) in plastics used in housings, reducing the variety of plastic used in a single product, developing recycling technologies for the glass used in displays, and eliminating the use of lead solder.

While for over three decades the techniques used to fabricate integrated circuits have been consistently improved, resulting in smaller and more powerful chips, physical limits are being approached. At some point fundamentally new technologies may be adopted to build chips capable of more complex computing. As transistors become smaller and more densely packed, quantum effects become significant. Quantum computing aims to harness these phenomena to produce devices capable of making highly complex calculations using minimal energy, and to perform tasks that would be impossible with conventional computers. Quantum computing devices have been demonstrated on the laboratory scale, and are far from a reality, but other methods are being explored to manufacture logic circuits where components are molecular-size. One possibility involves using organic molecules to build transistors, wires and other components. A research group at the University of Texas at Austin has isolated proteins that recognize and bind with silicon, gallium arsenide, indium phosphide, and zinc selenide. When the proteins bind with the inorganic materials they assemble into previously selected patterns. Because these techniques are experimental, it is impossible to predict the environmental consequences of their large-scale adoption for electronics manufacturing.

Far more likely in the near future is the continued extension of conventional integrated circuit manufacturing techniques, along with an emphasis on fitting more functionality, not just more transistors on a single chip. Instead of individually optimizing chip design and board design, manufacturers may start to design systems-on-a-chip which incorporate many of the components typically mounted on a board. The ability to embed optical switches and other optical devices in integrated circuits would also vastly improve the speed and capabilities of chips, while taking advantage of familiar manufacturing techniques.

19.5.1.2 Product Trends

Electronics products will continue to shrink in size and weight as consumers demand greater portability and manufacturers are able to reduce the size of chips and boards. Lower power devices will also be developed to increase the amount of a time a portable computer, cell phone, or hand-held device can be operated without recharging. Shortly, a single electronic "gadget" will perform the functions—for example, voice and data communication, personal organizing, and remote web access—of multiple products today. These developments may reduce environmental impact by reducing the material, and possibly the energy, devoted to providing these functions. On the other hand, the market for personal electronic devices will continue to grow and their obsolescence rate will likely increase rather than decrease, possibly resulting in greater material and energy use.

19.5.1.3 Social and Regulatory Trends

The electronics take-back and recycling regulation developed by the European Union has already had a significant impact on the manufacture of electronic products and will continue to do so. As a result of this directive, manufacturers worldwide are looking for alternatives to tin-lead solder. New economic methods for recycling plastics used in computer housings and cathode ray tubes (CRTs) used for displays are being implemented. CRT glass contains lead, so the recycled glass can be used only in certain applications or sold back to major CRT manufacturers. The EU directive has also encouraged electronic industry manufacturers to focus on design for disassembly and the environmental aspects of supply chain management. Although it only directly governs products sold in the EU, the directive has influenced the behavior of manufacturers worldwide in this global industry.

Text Box 19.1

Coping with Electronics Waste: The Question of Brominated Flame Retardants (BFRs)

One of the more complex and controversial elements of the European Union's directive on electronics waste (WEEE) is a ban on the use of brominated flame retardants (BFRs) in plastics used for computer housings. The ban is based on evidence that certain types of BFRs release highly toxic dioxins and furans when incinerated. When copper is present (from boards or chips), it acts as a catalyst and increases the risk of forming dioxins. Incineration is widely used in both Europe and Japan as a way of dealing with solid waste, but is less common in the U.S., where solid waste is typically landfilled. Within the electronics industry, a number of different BFRs are used and there is controversy over whether all or only a few of them are harmful when incinerated. Furthermore, there is debate over how widely the most harmful BFRs are or have been used. Despite this uncertainty, manufacturers are actively looking for substitutes, especially for use in the European and Japanese markets. Flame retardants are considered an essential additive for the plastics used in electronic components because plastics are highly flammable and electronic components generate heat. In the U.S., the continued inclusion of BFRs in electronics products seems to pose no environmental problem. However, plastic recycled from these products cannot be sold for use in Europe because it is very difficult to economically detect BFRs in the recycling process.

19.5.2 Scenarios

These scenarios are all based on an extension of today's processes for manufacturing integrated circuits. As discussed in the section on process trends, fundamentally new technologies may be used to manufacture chips when physical limits to current manufacturing techniques are reached. Because it is impossible to predict what will replace today's silicon-based integrated circuit technology (and when it will be replaced), these scenarios discuss options associated with the continuing evolution of such technology.

Trend World

In this scenario, the electronics sector will continue to address the specific environmental issues that are of concern today, against a background of increasing demand for higher-performance products. Manufacturers of integrated circuits will reduce their consumption of water and energy, while also working to control the release of hazardous process chemicals. Printed wiring board manufacturers will use lead-free

Text Box 19.2

Miniaturization and Dematerialization: Are Electronics Inherently Environmentally Friendly?

One of the goals of electronics is to design and manufacture products that are as small as possible. Tiny integrated circuits and related components permit higher data processing speeds, and allow much wider uses of computers in commercial and consumer products. As size decreases, so does the energy needed to store the same amount of information. For example, the current data storage products of IBM Corporation require less than 1 percent of the energy needed two decades ago to store 1 MB of data. Other corporations have performed similarly.

A major side benefit of this evolution to smaller sizes is that the consequences of energy use on the environment (climate change, acid rain, etc.) are sharply reduced. Another is that the energy, water, and chemical requirements of manufacturing are sharply reduced. However, the ease of data storage may mean that much more of it is now stored, cutting into these alleged benefits. When achieved, "dematerialization" can have both technological and environmental rewards.

Source: Designing with a Green Pen: RAMAC Array Family, IBM Storage Systems Division, San Jose, CA, 1995.

solder in new assemblies. However, the primary driver of innovation in both areas will be product performance, not environmental performance. As long as Moore's Law continues to hold, it will be economically attractive to force recent products into obsolescence by introducing even more powerful offerings. This forced obsolescence makes the manufacture of electronics products inherently inefficient from a materials and energy standpoint, unless design-for-disassembly or design-for-remanufacture approaches are aggressively pursued. On the other hand, electronic controls and products have enabled improved efficiency in the use of other systems, including industrial process control and building heating and cooling.

Green World

In a green world scenario, every part of the electronics manufacturing chain would minimize environmental impacts. Integrated circuit manufacturing facilities would have almost zero emissions, use closed-loop water recycling, and be considerably more energy efficient than today's facilities. In areas of the world that have high energy prices, manufacturers are already operating much more energy efficient facilities, and in areas where water is scarce some facilities have been designed to consume much less water. Printed wiring board manufacturers would minimize copper plating waste, possibly by adopting new approaches, like microvias, to replace plated through-holes. Lead would be eliminated in the manufacture of PWBs. Components now produced separately and attached to PWBs would be fabricated using integrated circuit technology, making the chips and board a more coherent system and eliminating material use and waste as the system is shrunk.

Electronic products would be assembled with ease of reuse and remanufacture in mind. For example, a computer may be upgradeable by replacing a chip and board rather than replacing the entire unit including the housing, display, keyboard, etc. Plastics and other materials used in electronic products would minimize use of hazardous additives to enable recycling. The marketing of electronics products would emphasize new functionality without having to purchase new gadgets; in this way, rapid obsolescence would not necessarily imply wasteful use of materials and energy. The environmental benefits of electronic controls would be maximized by including or retrofitting them in transportation, heating/cooling, and automation applications where energy consumption and materials use could be reduced.

Brown World

In this scenario, the current initiatives on electronics waste would hold only regional importance and would fail to influence the actions of electronics manufacturers on a broader scale. For example, manufacturers would continue to make products containing lead for sale into the U.S. market and would only adopt the environmentally favorable approaches where they are required by law, as in the European Union. Product performance and cost would be significantly more important that environmental impact and the manufacture of integrated circuits, PWBs and assembled electronic products would reflect this. The high rate of obsolescence of electronic products would not be offset by programs to reduce or recover electronics waste.

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Chapter 20

Synthetic Organic Chemicals

20.1 OVERVIEW

Chemical synthesis is the process of creating a desired substance by means of one or more controlled chemical reactions. The products of the synthetic organic chemicals (SOC) sector represent the penultimate goal of much of the chemical industry—the manufacture of chemicals tailored such that they are directly useful to the final customer (in contrast to the inorganic chemicals and petrochemicals sectors, which mostly produce intermediate materials). The industrial sequence involved is shown in Figure 20.1, and the connections between this sector and those of the inorganic minerals and chemicals sector and the petrochemical sector are obvious.

The diversity of the synthetic organic chemical sector may be appreciated by listing some of its subsectors, though even this list is far from exhaustive:

- Pharmaceuticals
- Flavors and perfumes
- Soaps and detergents
- Biocides (Pesticides, herbicides, fungicides)
- Adhesives
- Dyes
- Paints and coatings
- Biotechnology products

The products of the SOC sector may contain inorganic materials as well as organics; this is especially true for paints, in which inorganic molecules are used as pigments (colorants). Lead, chromium, and other potentially hazardous metals are common pigment constituents, and the paints must therefore be used with discretion.

Most final products contain not a single synthesized chemical, but many. For a typical detergent, for example, the ingredients are listed in Table 20.1. Each ingredient is itself the result of a synthetic chemical process, so that the totality of a single product

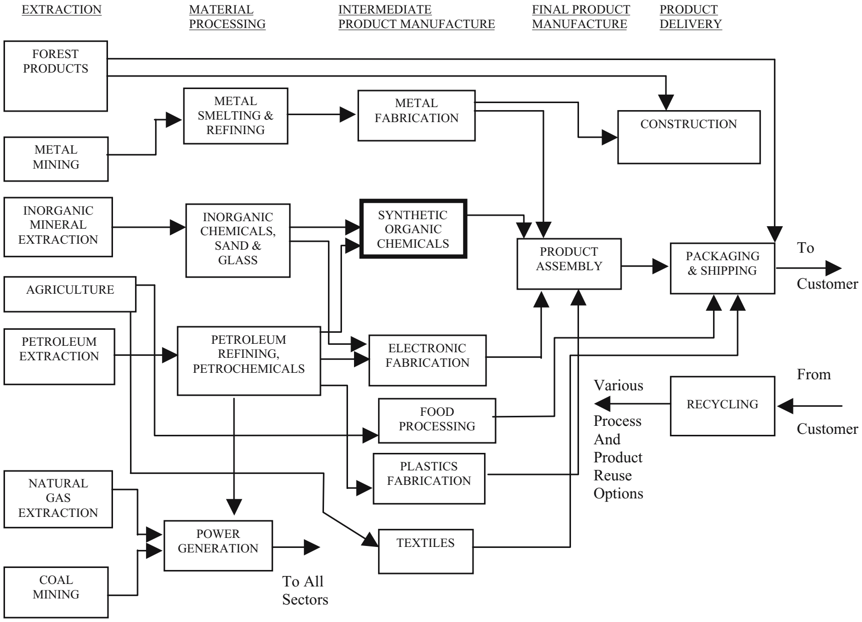

Figure 20.1. The technological sequence diagram for the synthetic organic chemical industries. The industry sector itself is indicated by heavy outlining.

Table 20.1. Ingredients in Detergents and Household Cleaners*

- *Acids and alkalis* (e.g., citric acid)—for the adjustment of pH
- *Antimicrobial agents* (e.g., triclocarban)—to inhibit the growth of odor-causing microorganisms
- *Antiredeposition agents* (e.g., polyethylene glycol)—to prevent soil from resettling on objects being cleaned
- *Bleaches* (e.g., sodium hypochlorite)—to remove stains and soils
- *Builders* (e.g., sodium tripolyphosphate)—for the reduction of water hardness
- *Corrosion inhibitors* (e.g., sodium salicilate)—to protect metal machine parts
- *Enzymes* (e.g., amylase)—to catalyze the destruction of specific types of soils
- *Fragrances* (many variations)—to mask the odors of other ingredients
- *Hydrotropes* (e.g., xylene sulfonates)—to prevent separation of ingredients
- *Preservatives* (e.g., gluteraldehyde)—to inhibit oxidation and other degradation
- *Solvents* (e.g., isopropyl alcohol)—to dissolve organic soils
- *Softening agents* (e.g., quaternary ammonium compounds)—to control static electricity
- *Suds control agents* (e.g., alkanolimides)—to stabilize sudsing
- *Surfactants* (e.g., alcohol ethoxylates)—to improve the efficiency of contact between water and the surface to be cleaned

*Adapted from E. M. Kirschner, Soaps and detergents, *Chemical and Engineering News*, Jan. 26, 1998, pp. 39–54.

encompasses an extremely extensive sequence of chemical processes, each of which involves the use of energy and materials and the production of various residues in addition to the generation of the target compound.

20.2 PHYSICAL AND CHEMICAL OPERATIONS

The physical and chemical operations that take place in the SOC sector can be appreciated by examining a few of the pathways for synthesis. All relate in some way to the classical chemical reaction

$$A + B \leftrightarrow C + D$$

where A may be considered the starting material (sometimes called the feedstock), B the reactant, C the desired product, and D the byproduct.

No chemical reaction proceeds completely from reactants to products. Rather, there is an equilibrium set up between the reaction in the forward direction and the reaction in the reverse direction. The rates of those reactions are the products of the concentrations of the reactants and a rate constant that applies to the specific reaction:

$$R_f = k_f[A][B]$$

$$R_r = k_r[C][D]$$

Since at equilibrium the forward and reverse rates are equal, dividing the forward rate by the reverse rate enables us to define an equilibrium constant K_{eq} for the reaction:

$$K_{eq} = k_f/k_r = ([C][D])/([A][B])$$

It is common practice in chemical manufacturing to shift the equilibria in process reactions so as to enhance the forward reaction rate. This is done by any of the following:

- Adding a catalyst
- For exothermic reactions (those that give off heat), cooling the reactor
- For endothermic reactions (those that require heat to react), heating the reactor
- For gaseous reactions, increasing the pressure
- Removing the products as they are formed

Three synthesis reactions will provide some perspective on the operations of this sector. The first, shown in Figure 20.2a, is the synthesis of adipic acid (an adhesive, a chemical intermediate in the production of nylon, and a food additive) starting with benzene. This is a relatively simple three-step process involving hydrogenation, oxidation, and ring opening. A substantially more complex synthesis pathway is that to the artificial sweetener saccharin (shown in Figure 20.2b). This is a five-step process that utilizes two of the major inorganic chemicals discussed in Chapter 11 (ammonia and

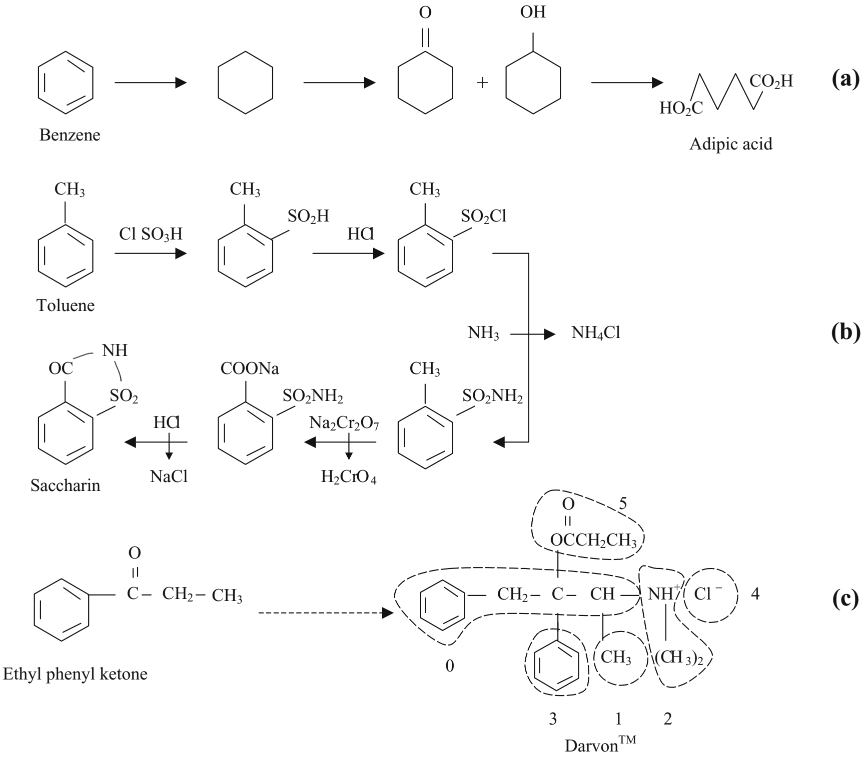

Figure 20.2. Synthetic routes or schematic diagrams for three target molecules. (a) adipic acid, (b) saccharin, (c) Darvon.

hydrochloric acid) and two derivatives of the inorganic chemicals sector (chlorosulfonic acid and sodium dichromate). Byproducts include ammonium chloride, chromic acid, and sodium chloride, and sodium hydroxide is used as a solvent in one of the steps.

The complexity of some of the synthesized products, especially in the pharmaceutical subsector, is indicated by Darvon™ in Figure 20.2c. Starting with ethyl phenyl ketone (the molecule at the left), the target molecule is built up in five steps, some of them employing quite complex reactant molecules. Without presenting the detailed reactions involved, one can nevertheless appreciate the chemical artistry that must be employed to reliably generate such complicated products, and the likelihood that aggressive reactants, substantial amounts of energy, and the generation of potentially hazardous byproducts are all part of the considerations involved.

A deeper level of molecular synthesis is provided by biotechnology, in which human intervention in the natural processes of living things (cells, bacteria, plants, animals) enhances certain biological characteristics over others. The flows of resources through industrial biotechnological processes are not large, nor are the associated residues, but this subsector is rapidly evolving and is likely to become increasingly important with time.

An alternative route to synthetic chemicals is provided through fermentation, in which chemical changes are induced by a living organism or enzyme. While fermentation processes have been known and used for millennia to make beer and wine from fruits and grains, the technique is now used widely in industry for a variety of purposes. The basic requirement of a successful industrial fermentation process is, of course, the identification of a microorganism that forms a desirable end product from a convenient raw material. The classic reaction is the formation of alcohols from sugars, with yeast as the active agent (see Figure 20.3a). Industrially, fermentation is used to form a variety of organic acids and alcohols, including citric acid, as shown in Figure 20.3b. Fermentation is especially common in the pharmaceutical industry, where a wide range of antibiotics including penicillin (Figure 20.3c) are produced by fermentation processes.

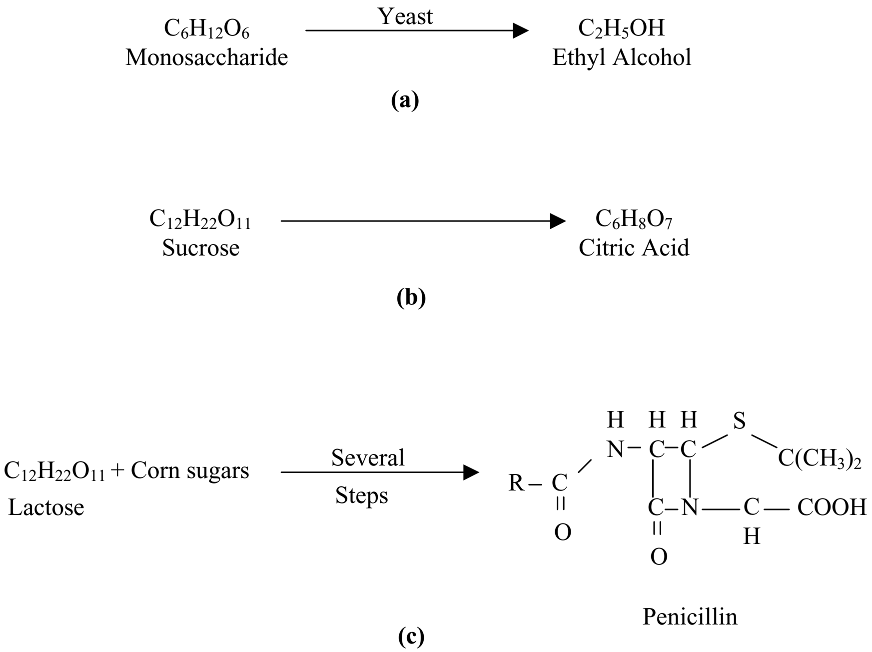

Figure 20.3. Fermentation approaches to the production of (a) ethyl alcohol, (b) citric acid, (c) penicillin.

20.3 THE SECTOR'S USE OF RESOURCES

The SOC sector deals in specialty products, not bulk products. As a consequence, it consumes less energy and material resources than is the case with either the inorganic minerals and chemicals sector or the petrochemical sector, but still a very substantial amount. On a per molecule basis, consumption of energy and materials is very high, and substantial opportunities generally exist for minimization of resource use. Water consumption is high, as many purification steps are typically involved.

20.4 POTENTIAL ENVIRONMENTAL CONCERNS

As noted above, the product tonnage of the SOC sector is much smaller than its associated sectors that involve basic extraction activity. Whereas oil refining deals with some 10 Tg of material annually, the bulk petrochemical industry handles only about one percent of this amount of material, as shown in Table 20.2. The SOC sector uses only about one percent of that latter amount, and the pharmaceutical subsector uses only ten percent of the material used by the SOC sector. On a product weight basis, the waste generation is exactly the inverse, a testimony to the numerous reaction steps and byproducts involved in specialty chemical manufacture.

20.4.1 Solids

Most of the SOC byproducts are disposed of as solid sludges.

20.4.2 Liquids

Specialty organic chemicals manufacture generates very large quantities of liquid waste—typically 100 kg of waste for every 1 kg of product. The principal reasons are:

Table 20.2. Throughput and Byproduct Generation in Different Sectors of the Chemical Industry*

Sector	Product Weight	Byproduct Generation#
Petroleum refining	$10^6 - 10^8$	0.1
Bulk petrochemicals	$10^4 - 10^6$	<1 – 5
Specialty chemicals	$10^2 - 10^4$	5 – 50
Pharmaceuticals	$10^1 - 10^3$	25 – 100+

*Adapted from J. A. Cano-Ruiz and G. J. McRae, Environmentally conscious chemical process design, *Annual Review of Energy and the Environment*, 23, 499–536, 1998.
#Ratio of the mass of byproducts to the mass of products

- A process sequence may use as many as ten different solvents. All become contaminated, and must be either regenerated by chemically-complex and energy-intensive processes, or discarded.
- Washing steps for the purification of intermediate products are frequent. As with used solvents, used washing solutions must be regenerated or discarded.
- Because many SOCs are used in pharmaceutical or other sensitive applications, purity is often a very high priority.
- Most SOC processes, including virtually all pharmaceutical processes, are batch processes, which have higher inherent residues per unit of product than do the continuous processes more common to the inorganic chemical and petrochemical sectors.

20.4.3 Gases

Volatile organic compounds of various types are potential emittants from the SOC sector.

20.4.4 Sustainability Evaluation

The processes, activities, and potential emittants for the synthetic organic chemicals sector are given in Table 20.3. The magnitude of generation of the potential emittants and their hazard potential are collected in Table 20.4 and plotted in the throughput-potential-hazard matrix in Figure 20.4. A number of the organic feedstocks (e.g., toluene) are quite toxic and thus require continual attention. Potential emissions from the biocide and pharmaceutical industries may be of high concern, though these subsectors customarily monitor their processes with great care.

The scarcity of input materials in the synthetic organic chemicals sector is given in Table 20.4 and plotted in the throughput-potential scarcity matrix in Figure 20.4. There are no dominant scarcity problems. The moderate scarcity potential materials are those which are derived in whole or part from petrochemicals, since oil is in the moderate scarcity category.

The PEC and PWC matrices are shown in Figure 20.5. As a heavy user of both energy and water, the high potential concern level is indicated for each.

Table 20.3. Processes, Activities, and Potential Emittants for the Synthetic Organic Chemicals Sector

Process Type	Sector Activities	Potential Emittants
Forming bonds	Chemical synthesis Biochemical synthesis	Byproducts, depleted catalysts Biowaste
Purifications	Product washing	Contaminated solvents

Table 20.4. Throughput-Hazard-Scarcity Binning of Materials in the Synthetic Organic Chemicals Sector

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
Organic feedstocks	H	Human	H	M
Inorganic constituents	M	Human	M	M
Pharmaceutical residues	M	Human	H	–
Flavor and perfume residues	L	–	L	–
Soap and detergent residues	H	–	L	–
Biocide residues	M	Ecosystem	H	–
Adhesive residues	L	Human	M	–
Dye residues	M	Ecosystem	M	–
Paint and coating residues	H	–	L	–
Biotechnology product residues	L	Human	H	–

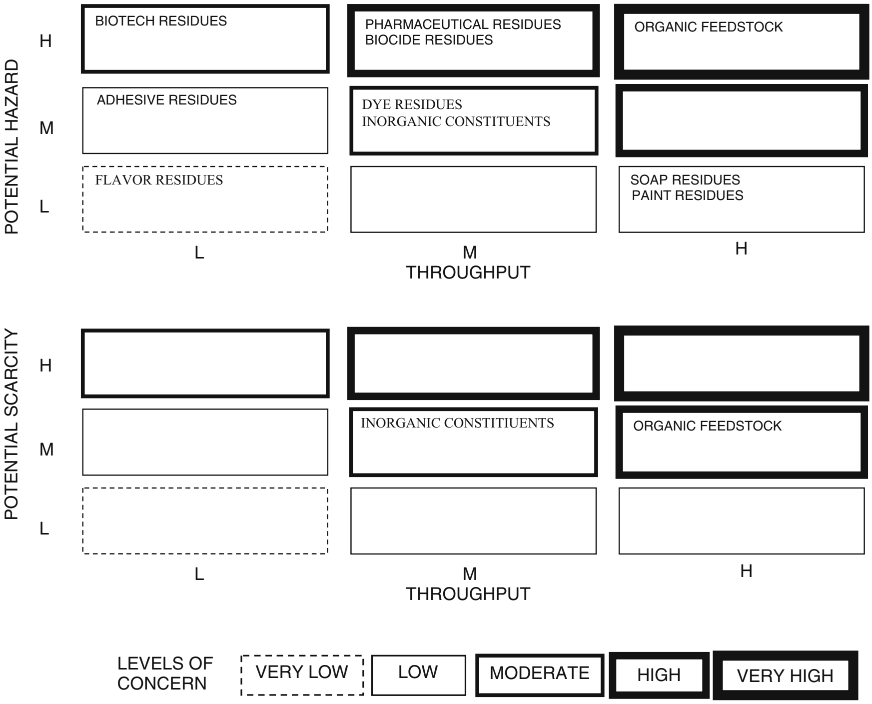

Figure 20.4. The throughput-potential hazard matrix (top panel) and throughput-potential scarcity matrix (bottom panel) for the synthetic organic chemicals sector.

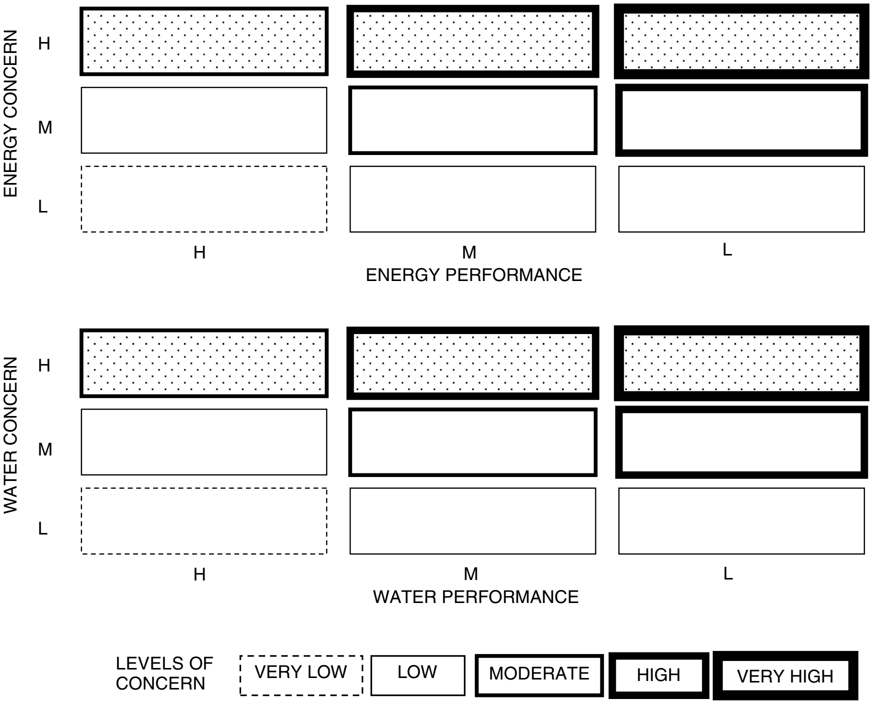

Figure 20.5. The performance-energy concern matrix (top panel) and performance-water concern matrix (bottom panel) for the synthetic organic chemicals sector.

The ΣWESH plot for the synthetic organic chemicals sector is given in Figure 20.6. The issues of highest concern are the potential hazard to organisms of organic feedstocks, and the high use levels of water and energy.

20.5 SECTOR PROSPECTS

20.5.1 Process Trends

In the mid-1990s, the chemical industry in general and the synthetic organic chemicals sector in particular began to research and adopt *green chemistry*—the use of chemical techniques and methodologies that reduce or eliminate the use or generation of feedstocks, products, byproducts, solvents, and reagents that are hazardous to the environment (defined broadly to include human health, biodiversity, and other potential environmental impacts). A key concept in green chemistry is that of "atom economy," conceived by Barry Trost of Stanford University. The goal of atom economy

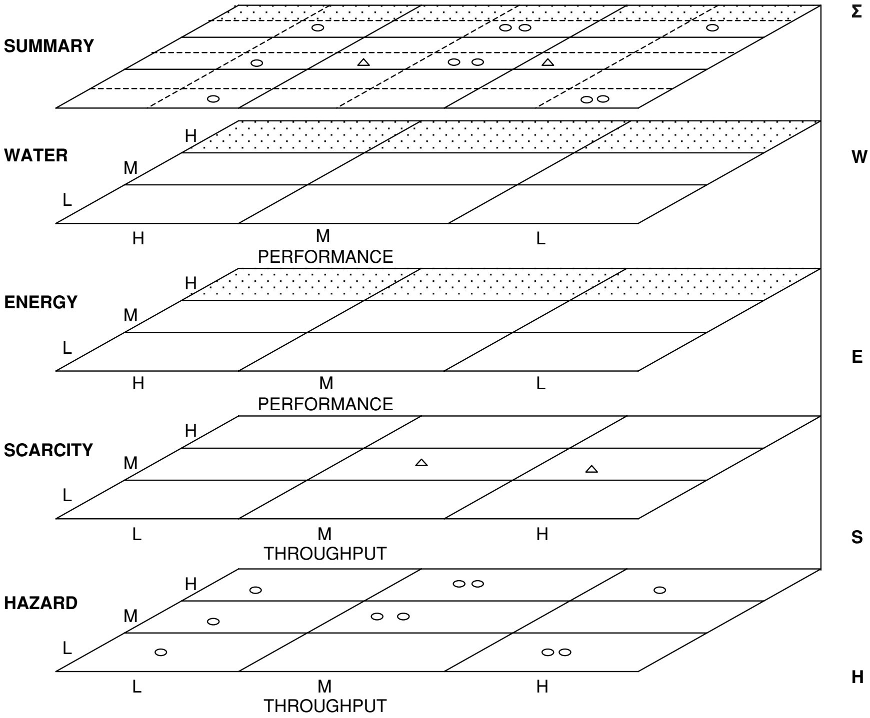

Figure 20.6. The ΣWESH plot for the synthetic organic chemicals sector. The squares and circles refer to the materials of Figure 20.4.

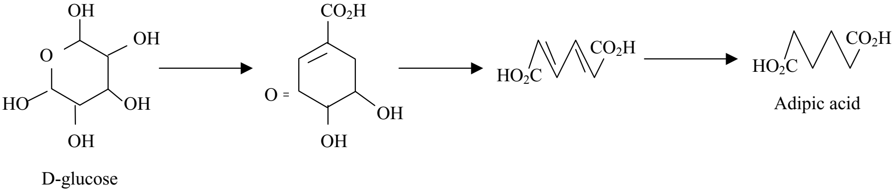

Figure 20.7. The alternative synthesis route through glucose for adipic acid.

is that the greatest possible percentage of atoms in the reagents end up in desired products, not in waste.

Using the atom economy concept as a guide, manufacturing processes will increasingly be developed that:

- Use addition reactions instead of displacement or elimination reactions, since the latter automatically generate byproducts.

- Use more benign feedstocks. An example, shown in Figure 20.7, is a synthesis of adipic acid from glucose (a common sugar) rather than from benzene, the carcinogenic traditional starting material (see Figure 20.2a). Feedstocks derived from renewable materials are preferable to those derived from nonrenewables.
- Reduce the use of reagents by employing selective catalysts, possibly mimicking those used by biological organisms.
- Reduce the use of harmful solvents, especially organics, by switching to alternatives like water or carbon dioxide, or eliminating the solvent altogether.
- Tailor the product molecule to its function and avoid unintended environmental or human health impacts.

An example of the application of green chemistry is provided by the ibuprofen synthesis approach of BHC Corporation of Dallas, Texas. The traditional approach involved six steps and achieved about 40% atom utilization. The new process involves only three steps and achieves 80% atom utilization. All three steps are catalytic, thus quite efficient, and two are solventless.

As green chemistry becomes more and more a part of the thinking of chemical process designers, there is every prospect that the very high rate of generation of SOC residues, especially solvents, will markedly decrease over the next few decades.

A concept related to green chemistry, that of "zero emissions," is also becoming more prominent among leading chemical manufacturers. While achieving absolute

Text Box 20.1

Green Chemistry Cleans up Water Treatment Process

High molecular weight polymers are customarily used to remove suspended solids and contaminants during water treatment. The traditional preparation technique for these polymers combines the monomer, water, and a hydrocarbon oil in about equal proportions. The oil is part of the process that converts the monomer into the appropriate polymer. The oil residues are not needed for the eventual water treatment use, but remain in the product mixture and are eventually released to the environment.

Nalco Chemical Company has now developed a process that dissolves the monomer in a solution of innocuous ammonium sulfate and then polymerizes it with a small amount of a reactive polymerization initiator. The process completely eliminates the need for, and discharge of, the hydrocarbon oil previously employed. In addition, the ammonium sulfate is acquired as the byproduct of another industrial process. Were it not used in this way, that ammonium sulfate would be discarded.

Source: P. Anastas, M. Kirchchoff, and T. Williamson, More 1999 Presidential Green Chemistry Awards, *Green Chemistry, 1*, G124–G125, 1999.

zero emissions is treated as a distant goal, some companies are adopting a "zero emissions mind set" in the design of processes or facilities. For example, Dupont opened a new facility in 1998 that achieves almost no emissions. The facility, which manufactures Terathane, a Lycra® precursor, significantly reduced discharges of salts and BOD (biological oxygen demand) by developing a reusable catalyst to replace a soluble one and developing recoverable organic intermediates that can be sold or recycled outside the plant. Because research, development, and process design time for zero emissions processes are longer than they are for conventional processes, the conversion to zero emissions processes will likely occur only as new facilities or processes are established.

A final process innovation that may become important for the manufacture of small volume, specialized materials is the use of microreactors. These units are just centimeters in size and resemble computer chips because they are fabricated in arrays on silicon wafers. Miniature heat exchangers and chemical separation devices can be fabricated and used to perform reaction steps, or combined to perform entire reactions. One three-layer unit has been fabricated that will manufacture the highly toxic methylisocyanate (MIC). Such devices could be used to manufacture small quantities of chemicals at their point of use, eliminating the need to transport and store toxic material, or allowing for novel delivery techniques. While they clearly will not replace all large-scale reactors, microreactors are likely to find niche applications throughout the synthetic organic chemical industry.

20.5.2 Product Trends

After several decades of focusing on pollution control at the factory site, chemical manufacturers are increasingly paying attention to how their products are used beyond their fence line. Product stewardship refers to the idea that a manufacturer is responsible for the environmental impacts of a material through various stages of its life—distribution, storage, handling, consumption, and final disposal. As a result, chemical manufacturers are auditing distributors to ensure they use safe handling practices, and they are educating customers and consumers about product use. In the future, it is likely that more manufacturers will build plants adjacent to major customers' facilities so that hazardous chemicals can be delivered directly by pipeline rather than transported by road or rail. Chemical manufacturers may begin to offer "total chemical management" where they retain ownership of hazardous chemicals as they are used in a customer's manufacturing process. The chemical manufacturer would then collect and dispose of or recycle by-products or waste. This idea is consistent with the general environmental principle of offering customers a service (the functionality of a chemical in a manufacturing step), rather than a product (the ownership of the chemical and its downstream consequences).

In the pharmaceutical subsector, a number of product changes are on the horizon. These changes include innovations in the design, production and delivery of pharmaceuticals. The design of pharmaceutical products is expected to change radically with the new information being made available about the human genome. Drugs may be tailored to specific genetic types, meaning different products will be used to treat the same disease in different people. With this development will come a further reduction in the volume of any particular drug manufactured, and a likely increase in the complexity of the molecule being manufactured. Already, the environmental impacts of pharmaceutical manufacture are different from those of other synthetic chemical manufacture because batch processes are used to create relatively small volumes of product (and relatively large volumes of waste solvents, reagents, etc.). Also, a pharmaceutical manufacturing process has a relatively short lifetime (because of patent expiration) so the in-process optimization that might occur over years or decades in the manufacture of a standard synthetic chemical does not typically occur. These issues, which point towards the need to consider environmental issues at the design stage of pharmaceutical manufacture, will only become more important as batch sizes decrease and product complexity increases.

20.5.3 Possible Future Scenarios

Trend World

In a trend world, the ideas of atom efficiency will be used to design SOC manufacturing processes that reduce the current very large rate of byproduct generation.

Text Box 20.2

New Methods of Small-Scale Chemical and Pharmaceutical Delivery Using Microchips

Delivery of pharmaceuticals may also be revolutionized by using microchips that dispense solids, gels, or liquid materials on demand. An early realization of this concept is shown in figure 20.8. The chemical is injected into the reservoir and sealed in with adhesive plastic and waterproof epoxy. The other opening of the reservoir is covered with a gold foil. The chip is placed in a weak chloride solution, as might be encountered in the human body, for example. When a small electrical potential is applied, the gold forms gold chloride and dissolves, and the chemical is released from its reservoir into the surrounding system. This delivery method may also be useful for other applications where miniaturization is appropriate, such as analytical chemistry or industrial process monitoring. A variety of new approaches to synthetic chemical dispensing have the potential to result in major decreases in the size and weight of chemical delivery devices as well as the use of smaller amounts of synthetic organic chemicals. It is likely that some of these devices will begin to be commercialized in about a decade.

Source: J. T. Santini, Jr., M. J. Cima, and R. Langer, A controlled-release microchip, *Nature, 397*, 335–338, 1999.

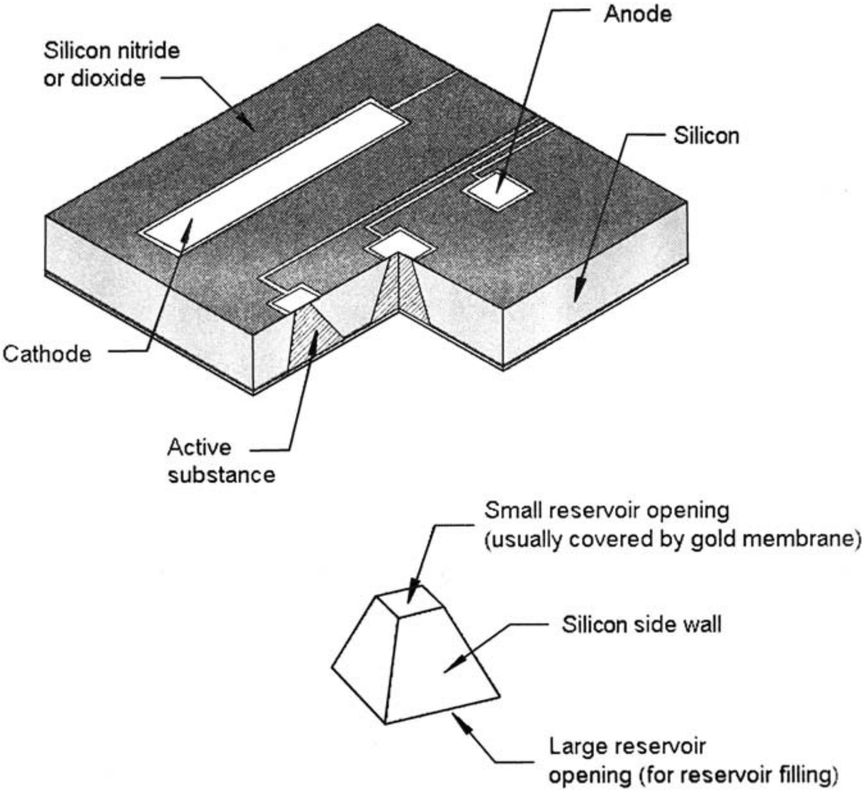

Figure 20.8. A schematic diagram of a prototype microchip for the controlled release of a chemical substance. An expanded sketch of the reservoir containing the liquid chemical is shown at the bottom. (Reprinted with permission from J. T. Santini, Jr., M. J. Cima, and R. Langer, A controlled-release microchip, *Nature, 397*, 335–338, © 1999 by Nature Publishing Group.)

Lessons taken from nature will figure importantly in the redesign of these industrial processes. Biological organisms synthesize a vast array of chemical compounds, but avoid creating harmful by-products and avoid the use of high temperatures and high pressures. The key to this efficiency lies in enzyme catalysis. Manufacturing processes for synthetic chemicals will start to use catalysts more extensively and, as a result, will reduce the use of reagents and the production of large volumes of harmful by-products. In this scenario, industrial processes will mimic biological enzyme reactions, but they will not necessarily be carried out by biological agents. These changes will most likely occur in the manufacture of complex molecules; traditional processes will likely dominate in the commodity or bulk chemicals sector where material conversions are already more efficient. In a trend world the industry will likely continue to rely on feedstock derived from petroleum, although as resource pressure mounts and the cost of petroleum increases, manufacturers will increasingly use starter molecules derived from biological material.

Green World

In a green world, in addition to industrial processes starting to mimic biological ones, biological systems may be employed to actually synthesize industrial chemicals. This approach would be partly driven by a move away from petroleum as the source of starter molecules. While the biological synthesis approach does away with the traditional environmental concerns associated with chemical manufacturing, like the production of large volumes of waste material, it brings up new concerns, like the potential disruption of ecosystems and the propagation of altered monocultures. The development of this scenario depends heavily on the social acceptance of using biological material in this way and in the safeguards put in place to minimize harm to ecosystem and human health.

Brown World

In a brown world, continued use of fossil fuels will force a sharp decline in petroleum reserves and a sharp increase in petroleum prices. As a result, petrochemical manufacture will be no longer economically viable and the SOC sector will be forced to rely on another source for starter molecules. Traditional manufacturing processes will dominate, but feedstock will be derived from biological materials once petroleum becomes too scarce. Opportunities to significantly increase the efficiency of SOC manufacture by reducing or eliminating by-product production will be largely unrealized.

FURTHER READING

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Chapter 21

Assembled Products

21.1 OVERVIEW

The final product development step in most industrial sequences is that of assembly. The task of assembly is not the manufacture of components of a particular type and a particular class of materials, but the combination of such components into a useful product. As Figure 21.1 demonstrates, these components are manufactured in a number of the industrial sectors treated in earlier chapters of this book.

Assembly is the stage where products of the highest integration are manufactured. Examples include portable electronics, home appliances, office machines, and vehicles. Most assembled products draw components from the metal fabrication sector, the plastics fabrication sector, the electronics sector, and sometimes the forest products sector. Cleaning and finishing the assembled products uses products of the synthetic organic chemicals sector. Assembly is the culmination of much other industrial activity.

Product assembly may be a very simple process in which a handful of metal and wood parts are joined together with screws, as in simple furniture. More commonly some preparation of the components and some industrial processes are involved—cleaning, soldering, welding, and the like. Following assembly, the products may receive a surface coating of some type, by painting, polymer dipping, or some other treatment. A list of the common manufacturing processes that may be encountered is given in Table 21.1; the processes are defined in the glossary. Some of these processes have been in existence throughout human history, others represent the state of the art of modern technology.

21.2 PHYSICAL AND CHEMICAL OPERATIONS

The physical and chemical operations that are commonly performed in the assembled products sector can be illustrated by examining a typical product: the generic

Table 21.1. Processes, Activities, and Potential Emittants for the Assembled Products Sector

Process Type	Sector Activities	Potential Emittants
Cleaning	Metal degreasing	Degraded detergents
Joining	Welding, brazing	Metal fumes
Surface treatment	Painting, coating	VOCs
Packaging and transportation	Component delivery	CO_2, CO, NOx, VOC

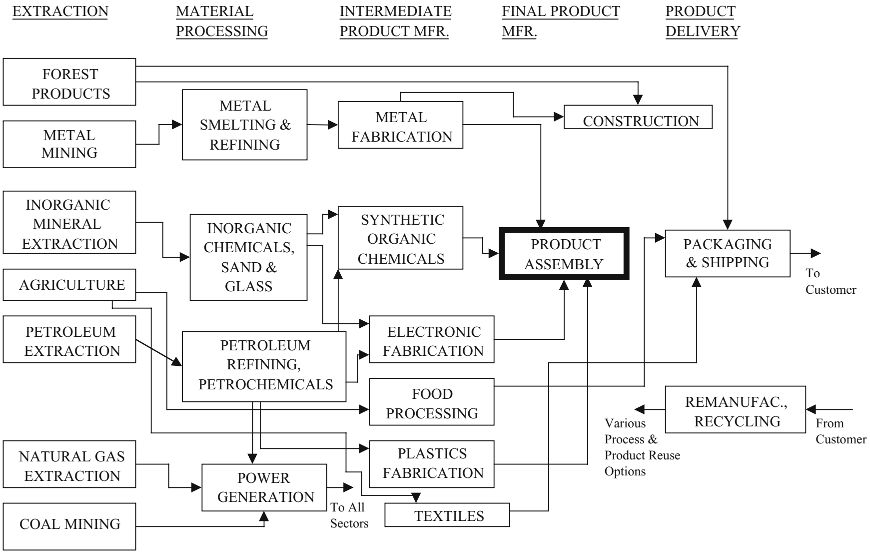

Figure 21.1. The technological sequence diagram for the assembled products industries. The industry sector itself is indicated by heavy outlining.

washing machine, shown schematically in Figure 21.2. This product performs 350–400 washes per year, on average, and has a life of 10–14 years.

It is useful to begin by reviewing the life cycle of the generic washing machine and the constituent parts and subassemblies from which it is made. The life cycle can be summarized in the following stages:

a) Fabrication of individual parts and materials, including the frame, the mechanical components, the electrical and electronic components, and the housing. Much of this fabrication is done by suppliers.

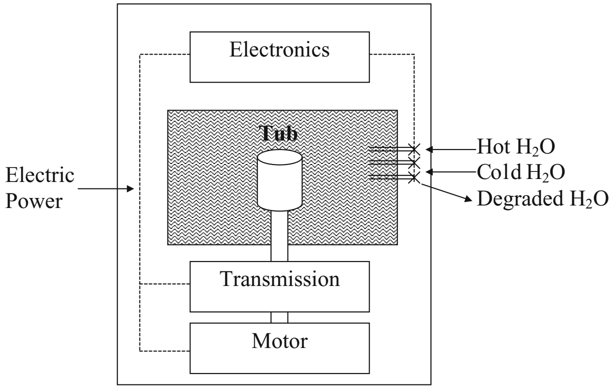

Figure 21.2. Components of a generic washing machine.

b) System assembly, in which mechanical and electrical components are assembled into frames, plumbing and wiring is added, and system tests are performed.
c) Product delivery, in which finished washing machines are packaged and shipped, sold, and installed on customer premises.
d) In-service use, in which the product is used by the customer.
e) In-service maintenance, in which repairs and updates to the machine are performed in order to keep it in use.
f) Recycling and/or disposal, in which materials from obsolete systems re-enter materials streams or are lost to the industrial process as a consequence of landfilling, incineration, or other disposal techniques.

The flow diagram for the washing machine life cycle is shown in Figure 21.3. The sequence proceeds from the top of the diagram to the bottom, and components and subassemblies enter from the left of the diagram. Waste products leave processing steps to the right. In general, incoming parts and components are packaged in a variety of plastic and cardboard containers, often with wood bases and metal strapping. No attempt is generally made to achieve uniformity in supplier packaging, or to coordinate or optimize supplier deliveries so as to minimize their environmental impacts.

In the first assembly step, the electrical components of the system (motor, transmission, etc.) are affixed in the frame. These components are made largely of steel and copper. Next, the mechanical components are added. These include the plumbing connections, made largely of stainless steel and plastic, and the tub and other components of the washing compartment, most of which are plastic. The third step is the addition of the control panel and of the wiring that connects the panel to the electrical components. These items incorporate electronic circuit boards as well as copper conductors and plastic cable sheathing. The next step is to affix the external housing: sides, top,

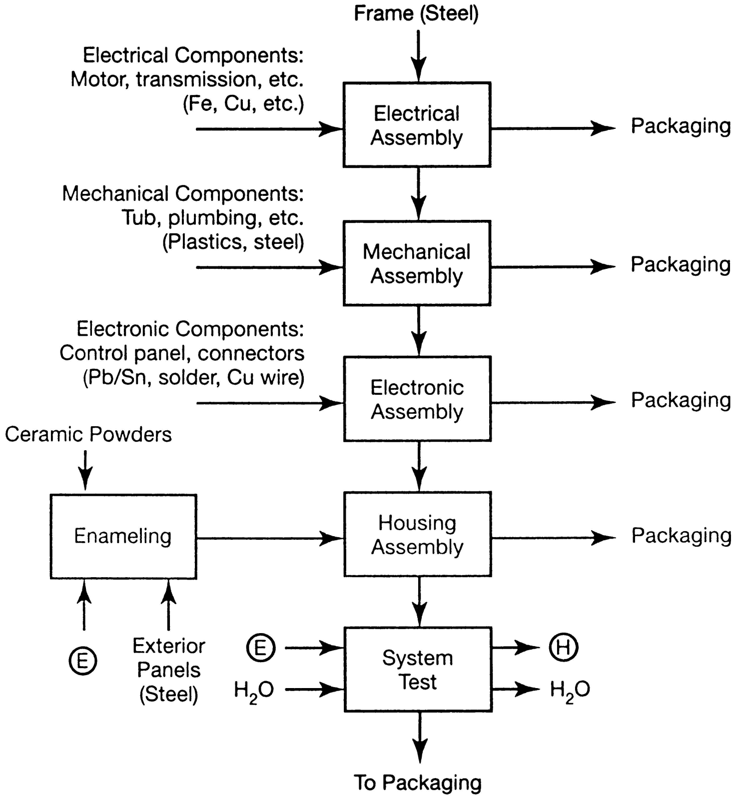

Figure 21.3. A flow diagram for the manufacture of a generic washing machine. Rectangles indicate process flow steps. Significant energy use is indicated by a circled E, significant heat loss by a circled H.

front, and back. Most of these items are manufactured of enameled steel. In all four of these stages, the components that are added have arrived at the manufacturing facility in their own packaging; that packaging must be discarded or otherwise dealt with. The final factory step is testing the completed unit, an operation that involves the use of energy and water, but no new materials.

More complex assembled products such as elevators or airplanes will have larger numbers of components and more diversity among them. Provided most of the components (body panels, electronic circuit boards, plastic parts) are manufactured by others, however, the sector processes tend to have quite modest energy and process chemical requirements.

The restricted set of processes common to the assembled products sector customarily includes welding, brazing, soldering, adhesive joining, and surface coating. All but the latter were discussed in Chapter 17.

The painting operation (or, more generally, the surface coating operation) is the largest source of pollution and the largest consumer of energy in the assembly process. Painting is performed on essentially all visible exterior and interior body components on all products. Painting has historically contributed most of the VOC emissions from the assembly operation, especially in auto manufacturing.

The automobile painting process involves many stages, all of which are chemically based, and thus carry polluting potential. The painting stages are as follows: a phosphorous pre-treatment of the panels is followed by electric coating to prevent corrosion, followed by sealant for water proofing, followed by primer surfaces to prevent chipping, and finally a top coat application that involves a base-coat and a clear-coat. This final top coat stage involves the application of the pigment. The pigment carrier has traditionally been organic in nature, and hence carries the most VOC emission potential. Some current carriers are aqueous solvents, and the industry is now beginning to utilize solvent-free electrostatic powder painting techniques.

The painting operation inherently requires the capture and disposal of paint overspray and involves the emission of greater or lesser quantities of volatilized paint and carrier. Because of the large quantities of air used in modern painting systems, the energy consumed is large as well.

The actual assembly operation commonly includes the physical joining of components using screws, rivets, or other devices. Following that step, and any surface finishing that takes place, an assembly evaluation is often performed in which the product is operated more or less as it is to be used. Depending on the product, the evaluation may involve the use of fossil fuel, water, heat, or other consumables or stressors.

21.3 THE SECTOR'S USE OF RESOURCES

Few new resources are used by the assembled products sector, which relies on components resulting from the use of resources by suppliers further upstream in the industrial sequence. Except in unusual operations, the principal resource that is consumed is the energy required for the various joining operations. Even the energy consumption, compared with that of upstream industrial sectors, is modest.

21.4 POTENTIAL ENVIRONMENT CONCERNS

The processes used by the assembled products sector generally raise only modest levels of environmental concern. Three are particularly worth noting. The first is the solid waste that typically results as multiple suppliers ship the components that are to be assembled. The components are often delicate—electronics, precision mechanical subsystems, cathode-ray tubes—and the packaging is thus both highly protective and voluminous. Unless steps are taken to prevent it, suppliers are likely to use a wide variety of packaging materials, some of which may be difficult or impossible to recycle.

A second concern is the surface finishing process, which generally begins with a cleaning step. Cleaning compounds tend to be chemically aggressive, and the cleaning process by its nature generates residues of adulterated cleaning fluid. Surface coating usually is accomplished by painting, a process in which the solvent carrying the pigment is designed to evaporate. VOC emissions from evaporating organic solvents are a local air quality concern.

A final consideration has to do with the gaseous and particulate emissions from the supplier vehicles making deliveries to the assembled products facility. It has been determined, in fact, that a significant component of Tokyo's air pollution has historically been due to vehicles making "just in time" deliveries of components. Whether these emissions should be charged to this sector or to the product delivery sector is a matter for debate, but their existence and cause is not—it is in large part due to the needs of the assembled products sector.

21.4.1 Sustainability Assessment

Table 21.1 displays the processes and potential emissions for this sector, and Table 21.2 uses that information together with a general knowledge of associated flow and hazard information to bin the potential hazard and scarcity concerns.

The TPH matrix appears in Figure 21.4, in which no elements are of very high concern. Moderate concerns apply only for the solder used in the assembly process. The TPS matrix also appears in Figure 21.4. There are no extreme concerns, but significant potential scarcity exists for lead in solder and batteries, and plastics from petroleum.

Table 21.2. Throughput-Hazard Binning of Materials in the Assembled Products Sector

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
Plated steel	H	–	L	L
Plastic components	H	–	L	M
Electronic components	M	–	L	L
Solder	M	Human	H	H
Surface coatings	M	Smog	M	M
Cleaning solutions	L	Ecosystem	M	L
Packaging	H	–	L	L
Batteries	M	Human	M	H
Radioactive Materials	L	Human	H	M
Heavy metal components	L	Ecosystem	H	M

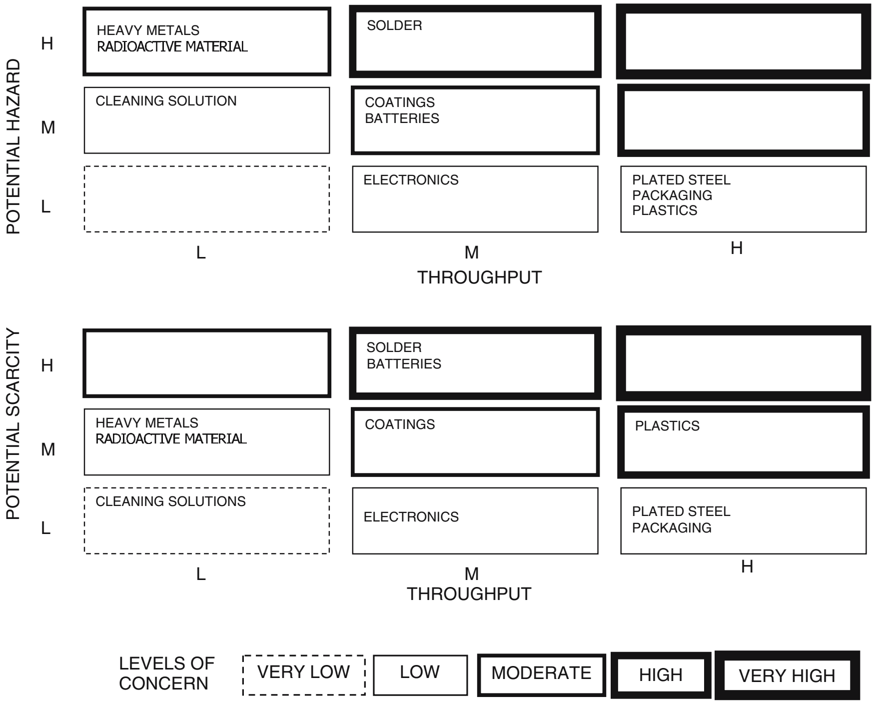

Figure 21.4. The throughput-potential hazard matrix (top panel) and throughput-potential hazard matrix (bottom panel) for the assembled products sector.

The assembled products sector uses processes that involve quite modest amounts of energy and water. The PEC and PWC matrix plots in Figure 21.5 both indicate low levels of concern.

The system ΣWESH plot for this sector is given in Figure 21.6. No very high concerns are present. The most significant relate to lead use in solder and the petroleum source for plastics.

21.5 SECTOR PROSPECTS

21.5.1 Trends

21.5.1.1 Process Trends

New and emerging technologies can address most of the environmental concerns of the assembled products sector. The industry has taken steps in recent years to

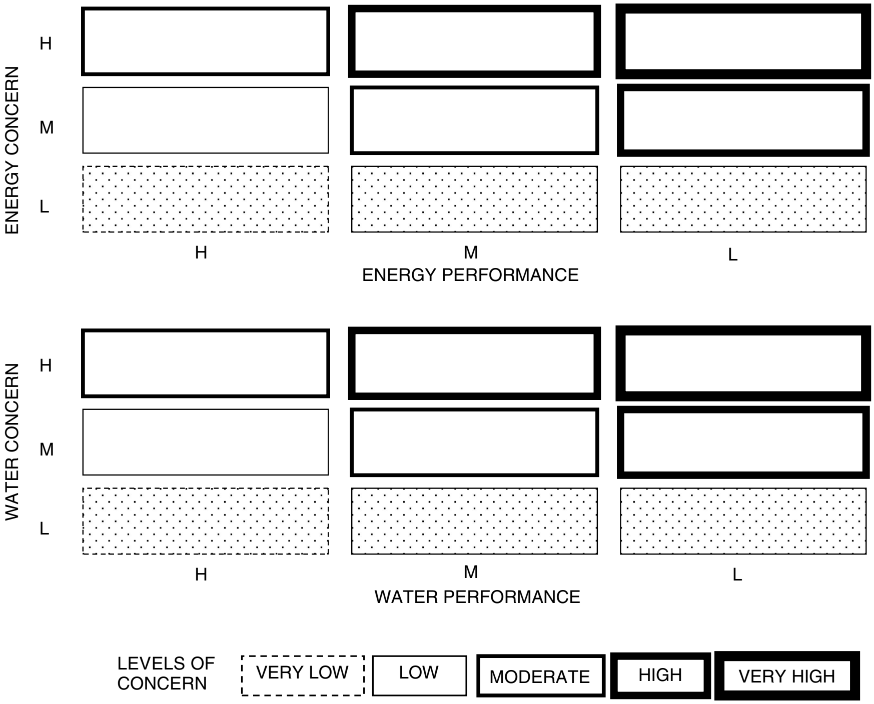

Figure 21.5. The performance-energy concern matrix (top panel) and the performance-water concern matrix (bottom panel) for the assembled products sector.

create pollution prevention measures to reduce environmental impacts and this trend is expected to continue.

