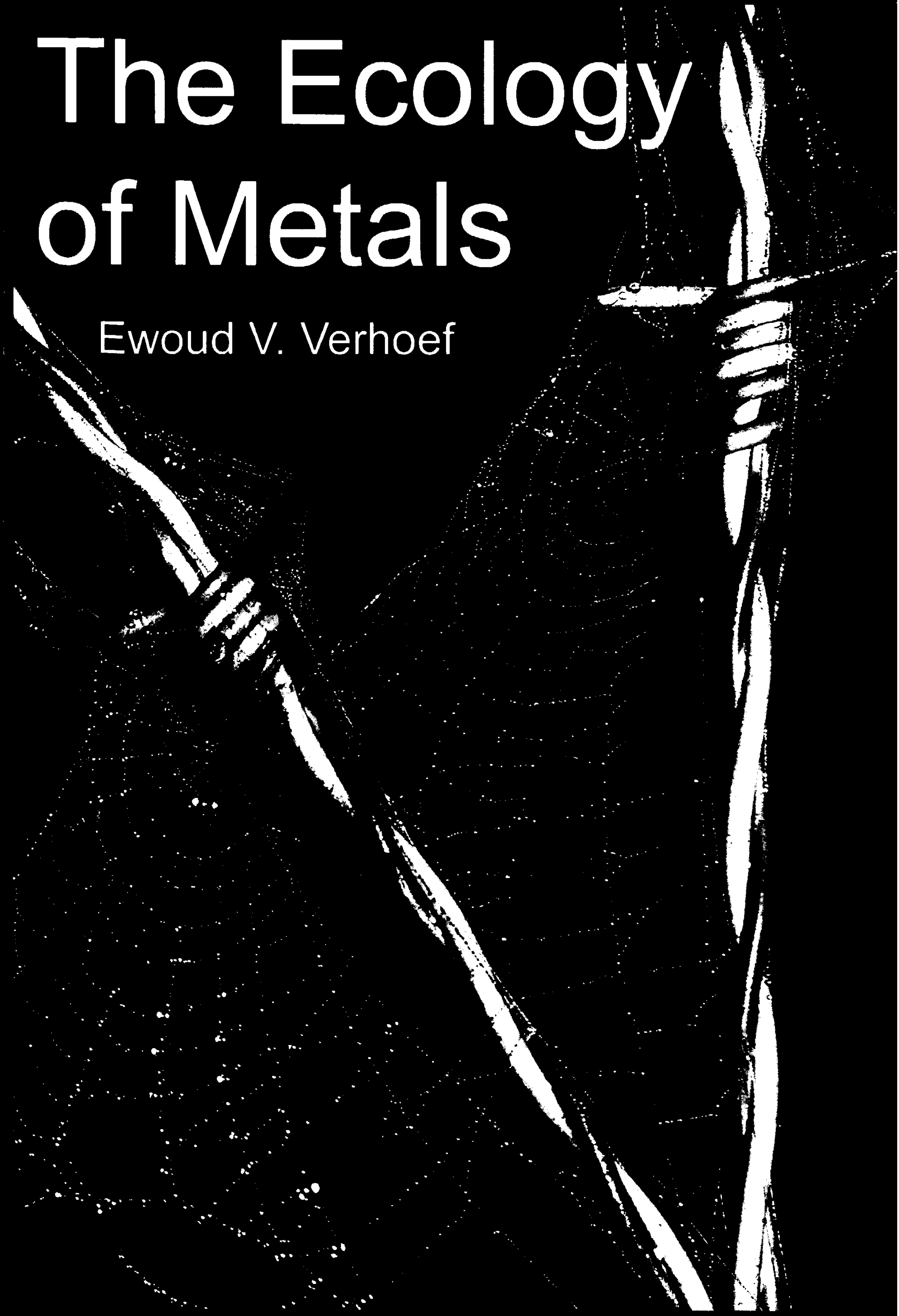
The Ecology of Metals

Ewoud V. Verhoef



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Preface

I have always been fascinated by the interaction between nature and technology. I believe the cover photo conveys much of the contents of and my interest in this study. It combines the words metal, environment and network. The barbed metal wire represents the dilemma of metals: while metals are useful – modern life can not be conceived without them – one can easily cut oneself if they are used carelessly. The spider web stands for the environment, which supports and surrounds the metallurgical process infrastructure. It also symbolizes the 'web of life' through which all things are connected in nature, economy and industry.

The ideas and concepts underlying this thesis have roots that date back many years. However, most of them matured and changed significantly in the course of the PhD project, through my numerous conversations with the colleagues, family and friends. In particular, I treasure the stimulating discussions with Markus Reuter, Gerard Dijkema, and my father; this thesis could not have been accomplished without their support and involvement. I am grateful to all not only for giving the opportunity to conduct and the support to finish this study, but also for allowing me to change the way I view the world.

Ewoud Verhoef, October 2004

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1 General Introduction

Summary

Many in the field of industrial ecology share the view that industrial progress is the central means for environmental progress and for an advance towards sustainability. So far, industrial ecology has failed to bridge the gap between its holistic concepts and the different industrial practices. This lack of a solid technological footing in the industrial ecology models, studies and literature is identified as a major bottleneck for the successful implementation of its strategies and concepts.

In this thesis the gap between metallurgy and industrial ecology is bridged. First, the metal ecology is described using a system perspective that spans metallurgical reactors, industrial plants and the global metal cycles. Second, a model is developed that connects activities at the different system levels of the metal ecology.

Neither in industrial ecology literature nor in metallurgical literature models have been developed that have been shown to connect the detailed models of engineers and the holistic models of industrial ecology. This very connection is required to facilitate the materialization of industrial ecology concepts.

In this chapter, the background, goal, scope and approach of the work presented in this thesis are addressed and an outline of the thesis is presented.

1.1 Incentives for this study

The 'web of life' is an ancient idea, which has been used by poets, philosophers, and mystics throughout the ages to convey the sense of interwovenness and interdependence of all phenomena (Capra 1997). This ancient idea underlies also many of the major problems of today: complex problems that can not be understood in isolation. There are solutions to these 'systemic' problems but these require radical change of our set of tools and a radical shift in our perceptions, thinking and values.

Ecology and systems thinking provide concepts that together provide a foundation and starting point for this shift. Ecologists, 'biological system-thinkers', view the web of life as a multidimensional network of ecological communities. By viewing an ecological community as an assemblage of organisms, bound into a functional whole by their mutual relationships, ecologists managed to shift their focus from organisms to communities, and integrate both by applying the same kinds of concepts at different kinds of system levels (Capra 1997). This perception is essential to understand the interwovenness and interdependence in the web of life. In this PhD thesis it will be shown that this view is equally critical to understand our industrial economy, and thus to develop the required tools, thinking, and values.

Viable, systemic solutions are those that are 'sustainable'. Industrial ecology is a new systemic concept emerging in the evolution of environmental management paradigms (Ehrenfeld 1995). It employs the analogy with ecology to assist the development of sustainable industrial systems (see e.g. Ayres and Ayres 1996 or Graedel and Allenby 1995, Lowe 1997, Allenby 1999, Ayres and Ayres 2002). Using industrial ecology, it will be shown that to develop and control such industrial systems, co-ordinated actions across all system levels are required. In terms of industrial ecology, we need to understand the 'metal ecology': the community of metallurgical reactors, the 'industrial organisms', their physical, technological, legislative and economic surroundings and the functional relationships between them.

The current lack of a solid technological footing in the industrial ecology models, studies and literature (the industrial organisms) will hinder implementation of its strategies and concepts. In this thesis the gap between metallurgy and industrial ecology is bridged. First, the metal ecology is described using a system perspective that spans metallurgical reactors, industrial plants and the global metal cycles. Second, a model is developed that connects activities at the different system levels of the metal ecology. Neither in industrial ecology literature nor in metallurgical literature models have been developed that have been shown to connect the detailed models of engineers and the holistic models of industrial ecology. This very connection is required to facilitate the materialization of industrial ecology concepts.

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1.2 Sustainability of metals?

The central theme of this study is the sustainability of metal production and use. A sustainable production is characterized by appropriate resource selection, effective resource utilization, the avoidance of waste and emissions. A sustainable metal use meets the needs of the present without compromising the ability of future generations to fulfill their own needs[1]. Meeting our present needs without metals is inconceivable. Metals have been part of human activity since pieces of native copper were first hammered into simple tools about 6000 BC. Today, metals are essential for the production of almost all manufactured products. No aircraft, automobile, computer, or electrical appliance can function without metals. Electrical power supply is dependent on copper and aluminum (NRC 1997). For that reason, metals should be included in any overall consideration of sustainability. In addition, metals can in theory be reused countless times, with huge savings in energy and reduction of waste compared to primary processing.

The sustainable production and use of metals may seem like a contradiction in terms to many people, as metals are not renewable resources in the biological sense, and are often associated with environmental problems. A productive, economic ore body can be composed of a few parts per million (gold) to a few percent (lead, zinc) metal, with the remainder being residue of little economic value. Consequently, production processes can have undesirable environmental consequences if not properly controlled. As a basis for the discussion on the sustainability of metals, a short introduction on metals is given (Cadre 1-1).

In this thesis, a number of non-ferrous metals are investigated using system thinking and ecology concepts in the context of sustainability. The role of this technological and systemic knowledge in the achievement of a more sustainable metal use, and the provision of that knowledge to stakeholders is the focus of this study.

As of the '60s and '70s the non-ferrous metals industry has been regarded as ‘dirty’ and ‘polluting’. In the last two decades of the Twentieth century, however, substantial and continuous technological development and significant investment have led to a dramatic improvement in environmental performance of the leading companies in the non-ferrous metals industry. In the late nineties, at least in the Netherlands the 'sanitation' of this industry had been completed. As of yet, this change of affairs has not been generally recognized nor appreciated by the general public (Dijkema and Mayer 2001a and 2001b). Therefore, improved communication between and the provision of comprehensive information to all stakeholders are necessary for the industry’s continuing environmental improvements to be recognized, used and steered towards sustainability.

The investigation into the ‘ecology’ of metals presented in this thesis provides an understanding of metallurgical processes as interconnected and interacting units. Their role in the interconnected resource cycles is elucidated. On the one hand, this understanding provides a better basis for more sustainable product designs, waste management and development of economics and policy and legislation; on the other hand, it shows the systemic constraints and opportunities for the design and operation of metallurgical processes.

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[1] Preliminary definition based on WCED (1987); the concept of sustainability is further discussed in chapter 2.

Cadre 1-1: Metals

Of the ninety-two naturally occurring elements, seventy are metals (NRC 1997). Metals in general are characterized by a number of properties including luster, malleability and the capacity to conduct heat and electricity. The metallic atoms readily lose electrons to form positive ions ('cations'). Chemically, metals are defined according to their position on the Periodic Table, and include different groupings: alkali metals, alkaline earth metals, transition metals, basic metals, and rare earth metals.

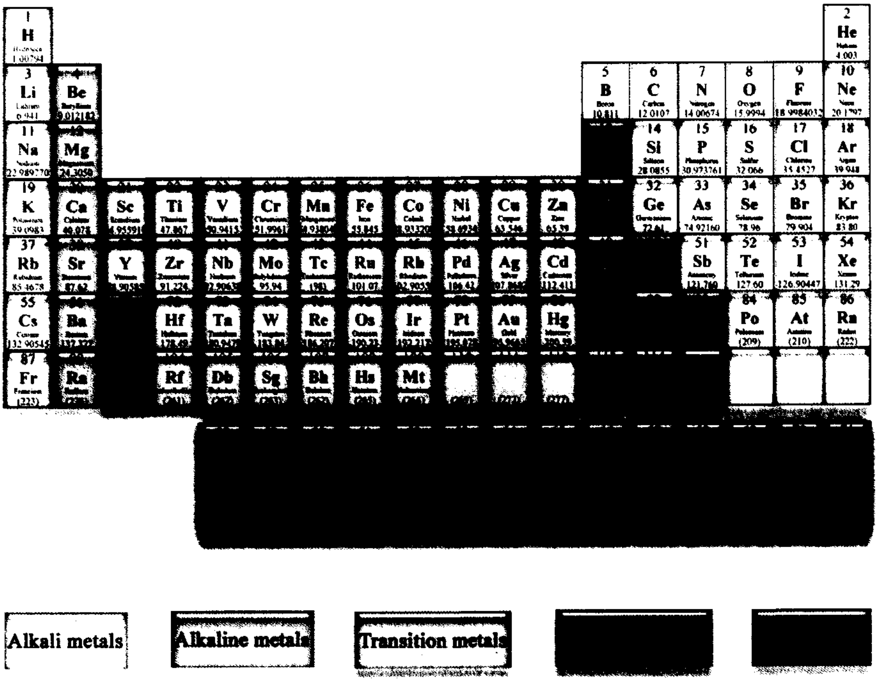

Figure 1.1: Periodic Table of Elements; the shaded parts in represent the different metal groupings.

By inspection of Figure 1.1 it may be seen that metals are located on the left side and the middle of the periodic table. Among the public, the label 'metal' is used for certain hard, fusible pure metals - these include gold, silver, copper, iron, tin, lead, zinc, nickel - and to mixed metals and metallic alloys, such as brass, bronze, steel, etc. In this thesis, the label 'metal' is used as per the use in common language.

1.3 Study approach

This PhD study has been part of the Delft Interfaculty Research Centre (DIOC) on the design and management of infrastructures. In our industrial society infrastructures determine to a great extent the design of our physical environment, our practical way of living, our economic prosperity, our safety and personal comfort.

There are infrastructures in the classic 'public' sense, such as waterways, railways and road systems, but there are also infrastructures that are not underpinned by a physical distribution network, for instance the knowledge infrastructure. The DIOC infrastructures project addresses public infrastructures that contain the basic facilities of a country, which enable it to function. These infrastructures comprise large-scale technological systems that consist of immovable physical facilities, and deliver an essential public or private service through the storage, conversion and/or transport of certain commodities (Slootweg and Verhoef 1999). Most public infrastructures include dedicated layered transportation networks that consist of transport arcs and transformation (or conversion) nodes. The essential service is provided through carriers, interfaces and/or production plants. Apart from the telecommunication infrastructure all infrastructures have storage function.

Based on the flow of the infrastructure commodity (electricity, waste water, etc.) three different types of infrastructures can be distinguished:

(i) *Single-to-many* infrastructures; an example of a one-to-many infrastructure is the electricity infrastructure. The electricity infrastructure connects many users to one or a few electricity producers. It has a dedicated layered transport network including many transformation nodes (from higher to lower voltage/ amperage) and dedicated interfaces (e.g. power points).

(ii) *Many-to-many* infrastructures; an example of a many-to-many infrastructure is the transport infrastructure. It connects many users to many destinations. Unlike other public infrastructures it has no dedicated interfaces or production plants, but consists of a transport network only. The network contains many transformation nodes: e.g. local roads (1 lane; 50-60 km/h) to provincial roads (1-2 lanes; 80 km/h) to highways (≥2 lanes; 100-120 km/h) or road to water/air/rail. The telecom infrastructure is another example of a many-to-many infrastructure.

(iii) *Many-to-one* or *reversed* infrastructures; an example of a many-to-one infrastructure is the waste water infrastructure which connect many waste water producers to one or a few waste water plants. The infrastructure involves a dedicated layered transport network, dedicated treatment plants (transformation of wastewater into clean water and waste). It contains dedicated interfaces (e.g. toilets), but no carrier, although some may argue that the water itself is the carrier.

The DIOC project focuses on a comparative study of technological, economic and administrative developments in these infrastructures and their public management to establish generic requirements for the design, operation and management of infrastructural facilities and the decision-making processes involved. As a part of the DIOC program, the work presented in this thesis involves the technical and systemic development of the waste infrastructure. It aims to support the decision-making on improved design, operation and management of this infrastructure.

1.3.1 Societal and scientific relevance

Current waste management in Europe results in an enormous loss of resources in the form of both materials and energy (EEA 1999). To minimize these resource losses and simultaneously realize the environmentally sound abatement of waste requires rethinking of the function of waste infrastructure.

The waste infrastructure, like other public infrastructures, is subject to many contradictory forces. These forces and the related infrastructure performance change over time. Generally, infrastructures are large-scale systems that suffer from inertia caused by high sunk cost (related to the high investments in the infrastructure), the associated legal framework and the administrative organizations involved (see Cadre 1.2). In the design of new infrastructures traditionally long technical life spans were assumed and logically also long time horizons for decision-making.

The change from public control to private ownership combined with the emergence of new or advanced technologies, has shortened the time horizon of decision-making on many infrastructures: The market for public services, such as waste management, increasingly becomes more international. Combined with the development towards liberalization and privatization of the utility sectors in the EU, it stipulates a short-term market-oriented approach. Obviously, this has many consequences for the infrastructure design, regulatory framework, the administrative organizations and capacity management (Koolstra et al. 2001, De Vries 2004).

Moreover, an improved design, operation and management of waste infrastructures can not minimize resource losses. The objectives for waste management are part of a larger objective, viz. prudent resource management and sustainability. Consequently, adequate design and management of waste infrastructures will require a change in the thinking, concepts and tools.

Present waste infrastructures are based on a many-to-one infrastructure design (see section 1.3 above): To control environmental impact the waste generated by many users is processed in a limited number of disposal options (see Cadre 1.2). The objectives of the sustainable waste management are twofold: On the one hand, waste management must concentrate and separate wastes to make subsequent recycling into new resources possible and economically feasible; on the other hand, it is an integral part of environmental protection. To reach both objectives, waste infrastructures must be designed, operated and managed as many-to many infrastructures.

Cadre 1-2: Development of waste infrastructures

Public infrastructures are large-scale technological systems that consist of immovable physical facilities that deliver an essential public or private service through the storage, conversion and/or transport of certain commodities. The (sunk) costs of these infrastructures were so high, and the consequent economic life spans of the infrastructures so long, that neo-classic economists considered them typical examples of natural monopolies. According to them, submitting a natural monopoly to the market forces, would lead to negative effects on the prices or on the equal availability of the infrastructure services (Stout 1998). This has led to government intervention into the public utilities in Europe.

The essential service the waste infrastructure delivers, concerns the removal, disposal and recovery of municipal solid wastes (MSW) with minimum harm to public health and the environment. Sound waste management is an integral part of environmental protection (Thomas et al. 1990). Improper disposal of municipal waste can result in unsanitary conditions, which in turn can lead to pollution of the environment and to diseases. This significance of waste management for public health and the environment has lead to the development of public waste infrastructures.

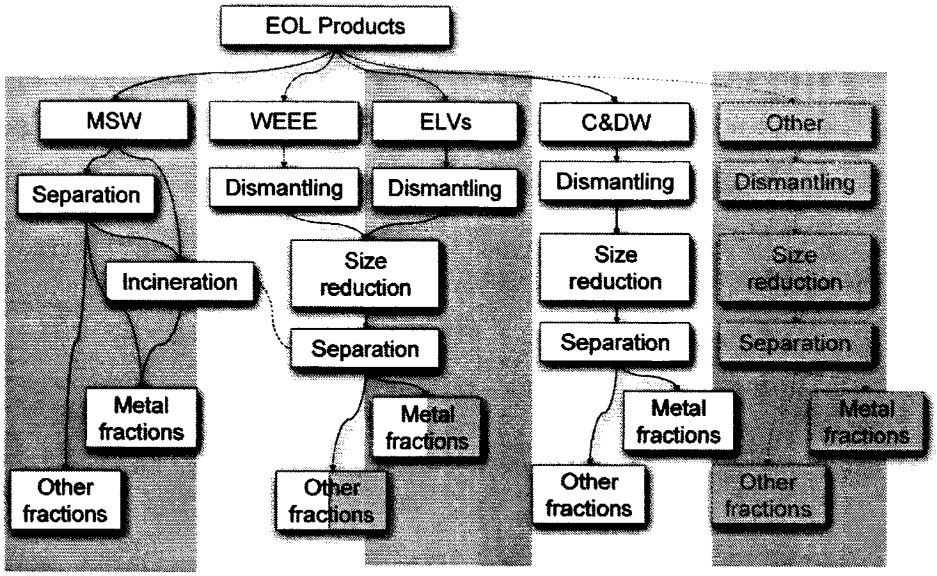

Figure 1.2: Schematic diagram of the waste infrastructure. Legends: MSW= integrally collected Municipal Solid Waste, WEEE= Wasted electronic and electric equipment, ELVs=End of Life Vehicles, C&DW= Construction and Demolition Waste.

Robust, durable infrastructures have been constructed to safely dispose of the waste generated, and minimize impacts on environment and public health. These infrastructures include waste collection systems, a network of transshipment and separation points, and a limited number of disposal options such as landfilling, incineration and composting. Generally, waste is collected in a multi-stream collection system (Figure 1.2). Each waste stream is transported via various transshipment and/or pre-treatment nodes that have a buffer function also. To a limited extent sorting of waste occurs after collection. The waste infrastructure converts remaining waste into electric power and heat, fertilizer, and ashes usable in e.g. road construction and cement production.

One of the typical waste infrastructure characteristics is that it deals with a great many different entities, whereas other infrastructures must only deal with a single principal entity (electricity, natural gas, water, or bytes). 'Waste' is really an aggregate term for a large variety of materials. The only common denominator of these materials is the fact that they are discarded after their useful product lives. In order to avoid resource losses, these materials must be recycled (i.e. processed into resources for new products).

For many materials, the actual recycling process is carried outside the waste infrastructure, viz. in the industrial production processes. In these processes, the wastes often (partially) substitutes virgin or primary materials. It can thus easily be seen that the minimization of resource losses in waste management is directly related to prudent management of resources, one of the cornerstones of sustainability. However, the focus on safe treatment of a large variety of discarded materials, and minimization of impacts on environment and public health, has lead to a development of more or less autonomous waste management policies and to infrastructures that are 'sinks' rather than 'sources' of raw materials for (the recycling) industry. Consequently, large amounts of final residues must be landfilled. In addition, the resources recovered are of relative low quality, apart from those obtained from separate collection systems, some scrap metals and electricity.

1.3.2 Support of decision-making

For prudent management of resources, restructuring of current waste management practice and infrastructures is required. From a systemic point of view, the necessity of an integrated resource (production-recycling-disposal) system is obvious. In this view waste is considered as an *only* 'emerging attribute' of a resource. This idea is not an entirely new one, as in many industries some processing of waste is already economically and ecologically feasible, and the substance or object previously labeled 'waste' changes into a 'resource' (Dijkema et al. 2000). This perspective also forms the foundation of a movement towards a cyclic economy that resembles the way nature's ecosystems are built up: a network of integrated processes that form cycles. For example, 'industrial ecology' uses this analogy to capture and build upon it a strategy for sustainable development (see e.g. Graedel and Allenby 1995, Ayres and Ayres 1996, Lowe 1997, Allenby 1999, Ayres and Ayres 2002).

In the concept of *interconnected* resource cycles industry and waste infrastructure technology provide the system content and system structure for the generation of products and the assimilation of waste (Reuter 1998, Reuter and Dijkema 1999, Dijkema et al. 2000). These systems span the 'life' of a resource from cradle to grave: resource extraction (mining, drilling, etc.), processing in to suitable raw materials, application in products (manufacture), consumption and finally disposal or recycling (Figure 1.3). Rather than a single-dimensional system, these resource cycles comprise networked industrial and infrastructure systems (Verhoef et al. 2004a, Dijkema 2004).

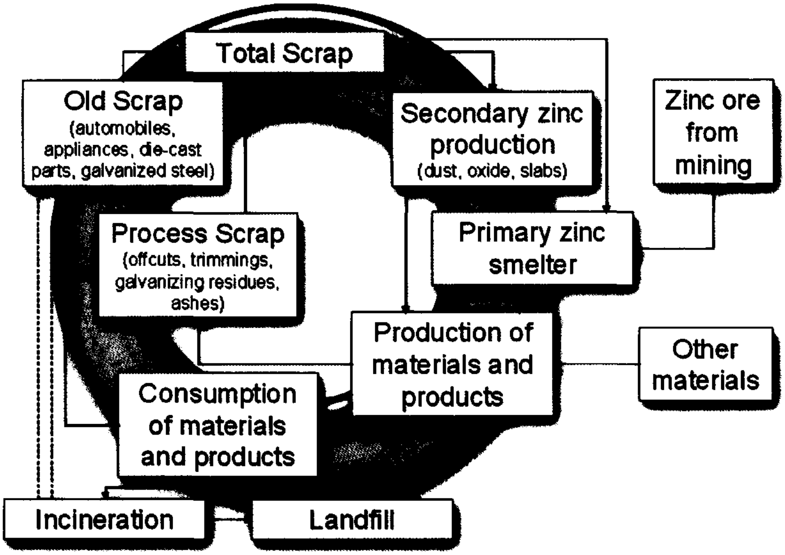

Figure 1.3: Schematic overview of the zinc resource cycle.

From an interconnected resource cycles perspective, waste management is an important node that affects the availability and fate of all chemical elements. In product manufacture, many different materials are combined into products. This leads to a coupling of the resource cycles of these materials (Figure 1.3). The subsequent discarding of these products generates waste that contains many of the chemical elements. Waste management must process and separate these materials so that these meet the capacity and specifications of industrial processes downstream. In other words, where product manufacture couples the resources of materials, waste management must partially decouple these again. The many different wastes must be fed back into many different resource cycles so that the materials contained in the waste can be effectively be recycled and recombined into new products. For prudent management of resources, waste infrastructures must connect to the different resources cycles rather than provide environmentally safe 'sinks' for used materials. *This requires a shift in current waste infrastructures design, management and operation from a many-to-one to a many-to-many type.*

The recycling of steel provides a suitable illustration. The manufacture of a car involves the combination of a great many materials, including steel, aluminum, copper, zinc, glass and plastics. Dependent on the specifications and capacity of the industrial recycling processes downstream, these must be separated in waste management processes. Steel, aluminum, and copper must be separated before recycling in metallurgical processes. If they are not separated, this can result in large process residues, and/or off-specification secondary metals and alloys (down-cycling), which inhibits the recycling of these metals. Zinc is used in the automobile industry for steel corrosion-protection (zinc galvanizing). Removal of zinc is essential for the resource cycle of zinc, as about half of the total global world production of zinc is used for galvanizing (Figure 1.4). However, zinc need not to be separated in waste processes. The presence of a zinc coating on steel does not restrict its recyclability, and zinc and steel are usually separated in steelmaking processes themselves. Only when recycling the steel-zinc concentrates in the oxysteel-furnaces, the zinc must be removed beforehand; otherwise it would destroy the furnace. Zinc and steel can be separated before feeding the scrap to the oxysteel-furnace, for example by electrochemical dezincing systems. However, at the moment most of the galvanized steel is recycled in the electric arc furnace (EAF) process. The zinc volatilizes in the process and is collected in the flue dust for reprocessing. Globally, approximately 30% of EAF dusts finds its way to zinc producers and the zinc resource cycle.

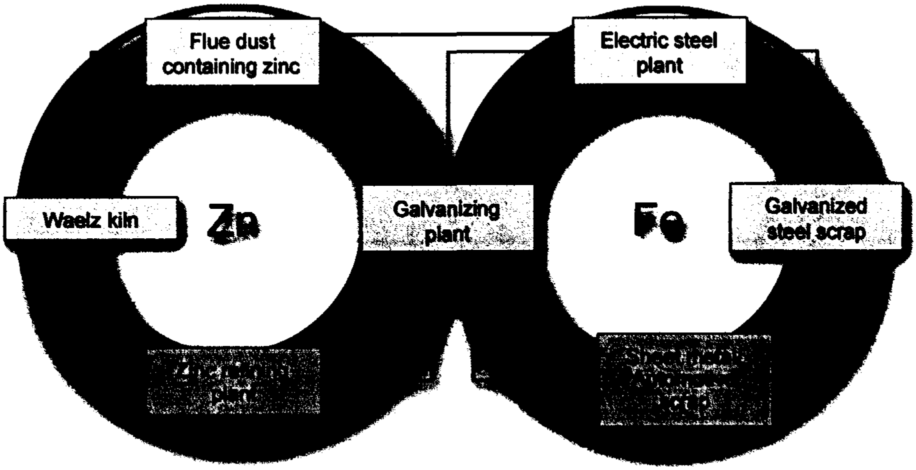

Figure 1.4: Schematic overview the connection between the zinc (Zn) and iron (Fe) resource cycles by the galvanizing of steel.

As a consequence, the waste infrastructure design problem includes the selection between a great many pretreatment and separation technology alternatives for each part of a waste management system. The feasibility of the alternatives is dependent on the capacity and specifications of industrial processes. Since decision-making on the use of these alternatives can not be done without considering the resource cycles, this concept offers a convenient method of abstraction to model the broad spectrum of technologies involved. It enables a shift in focus from single linear technologies to interconnected cyclic systems that must realize a prudent management of resources. The concept of interconnected resource cycles thus appears a good basis for the new approaches and tools required.

A requirement of these new approaches and tools is that they must connect different 'organizational' levels (chemical process design and control, micro-economics, local, regional and (inter)national policy and legislation). The design and management of sustainable waste infrastructures must be a combined effort of decision-makers at various organizational levels both in public bodies and industries, particularly in view of the current developments in the waste sector, such as internationalization, liberalization and privatization. Since process engineers act at a different organizational level than regulators or policy-makers, the approaches and tools must be able to link opportunities and constraints of waste recycling at the level of chemical reactors in the industrial processes to the organizational level of the regulators or policy-makers. Where regulation at governmental level is a control instrument to achieve a certain set of objectives, it is a boundary condition for an industrial decision-maker. The EU directive on the incineration of waste (EU 2000c), for example, excludes a number of environmentally sound industrial options for co-incineration. Consequences of regulations must be made transparent by demonstrating how these affect the technological system, and vice versa.

As decision-making on the use of these alternatives can not be done without considering the interconnected resource cycles, this concept also offers a convenient method of abstraction to model the broad spectrum of technologies involved. It enables a shift in focus from single linear technologies to interconnected cyclic systems that must realize a prudent management of resources. The concept of resource cycles thus appears a good basis for the new approaches and tools required. Using the interconnected resource cycles as leading concept, tools can be developed that facilitate communication between regulators, decision-makers and system designers and use an understandable logic originating from a solid technological base.

In this thesis, therefore, the flows of metal through society are described from reactor to the global, interconnected metal resource cycles. The consequences of prudent resource management for process design and operation of metallurgical reactors are discussed. The role of the identified metallurgical constraints and opportunities for recycling is analyzed with respects to product design, waste infrastructure design and operation, and policies and regulation, which create the economic incentives and boundary conditions that shape the flow patterns of metals through society. Finally, based on this analysis, a model of the interconnected metal resource cycle is presented to support co-ordinated decision-making across the different system levels.

1.3.3 Character of this study

Because of its broad scope, the character of this study is different from that of 'conventional' PhD studies. Usually, PhD studies focus on a relatively small area of research and well-defined problems and often can depart from a considerable body of existing knowledge. These types of PhD studies follow the heritage of Descartes' method of analytic thinking by further analyzing a well defined system part. Bertalanffy was among the first to argue problems can not always be understood by analysis alone. Some of the properties of the parts of the investigated systems are not intrinsic properties, but can be understood only within the context of the larger whole (see e.g. Boulding 1956, Bertalanffy 1940, 1950, 1968, and Capra 1997). This contextual, or system thinking is the opposite of analytical thinking. Where analysis means taking something apart to understand it, systems thinking means putting it into the context of the whole. The basis of system thinking is that in any system individual parts can be discerned, that these parts are not isolated, and that the nature of the whole system is always different than the sum of its parts (Capra 1997). Similarly, in systemic studies the added value or depth lies in the connection between the parts (see also Tempelman 1999).

The inclusion of sustainability and industrial ecology in this thesis necessitates a system thinking approach. The study started with a broad and ill-defined problem of an optimum 'arrangement of the network of waste processing facilities for metal containing wastes' with respect to sustainability. The determination of an optimum arrangement can not be based on the intrinsic properties of the infrastructure alone and must thus be considered in the context of the global, interconnected resource cycles. The underlying body of knowledge on sustainability and industrial systems thinking (i.e. industrial ecology) is relatively new and still 'maturing'. Thus, in contrast to PhD studies with a conventional agenda, the work presented in this thesis encompasses a relatively large area of research while it has started from a relative small body of knowledge. Its breadth augmented with the connection between the parts provides technology depth and systemic added value.

1.4 Hypothesis and research questions

The problems associated with metal production and use are not intrinsic properties of metals or metal processes, but can be understood only within the context of the larger whole, the metal ecology. The hypothesis of this study is:

> *The concept of interconnected resource cycles enables analyzing and modeling the metal ecology and communicating its description and prescription for sustainability from a solid technological footing and a systemic perspective.*

Similar to natural systems, the metal ecology is a dynamic system: its components and the relationships between them continuously evolve. The development of viable solutions to these problems must thus start with an understanding of the *dynamic behavior* of the organisms, the industrial processes. In the end industrial processes have to realize many of the industrial ecology strategies towards sustainability. Advancing towards sustainability thus must involve the design and management of these processes and development of their functional interactions. Because the process of design and management spans various organizational levels, it requires co-ordination of stakeholders across all these levels to approach a more sustainable metal production, use and recycling systems. Therefore, in this study it is investigated to what extent improved communication and the provision of comprehensive information to all stakeholders can lead to co-ordinated decision-making. This is then a basis for the development of a resource cycle model to support decision-making on resource management. The central research question of the Ph.D. study is thus:

> *How can the metal ecology be analyzed, modeled and communicated to stakeholders to facilitate dissemination and correct use of sound technological information and systemic know-how?*

Obviously, the ultimate goal of this study is to test this hypothesis based on a case study on the interconnected metal cycles. To this end, different sub-questions were formulated. In order to answer the central research question, one needs to understand and define the concept of sustainability. Second one needs to understand the role of technology in the achievement of sustainability. Tempelman (1999) showed that the role of technology in achieving sustainability is very ambivalent. Depending on how technology is used, it can either be part of the problem or solution. It is therefore essential to take a critical attitude towards technology. Industrial ecology puts technological development into the context of sustainability. As such industrial ecology appears a good analytic framework to investigate the role of technology and technological knowledge. This leads to the following sub-questions:

What are 'sustainability' and 'industrial ecology'?

To what extent has technological knowledge (know-how and know-to) been recognized as essential ingredient for sustainability or industrial ecology?

What is the potential role of technology and technological knowledge in advancing to sustainable metal production and recycling systems?

Finally, it is investigated whether industrial ecology models can provide the necessary knowledge to support decision-making of metal resource management, based on the current status-quo of the models and available data on system.

Can industrial ecology models provide the technological knowledge?

This is then a basis for the development of a resource cycle model to support decision-making on resource management. Although advances towards sustainability must include all material cycles, not all material cycles, or even all metal cycles can be considered in this PhD study. Therefore, this study was limited to the interconnected metal cycles of a number of non-ferrous and precious metals, viz. copper, lead, zinc, tin, bismuth, silver, nickel, gold, platinum, palladium and rhodium.

1.5 Contents of this study

As the hypothesis indicates, this thesis is intended for broad audience including metallurgists, industrial ecologists, policy-makers and legislators. Figure 1.5 shows a schematic overview of the contents of this thesis, which is divided in two parts. The separation of the thesis into two parts is a conscious choice. The first part contains the main thread of my argument. To ensure readability for a broad audience, I tried to keep the language as non-technical as possible and used figures to illustrate technical aspects as much as possible. For readers interested in the technical details I have included a comprehensive inventory of the interconnected metal production system and detailed information on the model architecture in the second part.

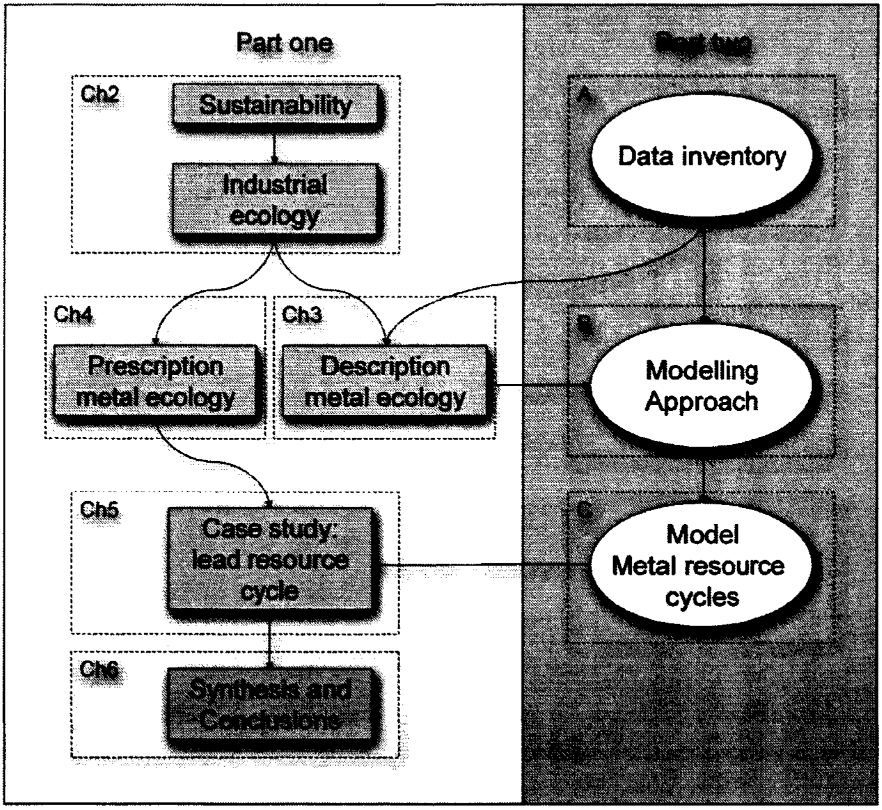

Figure 1.5: Schematic overview of the contents of this PhD study.

1.5.1 Part one

In part one, the sustainability of industrial ecology, the resource cycles of metals and the role of technological knowledge are discussed in six chapters. In this *first chapter*, study background, relevance, the hypothesis, research questions and goals are introduced.

In *chapter two*, the concept of sustainable development is explored. Industrial ecology is presented as a systems approach to sustainability. The concept and toolbox of industrial ecology are analyzed to examine its value for sustainability. In the toolbox, two types of approaches to support decision-making on industrial systems can be distinguished: descriptive approaches aimed at better understanding and quantification of the industrial systems, and prescriptive approaches that build on the descriptive approaches to evaluate industrial configurations and alternatives on their potential for sustainability.

Chapter three examines the value of descriptive industrial ecology approaches to contribute to improved understanding and quantification of the metal production and recycling systems. The resulting quantitative inventory and model approach will be used as a basis for the model of the metal resource cycles used in chapter five. In *chapter four*, the metal cycles are investigated from a prescriptive perspective, which addresses the analysis and control of materials and energy patterns through optimizing the ensemble of considerations that are involved. Bottlenecks are identified and the role of technological knowledge and models in the removal of these bottlenecks is examined.

In *chapter five*, an industrial ecology model of the interdependent industrial metal resource cycles is evaluated as a tool to assist decision-making on complex systems. The lead resource cycle is used as a case study. In the case-study, two complementary prescriptive strategies to reduce the environmental and human health impacts associated with the lead resource cycle are examined to illustrate what knowledge is necessary and whether industrial ecology approaches can provide this. Finally in *chapter six*, the role of technology and technological knowledge is investigated by answering the different research questions through a synthesis of the different chapters. *Chapter 7* (not included in Figure 1.5) contains the references.

1.5.2 Part two

The development of tools that assist in the dissemination of the knowledge to the stakeholders is discussed in part one. Tools that facilitate communication between regulators, decision-makers and system designers through dissemination of technological knowledge, must be based upon an understandable logic originating from a solid technological base and must based upon interconnected material cycles as leading concept. Because neither in industrial ecology literature, nor in metallurgy literature, models have been reported that can connect the detailed models of engineers and holistic models of industrial ecology, it requires a new level of industrial ecology modeling. The details of such a model are given in part two.

In *appendix A*, a detailed inventory of industrial data is presented, that is obtained through data reconciliation. Data reconciliation is a method from the engineering toolbox to adjust the experimental data to reduce and possibly eliminate discrepancies in the mass balance by using the standard deviation as a measure for the reliability of the data. In the reconciliation of the mass balances of process steps, the data is not based on measurements as common in process engineering, but on processing data of plants around the world found in the literature.

In *appendix B*, the model construction is further explained. It is described how a model of interconnected material cycles can be founded on a solid technological base by building the model on a network of process steps that define the functional relationships between the different processes. It is described how the networks of reactors can be aggregated into the global resource cycles using simple assumptions about the dynamic relationships between processes, and between the various stages in the resource cycle. It is shown, for example, how the effect of changing compositions and lifespans of products on waste generation can be modeled using distributed properties. In this way, the model can visualize the dynamics at process level and its effect on the total resource cycles in an understandable way at different organizational levels, and vice versa. Economical, legislative or environmental factors can be included in the model as constraints, and evaluated at process level.

Appendix C is not included in this thesis, but can be ordered on a separate compact disc[2]. The disc contains the model of interconnected metal resource cycles used in chapter 5. The dynamic model of the resource cycles of a number of metals, which provides the description of the different processes involved, explains their interaction and calculates their environmental impact. The model allows simulations of different dynamic scenarios, in which among others process configuration, produced product spectrum or waste recycling can be changed as a function of time.

1.6 Contributions of this study

1.6.1 Books/Journals

- Verhoef, E.V. 2001. Verbranding van huishoudelijk afval in Nederland [Incineration of municipal waste in the Netherlands]. In: Capaciteitsmanagement. [Capacity management] Editors: K. Koolstra, E. Ten Heuvelhof, en H. Stout. Utrecht: Lemma.
- Dijkema, G.P.J., Reuter M.A. and Verhoef E.V. 2000. A new paradigm for waste management. Waste Management 20: 633-638.
- Verhoef, E.V., G.P.J. Dijkema and M.A. Reuter. 2004. Process knowledge, system dynamics and metal ecology. Journal of Industrial Ecology 8(1-2): 23 - 43.
- Verhoef, E.V., Houwelingen, J.A. van, Dijkema, G.P.J. and Reuter, M.A. 2004. Industrial Ecology and Waste Infrastructure Development - A roadmap for the Dutch waste management system. Special Issue Technological Forecasting and Social Change, in press.
- Reuter, M.A., Verhoef, E.V. and Dijkema, G.P.J. 2004. A dynamic model for the assessment of the replacement of lead in solders. Accepted for publication in the Journal of Electronic Materials.

1.6.2 Reports

- Verhoef, E.V., Huisman, H., Dijkema, G.P.J. and Reuter, M.A. 2000. Exploring co-incineration. AOO 2000-01. Utrecht (Netherlands): Afval Overleg Orgaan [Dutch Waste Management Council].

1.6.3 Conference proceedings

- Dijkema, G.P.J., Reuter, M.A. and Verhoef, E.V. 1999. 30 – A Waste(d) World? Proceedings PRES'99, 2nd Conference on Process Integration, Modeling and Optimization for Energy Saving and Pollution Reduction, May 31- June 2, 1999, Budapest, Hungary. Editors: F. Friedler, J. Klemes: 239-244.
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awareness-tool. Proceedings of European Symposium on Computer Aided Process Engineering, Florence (Italy): 727-732.

- Verhoef, E.V., Dijkema, G.P.J. and Reuter, M.A. 2000. Waste co-incineration in the European Community - is the sky the limit? Proceedings of the 5th World Congress on Integrated Resources Management, Toronto (Canada). PEAK Ltd., Switzerland: 1201-1206.
- Dijkema, G. P. J., E. V. Verhoef, M. A. Reuter, and J. Ehrenfeld. 2001. Infrastructure ecology. In Book of Abstracts of Inaugural Meeting of International Society of Industrial Ecology. <www.yale.edu/is4ie>.
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- Verhoef, E.V., G.P.J. Dijkema and M.A. Reuter 2001. Decision support for dynamic waste management, modelling the waste infrastructure. Proceedings 6th World Congress on Chemical Engineering, Melbourne (Australia): 1-10.
- Verhoef, E.V., Reuter, M.A. and Dijkema, G.P.J. 2003. A dynamic model of metal production and waste management. Proceedings of the XXII International Mineral Processing Congress, SAIMM, Cape Town(South-Africa) edited by Lorenzen, L., Bradshaw, D.J., Aldrich, C., Eksteen, J.J., Wright, M. and Thom, E.: 1778-1788.
- Verhoef, E.V., Reuter, M.A. and Scholte, A. 2003. A dynamic model for assessing the impact of lead free solder. Proceedings of the TMS Annual Meeting Yazawa International Symposium on Metallurgical and Materials Processing: Principles and Technologies, San Diego Ca (USA) 2: 605-621.

2 Sustainability and industrial ecology

Summary

In the last decades, sustainable development has become the cornerstone of environmental policy, and a leading principle for resource management. In this chapter, the concept of sustainable development is explored (2.1. and 2.2). Industrial ecology is presented as a systems approach to approach sustainability. The concept (2.3) and toolbox of industrial ecology are analyzed (2.4) to examine its value for sustainability (2.5).

The strength of industrial ecology is that it provides a context for analyzing the industrial economy at different levels of aggregation, from individual reactors and processes to the global material cycles. Its pitfall is that the different industrial ecology efforts must contribute to the overall environmental performance of the economy as a whole to enable a deliberate and rational progress towards sustainability. This is currently still not the case. The modeling of the physical economy and its interactions to the environment across the different levels is a first, but critical step in this direction.

2.1 Sustainability or sustainable development?

Contrary to the belief of attributing ecological disaster exclusively to the industrial society, Mebratu (1998) showed that ecological factors were key elements in the rise and fall of ancient civilizations and in major social transformations. The concern about sustainability has historical roots that can be traced back to at least the bible and the earliest writings of human societies, even though the word itself has come into fashion only in the past decades. Ehrenfeld (2000) links sustainability to our instinctual survival patterns. He sees sustainability as or, better, unsustainability as a "*social construct of collective fears and anxieties whose roots are the biological patterns that every one of us possesses*". One of the first precursors to the concept of sustainable development dates back to the 1700s, when economist Thomas Robert Malthus observed limits to (population) growth caused by resource scarcity (Mebratu 1998, Ehrenfeld 2000, Pezzey and Toman 2002). Together with David Ricardo he tried to fit his 'environmental limits thinking' into the (classic) economic tradition. In the 1800s, Stanley Jevons also observed limits to growth: the 'probable' exhaustion of coal mines due to ever-increasing energy consumption (Pezzey and Toman 2002).

In the past three decades, the concern of 'running out' was complemented with the concern that the ever-increasing quantities of waste produced are overstressing the capacity of ecosystems. Meadows et al. (1972) in their book *Limits to growth* questioned the 'sustainability' of the whole of industrial civilization given the finiteness of the planet's capacity to provide material inputs to modern economies and to assimilate their waste outputs and emissions. These two concerns are at the basis of the concept of sustainability, which has become a key objective in most international and national policies and many corporate strategies. More recently, the discussion on sustainability and limits to growth also included social and political issues, because of the widespread believe that environmental problems can not effectively be solved if the political and social problems are ignored (and vice versa).

The inclusion of political and social issues in the definition of sustainability significantly adds to the difficulty of using the concept, let alone of defining it precisely. Sustainability involves determining many balances: between societal needs and economic development on the one hand, and the environmental capacity and value on the other, between the needs of different countries, or between short-term and long-term interests. The United Nations concept of 'sustainable development' is a widely accepted interpretation of sustainability that addresses the complex of environmental, technical, economical, political and social problems. It is based on what Brown in 1981 defined a sustainable society: "*one that satisfies its needs without diminishing the prospects of future generations*". The United Nations Commission on Environment and Development through the Brundtland Report popularized the concept of sustainability in 1987. The report, entitled *Our Common Future*, provided the definition of sustainability, viz. Sustainable development: development that *meets the needs of the present without compromising the ability of future generations to meet theirs* (WCED, 1987: 43). Five years later, this concept was formalized at the United Nations Conference on Environment and Development (UNCED Rio Declaration, Brazil 1992). The concept of sustainable development is anthropocentric, which means focused on the human species and considering all other life as it contributes to this end (Allenby 1999).

The concept of sustainable development contains within it two key concepts: '*(1) the concepts of needs, in particular the essential needs of the world's poor, to which overriding priority should be given; and (2) the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs*'(WCED, 1987: 43). Simply put, the first concept means global solidarity in meeting the present and future needs. The developed nations should reduce their disproportionate share in the use of the earth's capabilities, to enable the other, developing nations to meet their own needs while maintaining the quality of their environment. The rationale for this 'intragenerational' equity is that if developing nations would develop to the same resource intensity as the current developed countries, meeting the needs of future generation would pose far greater limitations on the state of technology and social organization, if possible at all. However, the realization of a fairer distribution of resources and wealth is complicated. The wealthy, developed countries that use resources will be difficult to convince giving up part of their wealth.

Although it is widely accepted, sustainable development is just an interpretation of sustainability. Allenby (1999) for example argues that equity has yet to be achieved through human history, which suggests that it may be unlikely in the near future. He views sustainable development as just one of the combinations of technology, social organization, and environment that potentially yield a sustainable global society, and it may well not be the most likely. The broad acceptance of sustainable development has unfortunately retarded the debate about other possible sustainable futures and the need for choice among the 'universe' of other sustainable futures. Nevertheless, it can be an important guide to significant conceptual progress.

Other authors question the feasibility of sustainable development as a guide to significant conceptual progress. They perceive the concept as vague and elusive. Instead of guiding conceptual progress, the concept runs the risk of being devaluated to a cliché. Daly (1996) and Mebratu (1998) observe that the vagueness of the concept of sustainable development allowed for its broad acceptance and consensus on its desirability. However, it also led to a large 'political battle' for influence over our future by linking interpretations to the concept. In trying to win the battle, the emphasis of conceptual development of the concept has shifted from logical coherence to that of semantics. For developing our understanding of the concept and using it as an important guide to achieving a sustainable world, strengthening the logical coherency of the concept (by overcoming the influence of the different battling groups) is essential.

Despite of the range of positions in the debate on sustainability, it is clear that one should be careful to equate sustainable development with sustainability. In this study, sustainability is defined according to Ehrenfeld (2000). He tries to define sustainability without limiting himself to a subset of the 'universe' of other sustainable futures. "*Sustainability is a possibility that humans and other life will flourish on the earth forever.*" This definition is a powerful way of thinking about sustainability, and overcoming differences in interpretation. It is clearly insufficient as a guide to significant conceptual progress, however. Ehrenfeld therefore suggest a more practical working definition of sustainability. "*Sustainability is a possible way of living or being in which individuals, firms, governments, and other institutions act responsibly in taking care of the future as it belonged to them today, equitably sharing the ecological resources on which the survival of humans and other species depends, and assuring that* *all who live today and in the future are able to flourish - that is, satisfy their needs and aspirations.*"

2.2 Achieving Sustainability

Although the basic ideas of sustainability are old and simple, sustainability proved a remarkably difficult concept to use and define precisely. Despite evident value of sustainability, it is often impossible to deduce concrete decisions for specific cases from the concept of sustainability. However, this does not mean that the concept is of no value, but it rather indicates the complexity of the concept. There are two fundamental reasons for the difficulty using sustainability: nobody knows what a sustainable society would be like, and or how to achieve it. Thus to achieve sustainability, one first must examine where to go to, and secondly how to get there.

2.2.1 Going where?

What would a sustainable global economy look like? The finite resilience of ecosystems, for example, is a key concern in all definitions of sustainability. All life depends on the environment, and the functions and viability of natural systems. Therefore, the industrial civilizations and the environment are interrelated and must become compatible to survive. Compatible implies a use of resources, and a generation of wastes and emissions at a level that is not likely to cause serious *damage* to the environment. Using and precisely defining, however, is complex: what extent of damage is acceptable?

Scientific knowledge and understanding alone are often insufficient for determining unambiguously a maximum compatible use of resources, or a total pollution limit. First, the effects of human interventions on the environment are still not well understood, and the effects of interventions may only become visible with significant delays, and may be irreversible. Furthermore, nature possesses self-regulating mechanisms, which are composed of a complex web of positive and negative feedback systems. Consequently, nature itself can also develop as a reaction to changing conditions. In polluted areas, different types of ecosystems may develop than in not polluted areas, with different characteristics, assimilation capacities or pollution thresholds. Due to these dynamics, and the complexity of natural processes, the assimilation capacity and resilience of environmental processes are very difficult to determine, and therefore to set a maximum permissible use of resources or a total pollution limit.

Moreover, is there a difference between one damage or another? Is ozone layer destruction worse than the greenhouse effect or local pollution of the groundwater? Also, must we consider 'damage' as a reduction of the opportunities or available resources for human activities, or has nature itself an intrinsic value as well, which should be protected? Conservation of the intrinsic value of nature will often be compatible with safeguarding the environment for human interests, but not necessarily always. The interpretation (operationalisation) of damage from a human perspective is prominent in most perspectives of sustainability. The damage to the environment is thus acceptable if future generations can still meet their needs and flourish. This poses limitations not only on the state of technology, but also on the social organization and on the environment.

Perhaps more important are the different mental models concerning the resilience of natural systems (to human interventions), and consequently what action should be taken in what time frame to ensure the flourishing of (present and) future generations. Allenby (1999) distinguishes four mental models and types of action. On the two extremes are the ones that believe that nature is virtually immune to human perturbation (action: continuation of status quo) and the ones that believe that nature is extremely fragile (radical ecology, action: immediate return to low technology). The centrists positions are taken by the ones that view nature as robust, but within distinct limits, that when transgressed can result in a sudden shift to another meta-stable situation. Dependent on how stable the meta-stable situation is assumed to be, the positions range from the use of appropriate technology, which is low-tech where possible (deep ecology), to reliance on technological evolution within environmental constraints and no preference for low-tech unless environmentally desirable (industrial ecology). In sustainable development, nature is also considered robust. It aims to counter the absolute impacts generated by economic growth by increased eco-efficiency: more product or service for the same or less negative environmental impact.

Finally, sustainability is so easy to understand, but so difficult to define, because it reaches the core of human nature. Determining a maximum damage limit is one thing, determining the conditions under which humans (and other life) will *flourish* on the earth is another. It involves reflection on our needs. Ehrenfeld's notion of flourishing is closely linked on Fromm's concepts of having and being. In *To Have or To Be*, Fromm (1976) distinguishes two fundamental modes of human existence. The 'having' paradigm, which has become the dominant mode in modern industrial cultures, has turned pathological, and only a shift to the radical, alternate 'being' mode can save both the human kind and the natural world[1]. Not only it is doubtful whether increased eco-efficiency can counter the impact of continued economic and material growth emerging from the having mode, quality of life cannot be achieved with 'having' alone (see also Maslov 1954, Achterhuis 1992, and Idhe 1993). Sustainability thus requires a change of heart. Only if humans can learn to value 'being' over 'having', sustainability can follow (Ehrenfeld 2000).

2.2.2 Getting there

Even if scientific knowledge on what damage is acceptable is, or becomes available, even if we can define our needs based on the having paradigm, the next problem is how to use this information to develop a sustainable global economy. It is likely that realization of sustainability will require some (global) consensus on the balance between the optimal use of the environment from a social and economic point of view with maintaining the intrinsic value of nature, if on some point there is a conflict between the two. Or that it will require consensus on the distribution of the use of environmental resources and the burden of reducing pollution over different industrial systems, or between countries, and how to reach that distribution. Consensus on the

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[1] The 'having' mode concentrates on material possession, acquisitiveness, power, and aggression and is the basis of such universal evils as greed, envy, and violence. The 'being' mode is based on love, in the pleasure of sharing, and in meaningful and productive rather than wasteful activity.

latter in particular is critical to develop a sustainable global economy. It is well accepted that sustainable development can be achieved easier when population is stabilized at a level consistent with the productive (but also assimilation) capacity of the ecosystem earth. If a consistent population level can scientifically be determined, this leaves the tough question of how to 'allocate' the population stabilization or reduction between countries. Particular, considering the rational behavior at an individual level gives rise to irrational level on the overall level (prisoner dilemma).

The earth is increasingly an engineered world in which human choice and technology determine the structure not only of human lives and environments, but for all life on the planet. Sustainable development or sustainability is an emerging property in systems terms, which means among others: that sustainability is a property of the system as a whole and that one can not know that the system is sustainable until in fact sustainability has been achieved. The concept of a sustainable subsystem in an unsustainable global system is fundamentally an oxymoron, i.e. it combines two opposite ideas and is thus impossible. The sustainability of any subsystem such as a community within the global system can only be defined in terms of the global system.

The degree and kind of controls and knowledge that controlling such a complex interlinked and highly non-linear system would imply, however, are currently beyond the state-of-art (Allenby 1999). Because of the systemic character of sustainability, the western concepts of reductionist science and linear short term and obvious causality will thus have to be augmented by more systems-based, comprehensive approaches to develop the appropriate tools.

Perhaps to the most important notion for achieving sustainability is that there is no getting 'there'. Sustainability is a continuous process, not an endpoint or a specific state of a system. As human culture, technologies, population levels and natural systems evolve, so will the parameters of sustainability. Similar to nature, society possesses all kinds of self-regulating mechanisms, which are composed of a complex web of positive and negative feedback systems. Change induces change. Virtually every modern institution - the national state, major religions, the private firms, academic institutions, the family etc. - change at an unparalleled, but little recognized rate. Because of these developments, the limitations to social organization must change as well. Evolution towards an economically and environmentally efficient economy will differentially favor certain industrial sectors and technological systems, and disfavor others.

Thus, sustainability has a temporal component: sustainable for how long and within what time frame? It is about a co-evolution of human and natural activities. A continuously developing world that slips in and out desirable states that are each sustainable over some time frame, a sort of 'punctuated equilibrium' (Eldredge and Gould 1972, Ojha 1997, Allenby 1999, Bowonder 1999, Anderson 2004). Only by understanding sustainability as a continuous process, society can direct their research and resources in the appropriate direction.

Despite the complexity of defining, using and realizing sustainability, it is assumed in this study that under optimal conditions some kind of reasonable and acceptable path towards a desirable, environmentally and economically efficient sustainable global economy does exist (after Allenby 1999). The next section discusses industrial ecology as a possible approach to analyze and restructure industrial activities along this reasonable and acceptable path.

2.3 Industrial Ecology

In the first textbook on industrial ecology Graedel and Allenby (1995) define the essence of industrial ecology as follows: '*Industrial ecology is the means by which humanity can deliberately and rationally approach a desirable carrying capacity, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surroundings, but in concert with them. It is a systems view in which one seeks to optimize the total material cycle from virgin material, to finished material, to components, to product, to obsolete product, and to ultimate disposal. Factors to be optimized include resources, energy, and capital.*' The words deliberately and rationally in the above definition indicate that the intent of the field of industrial ecology is to provide the technological and scientific basis for a considered path towards global sustainability, in contrast to unplanned, precipitous and potentially quite costly and disastrous alternatives (Graedel and Allenby 1995). Industrial ecology is therefore sometimes regarded as the science of sustainability.

Although industrial ecology is a relatively young field, the concept of industrial ecology is not new. There is little doubt that the ideas of industrial ecology existed well before the expression, which began to appear in the literature of the 1970s (Erkman et al. 2002). Erkman et al. (2002) found that the concept of industrial ecosystems was already clearly present in the writings of system ecologist such as Odum and Hall (Odum and Pinkerton 1955, Hall 1975). O'Rourke et al. (1996) trace the ideas back to the early seventies, for example to Barry Commoner's seminar book 'The closing circle' (1971), which asserted that 'present productive technologies need to be redesigned to conform as closely as possible to ecological requirements' (Commoner 1971: 283).

However, in the course of the past thirty years the several attempts to launch this new field yielded only marginal success (Erkman 2002). That is until 1989 when Frosch and Gallopoulos published an article entitled 'Strategies for Manufacturing' in Scientific American. The article sparked the current development of industrial ecology, and inspired many authors to write articles spreading their ideas in various academic and business circles. Among them, it was notably Tibbs (1991, 1993) who translated the ideas in the article into the language and rhetoric of the business world, which spread Frosch and Gallopoulos' ideas throughout the business world.

The ideas on 'industrial metabolism' of Robert Ayres provided means to support the decision-making on industrial ecological principles to key decision-makers, such as regulators, industrial managers or engineers (Kneese et al. 1970, Ayres 1989). Ayres suggested to describe the metabolism of the industrial system through detailed 'material balances', which could be compiled at different spatial scales, e.g. for a production unit, such as a factory, or a geographic unit as small as a village or as large as a continent.

The first university handbook of Industrial Ecology in 1995 (Graedel and Allenby 1995) marked the broad acceptance of industrial ecology. The launch of the Journal of Industrial Ecology in 1997 can be seen as official recognition of the academic community of this new field.

2.4 The concept

Industrial ecology is a new concept emerging in the evolution of environmental management paradigms (Ehrenfeld 1995). Because of its early stage of development, it is still mostly a cluster of concepts, tools, metaphors and exemplary applications and objectives, and has no clear demarcation of the field (Lifset and Graedel 2002). This review should therefore be seen as a somewhat 'impressionistic' painting of industrial ecology and its applications, rather than a comprehensive picture of the field.

The expression Industrial Ecology (IE), a combination of 'industry' and 'ecology', expresses some of the content of the field (Lifset and Graedel 2002). These two notions are the base colors in the painting of this new concept.

2.4.1 The industrial notion

The first word 'industrial' in industrial ecology states the focus on industrial processes. Many in the field of industrial ecology see industrial (or technological) change as the only means that offers a possibility of reducing the fundamental environmental impacts of human economic activity, at least in the short term. The importance of industrial change can be explained with the so-called master equation of sustainability. The master equation focuses thinking on the most efficient response that society can make to environmental stresses by examining the predominant factors involved in generating those stresses (e.g. Ehrlig 1971, Commoner 1972, Graedel and Allenby 1998 and 1995, Allenby 1999, Chertow 2001). It is not difficult to imagine that the stresses on many aspects of the earth system are predominantly influenced by the size of the population, and by the standard of living that that population desires. The master equation below is a well-known expression of those driving forces:

$$I = P \cdot A \cdot T \qquad (1)$$

In which

I = Impact
P = Population
A = Affluence (or Wealth indicated by consumption per capita)
T = Technology (indicated by the level of Impact per consumption)

To understand the role of industries, the three right-hand terms, and their probable change with time must be understood. The first two terms in the equation, viz. P and A are strongly tending upwards (e.g. Allenby 1999, Graedel and Allenby 1998, 1995, Ness 1997). Of these three categories of driving forces, population produces the most controversy. It is, however, one of the few variables for which worldwide data of reasonable accuracy are available, providing a basis for statistical assessments of its role in various kinds of environmental change. Despite diseases as aids or other epidemics, the global population is expected to grow substantially, mostly in the developing countries. Since 1970, population has already grown eight-fold. Projections of a peak in population of eight to twelve billion persons, or even more in this century are not regarded as unrealistic by demographers (Ness 1997, Allenby 1999).

At the present time, the 'quality of life', which is what A in equation 2.1 really refers to, is almost universally defined in terms of ability to appropriate goods and materials. 'Having' things, in particular status symbols such as automobiles, is an important goal for most of humanity (Graedel and Allenby 1998, Ehrenfeld 2000). It is unlikely that the world would be able to support a world economy if today's Western production and consumption levels are adopted by the developing countries, in particular given the expected growth in population. This may not be for reasons of absolute scarcity, new sources for materials and substitutes will be found as prices shift. The cumulative environmental impact of material cycling through the world economy can also destabilize, or (unacceptably) perturb existing natural systems (Allenby 1999).

Because of the strongly trend upwards of population and wealth factors in the equation, industrial ecology focuses on the third right hand term T: technology. This is the only remaining factor that, at least in the short term, can offer a possibility of reducing the fundamental environmental impacts of human economic activity[2]. It represents the degree to which technology is available to meet human needs without serious environmental consequences.

Chertow (2001) tracked the various forms the IPAT equation has taken over 30 years as a means of examining an underlying shift among many environmentalists toward a more accepting view of the role technology can play in sustainable development. She concludes that although the IPAT equation was once used to determine which single variable was the most damaging to the environment, an industrial ecology view reverses this usage, recognizing that increases in population and affluence can, in many cases, be balanced by improvements to the environment offered by technological systems. Many in the field of industrial ecology view on the one hand industry as an important source of environmental damage, but on the other hand technological or industrial development as a central means of solving environmental problems. Industries represent an important source of technological expertise critical to execution of environmentally informed design of products and processes. Furthermore, business is considered both a policy-maker and policy-taker (Lifset and Graedel 2002). Although this view is widely shared within the field, the degree to which technological innovation will sufficiently solve the problems, and for how long, is still a subject of ongoing debate (Lifset and Graedel 2002). The master equation also shows a limitation of the industrial focus of industrial ecology. Technological evolution can buy time for cultural/social evolution, but it is not a substitute. A typical example illustrating this is the development of cars. The improvement in car technology has not dramatically reduced emission and fuel consumption because people drive their cars further, and choose less efficient models (see e.g. Graedel and Allenby 1998). Thus technology here is both part of the solution and part of the problem, which illustrates the need for critical attitude towards technology as argued in the previous chapter.

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[2] Chertow (2001) concludes this industrial ecologist's vision on technology is partly pragmatic (technological variables often seem easier to manage than human behaviour) and partly a technocratic (belief in scientific advance).

2.4.2 The ecological notion

The ecological notion applies to the field in at least two ways: (i) natural ecosystems are used as a model for industrial activity and (ii) human technological activity is placed in the context of the ecosystems that support it. The different definitions of industrial ecology differ in the way that emphasize one of these ways. Graedel (1993) emphasizes the latter notion by defining industrial ecology as a multidisciplinary, "system-oriented concept [which] suggests that industrial design and manufacturing processes are not performed in isolation from their surroundings". Contextual analysis of technological activities has a strong link to forward-looking research and practice in the field of industrial ecology, acknowledging that it is important to avoid environmental problems that are irreversible, or too costly to remedy. Frosch and Gallopoulos (1989) focus on the first notion and describe industrial ecology as a concept in engineering and management whereby it is attempted to operate industrial estates as ecosystems through adaptation of typical ecosystem features: feedback (control) loops, minimal use of resources and minimal production of wastes by cascading the use of resources and energy. Arguably, the notion ecological also applies to the field in a third way. Industrial ecology also uses concepts, approaches and methodology from biological ecology. Analogous to ecology, industrial ecology emphasizes the need for systems perspectives. This perspective is manifested in different forms: the use of life cycle perspectives, of material flow and energy flow analysis, of systems modeling. Industrial ecology has a comparable sympathy for multidisciplinary and interdisciplinary research and analyses (Lifset and Graedel 2002).

Den Hond (2000) considered the biological analogy the most important, conceptual contribution of industrial ecology. Industrial ecology assumes that the functioning of ecosystems provides examples, ideas and prescriptions of how to design and operate sustainable industrial systems (Ehrenfeld 1998). The biological analogy involves a comparison of living ecosystems found in nature to industrial activities. Interestingly, the analogy is used the other way around. Microbiologists draw the analogy with industrial manufacturing processes when modeling metabolic pathways within the cell (Ortega et al. 1999). In the cadre below, ecosystem and ecology are discussed as a basis to explore the biological analogy.

Cadre 2-1: Ecosystems

An ecosystem is a functional unit in nature composed of (1) abiotic constituents, all non-living elements such as minerals, climate, soil, water, sunlight, (2) biotic constituents, all its living elements such as mammals, plants, insects, fungi, and (3) their interactions that link the abiotic and biotic constituents, viz. the cascaded energy flows through the ecosystem, and the cycling of nutrients within the ecosystem. Each organism in an ecosystem or the waste it produces is food for others. Specialized species convert wastes into the minerals required by the 'primary producers'. Mature ecosystems contain high biodiversity of species, organized in complex webs of relationships.

In these ecosystem networks, each individual in a species acts independently, yet its activity patterns cooperatively mesh with the patterns of other species. The result is a complex dynamic network where every material is used in the anabolism and catabolism of life, and the material cycles are largely closed. Ecology, the study of living ecosystems, therefore stresses that all the elements of an ecosystem form part of an integral, dynamic network in which each element interacts directly or indirectly with all others, and thereby affect the function of the system as a whole.

The many relationships are maintained through self-organizing process that keep efficiency and productivity of ecosystems in dynamic balance with their resilience to environmental perturbations ('autpoeisis' and 'homeostasis' see e.g. Odum 1969, Commoner 1971, Lowe et al. 1997a, Capra 1996). A change in the number and populations of species affects the operation of the ecosystem as a whole, and allows it to adapt to changing conditions. Ecosystems are thus flexible, ever-fluctuating networks according to Capra (1996: 302). The more 'network variables' (e.g. number of species, size of populations) are kept fluctuating; the greater its flexibility; i.e. the greater its ability to adapt to changing conditions. A diverse ecosystem will be flexible, because it contains more network variables that can fluctuate: many species have overlapping ecological functions that can partially replace and complement one other.

This actual adaptability or resilience is a consequence of its multiple feedback loops. These tend to bring the ecosystem back into balance, whenever there is a deviation from the norm, due to changing environmental conditions. Darwin's natural selection is an example of such a feedback mechanism. The best-adapted or fittest species flourish most and their number accumulates (positive feedback). The less adapted species must compete over the remaining resources, and their number will decrease. Eventually, this may lead to extinction, unless the species evolve or find ecological niches (negative feedback). However, as environmental conditions change over time, the relative fitness of organisms also changes. As a result, the species and populations of the different species change (old species become extinct or new species evolve) to maximize the efficiency and productivity of the ecosystem under the new conditions. As such, the environmental conditions limit the extent to which the different plant and animal populations can grow.

A balance in positive and negative feedback loops is of great importance for stability in all biological systems. Most growth phenomena in a biological setting involve positive feedback loops. Such a process of growth tends to increase very rapidly (viz. exponential growth) until it reaches a population in which other factors become important. These will typically act to limit the growth in a way, which can often be recognized as a negative feedback loop. In ecosystems with unbalanced positive and negative feedback - e.g. excessive amounts of a single or a few nutrients, or the absence of predators – can lead to exponential, growth of a single or a few species, which can lead to the extinction of other species, and eventually even to ecosystem collapse and succession. In particular, excessive amounts of plant nutrients (primarily phosphorus, nitrogen, and carbon) can lead to 'eutrophication' or 'nutrient pollution'[3].

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[3] A well-known source was the phosphorus in sewage when detergents still contained large amounts of phosphates. The phosphates acted as water softeners to improve the cleaning action, but also as powerful

Finally, it is important to note that the dimensions of ecosystems vary from very small, the oral cavity of man or a segment of man's intestine, to very large, tropical rainforest or lake (Schlegel 1992). The largest ecosystem is the 'natural' earth itself, which in turn can be considered to behave like an organism (e.g. Lovelock 1979, 1988).

Graedel and Allenby (1995) offered a typology of ecosystems that can be used as models for industrial activity in industrial ecology. They distinguished three types, dependent on the degree to which they rely on external inputs (energy and resources):

- Type I is the most linear system, and the most reliant on external input. These systems can exist in presence of unlimited resources, and unlimited sinks for wastes, for example when the number of organisms is small and the use of resources has no or negligible impacts on the availability of resources. (Examples: modern agricultural practices, which are based on large mono-cultures or biotechnological processes.) However, when the numbers of organisms increase, the external inputs and sinks will be influenced, which constrains the availability of sources and sinks.
- Type II system includes feedback loops and cycling that enable a more efficient use of available external inputs and sinks. These (quasi-cyclic) systems are more efficient than the linear, but eventually run out of inputs and sinks, and thus are not sustainable on the long run. (Example: developing ecosystems, fish tank or to a lesser extent green houses)
- Type III are completely cyclic systems were external resources are completely recycled (closed material cycles). These systems need only an external energy source to drive the resource cycles, and can be sustainable if a sustainable source of energy is available. Energy is cascaded to maximize utilization of energy available for growth and maintenance of the system.

Most (mature) 'natural' ecosystems approach type III, and idealistically the largest ecosystem earth can be considered as a type III system. Their efficient cycling of resources is considered ideal for industrial systems at many scales, and explains the strong emphasis of industrial ecology on closing the material cycles.

'Industrial ecology, in its implementation, is intended to accomplish the evolution from Type I to Type II and ultimately to Type III by understanding the interplay of processes and flows, and by optimizing the ensemble of considerations that are involved' (Graedel and Allenby 1995). This explains the interest in the field of industrial ecology for strategies aiming at closed loop systems, detoxification and dematerialization[4], but also

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stimulants to algal growth. The resulting excessive growth of algae among others blocked sunlight and led to oxygen depletion. As a result, it led to changes in ecosystem structure: bottom fauna and fish species disappeared (and/or were replaced by species more resistant to the new conditions).

[4] The evolution to a Type II or III system not only involves closing the material cycles, but also to use fewer resources to accomplish tasks. Dematerialization refers to reduction of the amount of material use to accomplish a task (sector, national, regional or global level), and eco-efficiency refers to reduced use of environmental resources given a certain level of output (firm level). Detoxification refers to the use of less damaging products, substances and materials to decrease the impact of products, substances and materials that cannot be properly recycled.

multidisciplinary and interdisciplinary research and analyses. Graedel and Allenby observe that the 'nodes' in industrial ecosystems (viz. the material extractor or grower, the materials processor or manufacturer, the user, and the scavenger or waste processor) have to be attuned to one another to accomplish the desired evolution.

The analogy provides also other suggestions for organizing industrial activity. Biodiversity and interconnectedness in ecosystems points at the fact that only networks can be sustainable; a single organism, company, or firm can never be sustainable (Ehrenfeld 1998). According to Ehrenfeld (1998) besides closed looped material cycles and cascading energy utilization, the ecosystem characteristics that have to be achieved are approximation of a "thermodynamic" steady state of minimum entropy generation and dynamical stability. Ecosystems must therefore continuously adapt to changes in their surroundings, or else they vanish by ecosystem transformation, or ecological succession. Ecosystems adapt by natural selection; the process by which species of animals and plants that are best adapted to their environment survive and reproduce, while those that are less adapted die out. Ecosystems survive by the continuous adaptation of all the organisms in ecosystems. Bertalanffy (1940, 1950) speaks of 'Fliessgleichgewicht' (literally flowing balance) to describe this dynamic stability, the coexistence of balance and flow, of structure and change, in all forms of life (see also Prigogine and Glandorff 1971, and Maturana and Varela 1980). By analogy, industrial ecosystems should be dynamically stable as well; they must meet continuously the needs of society, but be able to react dynamically on changes in its environment, by rerouting relationships between its components, or by changing the configuration of its components. An important lesson for controlling such systems is that the many relationships are maintained through self-organizing process, not top-down control (Lowe et al. 1997a). Côté (2000) recently suggested that more industrial 'biodiversity' (scavengers and decomposers) 'could increase the cycling of other materials that may be available and valuable in smaller quantities', and should also increase the resilience of eco-industrial parks such as Kalundborg.

The biological analogy is also explored in other directions, for example, its application to products as a source for design inspiration, a framework for characterization of product relationships, and a model for organizational interactions in technological webs (Lifset and Graedel 2002).

2.5 The toolbox

Given the wide scope of the field, it is not surprising that different approaches present themselves. In this section, it is attempted to provide an overview of the toolbox of industrial ecology[5]. The description of industrial ecology at the back of the journal reveals two groups of approaches, viz. descriptive '*Industrial ecology systematically examines local, regional, and global uses and flows of materials and energy in products, processes, industrial sectors and economies*' and prescriptive '*It focuses on*

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[5] Note that the review is not a complete overview of all available tools, but rather gives an overview of the range of tools available. It is based on a literature search of the journal of Industrial Ecology, the critical reviews of Den Hond (2000) and O'Rourke et al. (1996), the special issue of the journal of cleaner Production, and handbooks of Industrial Ecology (Ayres and Ayres 2002, Lowe et al. 1997, Allenby 1999, Ayres and Ayres 1996, Graedel and Allenby 1995, 1998).

the potential role of industry in reducing environmental burdens throughout the entire product life cycle'. A distinction can be thus made between (i) prescriptive approaches, eco-design studies that address the control of the patterns of flows and processes through optimizing the ensemble of considerations that are involved, and (ii) descriptive approaches, systemic analysis studies that describe and analyze the interplay of processes and flows (see e.g. Lifset and Graedel 2002, Den Hond 2000, O'Rourke et al. 1996)[6]. Figure 1 shows examples of the applications (tools) of both approaches. These are discussed the sections below.

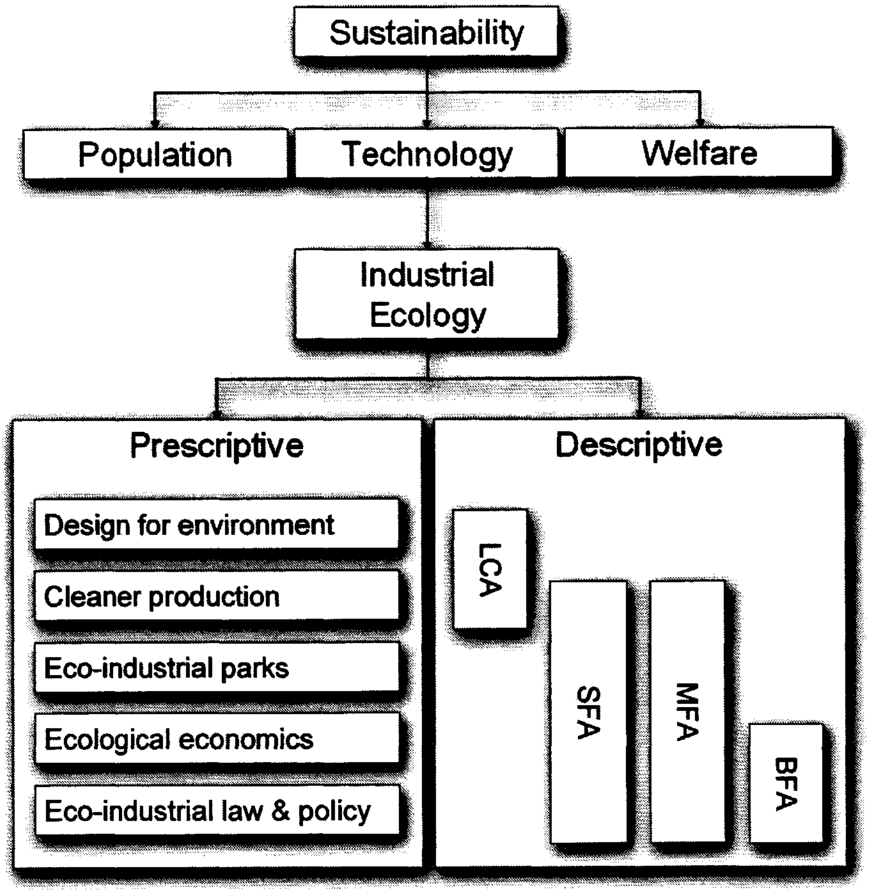

Figure 1: Industrial ecology approaches and examples of their applications (tools). Legends: LCA= Life Cycle Analysis, SFA = Substance Flow Analysis, MFA= Meso and Micro Material Flow Analysis, BFA= Bulk Flow Analysis.

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[6] In addition to this application-oriented conceptualization of industrial ecology, other conceptualisations are possible also, e.g. based on the variety of system levels at which industrial ecology operates: (i) firm level, (ii) between firms, (iii) regional and global (see e.g Lifset and Graedel 2002).

2.5.1 Prescriptive approaches

The prescriptive approaches involve the analysis of the influence of technical, economic, political, regulatory, and social factors on the flow, use, and the transformation of resources, notably how these factors can be put to use to steer the development and patterns of material and energy flows. Generic and specific activities can be distinguished.

2.5.1.1 Strengths

The prescriptive approaches in industrial ecology may be seen as responses to a nested set of challenges from the individual products development to global policies and legislation. Prescriptive approaches assist design and management across these levels to 'deliberately and rationally' approach sustainability. Examples of these prescriptive approaches across the different levels of design include: design for environment at product level, pollution prevention at process level, development of eco-industrial parks at regional level, and finally the development of economics theory, regulation, and market conditions at national or global level.

Design for environment (Dfe) designates a practice by which environmental considerations are integrated into process and product design, and materials and technology choices (Allenby 1994). Dfe has a close link with Life Cycle Assessment (see 2.5.2). Pollution prevention (or synonymously Cleaner production) is a well-developed field of environmental engineering that focuses particularly on the design of industrial processes. Pollution prevention does not generally address the relationships between industrial plants, but its design for environment tools could be very helpful in providing a systemic perspective for weighing trade-offs between competing options for change (Lowe et al. 1997: 59).

Industrial ecology can also be applied to organizations, e.g. of industrial process communities (industrial ecosystems), and to the rules and incentives of the organization process (development of the regulatory landscape, and market conditions). An eco-industrial park is a community of industrial plants that is based on the integrated model of an ecosystem. In the traditional model of industrial activity, manufacturing processes take in raw materials and generate products to be sold plus waste to be disposed of. In the ecosystem model, consumption of energy and materials is optimized, generation of waste is minimized and residues of one process serve as input for others (Frosch and Gallopolous 1989). An often-cited example is the spontaneous, but slow development of industrial symbiosis at Kalundborg.

The development of policy and legislation is an essential condition for successful implementation of industrial ecology at lower system scales (products, processes, eco-industrial parks). Private entities, acting alone, can make some progress, but can not compensate for wider systems-based barriers to progress towards sustainability. Therefore, boundary conditions need to be designed to encourage appropriate behavior on the part of the producers and consumers, and the conditions must be laid down in legislation and policy. In the first handbook of industrial ecology, Graedel and Allenby (1995) already recognized and discussed the role of governments, policy and legislation for the implementation of industrial ecology. Examples of more extensive, recent analyses in this area include Lowe et al. (1997a) and Allenby (1999).

The prescriptive approaches have tended to focus on design for environment, (technology) policy and legislation. Industrial ecologist discuss broader strategy occasionally in informal settings. In general the literature does not reflect this discussion except in side comments (see e.g. Lowe et al. 1997a, Graedel and Allenby 1995). Economic theory is critical to the implementation of industrial ecology. Many studies in the industrial ecology (IE) literature share the premise that material and energy flows can be deliberately and rationally influenced by (i) setting the 'right' prices (internalizing environmental and social externalities), (ii) providing the 'right' information (showing the environmental consequences of their actions) and (iii) setting the incentives and boundary conditions for activities in regulation (Den Hond 2000, O'Rourke et al. 1996). In this way, the 'invisible hand of the market' can co-ordinate decisions at different scales (individual, firm, regional, national or global) and thus provide the context for the co-ordination of the different tools. This believe in self-organizing capacity of (competitive) markets may be linked to the self-organization (or 'autopoeisis') of natural ecosystems through decentralized processes and survival of the most adapted.

To achieve a sustainable global society, there is a need for extending and integrating the study and management of "nature's household" (ecology) and "humankind's household" (economics)[7]. The journal of Ecological Economics started in 1989 as recognition that this integration is necessary 'because conceptual and professional isolation have led to economic and environmental policies which are mutually destructive rather than reinforcing in the long term' (Journal of Ecological Economics). The journal aims to provide a forum for new issues in this area, which are rapidly emerging from exploring the interactions between economics and (industrial) ecology.

2.5.1.2 Weaknesses

To deliberately and rationally advance to sustainability, the combined prescriptive approaches must contribute to the overall environmental performance of the system as a whole. This involves co-ordinated improvement of products, processes and process combinations, and the development of regulation and market conditions. This is currently not the case. Rather, the objectives and outcomes of the different prescriptive tools can be conflicting, and, as a consequence, do not contribute to an improved overall performance. For example, the conversion of waste into by-products can conflict with

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[7] Among others Costanza et al. (1997) realized that the value of ecosystems are not 'fully' captured in commercial markets or adequately quantified in terms comparable with economic services and manufactured capital. Consequently, they are often given too little weight in policy decisions, which may be the ultimate cause of the development into the present consumption society. Capturing the value of ecosystems is hindered by practical problems. Because data on impacts are scarce and uncertain, it is difficult quantifying social and environmental costs in terms of costs and benefits (Graedel and Allenby 1995:87). In addition, the economic translation of price signals into adequate decisions is flawed by assumptions and practical problems that, even if the price signal is correct, do not provide adequate decisions. Examples are the assumptions that money is worth more today than tomorrow (discounting), or the substitutability of resources (Allenby 1999, Graedel and Allenby 1995). In general, there is no consideration of the financial impact of eventual resource limitations, when discounting methodologies are utilised. The discounting concept as implemented in practice conflicts with the fundamental principle that the economy should function as to be indefinitely sustainable. Another assumption common to standard economics is that the substitutability of resources can be based on monetary value, which in turn reflects scarcity. The substitution assumption, however, is very questionable; some mineral resources may prove critical for future technologies.

the emphasis on waste reduction in pollution prevention, and *vice versa* pollution prevention based regulations can inhibit the reuse of waste, even within a company (see e.g. Lowe et al. 1997a: 61, Verhoef et al. 2001a).

An essential question for industrial ecology is, therefore, how to co-ordinate the tools that operate at different levels, and consider different aspects of the overall IE strategies. In economic systems, price mechanisms guide material and energy use and allocation of outputs, and co-ordinate the actions of the actors. In this way, the 'invisible hand of the market' can co-ordinate decisions at different scales (individual, firm, regional, national or global) and thus provides the context for the co-ordination of the different tools. However, consumers and firms are only partly informed by price, information and regulation. External conditions and internal motivations, such as strategic decision-making to eliminate direct opponents (see Kuit et al. 2002) also play important roles.

The market is an existing, but flawed tool for co-ordinating decentralized decision-making across different system levels. In order to effectively co-ordinate the prescriptive activities, industrial ecology calls for a consistent framework that connect different prescriptive efforts. The quantitative descriptions of the underlying physical systems could provide for such framework. Market designs must also reflect the physical reality of the underlying system in order to co-ordinate decisions effectively (De Vries 2004). The current design of the European electricity markets does not sufficiently do so and as a result can not ensure the market goal, the reliability of the electricity supply.

The eco-industrial park Kalundborg is perhaps the best-known application of industrial ecology. The development and management of eco-industrial parks, however, is not well understood, despite of the many studies on Kalundborg and other eco-industrial parks. A detailed mechanism or recipe, by which the conditions for the development of the required industrial symbiosis can be achieved, remains to be worked out (Ayres 2002). The symbiotic relations in eco-industrial parks are not invented, but tend to develop in a complex, organic way. Because of the many different actors, factors and processes involved, the steering of this process is complex, and involves many trade-offs. In addition to the technical and environmental aspects at process level, many other aspects play important roles. These include an obvious need for long-term co-operation and planning, e.g. to address the risk of loosing a critical supply in case one of the existing plants changes feedstock, or closes. The development also calls for a disclosure of relevant technical information, but then proprietary information could become available to competitors (Ayres 2002). It appears that a high level of organization is required to ensure successful co-operation. Gertler (1995) gives a comprehensive overview of the conditions for creating intercompany by-product exchanges based on Kalundborg. These include the regulatory changes needed, and the organizational options for creating and managing such changes. Other attempts to draw up recipes for the development of eco-industrial parks are given by Côté (1994, 1995) and Lowe (1997b).

Once these eco-industrial parks have been developed, they need continuous maintenance and management. While ecosystems 'unconsciously' and continuously adapt to their surroundings, the high level of organization and the strongly integrated designs of eco-industrial parks could lead to a lock-in of undesired technologies, continued reliance on toxic compounds or overall a limited flexibility (O'Rourke et al.

1996, Sagar and Frosch 1997, Oldenburg and Geiser 1997, Lowe et al. 1997a). Tibbs (1994) already recognized the need for a design for flexibility. He proposes that the concept of a learning organization can be used in the design of an eco-industrial park. One of the characteristics of a learning system is that one has the ease of making and breaking connections as conditions change. Therefore, internal technological choices and transactional arrangements must continuously be compared to the external competitiveness of the system as whole (Ayres 2002). It can thus be easily seen that understanding the technical systems that largely determines the technological choices and transactional arrangements is a condition to develop and maintain eco-industrial parks. It can thus be seen that adequate modeling of these physical, technical systems could provide for a framework to co-ordinate the activities of different actors, factors and processes involved.

Similarly, the shift in regulation endpoint from localized reduction of (usually human) risk implicit in much environmental policy and legislation to date, to a goal of global economic and environmental sustainability also involves controlling the highly complex technical infrastructure (see also chapter 4). Closing the material cycles, for example, involves the co-ordination of processes that can be dispersed worldwide (Dijkema et al. 1999). It thus can be seen that, adopting the systems perspective of industrial ecology carries with it a fundamental shift in focus from simple to complex systems. Allenby (1999) summarizes the fundamental difference between simple and complex systems as follows: Simple systems are intuitively "understandable". In contrast, many aspects of complex systems are difficult and counterintuitive[8], and frequently are illustrated only by the behavior of properly constructed quantitative models. Industrial ecology calls for the co-ordination of processes that operate at different time scales and spatial scales.