The most obvious process change that has reduced the environmental impact of this sector is the adoption of new surface coating techniques. Surface coating is the largest source of energy use and pollution from the assembly process, with the greatest emissions coming from VOCs. The coating process is being improved in two ways: by process innovation and by materials usage. Robotic painting technologies that only coat targeted materials decrease paint overspray. Material usage is also being improved with the use of new painting bases. An evolution of painting materials has recently occurred from high-solvents, to high-solids, to water-borne, and finally to the newly emerging "powder paints." Powder paints are air-sprayed onto the metallic surface where they attach electrostatically. Solvent is thus largely unnecessary. This technology is already being implemented with clear coats, and technology is developing for the later pigment coats. As this and other coating techniques are further developed, solvent emissions to the air and paint overspray losses to water supplies will become less and less of concern.

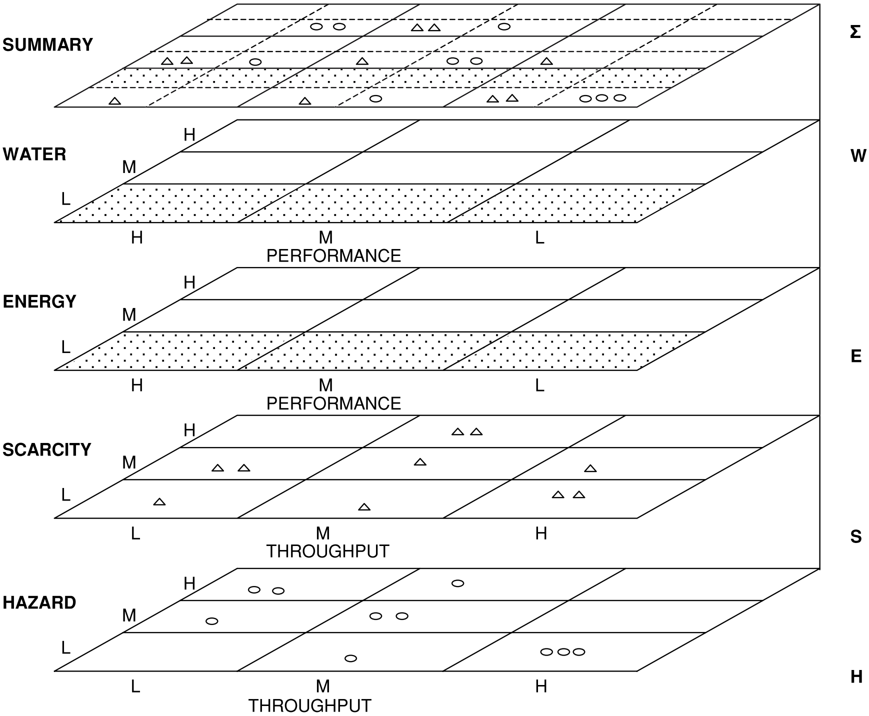

Figure 21.6. The ΣWESH plot for the assembled products sector. The squares and circles refer to the materials in Figure 21.4.

Improvements are also being made in the quantity of packaging waste produced by assemblers. Many corporations require their suppliers to retrieve and reuse packaging, or at least to utilize a small number of readily recyclable materials.

Reducing energy consumption is another major focus of effort in the assembled products sector. The opportunities normally exist in three areas: improving the energy efficiency of manufacturing equipment, reducing the energy used in testing finished products (especially tests at elevated temperatures), and making product shipment more efficient. Overall energy use reductions of 20 to 30 percent are likely over a decade or so.

21.5.1.2 Product Trends

Improvements in the design of assembled products will reduce their environmental impact during use, not just during manufacturing (see Text Box 21.1). Many products have greater environmental impact over the course of their life than they do in the

Text Box 21.1

Reducing Lifecycle Environmental Impacts: Electrolux and Refrigerators

The coolant fluid for refrigerators for decades was chlorofluorocarbons (CFCs). By the mid-1980s, it was clear that stratospheric ozone depletion was linked to CFC emissions. The Electrolux Corporation, headquartered in Sweden, decided in response that it should adopt a proactive strategy in which environmental care was the cornerstone. As a result, the company was able to release for sale in 1992 a full range of CFC-free refrigerators, well ahead of its competitors.

The replacements for CFCs were the hydrogenated CFCs (HCFCs with much reduced ozone depletion potential) and hydrofluorocarbons (HFCs with no ozone depletion potential but a significant global warming potential). Electrolux is now redesigning its refrigerators again, to use benign hydrocarbons as refrigerants. This aggressive strategy has not only resulted in products that have sharply reduced environmental impacts during manufacture and use, but the existence of competitive advantage for Electrolux has forced the company's competitors to do likewise.

Source: A. Brown, Green white good, *Tomorrow,* 7(6), 50–51, 1997.

process of being manufactured. The automobile is a prime example. Currently, a race is underway to create extremely fuel-efficient vehicles, or low-emissions vehicles (LEVs), and even no-emission vehicles (NEVs). NEVs run off an internal fuel cell powered by hydrogen. The immediate problem with NEVs is their development costs, which will fall as technology advances, and the lack of a hydrogen service station infrastructure. In the interim, LEVs such as hybrid cars will fill this void. The hybrid has two separate drive trains, one traditional, and the other electric. All electric charging is done by the gasoline-powered engine. The advantage of hybrids is that when a gasoline engine is particularly inefficient—idling in traffic, for example—the car operates on the battery and the engine is shut off. The battery power supplements the small gasoline engine when major acceleration is needed.

Corporations are beginning to evaluate the benefits of leasing services to the customer rather than selling products. In this concept, termed *extended producer responsibility* (EPR), the manufacturer retains ownership of products, maintains them, updates them, and eventually retires them from service and recycles them. The customer pays for the utility provided by the product, but is not burdened with environmentally-related aspects of ownership, especially how to properly relinquish ownership of an obsolete product. If the product reverts to the manufacturer, prospects for near-complete reuse and/or recycling are much enhanced.

Text Box 21.2

Volkswagen and German End-of-Life Vehicle Legislation

On April 1, 1998 the German legislature initiated the "Voluntary Agreement on the Environmentally Acceptable Recycling of End-of-Life Vehicles" (also known by the German abbreviation FSV). The agreement, which was accepted by 16 automakers and associations, calls for the reduction of the proportion of waste for disposal to 15 percent by weight by 2002, and to 5 percent by weight by 2015. Additionally, the agreement commits manufacturers to establish a nationwide network of take-back locations, facilitate consumer participation, ensure the environmentally acceptable dismantling and fluid draining of end-of-life vehicles, practice recycling-friendly material selection and design, and take back end-of-life vehicles up to 12 years old free of charge. Similar ordinances and laws apply in some other European countries.

Volkswagen has introduced a wide range of measures to implement end-of-life recovery and recycling for its vehicles. Dismantling studies are drawn up for every model built by the company. Additionally, several internal working groups have been set up to ensure that the topic of recycling is integrated into every division across the company. A key aspect is that "design for recycling," which is extracted from dismantling studies, be incorporated into the new vehicle development process. In order to ensure that information on vehicle recycling is communicated efficiently throughout the company, Volkswagen has set up recycling seminars for employees and suppliers. The seminars focus on such aspects as material selection with an end-of-life vision of recycling, and providing tips on designing products for easy dismantling. In 2003, Volkswagen collected more that 45 Gg of material and components, most of which made their way into recycling processes.

Sources: Okopol Institute for Environmental Strategies. (1999). "General requirements for monitoring the recycling of long-lived, technically complex products with an in-depth-analysis of end-of-life vehicles." http://www.oekopol.de/en/Archiv/Stoffstrom/monitoring_vehicles/monitoring_vehicles.php. Volkswagen. (2004). "Disposal of end-of-life vehicles." http://www.volkswagen-environment.de/

Take-Back Legislation is a form of policy incentive currently active in Europe. Take back legislation requires that companies implement extended producer responsibility programs. These laws have not yet caught on in the U.S., but government activity in this area will help both producers and consumers realize the importance of EPR.

A final action that the assembled products sector is taking is to examine the need served by a particular product and to investigate whether a different product might meet that need at lower environmental cost. Consider the microwave oven. This oven was developed in response to the customer's need for rapid cooking of food, not for a better traditional stove. Compared to the product it supplants, at least for some uses, the microwave oven serves the need faster and does so with lower initial use of materials and lower ongoing consumption of electricity.

21.5.2 Possible Future Scenarios

21.5.2.1 Trend World

The trend world for the assembled product sector involves the continued improvement of process technologies as a means to cut costs and enhance environmental performance. Managing hazardous waste is an expensive task, and non-compliance with regulatory standards can be extremely costly. Because of this, the assembled products industry will continue to reduce the use of hazardous materials as a means of saving money.

21.5.2.2 Green World

In a green world, the designers of assembled products, and members of their purchasing departments, will include consideration of overall environmental impacts in their daily practices. By specifying not only the attributes of products from the suppliers (e.g., purity, low toxicity, etc.) but also the environmentally-related performance of the supplies themselves, environmental improvement can be enhanced one or two stages earlier in the manufacturing sequence. Some large corporations have begun to work with their suppliers in this way, first by requiring ISO 14001 certification by their suppliers, then by cooperatively assessing environmental performance. Should such approaches become widespread, they could lead to ubiquitous attention to environmental performance as a part of doing business.

21.5.2.3 Brown World

In this scenario, the assembled products industry will not implement significant new process efficiency improvements or pollution prevention initiatives. Technological innovations that could improve environmental performance will be disregarded in favor of low-cost assembly. A scenario like this is difficult to imagine if this sector continues to operate in geographies that have relatively high labor and energy costs, as process improvements that increase efficiency also reduce these costs. On the other hand, if assembly is increasingly performed in areas where labor and energy costs are low, the pursuit of process efficiency may not be seen as so important to manufacturers.

International assembly can have extremely negative environmental effects when companies from industrialized nations move assembly plants to nations with less stringent and enforceable environmental laws. Safety and environmental standards may suffer and older, "dirtier" process technologies may be used. The energy needed to transport raw materials and finished goods to and from foreign assembly plants also increases the overall environmental of the finished product.

FURTHER READING

National Academy of Engineering, *Manufacturing Systems: Foundations of World Class Practice*, Washington, DC: National Academy Press, 1992.

U.S. Environmental Protection Agency, *Profile of the Motor Vehicle Assembly Industry*, EPA 310-R-95-009, Washington, D.C., 1995.

Chapter 22

Forest Products and Printing

22.1 OVERVIEW

This chapter deals with several subsectors, some of which are traditionally treated independently. For convenience, however, we focus here on four different industrial activities: pulp and papermaking, printing, lumber production, and wood products. All are related to the forest products sector, although printing is often regarded as distinct. The interrelationships are indicated in Figure 22.1 on an expanded sector sequence diagram. Except for a modest input of organic and inorganic chemicals in a number of processing steps, this sector is relatively isolated from the other industrial sectors discussed in this book.

On a worldwide basis, about 55 percent of the wood harvest is used for fuelwood, 31 percent for saw timber, and 14 percent for paper; only the latter two are of interest here. The proportions differ dramatically in different geographical regions. In the United States, for example, the respective percentages are approximately 21 percent, 48 percent, and 31 percent. The leading countries for the production of paper and saw timber are given in Table 22.1.

22.2 PHYSICAL AND CHEMICAL OPERATIONS

22.2.1 Forest Products Extraction

Timber harvesting is accomplished by gasoline-powered chain saws or by felling machines that use hydraulically-activated shears. The most industrially efficient harvesting technique, at least in the short term, is "clear cutting", in which all trees in a specified area are removed. Such an approach is very damaging to ecosystems, however, and in the long term will impair the ability of the land to generate further generations of trees. As a consequence, selective cutting is rapidly becoming standard practice in most countries.

Table 22.1. Principal Forest Products Supplier Countries, 1994

Country	Paper Production (Tg)	Saw Timber (million m^3)
United States	81	78
Japan	29	23
China	21	16
Canada	18	59
Sweden	9	13
Russia	<6	34
World Total	269	308

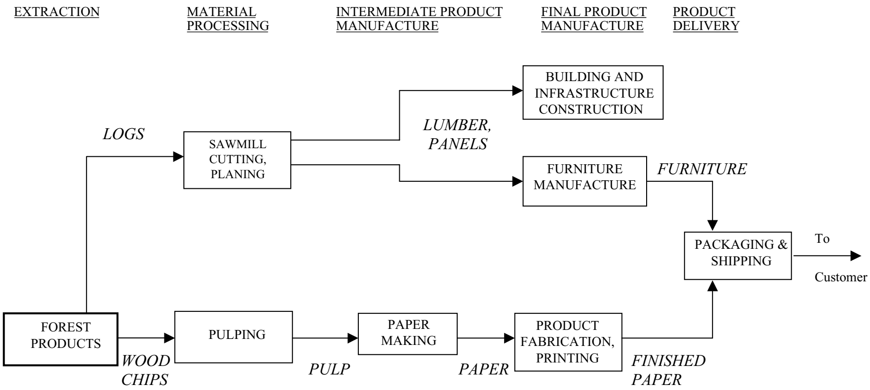

Figure 22.1. The technological sequence diagram for the forest products and printing industrial sector.

Once felled, the logs are transported to sawmills and pulp mills by water, trucks, or both. Wood fragments are utilized in making pulp or are burned to provide heat for subsequent processes. Some woods and many wood fragments are chipped as input to pulp mills.

22.2.2 *Lumber Production*

The production of lumber is a straightforward process in which logs are delivered to sawmills, debarked, graded, cut, and trimmed. The lumber is then dried to remove most of the moisture contained in the wood. Air drying may be used, but kiln drying is more common. It requires significant amounts of energy and releases large amounts of organic molecules, including terpenes and organic acids.

Lumber from sawmills is often protected against deterioration by applying various surface coatings; the compounds used are not highly toxic if the lumber is being sent for further processing. If the lumber is to be used directly in exposed situations such as underground or as railroad ties or outdoor decking, however, aggressive preservatives are applied as protection against termites and marine borers. The most common of the preservatives has been chromated copper arsenate [$CrCu_3(AsO_4)_2$]. Because of toxicity concerns, however, this material is gradually being phased out in favor of less problematic alternatives.

22.2.3 Pulp and Paper

The basic manufacturing sequence for paper involves pulping, bleaching, and papermaking, each of which is discussed below. A subsequent process, invoked with a large percentage of papers or boxboards (corrugated cardboards), is printing.

Wood is cellulose that is held together with lignin, a complex mixture of large organic molecules that can comprise as much as 25 percent of the weight of the wood. The initial step in papermaking is the removal of the lignin and thus the liberation of the cellulose fibers. This is accomplished in the "kraft process," the most common method of delignification, by cooking small chips of wood under high pressure and high temperature in the presence of sodium sulfide and sodium hydroxide (Figure 22.2). The chemical mixture, termed "white liquor", extracts most of the lignin from the wood. The residue stream from the process consists of lignin solids and used and unused pulping chemicals; it is known as "black liquor".

Black liquor is sent to a recovery boiler, in which the lignin and other organic residues are burned to provide energy for the operation of the pulp mill, while the inorganic residues are recovered. These residues, when mixed with weak solutions of the starting materials, form reconstituted white liquor following a reaction with lime. It is the ability to largely recover the process chemicals that makes possible the economical operation of the pulp mill.

Following lignin removal, the pulp (which is now a slurry of cellulose fibers in water) is washed extensively. If it is to be made into a whitened paper, it is sent on to a bleach plant where any remaining lignin in the fibers is oxidized and largely removed. The traditional bleaching chemical has been molecular chlorine (Cl_2); it suffers from the disadvantage that small amounts of the hazardous chemical dioxin are produced as byproducts. For that reason, many pulp mills have gone over to the use of chlorine dioxide (ClO_2) as the bleaching agent. Alternative agents that contain no chlorine and thus completely avoid dioxin generation are hydrogen peroxide (H_2O_2, generated from sulfuric acid) and ozone (O_3, generated from the ultraviolet radiation of liquid air). Chlorine dioxide is now the preferred bleaching method in North America, ozone is preferred in Europe. No matter which bleaching technique is used, bleaching involves several pulp washing stages and is a major user of water.

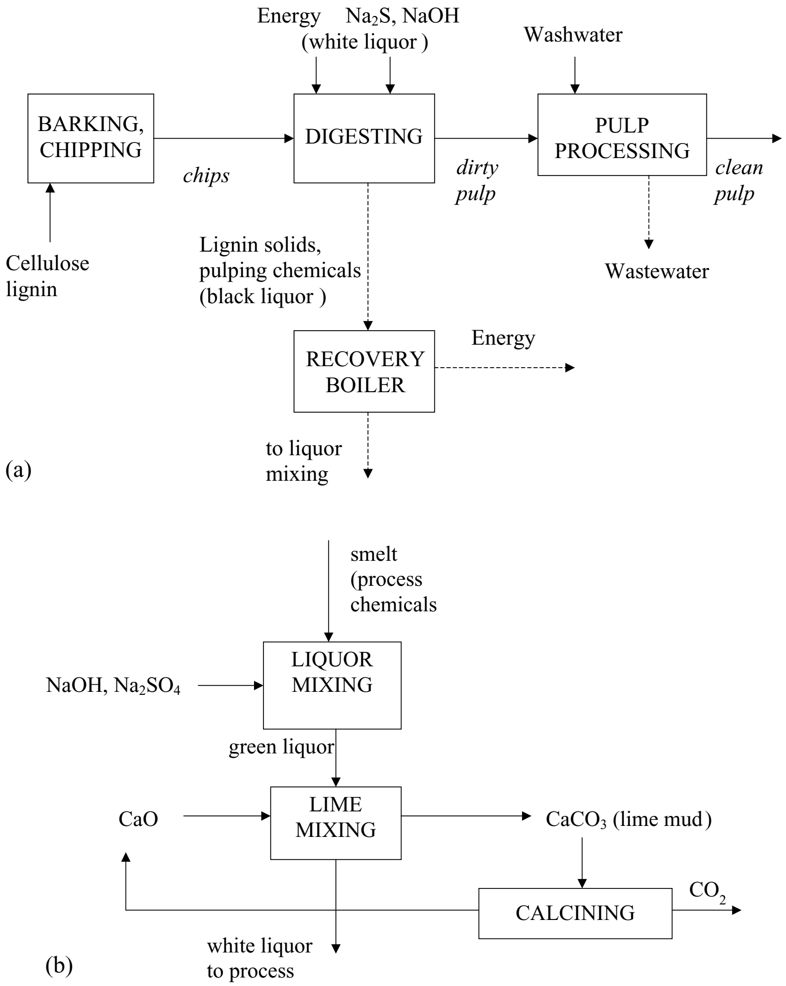

Figure 22.2. The chemistry of papermaking (the kraft process). (a) Delignification; (b) recovery of the process chemicals.

Roughly equal amounts of writing and printing papers, newsprint, and boxboard are produced in the United States, and the proportions are not too different elsewhere. Writing and printing papers are generally highly bleached, newsprint is mildly bleached, and boxboard (for "cardboard" boxes and the like) is generally unbleached.

The next step following the pulp mill is the making of paper, in one of the most visually spectacular of all industrial processes (shown in Figure 22.3). The pulp, consisting of about 4 percent fibers and 96 percent water, is dropped onto a wire

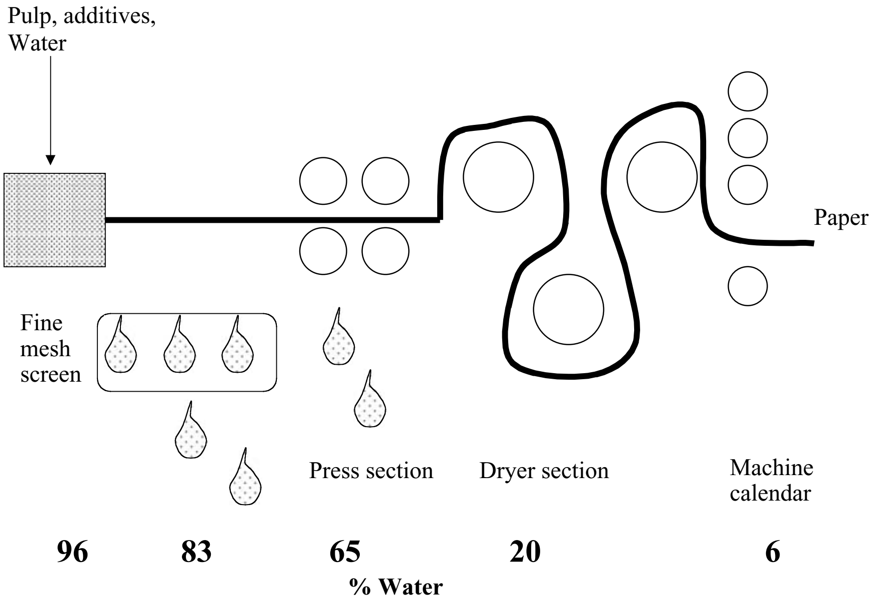

Figure 22.3. A schematic diagram of a typical fourdrinier paper machine.

screen moving at some 90 km/hr. As the fibers move along, the water is gradually lost by falling through the screen, by pressing, and by heating. Seconds after being deposited, the fibers have become dry paper and are rolled into cylinders for delivery to customers. This process, invented by the Fourdrinier brothers in France more than a century ago, has been performed in essentially the same manner, though with higher speeds and improved levels of control technology, since it was invented.

22.2.4 Printing

In the basic printing process, the image of the material to be printed is transferred photographically or electronically to an image carrier (or "plate") in such a way that the portions of the plate that are desired to be printed are raised above the level of the remainder of the plate. Alternatively, the desired image areas can be coated with ink-receptive chemicals. During the printing process itself, ink is applied to the desired areas and transferred to the paper or other receiving material. A number of finishing operations may then be carried out to improve the characteristics of the printed product.

There are four types of printing in which an impervious plate is used: lithography (shown in Figure 22.4), gravure, flexography, and letterpress. These differ largely in

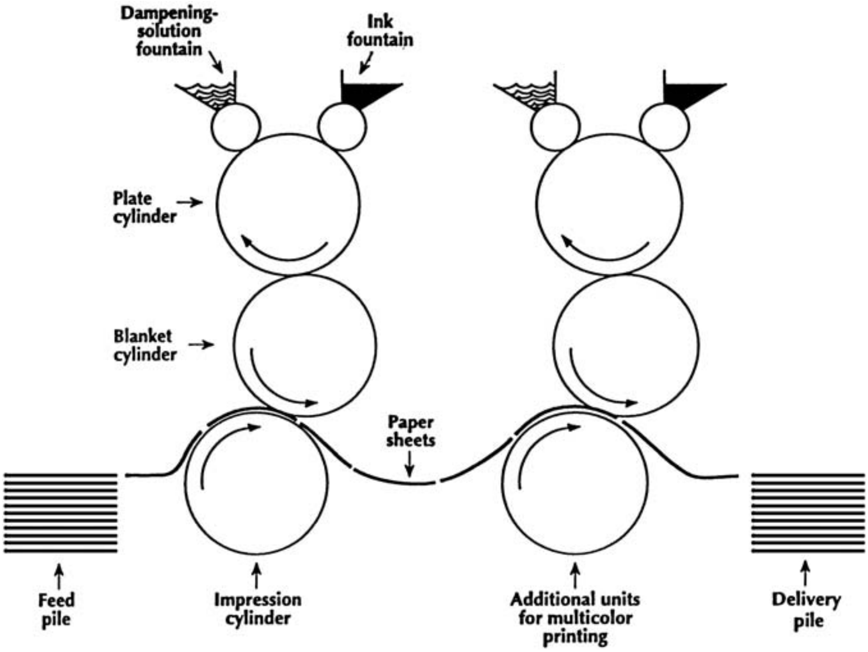

Figure 22.4. A schematic diagram of a lithographic printing press, a common printing process using impervious plates. (Reprinted from *Profile of the Printing Industry*, U.S. Environmental Protection Agency report EPA 310-R-95-014, Washington, D.C., 1995.)

the technique used to generate the image and to apply the ink to the paper, and the differences are not greatly significant for our purposes. A fifth technique, screen printing (shown in Figure 22.5), squeegees the ink through a fine wire mesh onto the target material.

22.2.5 Wood Products

The wood products with the largest throughput are panels made of veneers, plywoods, and reconstituted products such as particleboard. After forming, the panels are manufactured by adhesion using urea-formaldehyde or another adhesive.

Furniture products are much more labor-intensive, and have modest throughput. The planing and sanding operations produce only wood scraps. Assembly involves the use of adhesives, so methyl ethyl ketone, toluene, and other solvents are liberated. The finishing process involves staining or painting, again with the liberation of volatile carriers, usually organics.

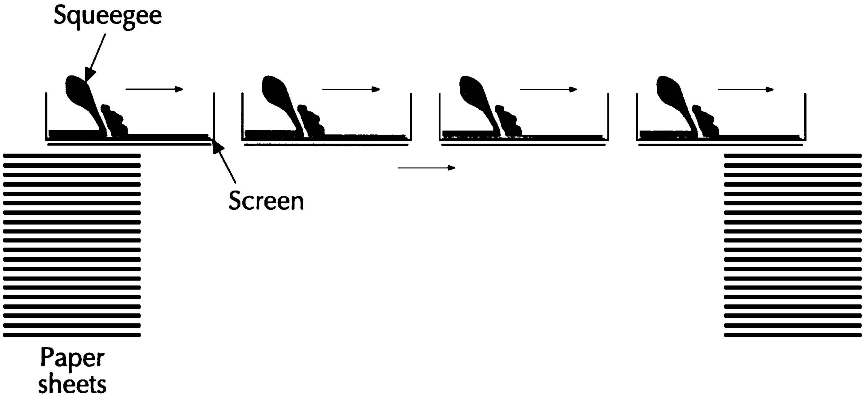

Figure 22.5. A schematic diagram of a screen printing press, where a porous polyester mesh is used. (Reprinted from *Profile of the Printing Industry*, U.S. Environmental Protection Agency report EPA 310-R-95-014, Washington, D.C., 1995.)

22.3 THE SECTOR'S USE OF RESOURCES

22.3.1 *Energy*

The forest products sector is a large energy consumer, ranking fourth among U.S. industrial sectors with a 1990 consumption of 2.3 EJ/yr. Most of this energy is used in pulp and paper mills. The energy used by U.S. pulp and paper mills in 1999 was about 26×10^6 Joules per kilogram of product.

22.3.2 *Materials*

The materials used in this sector are mostly renewables, at least in theory. In practice, they are truly renewable only if consumed at a rate no faster than they are regenerated. There are strong pressures on suppliers to exceed the regeneration rate, for example, the world wide average consumption of paper and paperboard is 48 kg/capita-yr and is rising. The use per continent is widely variable, as shown in Figure 22.6, and culture and business choices play important roles. Overall, however, the loss of old growth and tropical forests continues at a rapid rate, and forest products are, at present, sustainable only in certain regions and for certain wood species.

22.3.3 *Process Chemicals*

22.3.3.1 *Lumber Production*

The lumber production subsector does not use large amounts of any material with the exception of the wood itself.

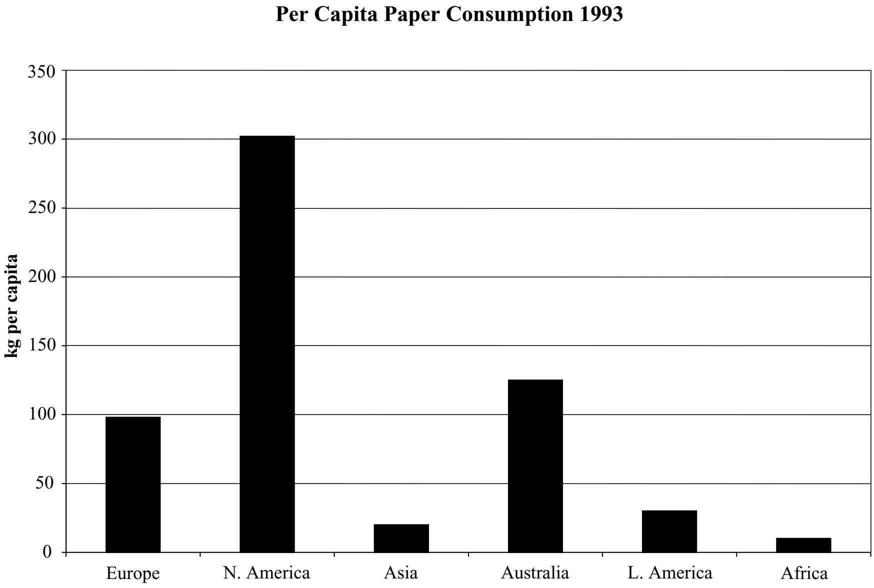

Figure 22.6. Per capita paper consumption on different continents. (Reprinted from a diagram furnished by the Pulp and Paper Institute, 1995.)

22.3.3.2 *Pulp and Paper*

The pulp and paper processes rely on the use of chemicals. These chemicals are, however, common inorganic species such as sodium sulfide or sodium hydroxide. Some are moderately hazardous if not carefully used, but most are retained in the kraft process recycling sequence and themselves are of minimal environmental concern. Bleaching has traditionally been a source of chlorinated species to local rivers, but the transition to peroxide bleaching is eliminating this concern over time.

22.3.3.3 *Printing*

There are two environmentally problematic steps in the printing process. One is the use of the ink itself. Typically, the ink particles are carried in a solvent base, and that base is generally toluene or a similar organic molecule; most are toxic. The second problematic step is the periodic cleaning of the printing plate. To dissolve away the ink, aggressive organic solvents, especially methylethyl ketone (MEK), have traditionally been the chemicals of choice. Toluene and MEK are the two largest emissions by far from the printing industry.

Total pollutant releases from the printing subsector are not of much significance in comparison to other sectors for most emittants. In the case of volatile organic carbon (VOC) releases to air, however, printing is roughly equivalent to the fabricated metals and automotive sectors, significantly trailing only petroleum refining, organic chemicals, and rubber & plastics.

22.3.3.4 Wood Products

The wood products subsector is a major user of adhesives in its manufacture of particle board, chip board, plywood, and other products formulated from fragments or small portions of wood that were formerly discarded. VOC emissions from these processes can be substantial if they are not well controlled.

22.3.4 Water

The forest products sector is a large water-using industry, larger than any other except agriculture (irrigation) and power generation (cooling water). Nearly all of this water is used in pulp and paper making, and is involved in rinsing and bleaching cycles, so has the potential to be polluted as part of its use.

The total effluent volumes in pulp and paper facilities range from 30–220 m^3/ton of product. (100 m^3/ton is about 100 grams of water per gram of product.) The majority of facilities are in the 60–100 m^3/ton range, and mills in which modern technology is applied can operate successfully at quite low water use levels.

22.4 POTENTIAL ENVIRONMENTAL CONCERNS

22.4.1 Lumber Production

The most significant potential environmental impact of timber production and logging is the way in which the industry uses land. This topic has received detailed attention elsewhere and will not be dealt with here in any detail. Suffice it to say that there are serious concerns connected with logging practices, watershed destabilization, displacement of rural communities, loss of diversity to monocultural planting, and global decreases in the extent of bio-rich tropical forests.

The U.S. subsector's use of compounds containing arsenic, chromium, and copper as wood preservatives is also a serious concern. These metals are used because they are biotoxicants, and this means that release during or after application to ecosystems where they are not intended can have obvious detrimental impacts. From a resource standpoint, it is of interest that this use of arsenic is the largest single use in the world, so the U.S. lumber industry is a dominant factor in the global budget of arsenic.

Text Box 22.1

Sustainable Wood Harvesting: The Menominee Indian Tribe

In principle, wood is an ideal material because it is renewable. In practice, the renewability of wood depends upon the use of sustainable forestry practices in planting, growth, and harvesting. In recent years, third-party evaluators have been used to certify that forest products from particular growers meet sustainability criteria; if so, they are said to be "certified."

An example of a certified forest products industry is that of the Menominee Indian Tribe of Wisconsin. They have practiced sustainable logging for nearly a century and a half, growing cherry, oak, ash, and several other species. Harvesting is accomplished in 15-year schedules, with an overall planning horizon of 150 years. Ecological diversity is maintained on the forest land. When certification began in the late 1980s, the Menominees were among the first to be certified. Their achievement is readily measured in two ways: the products are economically competitive, and the standing timber on the reservation has actually increased since the land was allocated to the tribe in 1854.

Source. D. McQuillan, Seeing the forest for the trees, *Environmental Design & Construction*, pp. 17–27, March/April, 1998.

22.4.2 Pulp and Paper

The emissions of the U.S. pulp and paper industry are well documented. Solid waste consists largely of sludge, ash, and wood waste, with the great majority of it not classified as hazardous waste. Data for U.S. pulp and paper mills show that, in 1999, 143 kg of solid waste was generated for each 1000 kg of product. Solid hazardous waste was generated at a rate of 0.015 kg per 1000 kg of product. Liquid waste consists of lignin compounds, wood extractives, and wastewater. For each 1000 kg of product produced in U.S. pulp and paper mills, 52,600 L of wastewater were discharged. Air emissions include VOCs, fuel gases, and reduced sulfur gases. The U.S. pulp and paper industry released a total of 84×10^6 kg of TRI (Toxic Release Inventory) chemicals to the air in 1999. Per 1000 kg of product, 4.5 kg of SO_2 and 3 kg of NO_x were emitted.

If it is assumed that pulp and paper mills worldwide have emissions roughly equivalent to those of U.S. mills, worldwide emissions can be estimated on the basis of the relative paper production given in Table 22.1.

22.4.3 Printing

The printing subsector's environmental concerns are largely related to gaseous releases. In 1999, Toxic Release Inventory emissions in the United States from printing amounted to 9.4×10^6 kg; of this, $9.3\ 4 \times 10^6$ kg were released to air. More than 75 percent of emissions from printing is toluene. Toxic air emissions from the printing industry are about one-tenth of those generated by the pulp and paper industry.

22.4.4 Wood Products

The wood products subsector's environmental concerns are largely related to gaseous releases. In 1999, Toxic Release Inventory emissions in the United States from the lumber sector amounted to approximately 16×10^6 kg, with air emissions contributing to 97 percent of total emissions. The chemical emitted in largest quantity was methanol, which is released when wood is heated during drying . Formaldehyde was also emitted in significant quantities; various organic solvents and pigment carriers made up the rest. This total quantity of emittants is a relatively small fraction of the gaseous emissions from U.S. pulp and paper manufacture. For the same year, U.S. pulp and paper mills released 84×10^6 kg of TRI chemicals to the air; more than half these releases were methanol.

22.4.5 Matrix Assessment

The potential emittants, activities, and hazards resulting from processes in this industrial sector are given in Table 22.2, and the materials binned for throughput, potential hazard, and potential scarcity in Table 22.3. The TPH matrix appears in Figure 22.7. It indicates highest concern for the biodiversity impacts of deforestation. Of high concern are gaseous emissions from kilns and pulping, and of bleaching chemicals, printing solvents, and the use of heavy metals in wood preservation activities.

The THS matrix is also given in Figure 22.7. The only concern is for the heavy metals in wood preservatives, arsenic having a depletion time of about 25 years, copper about 45.

Table 22.2. Processes, Activities, and Potential Hazards for the Pulp, Paper, and Printing Sector

Process Type	Sector Activities	Potential Emittants
Extraction	Logging	Ecosystem disruption
Cleaving bonds	Pulping	Lignin compds., wood extractives, sulfur gases, sludge
Purification	Bleaching, liquor regen.	Lignin compounds, dioxin
Cleaning	Printing plates	Toluene, MEK, glycol ethers
Joining	Wood panel mfr.	Formaldehyde
Surface treatment	Printing	Toluene, VOC
	Wood preservation	As, Cr, Cu dissipation

Table 22.3. Throughput-Hazard-Scarcity Binning of Materials in the Pulp, Paper, and Printing Sector

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
Deforestation	H	Ecosystem	H	M
Wood fragments	H	–	L	L
Pulping chemicals	M	Ecosystem	M	L
Bleaching chemicals	M	Human	H	L
Printing inks	M	Human	M	L
Printing solvents	M	Human	H	L
Wood preservatives	M	Ecosystem	H	H
Adhesive resins	M	Human	M	L
Kiln drying emissions	H	Smog	M	–
Pulping emissions	H	Ecosystem	M	–

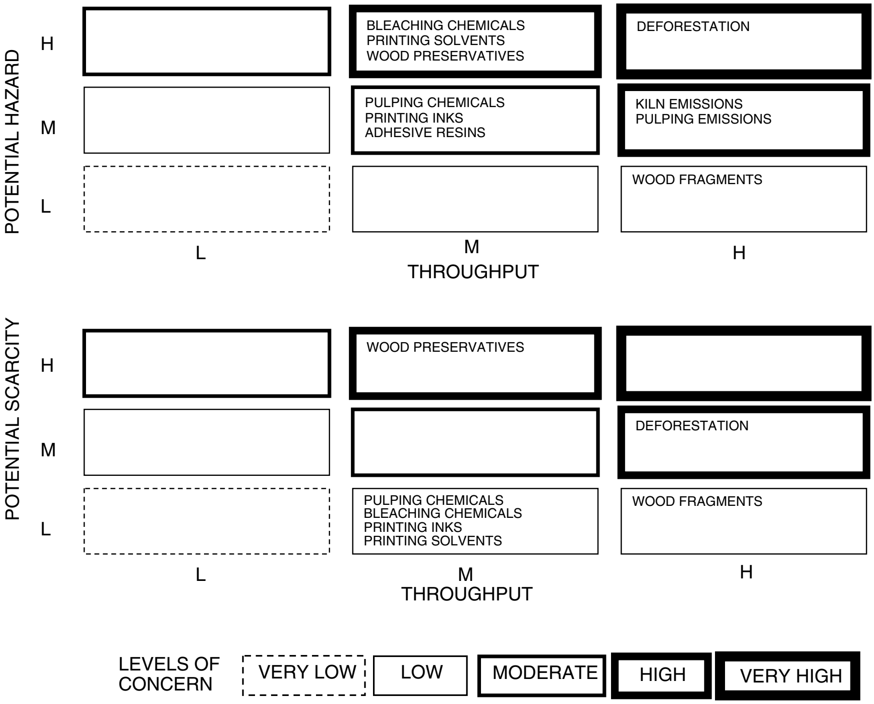

Figure 22.7. The throughput-potential hazard matrix (top panel) and throughput-potential scarcity matrix (bottom panel) for the forest products and printing sector.

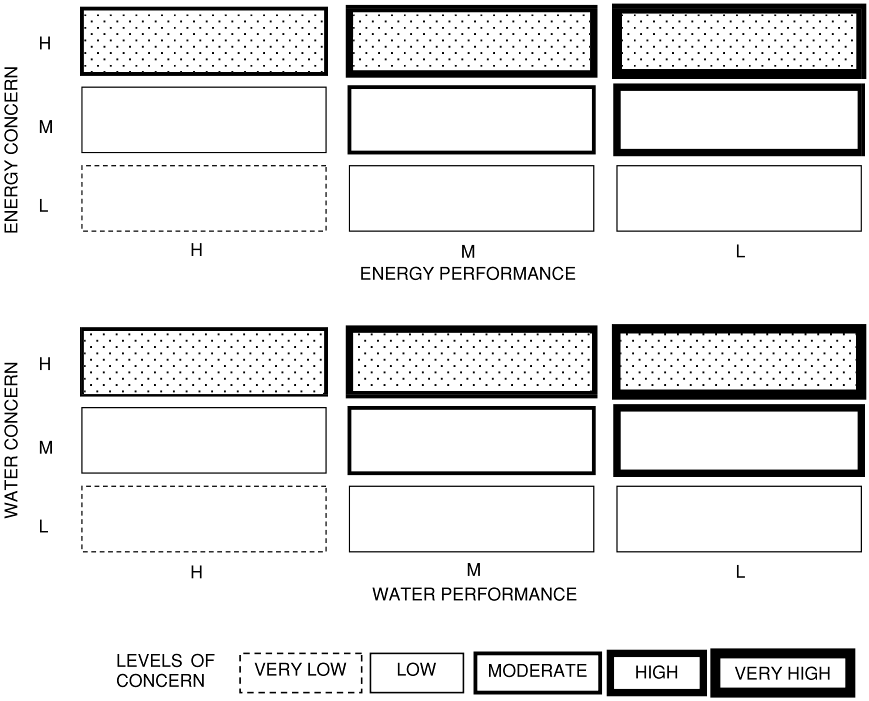

Figure 22.8. The performance-energy concern matrix (top panel) and the performance-water concern matrix (bottom panel) for the forest products and printing industrial sector.

The PEC and PWC matrices appear in Figure 22.8. Sector use of both energy and water is high, as indicated in the figure.

The ΣWESH plot for the forest products and printing sector appears in Figure 22.9. Energy use, water use, and the potential environmental consequences of deforestation are particularly called out for attention.

22.5 SECTOR PROSPECTS

22.5.1 Trends

22.5.1.1 Process Trends

Over the next twenty years, the productivity of timberlands will increase dramatically so larger volumes of forest products will be extracted from a given land area. By 2020, members of the American Forest Products and Paper Association plan to increase the yield of newly established plantations by a factor of two over 1994 yields. This

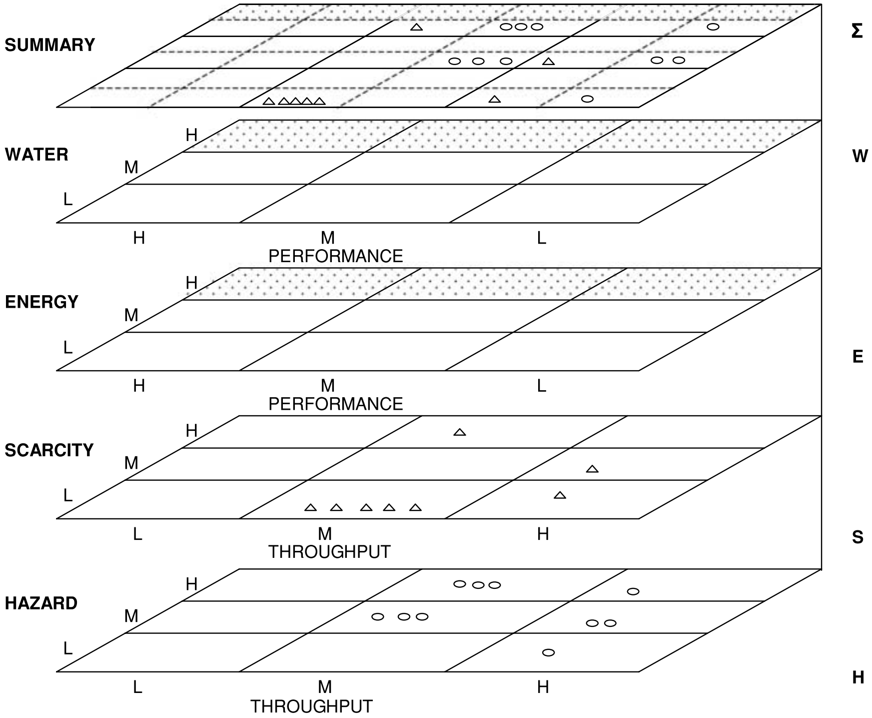

Figure 22.9. The ΣWESH plot for the forest products and printing sector. The squares and circles refer to the materials of Figure 22.7.

productivity improvement will be accomplished by advances being made in biotechnology and remote sensing, and by a better understanding of soil productivity and basic plant physiology. Biotechnology may or may not involve genetic modification but it will certainly involve cloning to reduce variability in the trees grown. Through remote sensing, the industry will begin to monitor its land holdings for inventory development, forest productivity, and forest health. Any changes in nearby land parcels that have the potential to influence forest products will be tracked as well. Nutrient monitoring and nutrient cycling analysis will permit soil productivity to be enhanced.

With these new approaches to forestry will come possible environmental costs and benefits. If higher productivity plantations can be sustainably harvested, the expansion of logging into virgin forests may decline. The use of remote sensing may improve measurement and mitigation of ecosystem impacts. On the other hand, the growth of cloned or genetically modified species may have unforeseeable ecosystem consequences.

The methods used to manufacture wood products will continue to evolve so smaller and lower quality trees can be used to make lumber. This trend is already

Text Box 22.2

From Wood to Plastics

It has been difficult to utilize recycled wood in construction applications because many of the sources—sawdust, planer shavings, short solid pieces, construction debris—have no structural strength. A new class of materials now entering the construction market is wood-filled plastics. These are not wood or composites glued together with adhesives (e.g., strandboard, plywood), but products made with conventional plastics processing equipment in which wood fiber serves as a reinforcing filler.

The Crane Plastics company of Columbus Ohio has developed a family of wood-filled plastics, made by standard extrusion processes. The use of wood filler in place of the more common fiberglass or inorganic minerals gives a product that is less expensive and lighter in weight. In addition, the product is low maintenance, requires no wood preservatives, and has significant (about 50 percent) recycled content. The wood fiber contained in the products would otherwise be considered waste.

Source: B. English, Using recycled wood in composite products, *Resource Recycling*, pp. 38–44, November 1999.

well underway with the development over the last decade or so of engineered lumber (see product trends below). The new manufacturing processes fit well with the pressure to increase land productivity because they can utilize trees that are harvested earlier than those required for traditional lumber products. Environmentally, these new manufacturing processes are larger emitters of VOCs (from adhesives) and larger consumers of energy than their traditional lumber counterparts. The manufacture of composite materials (e.g., plastics using wood fiber as filler, see Text Box 22.2) will closely resemble the manufacture of other materials (e.g., plastic).

A major process innovation is on the horizon for wood product mills and pulp and paper manufacturers. Biomass gasification combined cycle (BGCC) technologies will enable the facilities to be energy self-sufficient, and possibly sell their excess power to utility companies. Currently, these facilities generate more than 50 percent of the energy they consume by combusting wood by-products, in the case of wood products mills, or "black liquor" (spent pulping chemicals mixed with organic extracts from the wood), in the case of pulp and paper manufacturers. Gasification technologies greatly increase the efficiency of energy extraction from these two forms of biomass and are expected to become commercially important over the next decade. The biomass will be delivered to a gasifier and exiting gases will fuel gas turbine combustors or lime kilns. The use of BGCC will significantly decrease carbon dioxide emissions and increase the fraction of energy derived from renewable sources for the industry.

Other process trends include: reducing VOC emissions from wood drying operations, further reducing water consumption (through in-process reuse and recycling) during pulping and bleaching, and improving delignification and bleaching technologies. In the modern pulp and paper mills now being designed, essentially closed-loop systems are being approached in which water effluent volumes are being reduced to 5–8 m^3/ton of pulp, less than 10 percent of today's typical facility. New methods are being developed to remove ions from solution prior to discharge.

The printing industry is beginning to investigate alternative inks and cleaning solvents that avoid the toxicity and volatilization problems that exist with today's products. Replacing solvent-based inks and printing plate cleaning solutions with those based on vegetable oil or water is the likely method that will be utilized, but such systems have, in general, not yet proved satisfactory.

22.5.1.2 Product Trends

A new activity in the forest products industry is the designation of "certified wood." This is wood from forestry companies that have undergone a third-party certification process that verifies the company's responsible stewardship of the land and avoidance of harmful or non-sustainable logging practices. This approach, first introduced in the late 1980s, has the potential to improve forest practice in much the same way that ISO 14001 certification may improve the environmental attributes of a manufacturing facility. In both cases, the success will depend in large part on the degree to which customers seek out companies that have successfully completed the certification process.

In the coming decades, wood fiber that was once considered waste (due to its size or quality) will be employed in a range of new materials and products. Traditional lumber products are increasingly being replaced by engineered products made from wood pieces or chips that are bound together by adhesive. In residential construction applications, glue laminated lumber can replace large structural pieces (like 2 × 12s), oriented strand board can replace plywood, and fiberboard can be used for non-structural applications like molding. New composite materials made from wood fiber and other materials, like plastic, are already being produced and used for traditional lumber applications like decking, or for new applications. The manufacture of engineered lumber and composite materials will more closely resemble, from an environmental standpoint, a synthetic material manufacturing process rather than a traditional wood product mill. It is unclear whether these new materials and products will retain one environmentally favorable feature of traditional lumber—its ability to be recycled.

An ongoing trend in the pulp and paper industry is the increased use of recycled fiber. To make substantial further gains in the recycled content of paper, which currently averages around 40–50 percent, research is needed to develop efficient and economic separation technologies. One of the most urgent research needs in this area is to develop environmentally benign pressure sensitive adhesives. Currently, paper that is contaminated with removable notes that use pressure sensitive adhesives (e.g., Post-It Notes^{TM}) is very costly to process because it is difficult to separate out the notes using conventional technologies.

22.5.1.3 *Social and Regulatory Trends*

While lumber is a renewable resource, the rate and method of its harvest is subject to social and regulatory control. Cutting in old-growth forests in North America has been severely curtailed in recent years because of concern over preservation of unique ecosystems and important habitats for other species. In some other parts of the world, where widespread clear-cutting of old-growth forests is still allowed, timber companies are coming under pressure from environmental activists and NGOs (non-governmental organizations). Wood and wood products will be increasingly marketed as sustainably harvested, and certification programs that establish the validity of such claims may gain prominence.

One response to the decline in available virgin timberlands (either because they have been harvested or because their harvesting is restricted) is the intensification of efforts to enhance forest productivity. Genetic modification of trees can improve their characteristics, reduce variability, and shorten the time between planting and harvesting. The extent to which genetic engineering is used in the growth of timberlands will be determined partly by how acceptable it is to society as a whole. This factor is hard to predict; currently, concern about genetic modification of organisms is much higher in European countries than it is in the U.S.

The production of pulp and paper will also be influenced by social and regulatory actions. The significant reduction in discharges of chlorinated compounds from pulp and paper mills has been achieved in a context of high public awareness about the environmental effects of traditional bleaching technologies. Similarly, the increase in rate of paper and paperboard recovery (from 22 percent in 1970 to about 40 percent now) has been aided by public awareness and the establishment of local recycling infrastructure. Demands for environmentally sensitive pulp and paper manufacture will likely be sustained, with an emphasis on cleaner production methods and more recovery and recycling.

22.5.2 Scenarios

22.5.2.1 *Trend World*

In this scenario, "sustainable forestry" will become the catchphrase of the industry, with efforts put into increasing forest productivity in the near term and retaining it in the long term. Trees will be grown more quickly and with lower variability, and, once they are harvested, will be used more productively with minimal waste. Efforts to reduce emissions from and improve energy efficiency of wood mill operations and pulp and paper manufacturing facilities will continue. Wood and paper products will remain important materials in the industrial system because they are renewable and recyclable.

22.5.2.2 *Green World*

In a green world, the practices used to grow and harvest wood will come under greater environmental scrutiny. Large-scale planting of genetically modified trees will be restricted and traditional logging practices, like clear cutting, will be curtailed in all geographies because of their potential to damage ecosystems. Forest products will be treated as relatively scarce resources and a much more comprehensive system will exist for recovering and recycling both wood products and paper. The production of engineered lumber will be improved to reduce environmental emissions (e.g., from adhesives) and improve recyclability.

Eventually, alternative products, like reusable electronic "paper" may find widespread market acceptance, replacing traditional markets for this industry. Competition from other crops, like hemp, as raw material for paper and packaging materials may also become important.

22.5.2.3 *Brown World*

The brown world scenario envisions a growing, rather than shrinking, market for forest products. Similar to the trend world, the productivity of timberlands will increase so maximum value is extracted from each tree. Intensification of harvesting practices may not ensure long-term sustainability of harvest lands, however. In geographic areas where harvesting of virgin forests is still allowed, this practice will continue unabated.

In addition to its traditional markets, wood may be used as a substitute for materials created by the extractive industries as non-renewables become increasingly scarce. For example, if the price of oil rises above a certain point, it will be economically feasible to manufacture "petrochemicals" from wood. These chemicals could be used as feedstock for plastics manufacture. This development may result in the production of environmentally favorable (perhaps biodegradable) plastics, but it may also entail an unacceptable intensification of timber harvesting.

In a brown world, demand for pulp and paper will rise and recycling rates will not necessarily rise commensurately. Consumers may have little interest in buying products that are "green"—e.g. sustainably harvested lumber and recycled paper—and hence the market for these products will shrink.

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Chapter 23

Packaging and Shipping

23.1 OVERVIEW

Every product that is manufactured must be delivered to the customer, and is nearly always packaged before shipment. Strictly speaking, packaging and shipping constitute the final phase of the industrial sequence in Figure 2.3, a sector-expanded version of which appears in Figure 23.1. The "packaging" industry does not perform packaging operations, however, but rather manufactures the materials with which packaging is done—wooden pallets, boxboard, plastic film, cushioning materials, steel strapping tape, etc. The packaging industry is thus properly categorized as a fourth phase component of the industrial sequence, while the packaging operations themselves are generally done by the manufacturers of the goods to be packaged. In this chapter, we deal with the two quite separate but related subsectors: packaging manufacturers and shippers.

There are many different reasons why products are packaged:

- Contain the product
- Protect the product from damage
- Keep the product clean
- Tamper-proof the product
- Retard product spoilage or other degradation
- Provide corporate identification and information
- Satisfy legal information requirements
- Promote consumer safety
- Serve as a dispenser for the product

Each of these is important to at least some manufacturers, distributors, and customers, and the different requirements that are imposed render packaging complex and materially diverse.

Packaging and shipping are big businesses. In the U.S., it is estimated that about 10 percent of the Gross National Product is expended in this sector. Many businesses,

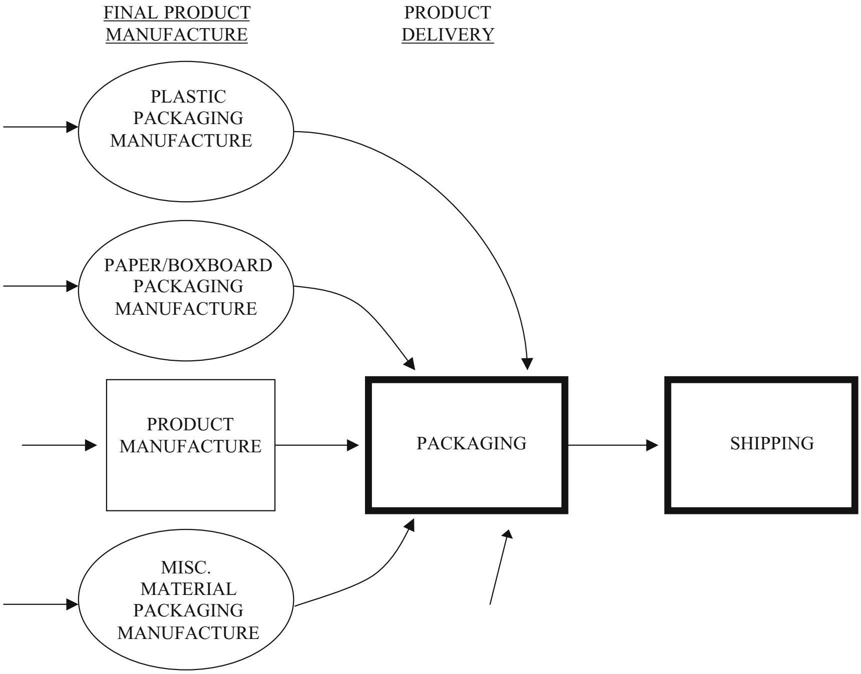

Figure 23.1. The technological sequence diagram for the packaging and shipping industries. The stages applicable to this sector are indicated by heavy outlining.

in fact, have converted to a "just-in-time" mode of operation in which material they need is delivered to them just as they need it. One result is that warehouses in which material is stored in anticipation of future use are becoming obsolete. The express shipper DHL, in fact, advertises that its planes and trucks are mobile warehouses for its customers.

Many different materials are used for packaging, but paper (including corrugated cardboard) is by far the most common packaging material used worldwide. As Table 23.1 shows, plastics and metals are also heavily used, but the relative proportions differ in different countries. The use of glass (bottles, etc.) and wood (packing crates, etc.) is steadily diminishing.

Data for the "life cycle" of packaging show that Canadian industry used 13.5 million tons (Tg) of packaging in 1990, 47 percent of it for food and beverages. 29 percent was for "other manufacturing," largely shipments from corporate suppliers to corporate customers. Shipments to wholesale and retail markets amounted to less than one-fifth of the total. Among the messages here are that food and beverage packaging offers the greatest numerical potential for packaging savings, and business-to-business shipments are also good savings targets.

Table 23.1. Percentage of Different Packaging Materials in Several Countries, 1998

Material	Japan	Germany	USA	UK	China
Paper	50.1	40.0	41.4	36.1	39.5
Plastics	16.2	26.8	15.2	15.7	22.1
Metals	14.4	20.8	28.0	27.6	7.7
Glass	4.3	8.2	10.9	11.7	5.8
Wood	9.7	3.9	3.3	4.0	9.7
Other	6.3	0.3	1.2	4.9	15.2

Source: D. Weng, *Ecomaterials* (in Chinese), Beijing: Tsinghau University Press, p. 142, 2001.

Once packaged, goods are transported by many different means. Data for shipments within the U.S. in 1995 show that nearly 80 percent (by revenue) was moved by truck, with rail, air, and water transport each contributing only between 4 and 8 percent of the total. Rail has a somewhat larger fraction in many other countries. Shipping has evolved into a business with detailed tracking of customers and shipments and of highly time-sensitive operations. Where once the activities of manufacturers, shippers, and customers of various kinds were quite distinct, they now tend to be tightly coordinated, with efficiency of operation the paramount concern.

Internationally, a very large percentage of shipments are moved by ocean cargo carriers, some by truck and rail, some by air. Global trade and the rise of multinational corporations have greatly increased the amount of international shipping over the past decade. As with domestic shipping, it is highly organized, computerized, tracked, and time-sensitive.

23.2 PHYSICAL AND CHEMICAL OPERATIONS

23.2.1 Packaging

Packaging is sometimes simple, as when a paper bag is used to hold nails from the hardware store. In that case, the manufacture of the bag is the province of the pulp and paper manufacturer and the packager is merely a user. Sometimes the packager does more than fill a container supplied by someone else. An example is the production of soft drinks or beer, where an aluminum can supplied by a metal fabricator has the lid affixed by the packager after filling. The manufacturing function at the final product packaging stage is generally trivial, however.

Several levels of packaging are commonly employed. For example, breakfast cereal is generally placed within an impermeable plastic bag and then enclosed in a cardboard container. This is the *primary packaging*, the only packaging normally seen

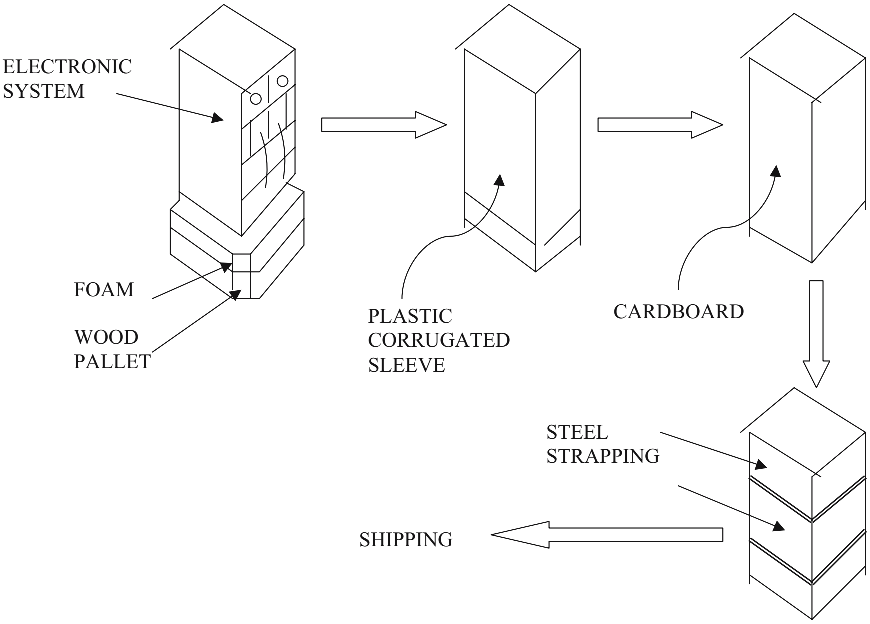

Figure 23.2. The sequence of steps and use of materials in packaging a modern electronic system.

by the final customer. The containers are, however, shipped in groups of twenty or so in a corrugated cardboard carton, the *secondary packaging*. Often, several cartons will be wrapped together with heavy plastic film for handling with fork-lift vehicles; the film is the *tertiary packaging*.

Packages can be made from a single material, but more often they are combinations of many different materials, each doing a specific job. Consider the packaging of a modern electronic switching machine for use in telecommunications (Figure 23.2). The packaging begins with a wooden pallet, which will be used for fork-lifting the product during shipment. A rugged foam pad is placed within the pallet to cushion the product. To protect the machine from dust and dirt, a plastic sleeve is placed over it, followed by a corrugated cardboard cover to provide protection during handling. Finally, steel stripping is applied to hold the packaging firmly in place. Each packaging material has a definite purpose, yet the use of so many different materials makes the eventual recycling of the packaging a real challenge.

Multimaterial packaging can be combined into a single packaging item as well, as shown in the snack chip bag of Figure 23.3. Each layer has a definite purpose, yet the co-mingling of so many dissimilar materials renders recycling completely impossible.

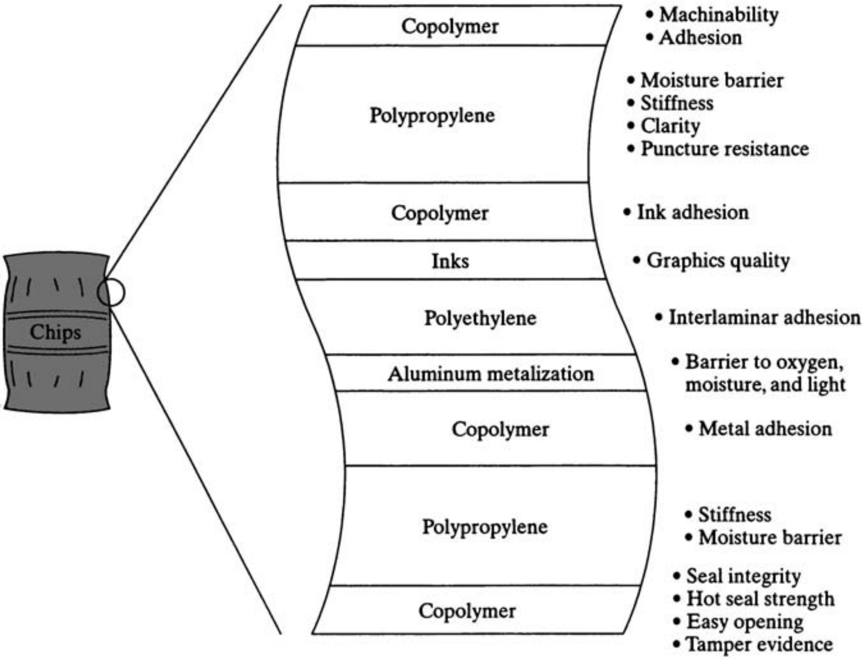

Figure 23.3. A cross-sectional view of a snack chip bag. The bag is about 0.05 mm thick and each of the nine layers is present to provide a specific function. (Reproduced with permission from Council on Plastics and Packaging in the Environment, 1992.)

23.2.2 Shipping

While trucking dominates other modes of transportation on the basis of revenue of shipments, the comparison would be somewhat different if weight rather than revenue was considered. Railroads and waterborne vessels carry very large amounts of low-value materials such as coal, chemicals, grain, and minerals, and air cargo shipments are generally of very high-value products. The approximate quantities of cargo handled by the different shipping modes in the United States are shown in Table 23.2.

One instinctively thinks of long-haul trucking in connection with product shipping, and it is in fact the largest component of the trucking industry, but local trucking and ground courier services are large as well (Table 23.3). All of these components have a significant influence on the sector's use of resources and its potential environmental impacts. The major change from a decade ago is that overnight package delivery has mushroomed during the 1990s. The major companies in the overnight delivery subsector maintain large fleets of trucks and planes to accomplish their missions (Table 23.4).

Table 23.2. Magnitudes of Material Shipped by Different Modes, United States

Shipping Mode	Quantity	Year of Data
Truck	1.8 Pg	1994
Rail	1.4 Pg	1994
Waterborne	1.0 Pg*	1995
Air	12.2 Gg#	1996

*Also 1.0 Pg of foreign freight.
#Ten largest U.S. cargo airports only.

Table 23.3. Employees in U.S. Ground Transportation Subsectors, 1992

Subsector	Total Employees
Long-haul trucking	758,000
Local trucking	355,000
Ground courier service	307,000

Table 23.4. Vehicle Statistics for the Overnight Package Delivery Subsector

Delivery Company	Deliveries (billion/yr)	Trucks (Thousands)	Aircraft
U.S. Postal Service	183	140	1500 (commercial)
United Parcel Service	3	147	499
Federal Express	1	39	596
DHL	0.1	12	209
World Total	425		

23.3 THE SECTOR'S USE OF RESOURCES

23.3.1 Energy

The amount of energy expended in packaging is small, as most of the work is done by hand. For shipping, the energy expenditure depends very strongly on the mode of transport used. If we set energy use per rail transport of a product at unity, transporting the same product by truck will consume some six times the energy, by air some forty times (Figure 23.4).

There are, at present, no general assessments of the amount of energy used in the packaging and shipping sector. Shipping will clearly dominate the final number, but the calculation is complicated by the difficulty of deriving appropriate figures for such contributions as local trucking and cargo traveling on scheduled passenger airliners.

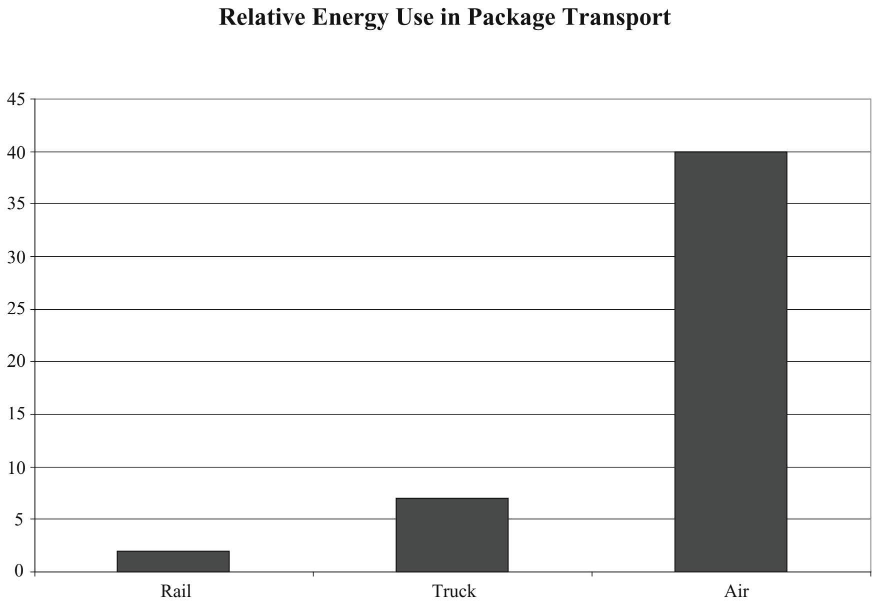

Figure 23.4. The relative energy used to transport a package by different means. (The data are from D. Rejeski, Electronic impact, *The Environmental Forum*, *16*(4), 32–38, 1999.)

23.3.2 Materials

Cartons of materials and large items are generally shipped on pallets—movable platforms easily handled by mechanized equipment. Most pallets are made of wood, and the wood consumption for some 500 million pallets a year in the U.S. alone is about 10 percent of all lumber used. These pallets generally make about five trips before being discarded or rebuilt.

Pallets can be made from materials other than wood. Corrugated cardboard is sometimes used; it is inexpensive, but generally good for only a single trip. Plastic and metal pallets are expensive, but can be reused a number of times and recycled when no longer serviceable. They tend to be used where a closed-loop recovery system is in place, as with suppliers of chemicals who regularly visit customers to deliver filled drums of chemicals on pallets and retrieve pallets from the previous delivery.

Plastic film, especially stretch wrap, is very common for packaging, some 1.1 Gg being used in 1992 in the U.S. Most stretch wrap is low-density polyethylene, which is eminently recyclable. However, only about 10 percent of stretch wrap is recovered and recycled. High-density polyethylene is commonly employed to make reusable bins. Foamed polystyrene and foamed polyethylene are used for cushioning and loose fill (i.e., "peanuts").

Glass is very widely used as a packaging material. In fact, packaging is the largest use of glass (6.7 Tg in the U.S. in 1990). It is a low-value product, however, its raw materials are abundant, and it is heavy to transport. As a result, it has a mixed recycling record.

Aluminum is another packaging material that is very abundant as a raw material. It is readily recyclable, and its value is high enough to assure substantial recycling. In contrast, tin-plated cans are less often recycled, as their value is not high. Overall, paper and fiberboard are the most used packaging materials, with glass and plastics also playing large roles. Plastic is low density, of course, so its rate of use is much higher than its relative weight would indicate.

It is very common for products to be overpackaged. Among the reasons for overpackaging are the following:

- Overly cautious approach to protection
- Large size to deter shoplifting
- Overly conservative test specifications
- Requirements of packaging machinery
- Decorative or representational packaging
- Large size to permit regulatory information, customer information, or bar coding

All of these are understandable, yet their implementation results, in the end, in large amounts of solid waste that might be minimized by better, more thoughtful packaging design.

23.4 POTENTIAL ENVIRONMENTAL CONCERNS

23.4.1 Solids

Packaging materials are discarded in large quantities, but the materials themselves have very low hazard potential. From a resource standpoint, the only widely-used packaging material with a fairly short depletion time is tin, at about 30 years.

23.4.2 Liquids

There are no significant liquid emissions problems in the packaging sector, especially for the products of final manufacture. Shipping is another story, however. Many of the vessels carrying materials (as opposed to products) must be cleaned between shipments. In such cases, rail tank cars, tank trucks, and waterborne vessels must undergo treatment with detergent, and the resulting detergent and chemical residues must be properly handled. One could extend the concerns to vehicle operations as well; this brings into play oil and lubricant emissions, aircraft deicing fluids, and paint removal residues. No overall study of the quantities of dissipated materials from these sources has been performed.

23.4.3 Gases

The transportation of products involves extensive consumption of fossil fuels, and thus the release of combustion-generated gases. Carbon dioxide is emitted in large quantities, and is a major greenhouse gas. Smog-forming gases that are emitted include NO_x and VOC. Some petroleum-derived fuels, especially bunker fuels for ships, contain sulfur and thus have the potential to emit sulfur dioxide, an acid gas precursor.

23.4.4 Sustainability Assessment

The processes, activities, and potential hazards for the packaging and shipping sector are given in Table 23.5. The materials are binned for throughput, potential hazard, and potential scarcity in Table 23.6. The TPH matrix appears in Figure 23.5. CO_2 emission is regarded as being of extreme concern, the other gaseous emissions of moderate to high concern.

Table 23.5. Processes, Activities, and Potential Emittants for the Packaging and Shipping Sector

Process Type	Sector Activities	Potential Emittants
Packaging	Goods packaging	Packaging material residues
Transportation	Goods delivery	All packaging materials, gaseous emissions from delivery vehicles Tank cleaning residues

Table 23.6. Throughput-Hazard-Scarcity Binning of Impacts in the Packaging and Shipping Sector

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
Wood	H	–	L	L
Paper, board	H	–	L	L
Glass	H	–	L	L
Plastic film	H	–	L	M
Plastic foam	M	–	L	M
Tinplate steel	L	–	L	H
Aluminum	L	–	L	L
Carbon dioxide	H	Climate	H	–
Nitrogen oxides	H	Acid rain	M	–
Volatile organics	H	Smog	M	–
Sulfur dioxide	M	Acid rain	M	–

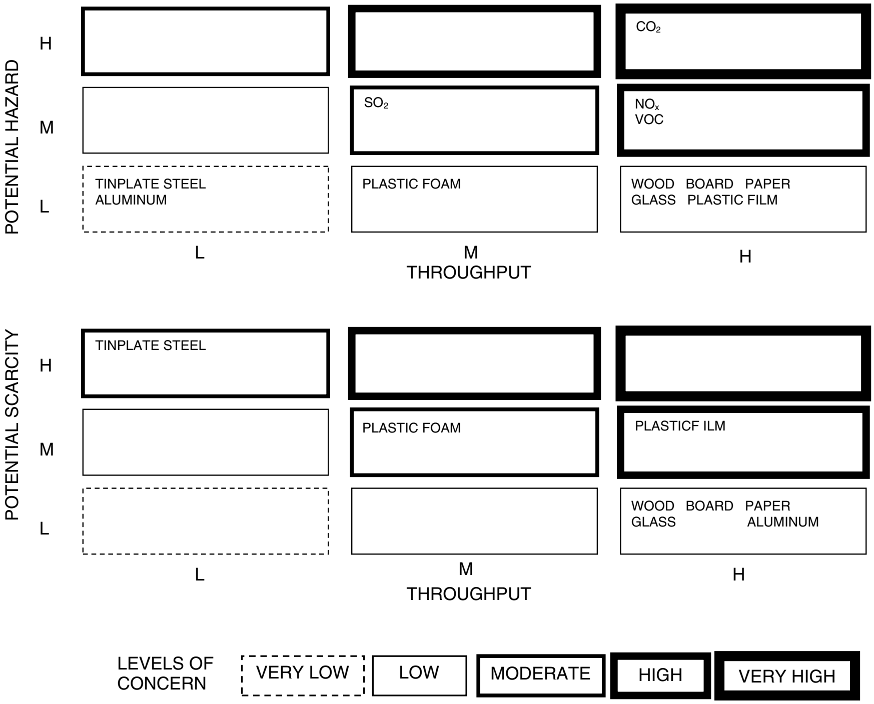

Figure 23.5. The throughput-potential hazard matrix (top panel) and the throughput-potential scarcity matrix (bottom panel) for the packaging and shipping sector.

The throughput-potential scarcity matrix also appears in Figure 23.5. Except for relatively minor concerns related to the use of petrochemical derivatives in the manufacture of foam and film, there are no entries of particular consequence.

The PEC and PWC matrices for the packaging and shipping sector are given in Figure 23.6. Water use by the sector is small. Energy use is small as well for packaging activities, but large for shipping (especially air shipping). Overall, the sector energy ranking is moderate.

The sector ΣWESH plot appears in Figure 23.7. The only items of particular concern are the energy used for shipping and the related emissions of the greenhouse gas carbon dioxide.

23.5 SECTOR PROSPECTS

23.5.1 Trends

Rather than using the conventional format of discussing process and product trends, this chapter divides trends into those related to transportation packaging

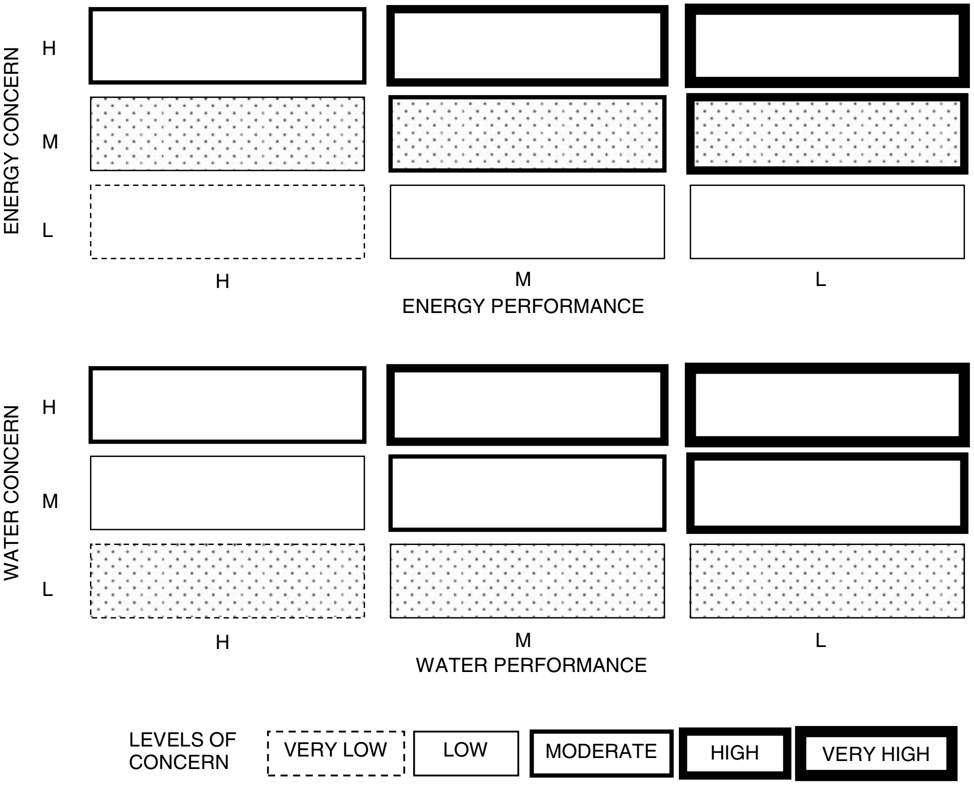

Figure 23.6. The performance-energy concern matrix (top panel) and the performance-water concern matrix (bottom panel) for the packaging and shipping sector.

(and shipping) and those related to consumer packaging. A subsection of social and regulatory trends is also included.

23.5.1.1 Transport Packaging Trends

The fraction of packaging material discarded in landfills will likely decrease in coming years as shippers and their customers respond to economic and regulatory incentives. Packaging material is generally of low intrinsic value, but rising landfill costs are making it attractive to reuse and recycle as much material as possible. According to one study, the cost of disposing corrugated boxes in New York City is as high as the original purchase cost. Because disposal costs are usually borne by the manufacturing and retail companies receiving shipments, these companies have a strong incentive to pressure their suppliers to reduce packaging waste. New regulation that limits or bans disposal is also spurring packaging reuse and recycling. In the U.S.,

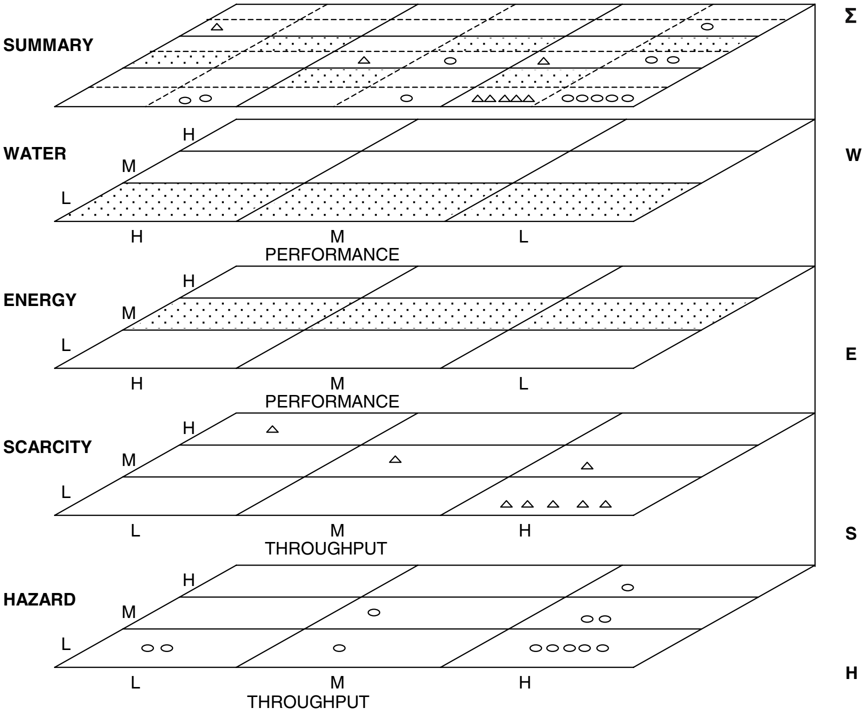

Figure 23.7. The ΣWESH plot for the packaging and shipping sector. The squares and circles refer to the materials of Figure 23.5.

some landfills cannot accept wooden pallets or steel drums and the state of Wisconsin has considered banning all industrial waste, including corrugated fiberboard, from its landfills. The German Packaging Ordinance (see Text Box 23.1), requires that all transport packaging be recycled or reused.

Several distinct practices are emerging in response to these pressures. These include the development of reusable transport packaging materials, reducing the quantity of packaging material used for a given quantity of goods, and increasing recycling rates.

Pallets and totes can be reused quite efficiently if they are recovered from a customer when a new shipment is delivered. Pallet rental companies now supply standard pallets for use in deliveries to manufacturing and retail customers. Several large manufacturers (e.g., General Motors) and retailers (e.g., Walmart) are asking suppliers to ship materials in reusable plastic totes rather than corrugated fiberboard containers ("cardboard boxes"). Aside from the environmental benefits, this arrangement gives the customer a standard package to work with, perhaps making warehousing operations more efficient or more easily automated. John Deere, a heavy machinery manufacturer,

Text Box 23.1

Regulating Recycling: The German Packaging Ordinance

Germany's 1991 Packaging Ordinance was one of the first efforts to create a comprehensive, privately operated, packaging waste recovery system. It requires that all transport packaging, and primary and secondary packaging, be returned to the distributor or manufacturer for recycle. The Ordinance set targets that, by 1998, 80 percent of all packaging waste had to be collected, of which 80 to 90 percent had to be sorted and 60 to 70 percent recycled. Collection services for homes, small businesses and schools are provided by 530 private and municipal waste management companies; in 1997, 89 percent of primary packaging was collected from homes and small businesses.

While it has been successful at achieving its goals, the German system is criticized for its high cost ($4.1 billion DM in 1997), and the fact that it encourages recycling, perhaps at the expense of the environmentally favorable practice of reducing packaging altogether. Nonetheless, the European Union established its own Packaging and Packaging Waste Directive in 1994. For the first five years, recovery goals of 50 to 65 percent and recycling goals of 25 to 45 percent were set. The EU regulations also establish mandatory return systems and mandate labeling that enables recycling.

Source: OECD Environment Policy Committee, Case Study of the German Packaging Ordinance, 1998. http://www.olis.oecd.org/olis/1997doc.nsf/linkto/env-epoc-ppc(97)22-rev2

gets 75 percent of its domestically supplied parts in collapsible, reusable containers. The use of the containers, which are made from recyclable polyethylene, has saved the company $2 million a year and reduced the amount of cardboard and wood used to ship parts. The cost, logistical, and environmental benefits of reusable transport packaging may cause it to be much more widely adopted by major customers. Reusing a package avoids the additional energy consumption associated with recycling.

Dematerialization is occurring as manufacturers and distributors find new ways to safely transport products using less material. Polyethylene shrink-wrap packaging is substituting for cardboard in some applications. For example, Electrolux has long packaged appliances in polyethylene film (with polystyrene or cardboard protectors on corners) rather than in individual corrugated fiberboard cartons. The resulting package is cheaper, uses much less material, and is lighter; polyethylene is also easily recycled. Other companies, from appliance manufacturers to baby food manufacturers are using similar packaging techniques. Shrink-wrapping, while it reduces the weight of material used, is an energy-intensive process.

Finally, increased recycling can contribute to lower packaging disposal rates. The packaging industry has historically been a heavy user of recycled material, particularly in its corrugated fiberboard containers. Recycling of other materials, including glass, plastic and steel, may increase as disposal becomes less desirable.

While the rate of packaging disposal is likely to drop, the volume of packaging materials going to landfill may not change significantly or may even increase. The recent success of mail-order and internet retail operations has caused in sharp increase in the number of packages shipped directly to end-use customers. Typically, far more packaging is used in these operations than would be used in traditional retail channels. Standard size boxes are used for a wide variety of goods and plastic, paper or foam fill is needed to protect the contents. Each item or set of items ordered by a customer is individually packaged for transport. In traditional retail settings, items are bundled and boxed or shrink-wrapped in multiples. The fraction of corrugated fiberboard recovered from individual customers is likely much lower than that recovered from retail operations who consistently receive it in large quantities.

In the shipping business, the fastest growing sector is shipping by truck. One trend that would improve environmental performance is the adoption of fuel efficient fleet vehicles. A collaboration between FedEx, a delivery service that operates 45,000 trucks, and the Environmental Defense Fund, a U.S.-based environmental group, has developed a hybrid delivery truck. Such trucks are much less polluting than conventional delivery trucks.

23.5.1.2 Consumer Packaging Trends

In the packaging of consumer products, heavy materials (e.g., glass and steel) are being replaced by lighter ones (e.g., plastic and aluminum). These changes result in substantial savings in transportation-related costs and emissions. Materials widely used in food and beverage packaging (plastics, aluminum, and glass) can be recycled (see Text Box 23.2), but the rate of recovery and recycling depends on consumer behavior and local infrastructure.

Text Box 23.2

Improving the "Tin" Can

A traditional approach to food packaging has been the "tin" can, a steel can with a thin layer of tin applied to the inner and outer surfaces to protect food and beverage flavors and to prevent rusting. Tin cans were once a major use of tin, but improved plating techniques have lowered the tin content from about 25 g per kg of steel in the 1930s to about 3 g per kg of steel today. As a result, the tin no longer creates problems in recycling furnaces, and tin cans can be used directly as feedstocks to steel recycling.

Source: C. Miller, Steel cans, *Waste Age*, pp. 69–70, January, 1993.

Packaging is, in some cases, becoming more complex and gaining functionality. For example, resealable plastic packages with "zippers" are replacing simple plastic wrappers for food. These types of changes may involve using more than one type of material in a single package, which can reduce recyclability.

Packaging is also being designed as an active, rather than passive, material. The concept is that the packaging works in concert with the product and its environment to produce a desired effect. For example, a packaging system designed to slowly release an antimicrobial agent could increase food shelf life, or a package could change color in presence of pathogens to serve as a warning signal. Modified atmosphere packaging (MAP) has been developed for fresh-cut produce. The impetus for this packaging approach is the realization that after produce is harvested it continues to live and breathe, converting glucose and O_2 to water and CO_2. If placed in a high-barrier package, the atmosphere around the produce becomes anaerobic, and rapid decay results. A very low-barrier package, conversely, transmits enough O_2 to allow the produce to age rapidly. MAP packaging has a transmission coefficient that allows CO_2 to build up to some degree, but not to very high concentrations. The result is longer product shelf life and better product quality. MAP approaches will become increasingly common for products that are subject to corrosion or degradation. Active packages will doubtless be physically and chemically complex, hence probably unrecyclable, but the benefits in some cases (e.g., less wasted food) may outweigh the disposal liability.

A final trend aims to reduce a customer's disposal problems by making a package consumable. Plastic resin pellets, produced by resin manufacturers and shipped in bags to manufacturers of plastic parts, can now be enclosed in a bag that is compatible with the pellets themselves. Once the pellets are poured into a compounding or mixing machine, the bag can be crumpled up and added to the same machine. Dupont ships some of its products in these ROTIM ("Return or Throw in Mixer") bags. A consumer version of this may also soon be developed. Researchers at the Department of Agriculture have made an edible film that can be used to extend the shelf life of fruits and vegetables. The film is made from dried, pureed fruits and vegetables and is readily recyclable, as well as being edible.

23.5.1.3 Social and Regulatory Trends

In the last decade or so, new regulations have come into force that govern the disposal, recovery and recycling of packaging waste. The goal of such regulations is to reduce the quantity of waste going to landfill. European regulations are the most advanced in this regard, but they may not become a more widespread trend. In the U.S. for example, the recovery and recycling of packaging waste is generally seen as something that the market can (and will) take care of. If the cost of reuse or recycling is lower than the cost of disposal, manufacturers and customers will work out ways to reduce or recycle materials. Arguably, this kind of a system may encourage more innovative techniques for reducing packaging waste or reusing it, rather than relying on costly and energy-intensive recycling. It is equally likely, however, that companies will fail to innovate and simply bear the costs of disposal as part of the cost of doing business.

The packaging and shipping industry is one sector where government regulations are not the only rules that govern practices. In the U.S., transportation industry associations have established standards that specify acceptable packaging materials and constructions for products. Corrugated fiberboard containers, for example, carry a stamp that shows the maximum weight that can be packed inside. These rules, while they have become less binding because of deregulation in the transportation industry, still influence how goods are packaged for shipment and have tended to hamper innovation in this area. With the growth in deliveries of consumer goods by truck (e.g., by UPS or FedEx) and the associated increased handling (relative to shipping bundled goods to retailers), the industry association representing carriers and packaging manufacturers is calling for a revision of the box weight limit standards. This would increase the amount of packaging material used for a given quantity of goods. Most countries outside the U.S. do not have equivalent rules established by industry.

Finally, the practices of individuals is an important factor in how consumer packaging waste is dealt with. Recycling in general has become much more prominent in the past several decades and increased rates of post-consumer recycling are seen. In many communities in the U.S., "blue box" programs operate so recyclables can be collected from homes; the actual materials recycled varies significantly from community to community, however. The extent to which post-consumer recycling continues to grow will depend on how easy it is for individuals to recycle, and how important they perceive it to be.

23.5.2 Future Scenarios

23.5.2.1 Trend World

In a trend world, recycling and reuse of packaging materials will increase, with the impetus for the increase differing according to geography. In Europe, regulations governing packaging waste will drive higher rates of recovery and recycling. In the U.S., changes will be largely due to individual company's efforts to cut cost, or improve handling efficiency. In other parts of the world, any combination of regulation and economic factors will drive changes in how packaging waste is dealt with.

While recovery, reuse and recycling rates for common transport packaging materials (e.g., corrugated fiberboard, plastic film, wood pallets) will likely increase, this does not mean that total packaging-related solid waste will fall. Instead, the number of product shipments, particularly to individuals or to manufacturers using just-in-time processes, may well rise. Shipping will concomitantly increase, although efforts to reduce the weight of packaging materials may partially offset the environmental impact of more shipping.

23.5.2.2 Green World

In a green world, companies, regulators and consumers would aggressively reduce packaging waste. An ultimate goal for this sector is to eliminate packaging altogether, or to make packaging immediately serve a second useful purpose (an example of the latter would be packaging that is consumable). In order to eliminate or at least sharply reduce packaging, one would need to maintain the attributes provided by packaging and listed in the introduction to this chapter: keeping the product clean, preventing theft, retarding spoilage, and so on. This goal can only be approached by a high degree of cooperation between manufacturers, shippers, and retailers to ensure clean, adequately protective, and carefully timed shipment. Some products will obviously be easier to deal with than others, but much progress could be made with a "Zero Packaging" goal. Short of achieving substantial packaging reduction, this scenario would be characterized by very high levels of packaging reuse and recycling. Packaging would be designed with reuse or recycling in mind; complex combinations of incompatible materials in a single package would be avoided.

It seems difficult to imagine an inherently environmentally favorable means for shipping products, especially when trends now point in the direction of more goods being transported longer distances. Global manufacturing has brought with it global shipping. It is not uncommon for auto parts to be manufactured in North America, shipped to Asia for assembly, and the finished vehicles shipped back to North America. To undo these trends, manufacturing and distribution practices would have to change radically, away from the current focus on economies of scale and toward a smaller, more distributed set of operations. This would not necessarily be environmentally favorable, as large-scale manufacturing may also be more efficient in terms of pollutant emissions and energy consumption. It is far more likely that shipping in a "green world" would be performed using much more fuel efficient modes and vehicles than are used today. Conversion of large fleets of trucks to hybrid systems would reduce long-term costs to the operators and significantly reduce pollutant emissions.

23.5.2.3 Brown World

In a brown world, packaging volumes and packaging diversity would increase, the latter negatively impacting recyclability. Sheer growth in the number of goods being shipped would drive growth in packaging material used, and little emphasis will be placed on providing incentives or infrastructure for recycling. Companies would reuse and recycle material only to the extent that it is economically favorable to disposal. Collection of packaging material from homes and small businesses would be relatively low as products would increasingly be packed for convenience, with disposal being an easy and socially acceptable option. Shipping practices, under this scenario, would change little from today. Diesel trucks, which are responsible for significant fractions of mobile source air emissions (in the U.S., heavy-duty diesel vehicles emit 15 percent of all vehicle NO_x emissions, and 33 percent of particulates), would continue to dominate in the ground-shipping industry.

FURTHER READING

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U.S. Environmental Protection Agency, *Profile of the Air Transportation Industry*, EPA 310-R-97-001, Washington, D.C., 1997.

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Chapter 24

Industrial, Residential, and Infrastructure Construction

24.1 OVERVIEW

Construction and operation of the built environment in the major industrial or OECD countries accounts for the greatest consumption of material and energy resources of all economic sectors. The U.S. construction industry, while it represents only 8 percent of the Gross Domestic Product, uses in excess of 40 percent of all extracted material resources in creating buildings; these buildings consume 30 percent of total U.S. energy production in their operation. In China, the construction industry represents 13.5 percent of GDP, and employs more than 70 percent of extracted material resources.

For moving sheer masses of materials, no other industrial sector even approaches that of construction. The major materials involved—crushed stone ("aggregate"), cement, reinforcing steel, and wood—together constitute approximately 40 percent by weight of all the materials moved by human action. As the sector sequence diagram of Figure 24.1 indicates, the sector is a major recipient of products from the fossil fuel, metal, and forest products sectors.

The construction sector is similar to the assembled products sector (Chapter 21) in that both combine and join materials coming from different sources. One difference between construction and assembled products is that the assembled products sector generally combines a greater diversity of products from previous stages (think of an airplane engine that houses thousands of completely different components). Another difference between the two sectors is that many assembled products such as a refrigerator or an elevator, use highly processed materials and components. Most of the materials of the construction industry are abundant, and they generally receive minimal processing prior to their arrival at the construction site. This distinction has a strong influence on the embedded energy in the materials and in their commercial value. One of the principal functions of this sector is the construction, modification,

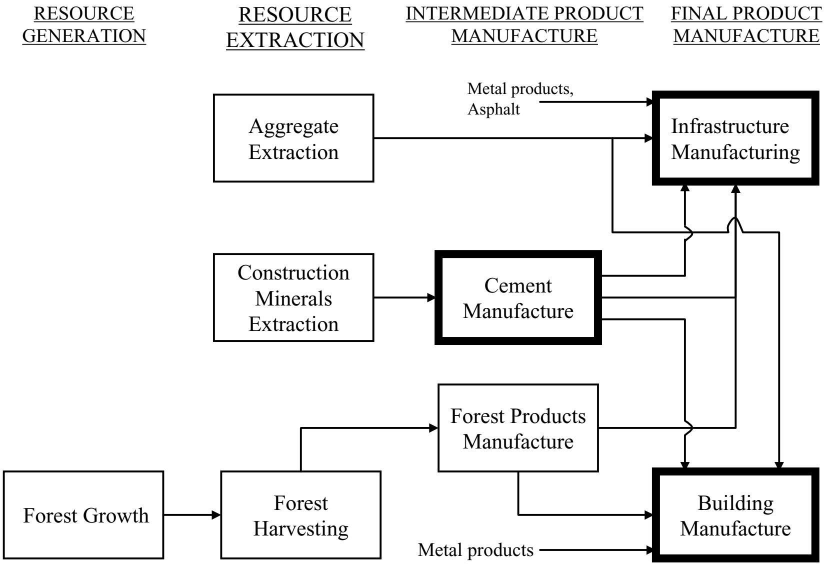

Figure 24.1. The technological sequence diagram for the construction industries. Purification processes are omitted for clarity. The stages applicable to this sector are indicated by the heavy outlining. See Figures 8.1, 10.1, and 22.1 for sector diagrams of fossil fuel, metal, and forest products.

and renovation of buildings—houses, offices, retail stores, skyscrapers, and so on. Unlike many of the other industrial sectors, residential and commercial construction is familiar to nearly everyone, at least in a casual way. The same is true of the second major function of this sector—that of constructing and operating the physical infrastructure that provides for society's common needs. The term "infrastructure" can be defined narrowly or broadly; in its broad sense it includes the following:

- Water and sewerage
- Electrical power
- Telecommunications
- Transportation
- Waste collection and processing

In a typical urban region, the infrastructure and building networks are in close proximity (see Figure 24.2) and their maintainability and reliability are important to all inhabitants. Typical lifetimes for the products of the construction sector are given in Table 24.1; they are so much longer than those of, for example, the electronics sector that one might well expect that the environmental interactions over time will differ substantially between the two sectors. Over time, of course, even long-lived

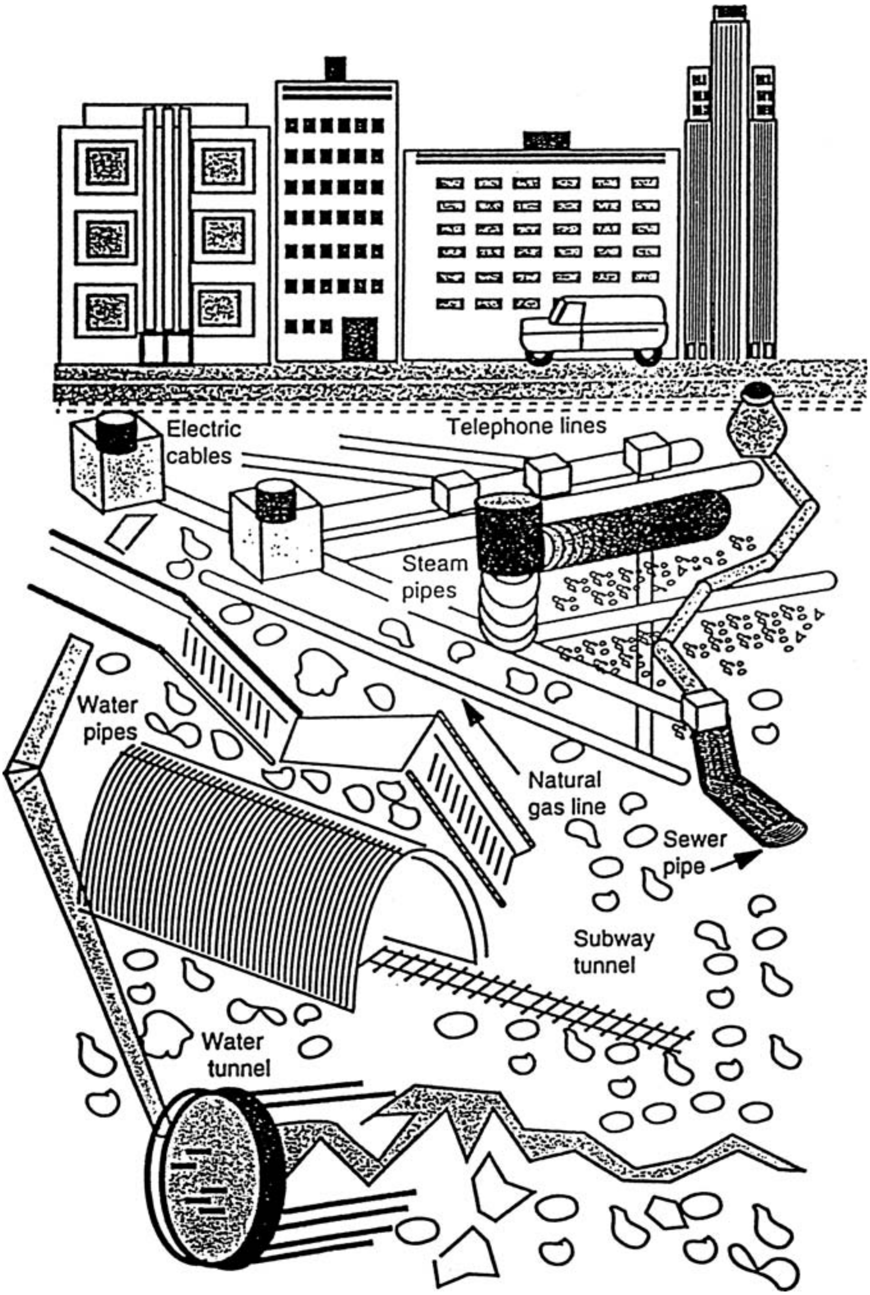

Figure 24.2. A cartoon image of urban infrastructure components. (From *A Scientist in the City*, by James Trefil and Judith Peatross, illustrator, copyright ⓒ by James Trefil. Illustrations copyright ⓒ Judith Peatross. Used by permission of Doubleday, a division of Random House, Inc.)

Table 24.1. Typical Lifetimes of Construction Sector Products

Electric power plant	20–30 years
Dam	300–1000 years
Bridge	50–100 years
Sewerage	50–100 years
Building	50–100 years
Road	5–20 years

buildings and infrastructure facilities require repair or replacement because they wear out, become too expensive to operate and maintain, or are simply superceded by new technologies.

24.2 PHYSICAL AND CHEMICAL OPERATIONS

This section presents brief descriptions of some of the more common construction processes and materials: site work, aggregate, asphalt pavement, cement, masonry, concrete, lumber, surface applicants, and insulation. Although many other important operations exist in the construction industry, the ones listed highlight the more widespread processes.

24.2.1 *Site Work*

Depending on the type and nature of any given project, site work is usually required to establish a foundation for the structure being constructed. This process can involve moving large amounts of earth, and compacting a foundation, both of which require the use of large machinery or blasting materials. Excavated soils may be transported off-site to a disposal facility, or they may be reused for foundation or landscaping purposes. If a project occurs at the same site as an existing structure, demolition may preclude any site work.

24.2.2 *Aggregate*

Construction minerals (broadly interpreted to include rock, sand, and stone) are the largest components by weight of buildings and infrastructure. Their manufacture is conceptually simple, though logistically demanding. As shown in Figure 24.3a, it begins with the extraction of the material from the mineral body, and generally proceeds with crushing and perhaps grinding to produce fragments a few centimeters or less in size. Size segregation is then performed by some form of sieving. Often this material can be used directly, as in the aggregate used to make asphalt and concrete.

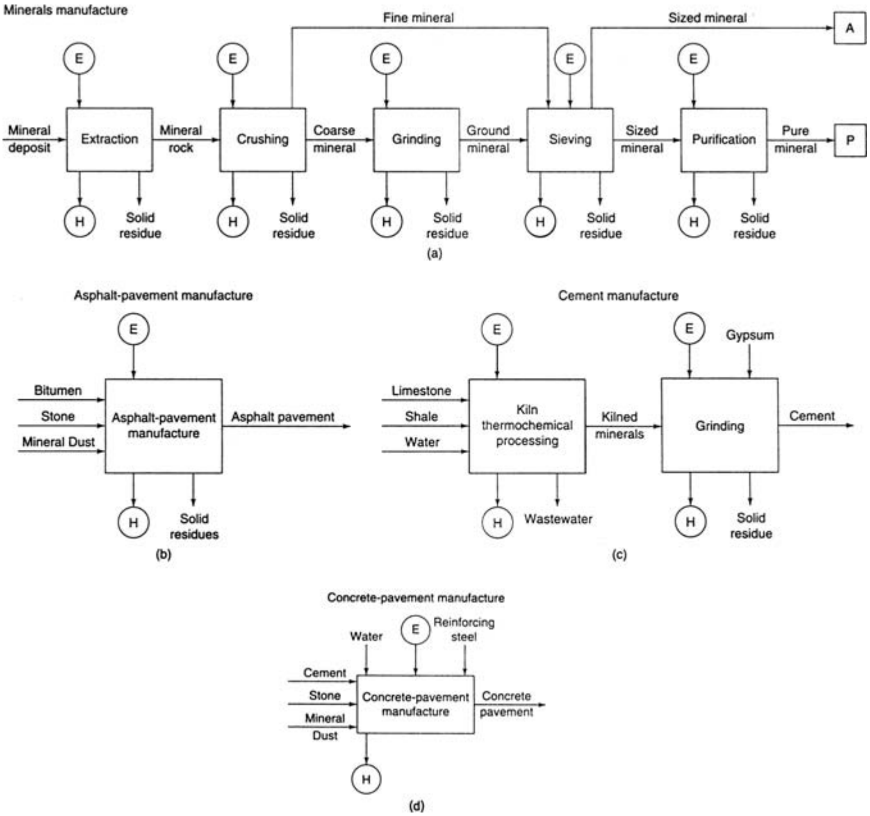

Figure 24.3. Representation of flows of materials and energy for the construction industries. (a) Construction mineral manufacture; (b) Asphalt pavement manufacture; (c) Cement manufacture; (d) Concrete manufacture. In Figure 24.3a, output A indicates a mineral material that will be used because of its physical properties, as with aggregate in making asphalt. Output P indicates a mineral material that will be used because of its chemical properties, as with gypsum in making cement. A circled E indicates energy input; a circled H indicates heat output.

Alternatively, it may undergo any of a variety of forms of purification if a pure mineral is required, as in the use of lime for soil stabilization.

24.2.3 *Asphalt Pavement*

Asphalt pavement is processed off-site, but is manufactured and finished on site. The on-site manufacturing process involves mixing bitumen, stone, and mineral dust in the proper proportions (Figure 24.3b). To begin, the bitumen is heated to 150°C to render it semi-liquid. The stone and mineral dust (the "aggregate") are then added and mixed, and the mixture spread on the pavement base. Most mixtures harden within a few hours. The byproducts of the process are heat and a minor amount of solid residues. It is worth noting that not all asphalt systems are the same; some last much longer than others, providing a form of "product life extension" and reducing the demand for maintenance material and early replacement. The use of "lowest cost" bidding procedures, which emphasizes initial cost over full life-cycle cost, unfortunately favor the less robust alternative.

24.2.4 Cement

The manufacture of cement is a very large activity throughout the world, as it is the basis for most modern buildings and infrastructure. The process combines limestone ($CaCO_3$), shale (a composite mineral of $Al_2O_3SiO_2$, and Fe_2O_3), and water. The mixture is then heated to 1300°C in a rotating kiln (Figure 24.3c). The resulting "clinker" material consists of calcium silicates and calcium aluminates. The clinker is ground to a powder and combined with gypsum to produce the cement. Typical proportions of the ingredients are 1000 kg of shale, 4800 kg of limestone, 140 kg of gypsum, and 6200 l of water.

24.2.5 Masonry

Concrete masonry units are made mainly of portland cement, graded aggregates, and water. Depending upon specific requirements, the concrete mixtures may also contain other suitable ingredients such as an air-entraining agent, coloring pigment, and siliceous materials. The manufacturing process involves the machine-molding of concrete in to the desired shapes, which are then subjected to an accelerated curing procedure at a specific temperature and pressure. This is generally followed by a drying phase so the moisture content of the units can be reduced prior to shipment. The texture, color, and other desired physical properties are obtained by varying the proportions of materials in the concrete mixtures and by altering the consistency of the mix.

24.2.6 Concrete

Concrete is usually processed off-site, but mixed and poured on-site. The manufacture of concrete pavement generally (though not always) begins with the placement of reinforcing steel, or rebar, on the pavement base layer. Cement, stone, mineral dust, and water, in precise proportions, are then mixed together (Figure 24.3d). When water is added to the cement, the calcium silicates in the cement are largely transformed into tobermorite gel (an amorphous, hydrated, calcium-containing product) and crystalline calcium hydroxide. The tobermorite gel, about 50 percent by weight of the reacted cement, is the principal adhesive agent joining the aggregate together. The mixture is poured into the pavement base layer, where it hardens within a few hours, though complete curing takes days to weeks.

24.2.7 Lumber

Lumber, a major component of buildings and a material utilized extensively in both building and infrastructure construction, is an output of the forest products sector. Its manufacture is described in Chapter 22. Typically only a fraction of the total quantity of lumber brought to a construction site is actually used in the project. Lumber products can undergo extensive cutting and sizing modifications to fit the design requirements at the site.

24.2.8 Surface Applicants

Paints, stains, solvents, and sealants are all widely used in the application of the "skin" or outer surface of a construction project. They are manufactured, site-installed, low-mass products. The physical and chemical operations used to manufacture these applicants are described in the synthetic organic chemicals chapter (Chapter 20).

24.2.9 Insulation

Insulation is a manufactured, site-processed material. It is typically produced off-site, and can take many forms, the most common of which is probably polyurethane foam. Insulation can be manufactured in sheets, where it is then cut and sized to the dimensions of the siding. Other application methods are spray foaming, where the material is actually blown into a cavity or netted enclosure. This process has a greater ability to eliminate voids.

24.3 THE SECTOR'S USE OF RESOURCES

24.3.1 Energy

Significant amounts of energy are required to manufacture buildings and infrastructure. The amount of energy invested in producing one gram of various construction materials ready for use (their "embedded energy") is given in Table 24.2. Bitumen is manufactured relatively efficiently from crude oil, and has a modest embedded energy. That for cement, which requires substantial heating in its manufacture, is about ten times higher. Steel, which is made by the recovery of iron ore, heating to a molten metal, alloying, and processing, is three times higher still. A possible mitigating

Table 24.2. Embedded Energy in Construction Materials

Material	Embedded Energy (J/g)
Bitumen	630
Cement	6700
Aggregate	74
Reinforcing steel	2.3×10^4
Steel beams	1.8×10^4

factor, however, is that steel is highly adaptable to reuse if employed in a structure from which it can readily be recovered when the structure is dismantled. The embedded energy of aggregate (crushed rock), although high, is by far the lowest of any material in the table.

The embedded energy in all the existing products of the construction sector remains to be computed, but for the world's roadway infrastructure an estimate has been made by combining the information on Table 24.2 with that on roadway type and distance. It appears that the minimum amount of embedded energy is 190 EJ and the true number may be 20–30 percent higher when all aspects of the infrastructure are accounted for. (For perspective, the total world energy use for all purposes in 1990 was 390 EJ, of which about 20 percent was consumed in transportation fuel use. The embedded energy in the world's roadway infrastructure is thus roughly half a year's world total energy consumption.)

From a life-cycle perspective, buildings consume far more energy during operation than during construction, a characteristic that emphasizes the importance of life-cycle design in architecture.

24.3.2 Materials

Construction projects can be very different, ranging from road-building to home-building. The fractions of total materials that are used across the entire sector are quite diverse, as shown in Table 24.3. The wide array of materials and products in construction projects can be generally divided into 5 categories:

1. Manufactured, site-installed commodity products, systems, and components with little or no site processing (e.g., boilers, valves, electrical transformers, doors, windows, lighting, bricks);
2. Engineered, off-site fabricated, site-assembled components (e.g., structural steel, precast concrete elements, engineered wood products, wood or metal trusses);
3. Off-site processed, site-finished products (e.g., cast-in-place concrete, asphalt, aggregates, soil);

Table 24.3. Average Materials Use per Million US Dollars of Construction Cost

Material	Use
Aggregates	90 Tg
Cement	3.3 Gg
Bitumen	1.8 Gg
Reinforcing steel	0.4 Gg
Concrete, clay, PVC pipe	0.4 Gg
Lumber	17 Mg
Guard railing	4.9 Mg
Al culvert	260 kg
Fuel & lubricants	110 kl

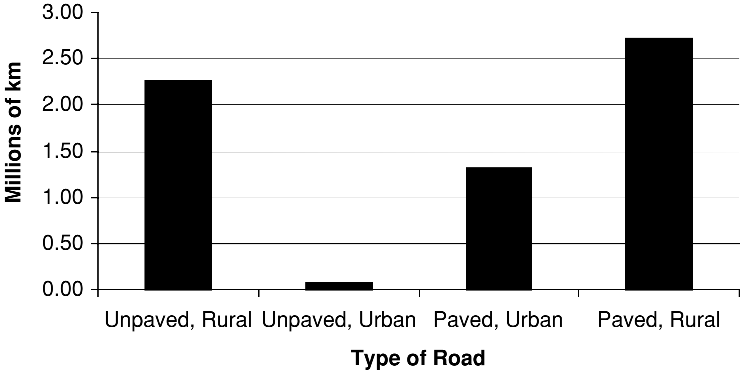

Figure 24.4. The 2000 U.S. road network, by type of road. The data are from *Highway Statistics 2000*, Federal Highway Administration, U.S. Dept. of Transportation, Washington, D.C., http://www.fhwa.dot.gov/ohim/hs00/hm12.htm

4. Manufactured, site-processed products (e.g., dimensional lumber, drywall, plywood, electrical wiring, insulation, metal and plastic piping, ductwork);
5. Manufactured, site-installed, low mass products (e.g., paints, sealers, varnishes, glues).

Over time, the proportions of the different materials in buildings and infrastructure change. For example, Figure 24.4 shows data on the composition of the U.S. road network in 2000. Half a century ago, there was an even higher proportion of gravel roads and very few concrete highways, and the amount of asphalt, concrete, and reinforcing steel was thus very much lower.

24.3.3 *Water*

A moderate use of water in the construction sector is for the on-site manufacture of concrete. Much larger quantities of water are used off-site in the processing of aggregate and sand. Relative to other industrial sectors and to other materials flows in the construction sector, the amounts appear not to be large, but have not been quantified.

24.4 POTENTIAL ENVIRONMENTAL CONCERNS

24.4.1 *Solids*

The construction industry is a major generator of solid waste, with estimates ranging from 10–30 percent of all solid waste from all sources. In the U.S., construction and demolition waste amounts to perhaps 500 kg per capita annually. For single-family wood-frame housing, studies have shown that waste generation rates are about 20 kg/m^2. The largest waste component is wood (plywood scraps, lumber segments, etc.). Next is drywall (gypsum with a thick paper cover). Third is corrugated cardboard. The remainder is divided among concrete, roofing materials, insulation, metals, and other minor components. For buildings constructed primarily of concrete, the proportion of the materials will change, but the total is nearly always high. Much of this material is potentially recyclable (see Chapter 25). In the U.S. the reuse and recycling rates of construction waste are not well known but are likely under 20 percent of the total mass and probably closer to 10 percent. Only concrete recycled for its aggregates and metals are recycled at high rates because of their relatively high economic value.

The construction industry generates large amounts of windblown dust, largely from cement production (the emission factor for uncontrolled cement kilns is about 55 kg of dust per metric ton of cement). Additional but undetermined amounts of dust result from site development and on-site construction activities.

24.4.2 *Liquids*

Except for precipitation and soil runoff during the early phases of site preparation, most liquid residues, especially most of those regarded as hazardous, occur during painting and finishing. Partially emptied containers of paints, roofing compounds, caulks, etc. are major items, along with solvents, adhesives, oils, and greases. While there have been efforts to properly dispose of such material, there has been little effort to reduce its use.

24.4.3 *Gases*

A major gaseous emission related to the construction sector is carbon dioxide from the manufacture of cement. So much energy is consumed in heating the raw materials to some 1300°C that about 2 percent of all worldwide CO_2 emissions are the result of cement manufacture.

A second, but harder to quantify, emission source is the large fleet of vehicles required to extract, move, and use the vast amounts of material used in the construction industry. The emittants are the usual suite expected from vehicles—CO_2, CO, NOx, and VOCs.

24.4.4 Habitat Disruption

When buildings or infrastructure components are constructed on previously unoccupied land, the degradation or destruction of wildlife habitat is common. This aspect of construction industry operations, traditionally widely ignored, is beginning to be a factor in land use planning and site development. Overall, however, construction activities, especially in environmentally sensitive areas such as wetlands, continue to exact a significant (but largely unmeasured) impact on the availability of habitat.

24.4.5 Sustainability Assessment

A number of different processes are used by the construction sector, and a number of emittants may result, as seen in Table 24.4. The potential hazards are collected and evaluated in Table 24.5 and the results are shown graphically in the TPH matrix, Figure 24.5.

Table 24.4. Processes, Activities, and Potential Emittants for the Construction Sector

Process Type	Sector Activities	Potential Emittants
Extraction	Aggregate mining	CO_2, NOx, VOC
Beneficiation	Comminution	Windblown dust
Forming bonds	Cement manufacture	CO_2
	Asphalt manufacture	VOC
Surface treatment	Painting, coating	VOC
Transportation	Bring materials to site	CO_2, NOx, VOC

Table 24.5. Throughput-Hazard-Scarcity Binning of Materials in the Construction Sector

Material	Throughput Magnitude	Hazard Basis	Hazard Potential	Scarcity Potential
Aggregate	H	–	L	L
Cement	H	–	L	L
Concrete	H	–	L	L
Asphalt pavement	H	Human	M	M
Lumber	H	–	L	L
Surface coatings	M	Smog	M	M
Habitat degradation	H	Ecosystem	M	M
CO_2	H	Climate	H	–
VOC	M	Smog	M	–
Airborne dust	M	Human	M	–

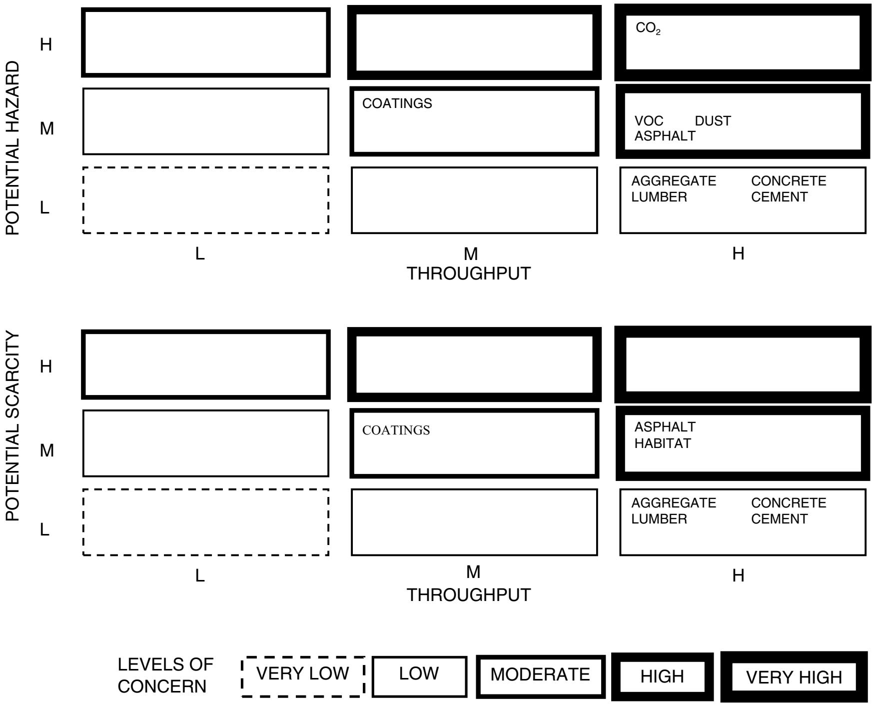

Figure 24.5. The throughput-potential hazard matrix (top panel) and throughput-potential scarcity matrix (bottom panel) for the construction sector.

As Figure 24.5 demonstrates, the high throughput of CO_2 from cement manufacture, VOCs from asphalt pavement manufacture, and habitat disruption from construction, are of significant concern. Surface coating emissions share a similar medium hazard ranking, but are lower in throughput, and are less of an overall concern. Materials used for aggregate, concrete, lumber, and cement all have high usage, but have lower associated environmental hazards.

Resource scarcity tends not to be an important consideration in the construction sector, because the materials used are nearly all very abundant and relatively benign. The only materials with even moderate scarcity evaluations are asphalt and surface coatings, both derived at least in part from petroleum. Loss of scarce habitat is also potentially significant. The throughput-potential scarcity matrix also appears in Figure 24.5.

The PEC and PWC matrices for the construction sector are given in Figure 24.6. In neither case is the rate of use particularly important. However, when assessing energy use for the construction sector, in-use consumption of energy for buildings is typically quite large, a consideration that is not shown by the EEC matrix here.

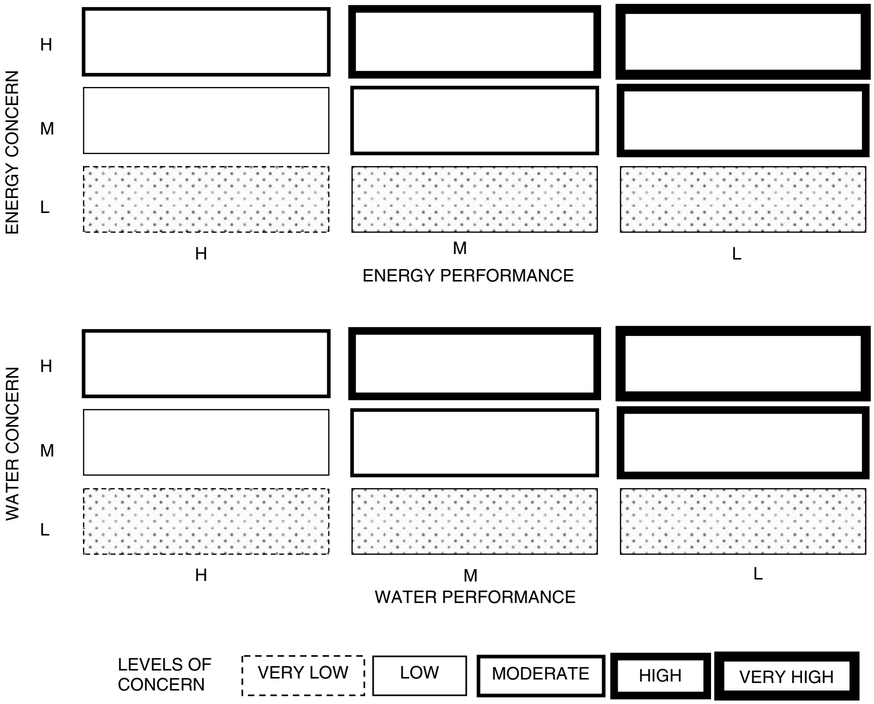

Figure 24.6. The performance-energy concern matrix (top panel) and the performance-water concern matrix (bottom panel) for the construction sector.