The principle of mass conservation provides a tool to describe processes across different time scales and spatial scales. Dutchin and Hertwich (2003) therefore consider the descriptive approaches, SFA in particular, as the unifying core of industrial ecology. The descriptive approaches are thus important for the prescriptive approaches for two reasons. First, they represent the experience in the quantitative modeling of the complex patterns of material and energy flows, and in the conversion of these patterns into quantitative support for the formulation and evaluation of options for decision-makers. Secondly, they should provide the context to co-ordinate the efforts of the different prescriptive approaches and as such provide a unifying core for industrial ecology.

2.5.2 Descriptive approaches

The descriptive approaches involve the analysis of the flows of materials and energy in industrial and consumer activities, and of the effect of these flows on the environment. Here a distinction can be made between studies that are performed in physical terms (resource studies) or in monetary terms (social and economic studies). This study will focus mainly on the first type.

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[8] Because complex systems typically operate far from equilibrium, they often have no causal or linear relationships, they exhibit discontinuities, thresholds etc.

2.5.2.1 Strength

The fundamental importance of identifying and tracing physical flows of materials and energy has been recognized for decades. Descriptive approaches provide snapshots of parts of the physical economy. They enable tracing environmental problems to their origins, assist in formulating policy or design alternatives, and predicting future bottlenecks towards sustainable global economy. Moreover, descriptive approaches can assist prescriptive approaches by providing a connection of the flows of mass and energy to social and environmental costs.

Based on different goals, concepts, time and spatial scales and target questions, Figure 1 shows that various methods have developed in industrial ecology. Material flow analysis (MFA) emerged as one of the primary methodological frameworks (Daniels and Moore 2001). All of these approaches are based on mass and energy balances of a certain part of the flows and processes of the global economy, associated with individual product and processes or national to global economies. The development of a paradigm embracing the identification and tracing physical flows of materials and energy has been slow, and still lacks a clearly defined methodology (Fischer-Kowalski and Hüttler 1999). The methods differ in how they present subsystems of global physical economy; for example which resolution they use to describe physical economy, or how they consider the dynamics of the system. The inputs and outputs of the inventory in life cycle analysis (LCA) generally lack a time dimension; they are amounts per se, or more precisely per functional unit of the product (or process) under investigation (Udo de Haes and Van der Voet 1997). In contrast, substance flow analysis (SFA) investigates the processes, flows and accumulations of certain materials over a certain period of time.

Bringezu and Moriguchi (2002) and Daniels and Moore (2001) attempted to classify the different methods based on their subject, i.e. which part of the global economy is described by the approaches. Daniels and Moore distinguish five families of methods based on the MFA framework:

- Macro-Bulk/Material Flow Analysis (Macro-BFA) investigates the total economic activity in a region of all material groups.
- Partial Macro-MFA differs from Macro-BFA in that it investigates only one substance, or material group.
- Meso-MFA considers all material groups, but focus at a single sector or activity field
- Micro-MFA, considers the same as Meso-MFA, but at micro scale (one or only a few products or enterprises)
- MFA-related methods include the remaining methods that consider the total economic activity of region or a process.

Bringezu and Moriguchi (2002) distinguish two categories of methods: MFA type I and II. Each category is divided into three subcategories, a, b, and c. The two categories represent opposite focuses: type I focuses on (a) substances, (b) materials and (c) products within firms, sectors and regions, and type II on (a) firms, (b) sectors and (c) regions associated with substances materials and products. The two classifications of MFA (and MFA related approaches) are summarized in Table 1.

Table 1: Summary of different MFA (and MFA related approaches) based on system boundary and application (after Bringezu and Moriguchi 2002, Daniels and Moore 2001).

Classification of the different MFA and MFA related approaches according to Daniels and Moore

MFA classification	Economic System investigated	Substances investigated	Examples approaches
Macro-BFA	Total economic activity/region	All material groups	Bulk internal flow MFA (MFA-BIF), Total material requirement and domestic output (TMRO), Physical Input/Output tables (PIOT)
Partial Macro-MFA	Total economic activity/region	One substance, or material group	Substance flow analysis (SFA)
Meso-MFA	Sector, activity field	All material groups	Product chain analyses, material flow balance studies focused on specific sectors.
Micro-MFA	One/few products, enterprise	All material groups	Material intensity per unit service (MIPS), Life cycle analysis (LCA), Company-level MFA
MFA-related	Total economic activity/region (ES, EFA) Process (SPI)	All material groups	Environmental Space (ES), Ecological Footprint (EFA), Sustainable process index (SPI)

Classification of the different MFA and MFA related approaches according to Bringezu and Moriguchi

MFA classification	Focus	Examples	Remarks
MFA type I: focuses on substances materials and products within firms, sectors and regions	a Substances	Cd, Cl, Pb	Usually coined Substance Flow Analysis SFA
	b Materials	wooden products, energy carriers, biomass, plastics	This kind of studies is related to Ic and IIb
	c Products	diapers, batteries	Usually classified as LCA
MFA type II: focuses on firms, sectors and regions associated with substances materials and products	a Firms	single plants, medium and large companies	Usually related to environmental management, and not classified as MFA
	b Sectors	production sectors, chemical industry, construction	When the analysis comprise all sectors of regional, or national economy closely related to IIc, if it comprises of one sector in detail to Ib.
	c Regions	total/main throughput, mass flow balance, TMR	The scope varies from cities, to regions (e.g Rhine basin), and national economies

2.5.2.2 Weaknesses

The strength of industrial ecology lies in its descriptions of the material world. Life cycle analysis accounts for most articles in the Journal of Industrial Ecology, and most sessions at professional meetings (Dutchin and Hertwich 2003). There are still substantial challenges in achieving conceptual and operational linkages between the physical balances and the formulation and evaluation of options for key decision-makers. One of the challenges for the descriptive approaches is the 'impact assessment' step, which involves evaluating the significance of hundreds of inventory items in terms of a small number of indicators (Hertwich et al. 1997). Environmental stressors may be aggregated into impact categories or themes such as climate change, ozone depletion, human toxicity, ecosystem toxicity, and biotic resource depletion. Alternatively, impact can be reported in terms of damages, like years of life lost or an estimate of the monetary cost of damage (see 3.5).

Nevertheless, advancing sustainability through a deliberate and rational eco-design of the industrial activities would benefit greatly from properly constructed quantitative models that can support and connect the different prescriptive efforts, and thus assist in their co-ordination.

The descriptive material flow analysis approaches available can support prescriptive approaches. Many prescriptive approaches rely heavily on the description of transformations and flows of materials and energy, such as, BFA, SFA, LCA, Input-Output analysis, economic accounting etc. The LCA profile of a product can be used for comparison against competing products, or for suggesting ways to improve a particular product design. The LCA profiles can also be used to justify the eco-labeling of product designs. BFA, micro/meso-MFA and SFA are helpful in identifying defects, inefficiencies or leaks in processes or systems of processes. When applied to production processes it serves as a basis for cleaner production or pollution prevention to remedy those problems by process innovations. When applied to systems of processes, it serves a basis of industrial policy.

A description of the processes and flows to address IE strategies, such as dematerialization, or closing the material cycles, requires both scope and depth. Realizing these strategies requires detailed understanding of the capabilities of the underlying material and energy processing systems. To enable continued cycling of materials, obsolete products, and residues must be transformed into resources of a comparable quality as the original resources. Available knowledge, process operation and thermodynamics restrict the range of material combinations that can be transformed into new resources and products, and differ with their geographical distribution. Policy, product and process designs based on environmental considerations need to consider these (technological) constraints. However, often holistic approaches, such as industrial ecology, concentrate on scope and are perceived by engineers to suffer from lack-of-content (Boulding 1956). Even highly detailed studies on the flow of substances, such as the collection of articles tracing stocks and flows of copper in Europe by Graedel and colleagues (Graedel et al. 2002), overlook the complexity of the industrial (metal) metabolism. Also in authoritative Industrial Ecology handbooks, including Graedel and

Allenby 1995, Ayres and Ayres 1996, and Ayres and Ayres 2002, the industrial process routes are often oversimplified, or many interconnectivities and interdependencies are neglected (Verhoef 2003a, 2003b, 2004a, and Reuter 1998). Consequently, many real impediments to closing the material cycles and other strategies may be overlooked. (See also chapter 4.)

The various descriptive methods were developed for specific goals, concepts, time and spatial scales, rather than providing an integrated description of the flows and transformations and their impacts on the environment across various levels in the physical economy. As a consequence, each method is a compromise between scope and depth. As shown in Figure 1 and Table 1, the different MFA approaches are complementary. Each approach addresses different aspects of the overall objective, and can contribute to the understanding and improvement of the overall metabolism at various levels. Many researchers in the field observe a methodological convergence in the current trends in research and modeling of environment related flows in the physical economy (Tukker et al. 1995, 1996 and 1997, Kleijn et al. 1997, Van der Voet and Van Oers 1997, Udo de Haes et al. 1997, Bare et al. 2000, Van der Voet 2001, Daniels and Moore 2001, Heijungs et al. 2003). Such convergence could yield significant benefits with respect to the underlying data collection, access and conformity, and analytical conformity. It enables studies at a high level of aggregation to build on studies describing the underlying systems, or *vice versa.* The combination of the methods can thus provide both scope and depth. This is crucial to address industrial ecology strategies that often operate at multiple levels, and go beyond the scope of the tools individually.

2.6 The promise of Industrial Ecology

Industrial ecology is sometimes regarded as the science of sustainability. Its promise is a deliberate and rational approach of sustainability, given continued economic, cultural, and technological evolution. This section investigates whether the concept (2.6.1) and tools (2.6.2) make up for that promise.

2.6.1 The concept of industrial ecology

Sections 2.1 and 2.2 showed that sustainability is a complex concept with many different aspects. A first question is therefore to what extent the implementation of industrial ecology leads to sustainability.

Ehrenfeld (2000) distinguishes three categories of strategies for sustainability, each reflecting different aspects of sustainability: *Rationalistic* strategies are based on the historic ‘rational’ ways of thinking and reflect dominant basic ideologies such as competitive markets, utilitarian and optimism in technology. *Naturalistic* strategies are based on models of natural systems and their limits in supporting human economic activities. *Humanistic* strategies emphasize the ‘flourishing’ aspect of sustainability.

Industrial ecology falls into the naturalistic category. It uses a biological analogy to describe and analyze industrial systems. It is based on models of natural systems that are thought to be the best or perhaps the only examples of sustainable systems. Nature consists of ecosystems: carefully balanced, and integrated closed loop systems of co-operating organisms and their physical surroundings. These ecosystems have certain properties that can be applied to the industrial activities to make them more sustainable. Although the analogy between the industrial ecosystem concept and the biological system is not perfect, much could be gained if the industrial system were to mimic the best features of the biological analogy (Erkman et al. 2002, after Frosch and Gallopoulos 1992).

The objective of a deliberate and rational approach of sustainability[9] reflects that industrial ecology may contain rationalistic elements as well. Graedel and Allenby 1995 explain that the words deliberately and rationally indicate that the intent of the field of industrial ecology is to provide the technological and scientific basis for a considered path towards global sustainability, in contrast to unplanned, precipitous and potentially quite costly and disastrous alternatives. Extended producer responsibility, resource or eco-efficiency, the precautionary principle and product-service systems are recent examples of rationalistic strategies (Ehrenfeld 2000) but are also important strategies in industrial ecology. A distinctive characteristic of industrial ecology is that it puts rationalistic strategies of reductionist science and linear short term and obvious causality by more systems-based, into context of comprehensive naturalistic approaches.

Desirable in the objective of industrial ecology[8] indicates that, given the potential for different technologies, cultures and forms of economic organization, a number of sustainable states may exist. It thus becomes a human responsibility to choose among them, and act so as to approach the desired state that otherwise would not have occurred. Industrial ecology strives to be objective, not normative. Thus where cultural, political or psychological issues arise in industrial ecology, they are evaluated as objective dimensions of the problem (Graedel and Allenby 1998). Hertwhich and Dutchin and Hertwich (2003) describe it as follows: *Industrial Ecology aims to provide information for decision makers, especially in a corporate setting, but also in public institutions and households. It has until now not embraced systematic approach to studying the economic, social and psychological aspects of decision-making. While Industrial Ecology is a truly interdisciplinary enterprise, the concerns of social scientists are addressed only on its margins.* Apart from converting products to services strategies, industrial ecology does not really address the 'flourishing' aspect of sustainability (see Ehrenfeld 2000).

Industrial ecology only involves some aspects of sustainability. It focuses mainly on industrial activities, and seeks technological evolution based on ecosystems models to keep industrial activity within environmental constraints. Industrial ecology optimizes only part of the system. As the concept of a sustainable subsystem in an unsustainable global system is a fundamental oxymoron, implementation of industrial ecology alone can not lead to sustainability. Industrial ecology is, rather than a systems approach to sustainability, a critical step towards sustainability that may buy the time necessary for the cultural/social evolution.

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[9] Industrial ecology is the means by which humanity can deliberately and rationally approach a desirable carrying capacity, given continued economic, cultural, and technological evolution. See section 2.3.

2.6.2 Tools

Allenby (1999) suggested that because of the systemic character of sustainability, the western concepts of reductionist science and linear short term and obvious causality will have to be augmented by more systems-based, comprehensive approaches to develop the appropriate tools to approach sustainability. Industrial ecology provides for at least part of the context that would allow for the development of these tools. The second question is to what extent the available set of tools enables the implementation of industrial ecology, and advance towards sustainability.

In potential, industrial ecology is a systemic framework that connects environmental problems, issues and analyses at different scales and a context for adapting and applying existing methods and tools, and for creating new ones (Lowe et al. 1997a: 37). In addition, industrial ecology could provide for a multidisciplinary 'forum' or a common language to overcome conceptual and professional isolation, and differences in interpretation.

The strength of industrial ecology is that is provides a context for analyzing the industrial economy at different levels of aggregation, from individual reactors, processes and products to the global material cycles. This ambitious domain of application is at the same time also the weakness of industrial ecology. The literature on industrial ecology is a cluster of more or less interrelated concepts, tools, metaphors and exemplary applications and objectives (Lifset and Graedel 2002), and has no clear demarcation of the field. Each of these concepts, studies and tools is based on different interpretations of the content of the field, and addresses different problems, which in turn results in different sets of system components and levels of aggregation used. The latter appears common also in ecological studies, where different 'ecosystems' can be chosen depending on the issue addressed.

The current vagueness of the concept opens the way for potential misuse as marketing or public relation tool (Den Hond 2000). It allows for trivializing the problem by emphasizing small, internal components of the industry rather than its large, more basic interaction with the environment (Commoner 1997). Or it loses its content as an analytical or prescriptive tool by including so many details that no realistic solution can be found (Boon and Baas 1997).

Boon and Baas (1997) promote a choice of optimization domain of industrial ecology; this could ease its acceptation as an analytical tool. However, sustainability is an emergent characteristic of the global economy as a whole. A too narrow choice of a domain may limit the set of problems and solutions visible, or lead to suboptimum or unsustainable solutions. The knowledge of the system to understand and guide industrial systems towards sustainability must be obtained through analyses and co-ordination of activities across different levels of aggregation (Lowe 1993, Frosch and Gallopoulos 1992, Sagar and Frosch 1997, Weston and Ruth 1997, Reuter 1998)[10]. Rather than a choice of optimization domain, Lifset and Graedel (2002) stressed the

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[10] Indurtsial ecology begins with process optimisation (Frosch and Gallopoulos 1992), but must go 'beyond individual company or plant boundaries to seek improvements in the performance of larger systems' (Lowe 1993).

importance of understanding the 'endeavors that comprise industrial ecology and how those endeavors interrelate to each other'.

In a recent editorial of the Journal of Industrial Ecology, Allen (2001) discussed the need for a set of core principles and tools. He also concluded that it is time to 'begin to more clearly articulate our field, its principles, its tools, and, possibly, its values'. Lifset and Graedel (2002) do not consider the current looseness as a fatal flaw in an emerging field, but rather as an opportunity for creativity and constructive discourse, and as a challenge. However, it is challenge that must be addressed to deliberately co-ordinate industrial ecology endeavors to accomplish the desired (technical) evolution.

The methodological convergence in the current trends in research and modeling of environment related flows in the physical economy appears a first, but critical step. For the development of a consistent framework connecting the prescriptive studies at various system levels, the different descriptive approaches must be connected as well, i.e. at least able to use each others data and results, and/or more advanced industrial ecology models must be developed span various system levels. Ehrenfeld (1992) once coined industrial ecology a technological approach to sustainability; the patterns and transformations of mass (and energy) flows, upon which all the model approaches are based, are largely shaped by the technological system. To realize a consistent framework, industrial ecologists should therefore particularly take care of a sufficient 'technological' depth in these models. To date, but most of the descriptive studies oversimplified this system.

2.7 Conclusion

In the last decades, sustainable development has become the cornerstone of environmental policy, and a leading principle for resource management. Sustainability, the continued welfare of human and other life on earth, is an emerging system property. The designation refers to the fact that sustainability is a property of the system as a whole and that one can not know that the system is sustainable until in fact sustainability has been achieved. Sustainability is not a specific system configuration that can be accomplished, but rather a property that emerges from the continuous co-evolution of human and natural systems. As a consequence the concept of sustainability provides little assistance for decision making in specific cases.

Industrial ecology is a promising systems approach that focuses on a part of sustainability. It can make the concept of sustainability applicable to decision-making. Based on sustainable examples in nature, ecosystems, it aims to achieve a deliberate (r)evolution of industrial activities within the boundaries set forth by natural systems they are founded on. Industrial ecology thus determines the industrial conditions for sustainability. Its implementation can buy time for the necessary societal evolution.

This deliberate development of industrial systems towards sustainability requires (i) the co-ordination of industrial activities mutually, and with the other activities in the resource cycles, and therefore (ii) the support of decision-making across various organizational levels that influence industrial activities. Two elements can be distinguished in industrial ecology approach: descriptive and prescriptive elements. The descriptive element describes the industrial system at and across system levels. The prescriptive element aims to stimulate decision-making based on considerations of sustainability. However, different prescriptive elements are not always complementary, and can be conflicting. For the realization of the objective, through co-ordination of decision-making across system levels, descriptive approaches should be able link the different prescriptive efforts by showing their effect consistently at the various levels of the industrial system. This can be realized by proper modeling of the underlying technological subsystems, and convergence of the different descriptive models that generally address the higher system levels. Only if industrial ecology models can build on the results of models of underlying systems (and the other way round), a consistent picture of the influence of different effort can be obtained.

3 A description of the metal cycles

Summary

The systemic perspective of industrial ecology calls for a shift from dealing with isolated, relatively simple systems to managing complex, interdependent systems. Quantitative models are essential in acquiring insight in the behavior of such systems, and thus for advancing industrial ecology. The interconnected metal cycles, the metal production and recovery system in particular, form an example of such a complex system. Industrial ecology inventories have oversimplified metal production system systems, and as a consequence cannot to be expected to invoke improvement in these systems.

This chapter presents a description of the metabolic routes through society as a basis for quantitative modeling, focusing on metal production and recycling. Most metal and material cycles are rather complex and interconnected, which calls for a suitable architecture before they can be simulated satisfactorily. How can interdependent networks of processes be mapped and characterized? What level of resolution is necessary to characterize the material cycles. What type of information is necessary and what information is available? The chapter starts with a general introduction on the metals production (3.1 and 3.2), the suitable modeling architecture (3.3) and the availability of data (3.4). Finally, the implications of this modeling/inventory approach are discussed with respect to the descriptive approaches of industrial ecology and the quantification of the physical economy (3.5).

3.1 Metal resource cycles

The systemic perspective of industrial ecology calls for a shift from dealing with isolated, relatively simple systems to managing complex, interdependent systems. Quantitative models are essential in acquiring insight in the behavior of such systems, and for advancing industrial ecology. Ideally, such models must be able to visualize the behavior of the systems, and link the behavior to environmental issues. This involves two stages: first, one must make a mathematical reconstruction to predict flows and transformations across system levels, as well as the emissions in and extractions from the environment caused by flows and transformations; second, one needs to translate these emissions and extractions into impacts to the environment, which are understandable to decision-makers. In this chapter, the quantitative description of the systems of the different interdependent processes involved in production and recycling of eleven metals is presented.

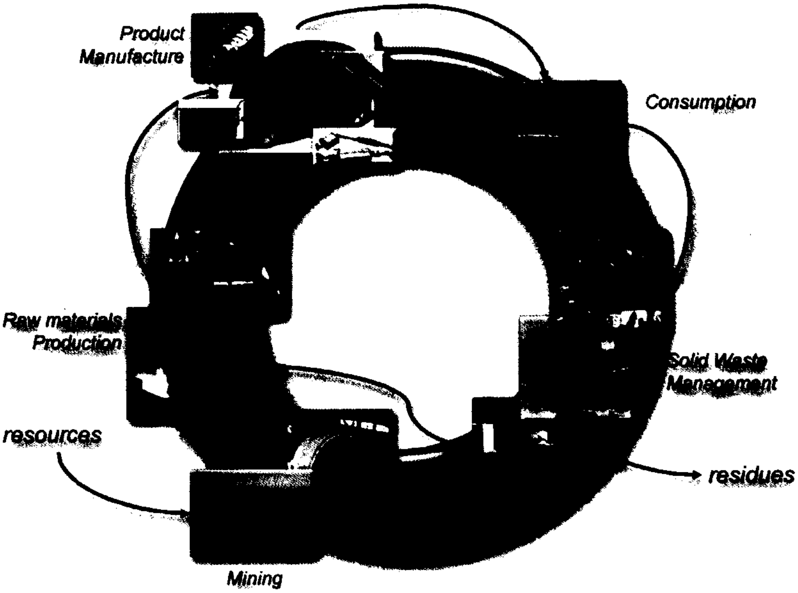

Figure 3-1: The life cycle of a car: natural resources (e.g. ores, oil) are mined/extracted, concentrated, and processed into raw materials (e.g. metals, plastics). The car components are made from these raw materials and combined in the manufacture of the end-product. After its useful life the car is dismantled, shredded and separated into new resources that complement primary resources (after Reuter 2004).

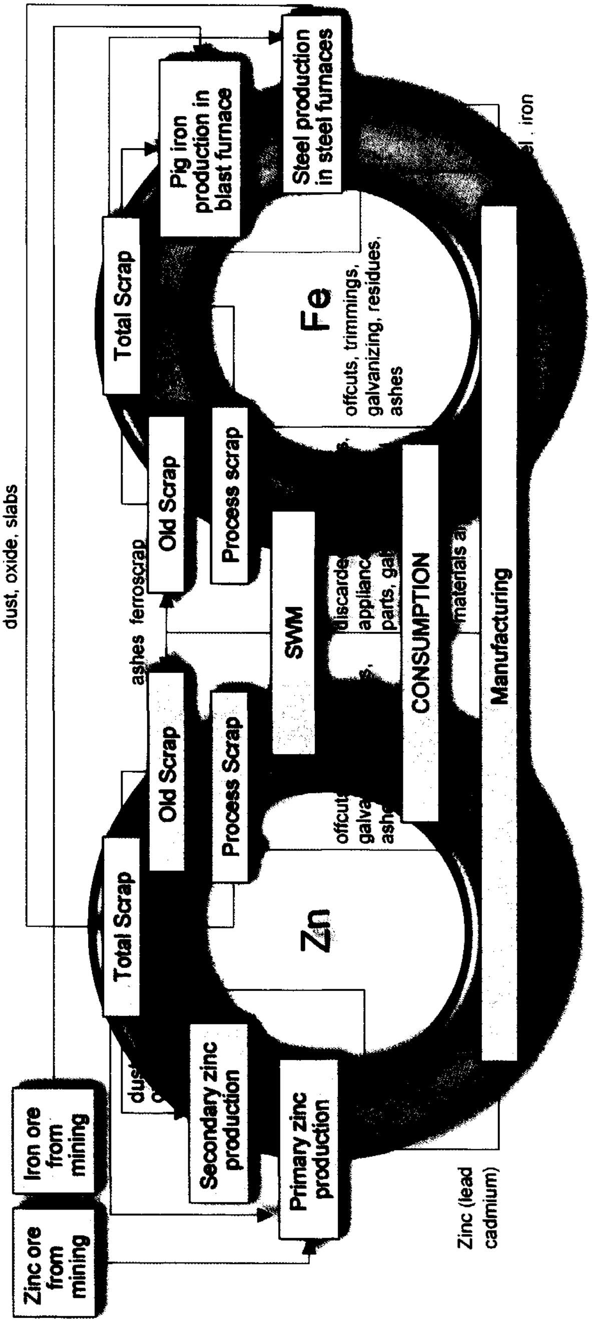

Figure 3-2: The coupling of the iron and zinc resource cycles through their combination in cars; zinc from the galvanized steel parts is separated in the steel furnace and concentrated in the Waelz kiln to be refined to a grade of zinc that can be used again for galvanizing.

An interconnected resource cycle perspective is used, which also a common way of abstraction in ecology and biology. In industrial ecology literature, often a life cycle perspective is used. Figure 3-1 shows the life cycle of a car. Because for the production, use and recycle many different materials are involved, its production connects the resource cycles of these materials (see also chapter 1 and 4). For example the zinc en steel cycles as illustrated in Figure 3-2. These interconnected industrial metal resource cycles – consisting of the metal mining, production, manufacture and recycling systems - appear an excellent case study to investigate the possibility of capturing complex systems in quantitative models for two reasons.

First, industrial ecology attempts to design and manage industrial systems as ecosystems through adaptation of typical ecosystem features including, minimal use of resources and minimal production of wastes by cascading the use of resources and energy. Because the industrial metal systems have been around for a long time, most of the metal processing technologies are well developed, and the 'industrial ecosystem' is well established. The next section, which discusses the metal production from an industrial ecological perspective, will show metal production systems have already largely adapted these and other typical ecosystem features (e.g. a certain 'resilience' to 'environmental perturbation' through interdependence and diversity of its components and diversity in its material flow patterns).

Second, metals constitute a significant part of the industrial materials consumption and are thus important resources in absolute terms. Moreover, metals have been catalyst for the development of biological life and in the development of our current civilization. Today metals have invaded virtually all aspects of the Western lifestyle.

Third, industrial ecologist perceive the metal production processes as an important source of pollution, but simultaneous recognize their importance for present industrial societies: Sagar and Frosch (1997) for example argue that metals are unlikely to be displaced by other materials to a significant extent in the near future because other materials suffer from constraints that will continue to make metals useful: polymers, for example, can not routinely offer the stiffness, strength, and heat resistance that metals can, and ceramics do not offer the same toughness or impact resistance.

3.2 An introduction to metal production

To meet the demand for metals, enormous quantities of metal ores are extracted from the earth's crust each year. Metal ores are minerals that contain a relatively high percentage of one or more metals, but typically contain many other elements as well (Figure 3-3). The production of refined metals from the ores involves the removal and processing of much more materials than the amount of refined metal eventually produced. A large amount of the extra material is removed at the mining sites as gangue or overburden. Even after this concentration process, the ores shipped to the metal production facilities are still very heterogeneous in nature; the exact composition of the ores varies with mining location. Secondary raw materials are very heterogeneous in nature as well and their composition changes with location and time.

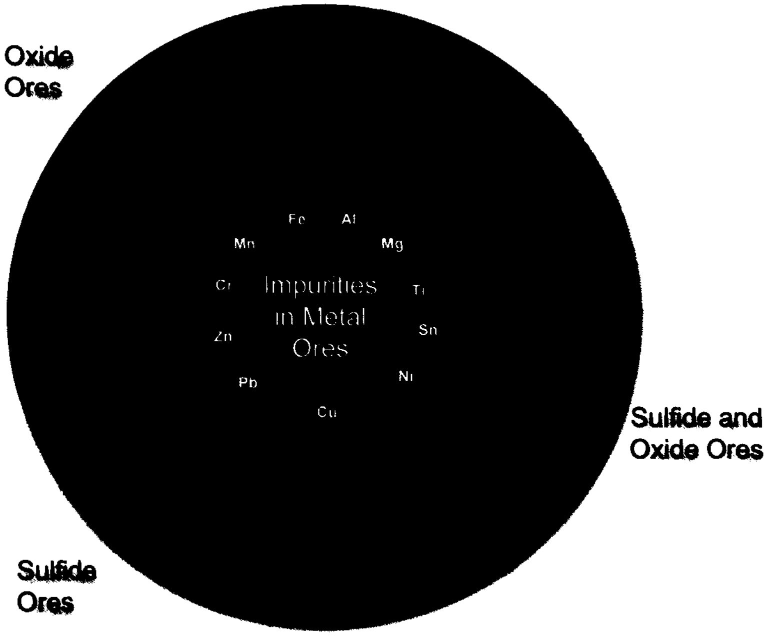

Figure 3-3: The impurities in the ores of different base metals. The bold radial lines divide the metals into three groups, sulfide ore, oxide ore, and a mixture of sulfide and oxide ores, whereas the lighter radial lines separate the individual metals. The light radial line odes not separate zinc and lead ores completely because these metals are typically mined together.

3.2.1 Interdependence

Ecosystems tend to develop towards increased diversity and interdependence. Similarly, the metal system has developed towards increased diversity and interdependence in order to maximize productivity and economic efficiency. The different ore compositions and effect of impurities (i.e. the other metals or 'co-elements') in ores on the metallurgy shaped the development of the industrial infrastructure for metals processing. Among others due to the slow development of metallurgical processes, their long lead times and economic life spans, the metal production network developed as an interconnected and integrated system that incorporates multiple production routes for a spectrum of metals. More often than not, the production or recovery of a single metal is related to or dependent on the generation or recovery of other metals. Diversity in and interconnectivity between metallurgical processes are key elements in the development of the metallurgical capacity to exploit the economic benefits of the impurities and to cope with increasing environmental pressure.

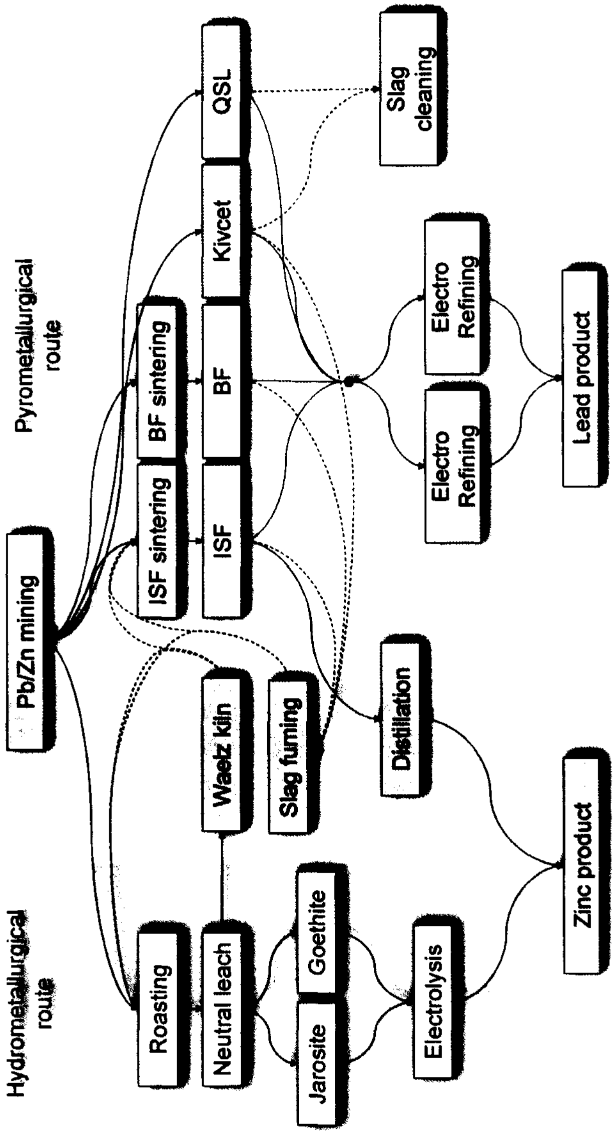

Figure 3-4: Simplified flow chart of the interconnected primary zinc and lead metal production routes. Legends: ISF = Imperial Smelting Furnace, BF= Blast Furnace, Neutral leach= Neutral Leach Process, KIVCET = KIVCET Furnace, QSL=QSL Furnace, Jarosite = Jarosite Precipitation Process, Goethite = Goethite precipitation Process (Verhoef et al. 2004a).[1]

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[1] Note that the hydrometallurgical pressure leaching route, which produces hematite as residue instead of goethite or jarosite, is not included as it is not a major route.

To illustrate this, the development of lead and zinc production is taken as an example. An overview of the major production routes of a number of other metals and their interconnectivity is presented in appendix A. In order to realize the potential economic importance of impurities and meet the increasing environmental pressure, research and development integrated the processes of copper production with those of lead and zinc, and connected the processes to those of among others silver, bismuth, tin and the platinum group metals (PGMs). The recovery of these metals is complex, as most of the elements must be circulated between two or more production circuits (e.g. PGMs are concentrated in the nickel and gold circuits, see Figure 3-13) before they are concentrated enough to make their extraction possible, and their recovery as a metal profitable. In addition to recoverable elements, there are a number of other elements that must be separated to allow production of high-grade metals. These elements are usually separated in the slag or off-gas treatment system, at one stage or another in the web of processes. As a consequence, the production of these metals is so interdependent that they can hardly be considered separately.

In zinc processing, for example, two complementary process routes co-exist (Figure 3-4). On the one hand, hydrometallurgical zinc production offers the lowest operating costs, but it can only be employed for very specific types of zinc ores. On the other hand however, one can employ a variety of primary and secondary raw materials in pyro-metallurgical zinc production, and recovery of by-products and residues is feasible (IZA 2001). The combination of these two routes can be more effective in minimizing the environmental impacts of the metal production system, than either one individually.

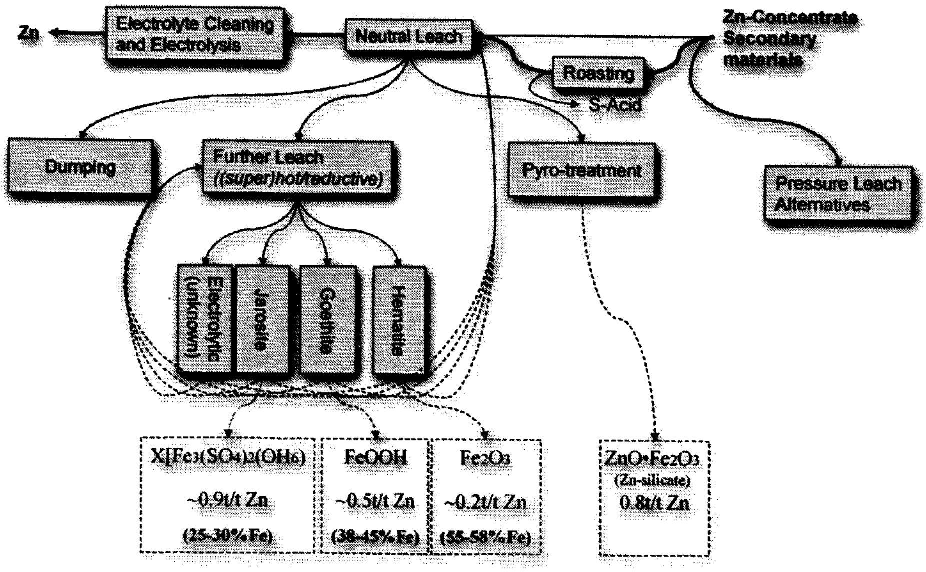

Figure 3-5: Process options for iron removal in hydrometallurgical zinc route (IZA 2001).

In case a feedstock contains iron compounds for example, the hydrometallurgical route would generate a hazardous iron residue in the neutral leach process (Figure 3-5) Processing the iron-containing feed in the pyrometallurgical route, would lead to the use of extra fossil fuel (cokes, coal etc.) and to more emissions compared to the hydrometallurgical route. In the combination, however, the hazardous residue that originates from hydrometallurgical zinc processing can be treated via the pyrometallurgical route. More specifically, the pyrometallurgical Waelz kiln or Imperial Smelter Furnace (ISF) can be integrated into the hydrometallurgical route and reduce zinc ferrite to form zinc oxide and iron (Sudhölter et al. 1996).

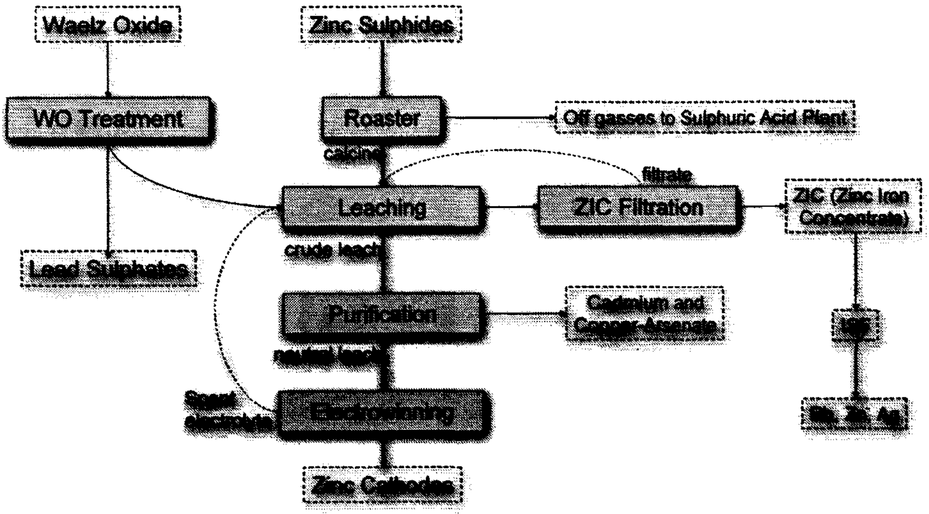

Figure 3-6: Schematic flowsheet of the Ruhr-Zink GMBH zinc plant in Germany (Auping et al. 2000).

For instance, at Ruhr-Zink about 30 different concentrates are roasted and subsequently leached for zinc dissolution and iron removal (Figure 3-6). After purification of the zinc containing solution zinc is recovered in the electrowinning plant. The leaching process at Ruhr-Zink passed through most of different technological developments in Figure 3-5 since its start up (1968). Iron was separated from the solution initially as Jarosite, later as Hematite. Pressure leaching was applied for a while to increase the production capacity. Today Ruhr-Zinc is back to a rather classical type of process, which in the midterm might turn out to be among the most modern and future oriented technologies (IZA 2001). While most of the world wide hydrometallurgical plants for zinc recovery still precipitate the iron from the leaching solution as jarosite which is dumped in ponds or caves, Ruhr-Zink stops its leaching operation before the iron content of the concentrate is dissolved thus producing a Zinc Ion Concentrate (ZIC) which is shipped to an Imperial Smelting facility for further recovery of the valuable elements Zn, Pb and

Ag. The iron in the Ruhr-Zinc process is bound in the stable slag of the IS-furnace, which can be used for road construction. Figure 3-6 shows that in addition to the primary concentrates, Ruhr-Zink also processes an increasing amount of secondary Waelz oxides.

Another example of successful integration is the zinc-lead Plant at Portovesme in Italy (Sardinia) that originally consisted of a sintering facility, an Imperial Smelter furnace, two additional Waelz kiln to pre-treat local ores, a small rotary kiln for the production of clinker, a cadmium plant, a zinc refinery and a sulfuric acid plant. The addition of an electrolytic zinc plant (1985) and a Kivcet smelter (1987) fully integrated the production of lead and zinc (Figure 3-7). This did not only result in a large production capacity for lead and zinc, but also in an optimum metal recovery and minimized amount of waste materials due to the internal cycles of flue dusts, residues, and other streams (IZA 2001).

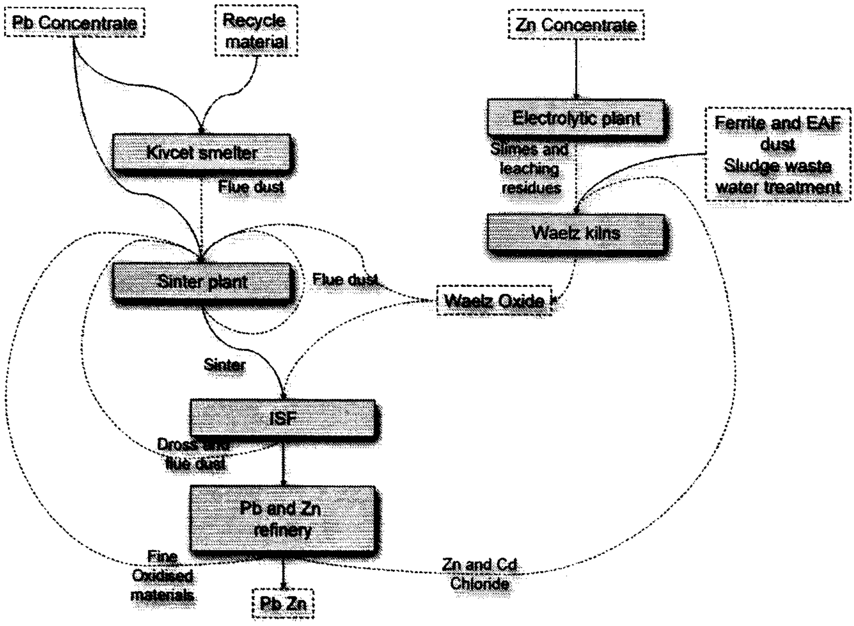

Figure 3-7: Schematic flowsheet of the residue processing at Glencore International AG zinc-lead Plant in Portovesme, Italy (IZA 2001).

3.2.2 Resilience

Ecosystems must continuously adapt to changes in their surroundings, or else they vanish by ecosystem transformation, or ecological succession. Ecosystems are resilient to changes in their environment through continuous changes in populations of all the organisms in ecosystems, and their adaptation on the longer run. In case, perturbations in the environment are larger than certain ecological thresholds, ecosystems may collapse to be replaced or develop into new ecosystems with a different community structure, often better adapted to the perturbations. Odum (1969), Lovelock (1979 and 1988) and others saw the development of ecosystems as a "strategy" of increased control of the physical environment toward achieving a homeostasis, which provides maximum protection from environmental perturbation. Increased biodiversity and pattern diversity are characteristic for the homeostasis-state.

The industrial diversity and diversity in production patterns also provide for resilience and flexibility in the production of metals. Each metal process has a different knowledge base (metallurgical, technological, fundamental and theoretical expertise), and technological capacity to deal with different concentrations of metal, impurities and valuable elements. Different ways of interconnection of the processes provide a flexibility to deal with concentrates of different composition and improved residue processing. Waelz kilns can process a wide range of raw materials with as lows as 25% (or even 15%) zinc content, among others hydrometallurgical leach residues, into suitable zinc concentrates of around 45% zinc content. Figure 3-8 shows the options for processing of the Waelz oxide and slag. Dependent on the raw materials used, and/or the demand for (zinc) concentrates, the slag and oxide can follow different routes to refined zinc, iron/steel and other metals.

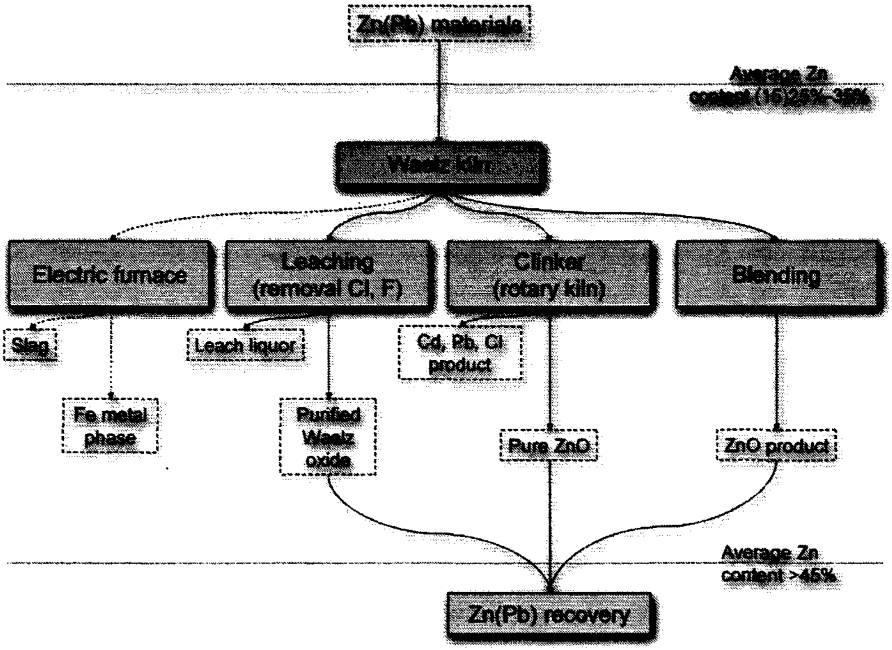

Figure 3-8: Process options for Waelz oxide and slag processing (IZA 2001). In addition, the Waelz slag can be applied for dike building etc. without or with limited further processing such as the removal of iron.