The sector ΣWESH plot is shown in Figure 24.7. Only the CO_2 emissions from cement manufacture and, to a lesser degree, asphalt emissions and habitat loss, are called out for particular attention. Actions to move any of these to lower concern levels would improve the environmental performance of the construction sector.

24.5 SECTOR PROSPECTS

24.5.1 Trends

Because of the very large quantity of materials moved by the construction sector, the large amounts of energy required during both the construction process and the use stage, the potential to use environmentally favorable materials, and the extended product lifetime, this sector offers great promise for reduction of total environmental impact, both during the construction process and the use stage.

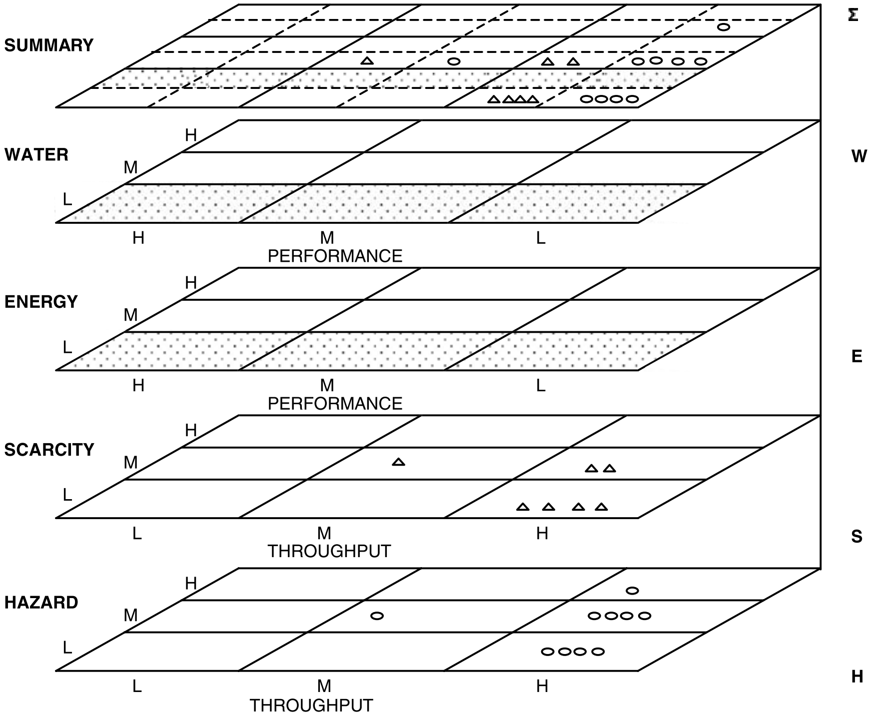

Figure 24.7. The ΣWESH plot for the construction sector. The squares and circles refer to the materials on Figure 24.5.

24.5.1.1 Process Trends

There are numerous opportunities during the construction process to minimize environmental impacts. Areas to consider include choosing materials, minimizing site disturbance, using materials and resources efficiently during construction, and minimizing and carefully managing construction waste.

Reductions in energy use will likely come slowly in the construction sector, since many of its efficiencies are achieved by employing energy-intensive construction approaches. For segments of the residential and commercial building market, modular construction is becoming more widely used. In this approach, semi-standard modules are produced at a manufacturing facility and transported to and assembled at the construction site. Computer-aided design of the modules makes assembly simple and reliable. Assembly-line speed is the attraction for the builder, but a substantial environmental benefit is that the generation of wood and drywall waste, the two largest waste streams at typical construction sites, is much reduced in a modular manufacturing environment. The energy consumed during the construction and transportation of

Text Box 24.1

Aluminum Industry's Waste Becomes Construction Material in India

The Building Material and Technology Promotion Council of India (BMTPC) has produced a composite from red mud, polymer, and natural fibers, called Red Mud Jute Fiber Polymer Composite (RFPC), to replace wood in the wood based panel products used by the building industry. This product uses zero energy-added raw materials and conserves energy by being manufactured at room temperature.

Red mud is a waste product of industrial aluminum production; it consists of alumina, iron oxide, titanium oxide, and small quantities of silica, calcium oxide and alkali. India's aluminum industry generates over 4 million tons of this by-product annually. This red mud is otherwise disposed off in ponds where it can leach into groundwater, or, during monsoons, be carried by run-off to surface water.

The RFPC can be processed and hardened through room temperature mixing and molding processes by combining red mud, lignin, and cellulose. The material can be shaped to make high quality exposable bricks, tiles, corrugated roofing sheets, and can be used as a binder for several useful products including composite doors and panels. The composite is also a great insulator. RFPC also has great applicability in developing countries where aluminum production occurs because it provides a low-cost, low energy, recycled building material that can be readily available to construction projects.

modular units is much lower than for homes constructed at a site because of the streamlined process. This energy savings likely outweighs the amount of energy consumed in transporting these units to a site.

The actual materials used in construction projects are incorporating more and more recycled products, thereby reducing environmental impacts from raw material extraction, processing, and transportation. There are many different ways to incorporate recycled products into useful construction material components. For example, fly ash (from incinerator waste from power generation) can be included in concrete, replacing a fraction of the total cement used. This diverts the fly ash from a landfill, conserves energy (and reduces emissions) from cement manufacturing, and actually increases the long-term durability of the concrete. This example illustrates just one way that recycled products can make effective and durable construction components.

24.5.1.2 Product Trends

A growing activity in the construction sector is to define the designs, materials, and practices that would result in *green buildings*. Although there is no formal definition of what a green building is, the term implies a building that is pleasing and environmentally friendly to its occupants, has minimal environmental impact, and is resource-efficient. Green building designs customarily include

- Energy efficiency
- Use of photovoltaics and fuel cells to generate electricity on-site
- Use of natural lighting
- Employment of renewable and recyclable materials
- Provision for flexibility in use
- Ease of renovation

There is good evidence that the rate of green building construction is likely to increase, that such buildings cost little or nothing more than conventional buildings, that occupants prefer them, and that over time their benefits to the environment are great. Certification schemes that ensure the quality of design for these structures are becoming more and more popular. Improved building technologies—careful use of space, advanced window coatings, improved lighting systems, efficient use of water, and so on—have the potential to make buildings much less environmentally hazardous as well as increasingly attractive to the occupants. It is typically the case that buildings employing modest energy-efficiency measures cost a few percent more to build, but the additional cost is recovered in the first few years of operation.

Energy efficiency is a central component to green building design. Buildings can incorporate geometries that maximize natural lighting to take the place of artificial lighting. Heating, ventilation, and air conditioning (HVAC) systems can be designed so that passive ventilation can be achieved, while relying less on air conditioning chillers or energy intensive heating furnaces. In large buildings, the savings in mechanical systems can more than pay for the energy improvements and actually reduce the total cost of a green building. Another aspect of green building design is the use of light and motion sensors to optimize artificial lighting and building climate control. These control systems conserve energy by detecting when occupants are and are not using rooms and adjusting heating, cooling, and lighting accordingly. Motion sensors and electronic controls can be used for both new and existing buildings, meaning that older structures that were not designed with energy efficiency in mind can be included in the green building trend.

A characteristic that might or might not be included in the green building concept but is nonetheless environmentally desirable is the design of buildings for facile adaptation. In current practice, a building is designed for first use only—its walls, floors, provisions for power, anticipated occupancy, etc. do not consider a possible second or third use: a retail store becoming apartments, a factory becoming offices, a church becoming a medical service facility. The result is that in order to refit the building for a new use it must often be half demolished. A few new designs have begun to allow for subsequent use—a WalMart store in Kansas is designed to be readily convertible to senior citizen housing, for instance. It is fairly likely that more such efforts will occur in the future.

Gradually, techniques, materials, and devices will be developed to permit the construction of “smart structures”—buildings and infrastructure components that would incorporate high-technology sensors and response components within traditional structural assemblies. Such devices would have several potential benefits:

- They would signal defects such as corrosion or deformation at an early stage, thus permitting effective maintenance and repair.
- They may be able to respond to defects by injecting adhesives or other chemicals to perform local repairs.
- Within limits, they may be able to actively respond to changes in their local environment. For example, a tall building might flex to minimize stress in response to local air turbulence.

Smart structures are desirable from an environmental standpoint as well as a commercial one. Longer-lived structures minimize resource use over time, for example, and buildings and bridges that flex actively would require a much smaller degree of overdesign than fixed structures, again preserving resources.

In the case of infrastructure, the road network will likely undergo design changes. Transportation systems work well only within regions that are planned with transportation as one of the central factors; very few regions have been so planned. The single most difficult attribute of North American urban/suburban development from the standpoint of efficient transportation has been the tendency for housing, shopping, and businesses to be located without regard for concentration or for utilizing the existing infrastructure of trains, buses, and walkways. Once any geographically dispersed use is established, collecting people into any efficient transportation network becomes expensive and difficult.

24.5.1.3 Social and Regulatory Trends

Visionary urban planners will see an evolution to metropolitan areas that are developed around a network of alternative and efficient transportation. Without sacrificing individual preferences and choices, providing the opportunity for pleasant housing and easy shopping and commuting in a variety of ways will be enabled by designing core residential and commercial areas around transportation corridors. Personal vehicles will likely be important for the first leg of any trip, but public transportation of several types would be relied upon thereafter. Safety, convenience, and cost would all need to be addressed in such a picture, but it is eminently clear that urban planning in the 21st century must encompass three factors: moving people, moving resources, and substituting information for transportation wherever feasible.

Roughly similar prospects could obtain for other types of infrastructure. One aspect is reduction of need. As products that utilize energy or water in their operation become more and more efficient, the infrastructure to support these resource flows can be correspondingly reduced. For water, further reductions are possible as water reuse becomes a higher priority and water used for such tasks as preparation of food or personal cleanliness is retained for such tasks as watering ornamental vegetation. In the case of telecommunications, the rapid advances in cellular telephony now permit many cities to do without a buried communications infrastructure at all. As the per-capita throughput of infrastructure is reduced, infrastructure will simultaneously become more dependable and longer-lived as a consequence of the incorporation of intelligent systems components. Tomorrow's buildings and their supporting infrastructure will respond beneficially to local conditions and to their own physiological status. The result will be better, longer-lived structures and much reduced environmental impact.

24.5.2 Possible Future Scenarios

24.5.2.1 Trend World

In this scenario, green building design and construction will remain a niche market. The majority of construction projects will be carried out with energy efficiency and environmental performance as secondary considerations, while building to code and for aesthetic appeal will be primary considerations. Interest in green building will increase only if energy costs rise substantially and people become aware of the options for reducing energy consumption. Because of the large stock of residential and commercial buildings already built, the retrofit of existing buildings for energy efficiency will be an important activity. This could be done relatively simply by installing electronic controls for HVAC systems, for example.

24.5.2.2 Green World

In this scenario, green building design will become the norm throughout both the developed and developing world. Information dissemination and knowledge sharing will allow the construction community to continually improve both construction materials usage and building design. Individual controls and motion sensors will be used extensively to moderate internal temperatures and lighting. Older buildings and building sites will be renovated or reused in ways that are compatible with green design. Tax and other incentives will be established to encourage building owners to invest in environmentally favorable materials and activities, rather than selecting the option that has the lowest initial cost. Urban planners will design infrastructure such that road networks are minimized and replaced with consolidated urban areas and train networks.

24.5.2.3 Brown World

In this scenario, the construction sector would not incorporate green building design widely, but would favor the lowest cost construction materials and processes.

Construction materials would not include recycled components, nor would they be designed with energy efficiency or environmental performance in mind. New buildings may continue to rapidly replace older and more outdated structures, without any effort to reuse buildings and building sites. This would add to the environmental stresses from raw material extraction and processing, as well as habitat degradation.

In a brown world, urban areas would be characterized by sprawl. Urban and regional planning efforts would expand the construction of infrastructure that caters to vehicle transportation over long distances. Road construction would continue to increase, and little attention would be given to the enhancement of light rail or pedestrian-based infrastructures.

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Chapter 25

The Remanufacturing and Recycling Industry

25.1 OVERVIEW

The remanufacturing and recycling sector gives materials another chance to be useful to society. As opposed to the waste industry, the remanufacturing and recycling sector recovers, separates, cleans, and reprocesses useful materials and products that are ultimately injected back into the industrial system. As shown in Figure 25.1, this vital sector is the one that closes the resource loop for our technological society. Figure 25.2 demonstrates that the output streams from this sector flow to many of the sectors early in the sector sequence.

The remanufacturing and recycling sector's effectiveness is controlled by seven factors:

- Amount of material—there must be enough of a product or material to justify its collection and processing.
- Concentration—the product or material must not be dispersed so widely that collection is impractical.
- Ease of separation—the material in products or other components of the discard flow must be readily separable.
- Purity—mixed materials require an additional separation step, decreasing efficiency and adding cost.
- Consistency—in order for efficient remanufacturing and recycling to occur, residue streams must be relatively similar, batch after batch.
- Proximity—a recycling or remanufacturing facility must be sufficiently close to the point of collection that transportation costs do not constrain recycling decisions.
- Inherent value—a residue stream with very low inherent value, for any reason, is unlikely to undergo reuse.

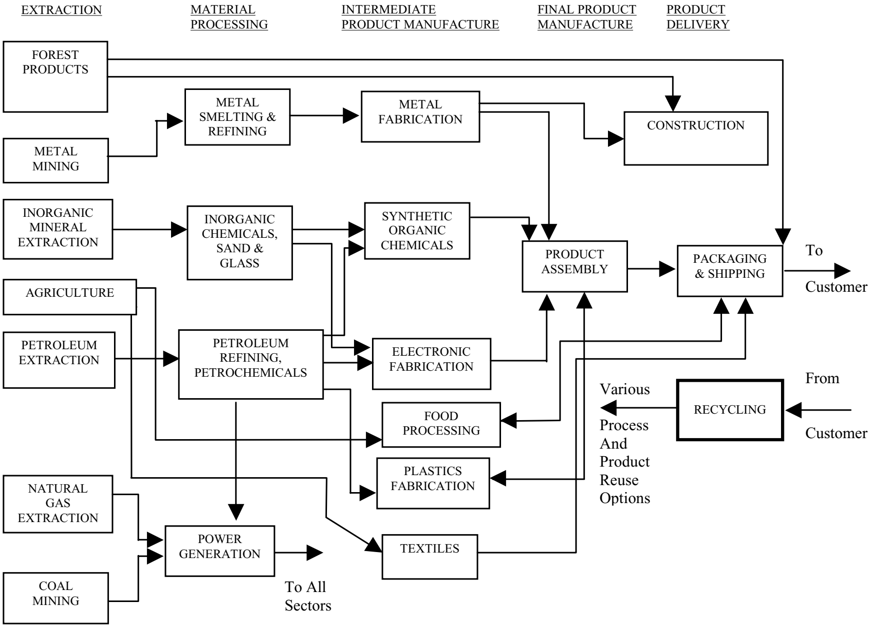

Figure 25.1. The technological sequence diagram for the remanufacturing and recycling sector.

The remanufacturing and recycling industry does not necessarily approach its job by assuming that complete dismantling of discarded objects is required. The point is made diagrammatically in Figure 25.3 where four approaches to product maintenance and modification are shown. This concept may differ slightly for different types of products, but the basic principles are product-independent.

From an industrial ecology standpoint, the preferred approach, shown as step “a” in Figure 25.3 is to practice preventive and therapeutic maintenance for as long as possible, including upgrading to capture efficiency and performance gains resulting from technological innovation. Sooner or later, however, further maintenance becomes impractical or products with superior capabilities become available and major renovation or replacement will be desirable. At that point, the characteristics embodied in the product by the designer will determine how high up the materials chain the remanufacturing or recycling of products or product materials can be accomplished. The ideal design permits renovation and enhancement to be accomplished by changing a small number of subassemblies and recycling those that are replaced (step b). Next best is a design that requires replacement of the product but permits many or most of the subassemblies to be recovered and recycled into new products. If subassemblies cannot be reused, attempts should be made to design components for recovery and use

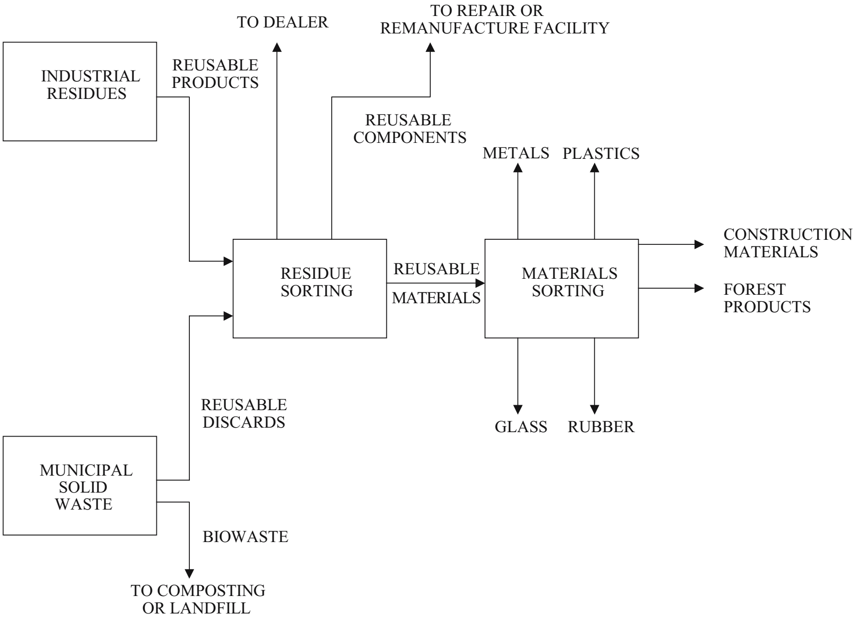

Figure 25.2. Flows of materials within the remanufacturing and recycling sector.

through several product cycles (step c). Usually the least desirable of the alternatives (step d) is removal of the product followed by recovery of the separate materials in it (or perhaps some of the embedded energy, if the materials are best incinerated) and the injection of the materials or energy back into the industrial flow stream. Disposal of the product without the possibility for any of these recycling options is not an acceptable alternative from the industrial ecology viewpoint.

It can often be the case that not all of the options shown in Figure 25.3 are feasible. In particular, it appears that remanufacturing potential is a strong function of the stability of a particular design over time. For vehicle starters, for example, a remanufactured product is a "drop-in" replacement, and starters are widely remanufactured. In the case of personal computers or cellular telephones, however, new, strikingly improved versions appear every year or two, and remanufacturing is mostly not an option. For those latter products, therefore, one should design for efficient materials recycling, but not necessarily for remanufacture.

When planning for product end-of-life, two complementary types of recycling should be considered: *closed-loop* and *open-loop*. As seen in Figure 25.4, closed-loop recycling involves reuse of the materials to make the same product over again (sometimes called *horizontal recycling*), whereas open-loop recycling reuses materials to

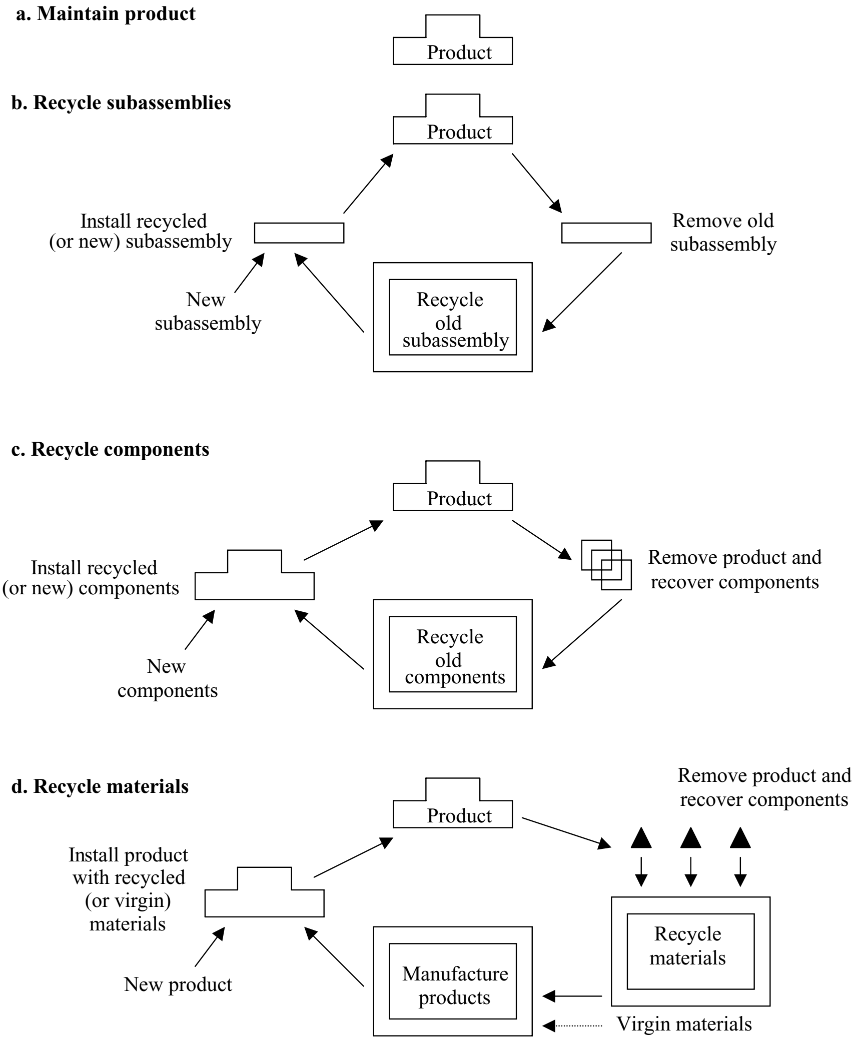

Figure 25.3. The hierarchy of preference in reuse of industrial products. Reuse should generally be accomplished as high up the chain as possible.

produce a different product (sometimes called *cascade recycling*). Typical examples are aluminum cans to aluminum cans in the first instance, office paper to brown paper bags in the second. The mode of recycling will depend on the materials and products involved, but closed-loop is generally preferred unless (as with steel) the material can repeatedly undergo either open-loop or closed-loop recycling.

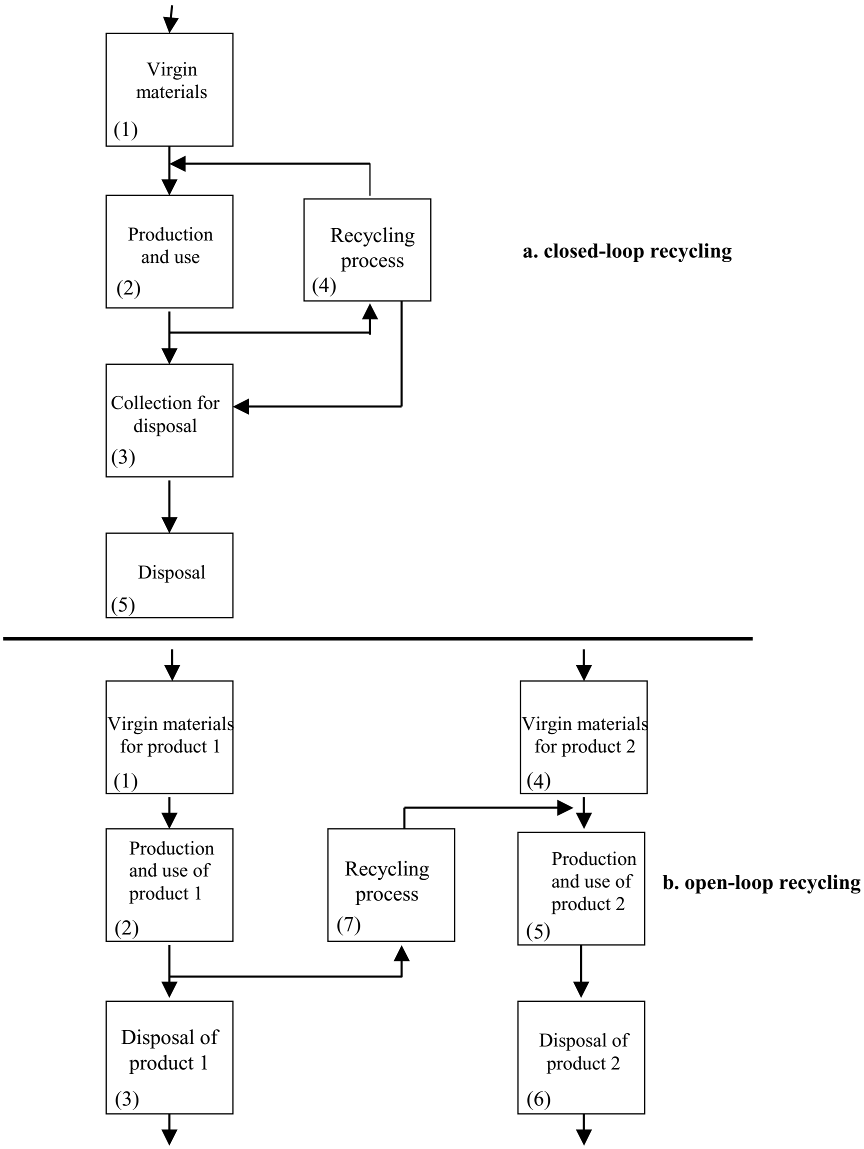

Figure 25.4. Closed-loop (top) and open-loop (bottom) recycling of materials. (Reprinted from B. W. Vigon, D. A. Tolle, B. W. Cornaby, H. C. Latham, C. L. Harrision, T. L. Boguski, R. G. Hunt, and J. D. Sellers, *Life-Cycle Assessment: Inventory Guidelines and Principles,* EPA/600/R-92/036, Cincinnati: U.S. Environmental Protection Agency, 1992.)

25.2 PHYSICAL AND CHEMICAL OPERATIONS

While the overall principles of remanufacturing and recycling remain consistent across the industry, the actual physical and chemical operations involved differ with the type of material being recovered and recycled. We discuss remanufacturing and then recycling of several common materials.

25.2.1 Remanufacturing

Remanufacturing is a form of recycling in which a product is refurbished so that it is in sound working condition and functions as a new product would. This activity is quite common, and the product lines recycled are diverse. Among the products commonly remanufactured are automobile parts, industrial robots, vending machines, copying machines, and office furniture.

Remanufacturing proceeds in five stages:

1. Complete disassembly of the product (certain welded or joined parts that would be damaged or destroyed by complete disassembly are partially disassembled).
2. Thorough cleaning of old parts (including de-greasing, de-oiling, de-rusting, and freeing the parts from old paint).
3. Inspection and sorting of disassembled and cleaned parts to evaluate the potential for remanufacture.
4. Reconditioning of used parts or provisioning of new parts.
5. Product reassembly and test.

The failure rates of most remanufactured products are quite low. This is because the failure rate is high at the start of a product's life (due to material defects or manufacturing errors), and again at the end of life (due to wear and fatigue of parts and materials). In the long period between those extremes, units arriving for remanufacturing often have most of their parts still in good working shape. As a result, the reliability of most remanufactured products tends to meet or exceed that of new products that perform the same function.

25.2.2 Recycling of Metals

Pure metals are supremely recyclable, and many of them have been historically recycled to a very high degree, as was shown in Figure 10.6. The recycling process involves the reentry of metal scrap into the refining process, often after a purification step largely involving the removal of oxides and other corrosion products.

Metals recycling is complicated by the use of mixed metals. If possible, products should use a single metal or metal grouping. This guideline is especially important if a small amount of a metal is used with a large amount of another metal, such as when steel is plated with cadmium. When the material is recycled, the plated metal is generally difficult and uneconomical to recover and tends to be discarded. A second example is when steel automotive scrap mixed with copper wire is recycled. Copper impurities in steel have substantial negative effect on its mechanical properties; aluminum wire is preferred if steel and electrical wire are to be recycled together.

For technical reasons, the residues of different metals follow different recycling paths. The flows of the ferrous metals (those with iron as the principal component, largely termed steels) have much larger magnitudes than is the case with other metals, and their magnetic properties enable them to be readily separated, baled, and sent to steel mills for recycling (Figure 25.5). Lead is also dealt with by itself, a process made relatively straightforward by lead's dominant use in easy-to-recover batteries. Components containing precious metals, of which electronic circuit boards and vehicle catalytic converters are common examples, follow a recycling path designed to optimize the recovery of gold, silver, palladium, and other valuable constituents. Other common industrial metals, largely aluminum, copper, and brass, have recycling paths as shown in Figure 25.5.

The industrial processes used for recycling metals are essentially those of the refining stages of metal production (Chapter 10). Rather large amounts of energy are

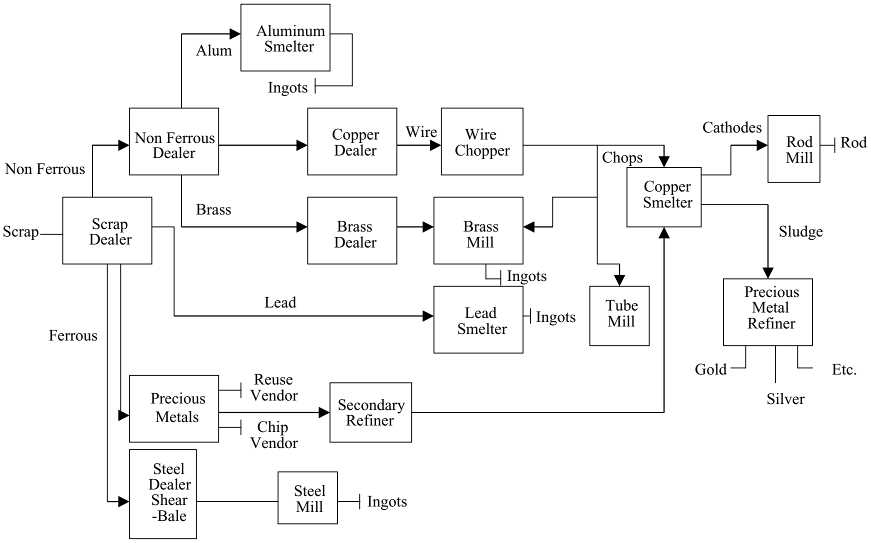

Figure 25.5. The metal recycling industry. (Adapted from a diagram devised by Lucent Technologies.)

used to liquefy and recast the metal into ingots or other metal products, but process chemicals and unusable residues are few.

25.2.3 Recycling of Plastics

If careful attention is given to design and materials selection, many of the plastics in industrial use can be recycled. This is particularly true of thermoplastics, which can be ground, melted, and reformulated with relative efficiency. Among the thermoplastics for which recycling facilities now exist are polyethylene terephthalate (PET), polyvinyl chloride (PVC), polystyrene (PS), and the polyolefins [such as high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polypropylene (PP)]. The utility of recycling these materials is a function of their purity, which implies that the use of paint, flame retardants, and other additives should be minimized or avoided if at all possible. Having plastics of many different colors in a product limits recyclability options as well. A further consideration is that designs should minimize the potential for plastics to become coated with oil or grease in use, since this also limits the efficacy of recycling.

The recycling process for thermoplastics consists of grinding the plastics into pellet-sized fragments and using those fragments as the input stream for injection

Text Box 25.1

From Carpet to . . . Carpet

Among the diverse products routinely sent to landfills is worn or discolored carpet—some 3 Tg/yr in 1998 in the US alone. Much of the carpet is made of nylon, a condensation product of adipic acid and hexamethylenediamine (HMD), generally with a polypropylene and latex backing and calcium carbonate filler. Over the years, various secondary uses have been found for old carpet scraps—carpet underpadding, soundproofing materials, and the like. Now several companies are attempting to recycle carpet materials into input materials for new carpet: to "recycle carpet forever."

One of the companies leading this effort is Evergreen Nylon Recycling of Augusta, GA. In cooperation with two carpet manufacturers, DSM and Honeywell, Evergreen reacts the nylon with ammonia. This cleaves the bonds that join the adipc acid and the HMD, creating raw material for new carpet manufacture. The carpet backing and filler materials are sent to a cement kiln, where the organics are incinerated for their energy content and the calcium carbonate becomes raw material for cement. The result is almost complete recycling of a product that until recently was discarded.

Source: A. H. Tullo, Du Pont, Evergreen to recycle carpet forever, *Chemical & Engineering News*, pp. 23–24, Jan. 24, 2000.

molding, extrusion, or film casting operations. Plastics unsuitable for these processes because of additives or colorants can undergo open-loop recycling to park benches and other secondary uses.

Recycling is much more difficult with thermoset plastics, a group that includes phenolics, polyester, epoxides, and silicones. Thermosets form crosslinked chemical bonds as they are created; recycling consists of reduction to lower molecular weight species by pyrolysis or hydrolysis. These processes are endothermic, however, and much of the embedded utility in the thermosets is thereby sacrificed. Incineration for energy recovery is preferable to landfilling, but represents a complete degradation of the material and is generally a recycling process of last resort.

25.2.4 Recycling of Construction Materials

The construction material recycled in the largest amounts is asphalt pavement. This process, shown in Figure 25.6, involves pavement fragmentation, followed by rotor-milling to reduce the pavement chunks to very nearly the size of the original aggregate. Depending on the availability of equipment and the ease of transportation, the milling may be done at the construction site or the paving fragments may be taken to a rotor-mill at a fixed site. The resulting milled material is then reheated, reformulated with the addition as necessary of new bitumen, and reapplied to the base surface material. It is often quicker to recycle pavement on-site than to import and

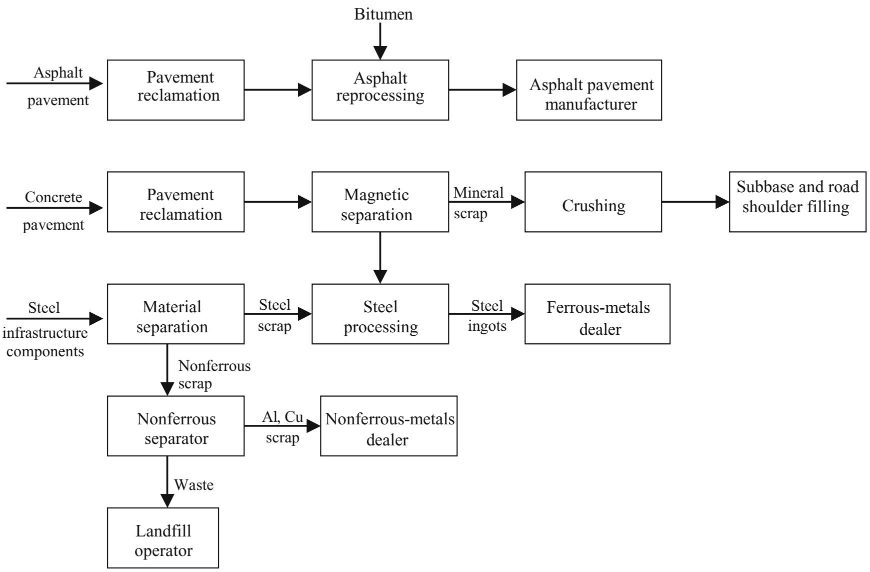

Figure 25.6. The recycling infrastructure for construction materials.

use virgin materials, a characteristic that permits minimum disruption of traffic flow during repaving activities.

The potential for recycling of asphalt pavement can be high if the proper materials were used in the pavement in the first place. The key ingredient is the aggregate, which must be non-porous and have good integrity so that it will retain a rough surface and contribute to a road surface with good traction. Such aggregates are said to resist "polish." Where attention has been given to incorporating high-quality aggregate, and where the rather expensive rotor-milling equipment is available, recycling rates of 90 percent or higher are not unusual. This is particularly true in urban areas. Overall, the asphalt recycling rate is probably in the neighborhood of 50 percent and is growing.

Concrete undergoes end-of-life processing by crushing, followed by magnetic separation to separate the steel reinforcing bar and rod fragments from the mineral matrix (see Figure 25.6). These metal fragments are then recycled as with any relatively impure industrial steel. The mineral-cement matrix has several potential uses. The best, if energy costs do not make it prohibitive, is sending lightly-crushed concrete to an aggregate supplier for final crushing. The resulting material is then used just as is granular material from natural sources. Alternatively, the crushed matrix material can be used as filler for highway construction or modification.

Obsolete building and infrastructure components can be recycled as can any large industrial product. Among current practices in a number of locations are the reuse of aluminum signs following stripping and cleaning (at one-third to one-fifth the cost of new signs), the reconstruction of metal-beam guardrail, and the reuse at the same or different locations of hardware such as manhole covers and frames, lighting standards, and chain-link fencing. For hardware components, especially, design for environment approaches can be helpful in making recycling easier and more profitable.

25.2.5 Recycling of Forest Products

Of all the raw materials that humankind utilizes, the one that best approaches the goal of industrial ecology may be forest products: paper, cardboard, wood, and so forth. The raw material itself can be regenerated within a few decades and the processed material is often utilized successfully for very long periods of time, as in housing timbers and frames. Following use, a significant fraction of forest products is recycled. The most highly developed recycling system is the several-stage process for paper. At each recycling state, the fibers in the paper become shorter and the acceptable use is more restricted, a normal cycle being from white bond to colored bond to newspaper to grocery bags to toilet paper. Lumber recovered from building sites or from buildings themselves can often be reused as is. Given the quality of old lumber, in fact, thriving businesses exist to retrieve and reuse valuable lumber during building demolition.

25.2.6 Recycling of Glass

From a technological standpoint, glass is recyclable. From a practical standpoint it often is not, because it has low value and its high density makes transportation to recycling facilities expensive. Accordingly, little glass undergoes closed-loop recycling. A better potential exists for open-loop glass recycling in which used glass is ground into small pieces and used in that form as a filler in fiberglass or asphalt (where the resulting product is termed "glassphalt"), as an abrasive, or as a reflective bead in roadway signs or lane markers.

25.2.7 Recycling of Rubber

Most rubber is used for vehicle tires, and the number of discarded tires is daunting—the United States alone throws away 250 million tires every year. For decades these tires were dumped in landfills and other less suitable places, but limited landfill capacity and a feeling that there must be better alternatives are gradually changing that approach.

Retreading tires is useful in lengthening service life, but merely delays the inevitable. Upon eventual discarding, a fraction of today's old tires are sent to modern facilities that shred and separate them into three flow streams: small tire chunks, steel shards, and crumbs. The steel is readily recyclable. The crumbs are burned for energy (each tire contains more than eight liters of recoverable petroleum). The chunks see a variety of uses—for running tracks, rubber boots, and rubberized asphalt, to name a few. The best use for old tires and other rubber products may be to serve as fuel for cement manufacture. Rubber burned in cement kilns provides significant amounts of energy that would otherwise have to be provided from other sources, and residues are small.

25.3 THE SECTOR'S RESOURCE BALANCE

25.3.1 Energy

Although the recycling industry consumes energy, it generally preserves much more embedded energy than it uses. As Table 25.1 shows, recycled metals can be made available at 7–30 percent of the energy cost for virgin metals, depending on the metallurgical processes involved. The remanufacturing sector does even better, typically preserving about 85 percent of the energy initially used to make the product. Worldwide, this is an energy saving roughly equivalent to the energy generated by eight average size nuclear power plants.

While saving embedded energy is one positive contribution of this industrial sector, another is the recovery of chemical bond energy in non-recyclable plastics,

Table 25.1. Energy Input (GJ/Mg) Required for the Production of Various Metals

Metal	Primary Production	Secondary Production
Steel	31	9
Copper	91	13
Aluminum	270	17
Zinc	61	24
Lead	39	9
Titanium	430	140

Source: The data are from P. F. Chapman and F. Roberts, *Metal Resources and Energy*, Boston: Butterworths, 1983.

rubbers, and forest products by incineration. When the incineration is well-controlled, it preserves a portion of society's investment in these materials that does not occur if they are landfilled.

The energy balance for the recycling of glass and construction materials is problematic, since their weight requires substantial amounts of energy to transport them to the reprocessing site. The decision to recycle or landfill these materials needs to be made on a case by case basis for that reason.

25.3.2 Materials

Unlike nearly all other industrial sectors, the recycling industry is a net producer of materials. This does not mean, however, that all materials should be recovered. In many cases, the energy and/or labor required for materials recycling may exceed the benefits of reusing the materials. The situation can be expected to tilt more strongly in the direction of recycling as products designed for ready disassembly and with minimal materials diversity begin to enter the recycling stream, but there will always be some residues that for various reasons are unsuitable for recycling.

25.3.3 Recycling Processes

The recycling industry is not a heavy user of process chemicals nor of great amounts of energy. Manual disassembly is common, as are mechanical processes such as crushing and sorting.

25.4 POTENTIAL ENVIRONMENTAL CONCERNS

The potential environmental concerns of the recycling sector are relatively modest. As seen from Table 25.2, almost all relate to the use of energy, generally from fossil fuels, or to the incineration of residues. Modest amounts of slag and other residues of

Table 25.2. Processes, Activities, and Potential Emittants for the Remanufacturing and Recycling Sector

Process Type	Sector Activities	Potential Emittants
Beneficiation	Concrete crushing	CO_2
	Glass crushing	CO_2
	Tire shredding	CO_2
Cleaving bonds	Plastic incineration	CO_2, VOC
	Wood incineration	CO_2, VOC
	Tire incineration	CO_2, SO_2, NOx, VOC
Purification	Scrap sorting	Discards to landfills
	Parts cleaning	Metals to water, VOC
	Metal refining	CO_2, slag
Transportation	Collection for recycling	CO_2, CO, NOx, VOC

Table 25.3. Throughput-Hazard Binning of Materials in the Remanufacturing and Recycling Sector

Material	Throughput Magnitude	Hazard Potential
Slag	M	M
Solvents	M	H
CO_2	H	M
SO_2	M	M
CO	M	M
NOx	M	M
VOC	M	M

little value from sorting processes require landfill disposal. Remanufacturing requires the use of solvents and abrasives.

The potential emittants from Table 25.2 are combined with a general knowledge of associated flow and hazard information in Table 25.3. The throughput-hazard diagram for the recycling sector appears in Figure 25.7. Carbon dioxide emissions from the use of energy in beneficiation and incineration constitute the only major concern. Since this sector deals with the recovery of materials, not their consumption, a throughput-potential scarcity analysis is largely inappropriate, with the use of solvents in remanufacturing the only moderate concern.

The PEC and PWC are given in Figure 25.8. In each case, the level of concern is low.

The ΣWESH plot for the recycling sector is shown in Figure 25.9. Combustion emissions—CO_2 and to a lesser extent SO_2 and NOx—are the only items of particular significance.

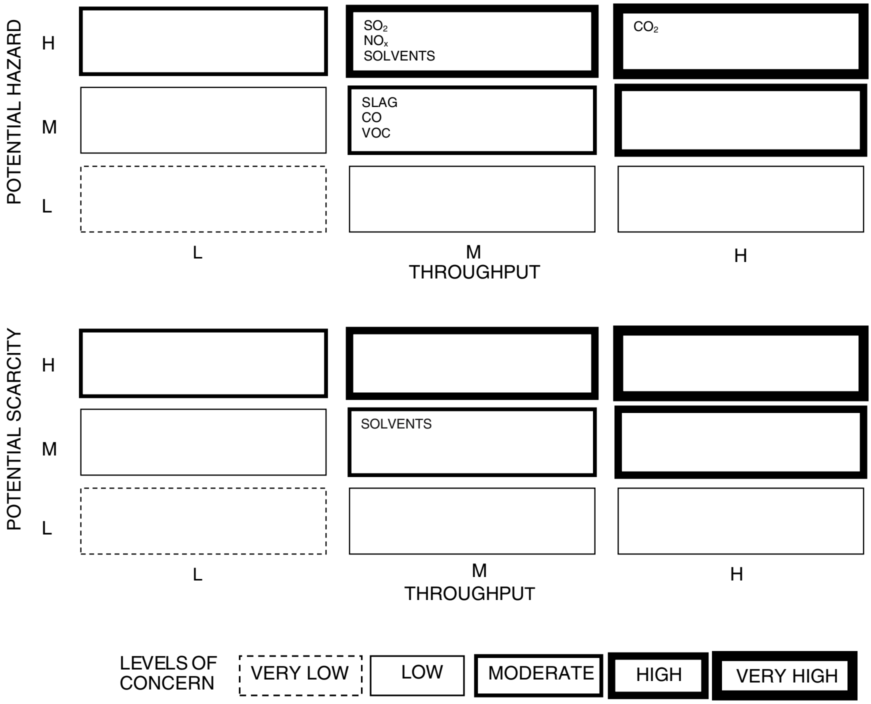

Figure 25.7. The throughput-hazard matrix for the recycling sector.

25.5 SECTOR PROSPECTS

25.5.1 Trends

The focus of many recycling efforts has been municipal solid waste. More and more, programs and policy incentives are extending this effort to durable consumer products and to industrial residues. As these activities stimulate the development of improved recycling infrastructure, rates of recycling of these latter residue streams will rise markedly.

As second thrust now well underway is the remanufacturing of commercial products. Especially where corporations find viable markets for refurbished products, this activity will increase and products will be kept from the waste stream.

A key factor in the economic viability of recycling companies is the speed with which incoming discards can be disassembled and recycled. With designers now beginning to incorporate "design for disassembly" into their thinking, disassembly speeds are likely to increase rapidly in the future. One aspect of designs that adds greatly to disassembly time is if it is difficult to identify the materials from which a product has been made, the functions of its modules, and other characteristics. Such considerations

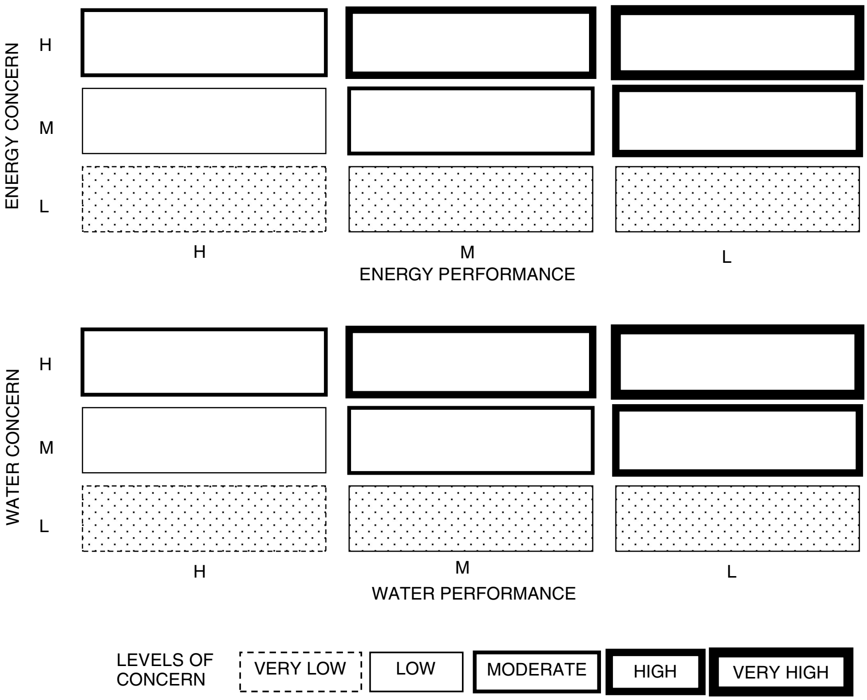

Figure 25.8. The performance—energy concern matrix (top panel) and the performance—water concern matrix (bottom panel) for the recycling sector.

are of little concern if a manufacturer receives its own products for recycling, but may be a major recycling roadblock in facilities dealing with the products of numerous industrial organizations. To alleviate this difficulty, Sony's technology center in Stuttgart, Germany, has proposed that all products incorporate in their design a "Green Port," that is, an electronic module that contains retrievable product materials data in tamperproof form. The module would be made to an industry wide standard and addressable through a diagnostic connector. It seems likely that some variation of this idea will eventually be implemented, at least for reasonably expensive and long-lived products.

So far as flows and markets are concerned, it is likely that these will improve with time as well. Designers are beginning to specify materials by their properties, not their source, i.e., "materials X of purity Y percent" instead of "virgin material X". As this trend increases, recycled materials markets will become more stable, and the recycling sector will become more and more predictable.

A rapidly developing trend is that of *extended producer responsibility* (EPR), in which ownership of a product is retained by the manufacturer and the service provided by the product is leased to the customer. Since the manufacturer is assured of having

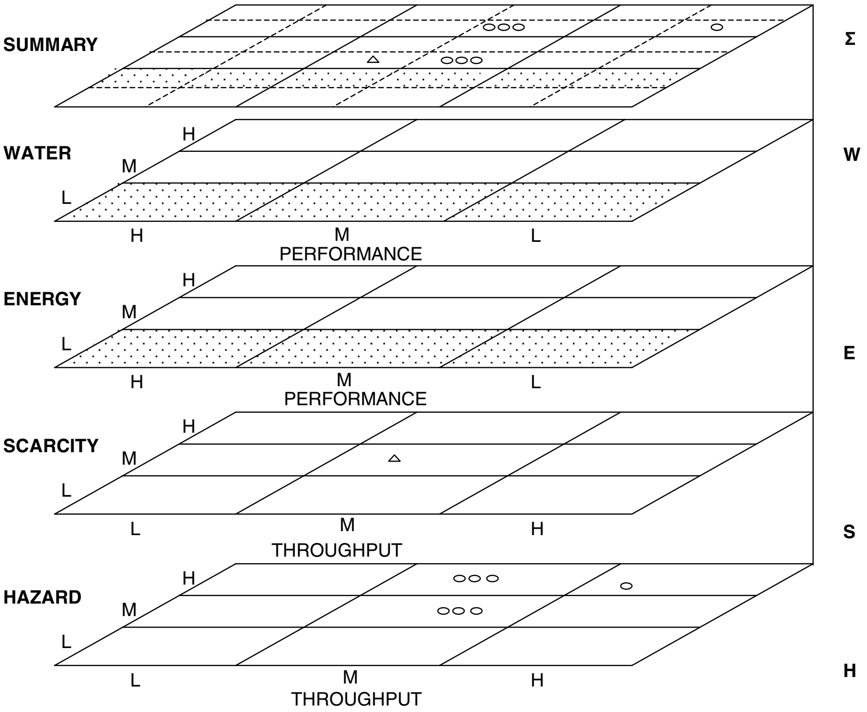

Figure 25.9. The ΣWESH plot for the recycling sector. The circles refer to the materials of Figure 25.7. Since this sector recovers materials rather than consuming them, there is only one entry in the scarcity mix.

to deal with the product when it becomes obsolete, there is considerable incentive to design it such that it is readily upgradeable and recyclable. It seems likely that EPR will become increasingly common, and that the recycling industry will partner closely with manufacturers to optimize the rate of material and component recovery and reuse.

25.5.2 *Possible Future Scenarios*

25.5.2.1 *Trend World*

The recycling of many materials will continue to rise gradually, but then will begin to level off at moderate percentages as collection and sorting costs make further improvement unprofitable. More attention to modular design will increase the rate of remanufacture for large, complex products, especially in industry. In contrast, smaller consumer products will increasingly be designed for single use, with limited possibilities for remanufacturing or recycling.

25.5.2.2 Green World

In a green world, remanufacturing and recycling rates will increase significantly, informed by a vision of near complete recovery and reuse. Architect William McDonough has proposed that all products be divided into two groups: *products of consumption* and *products of service.* The former are made of materials, mostly organics, that will biodegrade; it includes food products, most packaging, and perhaps many other things. These products need to be properly handled and contained until biodegradation occurs, perhaps after several reuse cycles for some of the materials. Conversely, products of service are those made of nondegradable and often biohazardous material that is used because of its particular physical and chemical suitability for the function being performed. Ideally, 100 percent of the products of service will be remanufactured or recycled, both to conserve the embedded energy and technology contained therein, and to avoid the potential environmental effects should they be dissipated. This vision of the complete treatment of the end of life of technology's products is, almost certainly, unrealizable, but approaching that goal will produce major environmental and resource benefits.

25.5.2.3 Brown World

In a brown world, design for environment will not be important to product design teams, and remanufacture, recycling, and reuse of many products will be problematic. The desire to prevent remanufacturing and recycling facilities from being located close to large populations will add costs and make most potential remanufacturing and recycling unprofitable. Cash-strapped governments will be unable to support collection and sorting for municipal discards. As a result, overall reuse rates will decrease, especially for consumer products.

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Chapter 26

Advanced Materials, Processes, and Products

26.1 OVERVIEW

The study of the structure and properties of materials—materials science—is a field with a rich history, and one in rapid evolution. These characteristics are shared by the materials industry, and especially by that component of the industry involved in the production of advanced materials. The realm of materials is broad, and its constituents may be grouped in several different ways, as seen in Table 26.1.

Increasingly, materials used in a variety of applications combine several types of materials—metal, plastic, wood, glass, or ceramic—into a structure with new properties. From biodegradable fast-food packages made from limestone, potato starch, and paper, to highway bridges constructed of fiberglass composites and carbon-fiber reinforced concrete, products and structures increasingly employ novel materials that are often manufactured in novel ways. These new materials and the techniques used to manufacture them may be derived from traditional ones (e.g., plastic-matrix composites are an extension of plastics manufacturing) or they may be enabled by entirely new technologies (e.g., nanotechnology). In this chapter, we refer to all of these materials as advanced materials and group them roughly into three categories:

- *Composite materials* that combine several materials to achieve new properties.
- *Functional materials* (sometimes called "intelligent," or "smart," materials) that can sense changes in their environment and respond.
- *Assembled materials* that, instead of being refined and extracted from other materials or feedstock, are built up using nanotechnology or biologically-based techniques.

These categories are not exclusive, as, for example, composite materials can be made using nanoparticles as reinforcing material, and functional materials may also be

Table 26.1. Approaches to the Classification of Materials

	Class	Subclass
According to composition	Metal Polymer Ceramic Composite	
According to physical or chemical properties	Conductivity Melting point Chemically inert	
According to manufacturing process	Metallurgy Assembly	
According to use	Constructional Functional	Steel Glass Electronic Biomaterials Smart materials

composites. The categories do allow us to organize these new advanced materials in a way that enables us to discuss both their properties and their manufacturing processes.

26.1.1 Composite Materials

Composite materials are the most widely used type of advanced materials and have been in use for the longest period of time, with materials like fiberglass coming into large-scale commercial use in the mid-1900's. Composite materials typically consist of a matrix made from metal, plastic, or ceramic, and reinforced with fibers or particles. Plastic-matrix composites made using a thermosetting polymer (often epoxy) are the most widely used composites. The reinforcing fibers may be made of glass, carbon, aramid (Kevlar™), or biomaterials like wood fiber, kenaf, hemp, or sisal. Fibers may be short and randomly distributed throughout the plastic, or they may be oriented in one or more directions, woven, or stacked in layers to give strength and stiffness in certain directions. The ability to tailor the structural properties of the final material by choosing the orientation of fibers is reflected in the name sometimes given to composites, "engineered materials."

Both metal-matrix and ceramic-matrix composites are more challenging to manufacture than plastic-matrix composites and tend to be used in specialized applications, like aerospace, where their superior thermal stability is demanded. A carbon-carbon composite (semicrystalline carbon fibers embedded in an amorphous carbon matrix) can withstand temperatures of 2,500°C while a plastic matrix composite cannot operate at temperatures higher than 300°C. Ceramic matrix composites typically use silicon carbide, silicon nitride, aluminum oxide, or mullite (a compound of aluminum, silicon and oxygen) as matrix materials and incorporate carbon or aluminum oxide fibers.

New reinforcing materials, like carbon nanotubes and clay nanoparticles, are being used to develop a new generation of composite materials. Because of their very high surface area to volume ratio, these reinforcing materials can be used in much smaller quantities than traditional fibers, yielding a lighter material that is still strong. Clay nanoparticles can comprise as little as 2.5 to 5 percent of a composite (for comparison, glass or biological fibers may comprise between 20 and 70 percent by mass of a composite). Composites made using nanoparticles may be more easily produced using techniques like injection molding, more ductile than fiber-reinforced composites when finished, and more easily recyclable. Use of carbon nanotubes as reinforcement also yields a composite with electrical conductivity, making it attractive for new applications. Although these materials are only beginning to be commercialized, they are likely to increase in prevalence as manufacturing techniques are refined and new applications found.

26.1.2 Functional Materials

Functional materials include "smart" or "intelligent" materials that are capable of sensing changes in their state or in their environment and responding to these changes. The materials, or their components, may respond to changes in temperature, moisture, electric or magnetic fields, mechanical stress, or they may detect the presence of biological or chemical agents. Although several functional materials, including piezoelectrics that move in response to changes in an electric field and shape-memory metal alloys that at a certain temperature revert back to their original shape after being stressed, have been manufactured for many decades, new technologies to control the microstructure of materials are being used to produce a host of new functional materials. Although they are not yet commercialized, shape-memory polymers, magnetic shape-memory alloys, self-repairing polymers, and bioactive sol-gel glass (that can absorb and release proteins in response to changes in temperature and pH) have been developed. The production of such materials will likely remain small, but they will increasingly be embedded in other, more traditional materials and products to lend new functionality. Some suggest that tomorrow's intelligent materials will be capable of not only sensing a predicted condition and responding in a predetermined manner, but of sensing multiple conditions, diagnosing the relationship among them, and devising an appropriate response. In other words, these systems will enable inanimate objects to become more lifelike.

26.1.3 Assembled Materials

We use the term "assembled materials" to refer to materials that are created by being precisely assembled from the "bottom-up" as opposed to being extracted or refined from the "top-down" from starting materials. The materials produced in this fashion vary widely, as do the techniques used to produce them. In some cases, material components are included in a solution and are precipitated out under carefully controlled conditions to assemble crystal structures. This technique has been used to produce polarizer coatings for LCDs (liquid crystal displays) that could replace the current sheet polarizers. Colloids, in which particles of one material (a solid or liquid) are suspended in another material (solid, liquid or gaseous), have also been used to produce fine ceramic structures. A filament is drawn from the colloid which, under the right conditions, hardens into minute structures such as rings or scaffolds. Similar techniques could also be used for creating non-ceramic structures if polymers or semiconducting materials could be suspended in the colloids.

Other techniques for producing assembled materials utilize biological and/or chemical processes. For example, goats have been genetically engineered to produce spider silk in their milk. Spider silk is an exceptionally strong, yet elastic, material that is a biological composite comprised of both amorphous and crystalline regions. Proteins have been designed that self-assemble inside a bacterium, eventually forming nanotubes that puncture the cell membrane. Self-assembled nanotubes can also be linked together to form structures or scaffolds on which other molecules are electrostatically attached. Protein molecules that bind at one end to a metal and at another end to a semiconducting material like gallium arsenide might be used to assemble nanoscale inorganic structures.

A final set of techniques that are used to build materials on the nanometer scale are based on physical processes. Optical lithography can pattern materials with 100 nm size features, and electron or ion beam lithography can pattern 10 to 20 nm size features, albeit much more slowly. Atom optics makes use of laser beams to focus neutral atoms into regions for precise deposition. These techniques extend the current technologies used to manufacture electronic circuits and could be applied to the production of higher density data storage media, microsensors, and novel materials.

While all of these techniques largely reside in research laboratories, they are likely to be increasingly commercialized and used to produce materials for niche markets or novel applications. Some assembled materials will begin cropping up relatively soon in mainstream products. Carbon nanotubes, discovered only in 1990, are poised for inclusion in flat-screen TVs. Because of their small size, arrays of carbon nanotubes emit electrons at very low voltages and can direct the electrons at a minute target, say a single pixel, making them an attractive alternative to bulky cathode ray tube (CRT) displays.

26.2 PHYSICAL AND CHEMICAL OPERATIONS

There is no single, generic sequence of operations used to manufacture advanced materials because the materials differ quite considerably and because, with the exception of composites, few are currently manufactured on a commercial scale. For this reason, we do not go into detail on the physical and chemical operations used in the fabrication of functional and assembled materials. These operations may resemble those used in other industries (for example, nanomachining may be similar to techniques used in electronics manufacture) but they may become more specialized as the field matures.

An example of production operations for advanced materials is that currently employed in the manufacture of composite materials. A portion of these operations is similar to those already discussed in other chapters. For example, the manufacture of plastic-matrix composites requires the manufacture of resins, the incorporation of additives, and the forming and shaping of parts. These steps, by and large, resemble those described in sections 18.2.1 to 18.2.3 of the plastics chapter. In the following paragraphs, we add information about the incorporation of reinforcing fibers and its implications for forming and shaping of plastic-matrix composite parts.

26.2.1 Forming and Shaping of Plastic Composite Materials

Polymer matrix composite materials are manufactured by adding reinforcement to plastic resins. The reinforcing material may be particles, whiskers (very fine single crystals), discontinuous (short) fibers, continuous fibers, and textile preforms (woven, braided, or knitted continuous fibers). Most plastic-matrix composites are manufactured using thermoset resins, but thermoplastic resins are also used. To manufacture a thermoset polymer composite, fibers are impregnated with liquid resin and the resin is then cured to create a solid part. Curing is achieved by heating and/or the use of a catalyst.

As in the case of plastic manufacturing, different techniques can be used to form the part. The choice of techniques depends on the shape and properties desired. Resin transfer molding (RTM) involves laying up a stack of dry fibers (often as woven fabric) in a mold. Resin is injected into the mold cavity to wet the fibers; a vacuum may be applied to draw the resin into the fibers. The resin is then cured and the final part removed from the mold. A similar infusion technique uses a single-sided mold. Fiber is laid down on the mold and the entire mold is enclosed in a vacuum bag. Resin is introduced into the vacuum bag and cured. This latter technique results in a part that has a molded finish on only one side. It is also possible to spray resin mixed with short fibers into a mold or to lay fibers down and apply resin by hand. Fibers may be pulled through a resin bath and then rolled on a mandrel to form cylindrical parts like pipes or tanks.

Thermoplastic composites can be melted and reformed, so their manufacture resembles some of the techniques used for metal forming. Pultrusion is a continuous process in which fibers and resin are pushed through a heated die and then drawn out and cooled. Pultrusion can also be used for manufacturing thermoset parts. Sheet forming uses a preheated preform (resin and fibers) which is conformed to a particular die shape and then cooled. Stretch forming is a variation of sheet forming in which a beam is heated and stretch over a curved die to shape it. Stretch forming orients the fibers in a thermoplastic that has been reinforced with long, discontinuous fibers, and can produce parts of a wide range of sizes.

26.2.2 Forming and Shaping of Metal Composite Materials

Metal matrix composites are formed using techniques the resemble some of the metal forming operations discussed in Chapter 17. There are three main types of processes used: conventional casting of liquid-phase material, powder metallurgy, and two-phase processing.

Conventional casting processes (described in section 17.2.1) can be used to form a metal matrix composite when the solid reinforcing material is mixed in to the molten metal. Alternatively, a preform made of reinforcing fibers can be filled with molten metal to cast the part.

Powder metallurgy uses fine metal powders that are blended with reinforcing material, compacted, and pressed into a die. The compaction is usually achieved using isostatic pressure to result in uniform compaction. The part is then sintered (heated to a temperature below melting point) to bond the particles and increase the strength and toughness of the material. Sintering temperatures are typically between 70 and 90 percent of the metal's melting temperature. Tungsten carbide parts for machine tools and dies are made using powder metallurgy. Tungsten and carbon particles are blended and heated to form tungsten carbide in powder form. A binding agent (usually cobalt) and a lubricant are added and the material is milled to produce a homogenous, uniform compound. The power is introduced into a die and sintered. During sintering, the cobalt melts and binds the carbide particles. Shrinkage of the part also occurs during sintering, so the process must be closely controlled to produce parts with accurate dimensions.

Two-phase processing involves mixing reinforcing fibers with a metal matrix that consists of both liquid and solid phases. Parts may be formed using spray deposition, in which atomized metal particles are sprayed onto a cooled preform mold where they solidify and bond. Rheocasting introduces a semisolid metal slurry mixed with reinforcement into a die where it is cooled. This latter technique is not widely used commercially.

Crucial to the performance characteristics of metal-matrix composites is the blending of the metal and reinforcement material so that it is homogenous and uniformly distributed in the die. The complexity of their manufacture makes these materials more costly and less widely used than plastic-matrix composites.

26.2.3 Production of Ceramic Composite Materials

Ceramic matrix composite materials are produced using operations that resemble the basic steps of ceramic manufacture, namely, the crushing or grinding of raw materials, blending and incorporation of additives, and shaping, drying and sintering of the part. Sintering gives the final part its strength and hardness because it both reduces porosity and forms bonds between the oxide particles in the ceramic.

Slurry infiltration is the most common process for shaping ceramic matrix parts with relatively low melting temperatures. A fiber preform is impregnated with a slurry of the matrix powder, a carrier liquid, and an organic binder. The part is then sintered.

Chemical synthesis using sol-gel techniques are also used to manufacture ceramic matrix composites. A colloidal fluid that contains fibers is converted to a gel which is heated to produce the solid material.

A final process used is chemical vapor infiltration, in which a fiber preform is infiltrated with the matrix using chemical vapor deposition (CVD). CVD involves introducing gaseous materials to a reaction chamber where they combine and are deposited on a substrate. This process is particularly costly and time-consuming, but can yield ceramic matrix composites that retain their physical properties at very high temperatures.

26.3 THE SECTOR'S USE OF RESOURCES

At present, the production volume of advanced materials is quite small relative to that of other sectors. As a consequence, resource use will not be a concern until and if the level of activity of this sector begins to approach those of the more traditional industrial sectors.

26.4 POTENTIAL ENVIRONMENTAL CONCERNS

As is the situation with resource use, the level of activity of the advanced materials sector is small enough at present that environmental concerns regarding activities are relatively modest. If and when production becomes large, the usual challenges related to air, water, and soil emissions will need to be addressed in detail.

There is another aspect of environmental concerns related to advanced materials, however. Because the products that may result from advanced materials can be predicted only in very general terms, there is considerable speculation as to potential impacts. Among the more extreme (but not necessarily inaccurate) proposals are for the emergence of health problems from nanoparticles, and ecosystem impacts from bioengineered organisms. The embryonic nature of this sector is such that these concerns cannot readily be evaluated.

One feature of advanced materials that appears in no doubt is that many of these materials are likely to be difficult or impossible to recycle, as a consequence of their structural and compositional heterogeneity. If these properties make them especially long-lasting, the tradeoff may be justified from an environmental and resource perspective.

26.5 SECTOR PROSPECTS

26.5.1 Trends

The advanced materials sector will certainly grow, as many of the technologies described in this chapter are currently at the research and development stage but hold great promise for producing materials with new or improved properties. The evolution of the sector is uncertain as the techniques and applications that become commercially successful are hard to predict at this early stage, as are their potential environmental impacts. However, a few general product and process trends can be identified for the sector.

26.5.1.1 Product Trends

Advanced materials can be customized to specific applications through, for example, the alignment of fibers in a composite, or the inclusion of certain microstructure sensors or actuators. It is likely that these materials will increasingly be produced to customer's orders, spawning a wide variety of compositions, properties, shapes, and applications. Products with new functionality enabled by advanced materials will start to replace products made with traditional materials. For example, the Kings Stormwater Channel Bridge in California was constructed using a fiberglass composite deck covered with a thin layer of concrete supported by carbon-fiber composite tubes. The bridge was built in one-third the time normally required to build a steel and reinforced concrete bridge, largely due to the lightweight materials used. At the other end of the spectrum in terms of size, miniature pumps and valves for use in medical, automotive, or aerospace applications are being made with a newly developed magnetic shape-memory metal alloy.

As the variety of customized, engineered materials produced grows and these materials are incorporated into products, concerns about recyclability also grow. Some new materials, like biologically based plastic-matrix composites that incorporate biodegradable fibers, may be more readily recycled than the materials they replace. For the most part, however, a product with a more complex composition is harder to recycle or reuse because of the difficulty of separating and sorting constituent materials.

New products are being developed that use recycled materials as feedstock and combine them in new ways. For example, wood plastic composites used to make siding or decking can be made from waste wood and recycled plastic film. EarthShell Corporation and Dupont have formed an alliance to manufacture food packaging material that is made from limestone, starch reclaimed from the commercial processing of potatoes, and recycled fiber. Some composite materials may be able to take advantage of recycled feedstock that would not be of high enough quality or have the appropriate properties for use in a traditional material.

Text Box 26.1

Nanoclays make Plastic Bottles Impermeable

A new product developed by Honeywell Engineering Applications and Solutions uses "nanoclays," platelets of clay materials only about 1nm thick, to produce a highly impermeable packaging material. The platelets increase the distance gas molecules must travel and this, combined with an oxygen-reactive compound, gives the plastic material its high impermeability. The barrier layer can be included in between two layers of PET and formed into beverage bottles. The final bottle meets the regulatory standards for impermeability needed to hold beer or juice, and the barrier layer adds only about 5 percent to 8 percent to the weight of the bottle. Because the barrier layer is not chemically bonded to the PET, the bottles can be shredded and air separated for recycling.

Source: Kim, I., The incredible shrinking process, *Chemical Engineering Progress, 97*(1), 10, 2001.

26.5.1.2 Process Trends

Improved automation and increased control of the manufacturing process are likely to accompany an effort to reduce the costs of manufacture for all types of composites. Relative to traditional materials, many composites remain costly and more complex to manufacture. This is likely to change as molding and forming techniques are refined, possibly using computer-aided mold design, and greater automation is employed. However, many composite manufacturing processes will remain highly specialized (e.g., those used for aerospace parts) and hence relatively costly.

New materials will continue to be used in composites or introduced into other materials and products. Also, new techniques will be used to join materials, allowing for parts to be made with new combinations of properties. For example, hybrid composites that are created by bonding a plastic matrix composite with a metal matrix composite are being developed. These processing techniques would reduce the need for finishing and joining two separate parts.

26.5.1.3 Social and Regulatory Trends

Advanced materials, unlike traditional materials, may have the potential to do things not heretofore possible—to change shape when desirable, or to repair themselves, or to prevent or cure disease. At the same time, there are concerns that these materials could cause serious environmental consequences or impact human health.

As a consequence, considerations of advanced materials, and the products that might be created from them, inevitably have ethical as well as technological aspects.

Brian Sager (see Further Reading) has captured some of this complexity as it relates to the biotechnology industry. He lists and discusses a number of promising areas of research and development: new materials, biologically-controlled industrial manufacturing processes, devices based on biological structures, and so forth. He recognizes, however, that the public perception of this field is ambivalent at best. The unpredictability of the interplay between technological promise and public acceptance creates several possible scenarios. The present day scenario includes low technological integration and low public acceptance, and is marked by the rare and discrete marketing of biotechnology products and public skepticism as to the potential of biotechnology. Other scenarios include increased public acceptance and/or increased technological integration of biotechnology. Public acceptance is likely to gradually emerge for applications in which biotechnology is truly useful, but only as a consequence of open discussions among all of society. Similar social trends are predicted for the entire advanced materials sector with only modest modifications.

26.5.2 Scenarios

Trend World

This scenario envisions the continued rapid evolution of advanced material compositions, functionality, assembly and manufacturing techniques, and applications. Public acceptance will likely be high for materials that enable valued new functionality and have no obvious immediate environmental effects. However, materials that have questionable impacts on environmental or human health will be regarded with greater skepticism and may be slow to gain regulatory approval (if applicable) and/or public acceptance. The incorporation of advanced materials into products will proceed rapidly where there is a clear market for such materials, with little regard for ultimate recyclability.

Green World

In a green world, the development and deployment of new materials would be undertaken more conservatively, with environmental impacts fully assessed before such materials are widely used. Designers will consider recyclability in the design of materials and products, and composites using natural fibers, as well as biodegradable plastics and other environmentally superior materials will be increasingly used. The careful use of some advanced materials will enable significant reductions in environmental impacts of traditional sectors—for example, materials that incorporate control technologies or other functionality could be used to reduce energy or water consumption in infrastructure or processes.

Brown World

In a brown world, designers of new materials would be largely unaware of potential environmental impacts and regulation would not be in place that ensure a precautionary approach. The public would be largely unaware of potential environmental impacts of new materials and there would be little transparency in the development and use of new materials. Products that incorporate new materials would become more difficult to recycle, and information necessary to enable recycling or recovery of materials would be difficult to find by end users.

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Part IV

The Future of Industry and Environmental Issues

Chapter 27

The Industries of 2050

27.1 INDUSTRY IN THE 21st CENTURY

Earth, its inhabitants, and their approaches to improving their lives are all in rapid evolution. There are many trends that are occurring or will occur over the next several decades that will transform today's industrial structure. They include:

- More people, from just over six billion at the beginning of the century to between nine and ten billion by 2050
- The social phenomenon of the "consumption society"
- The desire for higher standards of living, particularly in developing economies
- Probable technological evolution and revolution
- Globalization of commerce
- Resource constraints
- Environmental pressures
- Competition for habitable land

All of these factors suggest that the mix of industries a half-century from now will be rather different than it is at present, just as the once-vigorous buggy whip industry is no more, but how different will things be in 2050? Will the same sectors still exist? Which will have greater importance than now, which less? In this chapter we explore current trends and technological forecasts to predict the industrial landscape of 2050.

27.2 TODAY'S INDUSTRIAL SECTORS, LINKAGES, AND POTENTIAL IMPACTS

Recall that industries and industrial sectors do not stand alone, but are related to each other in a complex and interlocking structure (Figure 27.1). This implies that changes in one sector inevitably cause changes in others, especially when the sector

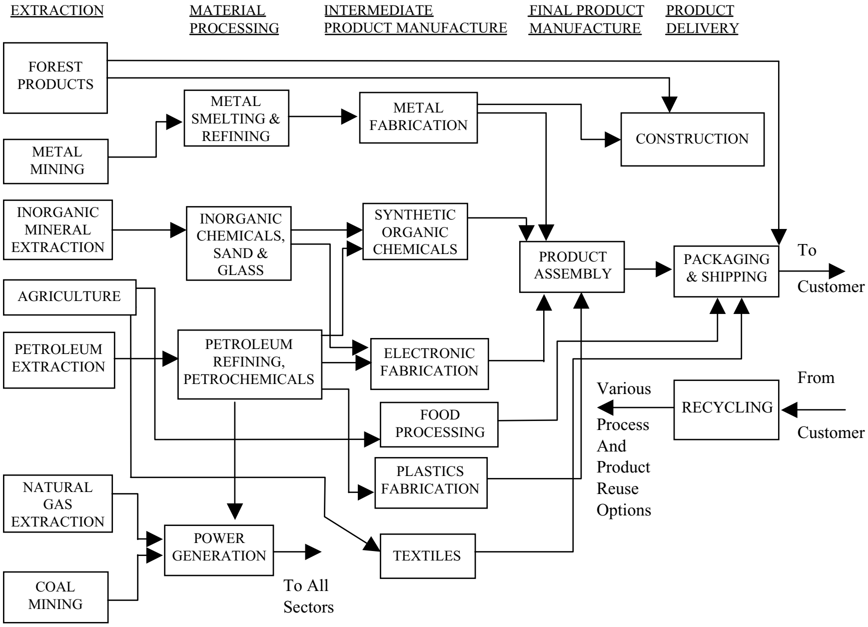

Figure 27.1. The current interlocking sector structure (reprise of Figure 1.4).

undergoing the initial change is an upstream sector. Let us examine the sectors one by one, predicting at least portions of their likely state a half-century from now.

Fossil Fuel Extraction and Processing

By 2050, currently identified reserves of oil and gas will be near exhaustion. Although the technology for burning coal without producing and dispersing environmentally-damaging emissions will be much improved, substitutes will have replaced most of the coal used today in industrialized nations. As a consequence of these situations, the fossil fuel extraction and processing industry will be much smaller than it is today, and will be regarded as primarily suitable for niche uses, such as for energy provisioning where alternatives cannot be used for one reason or other. Countries that currently constitute the developing world may well continue to use fossil fuels if they are locally abundant, remain relatively inexpensive, and if the technologies have not been provided to assist these countries to accelerate their industrialization without dependence on fossil fuels.

Power Generation

Commercial power generation today is largely through the combustion of fossil fuels and the use of nuclear fission. Many alternatives are under extensive development, and can be expected to develop rapidly as the supply of fossil fuels, especially oil and natural gas, diminishes over the next few decades. No matter what mix of alternative power sources dominate, it seems likely that future power generation will feature smaller, much more highly dispersed sources, in which the approach and equipment for energy generation will be as important as at present, but long-haul distribution networks will be less so.

Metal Ore Extraction and Processing

Metals have unique and eminently useful properties, and metal mining and processing will continue into the foreseeable future. What will change will be the suite of metals that are mined. The more abundant ore metals—iron, aluminum, etc.—will be dominant, while those whose reserves are being rapidly depleted—zinc, silver, etc.—will see prices rise rapidly and will be restricted to high value, specialty uses.

Inorganic Minerals and Chemicals

The minerals extracted and processed by this sector are crucial to the generation of fertilizers for agriculture, for the development of designed materials and composites for a variety of uses, and for the inorganic materials that make modern electronics possible. While commodity inorganic chemicals may play lesser roles in the future, the more targeted uses mentioned above will continue to make this sector central to industrial processes.

Petrochemicals

Petrochemicals are, by definition, based on petroleum feedstocks. If those feedstocks disappear or are severely limited by the decline of the fossil fuel sector, this sector will very nearly disappear also. The exceptions may be companies that employ small amounts of crude oil to generate high value specialty chemicals that for one reason or other cannot be produced from other potential feedstocks.

Agriculture

As petroleum feedstocks become more costly and less available in the future, and as populations grow in absolute numbers and in affluence, agriculture will play a central role in technological sustainability. The challenge will be to provide the desired nourishment for 50% more people than are now on the planet, and to do so while preserving local and global ecological health. The importance of this sector and the scale of its operations will inevitably increase, although the associated increase in land and energy use may be partially offset by increased sector efficiency, including the use of biotechnology.

The Food Processing Industry

Food processing is a necessary companion to agriculture in feeding Earth's population. The sector will inevitably grow in concert with the agricultural sector, and will become technologically more intensive than is the case at present.

Textiles and Leathers

The people of the world, and their various activities, will continue to need a sizeable textiles sector. In future decades the starting materials will largely move away from natural fibers (e.g., cotton) to a variety of synthetic fibers, both for reasons of reduced environmental impacts and for product flexibility. Many of the applications now served by metals or plastics may be subsumed by advanced textiles that are strong, resistant to damage, and capable of fabrication in a variety of forms. Leathers will decline, both because of the environmental implications of their processing and because their inherent properties will be increasingly duplicated or improved upon by alternative materials.

The Sand and Glass Industry

Products fabricated from sand and glass are increasingly being produced from other materials, or of composites of materials. As this trend continues, the sand and glass sector is expected to gradually give way to the fabricated materials/composites product sector. However, because of the abundance of its starting materials, the embedded technological base, and the widespread applications of its products, there will continue to be some activity in this sector.

Fabricated Metal Products

Products fabricated entirely of metal, especially small, specialty products, are increasingly being produced from other materials, or of composites of metals and other materials. As this trend continues, the fabricated metal product sector is expected to gradually give way to the fabricated materials/composites product sector.

Fabricated Plastic Products

Products fabricated entirely of plastic, especially small, specialty products, are increasingly being produced from other materials, or of composites of plastics and other materials. As this trend continues, the fabricated plastic product sector is expected to gradually give way to the fabricated materials/composites product sector.

Electronics

The electronics industry will continue to grow, as more and more everyday processes are enabled or controlled by electronic devices. Electronic devices will be much more distributed and smaller than they currently are. The ubiquitous personal computer will be replaced by numerous devices that can sense their environments and provide feedback and control. Electronics will be integrated into numerous other products including assembled products, materials, packaging, and even textiles, clouding the boundaries of the electronic products sector.

Synthetic Organic Chemicals

The synthetic organic chemicals industry, including its pharmaceutical component, will remain much as it is at present. Its distinguishing feature, however, will be a transition from petrochemically-derived starting materials to biotechnologically-derived starting materials.

Assembled Products

Although the materials from which assembled products are made will doubtless evolve with time, the assembled products sector will continue to function in much the same way, and at similar scale, as it does now, but with significant advances in the production technologies used.

Forest Products and Printing

Forest products are major factors in the construction industry and the manufacture and printing of paper. The former can be expected to continue; the latter may decline if the electronic transfer of information, long conjectured to replace the printed word, becomes the default mechanism for the storage and communication of intellectual property of one sort or another. Forest products are also likely to play a significant role in the biotechnology sector of the future by providing specialty raw materials more readily generated from forest precursors than from those of agriculture. With very little virgin forest available for logging, there will likely be greater reliance on farming of quick-growing trees and other agricultural products that can replace tree pulp for paper making. The use of forest products in construction will have declined, being replaced by engineered composite materials.

Packaging and Shipping

Although the materials from which packaging is made will doubtless evolve with time, as may shipping, the packaging and shipping sector will continue to function in much the same way as it does now. The packaging and shipping sector will likely operate at a larger scale, however, as commerce is increasingly globalized, with production of goods located in areas far from where they are ultimately consumed.

Industrial, Residential, and Infrastructure Construction

As regional and global populations increase over the next half-century, and as the demand for improved quality of life becomes near-universal, the construction sector will be a crucial one for meeting these needs and desires. There will be greater emphasis on designing buildings and infrastructure that use recycled materials rather than virgin metals or forest products, and that during their lifetimes use much less energy from fossil fuels. Urban spaces and "brownfields" (abandoned industrial sites) will be reclaimed and redeveloped in response to pressures for land near large population centers. Constraints on travel may result in different patterns of settlement in metropolitan regions. New forms of mass transit will likely shape new patterns of residential, industrial, and commercial space.

The Remanufacturing and Recycling Industry

As the abundant supply of natural resources begins to dwindle with time, the remanufacture of products and the reuse of materials will become increasingly important. This industry, now largely an appendage on a society that is committed to single uses of materials by design, will become considerably more sophisticated technologically than is the case at present, and will play a central role in the provisioning of suitable materials to the other industrial sectors. Producers of materials and manufacturers of assembled products will be fully integrated into the remanufacturing and recycling sector by either paying for others to reclaim and recycle materials or by operating subsidiaries to perform this role.

Advanced Materials and Composites

Materials whose properties can be tailored to the intended uses will be increasingly important in the next few decades. Such materials will gradually replace many of the current uses of plastics and metals. They are likely to be more suitable to the tasks demanded of them, longer lasting, and less resistant to degradation. But, because of the new combinations of materials that are integrated into a single material or product, it will be more difficult to reuse such materials; this is a design challenge for the future.

Summarizing Sector Trends

The sector-specific comments above are summarized in Table 27.1. Grouping the evaluations permits us to suggest the following:

- Several existing sectors are likely to grow rapidly from 2000 to 2050, especially electronics, and remanufacture & recycling. Remanufacturing and recycling will be concentrated in large companies or into existing producers of materials and products.
- Several existing sectors are likely to remain roughly stable from 2000 to 2050: Metals, inorganic minerals, construction, packaging, forest products, synthetic organic chemicals (including pharmaceuticals).

Table 27.1. Predictions for the Long-Term Future of Different Industrial Sectors

Sector	Trend	Key Factors
Fossil Fuel Extraction and Processing	↘	Only specialized uses of most fuels
Power Generation	→	Highly dispersed, equipment more important than distribution
Metal Ore Extraction and Processing	→	Still a big business for abundant ores (Al, Fe, etc.), other materials costly and seldom used (e.g., Zn, Ag)
Inorganic Minerals and Chemicals	→	Still needed for agriculture, specialty materials, and electronics
Petrochemicals	↘	High value specialties only
Agriculture	↗	Large product output, very efficient
The Food Processing Industry	↗	Large product output, very efficient
Textiles and Leathers	↗	Big business, largely synthetic fibers
The Sand and Glass Industry	↘	Many substitutes for glass
Fabricated Metal Products	↘	Substitutes for traditional metal uses
Fabricated Plastic Products	↘	Largely part of specialty materials
Electronics	↑	Crucial in the information-dominated future
Synthetic Organic Chemicals	→	Feedstock changes, sector remains
Assembled Products	→	A continuing need
Forest Products and Printing	→	Construction and biotech are drivers
Packaging and Shipping	→	A continuing need
Construction	→	Buildings continue to be needed
Remanufacturing and Recycling Industry	↑	Crucial to the reuse of materials
Biotechnology	↑	The feedstock of the future
Materials/composites	↑	Advanced material properties replace metals, plastics

- Several existing sectors are likely to decline from 2000 to 2050: Fossil fuels, petrochemicals, metal fabrication, power distribution, plastics fabrication.
- Two major new sectors will emerge during the first half of the 21st century: Biotechnology, and advanced materials/composites.
- Agriculture and food production are largely decoupled from the other sectors, but they can be expected to show significant growth from 2000 to 2050. A smaller number of large producers will exist as the sector becomes increasingly dependant on technology and capital investment.

27.3 A VISION FOR INDUSTRY IN 2050

Today's great businesses tend to be those that manufacture or assemble final products (autos, pharmaceuticals, etc., such as Ford, Pfizer) and those that make those products work (Intel, Microsoft). None of the leaders is a supplier of raw materials, except perhaps for petroleum (BP is the outstanding example). A few companies with intermediate sequence positions (e.g., DuPont) do well also.

One can imagine a scenario for 2050 (or perhaps two or three alternative scenarios) in which metals are scarce, miniaturization is ubiquitous, computer control is everywhere, and biotechnology plays a major role as a materials supplier. Several key questions related to this future world can be considered from this perspective:

- Which sectors will be retained?
- Which sectors will disappear?
- Which new sectors will emerge, and what they will look like?

The sectors expected to be retained are those that will continue to provide raw materials for industrial processes, or substitutes for today's raw materials. Additionally, many of the product assembly sectors will be retained even with altered inputs and altered technologies for processing.

The sectors expected to disappear include those whose supplies of raw materials are scarce, environmental burdens are overwhelming, and/or energy costs are prohibitive. In each case, for the sectors to disappear entirely an economically viable alternative must exist.

Finally, the sectors expected to emerge will be those that supply replacement raw materials, alternative sources of energy, alternative manufacturing materials, and improved remanufacturing and recycling capabilities.

The considerations above allow us to construct a speculative sector linkage diagram for the year 2050, shown in Figure 27.2. Over the half century, the actual sector linkages will respond to resource constraints, technological innovations, and human preferences in ways that can be predicted only imperfectly. The numerous other factors that contribute to the direction and pace of this change are considered in greater detail in Chapter 28. Nonetheless, Figure 27.2 suggests that the sectors expected to decline are generally those at the earlier stages of the sector sequence. In other words, the functions of the later stages will generally remain, in enhanced form in some cases, because those services are what is desired by the human population. It is the *ways* in which the services are provided that will constitute the bulk of the changes in the industrial sectors, and thus in the diagram.

27.4 IMPLICATIONS FOR THE ENVIRONMENT

The restructuring of industrial sectors, combined with anticipated technological progress in existing sectors, suggests that there are likely to be a number of changes in the relationships between industrial activity and the environment over the next few decades. Many of these changes are likely to be positive, including:

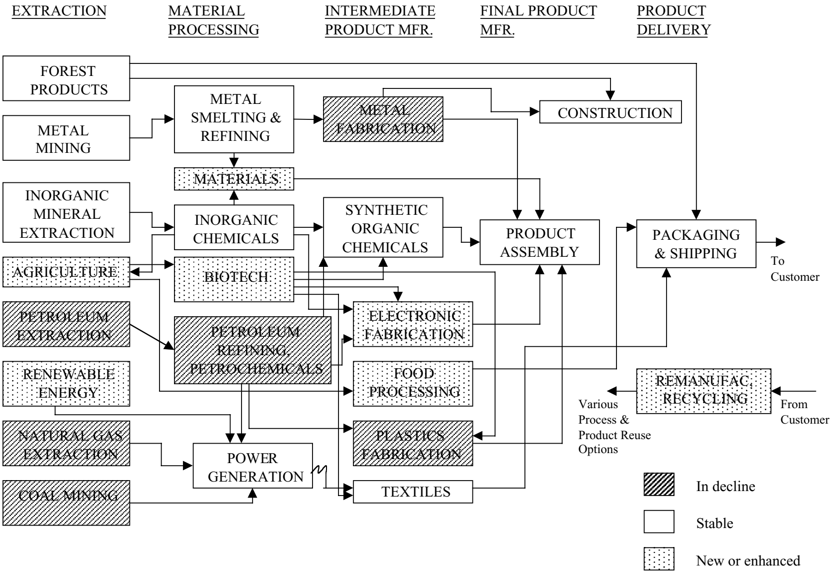

Figure 27.2. A potential interlocking sector structure diagram for the year 2050.

- Sharply decreased mining and processing impacts, resulting from a combination of better performance, a gradual decrease in throughput, and greater attention to sustainable resource extraction and reclamation
- A smaller footprint of industrial activities on habitable land (agriculture perhaps excepted)
- Decreased ecological burden due to distributed rather than centralized production of power and perhaps of manufactured materials
- Sharply decreased emissions from industrial activities, resulting from improved business practices, more comprehensive regulations, and rising costs of pollution production
- An increase in remanufacturing and recycling of materials
- A decrease in the rate of landfilling

There are also changes that may have the potential to produce negative environmental effects:

- Possible adverse impacts of genetically modified organisms on ecosystems
- Possible adverse impacts of personal pharmaceuticals on ecosystems
- Unanticipated environmental challenges related to newly-developed materials and composites
- Ecological pressures resulting from increased population and increased consumption levels

On balance, it seems likely that the new industrial sector structure will be beneficial for the environment, but it will be advisable to monitor the technology-environment relationship in detail as it evolves in the future.

27.5 IMPLICATIONS FOR CORPORATIONS

If the vision that has been presented above becomes reality, corporations that are paying attention may be able to profit from the information:

- Corporations in a dying sector (perhaps metals, petrochemicals, glass, fossil fuels, etc.), need to begin planning for a long-term change in their businesses. This transformation has already begun in some sectors. For example, several major petroleum producers (BP, Royal Dutch Shell) are investing heavily in alternative energy sources, including solar and fuel cell technology.
- Corporations in a growing sector (perhaps electronics, or remanufacturing & recycling), need to plan for optimization of this opportune position within an evolving industrial landscape. Again, the beginnings of this transformation are evident. For example, Ford Motor Company pledged that it would become a major recycler, and many European auto and consumer goods manufacturers are developing enhanced recycling infrastructures.
- Corporations in a sector predicted to be new and rapidly evolving (perhaps bioproducts, specialty materials, renewable energy) need to plan for growth as well as prepare to understand and address uncertainties in this evolution by early characterization of environmental impacts.

In short, just as with every other aspect of business, information or predictions concerning the future can present opportunities to be seized, for the benefit of the corporation (and, often, for the benefit of the environment). How organizations are able to capitalize on opportunities, rather than be threatened by these changes, is addressed in more detail in the next chapter.

Chapter 28

Achieving Industrial Change

28.1 THE MYRIAD PRESSURES FOR CHANGE

Regulation, resource constraints, and environmental impacts represent only a few of the pressures that push industrial organizations to change their practices. While the earlier chapters have emphasized these aspects and provided tools for those outside and within organizations to assess their environmental impact and design improved industrial processes, this chapter turns attention to the myriad competing pressures that can enable or constrain such changes.

Environmental practices are embedded in broader organizational and social contexts which are themselves evolving. Public acceptance of technologies and their impacts, industry norms for what constitutes socially responsible operation, and legal and regulatory requirements shift over time. Significant events (like a large oil spill or the dramatic growth in the Antarctic ozone hole) can rapidly shift public attention as well as industry norms and regulatory frameworks. As a result, the environmental practices of industry are evaluated with a changing yardstick. The most technologically desirable environmental improvements may not be those given highest organizational priority when these other considerations are given their necessary attention. Conversely, changes which have positive environmental impact may be spurred by events or trends that have little to do with an analysis of environmental impact and more to do with responses to technological, economic or social trends.

Further complicating this context for industrial change is the fact that environmental impact is no longer (if it ever was) considered in isolation. Increasingly, organizations, social institutions, and the public are focusing on the challenge of achieving sustainability. While different definitions of sustainable development abound, most agree on the ends of sustainability, that is, developing a global economy that the planet and its systems are capable of supporting indefinitely. Achieving this end will require not only minimizing environmental degradation, but also addressing social issues of poverty, healthcare, and education, and economic issues of income inequality, consumption, and economic growth. The notion of the "triple bottom line" has been advanced as a way of measuring business performance when economic, environmental, and social impacts are seen as interdependent and important measures of viability.

Our aim in this chapter is not to predict how organizations will respond to the call for sustainability, nor to prescribe how they should. Moving organizations toward sustainability or toward the narrower goal of reducing environmental impact involves organizational change at a fundamental level. It is the processes, opportunities, and constraints of organizational change that we choose to focus on here to improve understanding of the mechanisms by which such complex changes might come about.

28.2 DRIVERS OF ORGANIZATIONAL CHANGE

An organization's analysis of its environmental impacts and the opportunities for improvement are only one of a constellation of factors that drives it to change its environmental practices. We have seen already that regulation and international agreements (Chapter 3) strongly influence the types of issues to which organizations pay attention. These "regulatory drivers" must be attended to in order for a company to continue to operate. But other categories of important influences can be identified, including resource, market, and social drivers. Figure 28.1 shows how these drivers might act on the organization.

Resource drivers include factors that directly impinge on the organization's ability to acquire inputs and market or dispose of outputs. For example, banks and insurance companies require companies to meet certain environmental risk criteria before they provide loans or insurance policies. Shareholder groups can withhold investment in a company based on its environmental and social record. Buyers of a company's product may require that it meet certain standards (e.g., does not include hazardous materials, or has low energy consumption). Increasingly, assemblers of products such as automobiles or computers require that all companies in their supply chains are compliant with environmental standards.

Market drivers include those factors that influence an organization through its competitiveness in the marketplace. Consumers may choose to buy a company's "green" products, or boycott its less efficacious alternatives. The environmental practices of competitors can push companies to meet or exceed voluntarily adopted standards. In some cases, industry trade associations require all companies to comply with voluntary standards in order to retain membership.

Finally, social drivers may influence all of the other drivers, but they typically have less direct impact on a company's operations. Environmental groups, the press, academia (including both scientists and non-scientists), religious institutions, local communities, and courts all shape broader public opinion. They may expose unsound practices, provide evidence for new issues of concern, or praise exemplary actions.

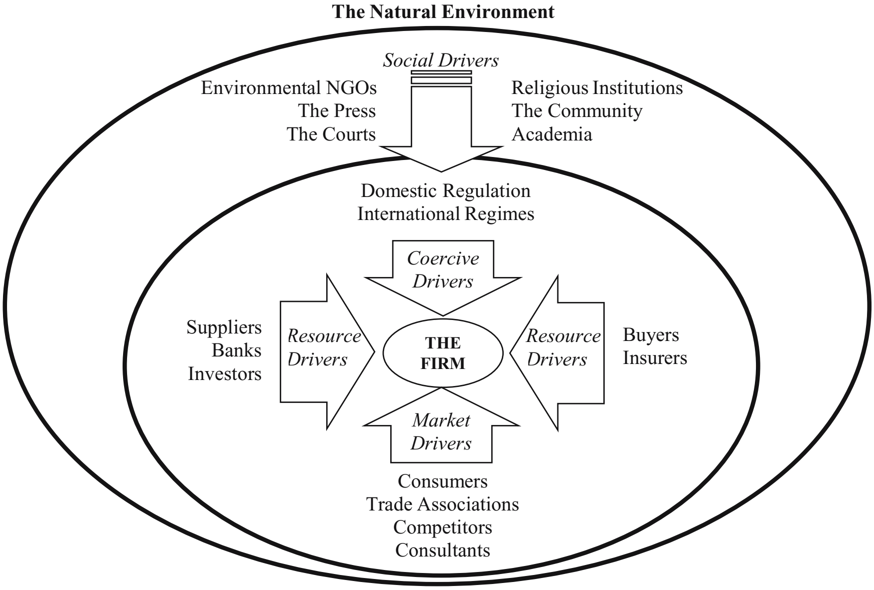

Figure 28.1. External drivers of an organization's environmental practices. (Adapted from Hoffman, A. J. 2000. Competitive Environmental Strategy: A Guide to the Changing Business Landscape. Washington, D.C.: Island Press. p. 29.)

Social acceptance can in turn influence the other, more direct drivers of a company's environmental strategies. For example, consumers may be more likely to avoid a company's goods if an environmental group has launched a compelling campaign against its practices. Alternatively, competitors may rush to "clean up their act" if the press exposes poor practices in another company or even another sector.

The social drivers of organizational change, while the most diffuse, can become very powerful, propelling issues to the fore. Much of the public was aware of Exxon's *Valdez* oil spill off the Alaska coastline and followed the clean-up and legal actions closely. Similarly, virtually everyone was aware of the Antarctic ozone hole discovered in the 1980's. But other oil spills, including much larger ones, have gone virtually unnoticed by the general public, and other issues, like global climate change, have failed to mobilize the public at large. In other words, the strength of social drivers does not necessarily correlate with the actual environmental impact of an event or issue. Some events seem to take on a life of their own, with media, scientific, environmental group, community, religious, or academic attention feeding on each other.

How does an industrial organization make sense of these social drivers? Why do some issues become urgent social concerns, while others fail to elicit much response? R.K. Mitchell and collaborators propose that social drivers, also viewed as the wishes of an organization's external stakeholders, differ in at least three dimensions that affect their ability to directly or indirectly influence organizational practices.

- Power—some social groups have power relative to industrial organizations because they have substantial resources, large memberships, are supported by powerful individuals, or can form alliances with powerful individuals or organizations.
- Legitimacy—social groups that represent broadly legitimate issues and use broadly legitimate means will tend to have a greater influence on corporate actions than those who do not.
- Urgency—social groups that advance issues considered urgent will tend to exercise greater influence than those advancing issues that are non-urgent.

When a social group possesses power, legitimacy, *and* urgency, it will be hard for an industrial organization to ignore its demands. This kind of group is labeled a definitive stakeholder in Figure 28.2. When a social group possesses only two of these three dimensions, it may influence an organization's practices under the right conditions, or it may need to ally with a group that possesses the final characteristic to be truly effective. Finally, a social group that possesses only one characteristic may be more effective at influencing broad public opinion than it is at generating an organizational response. For example, Friends of the Earth is an environmental group that does not possess great power because its membership and resources are limited and its tactics are typically viewed as lacking broad legitimacy, but it does capitalize on urgent issues, drawing attention to them and opening up space to other groups to use more moderate tactics to influence change.

28.3 MECHANISMS OF ORGANIZATIONAL CHANGE

Organizational change comes about as a result of actions at the individual level, the organizational level, and the institutional level. Institutions can include companies in an industry as well as groups or organizations that exert resource, market, or social pressures on a set of companies. Of course, the interplay among actions on the individual, organizational and institutional levels are extremely important in guiding change, but we first address each in turn.

28.3.1 Individual Level Actions

Anthropologist Margaret Mead commented "never doubt that a small group of thoughtful, committed citizens can change the world. Indeed, it's the only thing that ever has." All change begins with the commitments of individuals. On issues of environmental and social change, individuals are typically moved to act based on

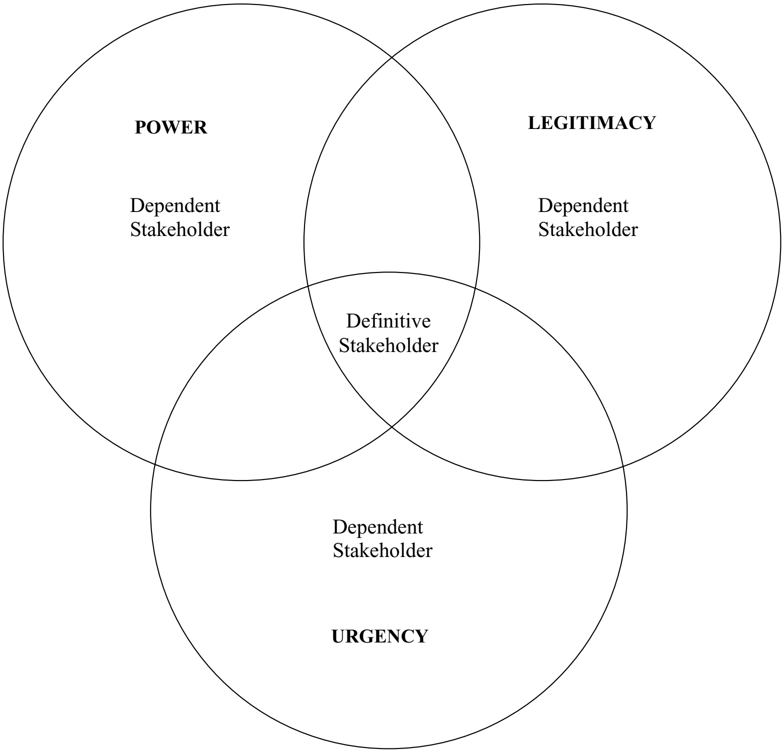

Figure 28.2. Typology of social drivers based on their possession of power, legitimacy, and urgency. (Adapted from Mitchell, R. K., Agle, B. R., & Wood, D. J. 1997. "Toward a Theory of Stakeholder Salience" Defining the Principle of Who and What Really Counts." Academy of Management Review. 22: 853–886. p. 874.)

values that they hold. The questions they raise are not simply technical (what can be done?) but normative (what ought to be done?).

When individuals outside an organization raise these issues, their primary channels of influence are as described above. They can organize to exert pressure on a company, or to boycott products. They can use their professional power as, say, a journalist, an academic, or a scientist, to shape the social debate on the issue. They can also invoke regulatory drivers by working through legal channels, or financial drivers by investing only in socially responsible companies. But while all change starts at the individual level, rarely do the actions of a single individual directly trigger organizational change. Or do they?

So far, we have discussed individual actions originating outside an industrial organization. But individual employees of a company may also have strong views about its environmental and social practices and can act as internal issue champions.

Indeed, with large fractions of the populations of many countries stating that they are environmentalists, it should come as no surprise that these individuals bring their values to work. As insiders, they have the advantage of already possessing a certain amount of power within their organizations. They know the channels of influence and the appeals that will have currency within the organization.

Increasingly, these internal issue champions are important in bringing about organizational change. Efforts to recycle office paper, restore and protect local ecosystems, or reduce commuting through carpooling might reflect individual employees' commitments to start acting on their values in the workplace. Today's employees are more likely than those of the previous generation to expect their organizations to respect and promote a diversity of individual values; indeed, the Conference Board notes that since the 1990s younger managers and their families have begun making demands on top management that previous generations would never have dared to do. This trend is likely only to grow stronger.

When individuals push their employing organizations to adopt new environmental and social programs the changes can be significant, but when these individuals are senior managers and corporate executives, the changes can be profound. For example, when Jeffrey Swartz, the CEO of Timberland, describes his company as operating on a five-point business platform focusing on product, distribution, marketing, business systems, and community, the inclusion of the final platform shows his commitment to pursuing social policies and putting them on equal footing with traditional business concerns. Swartz created a Social Enterprise department and initiated a program where all Timberland employees receive 40 hours of paid leave to perform community service. What corporate leaders like Swartz possess is the power to bring their values into action in their own organizations, which in turn can set standards that other organizations must live up to.

28.3.2 Organizational Level Actions

While individual commitment to change is an important precursor to organizational change, it is not sufficient. Perhaps it is not even necessary, as organizations can respond to pressures from regulatory, resource, or market drivers without their members explicitly valuing the environmental aspect of the issue. In either case, organizational change requires alterations to the structures, routines, or cultures of organizations. Without these transformations, even the best-intentioned, most technically sound, or legally mandated initiatives may fail to attract or retain resources and legitimacy.

Structural Changes

Most manufacturing and industrial organizations now include departments of environment, health, and safety (EH&S), and employ environmental specialists to ensure, at a minimum, that regulatory requirements are met. Some organizations have gone much further in adopting structures for environmental protection. For example, companies as diverse as General Motors and Tyson Foods have a senior executive (a Chief Environment Officer) charged with overseeing environmental practices. Other companies have created roles for environmental specialists outside the traditional EH&S department. Research and development, manufacturing, marketing, and even community relations departments have been altered to include environmental specialists. These moves are consistent with the goal of bringing environmental practice closer to the organization's core functions and no longer "buffering" the core from these demands.

Changes in Routines

Beyond structural changes, organizations adapt by changing the behaviors of their members. Routines, procedures, and management systems are formal ways for organizations to guide individuals' actions. Whether a person has environmental expertise or not, he or she can be called upon to consider environmental issues or flag environmental problems, especially if guidance is given in the form of certain tools or metrics. Indeed, the goal of such tools is to make everyone responsible for the environmental impact that may be associated with his or her job function. As consideration of this new aspect becomes part of everyday work it becomes more and more embedded in the organization's core functions.

Changes in routines and behaviors are certainly harder to accomplish than changes that only involve restructuring. New routines or tools must reflect people's actual work experiences, meaning that they are typically much more successful if those who will use the routines have had some stake in their development. A routine that is imposed by an outside group, that may ask for considerable changes in work practices, documentation, or both, and whose purpose is not clear or valued by those who will use it, is likely to be short-lived. In other words, new routines or tools must gain legitimacy in order to be used. When the content of the routines is fundamentally new to most people, gaining this legitimacy requires a patient, measured approach.

Even the most enthusiastic and committed champions of new routines or programs must be careful to frame the issues and tools in a way that others understand and value. A large, company-wide effort such as the adoption of the ISO 14001 environmental management system might be framed as a way to improve and document environmental performance in order to ensure continued business with key buyers. A smaller effort to change how a process development team evaluates environmental impact might be framed as a way to improve their productivity (and, ultimately, others' evaluations of their success) because it avoids costly and time-consuming re-work further along in the process. The familiar business mantra "what we measure, we manage" comes to mind here, but it does not mean that environmental programs have to measure their impact in dollars in order to gain attention. Instead, framing the new routines and tools in metrics and language that makes sense to recipients, and integrating them with the group's existing routines will greatly increase their chance of success.

Cultural Changes

Finally, the deepest level of organizational change occurs when the organization's culture has shifted to accommodate attention to new issues. When environmental considerations are no longer regarded as a novel addition to the mainstream work of the organization, but are so fully integrated so as to be almost invisible, then a fundamental change in the organization will have taken place.

An organization's culture consists of the largely unspoken norms, values and assumptions that guide everyday actions. Culture channels attention toward particular problems and away from others, because members of a culture tend to filter their experiences using familiar cultural categories and classifications. Members of a culture also tend to share similar approaches to problem solving, or at least to select their tools or strategies for action from a limited repertoire.

In organizations where environmental considerations have long been treated as an afterthought to the development of new products or processes, cultural transformation will take much effort and time. Development engineers who have been rewarded for delivering modules on time, on budget, and to meet certain performance and quality specifications will not necessarily embrace new routines or targets for environmental protection. Changing what counts as a valid problem and getting people to devote time and resources to it without questioning its value requires deeper change. The organization's leadership and management must "walk the talk," giving more than just lip service to new social and environmental goals by consistently demonstrating their commitment. This leadership must be matched by changes in incentives like performance evaluations and reward systems, and supported by new routines and tools. With sustained effort, changes in culture can be made and the hiring of new workers who inherently value social and environmental goals will support this cultural change.

While culture change is the most difficult and slowest mechanism for organizational change, it is also the most enduring. Cultures can outlast many changes to structures and routines. They are the "glue" that binds an organization's members and aligns them in pursuit of common goals. When environmental or social values are truly internalized in an organizational culture, its members will be able to tackle the associated technical challenges much more effectively.

28.3.3 Institutional Level Actions

Organizational change is not solely a product of individual and corporate efforts. It occurs in a larger social and institutional context, which is itself shifting. The cultural rules that give collective meaning to particular actions or events are termed "institutions". Different groups or organizations may be seen as members of an

Text Box 28.1

Reshaping the "Rules of the Game" in Semiconductor Manufacturing

In 1999 the semiconductor industry adopted a global voluntary commitment to reduce emissions of a certain class of global warming gases. While industry members saw reduction of global warming emissions as the right thing to do, their actions were triggered by a chemical supplier's pledge to reduce the quantity of gas it would sell. It was the need to ensure a steady supply of this critical process gas that lead semiconductor manufacturers to take ownership of the issue. Over time, manufacturers in the U.S., Europe, and Asia all agreed to voluntary reduction measures, favoring these over agreements negotiated with regulatory bodies in each country. The need to create a competitive "level playing field" in which no manufacturer would be disadvantaged by stringent restrictions on the gas became the primary concern at this point. Powerful actors within the semiconductor industry were able to reshape the issues, rules, and norms by interacting with others in the institutional field, namely suppliers and regulators.

Source: Howard-Grenville, J. (2002). "Institutional Evolution: The Case of the Semiconductor Industry Voluntary PFC Emissions Reduction Agreements." In A. Hoffman and M. Ventresca. (eds.) *Organizations, Policy, and the Natural Environment*. Stanford, CA: Stanford University Press.

institutional field, and as the actors for whom the institutional rules are particularly salient. An organization's institutional field can include all or many of the regulatory, resource, market, and social drivers discussed above. In general, institutions influence members of a field by setting the "rules of the game." These rules might take the form of actual legal requirements, they may be conventions, or they may be deeper assumptions about appropriate actions. These are, respectively, regulative, the normative, and cognitive aspects of institutions. As certain practices are adopted by many members of an industry or institutional field they may become taken for granted. Even if these practices are not technically efficient for a given organization, it may nonetheless adopt them to send the signal that it is complying with unwritten rules and that it is a fully legitimate member of the field.

When we view change from an institutional perspective, we see that organizations are embedded in networks of other organizations and that they are linked through many interdependencies. The actions of other organizations in a field can strongly influence the actions of a focal organization. For example, in the mid-1980's large chemical companies adopted voluntary standards for environmental, health, and safety practices and then required that all members of the U.S. Chemical Manufacturers Association (CMA) adopt these voluntary standards (known as Responsible Care®). Smaller chemical producers had little choice but to comply with the new standards if they wished to remain members of the CMA, an affiliation which gave them visibility and legitimacy in the marketplace, with legislators, and in their communities.

While organizations are subject to changes in the institutional rules, they can also initiate change in the rules. In the Responsible Care® example, one large chemical company was particularly influential in shaping the voluntary codes of practice and encouraging their adoption by the CMA. Rather than seeing organizations as simply responding to these shifting rules of the game, we can see them as active participants in shaping them.

Institutional evolution, while it may proceed slowly and in a way that defies accurate prediction, may nonetheless be one of the most powerful drivers of change in organizations. Institutions reflect the norms and values of society at large, embodying the drivers mentioned earlier—regulations that codify rules, and competitive and market pressures that can serve to "raise the bar" for performance in all areas. One need only look at how environmental protection (and environmentalism as a social phenomenon) has changed from the 1960's until today to see that this evolution is continuous and considerable. Great variation remains in how individual industrial organizations respond to environmental issues, but in general all industrial organizations are now operating significantly differently than they did several decades ago. Institutional pressures will only continue to mount in the area of environmental protection, and organizations will need to respond in order to retain their social license to operate.

28.3.4 *Interactions Among the Individual, Organizational and Institutional Levels*

It is clear from the preceding discussion that institutional change is highly interdependent with organizational change. But organizational and institutional change also depend on and shape changes in individual values and actions. At times, acts of individual leadership can reshape entire institutions. When British Petroleum's CEO, Jon Browne, spoke about his commitment to address global climate change by reshaping his company around a vision of "beyond petroleum," other companies in the industry responded. BP defected from the Global Climate Coalition (GCC), an industry group that opposed the Kyoto Treaty, and spurred others to follow suit. Royal Dutch/Shell subsequently quit the GCC and made \$500 million investments in solar and other renewable energy sources.

More commonly, change on the individual, organizational, and institutional levels interact more subtly. Organizations are the collective actors with the greatest capacity to make significant change to their environmental impacts. They have technical and practical control over their mechanisms of production, the resources to bring about changes, and the organizational mechanisms, through structure, routines, and culture, that can channel individual actions. Organizations respond to the motivations and commitments of their individual members, whether they are leaders or simply employees empowered to act. And they respond to the institutional pressures they face.

As industrial organizations increasingly take steps to reduce their impacts on the environment, they change the rules of the game that apply to other organizations, reshaping institutions. With these broader shifts come further change in individual values and beliefs about what is appropriate and what is possible. The evolution in organizational perspectives on technology and the environment will proceed haltingly, and will not depend only on technical factors. Nonetheless, further and significant change in how organizations consider and address their environmental and social impacts is inevitable in the long run.

28.4 THE MECHANICS OF ORGANIZATIONAL CHANGE

Sometimes a corporation's changing environmental goals are dramatic, as with British Petroleum's shift toward renewable energy. Other times, the goals will be modest, as in the desire to make a product or a process greener than it has been. In either case, a formal environmental management system (EMS) within the corporation enables the new goals to be addressed in a structured manner.

The key to an effective EMS is an Environment, Health, and Safety organization, with competent, well-trained personnel. Its members need to have solid links throughout the corporation, from upper management to the design shop to the line workers, because everyone is important in achieving superior environmental performance. Once that organization is in place, it must ensure that comprehensive and reliable data on operations and processes are being acquired. These data provide the underpinning for analyses of environmental performance at all levels. To evaluate an individual manufacturing process, for example, a process map of the type shown in figure 4.1 is constructed. The tools of chapters 3–7—compliance, pollution prevention, life-cycle assessment, and sustainability—are then brought into play (as shown in detail in the appendices) to reveal opportunities can then be prioritized on the basis of feasibility, cost, and the level of improvement that will result.

28.5 ENVIRONMENTALLY-RESPONSIBLE INDUSTRY IN THE FUTURE

Throughout this book, we have discussed tools and approaches for making tomorrow's industrial activities more environmentally responsible than is the case today. We find that certain sectors are quite problematic, while others are likely to have fresh opportunities open to them in the future. Corporate activities will increasingly be constrained or enabled by the relationships that exist among resource availability, technological opportunity, and potential environmental costs. Not all issues can be resolved by being aware of this interplay, but many can. Resolving these issues will involve change that occurs primarily at the level of individual organizations, but this inevitably includes and invokes change in individual values as well as change in broader social institutions. The greater the pressure from regulatory, resource, market, and social arenas, the more likely it is that manufacturing organizations will identify and accomplish technical improvements that minimize their environmental impacts. Greening the industrial facility can markedly improve the balance between human activity and its impact on the environment, an imperative for the pursuit of a sustainable future. All of us need to roll up our sleeves and get busy at this task.

FURTHER READING

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Matthews, D. H., G. C. Christini, and C. T. Hendrickson, Five elements for organizational decision-making with an environmental management systems, Environmental Science and Technology, 38, 1927–1932, 2004.

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Appendix A

Greening the Industrial Facility

Facility Visit Data Sheet

BASIC INFORMATION

Site Name:

Location:

Industrial Sector(s):

What gets done here?

MATERIALS FLOWS—INCLUDE APPROXIMATE QUANTITIES PER YEAR IF AVAILABLE

Raw Material Inputs:

Why are these materials used, and not others?

Industrial Products:

Why are these the specific intended outputs, and not others?

Wastes/Residues: ____________________ ____________________

____________________ ____________________

____________________ ____________________

____________________ ____________________

Why are these wastes/residues generated? ______________________________

____

____

PROCESS TYPES

___Resource generation
___Extraction
___Beneficiation
___Lubrication
___Cleaning
___Purification
___Formation of chemical bonds
___Cleavage of chemical bonds
___Shaping
___Joining
___Surface treatment
___Packaging
___Transportation

NOTES, OBSERVATIONS, COMMENTS

Water Use: ____

____

____

____

Energy Use: ____

____

____

____

Potential Hazard: ____

____

____

____

Other Observations: ____

____

____

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MATERIALS FLOW DIAGRAM SKETCH

Appendix B

Example of a Facility Visit Report Directed Toward Regulatory Compliance

INTRODUCTION

XXX Industries a global specialty chemicals and materials company that produces building block and specialty chemicals. XXX products are used in a wide range of markets, including agriculture, textiles, rubber, electronics, and automotive.[1] The XXX facility located in YYY is a resins manufacturer. The facility produces about 75 different types of resins and sells these products to a variety of markets. Some of the recognizable forms of their product are on can labels and interior coating, in metal plating, paint, on golf balls, and in paper products.

XXX began operations 1941. XXX operates a facility on about a quarter of the 250 acres of land it owns in YYY. The facility is convenient to the interstate and rail transportation. XXX receives materials and ships out products via trucks and rail cars. The facility is also located in an area that is surrounded by river, forest, and wetlands, as well as a residential development. Additionally, there are a few other industrial facilities within close proximity, including a small chemical plant and a resource recovery facility.

On September 19, 2003, the class visited the facility to better understand the operations as a whole. We took tours of the main manufacturing building, which houses equipment and materials used in the resin manufacturing process. This report will describe:

- the processes and flow of materials throughout the XXX facility;
- laws and regulations that XXX follows; and

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[1] XXX Industries Inc. website: http://www.XXX.com

- suggestions for improvement and areas for further examination to achieve environmental compliance and reduce waste.

PROCESSES AND FLOW

Resins are created from an initial phase of heating, cooling, and mixing materials to cause a reaction. The remainder of the process is spent attempting to purify the resin to the degree possible. As you will see in the description of the process, many materials are required. Additionally, the process is resource intensive for water use and energy use. Water is used in the reactors and cleaning processes and treated on-site. Energy is used to heat and pump the product from one step to the next. This description of materials and process flow can be followed using Figure B.1.

Raw Materials—Receiving

As a resins manufacturer, XXX takes raw materials from all over the world and creates a product that is in turn shipped out around the world. Raw materials arrive

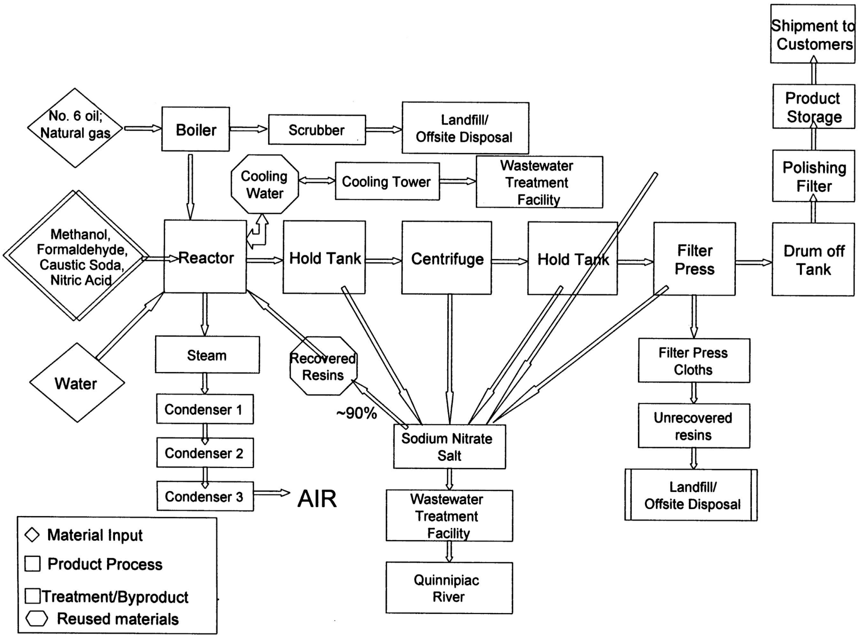

Figure B.1. Materials and process flows for XXX industries resin manufacturing plant.

at the facility on rail cars and tank trucks from other XXX plants and suppliers. Some of the raw material is stored in drums until use, while other materials are held in underground or above ground storage tanks. These raw materials, along with the water drawn from the city and aquifers located on XXX land, are used to produce the resin product.

Reactor

The resin process is controlled by computer operation controlled by plant operators in the control room. Resins manufacturing begins in a 12,000 gallon capacity reactor, when the reactor is filled with methanol and formaldehyde. Melamine, a solid (powder) raw material and caustic soda are then added. The caustic soda is added to adjust the pH to basic conditions. Next, the reactor is charged with more methanol and then nitric acid to adjust the pH back to acidic conditions. An agitator in the reactor mixes the materials together and a reaction occurs.

Following the reaction, the material has to be neutralized to halt further reaction. Additionally, unreacted materials need to be removed from the final material. To accomplish this, the reactor is heated to 250°F at atmospheric pressure and then cooled by cooling coils inside the reactor.

In addition to the materials used to create the resin, the reactor process requires energy to heat and water to cool the materials. The energy is supplied from the city's electric power grid. The cooling coils contain water that stays inside a closed loop of the process. Once the water has been used to cool materials in the reactor, it leaves the reactor and goes to the cooling towers, then back to the reactor process for the next iteration.