The primary product of the Waelz kiln is an impure grade of zinc oxide. The zinc oxide is usually calcined in a rotary kiln to produce clinker oxide, to make it suitable as raw material for the production of zinc metal and/or chemicals. Calcination is operated to volatilize Pb to PbO and also to remove other impurities such as Cl and F. The Waelz oxide can also be used as a raw material for the hydrometallurgical zinc process, but then the chlorides that contaminate the Waelz oxide must be removed by leaching (see also Figure 3-6). The iron compounds in the feed are removed in the slag (the secondary product of the Waelz kiln) as FeO or to some extent iron metal. Other principal components of the slag are CaO and SiO2. The slag is for instance reused for road construction, as fertilizers or as a base for the sinter mix in iron-making.

Figure 3-4 is a simplification; it shows the major production routes for zinc. The diversity and partial overlap in process functions between different metallurgical processes allow a certain flexibility in the zinc-lead production routes. Besides treatment in an ISF or Waelz kiln, hydrometallurgical residues can also be treated in a Kivcet smelter. Figure 3-9 shows the fully integrated processing of lead and zinc at the Trail facility. Iron and lead residues created in the zinc operations ('intermediates to smelter') are processed in the lead operation and comprise nearly half of the total feed of the Kivcet. Zinc-rich smelter fume is fed back to zinc operation and makes up about 15% of the total feed. Sulfur dioxide off-gases from the roasting process are fed to the sulfur gas handling plants in the zinc operation and wastewater streams from both lead and zinc operations are treated in the effluent treatment plant.

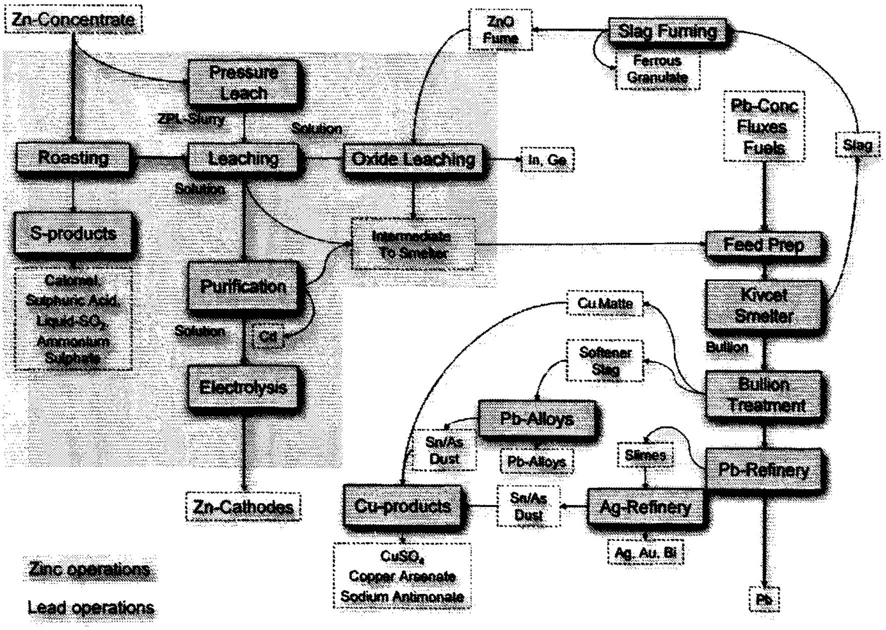

Figure 3-9: Schematic flowsheet of the Cominco zinc-lead Plant at Trail in Canada (source: De Groot et al. 2000).

The combined zinc and lead production can also recover indium, germanium, silver, gold, bismuth, arsenic metal, and copper products. Indium, germanium are recovered in an oxide leaching step, which pre-treats the zinc oxide fumes from the lead operations. Pressure leaching is integrated in the zinc operations, recovering elemental sulfur. The leach residues are a secondary sulfur raw material for the lead smelter. The cement from the purification of the zinc bearing solution is further treated to recover cadmium and a copper cake; zinc is produced in an electrolytic operation. The lead operations of the Trail plant treat zinc residues, lead concentrates, recycled batteries and lead bullion to produce silver, gold, bismuth, arsenic metal, copper sulfate, copper arsenate, sodium antimonite.

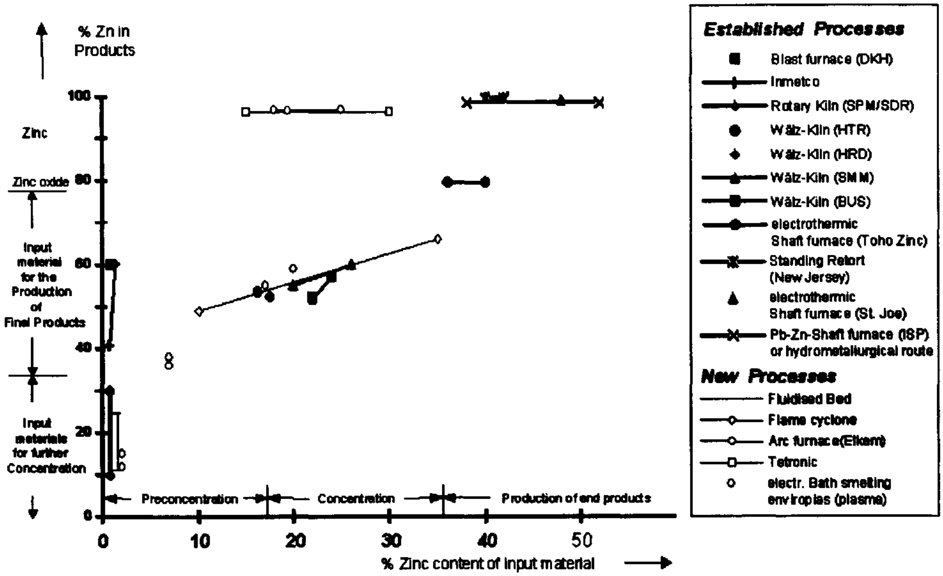

Figure 3-10: Processing specifications for zinc - overview (Grund 1995). Picture shows feed and product concentrations of zinc processes.

Because of the many different processes available for zinc production from concentrates with varying zinc concentrations (Figure 3-10) and impurity levels, the integrated metal production circuits also provide a limited flexibility to deal with varying concentration of the bulk metal. For zinc, for example, no processes are currently available for the processing of materials that contain 4-8% Zn. Figure 3-10 shows the available technology to process raw materials of different input concentrations of zinc (x-axis). On the y-axis one can read the produced zinc concentration of that technology. The figure illustrates that a combination of processes allows the processing of most concentrations of zinc.

Dependent on the concentration and composition of the concentrate different routes for metal production are available. Zinc concentrates of 2 % Zn can be processed in Rotary kiln to 10-30%, further concentrated in a Waelz kiln to 50-60% and finally refined to zinc metal in the Imperial Smelting process (ISP) or the hydrometallurgical route, for example. Above zinc concentration of 35%, zinc metal (100%) can be produced in one step. Usually the primary concentrates for zinc metal production lie around 55%. At system level, this means that for a continually changing feedstock, the geographical routes from (primary or secondary) raw material to metal can not be fixed, but must also be subject to change.

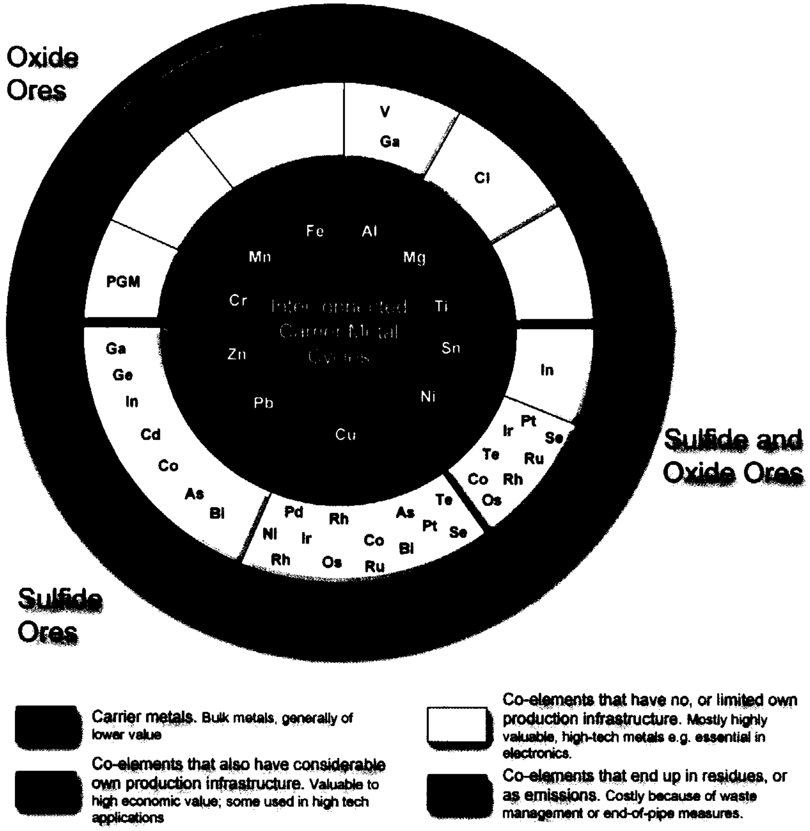

Figure 3-11: 'The metal wheel': The metal wheel complements Figure 3-3 by showing metal linkages in natural resource processing, illustrating the capacity of available metallurgical processes to deal with impurities in their (primary or secondary) feed. Co-elements are economically and technologically valuable minor elements or impurities found in ores of the carrier metals (Verhoef et al. 2004a).

3.2.3 Tacit Knowledge

It can be easily seen there is not a single technology available that can produce and recycle all metals. Rather the metallurgical system consists of large number of different processes that are interdependent and must co-operate and compete to produce metals from a wide-ranging and changing set of raw materials[2]. In an industrial ecology perspective, the metal ecology can be seen as an evolving system made up of (semi-) autonomous 'organisms', that have partially overlapping functionalities, and self-organize into many higher-level structures such as production circuits, or sectors in a bottom-up fashion (after Andrews 2002).These interconnected networks are examples of industrial ecology in practice, but unlike local eco-industrial parks, such as Kalundborg, the metal networks span the globe. At a global scale it can be seen that the metallurgical and other industrial or waste management processes, form complex networks of processes that are interconnected through mass and energy flows. The networks exhibit typical ecosystem type II properties. First of all, their networked organization enables the relatively high recycling rates of metals. High efficiency and flexibility of metal production, necessary to deal with changing primary/secondary raw materials, are maintained through the partial overlapping functions of the processes and the intensive exchange of by-products and residues. The function of each industrial organism in the networks is partly determined by characteristic features associated with its species (Waelz kiln, ISF etc.), but also partly by its history and development. Similar to nature where each individual of a species exhibits also unique behavior shaped by its personal experiences and development, each process type has typical strengths and weaknesses but is unique in its behavior.

Figure 3-11 illustrates the combined metallurgical expertise and capacity to deal with impurities and minor elements, in their feed. The inner ring shows the bulk metals, the three outer rings contain the impurities and minor elements, present in the ores the bulk metals are associated with. In order to maximize economic benefits and minimize environmental impact, metal production processes (of metals mostly associated with sulfide ores) have developed knowledge and technological capacity to recover most of these impurities as compounds (the two middle rings), and minimize the elements lost to process residues or emissions (the outer ring of the four rings).

A reasonable part of metallurgical expertise and technological capacity of metallurgical processes to deal with changing and complex raw materials is based on operational knowledge, because the physics and thermodynamics of the metallurgical processes are not fully known. Pyrometallurgical processes are complex and typically do not operate at thermodynamic equilibrium conditions, due to multiphase reactions at high temperatures and the resulting strong temperature gradients, complex ill-defined feeds, and large thermal and mass inertia. The dynamics of such processes are difficult to capture in mathematical models. The knowledge base and technological capacity of each process to deal with impurities and minor elements develop over time with variations and gradual changes in the input of each process ('learning-by-doing'). The type of process knowledge is important to deal with the dynamics in feed composition and enable flexible routing through the integrated metal production circuits, but also as a source of metallurgical expertise for the development of new processes, or adapt existing processes to new specifications, feeds or legislation. An example of the latter is the imperial Smelting process for zinc and lead production that over time 'learned' to process an increasing amount of secondary materials of widely varying compositions

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[2] Reasons for the development of such diverse and interdependent system include the long life spans of metallurgical processes and the slow development of new technology and alternative process options.

(Schneider and Schwab 1998, Lee 2000, Schneider et al. 2000). Today the Imperial Smelting process accepts nearly 100% secondary materials. The network resilience/flexibility and development of tacit knowledge point to another parallel with natural ecosystems: conserving biodiversity is critical to survival and development of natural ecosystems. Maintaining a sufficient industrial diversity of metal processes is also critical to conserve the pool of metallurgical expertise as well as technological capacity for production and recycling of metals indicated in the metal wheel.

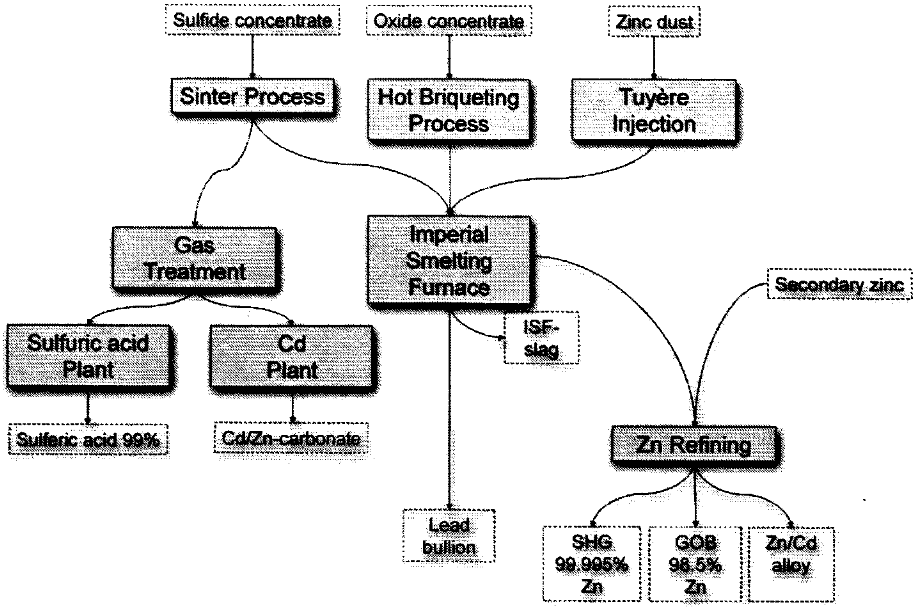

Figure 3-12: Imperial Smelting Process at M.I.M. Hüttenwerke Duisburg GmbH in Duisburg-Wanheim, German (Schneider and Schwab 1998).

3.3 Industrial ecology models for metal production/recycling

The industrial metal resource cycle operates and interacts at different distinct scales: from the exchange of intermediates at process or reactor level, to the global interactions between product manufacture, consumption, solid waste management, mining, and metal production. All of which affect directly and indirectly the flows of metals. This can lead to changes in the production efficiency or environmental impact of one or more metals because of differences in metal recovery efficiencies and environmental performances of each route. In addition, due to local differences between processes, changes in the geographical metal production routes affect the metal metabolism.

As mentioned in chapter two, the ideas on 'industrial metabolism' of Robert Ayres provided means to support the decision-making on industrial ecological principles to key decision-makers, such as regulators, industrial managers or engineers (Kneese et al.

1970, Ayres 1989). Ayres suggested to describe the metabolism of the industrial system through detailed 'material balances', which could be compiled at different spatial scales, e.g. for a production unit, such as a reactor, a factory, or the global metal production system. This approach would be suitable to model the metal ecology, which operates and interacts at different distinct scales: from the local exchange of intermediates to the global interactions between resource cycle stages. Without sufficient detail of the underlying networks of reactors, the flows between the different stages, and from and into the environment can not be adequately estimated.

Inventories in industrial ecology literature often simplify process routes for metals into simple averaging black boxes that represent whole processes, production routes, or even the total production of a metal. In this section, it will be shown that such a level of simplification hardly makes it possible to capture the detail of complex interconnected material processing systems, such as the metals processing system. Consequently, the contribution of these inventories as tools to invoke improvement for metals processing and recycling systems may be questionable. At least two reasons for simplification of process routes have been used. Some may argue that the system is too complicated to completely modeled, or that sufficient data is not (readily) available. The subsequent sections will show that these arguments do not necessarily block the consideration of metal production system at sufficient detail in industrial ecology studies.

3.3.1 Methodology

The metal resource cycles are rather complex and interconnected, which calls for a suitable architecture before they can be simulated satisfactorily (Reuter 1998). Methodology to construct material balances at the level of a production unit, such as a factory, is well developed (see e.g. Douglas 1988, Sinnott 1993, Allen and Shonnard 2002). As discussed in chapter two, Material Flow Analysis (MFA) provides a general architecture or framework to model the throughput of global industrial systems at larger system scales. In these systems different subsystems are generally distinguished involving the extraction, chemical transformation, manufacturing, consumption, recycling and disposal of materials (Bringezu 2002).

The methods within the MFA framework typically focus on specific part of the global industrial system, and differ in the way they consider the dynamics of the system. Life cycle analysis (LCA) for example typically lacks a time dimension, whereas Substance Flow Analysis (SFA) typically involves a time dimension. The development of a paradigm embracing the identification and tracing physical flows of materials and energy has been slow, and still lacks a clearly defined methodology (Fischer-Kowalski 1999). The LCA methodology is a good example of an industrial ecology architecture. LCA accounts for most industrial ecology studies and contributions to journals and conferences. The development of LCA methodology started in the 1970s, and a standardized LCA framework has been more or less established. Moreover, there is an increasing effort to develop such a methodology and/or combine elements of different methods for wider applicability (e.g. Tukker et al 1997, Van der Voet and Van Oers 1997, Daniels and Moore 2002). Because of its advanced state of development LCA can serve as a basis for the further development of these methods. An example of this convergence is the use the LCA framework for SFA (Van der Voet 2002, Udo de Haes 1997).

LCA methodology consists of four stages: goal, inventory, impact assessment and interpretation (e.g. ISO (1998) and SETAC standards). Despite the long history of standardization of LCA, the methodology is still 'under construction'. The inventory phase has developed furthest, while interpretation and impact assessment are least advanced. The main focus will be on the inventory phase; goal and impact assessment will only be briefly discussed (in 3.3.2 and 3.5 respectively). Although the ISO standards for LCA provide a starting point for constructing an LCA or SFA, they do not regulate all methodological choices. Consequently, virtually any result can be produced (Ekvall and Finnveden 2000). This holds particularly true for complex systems, such as the global metal production system, even when one considers only parts of it.

3.3.2 Goal, scope and resolution

According to Ekvall and Finnveden (2000), the "value of an LCA depends on the extent to which it increases our ability to anticipate environmental consequences of manipulating technological systems". Thus, the goal of any LCA should be to "provide as clear and comprehensive as possible a picture of the environmental consequences of our actions." Obviously, the required 'comprehensiveness' of LCA is goal dependent. According to the LCA methodology, establishing the goal of the study includes establishing the boundaries of the picture painted. The procedure for determining the assessment boundaries is iterative and can only be carried out while the inventory analysis is performed (Fleisher 1992, SETAC 1993). According to the ISO 14041 system boundaries should be selected so that at least all the inputs and outputs are elementary flows[3]. The assessment boundaries can be further determined by cut-off criteria, which in turn depend on the level of detail specified in the goal and may be stated in a percentage. If the change in substance or energy due to certain activities falls below a specified level of change, the process chain leading to the creation of the substance or energy needs not to be included in the study (Baumann 1998, ISO 1998, Ekvall and Finnveden 2000).

Todd and Curran (1999) argue that industrial processes are so extensively interconnected globally that complete consideration of all these interdependencies is prohibitive. The definition of the scope should be such that the breadth and depth of the study are compatible with the stated goal. Thus based on the stated goal, decisions must be made on which processes or activities will be included, and to which extent these activities or processes belong to the foreground or background systems. Todd and Curran (1999) discuss a variety of possible approaches for simplifying the LCI methodology and reducing the amount of data required. Typically, approaches to streamlining have entailed simplification of the life-cycle inventory (LCI) through the elimination of life-cycle stages (e.g., cradle-to-gate studies that ignore activities after the production stage) or reducing the data required on the unit process networks (e.g., by applying thresholds or cut-off criteria or by limiting the analysis to first tier contributions).

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[3] Elementary flows refer to (i) material or energy flows entering the system being studied, which has been drawn from the environment without previous human transformation, and (ii) material or energy flows leaving the system being studied, which is discarded into the environment without subsequent human transformation.

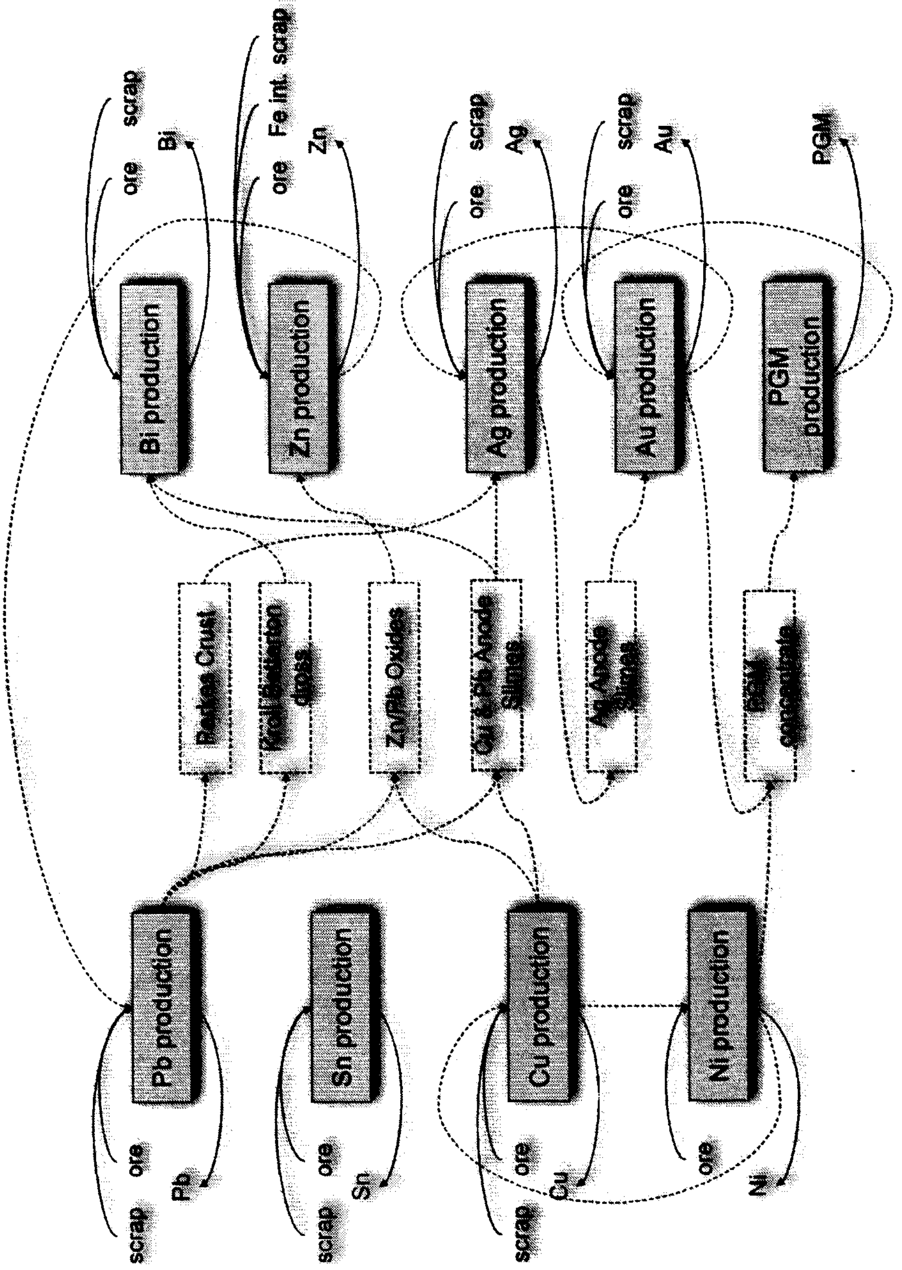

Figure 3-13: Overview of the interconnected production system of eleven metals. The dotted squares represent important intermediates connecting the metal production circuits.

In this context, Azapagic and Clifft (1996, 1999) found it useful to distinguish between a 'foreground' and a 'background' system. The foreground system is the set of processes that are directly affected by the goal of the study, while the background system is the set of processes that supply the foreground system with energy and materials. If the change in the background system is relatively small the system can be regarded as unaffected. If changes in the foreground system cause larger changes in the background system, the affected parts of the background system must be included in the foreground system. Some background systems, such as those that produce energy or transport metal products, do not show complex interdependencies, and effect of foreground changes on these systems can easily be predicted. Other systems are so complex that it is difficult to predict to what extent a change of a subsystem affects other subsystems, and thus what boundaries are needed or what level of detail is required.

3.3.3 Interdependence between metal production circuits

Metals are typically produced via globally interconnected production circuits. Figure 3-13 shows a generalized representation of the interconnections in the production of eleven metals. The dotted squares in the middle represent the major intermediates connecting the different metal production circuits.

The figure shows how the production or recovery of a single metal is related to the generation or recovery of other metals. Figure 3-13 shows that production of a number of metals from the interconnected metal infrastructure is complex, as most of these must be circulated between two or more production circuits before they are concentrated enough to make their extraction possible, and their recovery as a metal profitable. For instance, silver and bismuth in ores are concentrated in Kroll Betterton crust, Parkes crust and anode slimes in the lead(-zinc) circuit, before they can be recovered in the silver or bismuth circuits. PGM are circulated between even more circuits.

A model based on a black box approach for each of the metal production circuits can not sufficiently capture the interdependence in metal production and recycling. The interdependence between the metal production circuits is a consequence of the interconnections of the metal reactors that constitute the metal production circuits in Figure 3-13. Without sufficient detail on the underlying networks of reactors, the flows between the different circuits, but also from and into the environment can not be adequately estimated. Neglecting exchanges of intermediates between metal production circuits, and the interconnections between production and recycling of the different metals process level prohibits predicting to what extent a change of a subsystem affects other subsystems, and thus what boundaries are needed or what level of detail is required. In other words, because the metal production and recycling capacity is realized by a dynamic network of reactors, tools to invoke improvement in this capacity also require modeling at level of reactors.

3.3.4 Interdependence in metal production processes

Appendix B contains a detailed description of the interconnected 'web' of metallurgical reactors involved in the production and recycling of eleven metals: bismuth, copper, gold, lead, nickel, PGMs (palladium, platinum, rhodium), silver, tin and zinc. It is beyond the scope of this chapter to discuss all these metals individually.

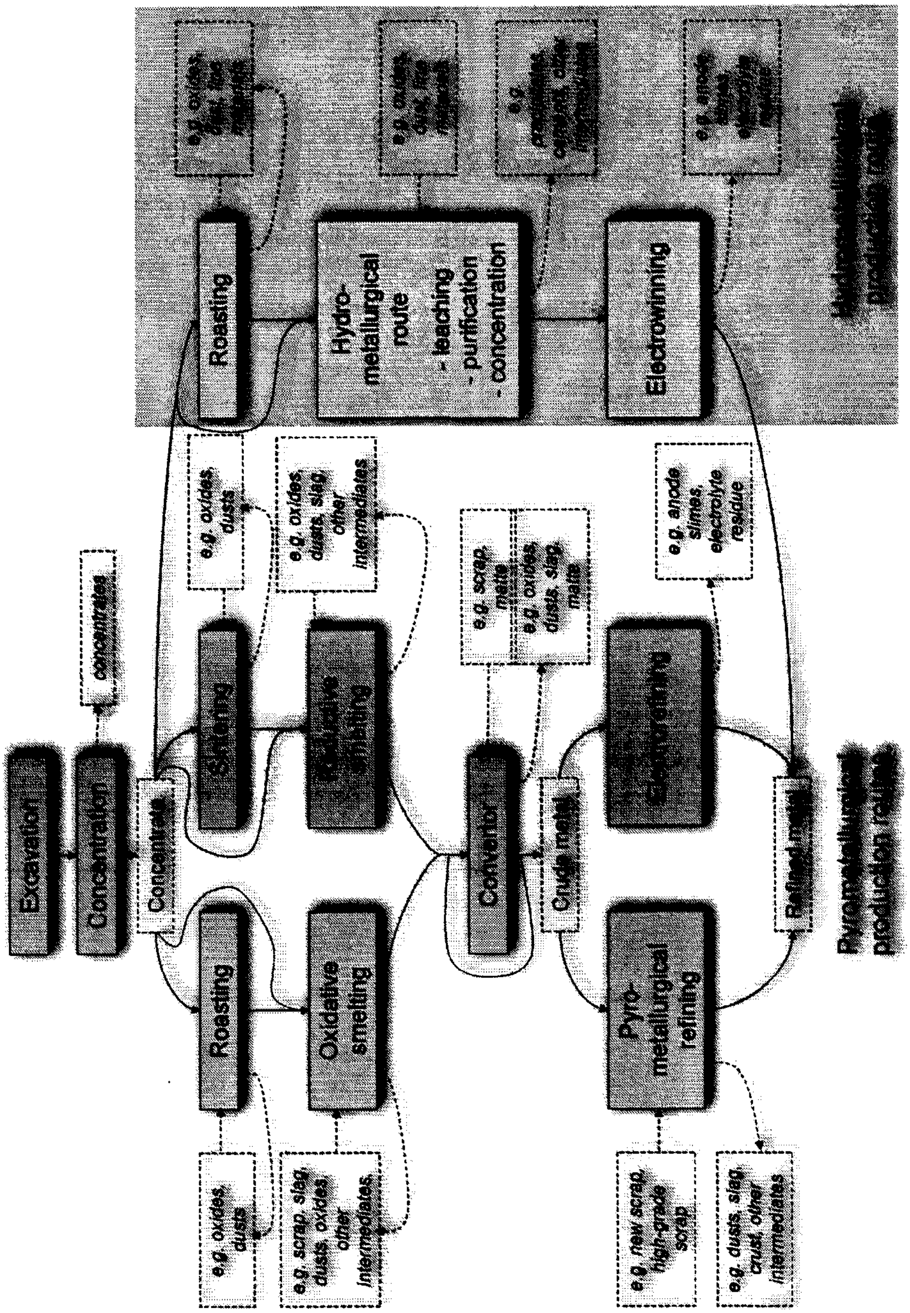

Figure 3-14: Generalized flowchart of the extraction and production of a metal. The dotted squares give examples of possible intermediates connecting the different metal production routes.

Figure 3-14 shows a generalized metal production circuit consisting of three basic metal production routes:

- Oxidative smelting route,
- Reductive smelting route,
- Hydrometallurgical route.

These routes are all capable of separating a large number of elements at the same time, but with various degrees of efficiency. They start with the excavation of metal ores at the mines, open pit or underground. The ores are first concentrated through crushing, grinding and flotation to reduce the volume to be transported. A single ore can produce several concentrates: the processing of 'zinc ore' generates zinc, lead and copper concentrates.

Both of the (primary) pyrometallurgical metal production routes, oxidatative and reductive smelting, start with the smelting of the ore to a crude metal and removing the gangue material and the main impurities. Subsequently, the crude metal is refined to a pure metal. In reductive smelting, usually sulfide ores are smelted under a reducing atmosphere together with a flux. The valuable metals are collected as metal sulfides in the 'matte phase', while the gangue material is collected as oxides in the slag. A density difference will ensure that these two phases segregate. The matte phase can be further treated in a converter to remove remaining impurities, mostly iron, and to convert the matte phase into the crude metal.

In oxidative smelting concentrates are smelted under an oxidizing atmosphere. The resulting metal oxides are subsequently reduced with carbon to produce metals. The gangue material will not react and remain in oxide form. The density difference between the phases will ensure that the metal phase separates from the oxide slag. The metal phase can be further processed in a convertor prior to the refining step. Some metals are produced from sulfide ores and need to be calcined (or 'roasted') to oxides before the can be treated through oxidative smelting. The crude metal produced via either route is refined using pyrometallurgical methods, or electrowinning.

In pyrometallurgical refining impurities are removed in several steps. In electrorefining, anodes of the crude metal and 'clean' cathodes are put in an electrolyte bath. By running a current from the anode to the cathode, the metal will dissolve and selectively deposit on the cathode. Impurities in the anode either are dissolved in the electrolyte, or collected as anode slimes. Some metal concentrates, such as copper or zinc, can be processed directly into refined metals through hydrometallurgical routes.

In the hydrometallurgical process metals are produced electrolytically. First, the concentrates are typically oxidized in a fluid bed roaster. This roasting (or calcination) step is followed by leaching to bring the metal oxides into solution. After purification and concentration, the metal-bearing solution is electrolyzed to produce the metal.

Dependent on the processing route, a large number of elements are separated together with the 'carrier' metal with various degrees of efficiency. In turn, the composition of the available raw materials determines which route the materials can follow from concentrate (or scrap) to refined metal (see 3.2.2 above). At each process step in the different production routes, metals and other materials are separated; the resulting residues, intermediates or concentrates can be used in other production routes. At the same time, primary and secondary concentrates, intermediates and residues of other production and recovery routes are consumed and further refined. The raw materials used in each route, the geographic location, the related sophistication of the process steps employed, and differences in environmental legislation determine the actual composition and quantity of the intermediates produced, consumed and disposed of. Consequently, the modeling 'unity' should be a process step, rather than a process plant or a complete production chain. This approach would link up with the modeling and data acquisition methods in chemical engineering, which are also based on mass balances over individual (but connected) process steps, and thus ensures the availability of reliable data on process performance.

3.3.5 Goal and scope revisited

Although complete consideration of all the interdependencies between industrial processes is laborious, it still may be necessary for adequate modeling of metal production and recycling. Due to the complexity and non-linearity of the metal production system, it is difficult to estimate in advance the level of detail required. A change in the production volume of a metal, or the set of processes employed in its production, may have large consequences for the production of other metals. In addition, a lack of system understanding and/or data may lead to arbitrary cut-off limits, which introduces bias and can lead to errors in estimates of environmental impact.

According to Todd and Curran (1999), it may thus be necessary to supplement the LCA with other tools or methods to provide a sound basis for decision-making. The metal wheel (Figure 3-11) can provide for a valuable tool to establish the different interdependencies between the production routes of different metals (Verhoef 2003b, and 2004c). Estimating the effect of a change in the production of one metal on other metals, however, would call for comprehensive modeling of the interconnected metal production system. SFA-type models can provide for 'unifying cores' as Dutchin and Hertwich (2003) suggested, or provide a frame for the quantitative systemic models that Allenby (1999) called for to support policy and other industrial ecology activities that span across multiple system levels. A first version of such a model is presented in chapter 5 and further described in appendix B.

3.4 Data availability

Different industrial ecology models can be distinguished, which differ particularly in the way they consider dynamics of the systems: the changes in flow and accumulations. As a consequence, data requirements vary considerably per model. The different types of models are briefly discussed below.

3.4.1 Mass balance models

Metal production system can be seen as a dynamic network of interdependent process steps (network nodes) that are interconnected through the exchange of intermediates (network arcs). The dynamics in metal processing can be captured by modeling the systems as a network of nodes. In the nodes (process steps) materials are transformed into products and intermediates. Between these nodes materials (intermediates) flow and accumulate. The flows and accumulation are a function of the raw materials entering, and the products flowing out the network. Udo de Haes and Van der Voet (1997) distinguish at least three types of SFA models for the modeling of transformations, flows and accumulations or stocks in the industrial system. These mass balance models differ in resolution and in the way they consider dynamics: (i) bookkeeping, (ii) stationary modeling and (iii) dynamic modeling. In the bookkeeping model, a flowchart for the system with all the stocks, flows and processes is made. For a given period, empirical data on the flows and stocks are collected. This method allows policy makers to spot trends and evaluate effects of certain changes.

Secondly, a stationary model can be used, in which the processes are formalized in such a way that the outputs can be formally computed from the inputs, or vice versa, the inputs can be computed so as to satisfy a given set of output values. Apart from possible changes in the immobile stocks and from changes outside the given system, it describes a stationary situation. In principle, data from the bookkeeping overview can be used to calibrate the mathematical equations of the processes. It is to be preferred to use data regarding the distribution characteristics of the processes themselves, if available, in order to avoid the inclusion of coincidental factors in the equations. The core of the stationary model is thus the development of a consistent mathematical structure, which renders it possible to specify relations between the different flows and stocks within the system. In this way, specific problem flows can be analyzed with regard to their origins. Also, the effectiveness of certain developments or measures can be estimated by comparative static analysis, which is not possible with the bookkeeping approach.

Where stationary modeling pictures one (or more) distinct system steady states, dynamic modeling allows analyzing the path towards the static equilibrium. Thus, it is the most suitable method for scenario analysis, and system or product design under dynamic conditions. As can be seen from the dynamics and interdependence in metal production, this is also the preferred method for modeling the interconnected industrial metal resource cycles. However, dynamic modeling also has the largest data requirements. When (accurate) data is lacking, dynamic modeling is not automatically preferred over the more, robust stationary approach. If the additional data can be obtained, software packages, such as Mathworks's Simulink (Matlab), allow for an easy conversion of the stationary model into a dynamic model as will be illustrated in chapter five.

3.4.2 Data requirements and availability

The choice for a certain model type or level of detail (breadth and depth) is constrained by the availability of adequate data - the data should be fit for the purpose- and the capability of shaping this data into an internally consistent model of the system.

Data available for modeling of the metal cycles is highly variable in quality, and level of detail. The data is sometimes hardly available, and must be obtained from very heterogeneous sources (e.g. encyclopedia, reference books, conference proceedings and literature reports, industry and internet). In order to describe the metabolism of the metal production system through detailed mass balances, three types of data are required. First, the description requires the elementary or chemical compositions of process inputs and outputs to construct mass balances of the individual processes (material transformations). Second, metallurgical system understanding and overview is necessary to combine the process mass balances into the interconnected metal production circuits (network structure). Finally, general metal statistics are needed to calibrate mining and metal production flowcharts, e.g. global mining, metal production and recycling/disposal (raw materials entering and products flowing out the network).

To construct mass balances for a process step, reliable data on process inflows and outflows must be obtained. A complication in collecting representative information on process steps is that their performance differs due to developed tacit knowledge or applicable environmental standards for example. Preferably, therefore, different *sets* of input and output data must be found for each process type in the mass balances representing their distribution around the globe. This allows reliable estimates of the average global performance per process step. In addition to obtaining data from credible sources, another constraint is the consistency of the data (Ayres and Ayres 1999). The consistency must always be verified using mass balance conditions.

A more fundamental limitation is the ability to capture the behavior of system components in simple mass-balance models. The operational knowledge in the processes controlling the behavior is tacit knowledge: it can not easily be captured in first principle models or be transferred, but is based on experience and gut feeling gathered over the years. Even in process control, it is accepted that a considerable percentage of the control is based on the experience of human 'sensors', and is specific for the process. It is part of the collective knowledge (or 'brain') of the process. Consequently, the effect of change on process operation is difficult to model in mass balances. Thus, to support the decision-making through detailed 'material balances', these mass balances must preferably be regularly updated to reflect changes in the materials transformations in processes.

Metal production and recycling

For a number of metals, the metallurgical industry already collects and publishes detailed inventories of the different processes employed, which can be used for quantitative modeling. Nevertheless, data coverage was not sufficient to obtain representative inventories for each process in the metal extraction and production system. The next section shows that mass balance conditions can be used to check data consistency, largely fill in the missing data, reduce errors, and construct an internally consistent map of the mining and metal production stages. A detailed description of the interdependent process steps involved in the production of these metals is provided in Appendix A and B.

Solid Waste Management

Secondary materials that substitute the primary ore concentrates may have very different compositions. As a consequence, the recycling of these raw materials may have a considerable effect on the metals that are separated together with the 'carrier' metal. This feedback of secondary resources into the industrial processes is a major challenge for modeling the metal metabolism through detailed mass balances.

A distinction can be made between production and end-of-life (EOL) waste. In the production of metals residues are generated (e.g. slag or flue dust) for which no recovery route exists, or intermediates for which there is no demand or recovery capacity. The composition of these wastes follows from the mass balances of the metal production processes. Data on the waste arising from the manufacture of final products or the discarding of these products after use, and on the subsequent separation processes into suitable raw materials for metal production is not sufficient to model the global metal metabolism through detailed mass balances.

Manufacture and Consumption

The manufacture and consumption stages in the metal resource cycles determine when and how secondary metal resources become available for recycling, or are lost through dissipative use. Graedel et al. (2002) observed that following the production of metals via semi-finished products to the final products, the metal flows not only become highly complex but the statistics become very sparse. Nickel, for example, is used in over 300.000 products including consumer, industrial, military, transport/aerospace, marine and architectural applications (INSG 2004).

Distributed properties

Data availability is not sufficient to allow a bottom-up construction of the many product manufacturing routes based on mass balances of individual manufacturing processes involved. As a consequence, product compositions, emissions and energy consumption of the manufacturing stage can not adequately be estimated through bottom-up approaches. For similar reasons, the residence times, energy consumption or the dissipation into the environment during use can not adequately be estimated through a bottom-up approach either. The residence time of metals in the consumption phase, for example, is an aggregate of the lifespans of the many different products the metals are used in. The actual lifespan of each of these products depends on individual consumer preferences and decisions to discard the products[4], shows considerable variation per product and may also change considerably over time.

In the modeling of waste flows from consumption stocks, Klein et al. (2000) suggest to model the stock as a 'time buffer'. Metals in use (economic stocks) and waste generation can then be approximated using general metal statistics that report on the different end uses of metals as function of time, and estimates of life span distributions for these end uses or rather end use categories (A1 in Figure 3-15). The total economic stocks of metals can than be determined by integration over the longest life span. The actual composition of the old scrap from separation processes can be estimated (A2 in Figure 3-15) similarly by partitioning the end use categories to standardized routes for typical waste categories (Municipal Solid Waste, Wasted Electric and Electronic Equipment or End-of-Life Vehicles etc.). Further detail on data availability of the manufacture, consumption and solid waste management stages and this approach can be found in the appendices.

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[4] Reasons for discarding include technical reasons, e.g. the product is irreparable, economic reasons, e.g. the cost of repairing the product is uneconomic, functional, e.g. new products have improved features and/or psychological reasons, e.g. the desire for new and fashionable products.