Because the reactor contains toxic materials, the conditions of the reactor are closely controlled and monitored by the operators. The reactor itself has explosion-proof housing on it and vents to prevent overpressure. The process also creates several by-products that are either returned to the reactor, are emitted to the air, or are sent for treatment or disposal. Steam and air emissions are released to three condensers in sequence to remove 99 percent of the harmful emissions before releasing to the air. The unreacted methanol, formaldehyde, and water recovered and returned to the reactor process in the subsequent batches. Additionally, any sodium nitrate (salt) that is collected in the water is treated at the wastewater treatment plant.

Hold Tank 1

From the reactor, the material is pumped to a hold tank. Since the material created in the reactor process contains impurities in the form of sodium nitrate created in the reaction, the material sits in the tanks to settle out. This sodium nitrate waste is explosive at extreme temperatures and is therefore collected from the hold tank and sent to the wastewater treatment plant.

Centrifuge

After the first hold tank settling, the material is pumped to the centrifuge to further treat the resins. In the centrifuge, the material is spun at high speeds to separate the salt by-product from the resin. The older centrifuges in the facility create a product that still contains about 15 to 20 percent salt, even after centrifuging. However, the newer centrifuge is predicted to leave only about 2 to 3 percent salt in the resin mixture after treatment.

The centrifuge process results in waste of additional salt that is removed from the resin which is sent to the wastewater treatment plant for treatment.

Hold Tank 2

Following centrifugation, the material is pumped to another hold tank for more settling to remove salts. The waste salt is again collected and sent to the wastewater treatment plant.

Filter Press

Next, the material is sent to the filter press. The filter press is comprised of 25 canvas cloths through which the material is forced. The cloths are of a gauge fine enough to catch remaining salts, but large enough to allow the viscous material to pass through. The cloths have to be disposed of every 2 to 3 days and may contain some valuable resin material that is not recovered, but also contain the hazardous salt, which makes it difficult to reuse the cloths. Additionally, the filter press process results in drippings up to about one million pounds per year that are recovered and sent back through purification for final products.

Final Products

After purification, the resin is usually ready to be shipped to most of XXX's customers. It is held in a drum-off tank until it is transferred to a container for shipping. XXX uses pails, drums, totes, and super sacks to ship the materials. The shipment container may be held in the storage room and sent by rail or truck.

However, if the product is intended for automotive coatings, it will also be sent through the polishing filter to create the purest product possible. Automotive coatings cannot contain salt since they are applied to metal products and would result in rust. Once the polishing filter is complete, the material is sent for packaging and shipping.

In total, the entire resin manufacturing process from raw material input to final resin product stage takes about 24 to 36 hours.

COMPLIANCE

As a manufacturing facility that uses chemicals in their process, XXX is subject to federal, state, and local laws as well as voluntary commitments they have made. The laws that pertain to environmental compliance regulate their air emissions, water effluents, and solid wastes. Additionally, XXX is subject to regulations that are intended to reduce risk to employees at the facility.

Air

XXX has air emissions that are generated primarily in the reactor step, but also from other points in the resins manufacturing process. Air emissions are regulated by the Clean Air Act which was amended in 1990 to include a list of 189 hazardous air pollutants (HAPs) selected by Congress on the basis of potential health and/or environmental hazard. As required by this Act, XXX must employ Maximum Available Control Technology (MACT) to reduce pollutant releases.

Additionally, the XXX facility is located in a nonattainment area as defined by EPA. This means that the National Ambient Air Quality Standards (NAAQS) are not met for a particular pollutant. Therefore, the DEP's state implementation plan requires stricter air emission standards for XXX than the federal requirements. Though XXX has equipment to minimize emissions (i.e., condensers), emissions still occur as the equipment is not 100 percent efficient at removing pollutants. XXX reported the following emissions in 2001, as required by the Pollution Prevention Act of 1990. This information is available through the EPA database called the Toxic Release Inventory (TRI). Emissions were reported of the following HAPs and quantities:

Chemical	Air Emissions (pounds)
ACRYLAMIDE	321
BENZO(G,H,I)PERYLENE	0
ETHYLBENZENE	520
ETHYLENE GLYCOL	34
FORMALDEHYDE	9,600
METHANOL	98,000
N-BUTYL ALCOHOL	39,300
N-METHYLOLACRYLAMIDE	0
NITRATE COMPOUNDS	0
NITRIC ACID	85
POLYCYCLIC AROMATIC COMPOUNDS	0
TOLUENE	670
XYLENE (Mixed Isomers)	2,310

Water

XXX operates an on-site wastewater treatment plant to handle the water containing salts and resins from their processes as well as other by-products. The treatment plant treats approximately two million gallons of water per day. Effluent from the treatment plant is regulated under the Clean Water Act and monitored by the State Department of Environmental Protection (DEP) under their Water Standards and Criteria. The DEP issued a National Pollutant Discharge Elimination System (NPDES) Permit to XXX to allow them to release effluent into the river following specific guidelines.

As with many coastal areas, the receiving water body has been experiencing a problem with nitrogen loading which leads to algal blooms in the Sound. The nitrates result from industrial and agricultural pollution draining from tributaries into the water body. From the wastewater treatment process, XXX reported releases of 69,000 pounds of nitrates released in 2001. Due to the high nitrate content in their waste XXX has voluntarily agreed to treat its waste to a level that exceeds the requirements of its NPDES permit and follow the guidelines to reduce nitrates in its effluent from the wastewater treatment plant on-site.

Solid Waste

XXX's solid waste includes the press cakes resulting from filter press, canvas filter presses, laboratory, and other miscellaneous wastes. Since it operates with hazardous wastes, much of this material is covered by EPA's Resource Conservation and Recovery Act (RCRA) and needs to be managed by certified treatment, storage, or disposal facilities. XXX reports that approximately 95 percent of the solid wastes are sent to facilities to be processed as fuels for cement kilns. In 2001, it reported that 716,000 pounds of waste were sent to TSDFs for further processing.

Safety

XXX also must comply with standards to protect community and employee health. One of the regulations that XXX must follow is the Title III section of the Superfund Amendments and Reauthorization Act (SARA). This Act requires XXX to make sure that the community is aware of routine releases (see TRI information above). In addition, XXX has an emergency response plan and onsite fire department to plan for and immediately respond to spills and emergencies on site. XXX also has a unique foam sprinkler system in the storage area of the facility that fills up automatically when certain conditions are met in the area.

XXX must also comply with standards set by the Occupational Safety and Health Administration (OSHA) to maintain the health of employees. It has a health monitoring program that tests for hearing and lungs as well as other health parameters.

Additionally required is that employees are periodically tested for hearing loss and that noise levels are tested using dosimeters or similar equipment in appropriate work areas. This testing ensure when if the noise level in a work area exceeds the long-term exposure limits it is identified and mitigated through engineering controls, management decisions, or personal protective equipment.

XXX also has material safety data sheets (MSDSs) as required by OSHA available around the plant to workers. These sheets describe the chemicals used in the plant for the following information:

- address and phone number of manufacturer;
- common and scientific names of the chemical;
- important physical and chemical characteristics;
- fire, explosion, and reactivity data;
- adverse health affects following overexposure;
- methods for safe handling, use, and disposal; and
- recommended methods for workplace control of exposure.[2]

RECOMMENDATIONS

XXX operates in an area that is sensitive to environmental pollution. The facility is surrounded not only by a residential community, but also by environmentally sensitive areas such as wetlands, a river, and forested property. In addition, XXX is located in a part of the country that has been deemed a nonattainment area by EPA. Therefore, environmental compliance is an important part of their footprint on the planet. Though I do not know of their actual compliance history since starting operations in 1941, the managers of the XXX facility who we spoke with voiced an effort by the company to maintain or exceed regulatory standards. One such instance was their voluntary joining of the QQQ initiative to reduce nitrates in the receiving water body. They also reuse products within the facility such as cooling water and recovered liquids. XXX additionally has explored purchasing alternative equipment that would increase efficiency, thus reducing emissions and by-products.

In light of these efforts, I propose several additional suggestions as a starting point to maintaining environmental compliance for the future. Thinking for the future would likely reduce the need to reengineer the resins process or to purchase new equipment when stricter environmental standards are released. Reducing resource consumption and by-products has the additional benefit of cost savings to the bottom line of the company. The suggestions below identify some possible areas for meeting long-term compliance goals.

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[2] "The Facts on File Dictionary of Environmental Science", Stevenson, L. Harold and Bruce Wyman, 1991, New York, NY.

1. Energy

   As demonstrated by the process flow description, a large amount of energy is used in the process to heat and cool the reactor as well as to pump the product from one step to the next. In fact, the largest raw materials purchased at the plant were reported to be fuel oil and natural gas to power the boilers.

   I propose that an energy inventory of the plant should be performed to assess where the energy is used. Once this step is completed, engineering measures may be used to determine if energy can be saved by relocating equipment to reduce pumping needs or if better insulation could be used on the reactors to minimize heat loss during heating.

2. Equipment Replacement

   XXX has already begun to explore the option of replacing centrifuges with newer technology. As the replacement of the one centrifuge demonstrated, the loss of material is reduced dramatically by purchasing the new equipment and the reported payback period for this piece of equipment was reported to be 2 years. XXX may consider eventually replacing all of its old centrifuges with newer ones.

   Additionally, XXX has investigated replacing the filter press technology with a newer alternative that would include cartridges and bag filters that are smaller, have less leakage, and take less time to replace. This equipment change out would reduce time off-line and costs of treating and sending away waste.

3. Monitoring the Process

   XXX monitors most equipment through the control room. However, to ensure environmental compliance, I recommend installing equipment that keeps track of boiler temperatures, reactor performance, effluent measurements, and air emissions in a central location. This macroscopic view of plant activity would allow for unusual events to be recognized immediately by plant operators.

   Monitoring is also something that could be performed manually by periodic and frequent checks of performance of each part of the process throughout the operations. This option is less costly, though specific events might be recognized at a later time than with computer monitoring.

4. Increase Reactor Efficiency

   As was noted earlier, the reactor creates an intermediate product that then goes through several stages to remove salts and other impurities due to incomplete reaction. A detailed analysis of the reaction may identify alternative mixing techniques, heating or cooling specifications, or even raw materials that would reduce by-products. This would not only reduce cost, but eliminate some of the emissions due to the purification stages of the resin manufacturing process.

In addition to these suggestions for compliance, I would also suggest that XXX explore a market that may use some of the by-products created. The salts sent to the wastewater treatment plant could be recovered and possibly sold to a market as fertilizer components. Additionally, since XXX is located next to two other plants (resource recovery facility and small chemical plant), these facilities could possibly benefit from one another. For instance, if the chemical plant currently sends wastewater offsite for treatment, XXX could process the water in their wastewater treatment plant. This would generate money and would reduce transportation costs for the chemical plant. Additionally, waste generated at XXX that does not require careful treatment as required by RCRA could be sent to the resource recovery facility to again reduce the need for transportation of waste off site.

CONCLUSION

XXX is a good example of an evolving manufacturing facility. They have implemented techniques and equipment to increase efficiency and reduce emissions. They additionally recognize areas for future improvements. With a continuous improvement of the process, XXX can continue to reduce by-products and harmful wastes.

Appendix C

Example of a Facility Visit Report Directed Toward Pollution Prevention

I. INTRODUCTION & INDUSTRY OVERVIEW

On 3 October 2003, this class inspected the XXX powdered metals manufacturing facility, located in YYY. The purpose of the site visit was to view this company's metal manufacturing process, and to obtain knowledge for preparation of a basic Pollution Prevention (P2) analysis. This report contains key findings from our site visit, as well as some general observations on the powdered metals industry, which will impact XXX's long-term business and P2 activities.

1.1 Process & Market Overview

The basic powder metallurgy process uses pressure and heat to form precision metal parts and shapes. It is a niche but growing sub-market within the larger metal fabrication industry, and is of special interest to our class due to its relatively benign production impact upon the environment, which will be discussed in greater detail later in this report.

Powder metallurgy was practiced from at least 3000 B.C., even before iron melting and casting processes were developed. Today, the powdered metal parts and products industry in North America has estimated sales of $5 billion, and powdered metal manufacture is international in scope with growing industries in all of the major industrialized countries." (from Metal Powder Industries Federation (MPIF) website).

Powdered metal parts are used in many end products. The largest buyer of powdered metal parts is the automotive industry, which accounts for approximately 70 percent of the North American powdered metal parts market. In 2001 the typical family vehicle contained about 17 kg (37.5 lb.) of powdered metal parts, an increase from 10.9 kg (24lb.) in 1990. Some SUV models utilize 27.2 kg (60 lb.) of powdered metal parts. (2003 speech by David L. Schaefer, MPIF President). A breakdown of powdered metal applications by market sector is given to the left:

1.2 XXX Corporation Market Niche

Within this highly-competitive powder metallurgy market, XXX is itself a small, niche operation, with estimated sales revenues of $4,800,000/year, according to the company CFO. The facility is located in an industrially-zoned section of YYY, nearby major rail and automotive arteries. The operations are housed entirely in a 100 year-old brick building, and include 40 employees, eight of whom work in the front office. Inspecting the facilities, one is aware that margins are not large: the machine and plant assets are aged (some machines are 40 years old), though in good condition, and many of the interim production steps are manually accomplished as opposed to automated. The company's largest expenses are, after powdered metal raw materials: energy, space, and labor.

XXX imports iron, steel, brass, bronze, stainless and nickel-silver powders to produce gears, fasteners, bearings, cams, contacts and structural parts of all sorts. XXX especially excels in the production of helical gears and miniature parts that are custom-engineered and made to order. In total, XXX produces approximately 150 unique parts for 50 customers. The largest component of XXX's business is automotive parts, which reflects the general trend of the larger powdered metals industry.

While XXX's powder metallurgy process avoids many of the environmentally damaging byproducts and emissions of standard metal fabrication processes, it still requires a significant amount of energy and heat to produce the metal products and is subject to various manufacturing efficiencies. This report analyzes XXX from the "enhanced" P2 lens, focusing on the production process, and on opportunities for the facility to become more closely aligned with the tenets of P2 in hopes of saving money and even further reducing the company's environmental footprint.

II. MATERIALS FLOW & DIAGRAM

2.1 Overview of the Powder Metallurgy (Powdered Metal) Process (Source: Metal Powder Industries Federation, http://www.mpif.org/)

The basic powdered metal process uses pressure and heat to form precision metal parts and shapes. Powder is squeezed (at room temperature in the XXX process) automatically in a rigid precision die at up to 200 tons per square inch into the desired engineered shape. After the mass of powder is squeezed into a shape and ejected from the press, it is fed slowly through a special high-temperature controlled atmosphere furnace to bond the particles together. They are metallurgically fused without melting, a phenomenon called "sintering".

In contrast to other metal forming techniques, powder metallurgy parts are shaped directly from powders while castings are formed from metal that must be melted, and wrought parts are shaped by deformation of hot or cold metal, or by machining. Ultimately, this allows for significant Pollution Prevention (P2) gains by the powder metallurgy process.

Figure C.1 shows a material flow diagram for XXX's manufacturing process.

2.2 XXX Powdered Metals System Inputs

XXX's largest system input is its powdered metal stock. The company purchases both virgin powder and pre-blended powder, both of which are delivered via truck to XXX's powder room in large 3,000 lb (when filled) octagonal cardboard boxes. In a given month, XXX will purchase some 200,000 lbs of brass, copper, iron and iron mix powders, apparently focusing on the high-production rather than specialized end of the marketplace.

Powder particles are specific in shape and size ranging from 0.1 to 1,000 micrometers. Major methods for making metal powders are atomization of molten metal, reduction of oxides, electrolysis and chemical reduction. These manufacturing techniques result in powders with different characteristics and appearance, for use in specific applications. A significant portion of XXX's particles include scrap iron, which is melted and along with virgin particles, air/water blown and annealed. The extraction and refinement process, both of which have significant environmental impacts, occur outside of XXX's facility and operations, and are beyond the scope of this P2 report.

After powdered metal, XXX's largest system input is energy, in the form of electricity, to drive its manufacturing process. Approximately 125 kw/month is utilized by the plant, with nearly 75 to 80 percent of this powering the furnace(s). Until recently, this energy input cost XXX $15 to $20,000 per month. Today, the facility consumes approximately $10,000 in electricity a month.

XXX also utilizes lubricants (formerly zinc stearate, a toxin, which has been largely eliminated from the manufacturing process; now synthetic and wax-based (apcrowax)) to help the powdered metal bond; water to clean the presses & other machinery and to operate the press compressors; ammonia and nitrogen to maintain a constant atmosphere in the furnace; cardboard packaging for product shipment (though this step is now largely one of recycled materials), small amounts of oil, grease and rust inhibitor for the presses and other automated machines, and oakite soap (use unknown, seen on a "hazardous materials" sign in the plant).

2.3 Production Process

Powder and lubricants, oils, and other materials are received at the Powder Room/Receiving. The powdered metals arrive in 3,000 lb cardboard octagons, and

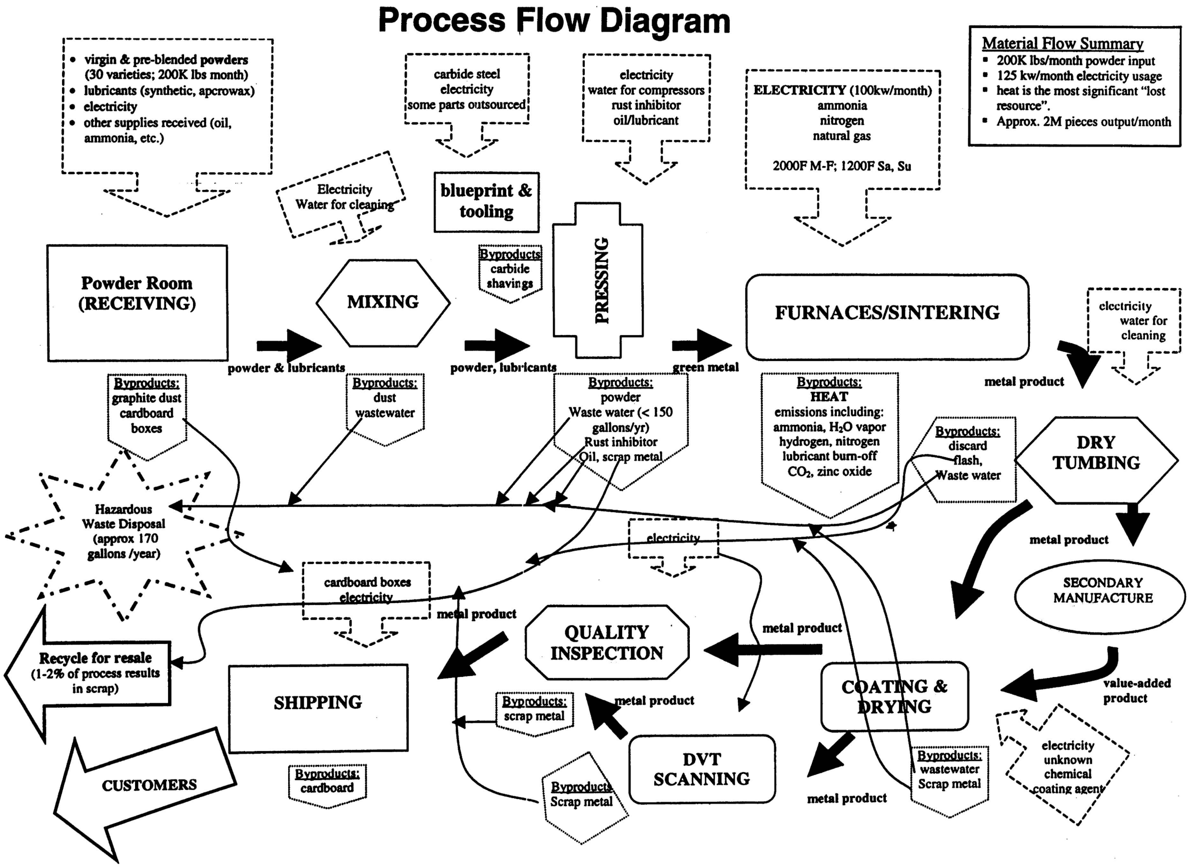

Figure C.1. Materials and process flows for powdered metal facility.

are stacked for later use. A significant amount of graphite powder becomes airborne during this stage, evidenced by the darkened floors, walls, employees and facilities.

The powders are then either directly brought to the factory floor, or are mixed in one of the two large mixers on site. In all, XXX utilizes some 30 types of powdered materials in its manufacturing process. Here, electricity and lubricants (for bonding) are applied to the process, and waste products include graphite dust and wastewater (from mixer cleaning).

Next the powder and lubricant (which comprises less than 1 percent of the powder mix) are placed into large funnels or feedshoe atop one of a number of presses, and a controlled amount of powder is gravity fed into the die carried by the powder feedshoe. The upper and lower punches move toward each other and apply a predetermined amount of pressure to the loose powder, creating a compact that conforms to the shape and size of the die and punches. The top punch is withdrawn from the die and the bottom punch moves up, ejecting the part from the die. At this stage, the compact is known as a "green" part or body. The bottom punch drops down to the bottom fill position, the powder feedshoe moves toward the die cavity, pushing the newly pressed part out of the way, and fills the die with powder for pressing of the next part. The pressures used to compact the parts at XXX range from 5 to 200 tons/square inch. Significant inputs for this process include: electricity, water for compressors, rust inhibitor and oil/lubricant. Byproducts include powder, waste water (<150 gallons/yr), rust inhibitor, oil and scrap metal (which is captured and later resold for 2–3 cents/lb.).

After pressing, the "green metal" is sent to one of two XXX furnaces for sintering. Here, the "green metal" is placed on a mesh belt and moved slowly through the sintering furnace. The temperature within the furnace rises slowly in the preheat zone until reaching the actual sintering temperature. It remains essentially constant during the time at temperature, and proceeds into the cooling zone where the drop in part temperature is controlled. The sintering temperature is kept below the melting point of the base metal. Some of the alloying additives may melt, which results in liquid phase sintering. Typically the furnace contains a protective atmosphere (at XXX: ammonia and nitrogen) to prevent oxidation of the parts in the hot zone, and to help reduce oxides still present.

As the parts travel through the furnace, the temperature cycle results in changes in composition and microstructure. In the preheat zone, the lubricant volatilizes, leaves the part as a vapor, and is carried away by air flow. In the hot zone metallurgical bonds develop between particles and solid state alloying takes place. The part then moves through the cooling zone. The microstructure developed during sintering determines the properties of the part.

The sintering stage utilizes a great amount of energy (some 100 kW/month, nearly 80 percent of the factory's total energy intake). Other inputs include ammonia and nitrogen as mentioned above, and natural gas. XXX currently runs the sinter seven days a week, with Monday—Friday temperatures at 2,000°F for work, and 1,200°F on weekends to maintain a safe range during the "down time".

Significant byproducts of the sintering stage include heat (which is mostly lost), and emissions including ammonia, H_2O vapor, hydrogen, nitrogen, lubricant burn-off, CO_2, and zinc oxide.

The metal product is then put into a large tumbler, which, over the course of 10–15 minutes of agitation, serves to remove rough edges from the metal products. Electricity and, periodically, water for cleaning out the mechanism are the inputs. Typical byproducts of this stage include discard, which is recycled and resold, flash and wastewater.

Next, depending upon the customer's need, XXX may either send out to a secondary entity the nearly finished product for various secondary operations, usually to improve the surface finish or modify the microstructure, or XXX may finish the product in house with a simple coating & drying process. XXX's most common add-on at this stage, via outsourcing, is plating. In this way, XXX avoids some of the nastier chemical/industrial finishing processes onsite.

After these finishing processes, XXX will scan piece by piece, if the products are for BBB Corporation's truck (a million dollar customer), in their Digital Vision Testing machine. The unique scanning step is due to the close resemblance of the two parts. Failure to accurately categorize, package and deliver these two small metal parts can be enormously expensive to XXX and result in significant financial penalties. From this stage, as with other previous stages, some failed product is identified, and captured for later recycle and resale.

Ultimately, all metal parts come to XXX's quality control, where samples are visually inspected and approved for shipment. Again, a small amount of failed product is identified, and captured for later resale. The approved products are sealed in cardboard boxes (mainly recycled boxes from the powdered metal delivery—all except BBB, the only customer to refuse this step), and shipped out to XXX customers primarily in the Eastern United States.

Collected hazardous wastes are shipped offsite in 2–3 55 gallon drums in the course of the year. Contents are primarily oils from machinery, rust inhibitor, ammonia, alcohol, oakite soap. It is not clear how waste waters are treated, a subject for follow up with XXX management.

III. EVALUATION OF XXX ENVIRONMENTAL IMPACTS AND ISSUES

This report analyzes XXX from the "enhanced" P2 lens; ie: corporate actions that reduce generation of hazardous substances, as well as the consumption of natural resources—with the end goal that every atom entering the manufacturing process, and every erg of energy used in the process should result in a salable product or product transformation.

3.1 Operations

Basically a "chipless" metalworking process, XXX's manufacturing process typically uses more than 97 percent of the starting raw material in the finished part. Because of this, the company is able to realize significant energy and materials conservation gains vis a vis standard metal fabrication.

Additionally, XXX's process is cost effective in producing simple or complex parts at, or very close to, final dimensions in production rates which can range from a few hundred to over a thousand parts per hour. As a result, only minor, if any, machining is required, again saving energy and materials versus standard metal fabrication.

Nonetheless, a significant amount of electricity is lost, in the form of heat, during XXX's process. Both as a result of an "open furnace" with corresponding emissions (too low for monitoring under the Clean Air Act), but emissions nonetheless, and as a result of keeping the furnaces running at 1,500°F during the weekends.

It is unclear after this tour how NPM manages the entirety of its waste water. But the CFO did state that the company shipped off site 2 to 3 55 gallon drums of hazardous waste per year, hardly a large amount for an industrial facility, and representative of the environmental gains made by the powdered metals process.

3.2 Regulatory Compliance

XXX's operations fall within jurisdiction of very few regional and national environmental regulations, due to the company's low levels of reported waste:

- **Wastewater:** volume and dispensation unclear, assumed offsite transport.
- **Air Emissions:** Furnace does emit ammonia, H_2O vapor, hydrogen, nitrogen, lubricant burn-off, CO_2, and zinc oxide. The latter is a toxic substance, but TRI indicates XXX's reported levels are too low to be monitored.
- **Solid Waste:** XXX outsources hazardous waste disposal of water (assumed) and rust inhibitor, oil, grease, and flash. As well as the bulk of product finishing, which again avoid hazardous waste generation on site.
- **Employee:** Occupational Safety and Health Administration, title 1910.119, ensuring that XXX employees work in a safe, secure environment (of particular interest to insurance companies). The amount of powdered metal particulates in the factory is great, and visible. While breathing masks are available, it did appear to be the exception rather than the rule that employees wore masks, even as they were coated by dust. Also, the pressing machines and furnace offer additional hazard.

Perhaps most importantly, as a major supplier to the automotive industry, XXX must adhere to ISO quality standards, and must certify to BBB that it is ISO compliant back to resource extraction. ISO 9000 also applies to XXX's production. As the CFO noted, XXX is expected to create "aerospace quality for Walmart prices".

In summary, then, XXX's production process is a significant step up in Pollution Prevention. Major remaining environmental challenges—on site—deal with capturing lost energy/heat, and in minimizing metal powder dust inhalation and product loss.

IV. POLLUTION PREVENTION OPPORTUNITIES & RECOMMENDATIONS

Upon analysis of XXX's operations and application of Pollution Prevention framework, the following options are presented for consideration, as means for the company to reduce its environmental impact, and to realize additional savings:

Option	Feasible	Capital Cost	Comments
Capture excess heat/heat loss from furnace(s) and			Possible air quality problems unless lubricant & ammonia/nitrogen burn offs can be captured/eliminated prior to recycling.
a. Recycle within XXX plant for heating; and/or	a. Good	a. Medium	a. Possible revenues <= $1,000 month
b. Sell & transport to adjacent manufacturing plants for heating/use	b. Possible	b. Medium	b. Possible revenues <= $500 month
Replace furnace chain-link conveyer belt with another product allowing for repeated heating/cooling	Possible. Does technology exist?	Likely medium/high	Expansion/contraction tolerant belt would allow XXX to shut down completely their furnaces each weekend, saving $2,500-$3,000/ month and significantly reducing energy waste. Currently furnaces held at 1,200F during weekend.
Incent BBB Corp. to streamline truck parts from 2 to 1 (these are the sole products that are run through the scanner to separate the two look-alikes)	Unlikely	Low/None	Eliminates Digital Vision Testing step: sell DVT machine at book value; write off depreciation; eliminate FTE personnel devoted to task; reduce packing materials.

(Continued)

Option	Feasible	Capital Cost	Comments
Eliminate ambient powder/dust in factory	Difficult	Medium	Magnetized capture devices (air purifiers, floor coverings etc) to for graphite dust in powder room & factory. Better product utilization and reduction in worker's comp insurance with carrier.
Obtain powder from recycled metals only, skipping ore extraction process	Unlikely. Cost/supply probably not sufficient.	Medium/High	Avoiding ore-extraction process of suppliers through 100% recycled metals powder unlikely unless XXX customer requests
Eliminate remaining secondary operations & finishing thru use of new powdered metal mixtures	Possible, but not likely.	Low	Assuming that new powders can be developed, XXX could profit by adding this step "in house"; significant environmental benefits.
Recyclable die molds	Unlikely. Technology does not yet exist.	Low/Medium	Allows for mold recycling, and faster lead times for mold creation for customers.
Recycle compressor/press cleanser waste water	Possible but unlikely.	High	Low benefit for high cost. Currently send off-site 2–3 55 gallon drums/year for $5K cost.
Recycle or sell process by-products: rust inhibitor, ammonia, alcohol, oakite soap	Unlikely	High	Low volume by this small plant makes on-site recycle & recapture inefficient; easier & cheaper to send off site.
Eliminate furnace emissions (CO_2, Zinc oxide, water vapor)	Unlikely	High	Current emissions below regulatory limits; little incentive to invest in new emissions capture technology.

V. CONCLUSIONS

A relatively benign production process brings XXX a long way towards realizing Pollution Prevention goals. With the main exception of energy loss, the facility has few glaring issues and is managed by a capable team.

Long-term survival in a very competitive industry will depend on XXX's ability to grow, adapt, and innovate. Currently aided by a strong labor force, but relying upon very old machinery, the company is vulnerable. Customers are demanding higher quality at lower price, with increasing intolerance for inconsistent product. Global competition and production is strong, and predicted to become only more so in the coming decade. With the continued growth in powdered metal product demand, North American manufacturers are gearing up by investing in new plant capacity. XXX would benefit by considering the above Pollution Prevention recommendations as it modernizes its facilities.

Appendix D

Environmentally-Responsible Product Matrix

Scoring Guidelines and Protocols

The Product Improvement Matrix is described in Chapter 5. In this appendix, a sample of possible scoring considerations appropriate to each of the matrix elements is presented. It is anticipated that different types of products may require different check lists and evaluations, so this appendix is presented as an example rather than as a universal formula.

PRODUCT MATRIX ELEMENT: 1,1

Life Stage: Premanufacture
Environmental Concern: Materials Choice

If any of the following conditions apply, the matrix element rating is 0:

- For the case where supplier components/sub-systems are used: no/little information is known about the chemical content in supplied products and components.
- For the case where materials are acquired from suppliers: a scarce material is used where a reasonable alternative is available. (Scarce materials are defined as antimony, beryllium, boron, cobalt, chromium, gold, mercury, the platinum metals (Pt, Ir, Os, Pa, Rh, Ru), silver, thorium, and uranium.)

If all of the following conditions apply, the matrix element rating is 4:

- No virgin material is used in incoming components or materials.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Is the product designed to minimize the use of materials in restricted supply (See above list)?
- Is the product designed to utilize recycled materials or components wherever possible?

PRODUCT MATRIX ELEMENT: 1,2

Life Stage: Premanufacture
Environmental Concern: Energy Use

If any of the following conditions apply, the matrix element rating is 0:

- One or more of the principal materials used in the product requires energy-intensive extraction and suitable alternative materials are available that do not. (Materials requiring energy-intensive extraction are defined as virgin aluminum, virgin steel, and virgin petroleum.)

If all of the following conditions apply, the matrix element rating is 4:

- Negligible energy is needed to extract or ship the materials or components for this product.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Is the product designed to minimize the use of virgin materials whose extraction is energy-intensive?
- Does the product design avoid or minimize the use of high-density materials whose transport to and from the facility will require significant energy use? (Such materials are defined as those with a specific gravity above 7.0).
- Is transport distance of incoming materials and components minimized?

PRODUCT MATRIX ELEMENT: 1,3

Life Stage: Premanufacture
Environmental Concern: Solid Residues

If any of the following conditions apply, the matrix element rating is 0:

- For the case where materials are acquired from suppliers: metals from virgin ores are used, creating substantial waste rock residues that could be avoided by the use of virgin material, and suitable virgin material is available from recycling streams.
- For the case where supplier components/sub-systems are used: all incoming packaging is from virgin sources and consists of three or more types of materials.

If all of the following conditions apply, the matrix element rating is 4:

- For the case where materials are acquired from suppliers: no solid residues result from resource extraction or during production of materials by recycling (example: petroleum).
- For the case where supplier components/sub-systems are used: none/minimal packaging material is used -or - supplier takes back all packaging material.
- For the case where supplier components/sub-systems are used: incoming packaging is totally reused/recycled.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Is the product designed to minimize the use of materials whose extraction or purification involves the production of large amounts of solid residues (i.e., coal and all virgin metals)?
- Is the product designed to minimize the use of materials whose extraction or purification involves the production of toxic solid residues? (This category includes all radioactive materials.)
- Has incoming packaging volume and weight, at and among all levels (primary, secondary and tertiary), been minimized?
- Is materials diversity minimized in incoming packaging?

PRODUCT MATRIX ELEMENT: 1,4

Life Stage: Premanufacture
Environmental Concern: Liquid Residues

If any of the following conditions apply, the matrix element rating is 0:

- For the case where supplier components/sub-systems are used: metals from virgin ores that cause substantial acid mine drainage are used, and suitable virgin material is available from recycling streams. (Materials causing acid mine drainage are defined as copper, iron, nickel, lead, and zinc.)

- For the case where materials are acquired from suppliers: the packaging contains toxic or hazardous substances that might leak from it if improper disposal occurs.

If all of the following conditions apply, the matrix element rating is 4:

- For the case where materials are acquired from suppliers: no liquid residues result from resource extraction or during production of materials by recycling.
- For the case where supplier components/sub-systems are used: no liquid residue is generated during transportation, unpacking, or use of this product.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Is the product designed to minimize the use of materials whose extraction or purification involves the generation of large amounts of liquid residues? (This category includes paper and allied products, coal, and materials from biomass.)
- Is the product designed to minimize the use of materials whose extraction or purification involves the generation of toxic liquid residues? (These materials are defined as aluminum,
- copper, iron, lead, nickel, and zinc.)
- Are refillable/reusable containers used for incoming liquid materials where appropriate?
- Does the use of incoming components require cleaning that involves a large amount of water or that generate liquid residues needing special disposal methods?

PRODUCT MATRIX ELEMENT: 1,5

Life Stage: Premanufacture
Environmental Concern: Gaseous Residues

If any of the following conditions apply, the matrix element rating is 0:

- The materials used cause substantial emissions of toxic, smog-producing, or greenhouse gases into the environment, and suitable alternatives that do not do so are available. (These materials are defined as aluminum, copper, iron, lead, nickel, zinc, paper and allied products, and concrete.)

If all of the following conditions apply, the matrix element rating is 4:

- No gaseous residues are produced during resource extraction or production of materials by recycling.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Is the product designed to minimize the use of materials whose extraction or purification involves the generation of large amounts of gaseous (toxic or otherwise) residues? (Such materials are defined as aluminum, copper, iron, lead, nickel, and zinc.)

PRODUCT MATRIX ELEMENT: 2,1

Life Stage: Product Manufacture
Environmental Concern: Materials Choice

If any of the following conditions apply, the matrix element rating is 0:

- Product manufacture requires relatively large amounts of materials that are restricted {see (1,1)}, toxic, and/or radioactive.

If all of the following conditions apply, the matrix element rating is 4:

- Materials used in manufacture are completely closed loop (captured and reused/recycled) with minimum inputs required.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Do manufacturing processes avoid the use of materials that are in restricted supply?
- Is the use of toxic material avoided or minimized? Is the use of radioactive material avoided?
- Is the use of virgin material minimized?
- Has the chemical treatment of materials and components been minimized?

PRODUCT MATRIX ELEMENT: 2,2

Life Stage: Product Manufacture
Environmental Concern: Energy Use

If any of the following conditions apply, the matrix element rating is 0:

- Energy use for product manufacture/testing is high and less energy intensive alternatives are available.

If all of the following conditions apply, the matrix element rating is 4:

- Product manufacture and testing requires no or minimal energy use.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Is the product manufacture designed to minimize the use of energy intensive processing steps?
- Is the product manufacture designed to minimize energy intensive evaluation/testing steps?
- Do the manufacturing processes use co-generation, heat exchanges, and/or other techniques to utilize otherwise waste energy?
- Is the manufacturing facility powered down when not in use?

PRODUCT MATRIX ELEMENT: 2,3

Life Stage: Product Manufacture
Environmental Concern: Solid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Solid manufacturing residues are large and no reuse/recycling programs are in use.

If all of the following conditions apply, the matrix element rating is 4:

- Solid manufacturing residues are minor and each constituent is >90% reused/recycled.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Have solid manufacturing residues been minimized and reused to the greatest extent possible?
- Has the resale of all solid residues as inputs to other products/processes, been investigated and implemented?
- Are solid manufacturing residues that do not have resale value
- minimized and recycled?

PRODUCT MATRIX ELEMENT: 2,4

Life Stage: Product Manufacture
Environmental Concern: Liquid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Liquid manufacturing residues are large and no reuse/recycling programs are in use.

If all of the following conditions apply, the matrix element rating is 4:

- Liquid manufacturing residues are minor and each constituent is >90% reused/recycled.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- If solvents or oils are used in the manufacture of this product is their use minimized and have alternatives been investigated and implemented?
- Have opportunities for sale of all liquid residues as input to other processes/products been investigated and implemented?
- Have the processes been designed to require the maximum recycled liquid process chemicals rather than virgin materials?

PRODUCT MATRIX ELEMENT: 2,5

Life Stage: Product Manufacture
Environmental Concern: Gaseous Residues

If any of the following conditions apply, the matrix element rating is 0:

- Gaseous manufacturing residues are large and no reuse/recycling programs are in use. CFCs are used in product manufacture.

If all of the following conditions apply, the matrix element rating is 4:

- Gaseous manufacturing residues are relatively minor and reuse/recycling programs are in use.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- If HCFCs are used in the manufacture of this product have alternatives been thoroughly investigated and implemented?
- Are greenhouse gases used or generated in any manufacturing process connected with this product?
- Have the resale of all gaseous residues as inputs to other processes/products been investigated and implemented?

PRODUCT MATRIX ELEMENT: 3,1

Life Stage: Product Packaging and Transport
Environmental Concern: Materials Choice

If any of the following conditions apply, the matrix element rating is 0:

- All outgoing packaging is from virgin sources and consists of three or more types of materials.

If all of the following conditions apply, the matrix element rating is 4:

- No outgoing packaging or minimal and recycled packaging material is used.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Does the product packaging minimize the number of different materials used and is it optimized for weight/volume efficiency?
- Have efforts been made to use recycled materials for product packaging and to make sure the resulting package is recyclable and marked as such?
- Is there a functioning recycling infrastructure for the product packaging material?
- Have the packaging engineer and the installation personnel been consulted during the product design?

PRODUCT MATRIX ELEMENT: 3,2

Life Stage: Product Packaging and Transportation
Environmental Concern: Energy Use

If any of the following conditions apply, the matrix element rating is 0:

- Packaging material extraction, packaging procedure, and transportation/installation method(s) are all energy intensive and less energy-intensive options are available.

If all of the following conditions apply, the matrix element rating is 4:

- Packaging material extraction, packaging procedure, and transportation/installation methods(s) all require little or no energy.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Do packaging procedures avoid energy-intensive activities?
- Are component supply systems and product distribution/installation plans designed to minimize energy use?
- If installation is involved, is it designed to avoid energy intensive procedures?
- Is long distance, energy intensive product transportation avoided or minimized?

PRODUCT MATRIX ELEMENT: 3,3

Life Stage: Product Packaging and Transportation
Environmental Concern: Solid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Outgoing packaging material is excessive, with little consideration given to recycling or reuse.

If all of the following conditions apply, the matrix element rating is 4:

- None or minimal outgoing packaging material is used and/or the packaging is totally reused or recycled.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Is the product packaging designed to make it easy to separate the constituent materials?
- Do the packaging materials need special disposal after products are unpacked?
- Has product packaging volume and weight, at and among all three levels, (primary, secondary, and tertiary) been minimized?
- Are arrangements made to take back product packaging for
- reuse and/or recycling?
- Is materials diversity minimized in outgoing product packaging?

PRODUCT MATRIX ELEMENT: 3,4

Life Stage: Product Packaging and Transportation
Environmental Concern: Liquid Residues

If any of the following conditions apply, the matrix element rating is 0:

- The product packaging contains toxic or hazardous substance that might leak from it if improper disposal occurs. (Such as the acid from batteries).

If all of the following conditions apply, the matrix element rating is 4:

- Little or no liquid residue is generated during packaging, transportation, or installation of this product.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Are refillable or reusable containers used for liquid products where appropriate?
- Do the product packaging operations need cleaning/maintenance procedures that require a large amount of water or generate other liquid residues (oils, detergents, etc.) that need special methods for disposal?
- Do the product unpacking and/or installation operations require cleaning that involves a large amount of water or that generate liquid residues needing special disposal methods?

PRODUCT MATRIX ELEMENT: 3,5

Life Stage: Product Packaging and Transportation
Environmental Concern: Gaseous Residues

If any of the following conditions apply, the matrix element rating is 0:

- Abundant gaseous residues are generated during packaging, transportation, or installation, and alternative methods that would significantly reduce gaseous emissions are available.

If all of the following conditions apply, the matrix element rating is 4:

- Little or no gaseous residues are generated during packaging, transportation, or installation of this product.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- If the product contains pressurized gases, are transport/installation procedures designed to avoid their release?
- Are product distribution plans designed to minimize gaseous emissions from transport vehicles?
- If the packaging is recycled for its energy content (i.e., incinerated), have the materials been selected to ensure no toxic gases are released?

PRODUCT MATRIX ELEMENT: 4,1

Life Stage: Product Use
Environmental Concern: Materials Choice

If any of the following conditions apply, the matrix element rating is 0:

- Consumables contain significant quantities of materials in restricted supply or toxic/hazardous substances.

If all of the following conditions apply, the matrix element rating is 4:

- Product use and product maintenance requires no consumables.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Has consumable material use been minimized?
- If the product is designed for disposal after using, have alternative approaches for accomplishing the same purpose been examined?
- Have the materials been chosen such that no environmentally inappropriate maintenance is required, and no unintentional release of toxic materials to the environment occurs during use?
- Are consumable materials generated from recycled streams rather than virgin material?

PRODUCT MATRIX ELEMENT: 4,2

Life Stage: Product Use
Environmental Concern: Energy Use

If any of the following conditions apply, the matrix element rating is 0:

- Product use and/or maintenance is relatively energy-intensive and less energy-intensive methods are available to accomplish the same purpose.

If all of the following conditions apply, the matrix element rating is 4:

- Product use and maintenance requires little or no energy.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Has the product been designed to minimize energy use while in service?
- Has energy use during maintenance/repair been minimized?

- Have energy-conserving design features (such as auto-shut off or enhanced insulation) been incorporated?
- Can the product monitor and display its energy use and/or its operating energy efficiency while in service?

PRODUCT MATRIX ELEMENT: 4,3

Life Stage: Product Use
Environmental Concern: Solid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Product generates significant quantities of hazardous/toxic solid residue during use or from repair/maintenance operations.

If all of the following conditions apply, the matrix element rating is 4:

- Product generates no (or relative minor amounts of) solid residue during use or from repair/maintenance operations.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Has the periodic disposal of solid materials (such as cartridges, containers, or batteries) associated with the use and/or maintenance of this product been avoided or minimized?
- Have alternatives to the use of solid consumables been thoroughly investigated and implemented where appropriate?
- If intentional dissipative emissions to land occur as a result of using this product, have less environmentally harmful alternatives been investigated?

PRODUCT MATRIX ELEMENT: 4,4

Life Stage: Product Use
Environmental Concern: Liquid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Product generates significant quantities of hazardous/toxic liquid residue during use or from repair/maintenance operations.

If all of the following conditions apply, the matrix element rating is 4:

- Product generates no (or relatively minor amounts of) liquid residues during use or from repair/maintenance operations.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Has the periodic disposal of liquid materials (such as lubricants and hydraulic fluids) associated with the use and/or maintenance of this product been avoided or minimized?
- Have alternatives to the use of liquid consumables been thoroughly investigated and implemented where appropriate?
- If intentional dissipative emissions to water occur as a result of using this product, have less environmentally harmful alternatives been investigated?
- If product contains liquid material that has the potential to be unintentionally dissipated during use or repair, have appropriate preventive measures been incorporated?

PRODUCT MATRIX ELEMENT: 4,5

Life Stage: Product Use
Environmental Concern: Gaseous Residues

If any of the following conditions apply, the matrix element rating is 0:

- Product generates significant quantities of hazardous/toxic gaseous residue during use or from repair/maintenance operations.

If all of the following conditions apply, the matrix element rating is 4:

- Product generates no (or relatively minor amounts of) gaseous residues during use or from repair/maintenance operations.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Has the periodic emission of gaseous materials (such as CO_2, SO_2, VOCs, and CFCs) associated with the use and/or maintenance of this product been avoided or minimized?
- Have alternatives to the use of gaseous consumables been thoroughly investigated and implemented where appropriate?
- If intentional dissipative emissions to air occur as a result of using this product, have less environmentally harmful alternatives been investigated?
- If product contains any gaseous materials that have the potential to be unintentionally dissipated during use or repair, have the appropriate preventive measures been incorporated?

PRODUCT MATRIX ELEMENT: 5,1

Life Stage: Recycling, Disposal
Environmental Concern: Material Choice

If any of the following conditions apply, the matrix element rating is 0:

- Product contains significant quantities of mercury (i.e., mercury relays) asbestos (i.e., asbestos based insulations) or cadmium (i.e., cadmium or zinc plated parts) that are not clearly identified and easily removable.

If all of the following conditions apply, the matrix element rating is 4:

- Material diversity is minimized, the product is easy to disassemble, and all parts are recyclable.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Have materials been chosen and used in light of the desired recycling/disposal option for the product (e.g., for incineration, for recycling, for refurbishment)?
- Does the product minimize the number of different materials that are used in its manufacture?
- Are the different materials easy to identify and separate?
- Is this a battery free product?
- Is this product free of components containing PCBs or PCTs (e.g., in
- capacitors and transformers)?
- Are major plastics parts free of polybrominated flame retardants or heavy metal-based additives (colorants, conductors, stabilizers, etc)?

PRODUCT MATRIX ELEMENT: 5,2

Life Stage: Recycling, Disposal
Environmental Concern: Energy Use

If any of the following conditions apply, the matrix element rating is 0:

- Recycling/disposal of this product is relatively energy-intensive (compared to other products that perform the same function) due to its weight, construction, and/or complexity.

If all of the following conditions apply, the matrix element rating is 4:

- Energy use for recycling or disposal of this product is minimal.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Is the product designed with the aim of minimizing the use of energy-intensive process steps in disassembly?
- Is the product designed for high-level reuse of materials? (Direct reuse in a similar product is preferable to a degraded reuse.)
- Will transport of products for recycling be energy-intensive because of product weight or volume or the location of recycling facilities?

PRODUCT MATRIX ELEMENT: 5,3

Life Stage: Recycling, Disposal
Environmental Concern: Solid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Product consists primarily of unrecyclable solid materials (such as rubber, fiberglass, and compound polymers).

If all of the following conditions apply, the matrix element rating is 4:

- Product can be easily refurbished and reused and is easily dismantled and 100% reused/recycled at the end of its life. For example, no part of this product will end up in a landfill.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Has the product been assembled with fasteners such as clips or hook-and-loop attachments rather than chemical bonds (gels, potting compounds) or welds?
- Have efforts been made to avoid joining dissimilar materials together in ways difficult to reverse?
- Are all plastic components identified by ISO markings as to their content?
- If product consists of plastic parts is there one dominant (>80% by weight) species?
- Is this product to be leased rather than sold?

PRODUCT MATRIX ELEMENT: 5,4

Life Stage: Recycling, Disposal
Environmental Concern: Liquid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Product contains primarily unrecyclable liquid materials.

If all of the following conditions apply, the matrix element rating is 4:

- Product uses no operating liquids (such as oils, coolants, or hydraulic fluids) and no cleaning agents or solvents are necessary for its reconditioning.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Can liquids contained in the product be recovered at disassembly rather than lost?
- Does disassembly, recovery and reuse generate liquid residues?
- Does materials recovery and reuse generate liquid residues?

PRODUCT MATRIX ELEMENT: 5,5

Life Stage: Recycling, Disposal
Environmental Concern: Gaseous Residues

If any of the following conditions apply, the matrix element rating is 0:

- Product contains or produces primarily unrecyclable gaseous materials that are dissipated to the atmosphere at the end of its life.

If all of the following conditions apply, the matrix element rating is 4:

- Product contains no substances lost to evaporation/sublimation (other than water) and no volatile substances are used for refurbishment.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the product meets DFE preferences for this matrix element.

- Can gases contained in the product be recovered at disassembly rather than lost?
- Does materials recovery and reuse generate gaseous residues?
- Can plastic parts be incinerated without requiring sophisticated air pollution control devices? Plastic parts that can cause difficulty in this regard are those that contain polybrominated flame retardants or metal based additives, are finished with polyurethane based paints, or are plated or painted with metals.

Appendix E

Environmentally-Responsible Process Matrix

Scoring Guidelines and Protocols

The Process Improvement Matrix is described in Chapter 5. In this appendix, a sample of possible scoring considerations appropriate to each of the matrix elements is presented. It is anticipated that different types of processes may require different check lists and evaluations, so this appendix is presented as an example rather than as a universal formula.

PROCESS MATRIX ELEMENT: 1,1

Life Stage: Resource Provisioning
Environmental Concern: Materials Choice

If any of the following conditions apply, the matrix element rating is 0:

- For the case where supplier components/sub-systems are used: no/little information is known about the chemical content in supplied process consumables and equipment.
- For the case where materials are acquired from suppliers: a scarce material is used where a reasonable alternative is available. (Scarce materials are defined as antimony, beryllium, boron, cobalt, chromium, gold, mercury, the platinum metals (Pt, Ir, Os, Pa, Rh, Ru), silver, thorium, and uranium.)

If all of the following conditions apply, the matrix element rating is 4:

- No virgin material is used in incoming components or materials.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the process meets DFE preferences for this matrix element.

- Is the process designed to minimize the use of materials in restricted supply?
- Is the process designed to utilize recycled materials or components wherever possible?
- Of the potential consumable materials, are those chosen the ones whose extraction results in the lowest environmental impact?

PROCESS MATRIX ELEMENT: 1,2

Life Stage: Resource Provisioning
Environmental Concern: Energy Use

If any of the following conditions apply, the matrix element rating is 0:

- One or more of the principal materials used in the process requires energy-intensive extraction and suitable alternative materials are available that do not. (Materials requiring energy-intensive extraction are defined as virgin aluminum, virgin steel, and virgin petroleum.)

If all of the following conditions apply, the matrix element rating is 4:

- Negligible energy is needed to extract or ship the materials or components for this process.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the process meets DFE preferences for this matrix element.

- Is the process designed to minimize the use of virgin materials whose extraction is energy-intensive?
- Does the process design avoid or minimize the use of high-density materials whose transport to and from the facility will require significant energy use? (Such materials are defined as those with a specific gravity above 7.0).
- Is transport distance of incoming materials and components minimized?

PROCESS MATRIX ELEMENT: 1,3

Life Stage: Resource Provisioning
Environmental Concern: Solid Residues

If any of the following conditions apply, the matrix element rating is 0:

- For the case where materials are acquired from suppliers: metals from virgin ores are used, creating substantial waste rock residues that could be avoided by the use of virgin material, and suitable virgin material is available from recycling streams.
- For the case where supplier components/sub-systems are used: all incoming packaging is from virgin sources and consists of three or more types of materials.

If all of the following conditions apply, the matrix element rating is 4:

- For the case where materials are acquired from suppliers: no solid residues result from resource extraction or during production of materials by recycling (example: petroleum).
- For the case where supplier components/sub-systems are used: none/minimal packaging material is used or the supplier takes back all packaging material.
- For the case where supplier components/sub-systems are used: incoming packaging is totally reused/recycled.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the process meets DFE preferences for this matrix element.

- Is the process designed to minimize the use of materials whose extraction or purification involves the production of large amounts of solid residues (i.e., coal and all virgin metals)?
- Is the process designed to minimize the use of materials whose extraction or purification involves the production of toxic solid residues? (This category includes all radioactive materials.)
- Has incoming packaging volume and weight, at and among all levels (primary, secondary and tertiary), been minimized?
- Is materials diversity minimized in incoming packaging?

PROCESS MATRIX ELEMENT: 1,4

Life Stage: Resource Provisioning
Environmental Concern: Liquid Residues

If any of the following conditions apply, the matrix element rating is 0:

- For the case where supplier components/sub-systems are used: metals from virgin ores that cause substantial acid mine drainage are used, and suitable virgin material is available from recycling streams. (Materials causing acid mine drainage are defined as copper, iron, nickel, lead, and zinc.)

- For the case where materials are acquired from suppliers: the packaging contains toxic or hazardous substances that might leak from it if improper disposal occurs.

If all of the following conditions apply, the matrix element rating is 4:

- For the case where materials are acquired from suppliers: no liquid residues result from resource extraction or during production of materials by recycling.
- For the case where supplier components/sub-systems are used: no liquid residue is generated during transportation, unpacking, or use of this product.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the process meets DFE preferences for this matrix element.

- Is the process designed to minimize the use of materials whose extraction or purification involves the generation of large amounts of liquid residues? (This category includes paper and allied products, coal, and materials from biomass.)
- Is the process designed to minimize the use of materials whose extraction or purification involves the generation of toxic liquid residues? (These materials are defined as aluminum, copper, iron, lead, nickel, and zinc.)
- Are refillable/reusable containers used for incoming liquid materials where appropriate?
- Does the use of incoming components require cleaning that involves a large amount of water or that generate liquid residues needing special disposal methods?

PROCESS MATRIX ELEMENT: 1,5

Life Stage: Resource Provisioning
Environmental Concern: Gaseous Residues

If any of the following conditions apply, the matrix element rating is 0:

- The materials used cause substantial emissions of toxic, smog-producing, or greenhouse gases into the environment, and suitable alternatives that do not do so are available. (These materials are defined as aluminum, copper, iron, lead, nickel, zinc, paper and allied products, and concrete.)

If all of the following conditions apply, the matrix element rating is 4:

- No gaseous residues are produced during resource extraction or production of materials by recycling.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the process meets DFE preferences for this matrix element.

- Is the process designed to minimize the use of materials whose extraction or purification involves the generation of large amounts of gaseous (toxic or otherwise) residues? (Such materials are defined as aluminum, copper, iron, lead, nickel, and zinc.)
- Does the process design avoid using consumable materials whose transport to the facility will result in significant gaseous residues?

PROCESS MATRIX ELEMENT: 2,1

Life Stage: Process Implementation
Environmental Concern: Materials Choice

If any of the following conditions apply, the matrix element rating is 0:

- Process equipment manufacture requires relatively large amounts of materials that are restricted, toxic, and/or radioactive.

If all of the following conditions apply, the matrix element rating is 4:

- Materials used in process equipment manufacture are completely closed loop (captured and reused/recycled) with minimum inputs required.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the process equipment meets DFE preferences for this matrix element.

- Does the process equipment design avoid the use of materials that are in restricted supply?
- Is the use of toxic material avoided or minimized? Is the use of radioactive material avoided?
- Is the use of virgin material minimized?
- Has the chemical treatment of materials and components been minimized?

PROCESS MATRIX ELEMENT: 2,2

Life Stage: Process Implementation
Environmental Concern: Energy Use

If any of the following conditions apply, the matrix element rating is 0:

- Energy use for process equipment manufacture and installation is high and less energy intensive alternatives are available.

If all of the following conditions apply, the matrix element rating is 4:

- Process equipment manufacture and installation requires no or minimal energy use.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the process equipment meets DFE preferences for this matrix element.

- Is the process equipment manufacture designed to minimize the use of energy-intensive processing steps?
- Is the process equipment manufacture designed to minimize energy-intensive evaluation/testing steps?
- Does the process equipment manufacture use co-generation, heat exchanges, and/or other techniques to utilize otherwise waste energy?

PROCESS MATRIX ELEMENT: 2,3

Life Stage: Process Implementation
Environmental Concern: Solid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Solid residues from shipping and installation are large and no reuse/recycling programs are in use.

If all of the following conditions apply, the matrix element rating is 4:

- Solid residues from shipping and installation are minor and are >90% reused/recycled.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the process equipment meets DFE preferences for this matrix element.

- Have solid shipping and installation residues been minimized to the greatest extent possible?
- Has the resale of all solid shipping and installation residues been implemented?

PROCESS MATRIX ELEMENT: 2,4

Life Stage: Process Implementation
Environmental Concern: Liquid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Liquid shipping and installation residues are large and no reuse/recycling programs are in use.

If all of the following conditions apply, the matrix element rating is 4:

- Liquid shipping and installation residues are minor and each constituent is >90% reused/recycled.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the process meets DFE preferences for this matrix element.

- If solvents or oils are used in the shipping and installation of this process equipment, is their use minimized and have alternatives been investigated and implemented?
- If water is used in the shipping and installation of this process equipment, is its use minimized and have alternative approaches been investigated and implemented?

PROCESS MATRIX ELEMENT: 2,5

Life Stage: Process Implementation
Environmental Concern: Gaseous Residues

If any of the following conditions apply, the matrix element rating is 0:

- Gaseous process equipment shipping and installation residues are large and are uncontrolled. CFCs are used in process equipment shipping and installation.

If all of the following conditions apply, the matrix element rating is 4:

- Gaseous process equipment shipping and installation residues are relatively minor and reuse/recycling programs are in use.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the process meets DFE preferences for this matrix element.

- Are greenhouse gases used or generated in any shipping or installation activity connected with the process equipment?
- Have the emitted amounts been minimized?

PROCESS MATRIX ELEMENT: 3,1

Life Stage: Primary Process Operation
Environmental Concern: Materials Choice

If any of the following conditions apply, the matrix element rating is 0:

- Large quantities of toxic and/or scarce consumables are used in the primary process.

If all of the following conditions apply, the matrix element rating is 4:

- No toxic and/or scarce consumables are used in the primary process.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the primary process meets DFE preferences for this matrix element.

- Is the use of toxic consumable materials in primary processes avoided or minimized?
- Is the use of radioactive consumable materials in primary processes avoided or minimized?
- Is the primary process designed ot avoid the use of large amounts of water?

PROCESS MATRIX ELEMENT: 3,2

Life Stage: Primary Process Operation
Environmental Concern: Energy Use

If any of the following conditions apply, the matrix element rating is 0:

- Energy use in the primary process is very high and no conservation is practiced.

If all of the following conditions apply, the matrix element rating is 4:

- Negligible energy is used in the primary manufacturing process.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the primary process meets DFE preferences for this matrix element.

- Does the primary process use energy-efficient equipment such as variable-speed motors?
- Is the primary process designed to minimize the use of energy-intensive process steps such as high heating differentials, heavy motors, extensive cooling, etc.?
- Is the primary process designed to minimize the use of energy intensive evaluation steps such as testing in a heated chamber?
- Does the primary process use cogeneration, heat exchange, and other techniques for utilizing otherwise waste energy?

PROCESS MATRIX ELEMENT: 3,3

Life Stage: Primary Process Operation
Environmental Concern: Solid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Large amounts of solid residues result from the primary process and no control is practiced.

If all of the following conditions apply, the matrix element rating is 4:

- No solid residues result from the primary process.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the primary process meets DFE preferences for this matrix element.

- Have solid primary process residues (mold scrap, cutting scrap, and so on) been minimized and reused to the greatest extent possible?
- Have opportunities for sale of all primary process solid residues as inputs into the products and processes of others been investigated, and modifications made to residues (if possible and necessary) to facilitate such transactions?
- Has packaging material entering the facility in connection with primary processes been minimized, and does it use the fewest possible different materials?
- Do suppliers take back the packaging material in which consumables for primary processes enter the facility?

PROCESS MATRIX ELEMENT: 3,4

Life Stage: Primary Process Operation
Environmental Concern: Liquid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Large amounts of liquid residues result from the primary process and no control is practiced.

If all of the following conditions apply, the matrix element rating is 4:

- No liquid residues result from the primary process.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the primary process meets DFE preferences for this matrix element.

- If solvents or oils are used in the primary process, is their use minimized and have substitutes been investigated?
- Have opportunities for sale of all primary process liquid residues as inputs into the products and processes of others been investigated, and modifications made to residues (if possible and necessary) to facilitate such transactions?
- Has the primary process been designed to utilize the maximum amount of recycled liquid specie rather than virgin materials?

PROCESS MATRIX ELEMENT: 3,5

Life Stage: Primary Process Operation
Environmental Concern: Gaseous Residues

If any of the following conditions apply, the matrix element rating is 0:

- Large amounts of gaseous residues result from the primary process and no control is practiced.

If all of the following conditions apply, the matrix element rating is 4:

- No gaseous residues result from the primary process.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the primary process meets DFE preferences for this matrix element.

- Have opportunities for sale of all primary process gaseous residues as inputs into the products and processes of others been investigated, and modifications made to residues (if possible and necessary) to facilitate such transactions?
- Are greenhouse gases used or generated in the primary process?
- If CFCs or HCFCs are used in the primary process, have alternatives been thoroughly investigated?

PROCESS MATRIX ELEMENT: 4,1

Life Stage: Complementary Process Operation
Environmental Concern: Materials Choice

If any of the following conditions apply, the matrix element rating is 0:

- Large quantities of toxic and/or scarce consumables are used in complementary processes.

If all of the following conditions apply, the matrix element rating is 4:

- No toxic and/or scarce consumables are used in complementary processes.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which complementary processes meet DFE preferences for this matrix element.

- Is the use of toxic consumable materials in complementary processes avoided or minimized?
- Is the use of radioactive consumable materials in complementary processes avoided or minimized?
- Are complementary processes designed to avoid the use of large amounts of water?

PROCESS MATRIX ELEMENT: 4,2

Life Stage: Complementary Process Operation
Environmental Concern: Energy Use

If any of the following conditions apply, the matrix element rating is 0:

- Energy use in complementary processes is very high and no conservation is practiced.

If all of the following conditions apply, the matrix element rating is 4:

- Negligible energy is used in the complementary processes.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the complementary processes meet DFE preferences for this matrix element.

- Do the complementary processes use energy-efficient equipment such as variable-speed motors?

- Are complementary processes designed to minimize the use of energy-intensive process steps such as high heating differentials, heavy motors, extensive cooling, etc.?
- Are complementary processes designed to minimize the use of energy intensive evaluation steps such as testing in a heated chamber?
- Do complementary processes use cogeneration, heat exchange, and other techniques for utilizing otherwise waste energy?

PROCESS MATRIX ELEMENT: 4,3

Life Stage: Complementary Process Operation
Environmental Concern: Solid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Large amounts of solid residues result from the complementary processes and no control is practiced.

If all of the following conditions apply, the matrix element rating is 4:

- No solid residues result from the complementary processes.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the complementary processes meet DFE preferences for this matrix element.

- Have solid complementary process residues (mold scrap, cutting scrap, and so on) been minimized and reused to the greatest extent possible?
- Have opportunities for sale of all complementary process solid residues as inputs into the products and processes of others been investigated, and modifications made to residues (if possible and necessary) to facilitate such transactions?
- Has packaging material entering the facility in connection with complementary processes been minimized, and does it use the fewest possible different materials?
- Do suppliers take back the packaging material in which consumables for complementary processes enter the facility?

PROCESS MATRIX ELEMENT: 4,4

Life Stage: Complementary Process Operation
Environmental Concern: Liquid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Large amounts of liquid residues result from the complementary processes and no control is practiced.

If all of the following conditions apply, the matrix element rating is 4:

- No liquid residues result from the complementary processes.

If neither of the above ratings is assigned, complete the checklist below Assign a rating of 1, 2, or 3 depending on the degree to which the complementary processes meet DFE preferences for this matrix element.

- If solvents or oils are used in complementary processes, is their use minimized and have substitutes been investigated?
- Have opportunities for sale of all complementary process liquid residues as inputs into the products and processes of others been investigated, and modifications made to residues (if possible and necessary) to facilitate such transactions?
- Have complementary processes been designed to utilize the maximum amount of recycled liquid species rather than virgin materials?

PROCESS MATRIX ELEMENT: 4,5

Life Stage: Complementary Process Operation
Environmental Concern: Gaseous Residues

If any of the following conditions apply, the matrix element rating is 0:

- Large amounts of gaseous residues result from the complementary processes and no control is practiced.

If all of the following conditions apply, the matrix element rating is 4:

- No gaseous residues result from the complementary processes.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the complementary processes meet DFE preferences for this matrix element.

- Have opportunities for sale of all complementary process gaseous residues as inputs into the products and processes of others been investigated, and modifications made to residues (if possible and necessary) to facilitate such transactions?
- Are greenhouse gases used or generated in the complementary processes?

- If CFCs or HCFCs are used in complementary processes, have alternatives been thoroughly investigated?

PROCESS MATRIX ELEMENT: 5,1

Life Stage: Refurbishment, Recycling, Disposal
Environmental Concern: Material Choice

If any of the following conditions apply, the matrix element rating is 0:

- Process equipment contains significant quantities of mercury (i.e., mercury relays) asbestos (i.e., asbestos based insulations) or cadmium (i.e., cadmium or zinc plated parts) that are not clearly identified and easily removable.

If all of the following conditions apply, the matrix element rating is 4:

- Material diversity is minimized, the product is easy to disassemble, and all parts are recyclable.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the process equipment meets DFE preferences for this matrix element.

- Have materials been chosen and used in light of the desired recycling/disposal option for the process equipment (e.g., for incineration, for recycling, for refurbishment)?
- Does the process equipment minimize the number of different materials that are used in its manufacture?
- Are the different materials easy to identify and separate?
- Is this battery free process equipment?
- Is this process equipment free of components containing PCBs or PCTs (e.g., in capacitors and transformers)?
- Are major plastics parts free of polybrominated flame retardants or heavy metal-based additives (colorants, conductors, stabilizers, etc)?

PROCESS MATRIX ELEMENT: 5,2

Life Stage: Refurbishment, Recycling, Disposal
Environmental Concern: Energy Use

If any of the following conditions apply, the matrix element rating is 0:

- Recycling/disposal of this process equipment is relatively energy-intensive (compared to other products that perform the same function) due to its weight, construction, and/or complexity.

If all of the following conditions apply, the matrix element rating is 4:

- Energy use for recycling or disposal of this process equipment is minimal.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the process equipment meets DFE preferences for this matrix element.

- Is the process equipment designed with the aim of minimizing the us of energy-intensive steps in disassembly?
- Is the process equipment designed for high-level reuse of materials? (Direct reuse in similar process equipment is preferable to a degraded reuse.)
- Will transport of process equipment for recycling be energy-intensive because of process equipment weight or volume or the location of recycling facilities?

PROCESS MATRIX ELEMENT: 5,3

Life Stage: Refurbishment, Recycling, Disposal
Environmental Concern: Solid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Process equipment consists primarily of unrecyclable solid materials (such as rubber, fiberglass, and compound polymers).

If all of the following conditions apply, the matrix element rating is 4:

- Process equipment can be easily refurbished and reused and is easily dismantled and 100% reused/recycled at the end of its life. For example, no part of this process equipment will end up in a landfill.

If neither of the above ratings is assigned, complete the checklist below: Assign a rating of 1, 2, or 3 depending on the degree to which the process equipment meets DFE preferences for this matrix element.

- Has the process equipment been assembled with fasteners such as clips or hook-and-loop attachments rather than chemical bonds (gels, potting compounds) or welds?
- Have efforts been made to avoid joining dissimilar materials together in ways difficult to reverse?
- Are all plastic components identified by ISO markings as to their content?
- If the process equipment consists of plastic parts is there one dominant (>80% by weight) species?
- Is this process equipment to be leased rather than sold?

PROCESS MATRIX ELEMENT: 5,4

Life Stage: Refurbishment, Recycling, Disposal
Environmental Concern: Liquid Residues

If any of the following conditions apply, the matrix element rating is 0:

- The process equipment contains primarily unrecyclable liquid materials.

If all of the following conditions apply, the matrix element rating is 4:

- The process equipment uses no operating liquids (such as oils, coolants, or hydraulic fluids) and no cleaning agents or solvents are necessary for its reconditioning.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the process equipment meets DFE preferences for this matrix element.

- Can liquids contained in the process equipment be recovered at disassembly rather than lost?
- Does disassembly, recovery and reuse generate liquid residues?
- Does materials recovery and reuse generate liquid residues?

PROCESS MATRIX ELEMENT: 5,5

Life Stage: Refurbishment, Recycling, Disposal
Environmental Concern: Gaseous Residues

If any of the following conditions apply, the matrix element rating is 0:

- Process equipment contains or produces primarily unrecyclable gaseous materials that are dissipated to the atmosphere at the end of its life.

If all of the following conditions apply, the matrix element rating is 4:

- Process equipment contains no substances lost to evaporation/sublimation (other than water) and no volatile substances are used for refurbishment.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the process equipment meets DFE preferences for this matrix element.

- Can gases contained in the process equipment be recovered at disassembly rather than lost?
- Does materials recovery and reuse generate gaseous residues?

- Can plastic parts be incinerated without requiring sophisticated air pollution control devices?
- Plastic parts that can cause difficulty in this regard are those that contain polybrominated flame retardants or metal based additives, are finished with polyurethane based paints, or are plated or painted with metals.

Appendix F

Environmentally-Responsible Facilities Matrix

Scoring Guidelines and Protocols

The Facilities Improvement Matrix is described in Chapter 5. In this appendix, a sample of possible scoring considerations appropriate to each of the matrix elements is presented. It is anticipated that different types of facilities may require different check lists and evaluations, so this appendix is presented as an example rather than as a universal formula.

FACILITY MATRIX ELEMENT: 1,1

Life Stage: Site Selection, Development, and Infrastructure
Environmental Concern: Ecological Impacts

If any of the following conditions apply, the matrix element rating is 0:

- The site is developed with massive disturbance or destruction of natural areas.

If all of the following conditions apply, the matrix element rating is 4:

- The site is developed with negligible destruction of natural areas.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Has the proposed site previously been used for similar activities?
- If not, have any such sites been surveyed for availability?

- Is necessary development activity, if any, planned to avoid disruption of existing biological communities?
- Is the use of heavy equipment for site development minimized?
- Are areas disturbed during site development carefully restored?
- Is the biota of the site compatible with all planned facility emissions, including possible exceedances?

FACILITY MATRIX ELEMENT: 1,2

Life Stage: Site Selection, Development, and Infrastructure
Environmental Concern: Energy Use

If any of the following conditions apply, the matrix element rating is 0:

- A complete new energy infrastructure is installed during site development.

If all of the following conditions apply, the matrix element rating is 4:

- The existing energy infrastructure is used without modification.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Is the site such that it can be made operational with only minimal energy expenditures?
- Has the site been selected so as to avoid any energy emission impacts on existing biota?
- Does the site allow delivery and installation of construction or renovation materials with minimal use of energy?

FACILITY MATRIX ELEMENT: 1,3

Life Stage: Site Selection, Development, and Infrastructure
Environmental Concern: Solid Residues

If any of the following conditions apply, the matrix element rating is 0:

- A large quantity of solid residues is generated during site development and no recycling is practiced.

If all of the following conditions apply, the matrix element rating is 4:

- Insignificant solid residues are generated during site development.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Is the site such that it can be made operational with only minimal production of solid residues?
- Have plans been made to ensure that any solid residues generated in the process of developing the site are managed so as to minimize their impacts on biota and human health?
- If any solid residues generated in the process of developing the site may be hazardous or toxic to biota or humans, have plans been made to minimize releases and exposures?

FACILITY MATRIX ELEMENT: 1,4

Life Stage: Site Selection, Development, and Infrastructure
Environmental Concern: Liquid Residues

If any of the following conditions apply, the matrix element rating is 0:

- A large quantity of liquid residues is generated during site development and no recycling is practiced.

If all of the following conditions apply, the matrix element rating is 4:

- Insignificant liquid residues are generated during site development.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Is the site such that it can be made operational with only minimal production of liquid residues?
- Have plans been made to ensure that any liquid residues generated in the process of developing the site are managed so as to minimize their impacts on biota and human health?
- If any liquid residues generated in the process of developing the site may be hazardous or toxic to biota or humans, have plans been made to minimize releases and exposures?

FACILITY MATRIX ELEMENT: 1,5

Life Stage: Site Selection, Development, and Infrastructure
Environmental Concern: Gaseous Residues

If any of the following conditions apply, the matrix element rating is 0:

- A large quantity of gaseous residues is generated during site development and no recycling is practiced.

If all of the following conditions apply, the matrix element rating is 4:

- Insignificant gaseous residues are generated during site development. If neither of the above ratings is assigned, complete the checklist below.

Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Is the site such that it can be made operational with only minimal production of gaseous residues?
- Have plans been made to ensure that any gaseous residues generated in the process of developing the site are managed so as to minimize their impacts on biota and human health?
- If any gaseous residues generated in the process of developing the site may be hazardous or toxic to biota or humans, have plans been made to minimize releases and exposures?

FACILITY MATRIX ELEMENT: 2,1

Life Stage: Principal Business Activity—Products
Environmental Concern: Ecological Impacts

If any of the following conditions apply, the matrix element rating is 0:

- Hazardous and/or virgin materials are used where suitable nonhazardous and/or recycled materials exist.

If all of the following conditions apply, the matrix element rating is 4:

- Negligible amounts of hazardous and/or virgin materials are used in the facilities equipment.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Does the process development avoid the use of materials that are in restricted supply?
- Is the use of toxic material avoided or minimized?
- Is the use of radioactive material avoided?
- Is the use of virgin material minimized?
- Has the chemical treatment of materials and components been minimized?

FACILITY MATRIX ELEMENT: 2,2

Life Stage: Principal Business Activity—Products
Environmental Concern: Energy Use

If any of the following conditions apply, the matrix element rating is 0:

- Energy consumption for facility operations is very high and no energy management is practiced.

If all of the following conditions apply, the matrix element rating is 4:

- Negligible energy consumption is involved in facility operations.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Is the product and process designed to minimize the use of energy intensive processing steps?
- Is the product and process designed to minimize energy intensive evaluation/testing steps?
- Does the process use co-generation, heat exchanges, and/or other techniques to utilize otherwise waste energy?
- Is the manufacturing facility powered down when not in use?

FACILITY MATRIX ELEMENT: 2,3

Life Stage: Principal Business Activity—Products
Environmental Concern: Solid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Large amounts of solid residues are produced by facility operations equipment manufacture and installation.

If all of the following conditions apply, the matrix element rating is 4:

- Negligible amounts of solid residues are produced by product manufacture.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Have solid manufacturing residues been minimized and reused to the greatest extent possible?

- Has the resale of all solid residues as inputs to other products/processes, been investigated and implemented?
- Are solid manufacturing residues that do not have resale value minimized and recycled?

FACILITY MATRIX ELEMENT: 2,4

Life Stage: Principal Business Activity—Products
Environmental Concern: Liquid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Large amounts of liquid residues are produced by product manufacture and installation.

If all of the following conditions apply, the matrix element rating is 4:

- Negligible amounts of liquid residues are produced by product manufacture and installation.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- If solvents or oils are used in the manufacture of this product is their use minimized and have alternatives been investigated and implemented?
- Have opportunities for sale of all liquid residues as input to other processes/products been investigated and implemented?
- Have the processes been designed to require the maximum recycled liquid process chemicals rather than virgin materials?

FACILITY MATRIX ELEMENT: 2,5

Life Stage: Principal Business Activity—Products
Environmental Concern: Gaseous Residues

If any of the following conditions apply, the matrix element rating is 0:

- Large amounts of gaseous residues are produced by product manufacture and installation.

If all of the following conditions apply, the matrix element rating is 4:

- Negligible amounts of gaseous residues are produced by product manufacture and installation.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- If HCFCs are used in the manufacture of this product have alternatives been thoroughly investigated and implemented?
- Are greenhouse gases used or generated in any manufacturing process connected with this product?
- Have the resale of all gaseous residues as inputs to other processes/products been investigated and implemented?

FACILITY MATRIX ELEMENT: 3,1

Life Stage: Principal Business Activity—Processes
Environmental Concern: Ecological Impacts

If any of the following conditions apply, the matrix element rating is 0:

- Large quantities of toxic and/or scarce consumables are used in the process.

If all of the following conditions apply, the matrix element rating is 4:

- No toxic and/or scarce consumables are used in facility processes.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Is the use of toxic consumables materials in manufacturing processes avoided or minimized?
- Is the use of radioactive materials in manufacturing processes avoided or minimized?
- Is the use of water in manufacturing processes avoided or minimized?

FACILITY MATRIX ELEMENT: 3,2

Life Stage: Principal Business Activity—Processes
Environmental Concern: Energy Use

If any of the following conditions apply, the matrix element rating is 0:

- Energy used in manufacturing processes is very high and no conservation is practiced.

If all of the following conditions apply, the matrix element rating is 4:

- Negligible energy is used in manufacturing operations.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Is vehicular activity in connection with manufacturing activities minimized?
- Does the manufacturing involve the use of energy-intensive activities such as high heating differentials, heavy motors, extensive cooling, etc., and have these activities been minimized as much as possible?

FACILITY MATRIX ELEMENT: 3,3

Life Stage: Principal Business Activity—Processes
Environmental Concern: Solid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Large amounts of solid residues result from the manufacturing activities and no control is practiced.

If all of the following conditions apply, the matrix element rating is 4:

- No solid residues result from the manufacturing activities.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Has packaging material from suppliers of replacement parts or consumables been minimized, and does it use the fewest possible different materials?
- Is it made from recycled materials?
- Are manufacturing activities designed so as to generate minimal and nontoxic solid residues?
- Are solid residues from manufacturing activities recycled?

FACILITY MATRIX ELEMENT: 3,4

Life Stage: Principal Business Activity—Processes
Environmental Concern: Liquid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Large amounts of liquid residues result from the manufacturing activities and no control is practiced.

If all of the following conditions apply, the matrix element rating is 4:

- No liquid residues result from the manufacturing activities.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Have manufacturing activities been designed to utilize the maximum amount of recycled liquid consumables rather than virgin materials?
- Are manufacturing activities designed to generate minimal and nontoxic liquid residues in use?
- Are liquid residues from manufacturing activities recycled?

FACILITY MATRIX ELEMENT: 3,5

Life Stage: Principal Business Activity—Processes
Environmental Concern: Gaseous Residues

If any of the following conditions apply, the matrix element rating is 0:

- Large amounts of gaseous residues result from the manufacturing activities and no control is practiced.

If all of the following conditions apply, the matrix element rating is 4:

- No gaseous residues result from the manufacturing activities.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Are manufacturing activities designed to generate minimal and nontoxic gaseous residues in use?
- If CFCs or HCFCs are used in the manufacturing activities, have alternatives been thoroughly investigated?
- Are greenhouse gases used or generated in processes within the facility?
- Are products designed to generate minimal and nontoxic gaseous residues in recycling or disposal?
- Are gaseous residues from manufacturing activities recycled?

FACILITY MATRIX ELEMENT: 4,1

Life Stage: Facility Operations
Environmental Concern: Ecological Impacts

If any of the following conditions apply, the matrix element rating is 0:

- None of the site is left in a natural state and fertilizers and pesticides are used freely.

If all of the following conditions apply, the matrix element rating is 4:

- Essentially all the site has been left in its natural state except for immediate building areas, and no pesticides or fertilizer are used.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Is the maximum possible portion of the facility allowed to remain in its natural state?
- Is the use of pesticides and herbicides on the property minimized?
- Is noise pollution from the site minimized?

FACILITY MATRIX ELEMENT: 4,2

Life Stage: Facility Operations
Environmental Concern: Energy Use

If any of the following conditions apply, the matrix element rating is 0:

- No site energy management of any kind is practiced.

If all of the following conditions apply, the matrix element rating is 4:

- Energy use for facility operations is minimal and is provided by renewable resources (solar, wind power, etc.).

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Is the energy needed for heating and cooling the buildings minimized?
- Is the energy needed for lighting the buildings minimized?
- Is energy efficiency a consideration when buying or leasing facility equipment: copiers, computers, fan motors, etc.?

FACILITY MATRIX ELEMENT: 4,3

Life Stage: Facility Operations
Environmental Concern: Solid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Solid residues from facility operations are large and are given the minimum treatment necessary to comply with legal requirements.

If all of the following conditions apply, the matrix element rating is 4:

- Solid residues from facility operations are negligible or are completely recycled on site.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Is the facility designed to minimize the comingling of solid waste streams?
- Are solid residues from facility operations reused or recycled to the extent possible?
- Are unusable solid residues from facility operations (including food service) disposed of in an environmentally responsible manner?

FACILITY MATRIX ELEMENT: 4,4

Life Stage: Facility Operations
Environmental Concern: Liquid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Liquid residues from facility operations are large and are given the minimum treatment necessary to comply with legal requirements.

If all of the following conditions apply, the matrix element rating is 4:

- Liquid residues (including stormwater) from facility operations are negligible or are completely recycled on site.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Is the facility designed to minimize the comingling of liquid waste streams?
- Are liquid treatment plants monitored to ensure that they operate at peak efficiency?
- Are unusable liquid residues from facility operations disposed of in an environmentally responsible manner?

FACILITY MATRIX ELEMENT: 4,5

Life Stage: Facility Operations
Environmental Concern: Gaseous Residues

If any of the following conditions apply, the matrix element rating is 0:

- Gaseous residues from facility operations are large and are given the minimum treatment necessary to comply with legal requirements.

If all of the following conditions apply, the matrix element rating is 4:

- Gaseous residues from facility operations are negligible or are completely recycled on site.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Is facility operations-related transportation to and from the facility minimized?
- Are furnaces, incinerators, and other combustion processes and their related air pollution control devices monitored to ensure operation at peak efficiency?
- Is employee commuting minimized by job sharing, telecommuting, and similar programs?

FACILITY MATRIX ELEMENT: 5,1

Life Stage: Facility Refurbishment, Transfer, and Closure
Environmental Concern: Ecological Impacts

If any of the following conditions apply, the matrix element rating is 0:

- Structures must be completely demolished, with major impacts on natural areas or existing ecosystems.

If all of the following conditions apply, the matrix element rating is 4:

- Site and structures can be reused with negligible impact on natural areas or existing ecosystems.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Will site and system closure have substantial impacts on natural areas?
- Will site and system closure have substantial impacts on existing ecosystems?

FACILITY MATRIX ELEMENT: 5,2

Life Stage: Facility Refurbishment, Transfer, and Closure
Environmental Concern: Energy Use

If any of the following conditions apply, the matrix element rating is 0:

- Very large energy consumption will be required for facility closure.

If all of the following conditions apply, the matrix element rating is 4:

- Negligible energy consumption will be required for facility closure.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Will site closure require the transport of large quantities of materials?
- Will building demolition or renovation require large energy expenditures?
- Will equipment demolition or renovation require large energy expenditures?

FACILITY MATRIX ELEMENT: 5,3

Life Stage: Facility Refurbishment, Transfer, and Closure
Environmental Concern: Solid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Large amounts of solid residues will be produced by facility closure and avoidance is difficult or impossible.

If all of the following conditions apply, the matrix element rating is 4:

- Negligible amounts of solid residues, and none with biotoxic characteristics, will be produced by facility closure.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Does the facility contain asbestos or lead paint?
- Can facility equipment be reused or recycled?
- Can unwanted building fixtures and components be reused or recycled?
- Can building structural components be reused or recycled?
- Can spare parts, supplies, or other solid facility activity consumables or residues be used or recycled?

FACILITY MATRIX ELEMENT: 5,4

Life Stage: Facility Refurbishment, Transfer, and Closure
Environmental Concern: Liquid Residues

If any of the following conditions apply, the matrix element rating is 0:

- Large amounts of liquid residues will be produced by facility closure and avoidance is difficult or impossible.

If all of the following conditions apply, the matrix element rating is 4:

- Negligible amounts of liquid residues will be produced by facility closure.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Will liquid residues be produced during demolition?
- Will liquid residues be produced during facility termination?
- Can liquid facility activity consumables or residues be used or recycled?

FACILITY MATRIX ELEMENT: 5,5

Life Stage: Facility Refurbishment, Transfer, and Closure
Environmental Concern: Gaseous Residues

If any of the following conditions apply, the matrix element rating is 0:

- Large amounts of gaseous residues will be produced by facility closure and avoidance is difficult or impossible.

If all of the following conditions apply, the matrix element rating is 4:

- Negligible amounts of gaseous residues will be produced by facility closure.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree to which the facility meets DFE preferences for this matrix element.

- Will gaseous residues be produced during demolition?
- Will gaseous residues be produced during termination of facilities operations?
- Can gaseous facility consumables or residues be used or recycled?

Appendix G

Health and Safety Matrix Scoring Guidelines and Protocols

The Health and Safety Matrix is described in Chapter 5. In this appendix, a sample of possible scoring considerations appropriate to each of the matrix elements is presented. It is anticipated that different types of products and facilities may require different check lists and evaluations, so this appendix is presented as an example rather than as a universal formula.

SAFETY MATRIX ELEMENT: 1,1

Life Stage: Pre-manufacture
Safety Concern: Physical Hazard

If any of the following conditions apply, the matrix element rating is 0:

- Suppliers are not compliant with state and federal health & safety regulations applicable to physical hazards related to premanufactured product delivery.

If all of the following conditions apply, the matrix element rating is 4:

- There are no known physical safety concerns associated with the premanufactured product or its delivery.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Do suppliers exceed state and federal health & safety regulations applicable to physical hazards during premanufactured product delivery?

- Have efforts been made by suppliers to prevent accidents during shipment?
- Have efforts been made by suppliers to respond to accidents during shipment?

SAFETY MATRIX ELEMENT: 2,1

Life Stage: Product Manufacture
Safety Concern: Physical Hazard

If any of the following conditions apply, the matrix element rating is 0:

- The manufacturing facility is not compliant with state and federal health & safety regulations applicable to physical hazards.

If all of the following conditions apply, the matrix element rating is 4:

- There are no known physical hazards associated with the manufacturing phase.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1,2, or 3 depending on the degree of hazard experienced during this life stage.

- Does the manufacturing facility exceed state and federal health & safety regulations applicable to physical hazards?
- Has the facility established prevention protocols to minimize accidents during the manufacturing phase?
- Has the facility made efforts to respond appropriately and supportively to accidents that occur during manufacturing?

SAFETY MATRIX ELEMENT: 3,1

Life Stage: Product Delivery
Safety Concern: Physical Hazard

If any of the following conditions apply, the matrix element rating is 0:

- Firms involved in the delivery process are not in compliance with state and federal health & safety regulations applicable to physical hazards.

If all of the following conditions apply, the matrix element rating is 4:

- Delivery of the product presents no known physical hazards.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Do delivery-chain firms exceed state and federal health and safety regulations applicable to physical hazards?

- Do delivery-chain firms make efforts to prevent potential accidents during transport, loading, and unloading?
- Are SOPs for tie-down and packing in place and widely available for all modes of transport and for all products shipped to customers?
- Have delivery-chain firms made efforts to respond to past and potential physical accidents?

SAFETY MATRIX ELEMENT: 4,1

Life Stage: Product Use
Safety Concern: Physical Hazard

If any of the following conditions apply, the matrix element rating is 0:

- Product does not meet state and federal health & safety standards applicable to physical hazards.

If all of the following conditions apply, the matrix element rating is 4:

- No known physical hazards exist during the product use stage.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Does the product exceed state and federal health & safety standards applicable to physical hazards?
- Do product documentation and signage on the product itself provide lists of activities or situations that could create hazards for users?
- Do product and product documentation provide a contact mechanism so that users can ask questions about product use?
- Are product limitations expressly stated in documentation and (if applicable) on the product itself?
- Do manufacturers or retailers of the product offer active education programs for consumers to reduce in-use accidents?
- Does the manufacturer have a recording/tracking/communication mechanism to measure types and causes of accidents during everyday operations?

SAFETY MATRIX ELEMENT: 5,1

Life Stage: End of Life
Safety Concern: Physical Hazard

If any of the following conditions apply, the matrix element rating is 0:

- The product's end of life stage involves danger of catastrophic failure or collapse.

If all of the following conditions apply, the matrix element rating is 4:

- No known physical hazards exist during the product's end-of-life stage.
- The end-of-life stage leaves the product in the custody of a responsible agent in the original manufacturing process.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Do the events which precipitate the end-of-life stage for this product pose a physical hazard in and of themselves—explosions, crashes, fires, or structural failures?
- If the product is intact at the end-of-life stage, does it remain physically hazardous (flammable, fragile, radioactive, etc.) once decommissioned?
- Is there an established chain of custody for products at the end of their useful lives?
- Does cannibalization pose risks that parts will be dangerously misused or that radioactive, sharp, or fragile parts will be exposed?

SAFETY MATRIX ELEMENT: 1,2

Life Stage: Pre-manufacture
Safety Concern: Chemical Hazard

If any of the following conditions apply, the matrix element rating is 0:

- Suppliers are not compliant with state and federal health & safety regulations applicable to chemical hazards related to premanufactured product delivery.
- Premanufactured products use substances from the Materials of Concern list.

If all of the following conditions apply, the matrix element rating is 4:

- There are no known chemical hazards associated with the premanufactured product or its delivery.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Do suppliers exceed state and federal health & safety regulations applicable to chemical hazards during premanufactured product delivery?

- Have efforts been made by suppliers to prevent chemical spills during shipment?
- Have efforts been made by suppliers to respond to spills during shipment?

SAFETY MATRIX ELEMENT: 2,2

Life Stage: Product Manufacture
Safety Concern: Chemical Hazard

If any of the following conditions apply, the matrix element rating is 0:

- The manufacturing facility is not compliant with state and federal health & safety regulations applicable to chemical hazards.
- The manufacturing phase uses substances from the Materials of Concern list.

If all of the following conditions apply, the matrix element rating is 4:

- There are no known chemical hazards associated with the manufacturing stage.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Does the manufacturing facility exceed state and federal health & safety regulations applicable to chemical hazards?
- Has the facility established prevention protocols to minimize the risk of spills or releases during the manufacturing phase?
- Has the facility made efforts to respond appropriately to releases and/or spills that occur during manufacturing?

SAFETY MATRIX ELEMENT: 3,2

Life Stage: Product Delivery
Safety Concern: Chemical Hazard

If any of the following conditions apply, the matrix element rating is 0:

- Firms involved in the delivery process are not in compliance with state and federal health & safety regulations applicable to chemical hazards.

If all of the following conditions apply, the matrix element rating is 4:

- Delivery of the product presents no known chemical hazards.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Do delivery-chain firms exceed state and federal health & safety regulations applicable to chemical hazards?
- Do delivery chain firms take measures to minimize risks of spills or releases during transport, loading, and unloading?
- Have delivery-chain firms made efforts to respond to past and potential chemical spills or releases?

SAFETY MATRIX ELEMENT: 4,2

Life Stage: Product Use
Safety Concern: Chemical Hazard

If any of the following conditions apply, the matrix element rating is 0:

- Product does not meet state and federal health & safety regulations applicable to chemical hazards.
- Use of the product involves substances from the Materials of Concern list.

If all of the following conditions apply, the matrix element rating is 4:

- No known chemical hazards exist during the product use stage.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Does the product exceed state and federal health & safety regulations applicable to chemical hazards?
- Do product documentation and signage provide indications of pressurized seals?
- Do product documentation and signage provide the locations and contents of any reservoirs of hazardous materials?
- Do product documentation and signage provide a contact mechanism so that users can ask questions about product use?
- Does the manufacturer have a recording/tracking/communication mechanism to measure types and causes of chemical exposures during everyday operations?

SAFETY MATRIX ELEMENT: 5,2

Life Stage: End of Life
Safety Concern: Chemical Hazard

If any of the following conditions apply, the matrix element rating is 0:

- At disposal, the product contains, emits, or produces substances on the Materials of Concern list.

If all of the following conditions apply, the matrix element rating is 4:

- No known chemical hazards exist during the product's end-of-life stage.
- The end-of-life stage leaves the product in the custody of a responsible agent to oversee recycling and/or reuse of the product, its subsystems, or its components.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1,2, or 3 depending on the degree of hazard experienced during this life stage.

- Do the events that precipitate the end-of-life stage for this product pose a chemical hazard in and of themselves—leaks or catastrophic failures?
- Does the disposal method for end-of-life products end in a "controlled" release of chemicals? For instance, is the product typically scuttled, or landfilled?
- Is there an established chain of custody for products at the end of their useful lives?
- Does cannibalization of the product pose risks of chemical hazard?

SAFETY MATRIX ELEMENT: 1,3

Life Stage: Pre-manufacture
Safety Concern: Shock Hazard

If any of the following conditions apply, the matrix element rating is 0:

- Suppliers are not compliant with state and federal health & safety regulations applicable to shock hazards related to premanufactured product delivery.

If all of the following conditions apply, the matrix element rating is 4:

- There are no known shock hazards associated with the premanufactured product.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Do suppliers exceed state and federal health & safety regulations applicable to shock hazards during premanufactured product delivery?
- Have efforts been made by suppliers to reduce exposure to shock hazards during shipment?

SAFETY MATRIX ELEMENT: 2,3

Life Stage: Product Manufacture
Safety Concern: Shock Hazard

If any of the following conditions apply, the matrix element rating is 0:

- The manufacturer is not in compliance with state and federal health & safety regulations applicable to shock hazards.

If all of the following conditions apply, the matrix element rating is 4:

- There are no known shock hazards associated with the manufacturing phase.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Does the manufacturing facility exceed state and federal health & safety regulations applicable to shock hazards?
- Has the manufacturer established prevention protocols to minimize the risk of shock during the manufacturing phase?
- Has the manufacturer effectively addressed any identified shock hazards in or around their facility?

SAFETY MATRIX ELEMENT: 3,3

Life Stage: Product Delivery
Safety Concern: Shock Hazard

If any of the following conditions apply, the matrix element rating is 0:

- Delivery-chain firms are not in compliance with state and federal health & safety regulations applicable to shock hazards.

If all of the following conditions apply, the matrix element rating is 4:

- Delivery of the product presents no known shock hazards.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Do delivery-chain firms exceed state and federal health & safety regulations applicable to shock hazards?
- Do delivery-chain firms make efforts to avoid shock hazards during transport, loading, and unloading?

SAFETY MATRIX ELEMENT: 4,3

Life Stage: Product Use
Safety Concern: Shock Hazard

If any of the following conditions apply, the matrix element rating is 0:

- Product does not meet state and federal health & safety regulations applicable to shock hazards.

If all of the following conditions apply, the matrix element rating is 4:

- There are no known shock hazards associated with the use of the product.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Does the product exceed state and federal health & safety regulations applicable to shock hazards?
- Do product documentation and signage provide lists of activities or situations which could create shock hazards for users? This is particularly important for products with aerial applications, especially near radio towers and power lines.
- Do product documentation and signage clearly indicate areas of the product which might create a shock hazard?
- Do product documentation and signage provide a contact mechanism so that users can ask questions about product use?
- Does the manufacturer have a recording / tracking / communication mechanism to measure types and causes of shock hazards during everyday operations?

SAFETY MATRIX ELEMENT: 5,3

Life Stage: End of Life
Safety Concern: Shock Hazard

If any of the following conditions apply, the matrix element rating is 0:

- The product at its end-of-life stage contains live components or remains connected to a live electrical current.

If all of the following conditions apply, the matrix element rating is 4:

- No known shock hazards exist during the end-of-life stage.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Do the events which precipitate the end-of-life stage for this product pose a shock hazard in and of themselves—burnout, electrical fires, or other failures?
- Does cannibalization of the product pose shock hazards during disassembly?

SAFETY MATRIX ELEMENT: 1,4

Life Stage: Pre-manufacture
Safety Concern: Ergonomic Hazard

If any of the following conditions apply, the matrix element rating is 0:

- Suppliers are not compliant with state and federal health & safety regulations relating to ergonomics during premanufactured product delivery.

If all of the following conditions apply, the matrix element rating is 4:

- No known ergonomic hazards exist in the premanufactured product or its delivery.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1,2, or 3 depending on the degree of hazard experienced during this life stage.

- Are all incoming containers clearly marked with weights? Do hand-carried containers include functional handles?
- Do suppliers exceed state and federal health & safety regulations relating to ergonomics during premanufactured product delivery?

SAFETY MATRIX ELEMENT: 2,4

Life Stage: Product Manufacture
Safety Concern: Ergonomic Hazard

If any of the following conditions apply, the matrix element rating is 0:

- Manufacturer is not compliant with state and federal health & safety regulations relating to ergonomics.

If all of the following conditions apply, the matrix element rating is 4:

- No known ergonomic hazards exist in the manufacturing phase.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Are on-site containers clearly marked with weights? Do hand-carried containers include functional handles?
- Do manufacturers exceed state and federal health & safety regulations relating to ergonomics?
- Do manufacturers maintain an active dialogue with employees regarding potential or actual ergonomic hazards in the work place?

SAFETY MATRIX ELEMENT: 3,4

Life Stage: Product Delivery
Safety Concern: Ergonomic Hazard

If any of the following conditions apply, the matrix element rating is 0:

- Delivery-chain firms are not compliant with state and federal health & safety regulations relating to ergonomics.

If all of the following conditions apply, the matrix element rating is 4:

- Delivery of the product presents no known ergonomic hazards.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1,2, or 3 depending on the degree of hazard experienced during this life stage.

- Are all outgoing containers clearly marked with weights? Do hand-carried containers include functional handles?
- Do delivery-chain firms exceed state and federal health & safety regulations relating to ergonomics?
- Do delivery-chain firms maintain an active dialogue with employees regarding potential or actual ergonomic hazards in the work place?

SAFETY MATRIX ELEMENT: 4,4

Life Stage: Product Use
Safety Concern: Ergonomic Hazard

If any of the following conditions apply, the matrix element rating is 0:

- Product does not meet state and federal regulations relating to ergonomics.
- Use of the product is known to pose serious ergonomic hazards.

If all of the following conditions apply, the matrix element rating is 4:

- Use of the product poses no known ergonomic hazard.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Does the product exceed state and federal regulations relating to ergonomics?
- Do product documentation and signage clearly identify ergonomic hazards?
- Are carrying handles and weights of portable components(if any) clearly marked?
- Do product documentation and signage provide a contact mechanism so that users can ask questions about product use?
- Do manufacturers or retailers offer active education or certification programs for consumers to reduce or prevent potential ergonomic injuries?
- Does the manufacturer have a recording/tracking/communication mechanism to measure types and causes of accidents during everyday operations?

SAFETY MATRIX ELEMENT: 5,4

Life Stage: End of Life
Safety Concern: Ergonomic Hazard

If any of the following conditions apply, the matrix element rating is 0:

- The product's end-of-use stage is known to pose a serious ergonomic hazard.

If all of the following conditions apply, the matrix element rating is 4:

- No ergonomic hazards exist during the product's end-of-life stage.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Do the events which precipitate the end-of-life stage for this process pose an ergonomic hazard in and of themselves?
- Does cannibalization yield parts that might be misused and cause ergonomic hazard?

SAFETY MATRIX ELEMENT: 1,5

Life Stage: Pre-manufacture
Safety Concern: Noise Hazard

If any of the following conditions apply, the matrix element rating is 0:

- Suppliers are not compliant with federal and state health & safety regulations applicable to noise hazards related to premanufactured product delivery.

If all of the following conditions apply, the matrix element rating is 4:

- There are no known noise hazards associated with the premanufactured product or its delivery.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Do suppliers exceed federal and state health & safety regulations applicable to noise hazards during premanufactured product delivery?

SAFETY MATRIX ELEMENT: 2,5

Life Stage: Product Manufacture
Safety Concern: Noise Hazard

If any of the following conditions apply, the matrix element rating is 0:

- Manufacturer is not compliant with federal and state health & safety regulations applicable to noise hazards.

If all of the following conditions apply, the matrix element rating is 4:

- There are no known noise hazards associated with the manufacturing phase.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Does the manufacturer exceed federal and state health & safety regulations applicable to noise hazards?
- Does the manufacturer maintain an active dialogue with employees regarding potential or actual noise hazards in the work place?

SAFETY MATRIX ELEMENT: 3,5

Life Stage: Product Delivery
Safety Concern: Noise Hazard

If any of the following conditions apply, the matrix element rating is 0:

- Delivery-chain firms are not compliant with federal and state health & safety regulations applicable to noise hazards.

If all of the following conditions apply, the matrix element rating is 4:

- Product delivery poses no known noise hazards.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Do delivery-chain firms exceed state and federal health & safety regulations applicable to noise hazards?
- Do delivery-chain firms maintain an active dialogue with employees regarding potential or actual noise hazards in the work place?

SAFETY MATRIX ELEMENT: 4,5

Life Stage: Product Use
Safety Concern: Noise Hazard

If any of the following conditions apply, the matrix element rating is 0:

- Product does not meet state and federal regulations applicable to noise hazards.
- Use of the product is known to pose serious noise hazards.

If all of the following conditions apply, the matrix element rating is 4:

- Use of the product involves no known noise hazards.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Do product documentation and signage provide guidance on noise hazards and hearing protection during product use, if applicable?
- Does the product take advantage of noise-reducing technology that is not otherwise indicated in product design goals?

- Does the manufacturer have a recording/tracking/communications mechanism to measure types and causes of noise hazards experienced during everyday operations?

SAFETY MATRIX ELEMENT: 5,5

Life Stage: End of Life
Safety Concern: Noise Hazard

If any of the following conditions apply, the matrix element rating is 0:

- The product's end-of-life stage poses a serious noise hazard.

If all of the following conditions apply, the matrix element rating is 4:

- No noise hazards exist during the product's end-of-life stage.

If neither of the above ratings is assigned, complete the checklist below. Assign a rating of 1, 2, or 3 depending on the degree of hazard experienced during this life stage.

- Do the events which precipitate the end-of-life stage of this product pose significant noise hazards in and of themselves—such as explosions, collisions, reverberations, or very high frequencies?

Appendix H

Example of a Facility Visit Report Directed Toward Streamlined Life-Cycle Assessment

INTRODUCTION

XXX is a diversified technology and services company that manufactures products including aircraft engines, medical imaging, plastics, household appliances, and power breakers. The XXX facility is one of 75 XXX facilities that make industrial switches, service entrance equipment, circuit boards, and electrical distribution equipment. Its primary products are two types of power breakers.

XXX is sited in a facility built in 1898 for an electrical distribution equipment plant, which XXX has occupied since 1945. In this facility, employees take parts and raw materials and manipulate and assemble them to create products through welding, molding, fabrication, and painting. XXX employs about 70 people with an average age of 55 and an average of 30 years of service for employees.

This paper includes a description of the processes used at XXX to manufacture products, including primary and secondary processes. It also includes a life-cycle assessment of the XXX facility. This includes a streamlined assessment of the life-cycle of the product, process, and XXX facility. Following this assessment, recommendations are included that describe how the operation can improve its performance to reduce the impact of operations on the environment.

PROCESS

XXX manufactures electrical distribution equipment for both large and small buildings. The manufacturing process consists of molding and pressing parts for the casing and assembling the parts together for end use. Much of the process is dedicated to creating the metal casing that holds the electrical components of the power breakers.

The XXX facility operates using Just-in-time (JIT) philosophy to eliminate waste. The JIT philosophy dictates that companies produce only what is needed at the time it is needed.[1] This philosophy is evident in the process description that follows.

This section describes each step of the process of creating the power breakers from receiving materials, through manufacture and at shipping. The following section will describe the life-cycle of XXX activities, which extends beyond the scope of the process itself.

Receiving

XXX has a shipping and receiving area with six truck bays where raw materials and parts for manufacture come in. Most raw materials used in the facility are received from other XXX facilities: $9 million of the total $12 million in material purchases. Much of this material includes large rolls of steel used to create the casing for the power breakers. These rolls weigh thousands of pounds and are lifted from the trucks with a hydraulic crane.

Materials are disseminated at the receiving dock to different areas dependent on type and demand within the facility. Component parts (pre-manufactured parts) such as copper springs, screws, and wiring are sent to the parts storage area until use. Plastic resins are sent to the compression molding area. The large steel rolls are stored on the factory floor until they are needed at the shearing process.

Shearing

The large rolls of steel must be straightened and cut before the metal can be used in the presses and benders. The shearing process achieves this through two shears. The first shear straightens the steel from the roll. In the second shear, the steel is cut into specified dimensions.

As dictated by the JIT philosophy, the steel is not sent through the shearing process until it is ordered within the plant and needed for manufacture. Despite this, about 34,000 pounds of metal scrap (2 percent of the total scrap waste) result from the shearing process per year. This scrap metal is separated and kept for recycling.

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[1] Russell, Roberta S. and Bernard W. Taylor III, *Operations Management: Focusing on Quality and Competitiveness*, Second Edition, Prentice Hall, NJ, 1995.

In addition to generating scrap, the shearing process is a loud part of the production process, a potential damage to hearing unless hearing protection is worn.

Presses

After the steel is straightened and cut, it is sent to one of the two presses to be cut and shaped. The press is a one-press system. The metal sheet enters the press and is stamped multiple times and results in a finished product. This one-press system presumably uses less energy than the die presses, where the metal sheet goes through a series of presses before it is ready for the next step.

The presses, powered by compressed air, use lubricants in the cutting and molding process to reduce wear on the machine. Some of this lubricant is spun off in the process and is collected and is recycled. Additionally, because every inch of the steel sheet cannot be used when parts are being cut out of them, planned scrap results from the process. This scrap is sorted and sold to an outside purchaser for recycling.

Benders

Next, the metal pieces are bended to fit specifications for the casing. XXX has three benders that operate though they have little waste as they simply change the shape of the metal sheets, rather than cut them.

Welding and Soldering

After being bended, the parts require welding and soldering. Spot welding performed on the pieces use a machine with copper tips to conduct the heat. However, the copper melts at a lower temperature than the steel and steel alloys, therefore chilled water is cycled through the tips to prevent melting. The water in the tips is cycled from the spot welder to a chiller located in the factory and back, a closed loop system. Though the copper tips are chilled, they still degrade and have to be replaced frequently, creating copper by-products.

Emissions are generated from welding and soldering that include zinc and copper oxides from the copper tips and from applying high temperatures to the steel. The welding tools have air filters on the workstation that capture particulate emissions, which are replaced frequently, generating a solid waste that must be removed by a waste handler.

Conveyors

After the metal parts are cut and formed, they are painted to meet customer requirements. The painting process starts by placing all the parts on hangers so that they can be evenly coated. These hangers then transport the parts into the power washer.

Power Wash

The power washer is powered by electricity during non-heating season and by the boilers on-site when they are also being used to heat the plant. It operates at 150–180°F and uses a heavy caustic cleaner and alkaline wash in the cycle to remove the oil from lubricants and machining as well as any metal shavings that may remain on them. Parts enter the cleaner on the racks and are cleaned and rinsed then cleaned and rinsed again.

Water from the cleaning that is used at the end of the cycle when the parts are the cleanest are reused in a second cycle at the beginning of the cleaning process. This use of counter-current flow reduces the amount of wastewater sent to an on-site wastewater treatment plant to about five gallons per minute. Prior to sending wastewater to the treatment plant the oil is separated from the water by skimming it off the top. This oil is then sent offsite for disposal. Once the water is discharged to the on-site treatment plant, it is treated to adjust the pH before being discharged for comprehensive treatment at the publicly owned treatment works.

Dry-off Oven

Next, the parts are sent through the dry-off oven powered by natural gas for a short amount of time to dry them prior to painting. The parts are only in the dry-off oven for a few minutes at temperatures of about 180°F and then the parts proceed to the painting process.

Paint Room

The painting process at XXX is a newer technology that uses powder paint electrically charged and then sprayed onto the parts, called electro-coating. When a part is not coated completely, it can be manually applied. The painting system does not require any additional adhesive for the paint to stick; it only requires energy to bake the particles onto the surface following spraying.

Curing Oven

Curing occurs in a gas-fired oven. In this oven, the parts are subjected to temperatures of 350–380°F for about 25 minutes. The oven is designed to reduce heat loss by allowing the parts to enter from the bottom and go up into the heated area. However, the curing oven was listed by XXX employees as one of the greatest users of energy in the facility.

Media Blast

Following painting, the hangers used to transport parts may need to be cleaned if they have a thick paint build-up. The hangers are typically cleaned by a large piece of equipment called a media blast after four or five uses in the paint line. The media blast uses energy to power high speed motors and zinc pellets to remove paint from the hangers. The residues from this process are paint and zinc pellets which are collected in 55-gallon drums and removed by the contracted waste handler. The paint chips from this process cannot be reclaimed because they've already been through the curing oven.

Soldering

Once the parts leave the painting line and are cooled from the oven, they are unloaded and may be sent for further soldering. The soldering equipment is operated by energy and uses gas to perform the soldering. Similar to the first welding and soldering area, this soldering also has filters to capture the particulates resulting in waste filters that result from having to periodically replace them. Additionally, VOCs generated at this stage are vented to the outside.

Compression Molding

The plastic components of the power breaks are made from plastic resins sheets that containing 23 percent glass. These resins are put into the compression molder and pressed at high temperatures to make the thermoset molds. While the mold is still warm, the operator inserts screws into the mold. The mold has some planned resin waste that is cut off and vacuumed out of the work station into a collection area. The waste plastic is then taken off-site to be treated.

Since this process is using heat applied to plastics, some VOCs are emitted and vented to the roof.

Drilling and Welding

Following compression molding, the plastic parts go through the drilling and welding process where they may be worked on to fit the part requirements. This process results in small amounts of scrap resin and possible VOC emissions.

Assembly Stations

All the component parts manufactured at XXX and other parts that are received from other XXX facilities and vendors are brought together at the assembly stage of the process. To complement the JIT philosophy, XXX has divided their facility into manufacturing cells where dissimilar machines are brought together to manufacture a family of parts in the assembly process. In each cell they assemble specific parts of each product. Using this procedure, XXX is able to minimize errors that may occur if they were using assembly line-type production.

Additionally, workers use a barcode quality control system throughout the assembly process to check each part for integrity. This also reduces the time to rework a part and replace component parts in comparison to having the quality control check at the final stage of production.

Assembly uses air compressors to power the hand-held tools that bring the parts together. However, there is not a large amount of power needed in these stations or a large amount of scrap generated. The scrap that may be generated is from mistakes rather than from forming the parts and product.

Quality Control

Following assembly the product goes through a thorough check of the overall system. The quality control inspector checks the electrical components and inspects for scratches, dents, stress marks, and visible holes in the product. If a product has errors its parts maybe sent back through the assembly process or it may have to be discarded.

Packaging

The power breaks range from small to large products, but all must be protected against shipping damages. XXX uses cardboard edges on each of their products and wraps them in plastic to prevent scratches of the paint. The larger breaks are then bolted to a wooden pallet that enables the forklifts to move them and additionally protects the bottom of the product.

The packaging results in little waste other than scraps of cardboard and plastic.

Shipping

Once products are ready for shipping they are kept in the shipping/receiving area until ready for delivery. However, they products do not stay in-house for too long following manufacture and assembly as this would go against JIT principles. Additionally, customers usually do not order large quantities of power breakers at one time since one or just a few are needed for each building. Therefore, it can be assumed that some shipments may not include an entire full load.

STREAMLINED LIFE-CYCLE ASSESSMENT

The following section includes an assessment of the product, process, and facility for XXX with respect to the impact of its existence on the environment. In this stream-lined life-cycle assessment (LCA), scores are assigned to each element of the matrix in the following manner:

4 = No environmental impact
3 = Minimal environmental impact (less than the expected average)
2 = Moderate environmental impact (about the expected average)
1 = Substantial environmental impact (more than the expected average)
0 = Very high environmental impact

Based on the information gathered at the facility visit and subsequent inquiries, the streamlined life cycle assessment was conducted for product, process and facility. Detailed reasons for each score are presented in the appendix. The assigned values for each matrix are described in the following sections.

Life-Cycle Assessment of Processes

The life-cycle assessment of processes involves taking a look at resource provisioning, process implementation, primary process implementation, complementary process implementation, and recycle or disposal of the process equipment. Table H.1 lists the scores assigned to each stage for the following environmental concerns: material choice, energy use, solid residue, liquid residue, and gaseous residue.

The process LCA shows that the facility's processes place the medium level burdens (many 2s and 3s) on the environment. First, the same phenomenon as the product LCA can be easily noticeable. The score is very low at the first stage, Resource Provision, which is equivalent to the product's Pre-Manufacture stage, due to the characteristics of raw materials. Material Choice at the Process Implementation received a low score for the same reason.

Both Primary Process and Complementary Process stages have relatively small impacts on the environment. The amount of residues generated is not large. Environmentally dangerous processes have been replaced with safer processes. For example,

Table H.1. Process Matrix

Process Matrix	Material Choice	Energy Use	Solid Residue	Liquid Residue	Gaseous Residue	Score
Resource Provisioning	2	0	2	2	0	6/20
Process Implementation	1	1	2	3	2	9/20
Primary Process Operation	3	2	3	3	3	14/20
Complementary Process Operation	2	3	3	3	3	14/20
Recycle/Disposal	2	1	2	3	3	11/20
Score	10/20	7/20	12/20	14/20	11/20	54/100

the facility reduced the amount of hazardous wastes by moving plating process to other plant. Metal parts are now painted by powder spraying instead of electro-coat painting. Also, some of the scraps and waste oil are sold. However, small concern should be pointed out with regard to Energy Use at Primary Process and Material Choice at Complementary Process. The use of energy at primary processes is not fully minimized yet due to many old machines that use electricity. Material Choice concerns with the use of lead solder.

Lastly, throughout the process life stages, Energy Use remains to be the most pressing environmental concern of all.

The overall score of the LCA for XXX processes was 54 out of a possible 100. This indicates that XXX processes have an impact on the environment that should be examined further for process improvements. Some suggested process improvements can be found in the Recommendations section of this report.

Life-Cycle Assessment of Products

The products produced at XXX were evaluated at each stage of their life cycle and for environmental concerns regarding material choice, energy use, solid, liquid, and gaseous residues. Table H.2 shows the scores for each stage of the life-cycle.

Circuit breakers and other electrical distribution equipment manufactured at XXX seem to be environmentally sound in the latter half of their life stages (i.e. Product use, Recycling). The product achieved a high score (17/20) for the Product Use stage with no or little residues in any forms. On the contrary, the score is very poor at the first stage, Pre-Manufacture. This is due to the product uses materials, namely virgin steel and virgin aluminum, that require large amount of energy for extraction and release large amount of liquid and gaseous residues.

In terms of environmental concerns, Material Choice and Energy Use need to be improved (8/20, 6/20, respectively). Material Choice at the Product Packaging stage received zero because no recycled materials are used for packaging. Energy Use scores are generally low throughout the life stages mainly because the products are not designed to reduce energy use.

Table H.2. Product Matrix

Product Matrix	Material Choice	Energy Use	Solid Residue	Liquid Residue	Gaseous Residue	Score
Pre-manufacture	2	0	2	0	0	4/20
Product manufacture	2	1	2	3	2	10/20
Product packaging	0	2	2	4	2	10/20
Product Use	3	2	4	4	4	17/20
Recycle/Disposal	1	1	2	4	4	12/20
Score	8/20	6/20	12/20	15/20	12/20	53/100

The overall score for product assessment was 53 out of 100 possible points. This shows that the facility is about average with its production operation. The recommendation section outlines several ways that XXX could operate in a more environmentally friendly manner to reduce its impact from the production line.

Life-Cycle Assessment of the Facility

The final assessment of the life-cycle was of the facility design, operation, and closure phases. The facility assessment included geographical location as well. The life cycle of the facility was examined for biodiversity impacts, energy use, and solid, liquid, and gaseous residues. The scores for these categories are summarized in Table H.3.

The facility LCA shows that the facility has the medium level burden (many 2s and 3s) on the environment. The scores are slightly better than those of product and process, with only one zero rating. With regard to life stages, Operation is being paid adequate attention while Site Closure seems to be under-attended. Site Selection stage was given relatively higher scores. Although the consideration given to environmental impacts might not have been enough at today's standard, it was probably reasonable at the standard of the time of development, which is at the end of 19th century. Ecological Impact and Energy Use marked relatively low scores. This is the same tendency as in the Product and Process LCAs. One thing worth mentioning is that there are no 4s in this matrix. It suggests that the facility needs to make efforts in this area in general.

From the overall score of the facility matrix, it is evident that the largest impacts that XXX has on the environment are in the closure of the facility followed by the process and product activities. The Recommendation section includes several suggestions to reduce this impact.

Table H.3. Facility Matrix

Facility Matrix	Biodiversity/ Material Choice	Energy Use	Solid Residue	Liquid Residue	Gaseous Residue	Score
Site Selection	2	3	3	3	3	14/20
Principal business activity—Products	1.6	1.2	2.4	3.0	2.4	10.6/20
Principal business activity—Prcoess	2.0	1.4	2.4	2.4	2.2	10.4/20
Facility operations	2	3	3	3	3	14/20
Refurbishment, transfer, and closure	2	1	0	3	3	9/20
Score	9.6/20	9.6/20	10.8/20	14.4/20	13.6/20	58/100

RECOMMENDATIONS

The LCA revealed several areas of improvement at XXX that would reduce the impact on the environment and raise their overall LCA scores. Many of these changes affect the environmental impact of the product, process, and the facility, and are therefore discussed below collectively.

1. Consider switching the metal casings to plastic.
   One of the most significant findings from the LCA is that the scores for product and process were largely dictated by the activities of the paint line. Not only is the paint line purely for aesthetic purposes, it additionally is only required for the metals. Therefore, XXX might consider changing the design of their entire power breaker product to use plastic as the casing rather than steel.

   This product re-design would eliminate the shearing, pressing, bending, welding and soldering, power washing, dry-off oven, painting, curing, and media blast operations. Instead, the casings could be created using a colored plastic resin.

   Recognizing that this suggestion is perhaps infeasible due to material requirements of the power breakers, recommendations 2, 3, and 4 are alternatives to this first suggestion of complete product redesign.
2. Look for options of alternative raw materials or use recycled materials.
   From the process evaluation, I found that the largest area of concern is in the resource provisioning stage. Though it is recognized that using a material other than steel for the casings may be infeasible, I recommend that XXX investigate the possibility of purchasing recycled steel rather than virgin steel.

   Also, though XXX managers state that all suppliers go through a "rigorous due diligence process prior to XXX accepting their product and/or services,"[2] it would be useful to determine if the suppliers are creating their pre-manufactured parts from virgin or other resources. Since XXX purchases much of its materials from other parent company facilities, it is possible to have a large influence of the product source.

   Another potential for reduced environmental impact is to replace the powder paint currently used with a powder that requires lower temperatures at the curing stage. This would reduce energy requirements for the facility at an area that is one of the primary energy consumers.
3. Consider equipment changes.
   One of the areas that generates solid waste is the welding and soldering stages of the product life cycle. XXX might consider replacing the current equipment as it is needed with equipment that needs less replacement of parts (copper tips). Additionally, XXX uses gases in the welding and soldering that are

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[2] Email communication from XXX, October 24, 2003.

vented to the environment. These gases might be captured and reused in the process.

4. Clearly identify parts for recycling, refurbishment, and replacement.
   Since steel is a recyclable material, and the power breaks might contain several reusable parts, XXX should consider identifying the parts clearly in the assembled part to facilitate reuse and recycle of the component parts. Additionally, XXX might include instructions for recycling with the equipment when it is delivered. Or, a more rigorous program to "take-back" their old breakers could be instituted. This would require tracking of the power breakers and contact with the owners to ensure that they understand how to return the product to XXX when it is no longer usable.
5. Reduce planned waste amounts.
   The current scrap rate of 17 percent yields about 1.7 million pounds of raw materials annually. Though much of this scrap is recycled, it would be ideal to reduce the scrap before created. Much of this is done at the design stage of products. XXX may want to consider examining the presses to determine if the parts could be cut to result in less waste.
6. Encourage recycling of packaging materials, either by shipper or by customer.
   Another opportunity for recycling is with the packaging materials. Waste plastic and cardboard are generated from the shipping of the power breaks that could be recycled by the consumer. Additionally, the wooden pallets could be reused or returned to XXX.
7. Consider changing from strict Just-in-time manufacturing to some blend of this and other manufacturing types.
   Though it is recognized that JIT manufacturing is effective in reducing waste on the facility floor, there are some implications of JIT manufacturing to transportation of materials and products. Instead of shipping full loads of products out, XXX may instead waste cargo space, a costly activity both financially and environmentally. To remedy this, XXX might reduce the impact of these activities by carefully scheduling shipments. This might involve some partnership with nearby facilities and might additionally involve evaluating suppliers for distance from the facility.
8. Consider redesign of the facility floor to eliminate unused space.
   It was noted that the XXX operations only occupy a portion of the large facility. However, it is also noted that a large amount of energy is used to operate facility lighting and the boilers that heat the facility in the winter. Because of this, XXX might consider moving some of their operations to a smaller space and closing off parts of the factory. This would effectively reduce lighting and heating needs of the facility as a whole.
9. Perform a site assessment and closure plans.
   As noted in the discussion of facility performance, XXX does not currently have plans for closure or transfer. As the facility has demonstrated dramatically

reduced operations over the last few years, managers should consider what steps they should take to begin to clean up their facility and develop a plan for closure.