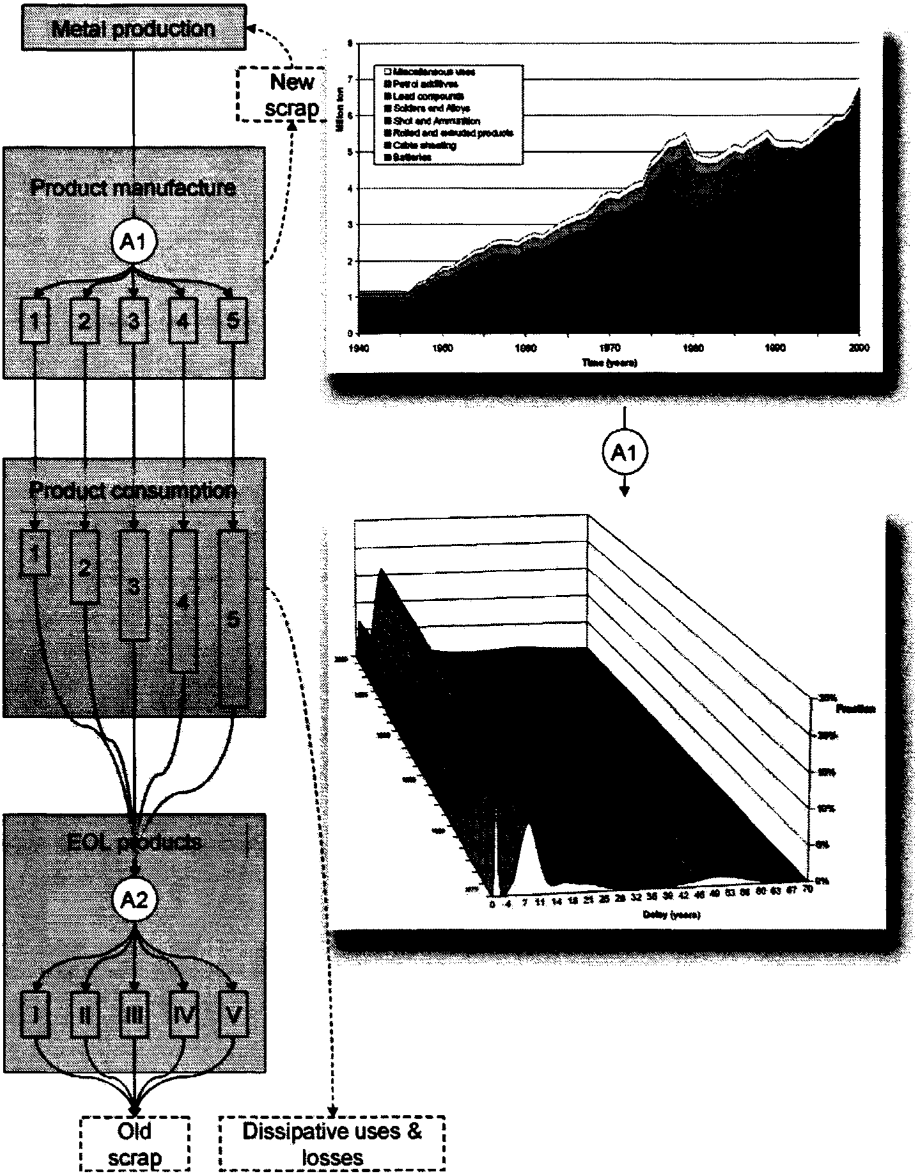

Figure 3-15: Estimation of metals in stock and waste generation using metal statistics on the different end uses of metals.

3.4.3 Data reconciliation

Because the processes were reported for different reasons, and with different levels of detail and completeness, mass balances for individual processes often could not be closed. Madron (1992) and later Veverka and Madron (1997) gave overviews of data reconciliation: a set of methods used to adjust the experimental data to reduce and possibly eliminate discrepancies in the mass balance. Data reconciliation is basically minimizing a sum of errors (the difference between each measured data and its reconciled value) weighted by the measurement error, *J(Y)*, subject to a number of constraints (the mass balance equations). The mathematical denotation for the data reconciliation is as follows:

$$J(Y) = \sum_{p}\sum_{i} J_{pi}(Y) \qquad (1)$$

$$J_i(Y) = \left[\frac{Q_{pi} - \bar{Q}_{pi}}{\sigma_{pi} * Q_{pi}}\right]^2 + \sum\left[\frac{P_{pik} - \bar{P}_{pik}}{\sigma_{pik} * P_{pik}}\right]^2 \qquad (2)$$

In which:

$J(Y)$ = Weighted sum of errors to be minimized

Q_{pi}, P_{pik} = Reconciled Magnitudes

$\sigma_{pi}, \sigma_{pik}$ = Measurement Error

$\bar{Q}_{pi}, \bar{P}_{pik}$ = Measured Magnitudes

$\bar{Q}_{pi}, Q_{pi}$ = Flow rate of phase $_p$ in stream $_i$

$\bar{P}_{pik}, P_{pik}$ = Fraction of component $_k$ of phase p in stream $_i$

Adjustments to experimental data are subjected to a number of restrictions, viz. the conservation of global flow rate (eq. 3), the conservation of global and elements flow rates (eq. 4) and the data integrity constraint (eq. 5):

$$\sum_{k} P_{pik} = 1 \qquad (3)$$

$$\sum_{i} Q_{pi} \cdot P_{pik} = 0 \qquad (4)$$

$$\sum_{i} Q_{pi} = 0 \qquad (5)$$

In the reconciliation of the mass balances of processes for the dynamic modeling, the data is not based on measurements, but on processing data of plants around the world found in the literature. The essentials of the data reconciliation technique, however, remain the same. Calculation of the average compositions as a basis for constructing the mass balance normally does not result in a completed mass balance of the unit operation employing linear algebra. Using the standard deviation in the data as a measure for the accuracy of the data, a closed mass balance can be obtained using data reconciliation.

Because the thermodynamics and physics of the processes are not always fully understood, and process outputs are partially controlled with the tacit knowledge of the process crew, these split-factors are difficult to determine and can vary between different processes, or with feed composition. The work of Reuter (1998) showed that the approach taken provides for a good representation for average process operation.

Application of data reconciliation methods significantly reduces gaps and inconsistencies in the mass balances of the individual process, and produces reliable estimates of feed, (by)product and residue flows. The software used for data reconciliation is Excel 2000. The maximum number of elements that can be reconciled is limited by the computational capacity of Excel's standard solver, and therefore only critical elements were included in the mass balance. In Appendix A, the reconciled mass balances for all processes in the interconnected metal production system are given (sections A-2 to A-10). Further details and the raw data can be found in Scholte (2003) and Van Tweel (2004).

In combination with statistics on the abundance of processes, production of metals and ore extraction, these reconciled balances can be used to obtain the process inputs or outputs of other processes (and thus close their mass balances), or reduce inconsistency in the interconnections in the production routes. For instance, the elemental compositions of ores found in literature often are limited to their major (or valuable) components. The input and output data of the crude metal production often provided higher detail. Data on the composition of concentrates or the production of co-elements and intermediates from the different reconciled processes downstream were used to derive more complete ore compositions. Data reconciliation is thus a powerful tool to improve data quality and check the internal consistency, but requires considerable effort. Figure 3-16 shows the reconciled mass flows in the interconnected metal production system. A detailed overview of the mass balances of different processes can be found in the part two of this thesis.

Data reconciliation can only be used when mass balance conditions can be imposed. It is for example difficult to apply to end-of-pipe or auxiliary equipment of processes, such as off-gas treatment. Because off-gas treatment equipment varies widely around the globe (Ayres 2002, Chapman 1989, Towle 1993), sulfur recovery efficiency per process or production circuit can not be estimated from the sulfur production statistics, but recovery efficiencies for off gas treatment units can be obtained from literature. The efficiencies for sulfur, carbon monoxide and dioxide, nitrous oxides and flue dust capture in the production of one metal can be used to estimate the efficiencies of an other metal for which more data is available (e.g. copper) with some basic chemical assumptions. When mass balance conditions can not be used to reduce uncertainty, the effect of the uncertainty in these estimates on the model outcomes should be tested by sensitivity analysis (see Van Tweel 2004).

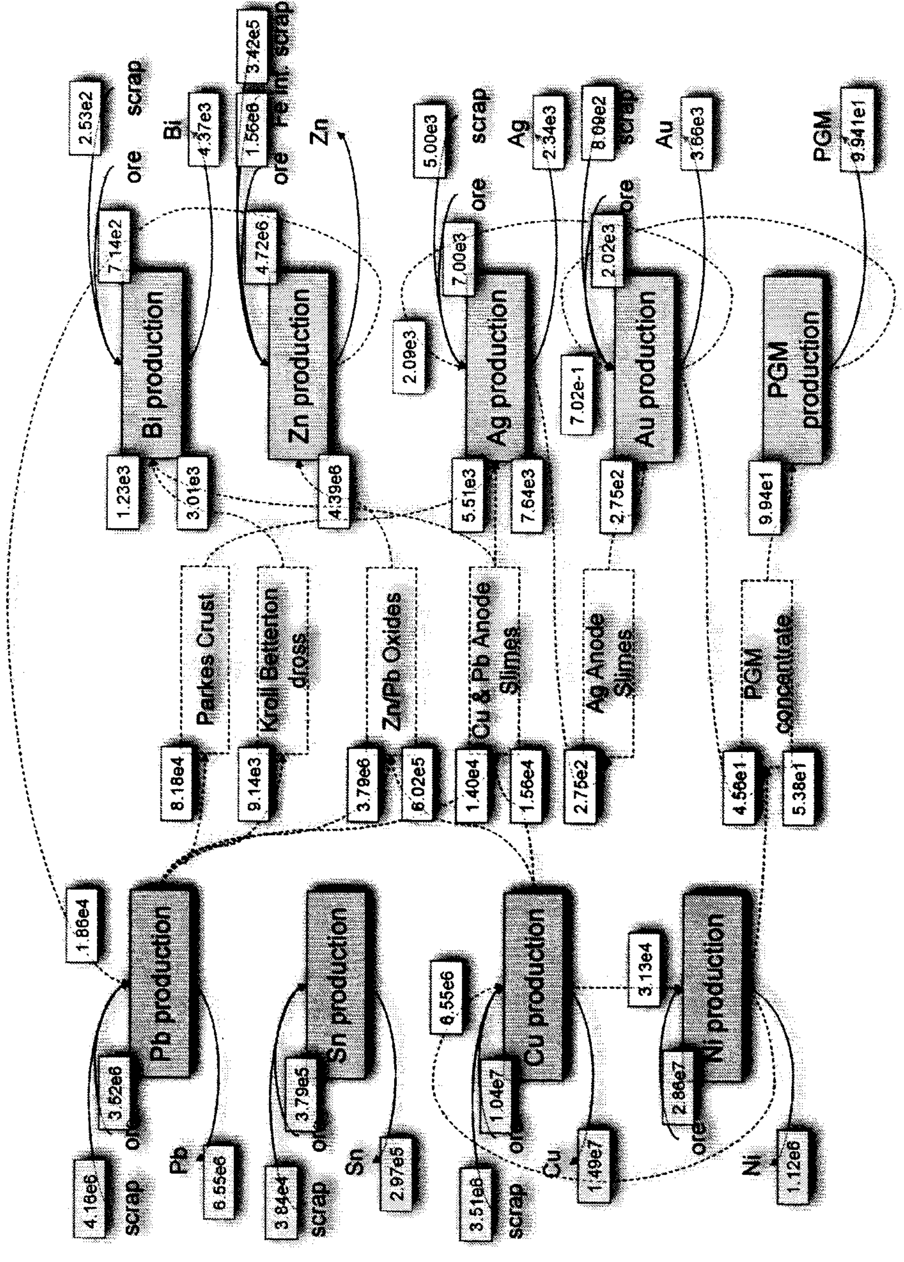

Figure 3-16: Simplified representation of the mass flows in the interconnected production system of eleven metals. Mass flows represent the flows of carrier metals in ton/a for 2000.

3.5 Potential for industrial ecology: convergence of methods

Advancing sustainability through a deliberate and rational eco-design of the industrial activities could benefit greatly from properly constructed quantitative models that can support and connect the different prescriptive efforts, and thus assist in their co-ordination. As argued in the introduction and chapter 2, the systemic perspective of industrial ecology calls for a shift from dealing with isolated, relatively simple systems to managing complex, interdependent systems such as the metal production and recycling system. To visualize the behavior of such a system and link the behavior to environmental issues, quantitative modeling involves two stages: first, the goal and inventory stage to predict flows and transformations across system levels, as well as the emissions in and extractions from the environment caused by flows and transformations; second the impact assessment stage, which translates these emissions and extractions into impacts to the environment, which are understandable to decision-makers.

As a consequence of the interdependence in metal production and recycling, the metallurgical system is difficult to adequately capture in quantitative models. Modeling metal production and recycling is possible with present industrial ecology (MFA) methods, but is very laborious: it requires an inventory of reconciled mass balances of all process steps from ore or waste to refined metal. The amount of work involved can be an impediment for some studies to consider the interdependence in metals production. These studies should then be supported by other models, such as SFA models at the right resolution. This illustrates the importance of a consistent methodological framework spanning all MFA models. Convergence is not only essential for goal and inventory stage, but also for the impact assessment phase. Currently many competing mechanisms are available for impact assessment. Each of these historically developed to support the decision-making process in different ways, and consequently lead to different outcomes and have different data requirements. This could result in problems with using the results, or underlying analyses and data of one study in another.

Cadre 3-1: Impact assessment methods

There are basically three ways of impact assessment: based on 'begin-points', 'mid-points' and 'end-points'. Begin-point assessment uses the inventory data with little or no further specification or aggregation. In most SFA studies, for example, the output is defined in terms of flows and accumulations of the material under study, or through the use of aggregation indicators like recycling rate and efficiency (Van der Voet et al. 1997). These indicators are used in reference to a norm or ideal value; deviation from this reference value can indicate problems. The relevance of the analysis is generally directly related to the hazardous character of the chosen material and will need no further specification (Udo de Haes et al. 1997). In some cases, there is an explicit need for further elaboration of the SFA results, for example, if a group of substances is studied. In such a case, it is difficult to make a comprehensive interpretation of the emission inventory data without some form of aggregation.

The impact assessment of SFA based on mid-points and end-points is far less developed (De Haes and Van der Voet 1997). For LCA studies there is a wide range of competing methods that link the life cycle inventories to environmental impact (Pennington et al. 2000, Hertwich et al. 1997). Each of these methods could be used for assessment, though the outcome can differ for each method (Dreyer 2003). The methods can be classified in two groups of approaches: the end-point (or environmental damage) approach and mid-point (or environmental themes) approach (Hertwich and Hammit 2001, Heijungs et al. 2003). Simply put, the mid-point category indicators can be defined as an attempt to model the intervention-impact-damage chain to a point where knowledge is still fairly sure and complete, and where the remaining end of this chain is only conceptually or partially known. End-point category indicators can be regarded as an attempt to let decision-makers decide on what they can understand, and to use scientific knowledge, even if unsure and incomplete, to specify the category indicators at this comprehensible level (Heijungs et al. 2003). An example of this is the climate change impact on human health.

The central difference between the mid-point and end-point approaches thus lies in how the valuation[5] step is integrated in the analysis: the mid-point approach separates characterization and valuation. Those partaking in the valuation exercise determine the relative importance of the indicators for each theme (valuation). In the end-point method, the relative importance is expressed in the calculated damage indicator. As a consequence, the damage approach allows a direct comparison of the damage resulting from different impact categories, which eases decision-making. In addition, the damages are closer to our concerns.

However, the prediction of damage (end-points) resulting from a change in the stressors is difficult due to the complexity of the underlying environmental, physiological, and economic processes (Hertwich and Hammit 2001). Thus although the end-points methods provides for the clearest link to the environmental problems, and allows for easy interpretation through reduction of the number of variables, care must be taken when interpreting these results. Because of the advantages and disadvantages of both methods, it is not surprising that there is increased consensus about the desirability to combine midpoints and endpoint indicators in a uniform framework. Recently a project started to develop a framework in which midpoints and endpoints support each based on CML (mid-point) and EcoIndicator '99 (end-point) methods (Bare et al. 2000, Heijungs et al. 2003).

A possible way to interpret the outcome of SFA studies is specifying the contributions of the substances to a number of environmental issues or environmental impact categories, such as global warming, ozone depletion, and acidification. This approach links up with the development of LCA impact assessment methodology. An example of such an approach is the recent SFA study on chlorinated hydrocarbons in the Netherlands (Kleijn et al.1997, Udo de Haes et al. 1997) that used environmental impact categories such as global warming, ozone depletion and ecotoxicity.

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[5] The valuation step specifies and aggregates the inventory outcomes in terms of their perceived contribution to public health and environmental impact.

Other examples include the studies on chlorine and PVC for the Dutch government and Norsk Hydro that also combined elements of SFA and Life Cycle Impact Assessment (LCIA) (Kleijn et al. 1997, Tukker et al. 1995 and 1996). Based on their studies, Tukker and Klein (1997) conclude that environmental evaluation methods like SFA and LCA can successfully be used in combination.
A problem of using LCA approaches in SFA (or for the comparison with SFA study outcomes) is that LCA does not consider time dependency: the effects of the damage over time, e.g. the actual resource depletion, are not accounted for in the related impact assessment methods. For instance, if metals ores are mined over time, the available stocks decrease and the seriousness of further depletion increases. This should be realized when interpreting the impact assessment results.
A dynamic SFA simulates the effect of future developments on the system and its environment. Rather than indicating damage scores due to resource depletion, it simulates the decrease of the available resource stock in a given scenario. While there is a growing consensus that different LCIA methods have complementary limitations and merits, it appears that this observation also holds true for the different LCA and SFA impact assessment procedures: LCIA provides a context to appreciate the different SFA indicators in context of environmental problems, and vice versa SFA indicators improve transparency of the LCIA values and provide additional information on the system, such as dynamic behavior (see appendix B: section B-4).

The brief discussion of different impact assessment methods in LCA and SFA showed the many different impacts assessment mechanisms available. In principle all of these can be used, though they produce different results. For consistency between different study outcomes, it is stated in the ISO (14042) standard that impact assessment results can not be the only source of information for comparative assertions. Impact assessment is basically viewed as a way to interpret the inventory in the context of the study goal. In this view the inventory determines the subsequent impact assessment. However, the opposite is also true: the requirements of the decisions or actions for which the study is undertaken dictate the type of impact assessment to be included. As the different methods have different data requirements, the data requirements for the impact assessment are, then, the major drivers for the inventory (Barnthouse et al. 1997:24). This bilateral interdependence shows that industrial ecologists must clearly define their data requirements by further developing the inventory and impact assessment methodology. Only if a model methodology is well defined, data can be collected and published in a structured way, and study outcomes can be compared and effectively used in (and interchanged with) different studies.

This chapter has focused mainly on the inventory stage. Although the ISO standards for LCA provide a starting point for constructing an LCA or SFA, they do not regulate all methodological choices, and as a consequence virtually any result can be produced (Ekvall and Finnveden 2000). The metal wheel is introduced as a simple means to visualize interdependencies in metal production and recycling, and can be used in the establishment of system boundaries for environmental impact studies. Based on the wheel, a methodological basis or suitable inventory architecture has been presented as a basis for tools to invoke improvement for metal processing and recycling systems. A full inventory of the reconciled mass balance of the metal production systems can be found in appendix A, a description of emissions and energy emission in appendix B.

3.6 Conclusions

In comparison with the well-known examples of eco-industrial parks, the interconnected metal production and recycling system is a less recognized example of industrial ecology in practice. The metallurgical industries minimized the use of resources and production of wastes by interchanging resources, intermediates and residues between processes. As a result, the production of metals is so interdependent that they can hardly be considered separately. The metal production and recycling system is an excellent case to study the potential of the current descriptive approaches to design and manage industrial systems as industrial ecosystems. To date, however, industrial ecology studies on metals production and recycling lack a sufficient depth to invoke improvement for metal processing and recycling systems. Because the metal production and recycling capacity is realized by a dynamic network of reactors, tools to invoke improvement in this capacity also require modeling at level of reactors.

The metal wheel is introduced as a simple means to visualize the interdependencies in metals processing. It can be used in the establishment of system boundaries. The (dynamic) interdependence in metals processing resulting from the ecosystem organization calls for a different model approach than for other resources that are less interdependent. Capturing the interdependence in MFA models requires modeling the interconnections between the metal process steps, i.e. based on detailed mass balances of individual processes and process steps. Without sufficient detail on the underlying networks of process steps, the flows between the different metal production circuits, but also from and into the environment can not be adequately estimated.

To construct a quantitative description of the metal cycles, it is necessary to rely on a mix of information from a great many sources often collected for different purposes, with different detail and accuracy. Statistical methods, in particular data reconciliation, are necessary to ensure the reliability and consistency of the data at the different system levels. The required efforts to do so may be an impediment for many (LCA) studies on the metals production and recycling system or parts of it. Additional tools to complement these (LCA) studies are required to calculate changes in the metallurgy. For these tools SFA models can be used based on reconciled mass balances of all metallurgical process steps involved.

Because this is a very data-intensive process, industrial ecologists must clearly define their data requirements. Only if a model methodology is well defined, data can be collected and published in a structured way. In this context, methodological convergence in the current trends in research and modeling of environment related flows in the physical economy is essential. Such convergence could yield significant benefits with respect to the underlying data collection, accessibility and conformity. Thus it could reduce the effort of considering the interdependences in metallurgical systems. For this reason, the data underlying the quantitative description is reported in detail in the appendix A. The data can serve as a solid basis for other studies on metals processing and recovery.

It is essential that the metallurgical, the manufacturing and waste management industries collect and present data on the different stages in the metal cycles (i) in a way that allows modeling of these systems, and (ii) in literature available to industrial ecologists (or other people that construct material inventories) rather than in specialist or professional literature, conference proceedings etc. alone. Availability of current data is even more important considering that the metallurgical system is an evolving system. The tacit knowledge plays an important role in the development of the performance of existing processes and of the development of new processes, but can hardly be modeled. For representative modeling of metallurgical systems, industry must ensure that model data and flowsheets (the configuration of the processes) represent industrial practice.

4 A prescription for the metal cycles

Summary

In chapter 2, the apparent value of an integrated description of the flows and transformations and their impacts on the environment across various levels in the physical economy was discussed for the industrial ecology goal. In chapter 3, an integrated description of the metal cycles was provided. In this chapter a multidisciplinary, qualitative prescription for the metal cycles is given.

Prescriptive studies address the analysis and control of the development and patterns of materials and energy through optimizing the ensemble of considerations that are involved. The metal cycle is therefore investigated from a multidisciplinary, ecological perspective, with a focus on waste processing and metals production (4.1 - 4.4). It will be shown that a solid and detailed understanding of metal processing and metal use is essential to assess *and* address the problems of industrial ecology strategies, including the risk of loss of the entire stock of high-quality metals with increasing recovery rates. Descriptive approaches can not always supply all the information necessary for control of the development and patterns of materials and energy, but may serve as a tool to assist communication between the parties involved. Finally, the control strategies for 'sustainable' production and recycling of metals are reflected on (4.5).

4.1 Metal ecology

In the previous chapter, the industrial 'metabolism' underlying the global metal cycles was investigated as a case study. In chapter 2 it was illustrated that descriptive approaches provide the quantitative frameworks to show the technological aspects of an economy operate and may assist in their restructuring if desired. This chapter investigates how these approaches can to assist a restructuring.

In a recent handbook on industrial ecology, Allenby (1999) predicted that the metal sector is one of the sectors that will undergo significant changes on the road to sustainability. It will be shown that an ecological perspective is essential to assess and address the problems for such significant changes. In an ecological perspective, one looks at relationships between systems components mutually, and between organisms and their environment. The term ecology refers to the relationships between organisms and their environment. The term 'metal ecology' will be used to refer to the relationships between metals extraction, production, manufacture and recovery processes (the metal 'organisms'), as well as the interaction with non-technical, environmental factors driving the system, such as legislation, and the natural environment (their environment).

Metals that participate in linked cycles can not be analyzed independently as many life cycle assessment studies attempt to do. As a consequence, process design, waste management, metals production and legislation/policy can not be considered separately either. They are cross-linked in metal production and recycling, combined in products and connected through feedback loops. The production, use and recycling of each metal thus affects the others. In theory, metals can be recycled infinitely and may be considered renewable resources. Plastics do not have this property since molecule chains are always broken due to thermal processing during recycling, ultra violet light, etc. as a function of time. In the management of metal cycles, therefore, a key objective in accordance with industrial ecology would be to achieve complete recovery of metals from sources in industrial society. Only thus, can the level of the stock of metals available for economic use be maintained and depletion of mineral resources prevented.

In practice, however, the dilution of metals—that is, their mixing and contamination—associated with use and recovery of metal is a major problem, because it limits the usability of secondary metals. A solid and detailed understanding of what might be termed, metal ecology, is essential to assess and address this problem: one needs to understand not only the processes and the technology, but also the relationships between processes mutually and between them and their environment. To our knowledge, neither in industrial ecology literature, nor in metallurgy literature studies or models have been reported that considered the dynamic interdependence in the metal ecology outlined in the sections below.

4.2 Goals for 'sustainable' metal metabolism

Industrial ecology promotes an industrial evolution that considers the characteristics of the natural world. Prescriptive approaches consider the natural world in at least two ways: First, industrial activities must be reorganized according to the limitations carrying capacity of the natural world upon which industrial activities are founded. Second, the organization of the natural world is used as a model for industrial activities:

industrial activities must be restructured according to type III ecosystem principles (see chapter 2). The different prescriptive approaches use both elements to develop strategies that minimize the environmental burden created by the releases of energy and materials into the environment, and to maximize the efficiency of materials and energy use.

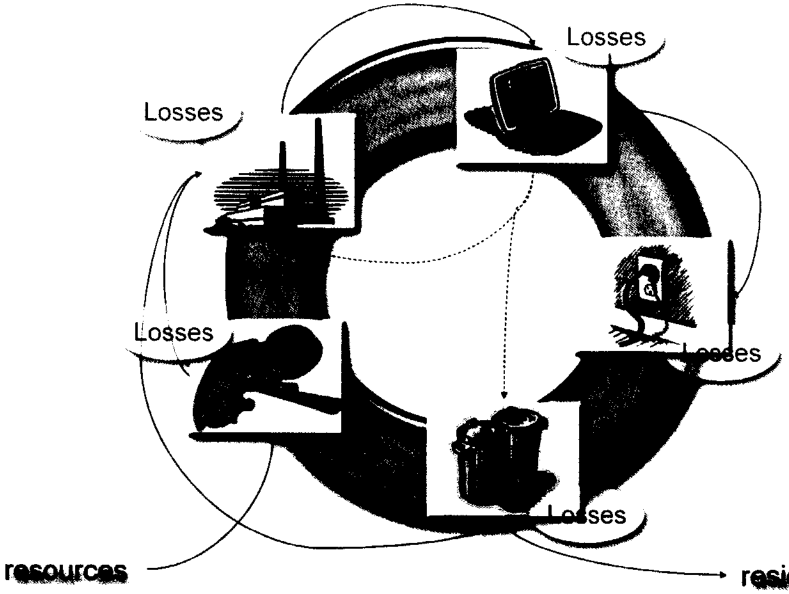

Figure 4.1: Generalized metal resource cycle: metal resources are mined and concentrated (mining), processed in metals (metal production), manufactured, consumed (product manufacture) and finally disposed of or recycled (SWM).

From an industrial ecology point of view, the industrial system is viewed as a physical system in and through which materials and energy flow and change into raw materials, products and residues, and from which wastes and excess materials may `leak' or be disposed of causing damage to the environmental or human health. This is illustrated in Figure 4.1: the transformations in each stage of the resource cycle lead to material and energy leaks or losses. If this perspective is adopted, two complementary strategies follow: (i) strategies aimed at prevention of the emissions from metal production and use by minimizing the circulation of materials, and (ii) strategies aimed at containing materials in the 'technosphere'. Dematerialization and detoxification are examples of the first strategy. Detoxification involves avoiding and/or minimizing the creation and transport of toxic and hazardous materials such as lead. Dematerialization, closely related to eco-efficiency, aims to provide the same or more service at less environmental impact. The first strategy thus views the use and production of metal as an important source of environmental burden, and prescribes a minimized use of metal to reduce impact. The use of metals can be reduced by the redesign or substitution of products and services.

The second strategy recognizes that most metals are difficult to replace, strategies of the first type alone cannot provide 'therapy' for all emissions. Assuming continued use of metal, this sets a new challenge to the production, manufacturing and waste processing infrastructure. To contain metal in the resource cycle and reduce leaks and disposal, technologies (and products) must be redesigned and rearranged to reduce the use of materials that disperse beyond possibility of recapture. Waste generation and disposal must be minimized, and all remaining waste must be defined as potential products for which markets must be sought. Containment of metal is also important from a resource management perspective. Only by a (near) complete recovery of metals from sources in industrial society, the level of stock of metals available for economic use can be maintained and depletion of mineral resources prevented[1].

4.3 Dynamics in the resource cycles

The basis of prescriptive approaches lies in the analysis of the role of the metal organisms, their current organization and their surroundings in the implementation of the strategies outlined above. Many industrial ecologists, including Verhoef et al. (2004a), Andersson and Råde (2002), Sagar and Frosch (1997), Oldenburg and Geiser (1997), Reuter (1998 and 2003), Weston and Ruth (1997) and Ruth (1998), recognized the need to study the dynamics of industrial ecosystems. Because of the interconnectedness of process design, waste management and metal production, and of metallurgical processes mutually, this holds especially true for the metal ecology. The production of most metals is still increasing, which (ceteris paribus) will result in higher metal emissions (to water, air and soil), and/or in metal accumulation in the economy, i.e. in capital goods, intermediate products, consumer goods and wastes. If strategies to reduce emissions from metals production and use overlook the accumulation, emissions may be only temporarily decreasing and may well increase in the future —e.g. through corrosion, inadequately controlled incineration and landfill or metal dilution (cf. Ayres et al. (1987), Stigliani and Anderberg (1994), Bergbäck and Lohm (1997), Verhoef et al. (2004a)). Too strict environmental measures may also export the metals and production/recycling facilities to foreign countries and thus shift the problem abroad. The restructuring of the metal sector is thus a dynamic problem, which is dependent on the dynamics of all components constituting the metal ecology.

To investigate this dynamic problem, again a resource cycle perspective is used, but the perspective is expanded to include the dynamics of the different components of metal ecology. As discussed in the previous chapter, the life cycle of a product is dependent on many different, interconnected resource cycles. The metal resource cycles are not only dynamically connected through their combination in multi-components products, but also through the networks of production and recycling processes. These resource

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[1] Current estimates of world population bringing the world population above 10 billion people in 2050, and the economic growth in developing countries necessary to bring the per capita GNP at least at the level of the developed country today, would drastically increase our need for resources. Prudent use of non-renewable resources is therefore essential to fulfil the needs of future generations, but also to minimize impacts on the environment today. See chapter 2.

cycles - describing the path of all constituting materials/elements that form part of the products - dynamically interact with the technological cycles of products.

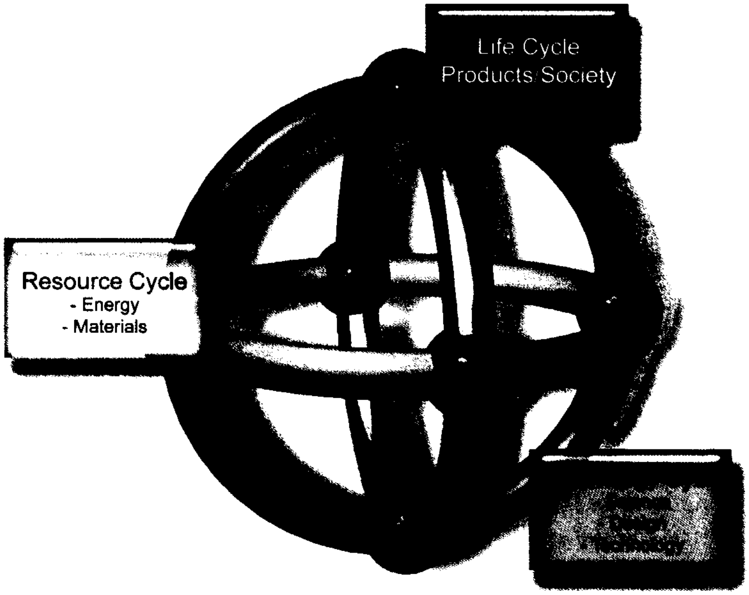

Figure 4.2: Interconnected technology, resource and society life cycle of a product (Van Schaik et al. 2002).

The technology cycles describe the cycle of the different technologies employed for the product from cradle to grave: from science, via process design, to the implementation of technology, which in turn leads to a better understanding of the processes (science) as a basis for new process design and development. The resource and technology cycles interact with the societal life cycle, which describes the societal life cycle of a product from cradle to grave, and governs the development of demand for products from society, the rate of product consumption, succession. Figure 4.2 shows the complete life cycle of a product, made up of these interacting cycles; each cycle having its own dynamics. The figure implies that all of these cycles must be attuned, to attain the industrial ecology objectives. Using this ecological perspective, the dynamics of the metal resource cycles are further investigated, and bottlenecks and strategies to reduce the use of non-renewable resources and product related impacts on the external environment are discussed.

4.4 The dilution of metals

From a technological perspective, it can be easily seen that, the technology cycles of pyrometallurgical reactors have a major influence on the resource cycles. They simultaneously perform the chemical transformations necessary to introduce or feed metals back into the material cycle. A change in the feedstock or operation of these networked processes has an effect on other processes upstream and downstream they network, and ultimately on the introduction or feedback of materials into the material cycles. Because of the long lead times and life span of metallurgical processes and waste infrastructure, the dynamics of the related technology cycles is relatively slow: production/recycling routes and technology of metals develop only gradually over time. Consequently, the available knowledge, the employed technologies and the developed network organization determine the possible options for changes in the resource cycles, such as the development of a (new) product. It will be shown that due to the relatively fast dynamics of societal cycles of many products, this particularly becomes a problem when the fraction of secondary raw materials increases (or in industrial ecology terms: when closing the material cycles).

4.4.1 Interaction with the society cycles

The relatively fast changes in products lead not only to changes in metal demand but also in the supply of secondary resources. Secondary resources (or wastes) often contain many of the elements in the periodic table, and exhibit changing composition and volume, particularly the end-of-life (EOL) products. Part of the metal-containing wastes is generated in the mining, concentration and production of metals. The low metal content in some of the wastes prohibits the economic recovery of the metals in these cases. Metal wastes are also produced in the manufacturing of end products. This 'prompt scrap' stays within the factory or production chain, the quality is generally well-known and homogeneous. As a result, this metal can readily return to the production cycle. Waste is also produced as a result of measures to control other environmental problems such as water and air pollution. Some of these increasing amounts of bulk wastes give rise to new problems—examples include sewage sludge and residues from cleaning of flue gases (EEA 1999). As an example, zinc in flue dusts can be recovered with current technology (see e.g. Grund 1995), but this is currently done only for materials which contain more than 20% zinc for economic reasons.

In particular the materials manufacturing and product assembly further down the resource cycle yield novel types of waste materials and by-products, and thus potentially problems for recycling. Similar to the products themselves, these waste materials exhibit dynamics changes in composition and significant complexity, consider for example the cut-offs in the manufacture of automotive applications (complex alloys or composite, lightweight materials), or off-spec printed circuitry boards. Metals accumulate in the resource cycle through their use in numerous products. These metals become available for further use after discarding of the products as 'old scrap'. Innovation, competition and fashion create a continuous flux of new products to the market. Thus, unavoidably, the flow of post-consumer solid waste material (and manufacturing wastes) exhibits continuous change with respect to both composition and quantity. The changes in composition of the aggregate of cellular phones produced worldwide illustrate the effect of these phenomena (see figure 3).

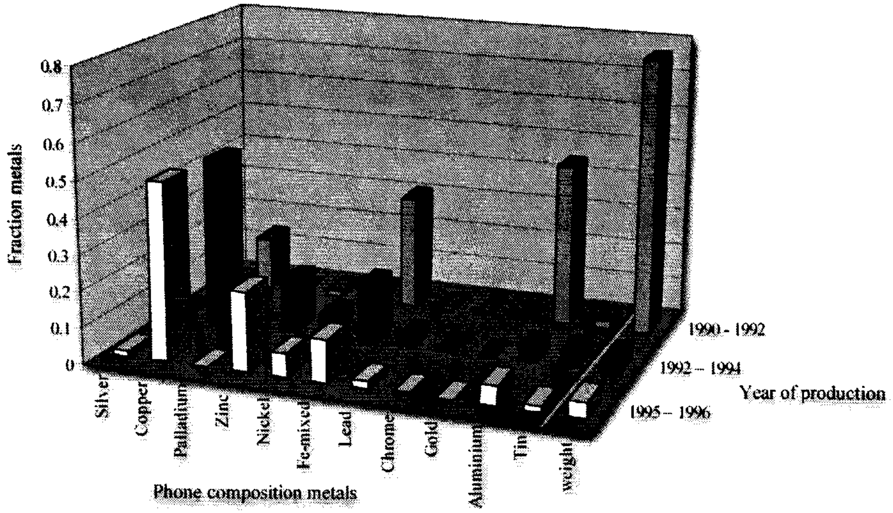

Figure 4.3: Changing composition of cellular phones (Van Houwelingen 2000).

Not only the compositions of cellular phones, cars etc. per se change, but also the products' complexity. An example of such complexity is the size reduction of electronics (see the decreasing weight of cellular in figure 3) or the increasing use of electronics and computer chips in consumer goods, cars etc. Also material and product innovations lead to the introduction of new physical and chemical linkages; for example, composite materials may include in a single matrix plastics, organic and inorganic fibers, pure metals, metal alloys of diverse composition and doped materials.

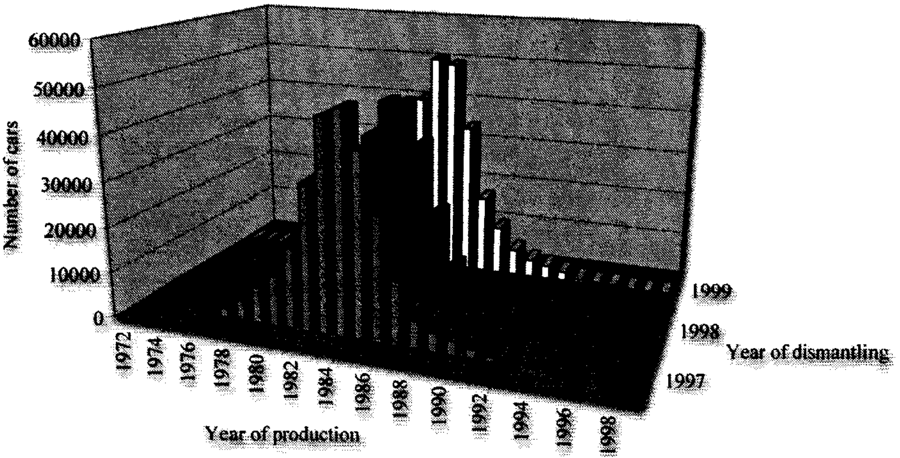

Figure 4.4: Distributed delay between the production and recycling of cars (Van Schaik 2004).

The inevitable time lag between a product's manufacture and its reception by waste management clearly ranges widely, because the average product life span varies per product and the actual product life span of a product depends on individual consumer preferences and decisions. Figure 4.1 illustrates this effect for cars in the Netherlands (Van Schaik 2004). Finally, the total volume of products consumed and eventually discarded, varies as a result of shifting consumer preferences, technology-push, economic prosperity and population. Therefore, waste from end-of-life products has a continually changing composition that is hard to predict.

4.4.2 Interaction with the technological cycle: Metal recycling

From a technological perspective, the waste infrastructure is also an important component in the metal resource cycles because it physically separates the EOL products for the subsequent recycling in metallurgical processes. The objectives of the solid waste management are twofold, however. On the one hand, waste management must concentrate and separate wastes to make subsequent recycling into metals possible and economically feasible; on the other hand, it is an integral part of environmental protection. Improper disposal of municipal waste can result in unsanitary conditions, which in turn can lead to pollution of the environment and to diseases. To date robust, durable infrastructures have been constructed to safely dispose of the waste generated, and minimize impacts on environment and public health, rather than to maximize recovery (see also chapter 1). To illustrate this, the three main processes in waste management, collection, separation and disposal, as well as the metallurgical recycling to new metal are briefly discussed.

Collection

Ideally, waste is collected in a multi-stream collection system. The separate collection enables subsequent individual treatment per waste category. Thereby, carry-over of impurities is avoided, and better separation can be achieved. Somewhere, however, an optimum must be reached with respect to the number of waste categories collected separately, the cost of the logistics, the implied diseconomies-of-scale in treatment as well as the 'willingness' of disposers to separately dispose of their waste. Consequently, only limited separation at the source is possible, and many wastes are collected with the remaining non-separated or remaining fraction.

Separation

In analogy to metal production and recycling, a number of authors observed also similarities between processing of primary metallic resources and secondary metals derived from waste collection (Veasey et al. 1993, 1997 Beenken 1992, Wilson et al. 1994, Reuter et al. 2001). Technologies for recovering metals from waste streams draw extensively on experience gained with processing primary ores (Veasey 1997, Wernick and Themelis 1998). Obviously, pieces of an individual metal are easiest to separate and recycle. The difficulty of separation increases with lower concentrations of metals in the waste, and increasing heterogeneity and complexity. There are two basic strategies to separate and concentrate metals from heterogeneous wastes:

(i) One is to use a number of different sensors to observe and measure physical properties and remove the commodities with the proper characteristics. Handpicking falls into this category. This type of separation is very selective, and is for example used for extracting valuables from specific demolition wastes. Often, however, the economics of handpicking are unfavorable to separate the bulk of the waste.

(ii) The second strategy is to shred and grind to a fine enough size to liberate the individual components as discrete particles and separate them. The particles can be separated by size (sieving or screening), density difference (e.g. air classifiers, minerals jigs or heavy medium separation), magnetic susceptibility (magnetic pulleys) or electrical conductivity (eddy-current separators). Although the fine grinding can lead to technically difficult separation procedures, the reclaimed products in this way may well be more homogeneous, and in a physical form that is easier to handle (Veasey 1993, 1997).

Neither strategy allows full recovery of metals from heterogeneous, continuously changing waste because these rely on physical phenomena only (see Cadre 4-1). Thus, by definition these do not affect or alter the chemical linkage in the material. It is the very downstream processing in metallurgical processes that effects chemical transformations of the waste material.

Cadre 4-1: Non-ferrous metal separation

For the recycling of metals at the desired grades, the effect of impurities in metals waste is critical. It is thus important to process the metal wastes into fractions that are compatible with the specifications of the metallurgical processes downstream the resource cycles.

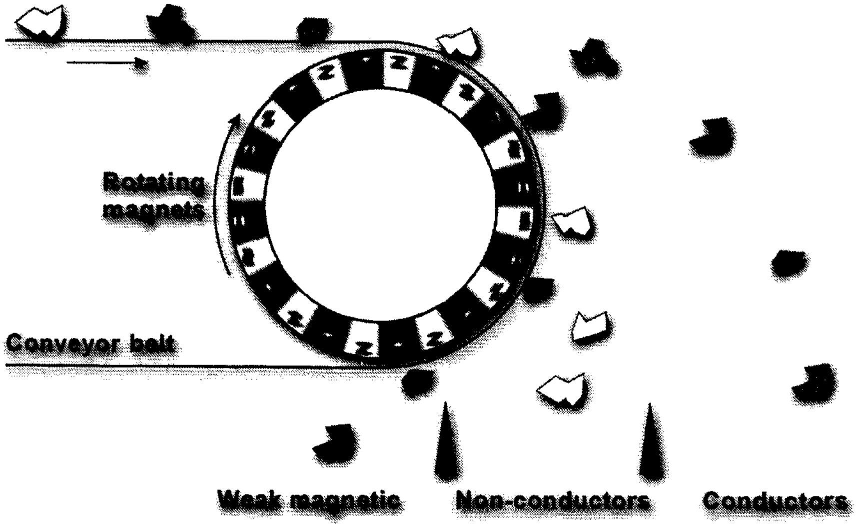

Figure 4.5: The principles of eddy-current separation (IZA 2001).

In this process, eddy-current separation is an important separation step for the separation of non-ferrous metals. In the processing of non-ferrous car scrap for example, eddy current separators separate the shredded scrap into a weak magnetic fraction, a non-conducting fraction such as glass, stones and plastic, including some small metal pieces, and the remainder of the weak magnetic stainless steel: and a fraction containing the conducting materials or metals (Figure 4.5). The position of the splitter plates determines the composition (or grade) and recovery efficiency of the products obtained. The particles in Figure 4.5 have different trajectories because they have different rates of acceleration in the magnetic field. This variation is among others caused by the difference in conductivity of the metals, or more precisely, the conductivity divided by the density[2]. The ratio of conductivity and density differs for each metal: consequently, the acceleration of an aluminum particle will be twice as much as that of a copper particle having the same dimensions. Poor conductors, such as lead and stainless steel, will respond with a slow acceleration to a changing magnetic field, whereas non-conductors, e.g. glass and plastics, will not acquire any acceleration from the magnetic field. In some eddy-current designs, weak and strong magnetic materials will travel with the magnetic drum until the point where the distance between the inside drum and the belt increases.

Figure 4.6: Limits liberation processes: complex physically connected components (Reuter 2004).

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[2] That is at low frequencies of a changing magnetic field. At high frequencies of the magnetic field, acceleration of particles will be dominated by their density.

In general, eddy current separators are used in the recycling industry in combination with a heavy media separation plant to improve the grade and recovery of the metal products. The grade and recovery of the metal fractions, however, is largely determined by the efficacy of the size reduction process(es) applied prior to eddy-current separation. The objective of size reduction is the disintegration of different types of mechanically joined materials (e.g. by screw, welding, etc.) to obtain particles of single components. It can be easily seen that when mechanically materials can not be effectively disintegrated by liberation processes, they can not be effectively be separated (Figure 4.6). The increasing complexity of products thus limits the capacity to separate metals into recyclable fractions.

In addition, chemically bounded materials can not be separated into particles of single components by liberation processes, and thus can not be separated into relatively pure fractions, which for example limits the recycling of composite materials.

Disposal

Most of EOL waste still disposed off with little or no treatment at all. The final disposal of the non-separated waste is limited to a number of allowable operations, including landfill, and incineration. For the disposal of metal containing wastes, incineration and landfilling are the most important options. Environmental impacts have been greatly reduced through among others lining and landfill gas recovery systems, and advanced off-gas treatment systems for incinerators. Landfilling stands alone as the only waste disposal method that can deal with all materials in a solid-waste stream. Consequently, landfills are (still) the most common route for waste disposal, but once landfilled, metals can not be recovered. Although it has been argued that landfills represent the mines of the future, the carry-over of impurities and dilution of metals inhibit feasible economical metal recovery from landfills. Therefore, in order to mine landfills in the future, landfills must be designed for recovery: wastes must be grouped into different landfill compartments, based on composition, which is currently not the case. In general, disposal processes are primarily built for environmentally sound disposal. Consequently, disposal processes have very limited capacity to concentrate and separate wastes; as a rule-of-thumb, metals should thus be prevented from entering disposal processes to allow their recycling. Incineration can however be an option to concentrate metals from waste with very low metals concentrations, such as paints for example.

4.4.3 Discussion

Metals present an interesting dilemma for industrial ecologists. On the one hand, they are an important source of pollution. On the other hand, metals can be recycled infinitely and considered renewable resources, and would perfectly fit into the closed-cycle industrial ecosystems, or at least in theory. In practice, the accumulation of impurity in the metals cycles (commonly referred to as down-cycling or down-grading) is a major problem, because it limits the usability of secondary metals. It can lead to increased 'leaking' in the resource cycles, and inhibits recycling into high-grade metals.

The metallurgical research and development developed significant technical infrastructure and knowledge to recycle and deal with a number of elements (see chapter 2). Waste composition, however, is not determined by the natural occurrence of metals in minerals, but by the product specifications and the capacities of the separation processes in the waste infrastructure. The production system and consumption patterns yield mixed waste materials that contain many different metals. The physical combinations and chemical compositions introduced in products and materials respectively cause carry-over of impurities during recovery, which can result in off-specification secondary metals and alloys. Because in most cases, metal applications require both high quality grades and the absence of specific impurities, their range of suitable applications is limited and a large fraction of the recovered material is useless. Thus, in contrast with common understanding - even in the absence of dissipative metal use and zero growth in demand - for many metals, recovery can not cater for the total metal demand.

To produce high-grade metals, incompatible scrap metal concentrations are refused, or mixed with large amounts of primary material that matches the technological capacity to dilute undesired impurities. The current practice of mixing low-quality secondary metals with primary metals does prevent considerable loss of stock in the short-term. The long-term effect of this dilution and down cycling of metals, however, appears to be a neglected issue in industrial ecological studies and strategies: it results in large economic stocks of 'polluted' metals that are very difficult to reuse, or at the cost of high environmental impacts, losses of material and energy consumption. This becomes even more important when realized that the desired increasing recovery of metals would imply the recovery of metals from more complex, heterogeneous wastes on the one hand, and smaller quantities of virgin raw materials to dilute the impurities on the other.

4.5 The role of metallurgy in closing the resource cycles

The objective of prescriptive studies in industrial ecology is the control of the metal 'organisms', their current organization and their surroundings to realize the strategies outlined in 4.2 through optimizing the ensemble of considerations that are involved. The investigation of the dynamics in the metal resource cycles (4.3) showed that industrial ecology concepts, such as closed material cycles, can not be developed from social, political or economic perspectives alone, but must be based on sound metallurgical knowledge. Without this industrial ecology will remain in the theory and philosophy books.

From an industrial ecology perspective, the cycling of materials through the resource cycles at the highest possible utility levels is of prime importance. To avoid the problems of metal dilution sketched in the previous sections, it essential to co-ordinate the different activities in the resource cycles, and thus to communicate sound technological information and systemic know-how on the constraints of recycling products that have reached the end of their useful life. In this section, therefore, the implications of the metal dilution problem are explored for the different stages (waste management, product manufacture and metal production/recycling) involved in metals recycling.

4.5.1 Waste managers: Adaptive waste management strategy

In order to recycle metals at the highest possible utility levels from the consumer and other EOL products, the continually changes in waste supply must be dealt with. Using political and economic arguments, Andrews (2002) concluded that today's continuously changing waste flows require adaptive waste management. It was argued that industrial ecology provides criteria and a systemic perspective that are helpful in the quest for such improved waste management practice. Little guidance, however, was offered on how to address the technological issues faced in bringing such adaptive waste management into being.

Waste often contains many of the elements in the periodic table, and exhibits changing composition and volume, particularly the end-of-life (EOL) products. These continually changing wastes must be separated and concentrated to make subsequent recycling into high-grade metal possible and economically feasible. This would require flexibility of the waste processing infrastructure, information on composition and volumes of generated waste upstream, and knowledge on the processing capacity downstream (see Cadre 4-2).

Cadre 4-2: Flexible waste recovery infrastructures

The present infrastructure systems for waste management can be labeled 'omnivores' (Dijkema et al. 2001) that devour the entire diversity of post-consumer waste. These systems have been realized, however, with the objective of waste abatement rather than for (metal) recovery (4.4.2 and chapter 1). To develop infrastructures with the objective of (metal) recycling, infrastructures must be designed to avoid metal wastes from entering disposal processes, because of their limited metal concentration and separation capacity. Incineration can be an option to concentrate metals from waste with very low metals concentrations as mentioned before. In addition, the chemical composition of recovered metal fractions must match the specifications of metallurgical processes, thus allowing production of high-grade metals downstream. However, waste infrastructures are generally characterized by slow dynamics, or adaptability that results from the scale-of-operations, the related capital-intensity and the size and complexity of infrastructure development projects. Particularly, the centralized disposal facilities in many waste infrastructures cause these slow dynamics of the infrastructures, because of their scale-of-operations and investments in environmental measures. Creating flexible infrastructures to separate continually changing waste flows - but also adapt to changing policy and environmental constraints – is thus a very challenging task.

Similar to the cascaded production and decomposition processes in ecosystems - or the cascaded structure of the metal production systems or industrial ecosystems such as Kalundborg- cascaded separation structures in which materials are subsequently stripped from the waste streams, could provide flexibility. This has been suggested in a case study on the Dutch municipal waste system (Verhoef 2004b). To avoid carry-over of impurities and improve the subsequent separation and concentration, wastes should be separated at the source. The residues that cannot be recovered must be disposed of in environmentally controlled landfills or incineration plants to minimize the impact (sound waste abatement objective). The opposite is also observed: cascaded separation requires high levels of organization and interdependence, which may partly cancel out the flexibility of such a system (Oldenburg and Geiser 1997, Sagar and Frosch 1997).

Sagar and Frosch (1997) for example notice that the industrial ecological park 'Kalundborg seems to have developed locked-in, rigid relationships' and expect that this will be a 'problem in the long run since the evolved design of this ecology is based on static optimization', which sometimes is 'difficult or expensive to adapt to new conditions'. In waste infrastructures, the large-scale, centralized disposal facilities can lead to such a 'lock-in' for example (Verhoef 2001a).

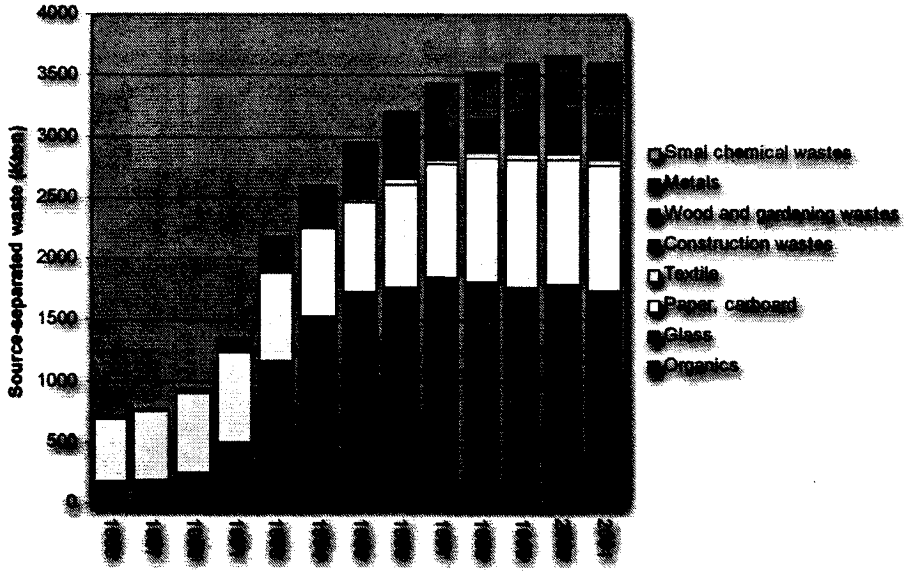

Figure 4.7: Source-separation of household waste in the Netherlands from 1940 -1999 (source: RIVM 2004).

Although it is still unclear to what extent Kalundborg has developed locked-in relationships, considering the flexibility of the system configuration seems particularly important when designing systems for long time spans such as waste and other infrastructures. For the cascaded separation system investigated, this appears not the case: changes in waste composition and quantity are manifested as changes in volume of collected streams. Separate collection, the first cascade, can adequately deal with the waste dynamics at limited cost, because it comprises mostly 'wheels' and logistics only. The cascaded structure also enables control of the residue composition and quantity downstream. In the 1970s and 1980s, household waste in the Netherlands gradually becomes more complex. Packaging materials (plastics) are introduced. Hazardous materials are found more frequently in household waste, such as batteries, paint, oil, and electronic equipment. The overall grade or quality of the waste for incineration is decreasing.

The increase in source separation of household waste (Figure 4.7) partly counters this effect. For instance, the source separation of glass not only produces a secondary resource for glass production, but also improves the quality of remaining household waste. The composition of waste becomes less complex and develops to a biodegradable mixture, which can be composted, and a combustible mixture. Not only for glass, this sequence of events can be identified, but similar trends can be observed for batteries, electronic waste, small chemical waste (e.g. personal care, paint, and oil), paper and biodegradable waste as well. In general, it can be seen that separate collection contributes to the quality of the non-separated household waste.

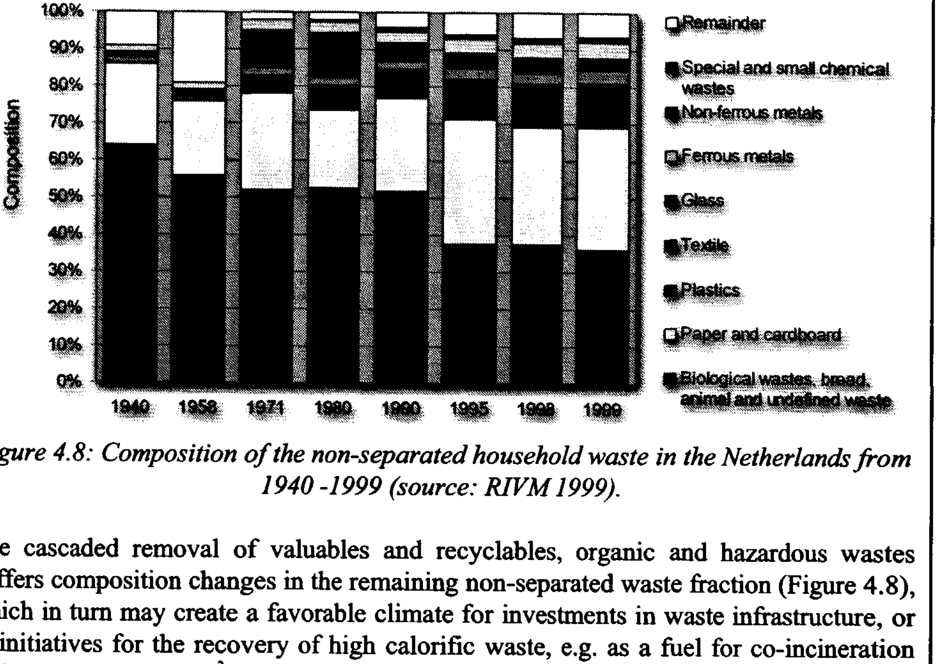

Figure 4.8: Composition of the non-separated household waste in the Netherlands from 1940 -1999 (source: RIVM 1999).

The cascaded removal of valuables and recyclables, organic and hazardous wastes buffers composition changes in the remaining non-separated waste fraction (Figure 4.8), which in turn may create a favorable climate for investments in waste infrastructure, or in initiatives for the recovery of high calorific waste, e.g. as a fuel for co-incineration and energy generation[3]. Thus moving downstream the cascade, the capacity-related costs and path dependency increase, but the dynamics of the wastes decrease. This would allow for designing flexible infrastructures. If composition of waste entering the infrastructure is known, residues can be optimized for disposal through incineration, or landfilling. In this way, infrastructures can simultaneously maximize the grade and recovery of metals, and minimize impacts to the environment and public health.

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[3] These alternatives also may lead to higher flexibility of the waste infrastructure, because fewer (sunken) investments need to be done in expensive incineration facilities. In addition, these facilities typically have higher energetic/material recovery efficiencies than dedicated waste incinerators. The energetic efficiency of power plants lies around 40%, while dedicated waste incinerators have typical efficiency of around 20%. (Verhoef 2001a)

Moreover, it would require improvement of current separation systems. For efficient metals recycling, the chemical composition of the recovered materials in waste collection and separation plants must match specifications of metallurgical processes. If the chemical composition does not match specification, metallurgical recovery rates can be significantly lower, or recovery into high-grade metals is not possible. Therefore, controlling the chemical composition of the materials from waste collection and separation plants through product design is essential to enable maximum recovery of high-grade metals downstream.

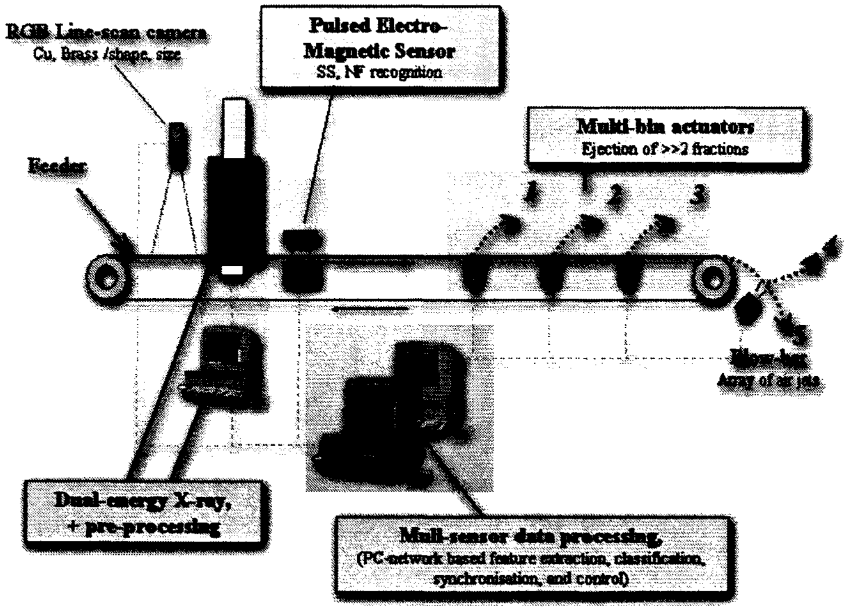

Figure 4.9: Multi-sensor separation technology to control the composition of the separated fractions (Dalmijn et al. 2001).

Sampling and separation technologies that can better control the composition of the separated fractions are just starting to develop (Dalmijn et al. 2001). Figure 4.9 shows an example of such a technology. Such a separation for recovery requires detailed knowledge of the metallurgical system downstream, but also monitoring of wastes upstream. The latter is important to ensure that the wastes follow the necessary separation steps. Given the complexity of many metal-containing products, or the low metal content in others, these separation technologies are not likely to become a full substitute for design for recovery/recycling. Thus, obtaining process compatible scrap metal fractions can not be achieved by adaptive waste management operations alone; it will also require efforts in the product design and manufacturing upstream, and in the metallurgical processes downstream. For metals, the bottleneck for maximum recovery and grade is the further treatment of separately collected waste categories. Controlling the chemical composition of the materials from waste collection and separation plants by correct product design is essential to enable maximum recovery of high-grade metals downstream. In other words, adaptive waste management will not relieve product designers and manufacturers of considering the specifications of the metal production downstream to ensure recyclability of their products.

4.5.2 Product designers: Design for metallurgy strategy

In a systems of closed resource cycles (or one striving towards that) the freedom of designers to select materials with physical properties suitable to the purpose at hand, is limited by the supply of those materials (and costs), their environmental impacts and their recyclability. In the selection of metals in product design, metal production and recycling constraints must be considered in the process design for at least three reasons:

(i) Some metals are exclusively produced from the intermediates of the production of other metals, the 'carrier' metals. This means that the amount of these metals is constrained by the production of the carrier metals.

(ii) Metal recycling is complicated by the use of products that combine metals that do not naturally occur together. In contrast to the design for recycling involving plastics, a design for metal recycling must not be simply based on the greater use of 'mono-materials' but on the use of specific metal groupings. The metal wheel in chapter 3 showed which metals commonly found together in ores, and thus for which common extraction processes have been developed. It also shows which metal combinations give rise to environmental problems, and/or high costs due to e.g. the need for end-of-pipe measures.

(iii) In addition, the neglect of metallurgical considerations in the design of products can lead to errors in estimates of the environmental impacts of the product (see chapter 5).

Graedel and Allenby (1995) illustrate the preferred grouping based on a very concise overview of trace metals recovered as by-products. According to them, metal groupings are especially important when a metal is used with a large amount of another metal, such as when steel is plated with cadmium. When the composite material is recycled, the plated metal is generally difficult and uneconomical to recover and tends to be disposed of. Their overview of interdependence of metals, however, is too concise as a basis for process design. Cadmium can be separated together with zinc, and recycled in an Imperial Smelting Furnace for example. The metal wheel in chapter 3 presents a more comprehensive overview of the metal groupings that can be handled in metallurgical processes. It can be used as a screening tool to select metal combinations in products that are not likely to result in problems for the downstream recycling into metals.

It must be stressed here that a 'design for metallurgy' does not mean minimization of the number of metals used in the design. Application of the wheel in product design would actually promote the use of multi-metal products; mono-metal based designs are often not desirable from either economic or environmental point of view. Many metals alloys are hard to substitute, and often the alloying elements take a free ride: they are recovered and concentrated at the 'cost' of recycling the carrier metal. Elements such as zinc and lead can be recovered from steel arc furnace dusts, and offer no constraints for steel-based product designs. A multi-metal design does not necessarily increase the complexity of the recovery of these metals, nor the cost and/or environmental impact. Moreover, a number of these materials do not have dedicated technical infrastructures, and are dependent on other metals for their recovery or production (the third concentric ring in the wheel). For a prudent resource management of these materials, a design for recovery is of extreme importance.

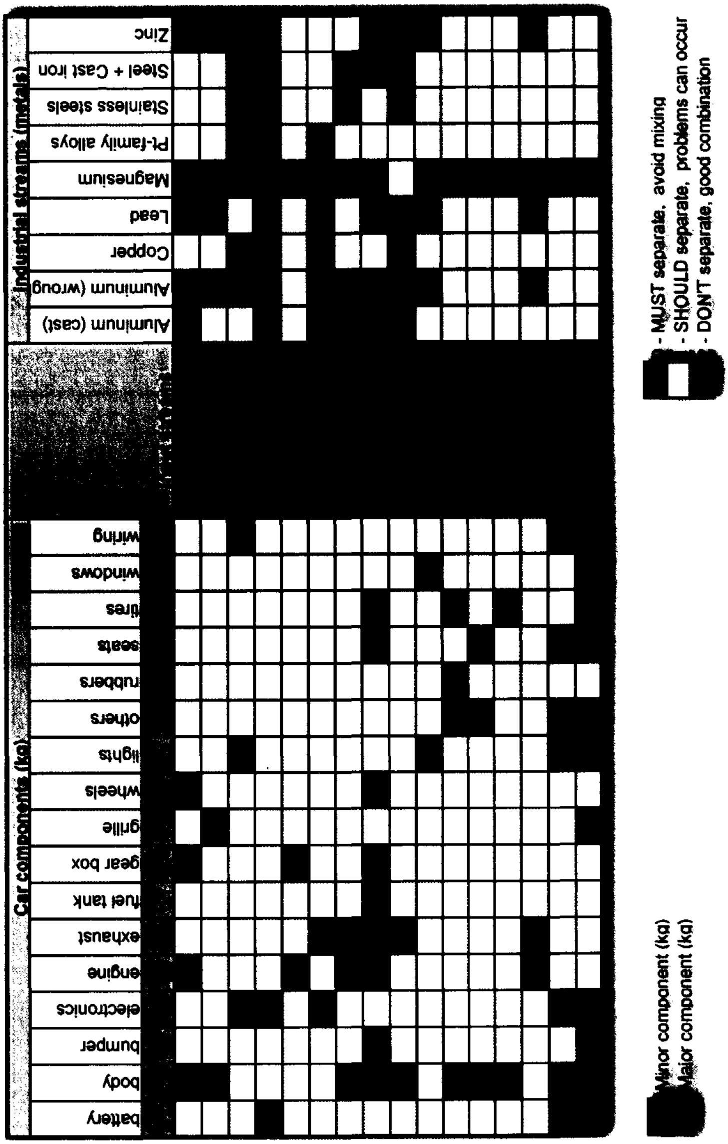

Figure 4.10: Metal grouping in car design (Castro et al. 2004).

A design for metallurgy is also important as some material combinations must be avoided, such as chemically linked steel and copper that are problematic for both copper and steel production, or the use of iron bolts in lightweight aluminum car frames (see Figure 11, chapter 3: the fourth concentric ring). Castro et al. (2004) translated these opportunities and constraints in a decision tree for design choices of materials for cars. Figure 4.10 shows which combinations of metals (and other materials) typically occur together in what car components, and which combinations should be promoted or avoided. It shows for example that stainless steel should not be mixed with aluminum or copper, but it can be combined with lead or zinc.

4.5.3 Metallurgists: new approaches to process control and design

Metallurgical reactors play a critical role in closing the metal resource cycles: they simultaneously perform the chemical reactions necessary to feed new materials into the resource cycles, and feed back old materials. If the constraints and opportunities of metallurgical reactors are not understood, sustainability at a bigger scale remains a myth: metal cycles can never be closed. Sustainability also calls for a radical change in the way the metallurgical reactors are operated, controlled and designed, and thus in the objectives and toolbox of metallurgists (see Reuter et al. 2003). To close metal resource cycles, it must be understood how the operation of the reactors is dependent on other (parts of) resource cycles, and how the operation of one reactor affects the others in the metallurgical network.

Process control and operation

Closing the resource cycles will affect control and operation of metallurgical reactors. Processed must be operated to reduce emissions and accept an increased fraction secondary materials, while simultaneously maintaining the quality of the products, intermediates and residues. The recycling of metals is inextricably bound up with production of metals from ores. Metals are produced through long chains of processes from either primary or secondary resources. In chapter 2, it was described that to meet increasing environmental and economic pressure, the production chains of the different processes are connected at many points to recover valuable metals typically found in the ores. This provides the metallurgical system with a certain flexibility to deal with variety of different resources. However, the recycling secondary resources often contain material combinations not common in ores, and exhibit far greater dynamics in composition and supply than primary resources. If the recycling rate of metals increases, processes can use less primary raw material to dilute undesired impurities, and have to cope with 'new' raw materials and greater variations in their feed. This can lead to the formation of lower-grade products, complex residues streams, and undesired harmful emissions. This inhibits the efficient and environmentally sound recovery of secondary metal resources and affects the economics of the plants that often have tight operating margins.

Feedforward and feedback are the two basic control mechanisms in (chemical) process control (Figure 4.11). The objective in both types of control is to keep values of the controlled parameters at the desired levels. Feedback control uses offsets in the controlled parameters to adjust for disturbances in the input. Feedforward control mechanisms use direct measurements of input disturbances, and based on the anticipated change in control objectives, adjustments are made to minimize offsets in control objectives. When offsets in the controlled parameters are critical, e.g. product quality or critical emissions, feedforward control is preferred. Feedforward enables ideal process control (i.e. no offsets in control objectives), however non-measured or non-modeled disturbances are not compensated for (Stephanopoulos 1984). Chemical process control therefore usually involves both feedback and feedforward control.

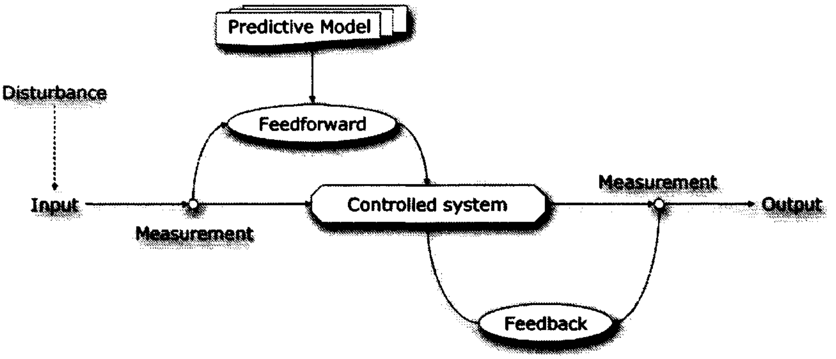

Figure 4.11: Principles of feedback and feedforward control.

The simultaneous decrease in emissions and increase in secondary feed will require more feedforward control. Reuter et al. (2003) have shown that the distributed chemistry of the (primary and) secondary materials of pyrometallurgical reactors has a significant impact on the reactor/process products, intermediates and residues/emissions and model predictions used for process control. Increased recycling will amplify these effects, and the current practice in process control based on classical models and the experience of human operators[4] may no longer be acceptable, at least from environmental point of view. Advanced predictive models of metallurgical reactors are required that allow the selection of suitable resources and adjustment of operating conditions to changes in the feedstock composition. These models must consider the distributed dynamics and chemistry of metallurgical processes; their development should be based on methods to extract useful data, such as data reconciliation (see chapter 2). A semi-empirical model approach based on these criteria is described in more detail in Eksteen et al. (2002) and Georgialli et al. (2001, 2002). Another, related approach is the recent use of the semi-empirical smelter feed model of Umicore validate a LCA valuation of the streams, taking into account their uncertainty and confidence level. This allows development of reliable strategies to minimize the environmental impacts of a crucial process in the end-of-life chain of electronic products: a copper smelter, as part of an integrated metals smelter and refinery (Van Heukelem et al. 2004).

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[4] Human operators learning-by-doing accumulate knowledge and develop mental models of how the processes respond to different raw materials. This illustrates how process control is one of the main drivers for development in extractive metallurgy.

Based on such models metallurgical processes can select proper resources, minimize emissions due to impurities in the feed, or maintain product quality. Because of the variation in the composition of secondary materials, this would require comprehensive sampling of secondary materials. If the compositions are known beforehand, some problematic impurities can be dealt with by adequate action in the metallurgy. The elements nickel, copper, tin, molybdenum, cobalt and tungsten are difficult to remove from steel products. Thus, these must only be present in the waste material processed if desired in the end-product. The presence of nickel, for example, would enable blending waste into an attractive metal source for the production of certain (stainless) steel alloys. In this the way, the down cycling of metals can be minimized. This feedforward resource selection is not a totally unfamiliar concept in metals processing. In secondary aluminum processing scrap is selected (and combined) in such a way that a proper alloy is created, taking into consideration scrap qualities, losses to salt etc. This can be explained from the tight tolerance for impurities in aluminum, and aluminum production processes.

Process design and integration

The efficiency of metal production and recycling is determined by all processes in the metal network, and the flows between the processes (network structure), by the mix of primary and secondary of raw materials and by the demand for metal grades. Traditional engineering approaches to process design, however, tend to focus on modeling and optimization of flows within a process, rather than the flow of materials and energy between processes (see e.g. Douglas 1988, Sinnott 1993, Allen and Shonnard 2002). Process integration techniques, such as heat- and mass-exchange network optimization, are effective for identifying opportunities for exchange of waste heat and reuse of water and other materials across unit process boundaries. Today these techniques are mainly applied to improving the efficiency of processes or process facilities. Considering the development of the metallurgical system (see chapter 3, section: 3.2), a reduction of metal-related emissions, and increase in metal recovery will result in further development of the interdependence between metallurgical processes. Increasing the efficiency of metal production and recycling would therefore call for process integration that goes beyond individual processes or process facilities, and that is based on economic, ecological and technological criteria.

Due to the complex interdependence, it is very difficult to determine whether the introduction of a new process (or the phase-out of an old) improves the resource efficiency of metal production and recycling. Without considering the effects on the metallurgical system as a whole, introduction of a new process or other innovations to increase the efficiency of a process can disturb the developed interdependencies, and possibly lead to lower overall efficiencies. For example, replacement of an ISF process with a hydrometallurgical process can reduce emission to air, but can also give rise to problems with the processing of primary iron containing or secondary lead-zinc concentrates, for example. Changes in the production of metals can also affect the recycling metals, and *vice versa* increased metals recovery can be expected to give rise to problems in metal production.

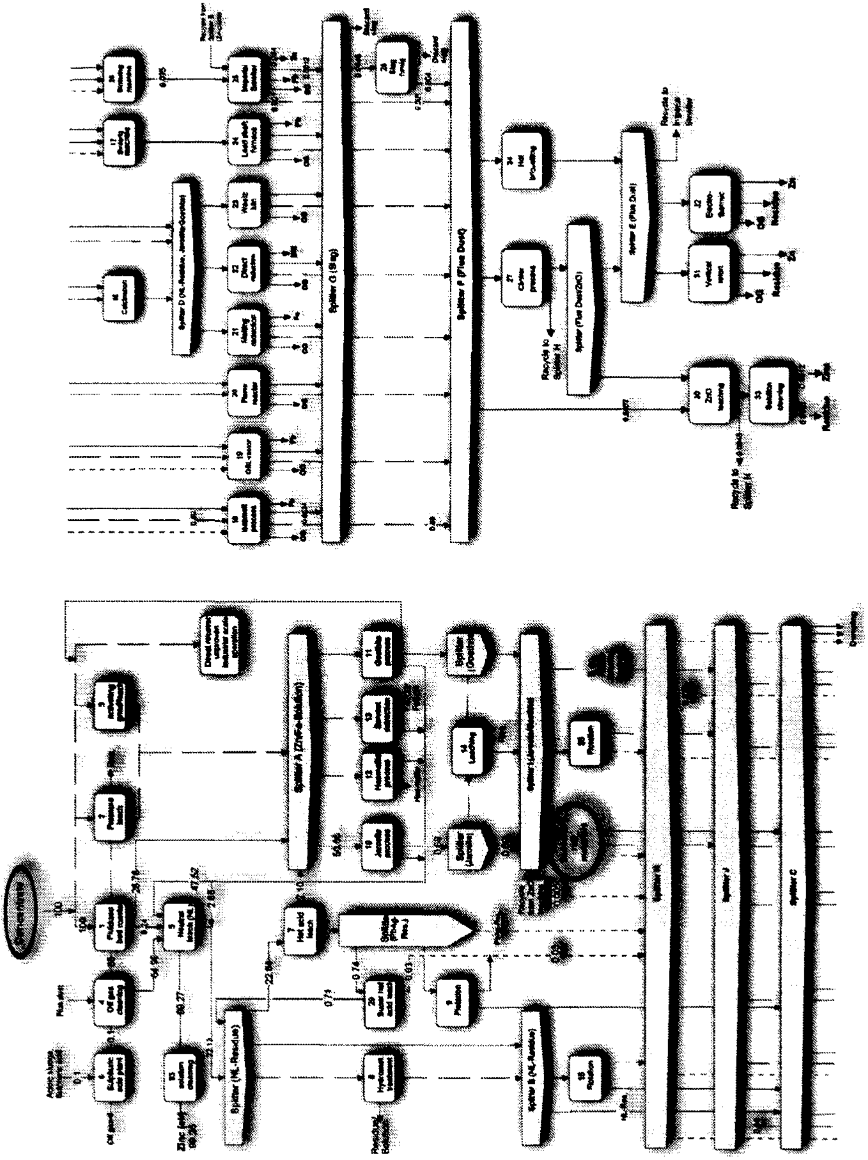

Figure 4.12: Example of computer simulation as a tool to systematically compare different process routes, given economical and environmental constraints (Reuter et al. 1996). The left flowsheet shows the hydrometallurgical processing of zinc containing materials and the feed of secondary materials to pyrometallurgical unit operations. The right flowsheet shows the pyrometallurgical and hydrometallurgical treatment of intermediate products and residues.

Systems approaches are thus required to put the process design in the context of the larger system. This critical change in the process design approach resembles the change in process design in the 1970s. Engineers began to realize that correctly assembling the process building blocks is just as important as properly selecting and designing individual components (see e.g. El-Halwagi and Spriggs 1998)[5]. However, where engineering procedures for the design of individual industrial units are well developed, the problem of determining the best arrangement of these interconnected units is far more difficult. The available tools, which focus mainly on optimization of an individual process, must thus be complemented by systemic assessments of the interconnected metallurgical system.

The development of computer simulation tools allows systematically comparison of different process routes, given economic and environmental constraints (see Figure 4.12). These systemic simulations also help identifying the impact of process introduction/substitution on the operation of the metallurgical system; for example, to what extent the intervention contributes to higher resource efficiency or lower environmental impact of the system as a whole. In the metallurgical (or industrial ecology[6]) literature only few examples of such comprehensive assessments could be found, viz. Reuter et al. (1996, 1997, 1998) and Südholter et al. (1996). These studies emphasized mainly the production chains of individual metals, rather than their dynamic interdependence. Reuter (1996) and Sudhölter et al. (1996) for instance investigated the synthesis of process routes for the production of zinc based on economic, ecological and technological criteria.

4.5.4 Discussion

It has been illustrated that closing resource cycles is dynamic problem: each stage in the resource cycles has its own dynamics and objectives. The cycles are continuously affected by new product designs, development of legislation and policy, new technology or increased recycling. Growing environmental awareness in society is reflected in an increasing set of environmental standards and protocols laid down in legislation. Technological development, competition and fashion produce continuously changing flow of products flowing through society. Consequently, the resource cycles typically are not in steady state.

A sustainable metal metabolism must thus be flexible because in a system of closed resource cycles, as each stage, process and activity is dependent on others but acts more or less independent. The prospects for sustainable metal metabolism are thus determined

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[5] The discovery of fundamental principles that can guide this assembly led to the concept of 'integrated process design' or 'process integration', which emphasizes the unity of the entire process. This design approach addresses the big picture first using fundamental principles, and then tackles design details only after the major structural decisions have been made. It assures that the correct details receive attention.

[6] Less comprehensive assessments of the metal production circuits include, for example, Ayres and Ayres (2002) or Graedel et al. (2002). Graedel et al. (2002) considered on the flows and accumulations of a single metal, viz. copper, in Europe. The purpose of their study was an initial characterisation, i.e. recognition and comparison of the major flows, and identification on the major data deficiencies, rather than providing a basis for improved synthesis of the production routes.

by society's capability to devise strategies to manage dynamically and globally linked industrial landscape. This will be difficult with our current approaches. Allenby (1999) therefore suggests 'we need to develop far more power in our systems models and thinking' (see chapter 2). Because of their complex, dynamic interdependence, this is especially true for the metal resource cycles.

To advance towards sustainability, product designers, waste managers or metallurgist must become good system thinkers. Changes at process level affect the dynamics of the larger system, and thus the decision parameters for product designers, waste managers or metallurgists. The role of the metallurgical reactor –a key processing component of the metal cycles- must be understood to assess and address problems in the bigger system, and *vice versa*. To our knowledge, neither in industrial ecology literature, nor in metallurgy literature models have been reported that considered the dynamic interdependence outlined in the sections above.

In industry on the one hand, metallurgists, metallurgical engineers and process engineers have largely focused on the entity of a catalyst system, a reactor system, or a single plant respectively. The planning and optimization of metallurgical (or refinery- and petrochemical) complexes has been largely the domain of operations research. These designs did not consider the role of a process, or pyrometallurgical reactor in the interconnected metal production system, but typically stopped at the 'battery limits'. Many of the standard texts of industrial ecology do not address the complexity of metals extraction, processing, metals use and recovery. One of the reasons may be that these texts originate from non metals-technologists. On the other hand, we conjecture that process system engineering may suffer from overspecialization (Boulding 1956) due to their focus on solving problems of limited scope (Verhoef 2001c). Resource cycles modeling can be used as the basis for tools that combines industrial ecology overview of the system and can link up detailed engineering models for in-depth information on its subsystems.

In contrast to many LCAs, SFAs or industrial ecology studies, this tool must support the communication between industrialists, waste mangers and product designers and represents an attempt to bridge the gap between the holistic view of industrial ecology and analytic view of process engineering. In addition to linking changes in the system to decision-parameters, these models may enable stakeholder assessment, or provide for a forum (or common language) to co-ordinate the different efforts. The description of the metal resource cycles in the previous chapter is a solid basis for construction of such models.

4.6 Controlling the resource cycles

In an ecological perspective, one also looks at the relationships between organisms and their environment. In section 4.1, therefore, the term 'metal ecology' was introduced to refer to the relationships between metals extraction, production, manufacture and recovery processes (discussed in 4.3 and 4.5), as well as the interaction with non-technical, 'environmental' factors driving the system, such as economics, policy, legislation and the natural environment (their environment). These 'environmental' factors are important because technological solutions alone will not result in a closure of the resource cycles.

In industrial societies, economic markets are the basic control mechanism by which available resources – the term resources is used here in the widest sense, including financial resources, materials resources, capital goods etc. - are allocated to the different processes across system levels, dependent on the societal demand for the services/products these processes produce. The control mechanism co-ordinates different processes to produce the desired services/products across all systems levels and throughout all stages in the resource cycles. In many textbooks on economics (e.g. Baumol and Blinder 1998) one can read that the 'invisible hand' of the market allocates resources efficiently. Without any guidance from governments, free market economies have achieved unprecedented levels of outputs, productive efficiency, variety in available consumer goods and general prosperity. However, the market mechanism has also weaknesses, among others its ability to cope with externalities (such as the environmental impact of economic activities, which has lead to concerns about the sustainability of current market economies. See also chapter 2). Because of the market inability to cope with externalities, governments have found it appropriate to intervene through policy and legislation, and create additional incentives, restrain or even prohibit certain activities. This section investigates the potential of markets/economics, policy and legislation to the close material cycles, using the EU waste legislation as a case. Because of the environmental impacts associated with waste management, different regulatory regimes apply for wastes and virgin or primary resources in the EU. Consequently, EU regulation largely shapes the technological choice for waste disposal, incineration, or recovery options.

Cadre 4-3: The need for integrated waste policy and legislation

The goals for waste policy and legislation are simple: stimulate waste prevention and recycling, and minimize impacts of waste processing. This has led to the so-called 'waste management hierarchy' that is the basis of the EU waste policy and legislation (EU (1975) the 'Waste framework' directive). Waste should be prevented as much as possible. If waste can not be avoided it should be recovered (reused, recycled, or 'thermally recycled'). Final residues that can not be prevented or recovered must be disposed of with as little (negative) environmental impact as possible.

In the western world, policy and legislation have been particularly successful in controlling the pollution of metal recycling and waste disposal processes, typically resulting in end-of-pipe solutions. Wernick and Themelis (1999, after Frosch 1996) observe that while U.S. regulations have been 'successful in controlling air and water emissions from point sources', they have been far less successful in the development of policy and legislation 'that serve to protect the environment as well as encourage optimal metal recovery'. This appears the case for the European waste legislation as well. EU waste legislation in many countries raised standards, which resulted in a better regulation and monitoring of potentially harmful activities, rather than in effective control of the growth in waste generation (prevention), or stimulation of recovery and recycling and reduction of disposal (Tromans 2001, EEA 1999).

One of the reasons is that waste management is a complex, politically loaded and emotionally charged issue that is neither well structured nor well understood (Tchobanoglous et al. 1993, MacDonald 1996, Tromans 2001). The success or failure of the EU waste policy and legislation depends on a complex partly market-based system governed by different local, national, and international regulations, the capacity of treatment facilities and the price structure between treatment forms and between nations. In theory, the process of developing legislation should provide for examination and balancing of scientific evidence and policy goals. There are both conceptual and practical difficulties in collecting factual data and linking them in a meaningful way to the impact of legislative and policy instruments. The composition of waste flows and the capacity of processing facilities are not well known. European waste statistics are still based on inconsistent approaches to the categorization and listing of the types of wastes. Hardly any information is available on the capacity for reuse and recycling of different wastes and assessment of that capacity is complicated by the fact that many recyclable materials – metals in particular - are traded on the world market (EAA 1999). Without feedback on system performance through consistent statistics on waste generation, it is difficult to determine the effectiveness of policies and legislation on disposal and recovery. Consequently, there is a need for structuring the problem of waste management, and examination of the effectiveness of the traditional regulatory, market-based incentives, but also for new policy instruments such as voluntary approaches (see e.g. O'Rourke et al. 1996, Harrisson 1998, Andrews 2002 and Thomas et al. 2003). In addition, the fragmentation in the development of policy and legislation complicates acquiring a coherent, transparent legislative framework (Lowe et al. 1997a). Even within EU member states, the development process is still often fragmented across many governmental bodies, media of pollution, and/or stages in product life cycles.

As a result Tromans (2001) observes that the apparently simple principles of the waste management hierarchy gave rise to 'a body of EC and national law that is notoriously difficult, even for specialist lawyers and which – even for such lawyers- makes little sense in terms of some of its points of detail.' Waste policy and legislation rigorously define wastes and their sources to avoid environmental problems, but at times severely limit their transport, reuse and recovery (Verhoef et al. 2000a, 2000c, and 2004a, Lowe et al. 1997a, Bontoux and Leone 1997). Perhaps more important, the lack of a clear, consistent regulatory framework also inhibits effective regulation and co-ordination of the different activities and processes involved in prevention, recycling and disposal of waste.

From an industrial ecology perspective, the main distinction between point source (or emission) control on the one hand, and preventing waste generation and stimulating recycling on the other, is that the latter two require co-ordination of the different activities and processes involved. When waste is considered an 'emerging attribute' of materials, substances and products (see chapter 1), waste management becomes a wider subject than waste treatment alone. It follows that many solutions to waste problems can not be found in waste management itself but must be looked for in the processes upstream and downstream. Neither can the challenge of increasing waste quantities be solved in a sustainable way by efficient waste management and recycling alone.

The recycling of metals is a function of the extraction and production of metals, the manufacture of products, consumption activities as well as waste management. Thus to stimulate recycling of waste, it must be analyzed and handled as an integrated part of total material flow through the *global* society (e.g. EEA 1999). It thus requires co-ordination of the different activities and processes in the resources cycles, and calls for integrated policies and legislation.

4.6.1 Integrated control of the metal resource cycles

Stimulation of the recycling of waste requires co-ordination of the different activities and processes throughout the resources cycles, and calls for integrated policies and legislation (Cadre 4-3). Integrated policies and legislation address the problem of resource management, rather than waste management alone. The required co-ordination of the different activities and processes in the resources cycles to minimize losses is a dynamic problem. The industrial ecology metaphor is a convenient way of structuring the dynamic problem of waste/resource management. Lowe et al. (1997a) argue that the metaphor of industrial ecology is particularly powerful in terms of ecosystem interaction and dynamics; natural ecosystems are 'tested' sustainable systems, evolved over millennia and flexible in the face of change[7]. The dynamic stability of ecosystems is a result of their organization as bottom-up or self-organizing feedback systems (see chapter 2). The resemblance of self-organizing capacity of (competitive) markets with the self-organization (or 'autopoeisis') of natural ecosystems through decentralized processes, may explain the sympathy for market as co-ordination mechanism in prescriptive industrial ecology studies.

To use the self-organizing capacity of markets, legislation and policies must provide for incentives and restrictions without inhibiting industrial change and innovation. In the EU, some of these incentives and restrictions have already led to the development of legislation. The directive on the landfill of waste has laid down objectives for the landfilling of waste, and should increase recycling as a consequence. The European Union's proposed Integrated Product Policy (IPP) seeks to stimulate demand for greener product lifecycles (EC Commission 2001). Recent initiatives that lay down concrete objectives for recovery/recycling at the product manufacturers are the directive on packaging, end-of-life vehicles and wasted electric and electronic equipment. Much work still need to be done before waste is regulated as an integrated part of total material flow through the global society. In the next sections, waste management is structured from an industrial ecology perspective.