SUMMARY

The XXX facility has made several strides towards reduced environmental impact through facility changes such as motion-detectors for lighting and reduced wattage bulbs for exit lighting. They have redesigned welding and soldering and wash procedures to reduce liquid residues. They additionally actively collect scrap metal for recycling. XXX also has become certified under the OSHA program VPP which indicates that they are a benchmark performer for worker safety.

However, these are just the beginning of possibilities for environmental improvement. By implementing several of the changes listed above, XXX can further reduce the impact of the facility and products and process upon the environment.

Appendix I

Techniques for Environmental Evaluation of an Industrial Process

In Chapters 6 and 7, four assessment matrices were defined and the ΣWESH plot presented. Subsequent chapters presented sector-level perspectives, using the matrices as display vehicles. In this appendix, we discuss the use of these tools to evaluate an individual industrial process within an individual facility.

I.1 DATA ACQUISITION

The first step in this evaluation is to construct a detailed flow diagram of the process. The components of this diagram include identification of materials inputs and product outputs, specification of all individual process steps (welding, cutting, cleaning, assembling, etc.), determination of process chemicals and process residues, and specification of process steps that utilize large amounts of energy and/or water. An accurate qualitative description of the process is essential, while quantitative details are much less important. A generic example of such a diagram is shown in Figure I.1.

In addition to a detailed flow diagram, notes on aspects of resource use, residue production, the types of processes used at a facility, and reasons for employing specific process steps and specific chemicals are crucial to a good assessment. A structured approach to note taking is advisable; we attach in Appendix A a form that we have found useful for this purpose. Data acquisition by a small team is often preferable to that by a single individual in assuring that nothing is missed.

A useful evaluation requires that enough information be available to construct the four matrices presented in Chapter 6: water, energy, scarcity, and hazard. The assessor

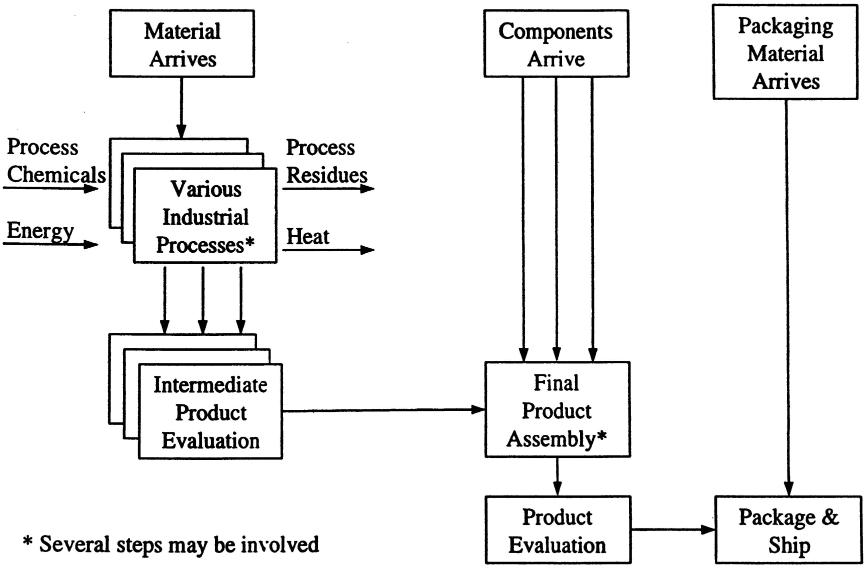


Figure I.1. Generic flow diagram for an assembled product.

therefore needs to determine before or during a plant visit which pieces of information are readily available (such as input materials) and which may be less readily available (such as a full list of process residues), and design the information gathering to arrive at a complete set of the necessary data. The process flow diagram is often very helpful in this regard.

I.2 MATRIX CONSTRUCTION

Once the flow diagram is constructed, the throughput analysis can be made, using the approach of Section 6.2. It will not often be the case that exact weight figures are readily available, but for the three-level binning process, rough estimates are usually perfectly adequate. Note that the weight percents of inputs should sum to approximately 100 percent. Since many outputs are small fractions of total input flows, the weight percent of outputs is unlikely to total 100 percent even if product flows are included. The result of the throughput analysis will be a table similar to Table I.1.

Using the results from the throughput analysis, and following the water concern, energy concern, potential scarcity, potential hazard analysis systems outlined in Chapter 6, a Throughput-Hazard-Scarcity binning table can be constructed. A sample Throughput-Hazard-Scarcity Table is shown in Table I.2.

Table I.1. Industrial Process Throughput Analysis (Example)

Material	Approximate wt.% of Total Inputs	Throughput Binning (H, M, L)
Input material M_1	65	H
Input material M_2	30	H
Process Chemical C_1	3	M
Process Chemical C_2	0.5	L
Emission E_1	10	H
Emission E_2	0.5	M
Emission E_3	0.5	M
By-product B_1	0.05	L

Table I.2. Sample Throughput-Hazard-Scarcity Binning

Significant Material	Throughput	Scarcity Potential	Hazard Basis	Environ. Concern	Potential Impact	Potential Hazard
INPUTS						
Input M_1	H	M	Ecosystem damage	H	M	M
Input M_2	H	L	Ecosystem damage	H	L	L
Process Chemical C_1	M	H	Ecosystem damage	H	H	H
Process Chemical C_2	L	L	Human damage	H	M	M
OUTPUTS						
Emission E_1	H	–	Climate change	H	H	H
Emission E_2	M	–	Acid deposition	M	M	M
Emission E_3	M	–	Odor	L	M	L
Byproduct B_1	L	–	Ecosystem damage	L	L	L

WATER/ENERGY	Performance	Concern
Water	H	L
Energy	M	M

The four evaluation matrices are constructed according to the approaches given in Chapter 6, and are shown in Figures I.2 through I.5. They are then used to develop the ΣWESH plot for the industrial process being evaluated, as shown in Figure I.6. The items of particular interest appear toward the upper right corner of the summary matrix; they are a mixture of current performance and potential concerns. The particular virtue of the ΣWESH plot is not that it provides a rigorous evaluation of environmental performance, because there are generally too many complexities and constraints involved in rigorous analysis. Rather, it raises for discussion and potential improvement many issues that might otherwise receive only passing attention.

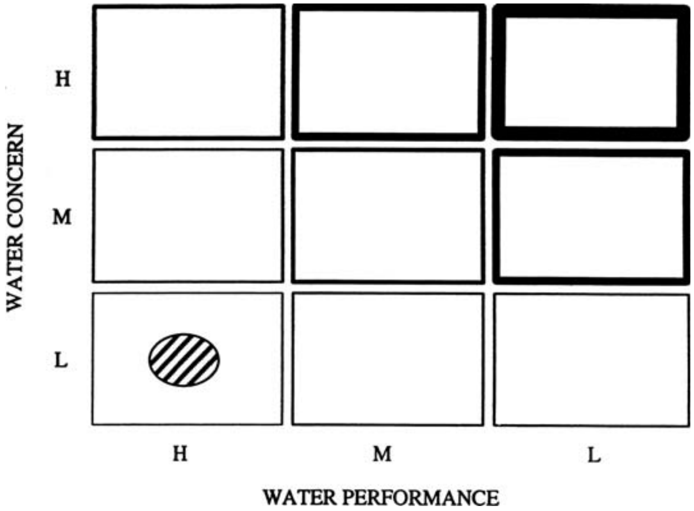


Figure I.2. Throughput-Water Concern Matrix for Sample Facility.

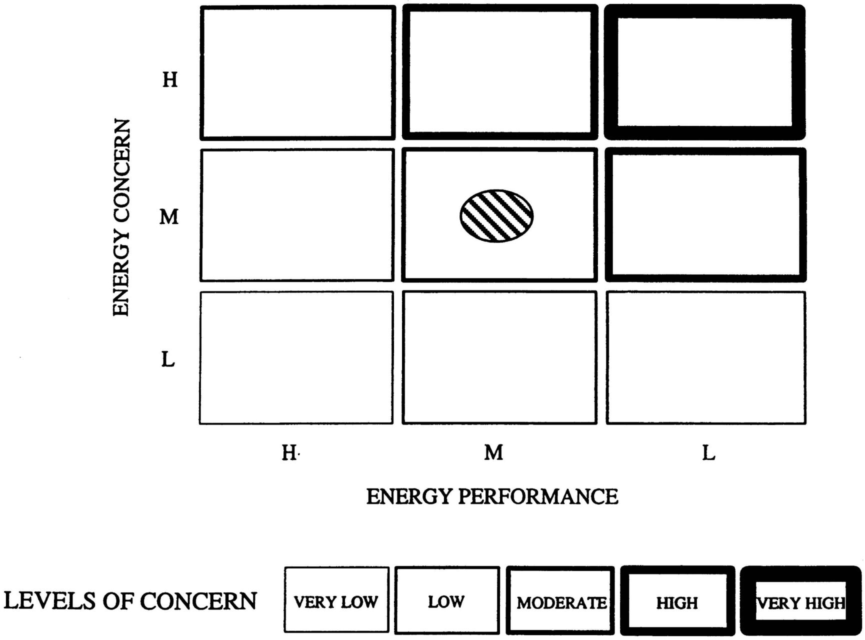


Figure I.3. Throughput-Energy Concern Matrix for Sample Facility.

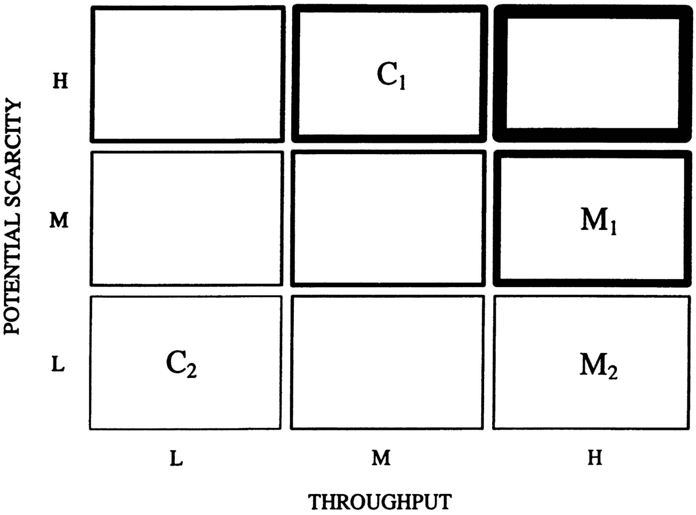


Figure I.4. Scarcity-Throughput Matrix for Sample Facility.

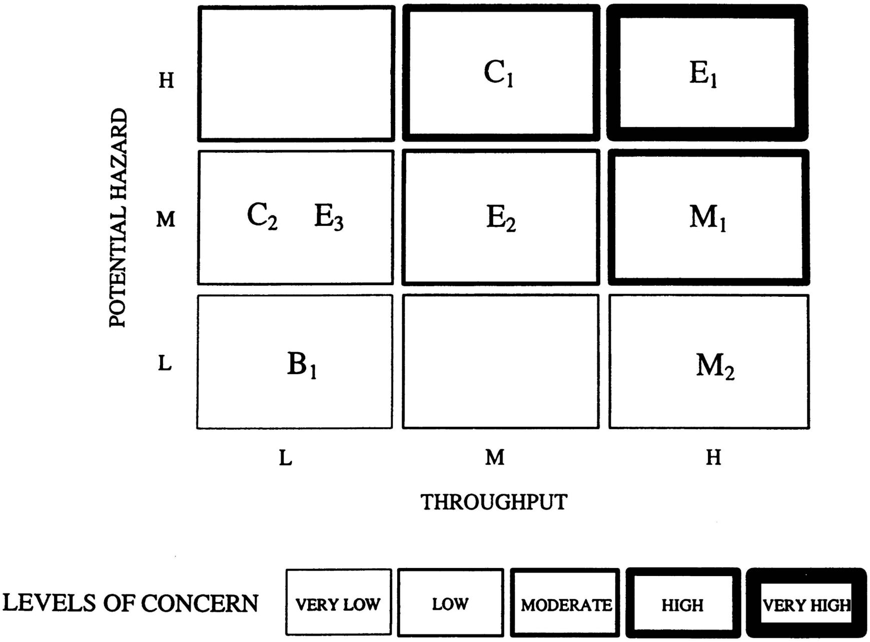


Figure I.5. Hazard-Throughput Matrix for Sample Facility.

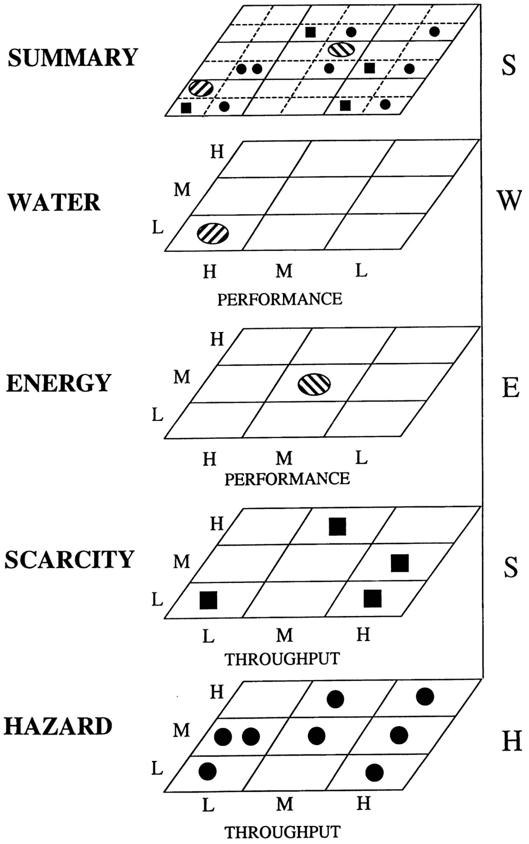


Figure I.6. ΣWESH plot for Sample Facility.

I.3 DISCUSSION

An evaluation of an industrial process is not complete without recommendations for improvement. These recommendations should be presented in high, medium, and low priority groupings. Recommendations are keys to environmental improvement, because they provide a ready means for decision-makers to act on the evaluation results.

It is important to note that an individual process need not actually exist to be evaluated. If a new process is being designed, a ΣWESH assessment of optimal approaches can often result in an environmentally superior processed being developed and implemented.

Appendix J

Example of a Facility Visit Report Directed Toward Sustainability

I. INTRODUCTION

Located in YYY, the 400 acre facility is one of sixteen plants owned and operated by XXX in the United States. The facility hosts research and development (R&D) activities and synthesis operations for bulk active materials. The R&D operations are managed by the Central Research, while the production of bulk active materials is part of the Global Manufacturing division. Together these divisions employ roughly 5,500 people at the facility, with only 10 percent of employees directly supporting on-site manufacturing activities.

The facility was originally developed as an industrial site during World War I when it was used as a shipyard. Following WWI, it was converted into a fish cannery. During World War II, the facility was again used as a shipyard. XXX purchased the facility in 1946 from the War Assets Administration. It has undergone a major modernization effort over the last ten years. The site now includes a variety of specialized equipment capabilities, including: two organic synthesis production facilities, a solvent recovery and treatment facility, a wastewater treatment facility, and a co-generation plant. Today, the XXX portion of the facility is used to produce the bulk active components of a wide variety of therapies and developmental substances for use in clinical trials.

Our facility tour began in one of the two organic synthesis production (OSP) facilities. The facility was recently constructed and came on-line in 1999. It took only two years to complete from the start of construction through to qualification and certification. Since gravity is used to facilitate the feeding of materials through the process cycle, we started on the fifth floor of the building and worked our way down through the in-let hoppers and the head tanks to the transfer station and main reactors, and finally the filtration and drying trains. Our tour continued in the wastewater treatment facility (WWTF), where the primary processing phases include: equalization, neutralization, aeration, filtration, and adjustment prior to release or combustion.

This report will begin with a general overview of the process flows for both the OSP facility and the WWTF followed by the application of the ΣWESH plot approach to technological sustainability assessment. Finally, some recommendations will be presented based on the ΣWESH analysis for potential areas of improvement and their expected impact on the assessment.

II. PROCESSES AND MATERIAL FLOWS

The production of synthetic organic chemicals for use in the pharmaceutical industry is a relatively unique process compared to the manufacturing processes associated with the production of other bulk chemicals. The synthesis itself is extremely complex and utilizes a number of substances as inputs that are themselves the result of relatively involved production processes. Furthermore, the stringent purity requirements necessitate the use of batch production techniques. This not only increases the control burden associated with production, but also slows the rate of overall production due to the need for extensive cleaning between production cycles. Finally while the quantities produced are large in an absolute sense, they are at least an order of magnitude smaller than those in other precursor processes.

The design of the OSP facilities is structured to allow for maximum synthesis flexibility given the number of different products that they may produce. Depending on the compound, between three and seven synthetic steps may be required. Once in production, the facility allows for six simultaneous process steps. Since the changeover of equipment between products is both labor and time intensive, product production is typically run in "campaigns" where only one product is produced at a time. Due to the diversity of products manufactured in this facility, the thrust of the discussion of the process flow diagram will center on the mechanistic processes rather than the exact nature of the chemicals used and the synthesis chemistry. In this light, the production process can be described as consisting of five phases: batch charging, reaction, filtration, distillation/granulation, and filtration/drying.

Batch Charging

Using gravity as a primary transfer mechanism, reactants for use in charging the reactor vessel are introduced from a combination of charge hoppers and day tank storage vessels beginning on the 5th floor. Reactants that are used in large quantities are transferred into smaller day tanks from which the material can be directly metered into the process. Vacuum pumps are used to supply reactants of smaller quantities, while intermediate quantities are introduced directly into the head tanks on the 4th floor. Throughout the process the quantities added to the process are monitored using weight cells on which tank and reactor vessels are mounted. Within the head tanks, solids are mixed with solvents. The integrity of the head tank is monitored using pressure indicators. The head tank capacity ranges from between 200 and 500 gallons.

Reaction

Eighteen CSTRs ranging in capacity from 1,000 to 4,000 gallons are positioned on the 3rd floor. These reactors are connected via an elaborate transfer manifold that allows for a variety of process configurations. The steel reactor vessels are lined with glass to maximize resistance to caustic materials. The connective piping is made of Teflon lined steel. The reactors are fed from the head tanks, solvent storage vessels, and charge hoppers. The reactions are carried out under temperature and pressure conditions specific to the desired product. All of the reactors are equipped with thermal jackets and some have internal tubing for thermal transfer. The steam is produced by a co-generation facility on-site that generates 50 percent of the energy demand. Steam is typically maintained at approximately 140°C. Non-contact cooling capacity can reach -20°C. The reaction conditions can be extremely energy intensive, requiring sequential cycles of heating and cooling. The reactions can also be carried out under pressure, which requires more energy. Vapors resulting from the reactions are collected and passed through a series of condensers. Portions of these streams are passed to the solvent recovery process. The remainder is passed through scrubbers prior to release into the air. Some of the condensed liquids (likely to be mostly solvents) are reintroduced directly into the reactor vessel. The target conversion yield is between 60 and 75 percent. Redox probes and sample ports are used to monitor the reaction. These samples are sent to the QA/QC labs located on the 5th floor. The cleaning process can also be potentially water intensive using filtered water from the city supply in cleaning (also potentially as part of the synthesis process, although this is less likely).

Filtration

The reactor effluent is passed to a filter prior to distillation and granulation in another CSTR. This filtration step is designed to removal of any undesirable byproducts that may have formed during reaction and would otherwise pollute the distillation process. Without this step, some of these compounds could end up in the mother liquor extract from which becomes the bulk product. Depending on the composition of the filtrate, the solids could be passed on to the Wastewater Treatment Plant for thermal drying/dewatering and combustion in a fluidized bed incinerator.

Distillation/Granulation

Following initial filtration, the product stream is passed into another CSTR where the reaction conditions are modified to cause the vaporization of some solvent material. These solvent vapors are fed to a condenser prior to introduction into the solvent recovery system. These CSTRs are also capable of the same range of temperature and pressure modifications as those in the reaction phase. In addition to the overall reduction in the volume of the product stream, the conditions (and potentially the addition of catalysts) cause the formation of the solid product compound.

Filtration/Drying

A series of solvent rinses are used to purify the product. The solvents are recovered and processed in the solvent recovery system. Two different types of filtration equipment are used to separate the bulk product from the solvent rich mother liquor. The first is a filter/dryer. The second is a centrifuge with a vertically mounted basket. In all, four filtration trains are necessary to meet production throughput requirements. The purification process is both energy and solvent intensive. The filtered, bulk active material is passed through a dryer prior to being placed into drums for shipment to a compounding facility.

Solvent Recovery

The WWTF has three distillation columns. One functions as a solvent recovery column which allows for a reduction in the quantity of solvent that has to be purchased for production. Approximately 50 percent of the solvents used in the manufacturing process are currently economically viable for recovery. The pharmaceutical industry has special regulatory requirements associated with such recycling processes that can delay the use of any recovered material for up to two years. However once the synthesis process and recovery products are approved for use, the process becomes more standardized. The unrecoverable solvents are either diluted and biologically processed on-site or sent off-site for addition treatment and disposal.

WWTF

The production process is structured so as to prevent regulatory compounds from entering the WWTF. Thus, the inputs into the biological treatment process are largely non-toxic aqueous solutions. Ultimately, the carbon in the solvent/waste stream is converted into carbon dioxide (80 percent) and cell material (20 percent). To begin the stream is equalized in blending tanks. At this point the solution is basic. The next phase is a two step neutralization process to reduce the pH to between 7.5 and 9. Within the liquid train, single cell mesophilic bacteria (especially temperature sensitive) are added to solution to convert the available carbon. The stream is then passed on to be aerated (further reducing the pH to 6.5–7.5) and processed through secondary clarification. A portion of the volume is released into the disinfection process where is will be disinfected using bleach and chlorine and then de-chlorinated prior to release. The remainder is passed to the RAS (return activated sludge) tank, where some of the biosolids are separated and reintroduced into the biological treatment train. The waste sludge then enters into the filtration process which focuses on dewatering to reduce the incinerator burden. From the waste sludge holding tank, the material is processed in a belt filter press where TSS (total suspended solids) are increased to between 12–14 percent. The waste sludge is dried using a rotary dryer to 30–35 percent TSS. This is an energy intensive process however they have made adaptations to that allow for wetter material to be combusted in the incinerator. The incinerator is a specialized fluidized bed incinerator that uses silicate compounds to manipulate the eutectic point, thus eliminating the formation of glass which reduces maintenance costs and increases availability. The incinerator is capable of processing 20,000 lbs and reaches 15,000°F (burns fuel oil). All emissions are monitored by a CEMS for compliance with CAA permits. The resulting ash is landfilled along with half of the clay. Overall, 20 percent of the power utilized in the WWTF is supplied by the on-site power house.

III. ΣWESH PLOT ANALYSIS

Before beginning the discussion of the ΣWESH plot analysis, it should be noted that the materials considered in the assessment were based upon those explicitly provided—the inputs were assumed to be "starting materials," methanol, toluene, tetrahydrofuran, and ethanol; the outputs were generally treated as "drug products."

Hazard (Figure J.1)

Potential hazard rankings of high (H) were given for both the "starting materials" and "drug products." This is consistent with the idea that pharmaceuticals are inherently bioactive and therefore a hazard in the event of unintended exposure to the environment or humans. Many of the starting materials also have similar potential impacts or may come from processes that further aggravate situations listed as "Crucial Environmental Concerns" (i.e. global warming, human organism damage, ecosystem organism damage, etc.). With regard to the solvent inputs, the hazard basis is listed in Table 1. Both methanol and ethanol they can be derived from renewable resources. The majority of methanol is currently produced from natural gas. Therefore in an effort to reflect the potentially renewable nature of the input, the overall environmental concern for methanol was reduced from high due to the associated depletion of fossil fuels to medium. Ethanol is produced from corn. Many of the ethanol production

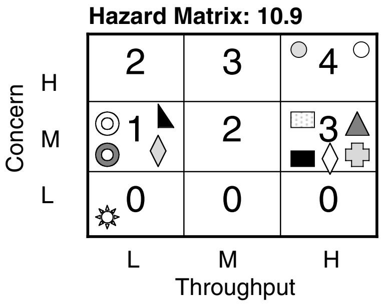
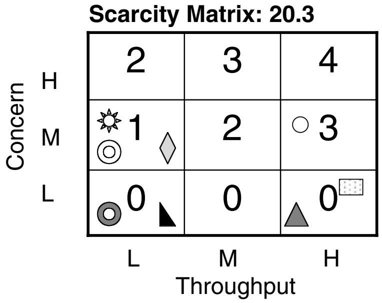


Figure J.1.



* Matrix element scores are shown in gray

Figure J.2.

Material	**Symbol**
Titanium alloy	▨
Nickel alloy	○
Aluminum	▲
Ethylene glycol	◉
Lubricating oil	◆
Acetone	☼
Phosphoric acid	◎
Sodium hydroxide	◣
Jet engines	●
Metal scrap	■
Lubricant residue	◇
Cleaning residue	✚

facilities in US utilize corn from large-scale agribusiness. This may reduce the biodiversity of plant stock and it may also increase the stress on water supplies in the Midwest. Toluene presents several environmental concerns due to its high volatility and its adverse impact on human health. It is also amongst the olfactory pollutants listed in the text, however this aesthetic degradation only rates a medium ranking. In light of its ability to damage human health, toluene was given a ranking of high. Similarly, tetrahydrofuran was also given a ranking of high due to concerns associated with damage to human and ecosystem organisms. However, the impacts of tetrahydrofuran have not been as well publicized as other chemicals.

The potential impacts of the inputs and outputs are based on assessments complied by scorecard.org. The overall value score is a combination of the human health effects and the ecological effects. Three of the four solvents are ranked as medium potential impact, while the one high throughput solvent (methanol) is ranked as low potential impact. The total potential hazard for each input and output was calculated using the rubric established in Table 6.3 of the text. The overall score using the bin weighing distribution shown in the hazard matrix was found to be 12.5. Since the two elements that end up in the high throughput, high concern portion of the matrix are the "starting materials" and the "drug product," it seems unlikely that the score would change significantly barring radical redesign of the products themselves. Since bioactivity will remain a guiding design principle, the hazard associated with the product will continue to pose a threat. Perhaps it would be possible to design drugs that are component based such that the individual elements are less bioactive and only achieve full therapeutic capability when mixed by the end user. The sheer technical and mechanical complexities of such a process preclude this from being even a medium term goal. Overall considering the potency of the products, a hazard score of 12.5 out of 25 is relatively low. It would be interesting to conduct the same assessment using the specific chemicals reactants from a particular synthesis. Unfortunately, the score could decrease if the number of "medium, high" materials were to increase instead of being lumped into the "high, high" ranking of the "starting materials" and "drug product." The most feasible gain from movement within the matrix would seem to come from a reduction in the amount of toluene that is currently used. This could be accomplished by limiting the overall use of toluene in synthesis or by placing a greater emphasis on recovering toluene in the solvent recovery system, thereby reducing the volume of virgin inputs.

Scarcity (Figure J.2)

Based on the scarcity data proved for simplified set of input being assessed, facility performance in the area of scarcity is superior. All of the inputs are rated as having low scarcity (>100 years to depletion) and therefore the scarcity score is 25 out of 25. All low level scarcity inputs are weighted as zero points so, throughput becomes irrelevant. The only potential area of concern would be preserving this level of performance by anticipating the potential impacts of substitutions to achieve gains in other areas.

Energy (Figure J.3)

The energy score is 10.4 out of 25. This score reflects a combination of concern and performance. While national energy concern is only marginal, both the regional and the sector energy concerns were found to be high. Using regional energy price data supplied by the Energy Information Administration (EIA) for 1999, the price per MMBtu was calculated to be 38 percent higher than the national average. Generally the organic synthesis industry requires significant quantities of energy input and reliable energy service. Since the processes run 24 hours a day, it is not realistic to structure the production cycle so as to run during non-peak hours. XXX does generate a portion of its energy in its on-site co-generation facility and therefore this sector level categorization may be unduly critical. Although, I would expect that other pharmaceutical facilities would have similar generating capacities. Turning to performance considerations, according to the site manager significant improvements

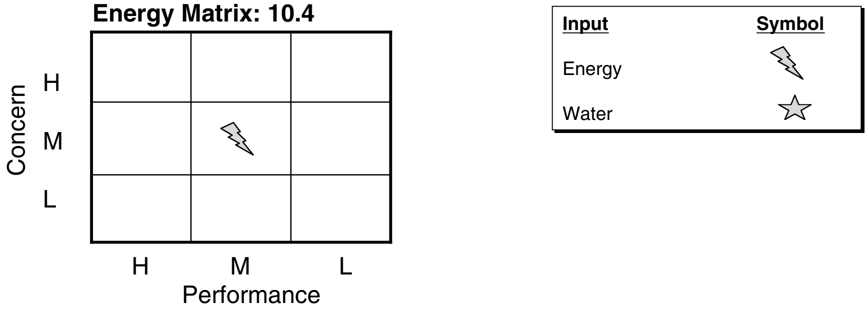
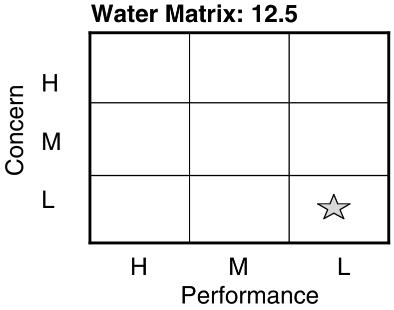


Figure J.3.



* Matrix element scores are shown in gray

Figure J.4.

have been made in baseline energy consumption over the past several years. I assumed that these improvements would merit a ranking of high ("reduction in normalized energy usage by more than 5 percent" according to the text). Again, information from EIA was used to determine the distribution of generating capacity across sources. The bulk of power supplied to the region comes from nuclear power plants. The aggregate industry score is 1.68 which exceeds the lower threshold for performance and was therefore scored as a medium (>1.5 and <2.5). Based on my overall impression of the facility, I assumed that while conservation practices and control technologies are in place the emphasis is on development and output. The value of the product is much greater than other industrial processes so, it is my impression that the relative savings from conservation are less compelling relative to greater production. There is also quite a lot of effort put into making the facility esthetically pleasing for the workers. Some of these activities may be at odds with strict conservation practices.

Water (Figure J.4)

The water score is 16.7 out of 25. Like the energy scoring approach, the water score reflects a combination of concern and performance. The US has a relative water surplus which translates into a low water vulnerability score. On a regional level, a NOAA precipitation map indicates that the city receives approximately 135cm of precipitation a year. This earns a medium ranking (>75 cm and <150 cm). This is at the higher end of the range of precipitation within the US. Thus from a macro geographic point of view, the XXX facility is positioned such that water supply should not be a severely limiting constraint on the water intensive activities of commercial organic synthesis (ranked high). In evaluating water use performance relative to baseline consumption, I assumed that the improvements in water conservation over the past few years were sufficient to merit a ranking of high ("reduction in normalized water usage by more than 5 percent" based on the text). With respect to wastewater treatment, the WWTF facility at XXX's facility processes the waste streams in a manner consistent with treatment above secondary wastewater for those streams that require treatment. The chlorination and de-chlorination processing step is not strictly required by the state DEP. This extra processing beyond secondary treatment merits a ranking of high. In terms of water reuse, the cycling of non-contact cooling water that remains of a high quality and does not require treatment saves on water usage. However, I assumed that overall the amount of water reused is between 1 and 10 percent. This justifies a ranking of medium. I am unaware of any formalized water reuse program at the facility.

III. CONCLUSIONS AND RECOMMENDATIONS

The overall numerical score for environmental performance at the XXX facility is 64.6 out of a possible 100. Since the pharmaceutical industry as a whole tends to be on the cutting edge of industrial chemistry, the fact that this score does not reach into the upper quartile indicates that while there have been many advances in processing technologies over the past decade, there remains much room for improvement with respect to environmental considerations. The extent to which economic viability effectively limits this progression and actually reduces the achievable scale to something less than 100 depends on the incentives (regulatory or otherwise) designed to prompt further innovation.

Looking at the ΣWESH plot shown in Figure J.5, several conclusions and recommendations are apparent:

Conclusions

- Performance with respect to scarcity is superior.
- Water management is obviously a priority and the geographic factors play a significant role in ensuring the large volume required is not immediately limited.

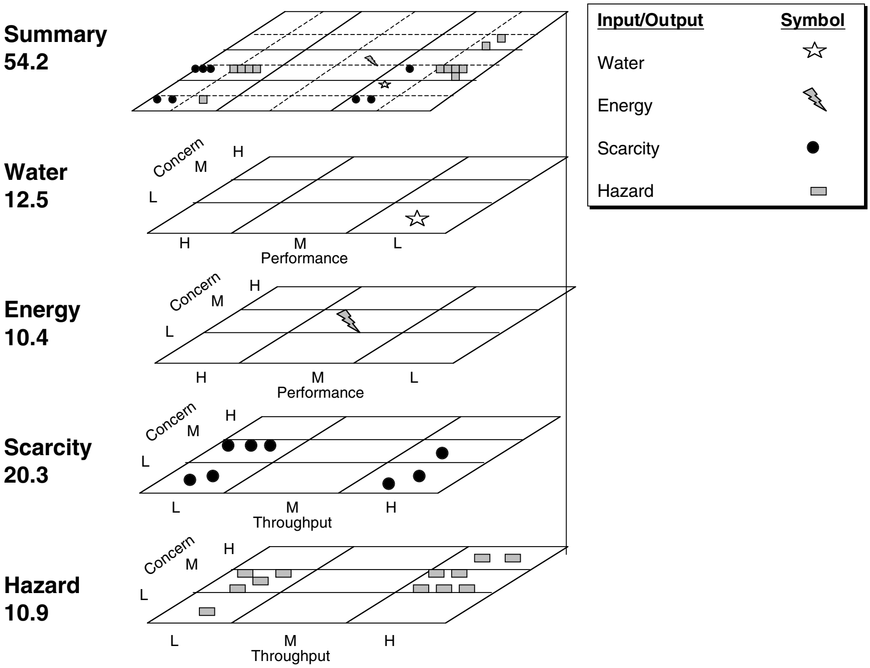


Figure J.5.

- The process is both water and energy intensive.
- The hazard score may not be completely reflective of the actual distribution of hazard amongst those substances that are currently approximated as "starting materials" and "drug products." I anticipate that if these grouping were broken out by specific substances that the score would decline slightly as I expect that the majority of the compounds would at the least be listed as "medium, high." The hazard score will likely continue to be driven by the inherently bioactive and therefore hazardous nature of pharmaceuticals.
- Based on the scoring, energy performance is the area with the lowest performance. While the facility does not assert direct control over the utilities, it does have some market power and could exercise it so as to ensure more use of hydroelectric and other alternative sources. The co-generation facility does provide some insulation from the energy market, but the score is still significantly impacted by the high relative price of energy charged in the Northeastern US.

Recommendations (Impacts shown in Figure J.6)

- Water: Work to reduce usage. Consider greater reuse of WWTF outlet streams.
- Energy: Specify a percentage of energy purchased from utilities be supplied by hydroelectric or alternative sources. Create a program that rewards employees for suggestions

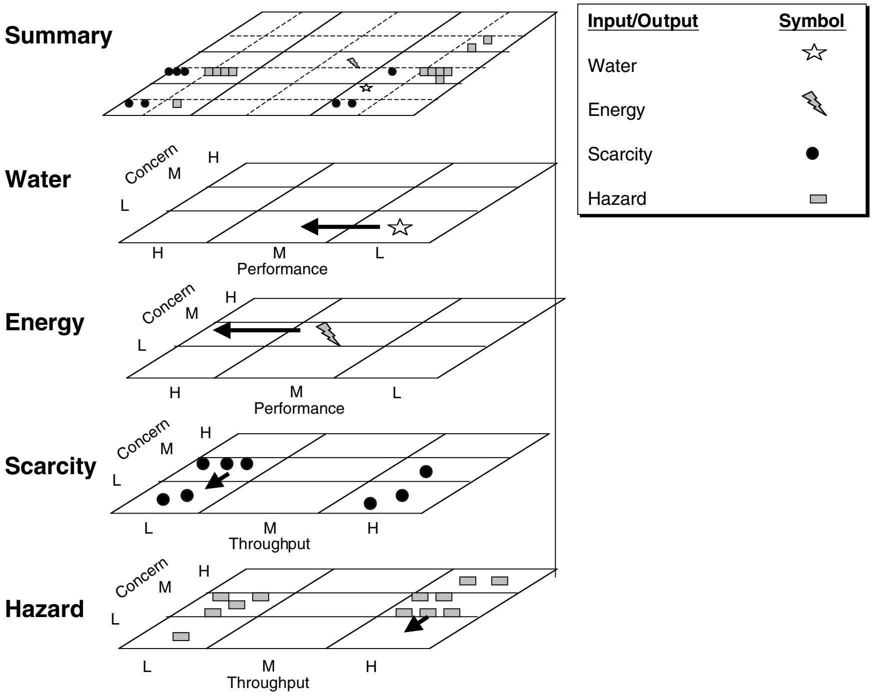


Figure J.6.

that lead to energy savings. Investigate the potential of using on-site generation during peak hours when the overall efficiency of generating units declines due to the use of "peakers". Investigate other types of bacteria with higher conversion rates to reduce the treatment stream volume.

- Hazard: Reduce the use of toluene and endeavor to allow for preferential recovery. Consider adapting synthesis guidelines to make solvent selection an explicit part of the process during the early portions of the design/scale-up process. Bring the operators together with the R&D investigators earlier in the process to potentially reduce the need for solvent (number of solvent washes) and solvent recovery.
- Rotate investigative staff on small discovery teams that spend a small portion of time each week working on a problem outside their primary focus area to simulate unconventional thinking.

Appendix K

Units of Measurement

The basic unit of energy is the joule ($= 1 \times 10^7$ erg). One will often see the use of the British Thermal Unit (Btu), which is 1.55×10^3 J. For very large energy use, a unit named the *quad* is common; it is shorthand notation for one quadrillion British Thermal Units. Thus, 1 quad $= 1 \times 10^{15}$ Btu $= 1.55 \times 10^{18}$ J.

The units of mass in the environmental sciences and in this book are given in the metric system. Since many of the quantities are large, the prefixes given in Table B1 are common. Hence, we have such figures as 2 Pg $= 2 \times 10^{15}$ g. Where the word tonne is used, it refers to the metric ton $= 1 \times 10^6$ g.

The most common way of expressing the abundance of a gas phase atmospheric species is as a fraction of the number of molecules in a sample of air. The units in common use are *parts per million* (ppm), *parts per billion* (thousand million; ppb), and *parts per trillion* (million million; ppt), all expressed as volume fractions and therefore abbreviated ppmv, ppbv, and pptv to make it clear that one is not speaking of fractions in mass. Any of these units may be called the *volume mixing ratio* or *mole fraction*. Mass mixing ratios can be used as well (hence, ppmm, ppbm, pptm), a common example being that meteorologists use mass mixing ratios for water vapor. Since the pressure of the atmosphere changes with altitude and the partial pressures of all the gaseous constituents in a moving air parcel change in the same proportions, mixing ratios are preserved as long as mixing between air parcels can be neglected.

Particles can be mixtures of solid and liquid, so a measure based on mass replaces that based on volume, the usual units for atmospheric particles being micrograms per cubic meter (μg m^{-3}) or nanograms per cubic meter (ng m^{-3}). For particles in liquids, micrograms per cubic centimeter (μg cm^3) is common. It is sometimes convenient to compare quantities of an element or compound present in more than one phase, say as both a gas and as a particle constituent. In that case, the gas concentration in volume units is converted to mass units prior to making the comparison.

For constituents present in aqueous solution, as in seawater, the convention is to express concentration in volume units of moles per liter (designated M) or some

Table K.1. Prefixes for Large and Small Numbers

Power of Ten	Prefix	Symbol
+24	yotta	Y
+21	zetta	Z
+18	exa	E
+15	peta	P
+12	tera	T
+9	giga	G
+6	mega	M
+3	kilo	k
−3	milli	m
−6	micro	μ
−9	nano	n
−12	pico	p
−15	femto	f
−18	atto	a
−21	zepto	z
−24	yocto	y

derivative thereof [one mole (abbreviated mol) is 6.02×10^{23} molecules]. Common concentration expressions in environmental chemistry are millimoles per liter (mM), micromoles per liter (μM), and nanomoles per liter (nM), Sometimes one is concerned with the "combining concentration" of a species rather than the absolute concentration. A combining concentration, termed an *equivalent*, is that concentration which will react with 8 grams of oxygen or its equivalent. For example, one mole of hydrogen ions is one equivalent of H^+, but one mole of calcium ions is two equivalents of Ca^{2+}. Combining concentrations have typical units of equivalents, milliequivalents, or microequivalents per liter, abbreviated eq/l, meq/l, and μeq/l. A third approach is to express concentration by weight, as mg/l or ppmw, for example. Concentration by weight can be converted to concentration by volume using the molecular weight as a conversion factor.

Acidity in solution is expressed in pH units, pH being defined as the negative of the logarithm of the hydrogen ion concentration in moles per liter. In aqueous solutions, pH = 7 is neutral at 25°C; lower pH values are characteristic of acidic solutions, higher values are characteristic of basic solutions.

Glossary

Acid deposition	The deposition of acidic constituents to a surface. This occurs not only by precipitation but also by the deposition of atmospheric particulate matter and the incorporation of soluble gases.
Aggregate	Gravel, sand, and crushed stone used in construction as filler material and in the making of concrete.
Alkylation	The introduction of a paraffinic hydrocarbon group (an alkyl) into an organic molecule.
Alloy	A substance with metallic properties, composed of two or more chemical elements of which at least one is a metal.
Anion	an ion having a negative electrical charge.
Anodizing	Electrolytically coating a metallic surface with a protective oxide.
Anthropogenic	Derived from human activities.
Assembled materials	Products manufactured without the use of physical or chemical transformations, using parts and components produced by suppliers.
Beneficiation	Any process by which an ore is concentrated in preparation for further processing. Common beneficiation processes include screening, washing, milling, and magnetic separation.
Biodiversity	The diversity of species within a geographical area of interest.
Biomass	Plant materials and animal waste used as a source of fuel.
Biosphere	That spherical shell encompassing all forms of life on Earth. The biosphere extends from the ocean depths to a few thousand meters of altitude in the atmosphere, and includes the surface of land masses. Alternatively, the life forms within that shell.
Biotechnology	Technology enabled by biological processes.

Blow molding	The production of hollow thermoplastic products by supplying sufficient air pressure to a thermoplastic tube within a mold to cause it to expand and take on the shape of the mold.
Boring	*(See Drilling).*
Brazing	Joining two pieces of metal together by flowing a thin layer of molten filler metal into the space between them.
Brownfield	Land that has previously been used for industrial, commercial, or residential purposes. (The antonym of *Greenfield.*)
By-product	A useful product that is not the primary product being produced.
Cascade recycling	See *Open-loop recycling*
Casting	The process of heating metal until it is molten, pouring the molten metal into a mold, and letting the metal harden into the desired shape.
Catalyst	A substance that influences the rate of a chemical reaction without being consumed or undergoing chemical change.
Cation	An ion having a positive electrical charge.
Cement	The binding constituent in concrete.
CFCs	Chlorofluorocarbon compounds, i.e., organic compounds that contain chlorine and/or fluorine atoms. CFCs are widely recognized as hazardous to stratospheric ozone.
Chem-milling	Accomplishing a milling process by means of chemical rather than mechanical action.
Chip	A minute piece of semiconducting material processed to have specific electronic characteristics; especially, such a device before the attachment of electrical leads and packaging as an integrated circuit.
Clinker	Decarbonized, sintered, and rapidly-cooled limestone. Clinker is an intermediate product in cement manufacturing.
Closed-loop recycling	A recycling system in which a particular mass of material is remanufactured into the same product (e.g., glass bottle into glass bottle). Also known as *Horizontal recycling.*
Cogeneration	The use of the energy rejected from a power plant to generate steam.
Cold working	Altering the shape or crystal structure of a metal in the absence of heat. Combined-cycle generation
Comminution	The size reduction of materials by grinding, cutting, shredding, chopping, or other physical action.
Complementary process	A manufacturing process that is required as a consequence of carrying out a primary manufacturing process, such as a polishing process that follows a cutting process. See also *Primary process.*

Composite material	A macro-scale combination of two or more materials that are solid in the finished state, are mutually insoluble, and differ in chemical nature.
Concrete	A material produced by mixing a cement binder with water and aggregate. The fluid mass undergoes hydration to produce concrete.
Coproduct	A marketable byproduct from a process. This includes materials that may be traditionally defined as wastes such as industrial scrap that is subsequently used as a raw material in a different manufacturing process.
Cutting fluid	A liquid applied to a cutting tool to wash away chips and/or serve as a lubricant or coolant.
Depletion time	The time required to exhaust a resource if the present rate of use remains unchanged.
Design for environment	An engineering perspective in which the environmentally related characteristics of a product, process, or facility design are optimized.
Die casting	Forming a metal product of desired shape by forcing molten material into a die cavity and allowing it to harden.
Disposal	Discarding of materials or products at the end of their useful life without making provision for *Recycling* or *Reuse*.
Dissipative product	A product that is irretrievably dispersed when it is used (e.g., paint, fertilizer).
Dose–response curve	A curve plotting the known dose of a material administered to organisms against the percentage response of the test population. If the material is not directly administered, but is present in the environment surrounding the organism (e.g., water, air, sediment), the resulting curve is know as a "concentration–response curve."
Drawing	Shaping a piece of material by pulling it into a desired position (often with vacuum).
Drilling	Making a hole in a hard material by using a metal rod with cutting edges and a pointed end.
Dross	Waste impurities formed on the surface of molten metal during smelting.
Ecoprofile	A quick overview of a product or process design to ensure that no disastrous features are included or to determine whether additional assessment is needed.
Electroplating	The deposition of a thin layer of metal on an object by passing an electric current through an aqueous solution of a salt containing ions of the element being deposited.
Embodied energy	The energy employed to bring a particular material or product from its initial physical reservoir or reservoirs to a specific physical state.

Energy audit	An accounting of input flows, output flows, and losses of energy within an industrial process, a facility, a corporation, or a geographical entity.
Environmental supply chain management	The process of oversight of the environmentally-related activities of suppliers.
Extrusion	Shaping material by forcing it to flow through a shaped opening in a die.
Feedstock	The material input to a chemical process. The term is most commonly applied to petroleum-derived hydrocarbons when they are used for the production of gasoline, fuel oil, and petrochemicals.
Fermentation	A chemical change induced by living organisms or enzymes.
Ferrous metals	Alloys that contain iron as the principal constituent.
Forging (n.)	A metal part that has been worked to a predetermined shape by beating, rolling, or hammering.
Forging (v.)	Heating metal and beating it, rolling it, or hammering it into shape.
Fossil fuel	A general term for combustible geological deposits of carbon in reduced (organic) form and of biological origin, including coal, oil, natural gas, oil shales, and tar from agricultural lands.
Fugitive emissions	Emissions from valves or leaks in process equipment or material storage areas that are difficult to measure and do not flow through pollution control devices.
Gangue	The non-metalliferous or worthless materials contained in ore.
Green building	A building designed or renovated with the goal of minimizing its impact on the surrounding natural environment.
Green chemistry	Employing chemical techniques and methodologies that reduce or eliminate the use or generation of feedstocks, products, byproducts, solvents, and reagents that are hazardous to the environment.
Green engineering	The use of environmentally-preferable approaches to the design and development of products and processes.
Greenfield	Land that has not previously been used for industrial, commercial, or residential purposes. (The antonym of *Brownfield*.)
Greenhouse gas	A gas with absorption bands in the infrared portion of the spectrum. The principal greenhouse gases in Earth's atmosphere are H_2O, CO_2, O_3, CH_4, and N_2O.
Hazard	(as used in risk assessment) A material or condition that may cause damage, injury or other harm, frequently established through standardized assays performed on biological systems or organisms. The confluence of hazard and exposure create a risk.

Heat treatment	Altering the shape or crystal structure of a metal in the presence of heat.
Hitchhiker resource	A resource acquired principally as a byproduct of the mining of other resources.
Home scrap	The waste produced within a fabricating plant, such as rejected material, trimmings, and shavings. Home scrap is recirculated within the fabricating plant and does not become external waste.
Horizontal recycling	See *Closed-loop recycling*
Hot working	See *Heat treatment*
Indicator	A qualititative measure of the status of a chosen parameter, environmental or otherwise.
Industrial ecology	An approach to the design of industrial products and processes that evaluates such activities through the dual perspectives of product competitiveness and environmental interactions.
Industrial symbiosis	See *Symbiosis*
Ingot	A cast form of metal suitable for remelting or fabricating.
Injection molding	Forming a plastic product of desired shape by forcing liquid plastic into a mold and allowing it to harden.
Integrated circuit	A minute piece of semiconducting material processed to have specific electronic characteristics; especially after the attachment of electrical leads and packaging.
Intelligent material	A material or structure that can sense its surroundings and react to changes in the surroundings in a useful way. Most intelligent materials incorporate sensors, information processors, actuators, and feedback functions. Examples include materials for drug delivery under certain chemical conditions or materials that release adhesives to repair cracks in themselves.
Inviolates list	A list of design decisions never allowed to be taken by product or process designers.
Ion	An atom that has lost or gained one or more electrons and thus acquired an electrical charge.
Kiln	A large industrial oven.
Leachate	The solution that is produced by the action of a solvent on a permeable solid, as in an industrial process or a landfill.
Leaching	Extracting one component of a mixture of two or more materials by exposing the mixture to a solvent in which the desired component is soluble.
Life cycle	The stages of a product, process, or package's life, beginning with raw materials acquisition, continuing through processing, materials manufacture, product fabrication, and use, and concluding with any of a variety of waste management options.

Life cycle assessment	A concept and a methodology to evaluate the environmental effects of a product or activity holistically, by analyzing the entire life cycle of a particular material, process, product, technology, service, or activity. The life cycle assessment consists of three complementary components, inventory analysis, impact assessment, and improvement analysis, together with an integrative procedure known as scoping.
Material flow analysis	An analysis of the flows of materials within and across the boundaries of a particular geographical region.
Metric	A quantitative measure of the status of a chosen parameter, environmental or otherwise.
Milling	Reducing a solid substance into minute grains by crushing or grinding (as done, for example, in a pepper mill).
Mineral	A distinguishable solid phase that has a specific chemical composition, e.g., quartz (SiO_2) or magnetite (Fe_3O_4).
Mold	A frame or model on which or in which something is shaped.
Molding	Shaping in or on a mold, generally by the application of heat and pressure.
Molecular flow analysis	An analysis of the flows of a specific molecule within and across the boundaries of a particular geographical region.
Monomer	A molecule or compound, usually of relatively low molecular weight and simple structure, which is capable of conversion to a polymer by combination with itself or other similar molecules or compounds.
Moore's law	Gordon Moore's empirical observation that the packing density of integrated circuits doubles about every eighteen months.
New scrap	See *Prompt scrap*
Non-ferrous metals	Metals or alloys that do not contain iron as the principal constituent.
Non-point source	See *Source*
NO_x	The sum of the common pollutant gases NO and NO_2.
Old scrap	See *Postconsumer solid waste*
Open-loop recycling	A recycling system in which a product from one type of material is recycled into a different type of product (e.g., plastic bottles into fence posts). The product receiving recycled material itself may or may not be recycled. Also known as "cascade recycling".
Ore	A natural rock assemblage containing an economically valuable resource.
Overburden	The material to be removed or displaced that is overlying the ore or material to be mined.
Ozone depletion	The reduction in concentration of stratospheric ozone as a consequence of efficient chemical reactions with molecular fragments derived from anthropogenic compounds, especially CFCs and other halocarbons.

Packaging, primary	The level of packaging that is in contact with the product. For certain beverages, an example is the aluminum can.
Packaging, secondary	The second level of packaging for a product that contains one or more primary packages. An example is the plastic rings that hold several beverage cans together.
Packaging, tertiary	The third level of packaging for a product that contains one or more secondary packages. An example is the stretch wrap over the pallet used to transport packs of beverage cans.
Planing	Smoothing or finishing by means of a tool with an adjustable blade.
Plastic	A high polymer material in combination with ingredients (colorants, fillers, plasticizers, reinforcing agents, etc.) added to provide specific physical properties.
Plating	The act of depositing a thin layer of metal upon the surface of a dissimilar metal.
Point source	See *Source*
Pollution prevention	The design or operation of a process or item of equipment so as to minimize environmental impacts
Polymer	An organic macromolecule composed of a large number of monomers.
Polymerization	A chemical reaction in which a large number of relatively simple molecules combine to form a chain-like macromolecule.
Postconsumer scrap	See *Postconsumer solid waste*
Postconsumer solid waste	A material that has served its intended use and has become a part of the waste stream. (Also called *Old scrap* and *Postconsumer scrap*)
Potential to pollute	The potential of all industrial processes, if not carefully designed and thoughtfully performed, to cause detrimental impacts on the environment.
Powder metallurgy	The technology of powdered metals, especially the production and utilization of metallic powders for the production of shaped objects.
Primary process	An industrial processes that accomplishes a desired chemical or physical transformation. See also *Complementary process*.
Printed wiring board	An insulating substrate upon which is deposited, in predetermined patterns, a conducting metal. Integrated circuits and other components are later affixed to the printed wiring board to form the desired electronic product.
Prompt scrap	Waste produced by users of semifinished products (turnings, trimmings, etc.). This scrap must generally be returned to the materials processor if it is to be recycled. (Also called *New scrap*).
Punching	a piece of desired shape is punched from the interior of a larger metal plate or strip
Reaming	To shape, smooth, or enlarge a hole with an appropriate tool.

Recycling	The reclamation and reuse of output or discard material streams useful for application in products.
Refining	The purification of a material by the removal of undesirable components.
Reforming	The decomposition of hydrocarbon gases by low-octane petroleum fractions using heat and pressure.
Remanufacture	The process of bringing large amounts of similar products together for purposes of disassembly, evaluation, renovation, and reuse.
Reserve	The total known amount of a resource that can be mined with today's technology at today's market prices.
Reserve base	The total known amount of a resource that can be mined, without regard for technology or market prices.
Reservoir	A receptacle defined by characteristic physical, chemical, or biological properties that are relatively uniformly distributed.
Resin (synthetic)	A synthetic high polymer resulting from the chemical reaction of two or more substances, usually with heat or a catalyst.
Reuse	Reemploying materials and products in the same use without the necessity for *recycling* or *remanufacture*.
Risk	The confluence of exposure and hazard; a statistical concept reflecting the probability that an undesirable outcome will result from specified conditions (such as exposure to a certain substance for a certain time at a certain concentration).
Riveting	To fasten metal plates or other objects together with single-headed metal pins, the plain end being hammered down after insertion.
Roasting	Heating in air or oxygen, especially to convert sulfide ores to oxides as a step in the recovery of metals.
Routing	To scoop, hollow, or gouge out material with a rotating tool.
Sand casting	Forming a metal product of desired shape by pouring molten meal into a mold made of sand mixed with various organic binders.
Scenario	A plausible vision of how the future might unfold.
Shearing	The removal of the edge of a piece of metal by the rapid impaction of two high-strength shear blades to the top and bottom of the metal piece.
Shot peening	Smoothing, shaping, or indenting a material by physical interaction with small spheres ("shot") of a harder material.
Sintering	The agglomeration of metal or earth-based powders at temperatures below the melting point.
Slag	The fused residue that results from the separation of metals from their ores.
Smart materials	See *Intelligent materials*
Smelting	Melting ore in order to extract the metal it contains.

Smog	Classically, a mixture of smoke plus fog. Today the term *smog* has the more general meaning of any anthropogenic haze. Photochemical smog involves the production, in stagnant, sunlit atmospheres, of oxidants such as O_3 by the photolysis of NO_2 and other substances, generally in combination with haze—causing particles.
Soldering	The joining of metal by an alloy of tin and lead made molten by heating to about 160°C.
Solute	The substance dissolved in a *Solvent*.
Solution	A mixture in which the components are uniformly distributed on an atomic or molecular scale. Although liquid, solid, and gaseous solutions exist, common nomenclature implies the liquid phase unless otherwise specified.
Solvent	A medium, usually liquid, in which other substances can be dissolved.
Stratosphere	The atmospheric shell lying just above the *troposphere* and characterized by a stable lapse rate. The temperature is approximately constant in the lower part of the stratosphere and increases from about 20 km to the top of the stratosphere at about 50 km.
Streamlined Life Cycle Assessment (SLCA)	A simplified methodology to evaluate the environmental effects of a product or activity holistically, by analyzing the most significant environmental impacts in the life cycle of a particular product, process, or activity. The streamlined life cycle assessment consists of three complementary components, restricted inventory analysis, abridged impact assessment, and improvement analysis, together with an integrative procedure known as scoping.
Stressor	A set of conditions that may lead to an undesirable environmental impact.
Strip mining	The extraction of ore by removing soil and overburden and then mining from above ground, as opposed to underground mining.
Substance flow analysis	An analysis of the flows of a specific chemically identifiable substance within and across the boundaries of a particular facility or geographical region. The word "substance" typically incorporates atoms and molecules of the entity of interest without regard for chemical form.
Supply chain management	The process of oversight of the activities of suppliers.
Sustainability	In the context of industrial ecology, sustainability is the state in which humans living on Earth are able to meet their needs over time while nurturing planetary life-support systems.
Swaging	Bending or shaping of cold metal.
ΣWESH plot	A graphical display of the environmentally-related attributes of a facility.

Symbiosis	A relationship within which at least two willing participants exchange materials, energy, or information in a mutually beneficial manner.
Tailings	The residue remaining after ore has been ground and the target metallic minerals separated and retained.
Tanning	The preservation of hides or skins by means of chemical treatment that renders them supple and immune to bacterial attack.
Thermoplastic	A high polymer that softens when exposed to heat and returns to its original condition when cooled to room temperature.
Thermoset	A high polymer that solidifies or "sets" irreversibly when heated, usually because of cross-linking reactions among the molecular constituents.
Trimming	Cutting away excess material remaining from casting or forming processes.
Troposphere	The lowest layer of the atmosphere, ranging from the ground to the base of the stratosphere at 10–15 km altitude, depending on latitude and weather conditions.
Visibility	The degree to which the atmosphere is transparent to light in the visible spectrum, or the degree to which the form, color, and texture of objects can be perceived. In the sense of visual range, visibility is the distance at which a large black object just disappears from view as a recognizable entity.
Waste	Material thought to be of no practical value. One of the goals of industrial ecology is the reuse of resources, and hence the minimization of material regarded as waste.
Waste audit	An accounting of output flows and losses of wastes within an industrial process, a facility, a corporation, or a geographical entity.
Water audit	An accounting of input flows, output flows, and losses of water within an industrial process, a facility, a corporation, or a geographical entity.
Weaving	To interlace natural or synthetic fibers into a cloth
Welding	Joining metals by applying heat, sometimes with pressure and sometimes with an intermediate or filler metal having a high melting point.

This glossary was compiled from various sources, including particularly: T. E. Graedel and P. J. Crutzen, *Atmospheric Change: An Earth System Perspective*, W. H. Freeman, New York, 446 pp., 1993; B. W. Vigon, D. A. Tolle, B. W. Cornaby, H. C. Latham, C. L. Harrison, T. L. Boguski, R. G. Hunt, and J. D. Sellers, *Life Cycle Assessment: Inventory Guidelines and Practices*, Report EPA/600/R-92/245, US Environmental Protection Agency, Washington, D.C., 1993; and G. G. Hawley, *The Condensed Chemical Directory*, Ninth Ed., New York: Van Nostrand Reinhold, 1977.

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