4.6.2 Metal resource cycles as self-organizing feedback systems

Increasing the recycling of waste and closing the resource cycles require the simultaneous control of a great many processes and activities that are connected in a network of mass and energy flows. Many of these network relationships are determined at process level. The match between the operational knowledge, and technological

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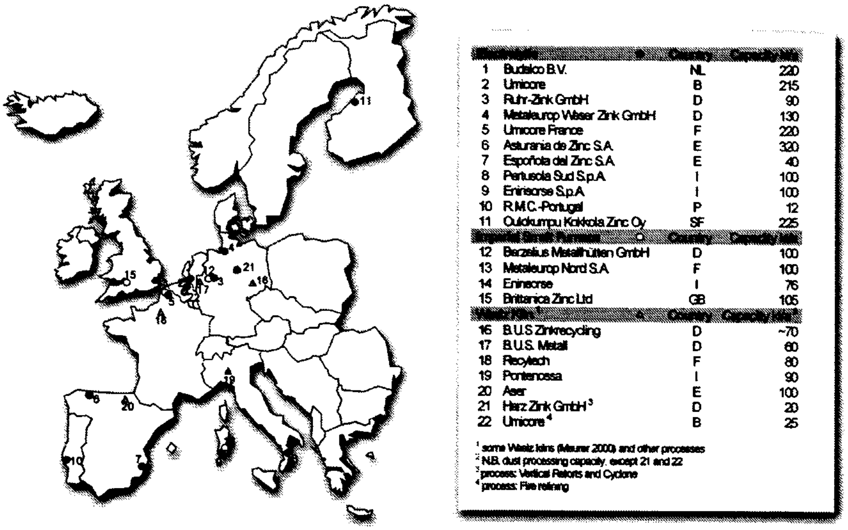
[7] Many other industrial ecologist also stress the importance of dynamic perspectives in IE studies (see section), and draw on ecosystems as inspiration for industrial systems (see chapter 2: e.g. Allenby (1999), Graedel and Lifset (2001), Ehrenfeld (1998))

capacity of processes and physical and chemical composition of resources, determines its value as a resource or its hazard to the environment. Because waste composition and the industrial recycling capabilities are not well known by regulators, top-down control has resulted in the lack of clear definitions on key terms, and the imposition of wide and open-ended objectives, which leads to further complications due to differences in interpretation internationally. A typical example is the definition of waste and recovery in the regulation of cross-border transport of waste (Verhoef 2000a, 2001a and 2004a, Malcolm and Clift 2002, Tromans 2001). The top-down policy and legislation, set out to minimize the hazards of waste transport, may actually discourage the use of secondary resources. Because the match between process capabilities and waste composition can be better determined at process level, regulatory efforts should use the decentralized knowledge of industrial processes. In other words, it should be based on bottom-up control and the self-organizing capacity of primary and secondary resource markets. This will be illustrated in Cadre 4-4.

Cadre 4-4: Cross-border transport of waste

The very qualification of a material as waste or secondary raw material has many consequences on what is allowed or not, what administrative procedures apply to its transport, export or processing, and what costs will be incurred (Bontoux and Leone 1997). The problem is that the present qualification waste has no direct link with the potential of the waste to be recycled, or the impact of the waste treatment. Products, substance or materials become waste, when they are discarded, or when they are intended, or are required to be discarded (EU (1975) Waste framework directive). This inhibits the recycling of some metals because of the rigorous processing requirements, and the more onerous permit and transport requirements for secondary materials than for primary, but also because of the negative image conferred to the material. In addition, the differences in interpretation between member states or internationally may yield divergent standards for metal recovery (resulting in 'unfair competition' or barriers to trade) or restraint transport of waste to suitable recycling facilities in other countries. Figure 4.13 shows that because zinc processes are distributed around Europe, metals often must cross national borders to be recycled.

In the EU, the regulation (1993) on the shipment of waste is based on 'red, amber and green lists'. Wastes are categorized according to their hazard: from non-hazardous waste (green) to hazardous waste (red). This categorization, and its intended use (recovery or disposal), determines the conditions under which the waste may be transported. Because of the difficulty of labeling products as waste, and processes as recovery operations, the treatment of unassigned wastes leads to different interpretations among member states, and even institutions within the EU (Tromans 2001).



	[illegible] ●	Country	Capacity kt/a
1	Budelco B.V.	NL	220
2	Umicore	B	215
3	Ruhr-Zink GmbH	D	90
4	Metaleurop Weser Zink GmbH	D	130
5	Umicore France	F	220
6	Asturania de Zinc S.A	E	320
7	Española del Zinc S.A	E	40
8	Pertusola Sud S.p.A	I	100
9	Enirisorse S.p.A	I	100
10	R.M.C.-Portugal	P	12
11	Outokumpu Kokkola Zinc Oy	SF	225
	[illegible] ○	Country	Capacity kt/a
12	Berzelius Metallhütten GmbH	D	100
13	Metaleurop Nord S.A	F	100
14	Enirisorse	I	76
15	Brittanica Zinc Ltd	GB	105
	[illegible][1] ▲	Country	Capacity kt/a[2]
16	B.U.S Zinkrecycling	D	~70
17	B.U.S. Metall	D	60
18	Recytech	F	80
19	Pontenossa	I	90
20	Aser	E	100
21	Harz Zink GmbH[3]	D	20
22	Umicore[4]	B	25

[1] some Waelz kilns (Maurer 2000) and other processes
[2] N.B. dust processing capacity, except 21 and 22
[3] process: Vertical Retorts and Cyclone
[4] process: Fire refining

Figure 4.13: Location and capacity of zinc processes in the EU.

National authorities can assign (as is the case in the Netherlands, for example) mixtures of components that individually are listed as green or amber, and are not specifically assigned to any of the lists to the red list (hazardous waste)[8]. Consequently, it is difficult for the metal recycling companies to see the trees in this dense regulatory forest, due to the complex categorization of waste, recovery operations, and national policies; and the ambiguous transport requirements discourage recycling.

The problem is that the actual hazard or value of wastes as a resource is determined by the match between the specifications of the process with the (physical and chemical) composition of the waste. The diversity in waste and metals recycling processes complicates developing a more consistent approach to the categorization of products as waste in standardized list, or processes as recovery operations. Because of the continuous variation in waste material combinations and volumes, not all waste substances, materials or products can be included in the list, and this rigid top-down regulation restricts and complicates the transport and, therefore, the recycling of metals.

In ecosystems, the exchanges of nutrients between organisms are maintained through self-organizing process as well, not top-down control (Lowe et al. 1997a). By analogy, a shift to decentralized or bottom-up control through policy and legislation could provide more freedom for the processes to select and transport suitable resources, and thus a more stable supply of resources.

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[8] A typical example is electric wiring: individually plastic and copper are on the green list; however, electric wiring that consists of plastic and copper is treated as hazardous waste, although it can be very well recycled (see for example MRF 2003).

Bottom-up legislation could be based on their environmental impact (e.g. operating licenses), rather than on restricting the flow of wastes based on standardized lists. Processes are allowed to use different resources as long as they obey strict environmental limits and standards, and obviously meet specifications of the product manufacturers. Because emissions and residues are determined by the match between feedstock and process capacity, this will force metal producers to judge continuously secondary resources based on their hazard and their value for the process. The obvious advantage of this form of decentralized control is that it builds on the decentralized knowledge stored in individual processes to select resources that are compatible with the required overall system performance.

Relationships between activities and processes in the metal resource cycles are maintained through economic markets that can be viewed as self-organizing feedback systems. A balance in positive and negative feedback loops provide markets with an element of stability. Positive feedback stimulates certain behavior, whereas negative feedback curbs certain activities. If for one reason or another, a metal becomes less available, its price rises. This causes a number of actions to occur which limit the rise, and or affect the production of the metal. Higher prices stimulate people to use less of a product (negative feedback). Higher prices also encourage metal producers to increase process capacity based on existing technology, or find new ways through research on alternatives (positive feedback). The dynamic performance of the industrial system as a whole is controlled through 'economic' selection: the sum of positive and negative feedback. If a process becomes less economically 'fit', the technology is less likely to be reproduced in new processes. Consequently its population declines, unless it is able to adapt. Too strict 'economic' selection, however, may offset the balance between the 'static' productivity and efficiency of the industrial system and its 'dynamic' flexibility or adaptability to cope with changes in material or energy flows.

Because environmental impacts are difficult to express in monetary units (so-called economic externalities), the negative feedback from the environment perceived by industrial activities is typically much smaller than the positive feedback of the economic profits resulting from the activities. Therefore, the goal for environmental policy and legislation must be to strengthen the negative feedback loop by measuring and monitoring the environmental impacts of flows into the environment and internalizing these impacts into economic theory and practice.

The problem of 'dilution of metals' described in section 4.3 can be considered a problem of balancing feedback loops. A key principle in industrial ecology is the cyclic use of materials. In society metal retention - that is the ongoing use or availability of metal in the economy, between the life cycle stages of resource extraction and final disposal back into the lithosphere - is finite because of the limited grade of secondary (recycled) metals. Currently, metals are maintained in their utility through the addition of high-grade primary (virgin) metals, bringing the concentration of impurities in the metals produced to desired levels. This mixing with high-grade primary metals keeps these recycled metals in the cycle. Consequently, there is no negative feedback on the composition of products. The selection of metals for products is primarily controlled by the positive feedback from the economic benefits of using the specific properties of the many different metal alloys and combinations. Long-term, this practice of dilution of the undesired substances prevents a closure of the material cycles, whereas recovery without dilution will reduce the quality (or quantity) of recycled metals.

Simultaneous minimization of environmental impacts, increase in recycling and avoidance of metal dilution, will call for integrated legislation and policies (see 4.5 and Cadre 4-3) The 'extended producer responsibility' can strengthen the negative feedback loop in selection of metals for products by making manufacturers responsible for the recycling of their products. Somewhere a balance must be found between the protective constraints of legislations, and the freedom of industry to adapt. Metallurgical processes need room to adapt and innovate, in order to achieve (or exceed) the required legislative requirements and desired product grades under dynamic conditions. Process boundary conditions continuously change due to fluctuations in the demand for metals, the supply of primary and secondary raw materials or the development of policy and legislation. Positive and negative feedback mechanisms in markets must therefore not select on environmental efficiency and economic productivity alone, since this could offset the dynamic balance with flexibility of the metal production systems. If the goal of legislation is environmentally sound recycling rather than dilution of metals, legislation can not fix all degrees of freedom of process operation: restrict the supply of secondary resources, prescribe the use of the best available technologies, and set limits to emissions and residues. Rather it must select a critical set of process outcomes. The puzzle of bottom-up control is thus finding a set of process constraints that lead to the desired industrial performance but do not restrict industry to adapt and innovate. This is further illustrated in the cadre below.

Cadre 4-5: Best available technologies

Waste/environmental policy and legislation are often perceived as an inevitable trade-off between the social benefits of mandated environmental standards and industry's private costs of prevention, control, and clean-up. According to Porter and Van der Linde (1995a, 1995b), this perception neglects the dynamic character of industrial innovation in response to environmental pressures. They argue that environmental regulations can actually benefit competitiveness, if they allow industry to change and innovate. In this way, industry can simultaneously increase resource efficiency and enhance their competitiveness.

Such policy and legislation must not be based on top-down prescription of technical solutions, which has been one the most limiting aspects of environmental regulation, but on process outcomes (Lowe et al. 1999a, Porter and Van der Linde 1995a, 1995b, Verhoef et al. 2000a). If a process or industry is not locked into a certain answer, it has the room to adapt and innovate, and to achieve or exceed required performance. This bottom-up type of legislation and policy offers industry a more degrees of freedom to respond to changing regulation or changes in other process conditions. The problem is how to measure and enforce process 'outcomes' without prescribing technological solutions.

The EU IPPC directive (EU 1996) lays down that emission limit values, parameters or equivalent technical measures should be based on the Best Available Technologies (BATs), *without* prescribing the use of one specific technology and considering the technical characteristics of the installation concerned.

Enforcing the directive is difficult, because the best available technology alternatives are likely to be plant level specific, if not site specific. Older pyrometallurgical furnaces generally have higher energy consumption and/or emissions. This easily leads to the assumption that using these furnaces can not be regarded as employing best available technologies. Often however these furnaces are integrated into process plants or used by other plants (see chapter 2 for examples), and thus can not be considered independently of the other processes. They can add specific tasks or capacities to the process plant as a whole, such as the production of high-grade metals from complex metal resources, co-recovery of metals which recovery otherwise would not have been feasible, or handle of critical residues from other processes. At system level, the resultant diversity in metallurgical process enables effective recovery of different resource mixes, and recycling of residues.

To minimize the potentially negative impact of environmental protection on industrial competitiveness, implementation of BAT policies requires solid understanding of the industrial system. First, BAT policies can hold back innovation, as technological innovation is generally faster than legislative development. Second, without proper consideration the role of a process in the metallurgical network, implementation of BAT legislation could also render critical processes in the metallurgical network unprofitable. It in turn can restrict the use of metal in different products, or inhibit the recycling of certain metal wastes. This explains why Porter and Van der Linde (1995a, 1995b) conclude that in order to balance the protective constraints of legislations and the freedom of industry to adapt, industry should participate in the setting of environmental standards and the development of BAT policies from the beginning to feed the necessary technological information into the decision-making process. In addition, the regulatory process should become more stable and predictable, so that its expected outcome can be included in the planning of product development, technology, marketing and organizational support.

In addition, there are also limits to the self-organization activities and processes in the resource cycle through feedback. Feedback control is reactive, which means that when offsets in the control objectives are measured, actions are taken to minimize the offsets. Moreover, even if positive and negative feedback loops are in balance, feedback systems can become unstable. Many natural, industrial and economic feedback systems have delays in adjusting and consequently are prone to 'hunting'. Due to the delay, the negative feedback corrections may come too late, and give rise to a series of over-corrections, a phenomenon commonly known as hunting. In chapter 2, it was argued that the more variables fluctuating in ecological networks, the larger their capacity to adapt to changes in environmental conditions. In economic systems, these oscillations in network variables (e.g. material and energy exchanges, process populations) may be unacceptable. Due to the operation-of-scale, the sunken investments, the long lead times and economic life spans, oscillations in process populations are limited. Section 4.3 showed that oscillations in flows between processes arising from the fast dynamic in societal cycles are a problem when these dynamics are faster than the technology cycles of process innovation. As a consequence, they lead to increased emissions, residues, and/or decreased product grades (metal dilution). Controlling these oscillations becomes even more essential for two reasons: On the one hand, because the development towards closed resource cycle will lead to more feedback through the system; this increases the *chance* of oscillations. On the other hand, the closer industrial activities approach the carrying capacity of the planet, the higher the *hazards* of these oscillations (i.e. the faster increases in emissions and residues (irreversibly) affect the function and viability of ecosystems).

4.6.3 Feedforward control of resource cycles

To stabilize the dynamics in the resource cycles and minimize emissions and residues, industrial policy and legislation should be based on more feedforward type control of the system. In process control, feedforward loops allow 'ideal' control even when systems exhibit delays: no offsets in the control objectives (see 4.5.3). The delays provide time to adjust process conditions to disturbances. Although not often recognized as such[9], even in nature feedforward is an important control mechanism that stabilizes the ecosystem dynamics. Although feedback is a process of reaction, feedforward expectations are often part of the feedback loops in nature. These expectations based on previous experiences intuitively affect future experiences: If for example an animal has eaten food that is hard to digest of gave other problems, it will adjust its diet to avoid these problems.

A first requirement for feedforward control is a predictive, dynamic model of the controlled system. In ecosystems, the feedforward expectations use the mental models of how individuals see their environment. These mental models in turn influence the environment because individuals then base decisions on these models. According to Capra (1996: 275), this process of anticipation - or cognition as he calls it - is common to all organisms[10]. The predictive model is linked to the physical development of organisms: the physical structure of organisms is 'a record of previous structural changes' which in turn are a reflection of its experiences. The requirement of predictive models for feedforward control explains why in industrial systems, much of the environmental policy is necessarily reactive. The world is too complex to predict the environmental consequences of technological, policy or legislative changes. Specific activities and processes, however, can be modeled.

The second requirement for feedforward control is that disturbances must be measured beforehand: disturbances that are not measured can not be compensated for. Predictive models of processes can be developed that enable feedforward control (see 4.5.3), if processes can measure possible disturbances beforehand. Each process must receive

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[9] In Industrial ecology, ecosystem models are often based on the principles of natural selection and feedback. Interestingly, the IE strategies, such as extended producer responsibility and design for environment strategies, can be considered feedforward concepts. The strategies seek to reduce the impact of a product using some model of the industrial activities to consider the disposal, reuse and recycling options arising from the designed products. Ideally, this model should present available technology for processing materials, gaps in the available technology and constraints of these technologies as input for the design.

[10] Cognition is not limited to organisms, but a property of all life. In this context, ecosystems can also be considered cognitive systems; their reaction to change is shaped by the available diversity of organisms. Although the cognition itself is a feedback process, it gives rise to another basic mechanism: feedforward control.

information that should be tracked upstream and downstream in order to timely alter the operation, when these 'signposts' reach critical levels that require action.

To stimulate feedforward self-organization, policy and legislation can help develop, introduce and standardize these signposts. Obviously, the earlier in the metal life cycles changes are measured the better the system can respond. This is particularly true for large-scale systems, such as waste infrastructures, that because of their large inertia require considerable time to adjust operation. By careful tracking of consumption patterns and waste disposal per category, one can anticipate changes in waste composition and quantity and change the frequency of collecting, building or depleting stocks and gradually increase or decrease processing capacity. In this way, the life span of products buys time for metallurgical processes and/or waste processors to react to changes in product manufacture by modification of existing, or development new (pre-treatment) processes. Also for other disturbances such as changing legislative requirements of processes, e.g. process temperature, residence time and emissions, or increased energy recovery, it is important to receive this information as early as possible.

4.6.4 Hybrid Feedback and Feedforward control

Tibbs (1992) already argued that industrial ecology should be proactive (feedforward) not reactive (feedback). While it should be initiated and promoted by industrial concerns because it is in their own interest and in the interest of those surrounding systems with which they interact, not because it is imposed by the feedback one or more external factors, additional control through policy and legislation will be necessary. The problem of feedforward control is that non-measured or non-modeled disturbances are not compensated for. The problem of feedback control is to define a critical set of process outcomes. Due to the complexity of resources cycles, its control must be hybrid: both feedback and feedforward. This can be illustrated using the concept of extended producer responsibility (OECD 2000) for instance, which contains both feedforward and feedback elements:

- Feedback: the responsibility (physically and/or economically, fully or partially) is shifted upstream to the producer and away from municipal waste managers, and metal recyclers. In this way, the consequences of the product recyclability are led back to the manufacturer, providing positive or negative feedback on the design activities.

- Feedforward: incentives and objectives are provided to producers to take environmental and recyclability considerations into account in the design of the product. EU regulation aims to achieve 85% recovery of cars in 2008 (EU 2000a) and 95% in 2015. This is a way to feedforward the constraints of recovery in the design of products, by setting minimum recycling percentages of products.

The objectives for the self-organizing capacity can only be defined based on some (predictive or feedforward) model of the system. In the definition of the objectives, it is essential to determine at what point in the recovery or recycling process it can be properly claimed that a waste has been recovered or recycled. Recycling or recovery objectives can refer to the percentages of the car materials that enter the metallurgical recovery process, or to the amount of metal that find its way into new products. This distinction is important because how the materials are delivered to the metallurgical process has great influence on the amount of metal containing products that can be recovered as high-grade metal. In case of the latter interpretation the objective of the EU seem unrealistically high, particularly considering the trend towards greater complexity of cars, and increased use of composite materials. Following the first interpretation optimization of the amount of material separated from the vehicle may, in fact, even lead to a reduction of the overall recycling, or contribute to the dilution of metals.

The concept of feedforward control illustrates the role of descriptive approaches in the co-ordination of decision-making across system levels. They provide 'snapshots' of parts of the physical economy and connect the flows of mass and energy through the economy to social, environmental costs, or other decision or performance parameters. If properly constructed, these models allow policy-makers, legislators, but also products designers or engineers, to anticipate and minimize environmental impacts. Predictive, quantitative models of the system are required to promote feedforward control of the system.

An example of such a feed forward model approach is presented by Van Schaik et al. 2002 (Figure 4.14). Her model – based on the dynamics at process and product level – provides a basis for improvement of recycling legislation. Such dynamic modeling can show the effect of changing lifetime, weight and composition of cars on the recycling rate of End-of-Life vehicles (ELVs). As such, it can support a design for recycling, optimization of the dismantling, mechanical separation and pyro/hydrometallurgical processes involved in ELV recycling, and thus the establishment of proper legislative incentives, such as a minimum recyclability of cars.

As said before, the world is too complex to predict the environmental consequences of technological, policy or legislative changes. Even if there does not exist — and maybe there never will exist — an integrated model capable of describing such changes, striving towards such a model structures problems and gives valuable insights about how the processes interact and how this might effect the environment. This knowledge then can be used to include the proper stakeholders in the development process of legislation and policy. This is important because including the proper stakeholders brings a knowledge base into the processes, which may lead to better a feedforward model. Direct involvement of industry can ensure that technical complexities of the legislation are not overlooked, and can assist in formulating policy alternatives. Finally, industry should participate in the setting of environmental standards from the beginning to be able to include these in planning of process development, technology, marketing and organizational support

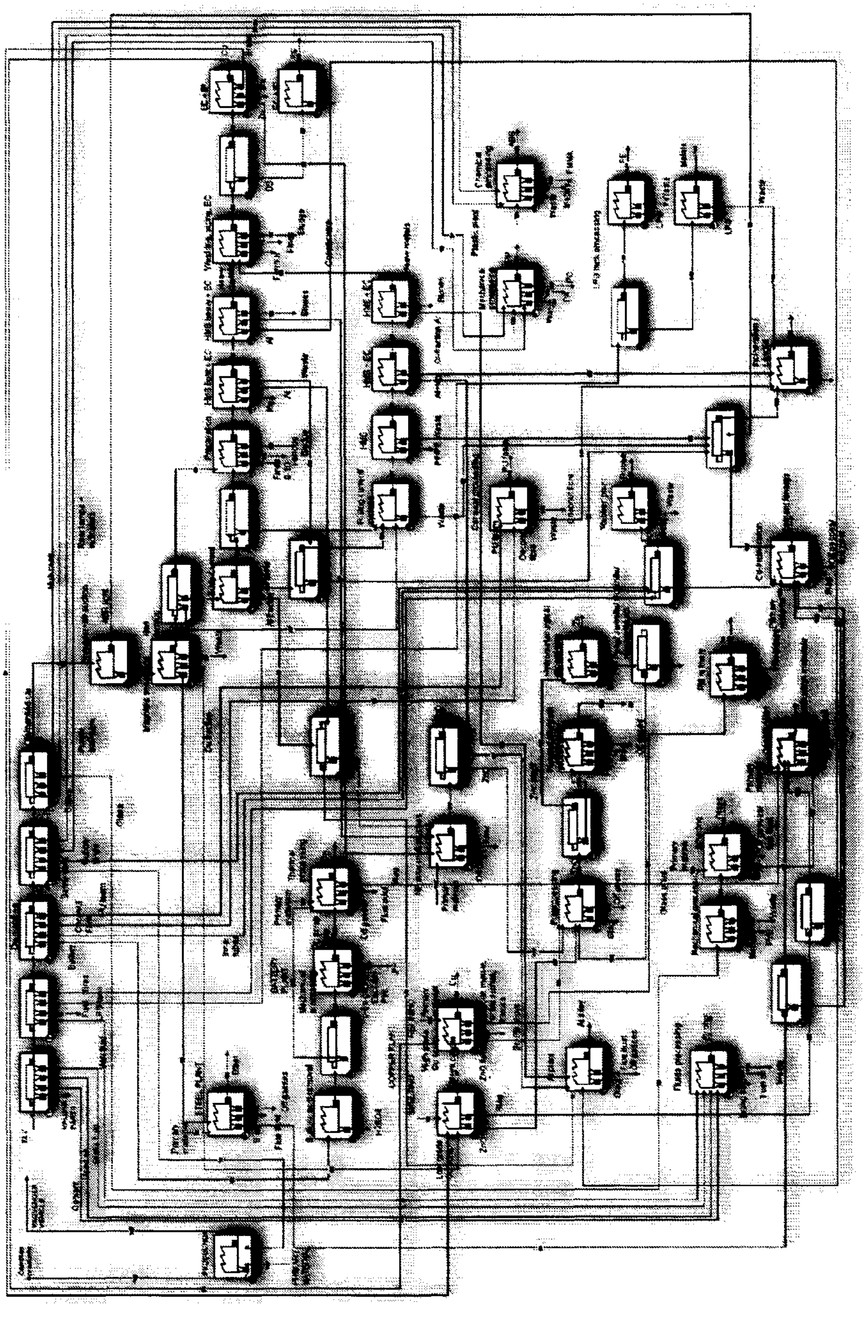

Figure 4.14: A model of the complex ensemble of technological processes that need to be co-ordinated of effectively recycle cars (Van Schaik et al. 2002).

4.6.5 Discussion

The goals of reduction of emissions and increasing resource efficiency as a long-term solution present a tremendous challenge, and will result in complex non-linear systems. The main problem is - as Allenby (1999) pointed out- that the degree and kind of controls and knowledge that such a complex, non-linear systems would imply are currently beyond the state-of-the-art. Where simple systems are intuitively "understandable", many aspects of complex systems are difficult and counterintuitive, and frequently are illustrated only by the behavior of properly constructed quantitative models.

These quantitative models are closely linked to feedforward control, or the forward-looking research and practice in the field of industrial ecology. In order to effectively cope with dynamics in a complex interdependent system, both feedback and feedforward control strategies are essential for policy, process design and process control alike. When offsets in the controlled parameters are critical, feedforward control minimize offsets in control objectives. Where direct measurements of input disturbances, or anticipation of change in control objectives is not possible, feedback provides a second control mechanism.

To advance towards sustainable metal metabolism through increased feedforward control, product engineers, waste managers and regulators must become good systems thinkers; they must be able to link the dynamics of the global metal metabolisms to the dynamics at process level, and vice versa. Few product engineers, waste managers and regulators will have a good overview of the operation of the metal metabolism as an interdependent system. In order to co-ordinate actions in the metal metabolism, a model of the dynamic, interconnected and interdependent metal cycles must be developed that bridges the gap between 'holistic' models of industrial ecology, and detailed models of process engineering. This will be further discussed in the next chapter.

The development of such models is essential to meet the industrial ecology goals for two reasons. First, construction of such models will at least lead to an understanding of the system dynamics, or structures problems. In such a way, the effects of changes to the technological infrastructure (e.g. new legislation, product designs, waste recovery operations or metal production processes) can be estimated, and possible bottlenecks identified. Second, such models would be suited to initiate further development of the products, or the production network by the stakeholders involved even if not all dynamics can be adequately captured. As such, the model could also assist in making the complex metallurgical knowledge available for waste management, policy and product design.

4.7 Conclusion

Implementation of industrial ecology leads to increasingly complex, interdependent systems. Because of their critical role in the metal resource cycles, a solid and detailed understanding of metal production and recycling is essential to *assess* and *address* the problems of industrial ecology strategies with respect to metals. A further development towards a reduction of metal-related emissions, and increase in metal recovery is likely to result in further development of the interdependence between processes, and stronger feedback through the metal cycles. Because of this interdependence, increased recovery can lead to contamination of stocks of metals in use, and therefore to degradation of the metals′ capacity to be (infinitely) recycled. Therefore, a sustainable metal metabolism is shaped by our ability to effectively control this infrastructure, and understand the changing role/requirements of the players in the metal ecology.

Industrial metals represent a network of globally linked materials that can not be studied usefully in isolation, but require an integrated approach for its understanding and improvement: the technical characteristics of the installations concerned, and their roles in the dynamically interlinked production and recovery system linked to environmental performance. Only through a 'concerted' effort can society approach closed material cycles. Product manufacturers must design products for the environment, deliberately considering the recovery of the products after use. Waste processors must optimize the source separation, and further develop separation plants. Industry must develop better technology to isolate and recover maximum value from metals in waste streams, and deal with changes in inputs. Governments must develop regulation that promotes recovery, and institute policies that remove barriers to the economically and environmentally sound recovery of metals.

Market co-ordination of these actions through either feedback or feedforward control requires multidisciplinary knowledge that link transformations and flows of materials and energy to the dynamics of the metal metabolism. In particular, metallurgical knowledge is essential in this process. In the design of products for environment/recycling, a consideration of the metal grouping in the products, or product components and resulting waste flows is imperative to enable future recovery of metals. The wheel visualizes these interdependencies. For effective (feedforward) control of the system, however, dynamic, predictive/quantitative models of the system are required that are rooted in a solid understanding of technological infrastructure. The (pyro)metallurgists' role is crucial developing such models. They must actively be engaged in making metallurgical knowledge available, and ensure that the databases and models represent the industry. Even if such quantitative models can not completely capture the development and patterns of materials and energy, they may serve as a tool to assist communication between the parties involved and further develop the required multidisciplinary knowledge.

5 Case study: lead production

Summary

In this chapter, an industrial ecology model of the interdependent resource cycles of metals is evaluated as a tool to assist decision-making on complex systems. The lead resource cycle is used as a case study. Lead is a very useful, but also very toxic metal. In the case-study, therefore, two complementary, prescriptive strategies to reduce the environmental and human health impacts associated with the lead resource cycle are examined. First, prevention or detoxification is an important theme in industrial ecology. The EU directive on lead substitution is one of the detoxification strategies. A second strategy is the containment of lead in the industrial system, by process development or increased recycling. This strategy is related to the IE strategies to increase the eco-efficiency, and close the material cycles.

Any strategy to reduce the impact of lead requires knowledge of the potential bottlenecks and environmental benefits. This chapter first discusses the toxicity and exposure of lead and the existing legislative framework (5.1). As an example of the first strategy, possible lead substitutes are investigated (5.3) using a comprehensive model of the metal cycles (5.2). As an example of the second strategy, different measures to reduce the emissions from lead use and production are studied (5.4). Finally, some conclusions are drawn with respect to the use of industrial ecology models to support decision-making on these strategies (5.5 and 5.6).

5.1 Why lead production?

Industrial ecology requires co-ordination across system levels, and between system components. As a consequence, it involves a shift from dealing with relative simple, well-defined subsystems, to dealing with complex and often globally interconnected systems. In the previous two chapters on metal ecology, it was argued that metals that participate in linked cycles can not be analyzed independently, nor can product design, waste management, metals production or legislation/policy be considered separately.

In this chapter, a model as a tool to assist decision-making in such complex, interdependent systems is presented and evaluated. Lead production is selected as a case study because on the one hand lead is a very useful metal with a great many different applications, on the other hand lead is a heavy metal with a high toxicity.

In this chapter, two complementary strategies to reduce the environmental and human health impacts associated with lead use and production are examined, viz. prevention and containment. Lead emissions can be prevented by substitution of lead in products. This strategy is related to the concept of 'detoxification' in industrial ecology. Alternatively, lead can also be 'contained' in the industrial system. Increased emission control in industrial and public infrastructures in combination with increased recycling can positively affect the environmental and human health impacts of lead use and production.

As a background for these strategies, the sections below discuss the sources of lead exposure (5.1.1), the environmental and human health impacts of lead (5.1.2), and finally the existing legislative framework (5.1.3). A model of the interconnected metal resource cycles is presented (5.2) and evaluated on its potential to support decision-making of the different stakeholders involved using examples of both strategies (5.3 and 5.4). Finally, conclusions are drawn with respect to the value of the model to co-ordinate decision-making on the design, operation and management of the metal resource cycles (5.6).

5.1.1 Sources

Anthropogenic emissions are the most important sources of lead. Natural emissions of lead rarely results in elevated concentrations in any environmental compartment. Lead occurs naturally in low concentrations in all rocks, soils and dusts, usually ranging from 2 to 200 parts per million. In the last two centuries, however, the anthropogenic sources of lead have increased dramatically. The total emission to air from natural sources is roughly ten per cent of the total anthropogenic air emissions in the mid-1990s (Nriagu 1989). The ratio anthropogenic/natural emissions for lead is significantly higher than for other heavy metals, such as Hg and Cd, for which anthropogenic and natural emissions are roughly in the same order of magnitude.

Anthropogenic sources of lead include release during production, from industrial effluents, dissipative use, disposal and transportation accidents and a wide variety of patterns of use. In 2000, roughly 3.5 million tons of lead were extracted from the earth's crust by man and brought into cycling in the 'technosphere' (i.e. the industrial system as opposed to the biosphere). In addition to this, also a significant amount of lead was extracted, but ended up as process residues, or was mobilized as impurity by the extraction of other minerals such as coal and lime. Detailed descriptions of the anthropogenic sources of lead includes the work of Nriagu and Pacyna 1988), and more recently Pacyna and Pacyna (2001).

Table 5-1: The total world-wide emissions of lead from all sources (Nriagu and Pacyna 1988).

	Emission to atmosphere (t/y)	Emission to water (t/y)	Emissions to land (t/y)
Metals and mining industry	31,125 - 83,840	5,560 – 37,320	329,100 – 791, 000
Use and disposal of lead	249,670 - 251,130	4,400 - 2,800	215,800 – 461,700
Other sources	7,886 - 41,854	240 - 1,200	57,190 – 303,700
Total	288,681 – 376,024	10,200 - 66520	602,090 – 1556,400
Atmospheric fall-out		87,000 – 113,000	202,000 – 263,000
Total	288,681 – 376,024	97,200 – 179,520	804,090 – 1819,400

Generally, human exposure to lead comes from the following main sources: using leaded gasoline, using lead-based paint, having lead pipes in water supply systems, and exposure to industrial sources from processes such as lead mining, smelting, and coal combustion. The major exposure route for the general, non-smoking adult population is from food and water. Inhalation is the dominant pathway, for workers in industries that produce, refine, use or dispose lead or lead compounds. In countries where leaded gasoline is still used, airborne lead exposure is a significant pathway. Increased awareness and environmental measures may reduce lead emissions as shown for instance by the phase-out of lead in gasoline in developed countries over the last two decades. Von Storch et al. (2003) showed how lead emissions in Europe underwent significant changes, from an almost unabated increase to a series of sometimes drastic reductions since the 1970s.

5.1.2 Lead toxicity

The fact that lead is toxic has been known for more than 2,000 years, and its effect on human and environment have been extensively studied (e.g. WHO 1989, WHO 1995, Royce et al. 2001, Nordic Council 2003).

Lead serves no known useful purpose in the human body, and its presence in the body can lead to toxic effects, regardless of exposure pathway. Lead can cause blood-related diseases, is toxic to the reproductive process and suspected to be carcinogenic. Acute high levels of lead exposure can cause serious physiologic effects, including death or long-term damage to brain function and organ systems. Lower levels of exposure have been shown, through population studies, to have many subtle health effects. The effects in children generally occur at lower exposure than in adults (e.g. Silbergeld 1995, 1996, Schwartz 1998, and Lanphear 2000).

Lead is not degradable in nature. Once released into the environment, it will thus recycle in the physical, chemical and biological processes in the environment. Lead is known to be toxic to plants, animals and micro-organisms. Both wild and domestic animals can ingest lead, for example while grazing, and experience the same kind of effects as people who are exposed to lead. Lead in the environment is typically bound to particles or found as compounds with a relatively low mobility and bioavailability (i.e. the extent to which lead can be assimilated by organisms). Lead accumulates in most organisms, in particular in organisms that primarily feed on particles, such as mussels and worms (a process commonly known as 'bio-accumulation'). There appears to be no increase in concentration of the metal in the food chains ('bio-magnification').

Given the increasing evidence of lead toxicity to humans at low levels of lead exposure, its toxicity and persistence in the environment (long-term exposure), it is essential that lead discharges, emissions and losses are prevented, or significantly reduced.

5.1.3 Legislation

In the literature, many overviews of legislation concerning restrictions on lead-containing products in different countries can be found (OSPAR 2000, OECD 1993, Thornton et al. 2001, Brønnum and Hansen 1998, Broeckmann 2003, and the Nordic Council 2003). A number of international agreements have been established in order to manage and control releases of lead to the environment. Perhaps the most well known of these is the Basel Convention that lays down binding commitments regarding the international transport of hazardous waste, and procedures for information and approvals on import and export of hazardous waste. In the convention, any waste containing lead or its compounds as constituents or contaminants is considered a hazardous waste, excluding metal waste in its massive form.

In addition, in many countries legislation and standards have developed to contain lead in the technosphere aiming to minimize lead releases to air, water and soil. These include legal standards for maximum concentration of lead in drinking water and quality standards for ambient air, fresh water and salt water, lead threshold limits for occupational air exposure, and emissions limits for the incineration of hazardous and non-hazardous wastes. In several countries, also voluntary agreements between industrial associations and environmental authorities have been used as an alternative to formal legislation. As an example of such an agreement, the European PVC industry has adopted the following reduction targets for replacing lead stabilizers on the basis of 2000 consumption levels: 15% in 2005, 50% in 2010 and 100% in 2015 (OSPAR 2002).

In line with the prevention principle, lead substitution has become an increasingly popular approach in Europe to reduce lead emissions at the source. The proposed EU directives on electrical and electronic equipment (2000b) are exemplary for this approach. Other bans on the use of lead are in place, or are taking effect in the near future, e.g. in vehicles, with certain exemptions (EU 2000a). In Denmark already bans on most uses of lead compounds not covered by EU legislation, and on many uses of metallic lead are imposed. The OSPAR Commission recommends that lead should be further substituted where appropriate. However, the commission adds that 'a detailed investigation of the use of lead in such products, including the effectiveness and safety of proposed substitutes and an appraisal of the advantages and disadvantages of carrying out specific substitutions will need to be carried out in order to assess the practicability of phasing out lead in products' (OSPAR 2002). As will be illustrated by the case study on lead production, the feasibility and overall environmental benefits of lead substitution or containment are not always obvious.

5.2 Modeling the metal cycles

The problem – and thus the necessity for modeling - for either prevention or containment strategies is that lead processes form an integrated part of the total base-metal production system. Examining the effect of lead substitution, or changes in the lead processes may therefore dynamically affect the production and recycling of many other interconnected metals. To our knowledge, neither in the industrial ecology literature, nor in the metallurgy literature studies have been reported that provide the required in-depth coverage of the dynamics and interconnectivity of the metal resource cycles in technical sense described in the two previous chapters.

In this section, therefore, a dynamic model (programmed in Simulink^{TM}/Mathlab^{TM}) is presented which attempts to capture these dynamics. Results of the model simulation are reported for the examples of introducing lead-free solder world-wide, and changes to the technological infrastructure for lead production and recycling. The model presented here is a model, which connects the industrial resource cycles of lead, tin, copper, bismuth, zinc, silver, gold, nickel, and PGMs with each other.

5.2.1 Bottom-up approach

The model has been constructed by employing a bottom-up approach, where the interconnected circuits for metal production are represented by a series of individual processes and/or reactors (see chapter 3). In Figure 5.1, the model levels are presented. Level II incorporates the five phases in the resource cycle of a metal: mining, metal production, product manufacturing, consumption, and solid waste management. From level III onward, the levels show increasing technical detail. Level III shows the interconnected metal production circuits (see also Figure 3.14). In level IV, the different production routes for a single metal are shown. Level V zooms in the model of each process step. This hierarchical method of modeling and representation provides a transparent overview of the interconnected metallurgical production circuits. This transparent view is well suited to initiate further development of the products or the production network by the stakeholders at different system levels; for example by making changes in the metallurgical production networks visible to waste managers, policy-makers, legislators, or product designers.

Mass-balance calculations based on data reconciliation allow simulation of system change and track the effect on the system performance. In addition, the model is structured in such a way that emissions can be traced down to individual processes or reactors. The model allows the investigation of a wide range of scenarios, because all parameters can either be fixed over time or given a scenario for change over time. The effect of the development of new products can be modeled by a change in the metal production rates, distribution of the metals concerned over products and waste categories. A new technology or process step can easily be included in the model because of the bottom up modeling approach combined with the modular structure of Simulink^{TM}/Matlab^{TM} programming environment. By using the options available for parameter manipulation, the effects of a shift in employed technology can be analyzed.

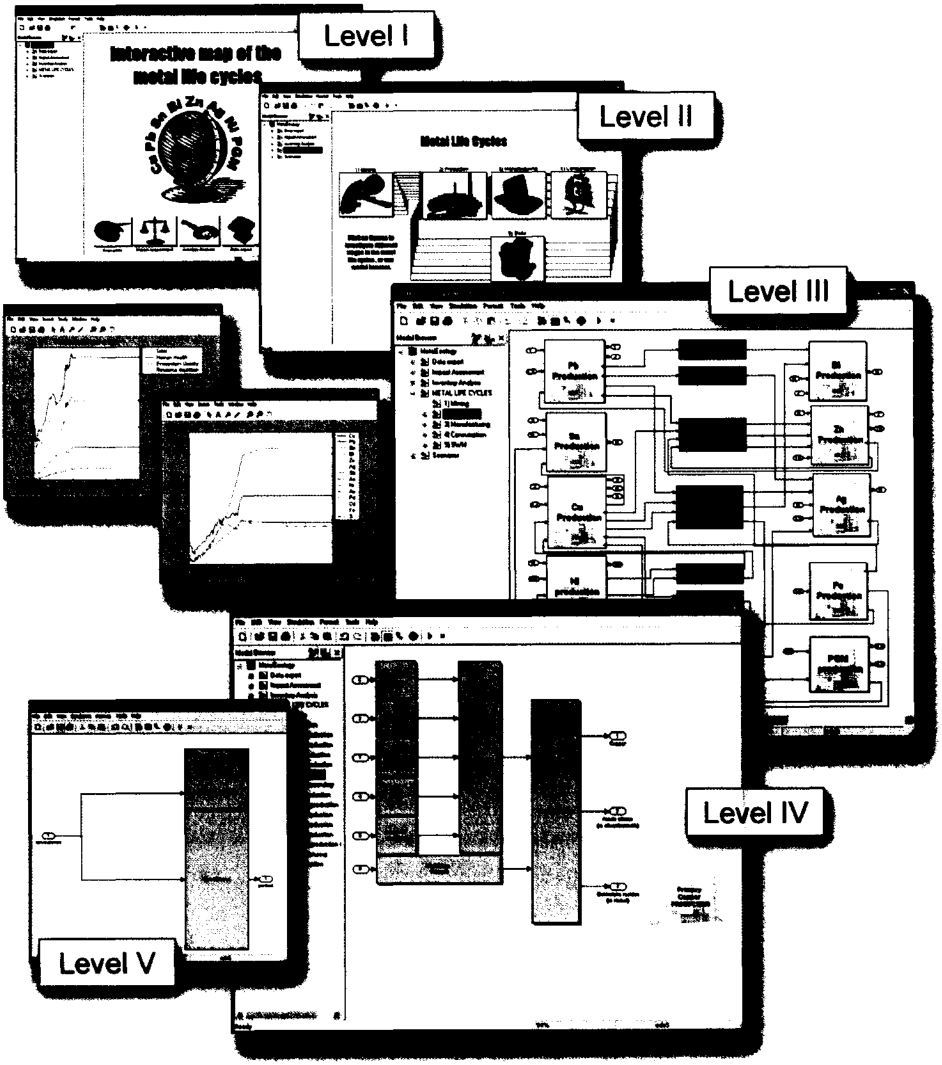

Figure 5.1: Interconnected metal cycles in Simulink (Matlab).

5.2.2 Flowcharts of the metal cycles

In order to adequately and realistically capture the dynamics, any model of a metals production infrastructure or part thereof, must have sufficient scope to account for the interconnectedness and interdependencies in the global system, as discussed in chapter 3 and summarized in the metal wheel. For the case study on lead production, at least the interconnected zinc, copper, tin, silver, and bismuth cycles must be modeled. In the model, the flows between the production processes consist of these metals, but also of representative co-elements (impurities in the wheel): antimony, arsenic, nickel, gold, platinum, palladium, rhodium, cadmium, cobalt, iron and sulfur. The elements considered allow a good representation of the compositions of the residues, leachates and emissions. Such modeling has to be based on the fundamental thermodynamics of each metallurgical reactor, its geographical distribution and the prevalent knowledge (see chapter 3). To meet these criteria, literature reports of the individual process steps in the production of metals were reviewed to obtain input and output data for each process step in the network. An integrated flowchart of primary zinc and lead production was given in chapter 3, detailed production/recycling flowcharts for all metals are given in appendix A.

In the dynamic modeling of these flow charts, two types of parameters determine material flows as a function of time: process and structural parameters (Figure 5.2). The process parameters ($p_{j,i}$) determine which part of the raw material is converted to one of the four possible outputs: product, intermediate, residue or emission in process step j. Because the thermodynamics and physics of the processes are not always fully understood, and process outputs are partially controlled with the tacit knowledge of the process personnel, these parameters are difficult to determine and can vary between different processes, or with feed composition. Consistent with the research of Reuter (1998), linear relationships between feed and process outputs were used to approximate the fundamental thermodynamics and physics in each production and process step. Each process can produce five different products: Product 1 (i=1) of a process *j* as function of time is given by process parameter, $p_{j,1}$, multiplied by its the feed. Data reconciliation was used to resolve discrepancy between data, which was often collected for different purposes, and to obtain reliable process parameters. In addition, extensive industrial knowledge obtained through reliable personal industry contacts, as well as extensive in-house knowledge ensured that the data is of high quality and reflects the current state-of-the-art.

The structural parameters (s_n) determine the flow of material through the different processing routes and thus the feed of the different processes. At any point in time, the feed of process 1 is given by multiplication of the supply of raw material at that time by the structural parameter s_1. Distribution of the mass flows over the process routes is based on the literature and extensive experience. The partitioning of the elements over the mass flows is determined by dividing the average (reconciled) feed compositions by the total composition of raw materials. Note that for primary material, new scrap and old scrap routes, the structural parameters differ. In the flowchart, two processes (process 1 and 2) produce an intermediate that is consumed by another process (process 4). The other two processes produce intermediates, but these are not used and disposed of. The amount of intermediate disposed of (R(t) from the intermediate stock in Figure 5.2) is determined by the average residence time of the intermediate in the stock (1 year), the demand for (process 4), and supply of intermediate (processes 1 and 2).

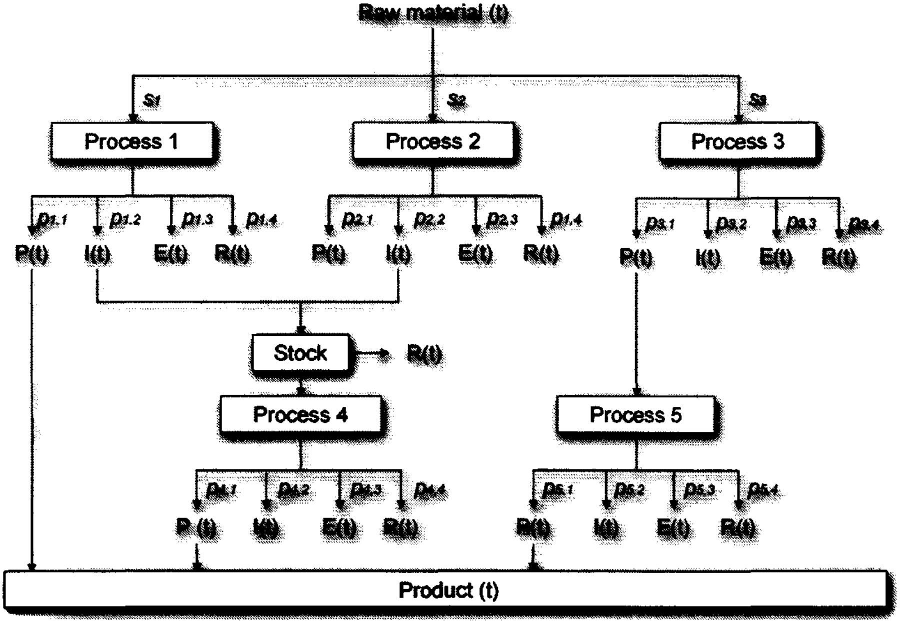

Figure 5.2: An example of a flowchart for the production of a metal consisting of five different processes; Legends: P = product, I= intermediate, E= emissions, R= residue, $P_{j,i}$ *= process parameter, and* S_j *= structural parameter.*

Global mining and metal production figures were obtained from metal statistics (WBMS 2000, USGS 2003). The return flows to production from recycling were based on worldwide statistics reported on the fraction of metals recovered from secondary sources (Holmes et al. 1979, WBMS 2000, Gold fields Mineralogical Services Ltd. 2002, INSG 2003, USGS 2003, GFMS 2003). Depending on the end uses of the metal, different life spans were assumed in the modeling of the distributed nature of the consumption phase. Per metal, the mass balance was completed by assuming that materials were either recycled or disposed of on landfills, or incinerated. A complete description of the model is given in Appendix B.

5.2.3 Simulations

To investigate the feasibility and environmental impacts of changes to lead production on the metal ecology, the model allows two operating modes: an equilibrium (or quasi-dynamic) and a dynamic mode. The equilibrium mode can be used for *ceteris paribus* scenarios in which in this case only the effect of substitution of lead in solders is investigated. The dynamic mode also allows changing composition of waste composition and quantity, change in metal demand and metal recovery over time. A simplified illustration of a simulation scenario is depicted in Figure 5.3. The environmental impact (based on the Eco-Indicator 99, see 5.3.3) can be measured for an individual metal resource cycle, or for the interconnected resource cycles as a whole.

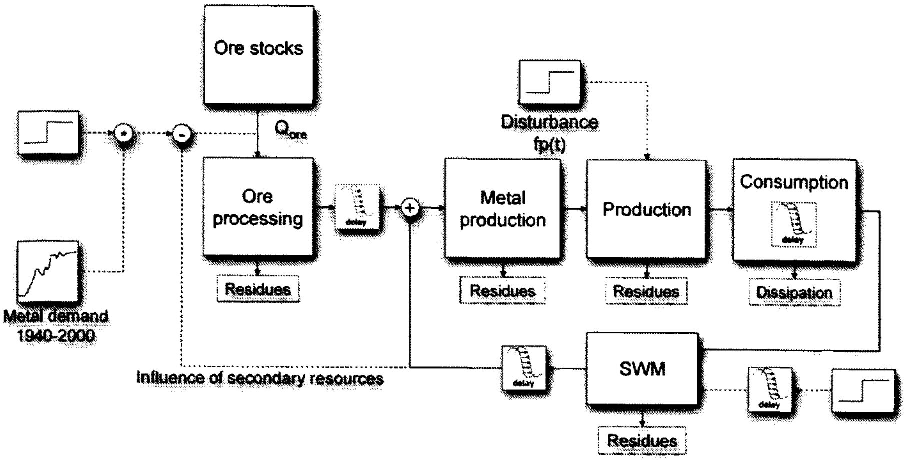

Figure 5.3: Simplified illustration of the lead-free scenarios in the dynamic model.

Because of the interconnectedness and dynamics present in the world metals production system, changes trickles through the system and results in different resource demands, different amounts of intermediate disposed of or further processed, and different emissions. This can be easily seen using the lead-free solders, that are investigated as an example of a detoxification strategy below (5.3). For the lead-free solder scenarios, the equilibrium mode is used. Figure 5.3 shows the disturbance of the equilibrium conditions as a result of the substitution. In order to obtain acceptable solder characteristics, lead-free solder is not simply tin without lead, but a new tin alloy that can contain different amounts of silver and copper, zinc, bismuth and antimony as argued above. Substitution would, therefore, affect both the interconnected metal cycles of the original and the new materials. The introduction of lead-free solder thus disturbs the demand for the different metals ($f_m(t)$): Lead demand declines, and tin demand increases due the higher tin content of the lead-free solders investigated. Dependent on substitute solders, the demand for bismuth, copper, zinc, silver and antimony rises. Furthermore, the solder substitution disturbs the distribution of metals over the different product categories ($f_p(t)$), and disturbs the waste management and recovery of the metals ($f_w(t)$). Over time, a decreasing amount of lead is collected as electronic wastes. Furthermore, since electronics are mainly recovered through the copper circuit, the substitution also affects the recovery/recycling routes of lead and the substitute metals.

The metal waste generation in 2000 in the equilibrium mode is estimated based on a simulation in the dynamic mode of the production of metals from 1940-2000 and their estimated residence times (or delays) in the consumption stage of the resource cycle during that period. Hereto the dynamic simulation starts at t=1940, at which products are assumed to be produced only from virgin ore material ($Q_{ore}=Q_{demand}$). From t=1940 to t=2000 the model simulates the global metal production network, based on global metal production data, end-use of metals and recycling rates. In this period, the system converges to the actual state in 2000. The materials accumulate in the consumption stage and are assumed to reach the actual system material stocks. The secondary raw material stream partly replaces the primary concentrate according to the current recycling levels.

Except for the delay in the consumption phase, and in waste management all other delays were assumed negligible. At the time of substitution of lead for example, the metal demands is disturbed stepwise, as is the distribution of the metals over the products. Figure 5.3 shows that the change in metal over the different wastes in the solid waste management, $f_w(t)$, is delayed as well. Because of the normally distributed delay assumed for the products in consumption phase, the fraction of metal partitioned to a waste slowly changes over time. Apart from the consumption and waste management, time delays are only included in the model to break 'algebraic loops'[1], which severely slow down and complicate simulation. These delays are one time step.

5.3 Detoxification strategy – lead-free solders

Solder is used throughout the manufacture of electrical and electronic equipment. The toxicity hazards of lead, particularly in end-of-life processing of electrical and electronic equipment, have led the European Union to develop a directive on the restriction of the use of certain substances in these products (EU 2000b). More specifically, the proposed directive stipulates the substitution of lead in consumer electronics to reduce emissions associated with lead content of landfills. Lead on landfills poses a risk to health and environment through leaching and consequently exposure through groundwater. Most of the lead in landfills in Europe originates from wasted electrical and electronic equipment (WEEE), and similar trends were observed in the U.S. However, most of the lead was found to originate from cathode ray tubes (Price 1999, Fishbein 2002, Flannery 2003).

In the case study described below, the effect of lead elimination in solders for electronics on the global metal cycles is investigated. The possible changes in the metallurgical system underlying the introduction of lead-free solder are not known to all environmentalists, industrial ecologists and legislators, but this type of systems knowledge is necessary to co-ordinate decision-making across the resource cycles. The study investigates how the phase-out of lead influences the operation of the resource cycles, and how this affects the different stakeholders. For example, how effective is the directive in terms of prudent resource management, and the environmental impacts of the metal resource cycles? What problems can be expected with implementation of the directive, and thus which additional measures may be required from the legislators and policy-makers? How do changes in the operation of the resource cycles influence the environmental impacts of the lead-free alternatives? What problems can be expected for metallurgists? Lead substitution affects the configuration of the metal production system, and thus may lead to shortages of raw materials, or different environmental performance of metal production. *In the next sections it will be shown that the underlying dynamics in the metal resource cycles must thus be understood, to evaluate*

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[1] An algebraic loop generally occurs when an input port with 'direct feedthrough' is driven by the output of the same block, either directly, or by a feedback path through other blocks with direct feedthrough. Direct feedthrough means that the output of these blocks can not be computed without knowing the values of the signals entering the blocks at these input ports.

the environmental impact and feasibility of the alternatives. As such, it provides a basis for policy on lead-free solders, or a basis for Life Cycle Analysis (LCA, see chapter 2) studies on the phase-out of lead from electronic products

5.3.1 Lead-free solders options

A relatively large number of lead free solders have been proposed so far, by researchers and manufacturers. Abtew et al. (2000) counted approximately 70 candidates and Miric (2000) counted 100 patents for lead free solder alloys. The ultimate goal of lead-free soldering research is finding a universal 'drop in' replacement. Despite considerable research efforts for most applications, no single solder appears as suitable as the mainstream lead-based solder. The main substitute alloys are alloys based on tin as primary constituent with smaller additions of mainly silver and/or copper and, especially in Japan, bismuth. Besides these main substitutes, there are other alloys containing a wide variety of other metals like zinc, aluminum, nickel, antimony, germanium or indium. Indium appears because of its scarcity only an option in niche markets, rather than a substitute for lead in the mainstream solder alloys.

Table 5-2: Compositions and characteristics of the lead free solders considered.

	Cost[1]	Composition (%)						
Solder type	(€/kg)	Sn	Pb	Bi	Sb	Cu	Ag	Zn
SnPb	2.5	60	40					
SnAgCu	9.1	95.5				0.7	3.8	
SnCu	3.9	99.25				0.75		
SnAgSbBi	5.5	92		5	2		1	
SnZnBi	4.7	78		19				3
SnZn	3.6	91						9

[1] Cost of a solder estimated based on the LME prices of metals (9/2002)

The IDEALS Project (1996-1999) was a landmark collaborative European lead-free soldering project that for the first time evaluated lead-free soldering assembly under real-life conditions. In the project it was found that lead-free soldering technology based on SnAgCu(Sb) and SnBiSbAg alloys is technically and industrially viable. The selection of the lead-free alloys investigated in this study was made in collaboration with Philips (a large European consumer electronics manufacturer participating in the IDEALS project). Table 5-2 lists the solders investigated. A common solder alloy of 60% tin and 40% lead is used as a reference. Two binary solders are included representing the least expensive solder alloys, viz. tin-zinc and tin-copper alloys. A tin-zinc-bismuth alloy is included, which has a melting point close to the mainstream solders. In addition, two copper-silver-tin alloys are included: silver-bismuth-antimony-tin alloy and copper-silver-tin alloy[2].

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[2] Note: SnAgCu is generally perceived as the most promising substitute alloy. Because the composition of SnAgCu in the table is patented, the Japanese use SnAg$_3$Cu$_{0.5}$ and the European and Americans use SnAg$_4$Cu$_{0.7}$. On average, the composition in the table is probably right (Deubzer, personal communication).

To illustrate the dynamics, it is assumed that all alternative solders in Table 5-2 represent universal 'drop in' replacements. In addition, it is assumed that these solders substitute all tin lead solders in a stepwise fashion. A stepwise introduction is chosen as this is the most extreme scenario; the effects of substitution are clearly visible, and easy to relate to the point of substitution

5.3.2 Metallurgist

As mentioned before, only a small fraction of lead is substituted - solder for electronics accounts for only 1.5 % of the lead production on a present year basis. Consequently, the transition to lead-free solder does not affect the 'stability' of the interconnected metal production system for all but the bismuth-based solders: Shifts in resource consumption patterns occur, but overall no shortages of intermediates result. Rather the surplus of intermediates, which is disposed of, is reduced, leading to higher overall metal recovery efficiencies, and less impact per unit of metal produced since the intermediates are used and not disposed of. Figure 5-4 (see also chapter 3, Figure 3.14) shows the base situation in 2000,

Table 5-3 shows the relative raw materials consumption and metal and intermediate production values in percentages after lead substitution compared to the base situation in for a number of metals. These illustrate that changes in the metal production circuits are important to consider, particularly if lead is substituted by bismuth and/or silver.

In the base situation (2000) the by-products of gold and lead production form a considerable source of the raw materials for silver. There is no (gold) or a small (in the case of lead, from the Parkes process) surplus of the by-product that can be used in case of higher demands. As a result, the growth in the demand for silver (141%) due to transition to a tin-silver-copper solder can not (holding all other factors constant) be matched by a greater supply of the gold (93 %) and must be compensated for by greater consumption of lead (159 %) intermediate and ore (159 %). This means that the raw material mix per unit silver produced changes, and the demand for copper and lead anode slimes, and silver ores increases. The increase of silver in electronic scrap leads to an increased recovery as copper anode slimes (134 %).

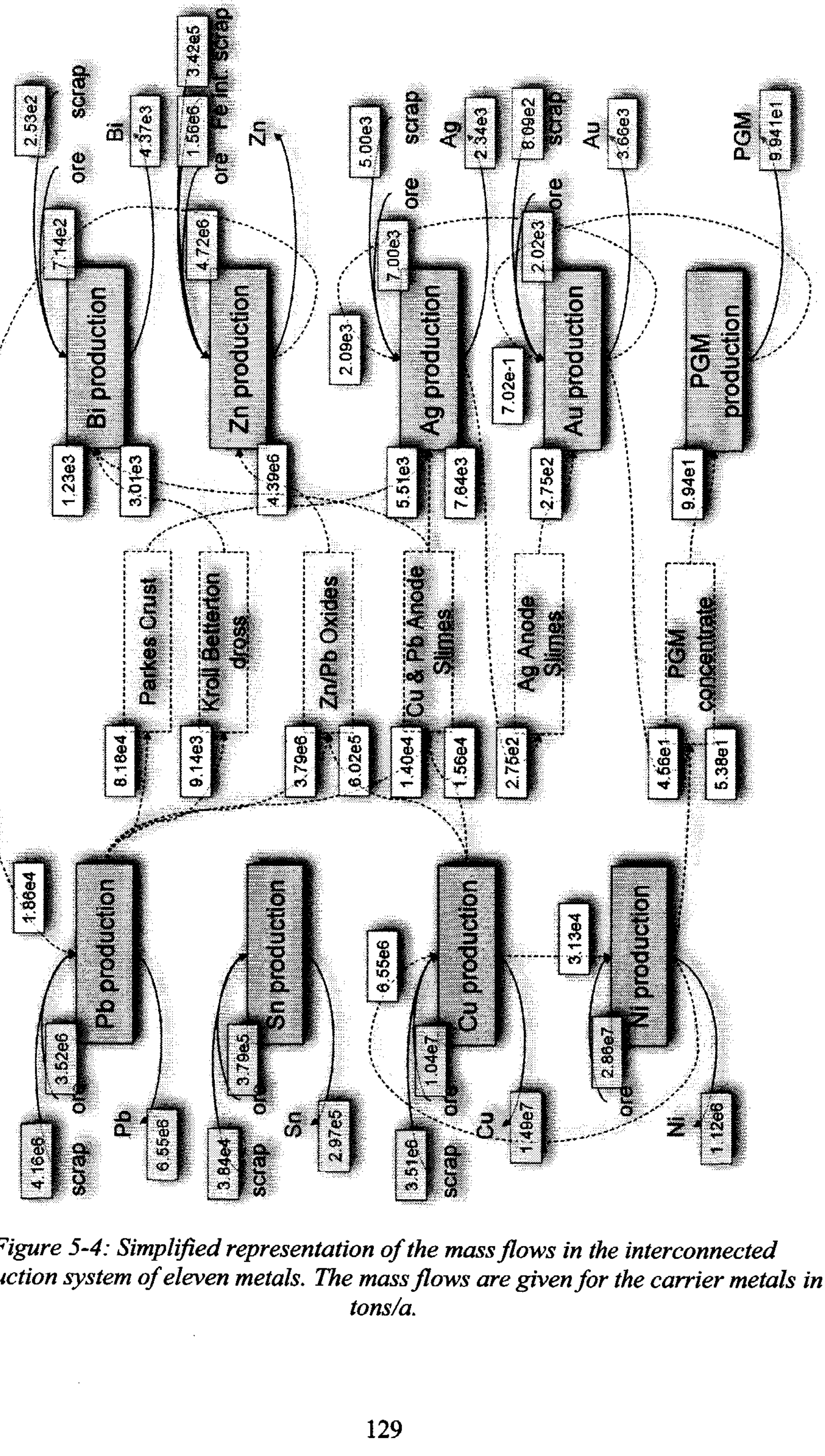

Figure 5-4: Simplified representation of the mass flows in the interconnected production system of eleven metals. The mass flows are given for the carrier metals in tons/a.

Table 5-3: Relative raw materials consumption, and metal and intermediate production values in percentages compared to the equilibrium situation in Figure 3.14 for a number of metals, resulting from the introduction of the lead free solders considered. (Legends: no shading= consumed; grey shading= produced)

Metal	Raw materials	Solders investigated				
		SnAgCu	SnAgSbBi	SnZnBi	SnZn	SnCu
Pb	Ore	98	98	98	98	98
	Scrap	99	99	99	99	99
	Zinc int.	94	94	94	94	94
	Lead	98	98	98	98	[illegible]
Sn	Ore	126	123	113	123	128
	Scrap	168	162	134	160	177
	Tin	130	127	115	126	[illegible]
Cu	Ore	100	-	-	-	100
	Nickel int.	100	-	-	-	100
	Scrap	100	-	-	-	100
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Bi	Kroll B.	-	336	462	-	-
	Anode S.	-	259	453	-	-
	Special R.	-	640	3939	-	-
	Other	-	529	3254	-	-
	Bismuth	[illegible]	387	1157	[illegible]	[illegible]
Zn	Ore	-	-	100	100	-
	Iron int.	-	-	100	100	-
	Scrap	-	-	100	100	-
	Zinc	-	-	100	100	[illegible]
	Lead int.	-	-	94	94	[illegible]
Ag	Parkes C.	159	115	-	-	-
	Anode S.	159	115	-	-	-
	Ore	159	115	-	-	-
	Gold int.	93	98	-	-	-
	Scrap	110	103	-	-	-
	Silver	146	111	-	[illegible]	[illegible]
	Silver int.	152	113	-	[illegible]	[illegible]

For bismuth (Figure 5.5) the situation is even more pronounced as bismuth has no dedicated ores, and lead production processes are the main sources of raw materials for bismuth. Figure 5.5 shows the effects on the metal production system for the SnZnBi solder: the demand for lead decreases (to ~ 99%), while demand for zinc slight increases with a tenth of a percent, tin (115%) and bismuth (1191%) increases. As a consequence, the figure shows a significant impact on the supply and consumption (and thus disposal) of intermediates, and on the production routes of bismuth and tin. The present surplus of bismuth intermediates is reduced, because its supply from lead production dwindles, while bismuth production and demand for intermediates increase. As the lead intermediates (Kroll Betterton dross and anode slimes) are prime feedstock for bismuth producers, its decreased availability forces bismuth producers to look for, and switch to alternate feedstock. In the base situation (2000) only a small portion of the bismuth production comes from other intermediates (represented by resources from special refinery and other processes in Figure 5.5) in proportion to the lead intermediates, and it is doubtful whether sufficient of these intermediates are available to enable a full transition to SnZnBi-solders.

Thus, new intermediates from the production of other metals must be found, for example from tin production (see the metal wheel in chapter 2). This example shows a paradox: bismuth is to replace lead in solder, but lead is its source. In the model, this paradox is solved by assuming that new resources for bismuth can be found. If bismuth is produced from intermediates, effect on resources depletion will be minimal, obviously dependent on the efficiency of these alternative production routes.

Another problem of the paradox is that an increased content of bismuth in electronic scrap may lead to problems in copper processing and thus for the recycling of the solders (Kindesjö 2002). The copper smelters produce high purity copper cathodes, but some of the bismuth in the feed follows the copper smelt and contaminates the cathodes. Since the European smelters – the Boliden, Noranda and Norddeutsche Affinerie smelters - currently, with the exception for Umicore, have no possibility to separate the bismuth from the cathodes[3], the use of bismuth-containing solders could result in the situation that the smelters can no longer recycle the electronic scrap.

In this study, the two alloys containing bismuth could cause significant problems. The metal wheel shows that metallurgical expertise and capacity is available to recover the bismuth from electronic scrap in copper processes. Metallurgically, lead and bismuth are similar metals. Umicore has a lead smelter, and can therefore separate the bismuth downstream of the copper furnace. As discussed above, bismuth is separated during lead refining. Thus, by attuning the copper process so that bismuth reports to the lead slag, bismuth can be recovered. Bismuth follows lead in the lead slag processing and is recovered in the Kroll Betterton dross. Paradoxically, lead processes may prove necessary for recycling of metals from lead-free solders.

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[3] Today, the smelters are keeping the bismuth content of the feed within operating parameters by sampling the wasted electric and electronic equipment. If the bismuth content is above a certain level, the smelters impose penalty fees that the suppliers have to pay.

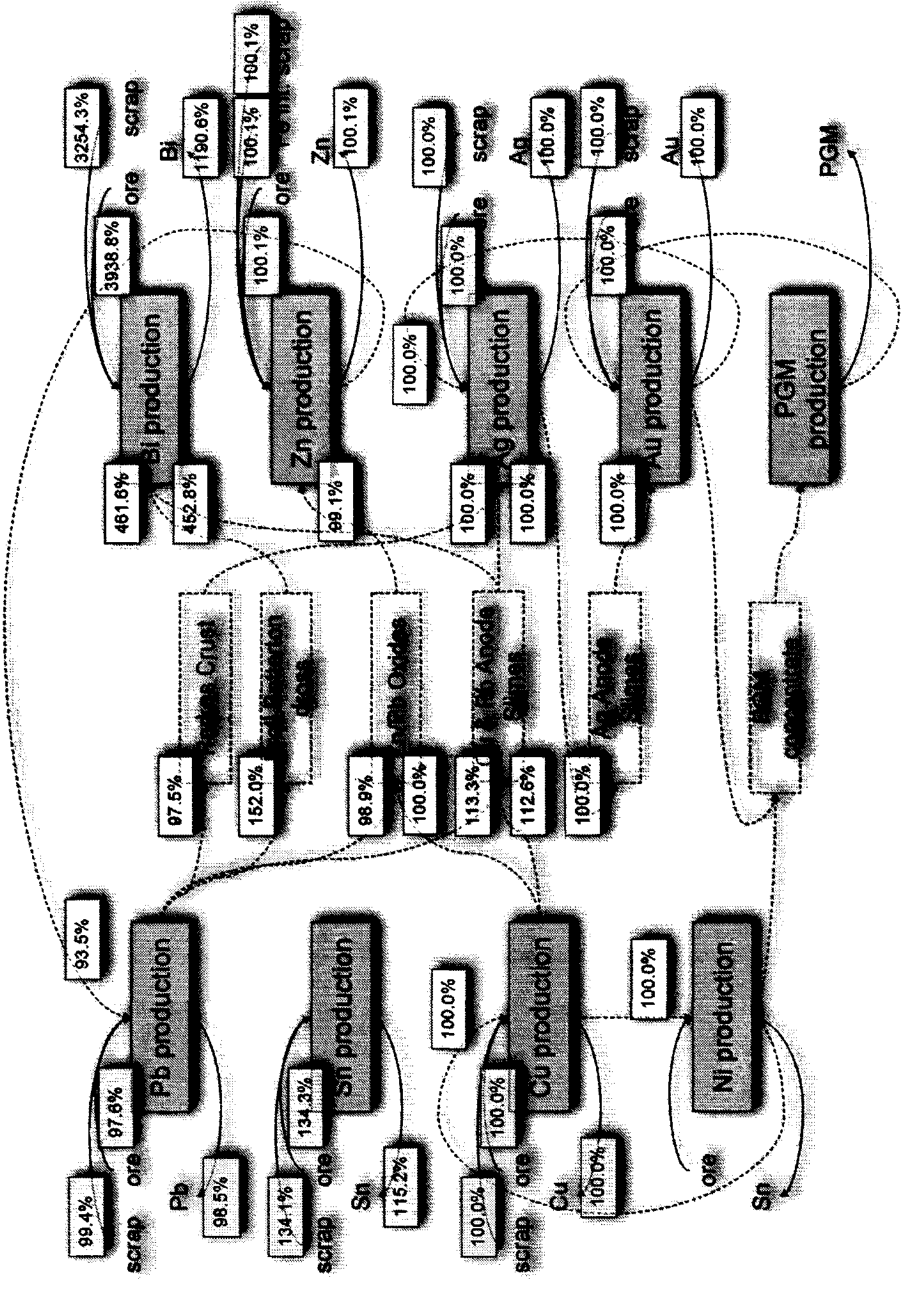

Figure 5.5: Transition to SnZnBi solder. Relative mass flows in the global metals compared to the base situation are given in percentages.

5.3.3 Product designer and manufacturer

Designers and manufacturers have to solve some obstacles to produce lead-free solder based electronics, including costs, resource availability, energy consumption, and the characteristics of the substitute solders such as processing temperature, and reliability. Much of the research efforts have focused on a direct replacement for the mainstream (63/37 or 60/40) tin-lead alloys; possible candidates should at least have comparable characteristics. The effects of the generally higher melting temperatures and other solder characteristics on the reliability of the soldering or on the soldering process are not included in the case study. In comparison to the wide range of investigations on the characteristics of alternative solders, other problems such as environmental impacts, resource depletion and energy consumption received little attention (Deubzer et al. 2001).

Because of the focus on the metal resource cycles - rather than on solder life cycle as common in life cycle analysis of products (LCA, see Chapter 2) - the energy consumption in the manufacture of electronics is not included in the study, nor the energy use during consumption of these appliances. Rather this case study is meant to feed the ongoing discussion whether lead free solders improve the environmental performance of electronic products (see e.g. Fishbein 2002, Deubzer et al. 2000, 2001, Hamano et al. 2001, Turbini et al. 2000 and 2001). As mentioned in chapter three, the interconnections of industrial processes are often not or only partly considered in LCA studies. However, due to the complexity and non-linearity of the metal production system, a neglect of these interdependencies may lead to considerable errors in the LCA results.

To investigate the effect of interdependency on environmental impact an impact assessment method must be selected. In chapter three, it was argued that on the one hand uncertainty magnifies progressively in moving from inventory-level indicators to impact-type indicators; but on the other hand, impact-type indicators provides for the clearest link to the environmental problems of concern. Selection of the adequate methods thus comes down to the use to which such metrics are to be used (see chapter 3: Cadre 3-1). Because of the objective to support other LCA studies, conformity of the impact assessment method is important - facilitating easier adaptation of the results obtained with the model in other studies. The endpoint or damage-oriented Eco-Indicator 99 method (Goedkoop et al. 2000)[4] was chosen, which is used in many LCA studies on lead-free solders and in the screening of lead-free solders at Philips.

The method aggregates the different emissions, and calculates the damages the environmental emissions cause to human health, ecosystem quality and resources, using damage functions. The damage functions represent the relation between the impact and the damage to human health or to the ecosystem. The method expresses the damages the environmental emissions cause to human health, ecosystem quality and resources in Eco-indicator points (Pt). In the damage function of human health, these points represent the number of year life lost and the number of years lived disabled. In the damage function of the ecosystem quality, they represent the loss of species over a certain area during a certain time, and in the damage function of resources the surplus

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[4] A complete description of the application of the Eco-Indicator method can be found in Scholte (2002) and Van Tweel (2004).

energy needed for future extractions of minerals and fossil fuels (surplus energy method). Although the weighting of the three impact categories into a single score allows easy interpretation, it is also the most critical and controversial step in the methodology. Therefore, both the aggregated score, as well as the individual damages will be used in the evaluation of environmental impacts.

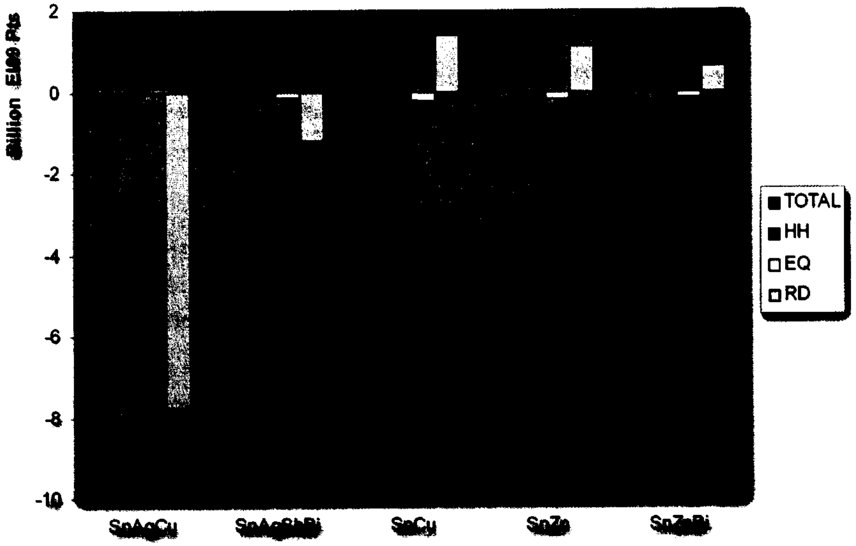

Figure 5.6: Standard Eco-Indicator '99 scores for substitution of conventional by lead-free solders.

As an estimate of the impact of the introduction of lead-free solder, the difference between the base lead-tin scenario and the lead free scenarios is used. Figure 5.6 shows the difference between the base scenario and the lead-free solder scenarios. The X-axis displays the different solders scenarios. The Y-axis gives the relative impact of the scenarios, as a single score (Total) and subdivided into damages to resource reserves (Resource Depletion, RD), ecosystem quality (EQ), and human health (HH). A positive number for any of these damages means increased environmental consequences while a negative number means improvement.

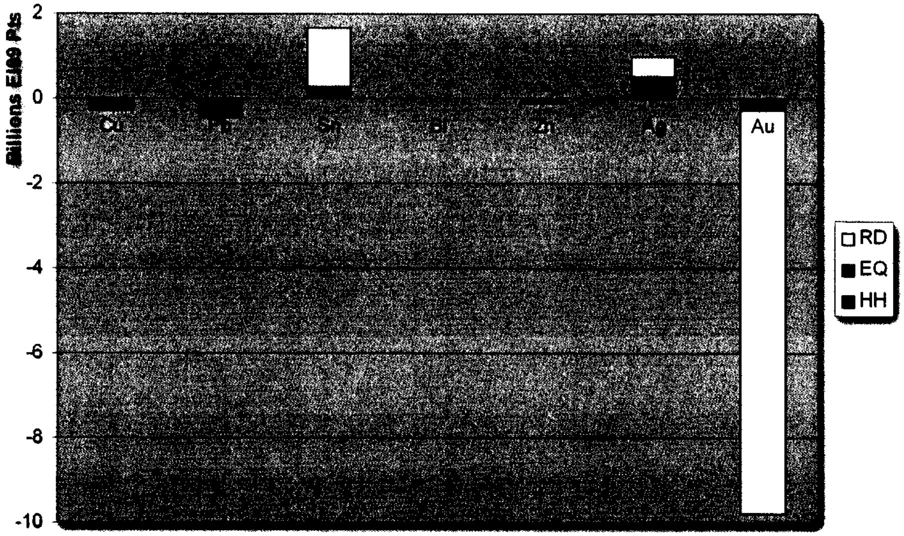

Figure 5.7: The impact of the SnAgCu solder on different metal resource cycles (determined using mass allocation).

The results indicate that the Eco-indicator '99 LCA scores for a number of lead-free solders are higher than for the conventional solder. This is partly due to the higher environmental impact of tin resource depletion compared to lead resource depletion: all solders have higher tin concentrations. The silver containing solders have lower impacts, due to the interconnections between silver and gold production: in silver production intermediates are produced that serve as raw materials for gold production (Figure 5.7). An increase in silver production leads to an increase in gold intermediate (152% for SnAgCu) and thus to a reduction of the amount of gold ore that is required, but also to a reduction of silver intermediate produced in gold production (93%). Because gold is a scarce metal and its stocks are highly valued in the Eco-Indicator method (expressed as a high value of gold ore for resource depletion), this leads to lower resource depletion values.

Changes in the metallurgical system can thus affect the availability of metals, and therefore the economics and feasibility of lead-free solders. Despite the higher costs of the alternatives, switching to lead-free solder will not increase the cost of printed wiring boards, because solder accounts for such a small percentage of total costs (e.g. the Ideals report 1999, Deubzer et al. 2001). In general the availability of metals for solders appears difficult to estimate[5]. To estimate availabilities often the resource reserves are used (e.g. Turbini et al. 2000, 2001, Deubzer et al. 2001). The US geological survey

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[5] For instance, the maximum contents of bismuth reported in literature range widely: In the ZWEI report a maximum content 5-7 wt% bismuth is estimated. The National Centre for Manufacturing (1997) characterized Bi as a rare metal, and reported a maximum content of 15 wt% in solders. Other reports estimate that the Bi supply is enough for tin-bismuth solders containing as much as 58 wt% bismuth (Suganuma 2001).

defines a 'reserve base' as that part of an identified resource – a resource of which location, grade, quality, and quantity are known or estimated from specific geologic evidence - that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth (USGS). The term 'reserves' need not signify that sufficient extraction facilities are in place and operative to meet the demand for the metals.

Figures on production and production capacity are therefore required to estimate the availability of the various metals. Turbini et al. (2000) use the global mining of silver in addition to the reserve base to indicate the availability of silver. In the manual on lead-free solder, the German electrical and electronic manufacturers (Benzler et al. 2000) base their estimates on the difference between current production capacity and current production levels, the difference being the availability of the metals for lead free solders.

The effect of lead substitution on the configuration of the interconnected metal production system, which at least partly determines whether this capacity can be exploited, was not considered in these estimates. However, switching to silver solders could consume 6 to 9 % of the world's total output of silver, putting pressure on silver supplies. Deubzer et al. (2000) recommended the use of silver but emphasized the need for high rates of take-back and recycling. The recommendation did not address what rates of take-back and recycling would be sufficient to ensure the availability of silver for the use in lead free solders. The simulation results show that a substitution by SnAgCu would increase silver ore consumption by more than 9% as reported in the literature, and that recycling must increase significantly to counter this effect. Based on this analysis, bismuth production can increase to 453% without changes in the raw materials consumption pattern[6]. This corresponds to a Bi percentage of 15% in the substitute solders, or a substitution of conventional solders by SnZnBi or SnAgSbBi alloys of respectively 32 % or 55 % (holding all other factors constant).

5.3.4 Waste manager

The EU directives require in addition to constraints to the composition of wasted electric and electronic equipment, also minimum levels of recovery. The elimination of lead from electronics products can increase their recycling value: lead is a major contaminant where substitutes such as silver have considerable value (Deubzer et al. 2000, Turbini et al. 2000). Turbini et al. (2000) even argued that the focus of future regulation should be on the recovery and recycling of the solder ('containment') rather than on the elimination of lead-based solder. In this process, the higher costs of the lead-free solders can provide an incentive for increased recycling of the electric and electronic scrap, and reduce recycling costs.

The recycling of the metals is only partly determined by the waste processes; metallurgical processes perform the actual recycling. Generally, non-ferrous fraction resulting from treatment of the WEEE is processed in copper smelters. The metal wheel (in chapter 3) shows that metallurgical knowledge and capacity is available to recover

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[6] Note that this percentage is even lower (viz. 7%) for the SnAgSbBi solder, because anode slimes are also consumed by the silver production processes.

all the metals from the lead-free solders through the copper production circuit. Obviously copper does not present problems. Neither is the recycling of silver a problem since the increased value of the scrap can counter the potentially higher cost of recycling. Because all the lead-free solders investigated contain higher contents of tin, recycling of electronic scrap may present problems in terms of emissions due to its high volatility, or in terms of the market for the captured flue dust that contain high amounts of tin. Due to the low current yields of tin in solders, there is no substantial concern about the presence of tin. Bismuth can also be recycled in copper processes, but this will require some modifications if the bismuth levels are too high (see 5.3.2).

5.3.5 Policy-maker and Legislator

The potential risk for pollution of groundwater by the lead present in landfills led to the development of the directive on lead substitution in consumer electronics. However, the simulations show that related human health toxicity hazard is not dominant in the LCA scores. Rather, the LCA scores indicate that resource depletion mostly determines environmental impact of lead substitution. This is a remarkable observation, which raises the question of how to compare one environmental problem (human health toxicity) to another (damage to resources).

As argued in chapter 3, Life Cycle Analysis is a methodology, which is partially based on scientifically backed methods, but also contains subjective steps. If the final weighting step was carried out using different weighting factors, human health toxicity hazard may have been more prominent in the outcomes, and results may be different .It is often the perception of the relative importance of the different environmental problems or damages that in the end determines the environmental performance, or ranking of alternatives. Figure 5.6 and Figure 5.7 show, that the eco-indictor scores are dominated by resource depletion. For the above impact assessment, the Hierarchical weighting perspective is used, which weights human health, ecosystem quality and resource depletion damages as 30:40:30.

Sometimes, however, resource depletion is considered more of an economical than environmental problem. Moreover, the uncertainty in the 'surplus energy method' used in the Eco-Indicator '99 may lead to overestimation of the mineral depletion values in particular for gold and nickel (Chapman 1983, Spriensma et al. 2002, Huisman 2003). Huisman (2003) therefore suggested to reduce the weighting of resource depletion in the Eco-Indicator method from 30% to 5%, or not to consider resource depletion at all (the remainder being divided between damages to human health and ecosystem quality). If resource depletion is not considered, than all lead-free solders scenarios show a reduced environmental impact, more or less in the same order of magnitude; the silver containing solders score worst, and the tin-copper solder scores best. If the weighting of resource depletion is reduced to 5%, all lead-free solders score better than conventional solders. The silver containing alloys score better than the other lead-free alternatives. The impact of the three other solders is in the same order of magnitude, the SnZnBi alloy having the lowest impact.

This points to the fact that quantitative models of the metal production/recycling system would benefit from a general value system for weighting different damages, in addition to a further convergence in the different impact assessment mechanisms. Consensus on environmental impact arising from emissions and extractions would improve the capacity to link different efforts on product design, process improvement and legislative and policy instruments in a meaningful way to the impact on the environment and to each other.

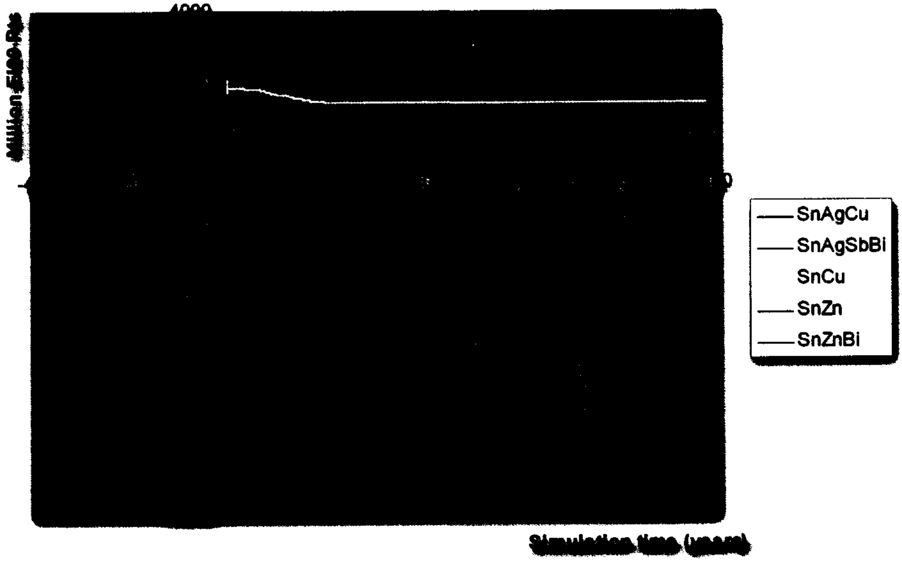

Figure 5.8: Resource depletion scores (Eco-Indicator '99) of the different scenarios as a function of simulation time in years.

Independent of the environmental impact of resource depletion, the effects on resource availability are important to consider for legislators and policy-makers. The simulations show that because of the life spans of electronics, and the model dynamics, it takes more than three decennia before the model reaches a new steady-state. Secondary materials only become available after some time, and partially replace the demand for other intermediates. On the one hand this means that the temporarily shortages of intermediates for silver and bismuth can be more serious than can be expected based on the end (equilibrium) situation alone or vice versa, due the long residence time of the metals in the consumption phase. This is reflected in the impact assessment pattern of the simulation (Figure 5.8): Overall, the slow increase in secondary materials due to higher production volumes of the lead-free solder metals result in lower impact. For the silver containing solder alloys, another effect is important: In case of substitution with the SnAgCu solder for example about 34% more silver from scrap becomes available. As this has a lower gold content than silver ore, and consequently less gold is collected in the anode slimes in silver refining process. This effect partly counters the decrease in impacts due to increased recycling.

On the other hand, this also implies that problems with the availability of resources can be minimized by gradual implementation of lead free solders combined with effective recycling of its constituents. The effective recycling of bismuth and tin in solders can be become problematic. The use of these materials in the alternative solder alloys could therefore require additional policy and legislative actions. The use of tin and bismuth in lead-free solders may run into problems with the availability of raw materials (bismuth), but may also inhibit recycling of the electronic scrap in copper processes (tin and bismuth). If more than 15% of lead is substituted, new raw materials for bismuth must be found, which may require significant changes in the metallurgical processes delivering these raw materials. As a consequence, lead-free solders may only be gradually introduced; over time bismuth may become available through recycling of electronic scrap in copper processes.

In copper smelters, bismuth contaminates the product, and in copper refining processes, only a limited amount can be separated in the anode slimes. At the level of copper smelters, the use of bismuth would entail a change in the operating conditions and process control to make bismuth report to the lead slag, as well as adjustment of lead production processes to accept the extra slag. Adaptation of the copper smelters to deal with elevated bismuth levels is costly. According to Umicore, owning an adapted copper smelter, bismuth is more costly to recover then its intrinsic value can justify and should therefore be avoided (Kindesjö 2002). It requires economic incentives to make sure that the smelters will actually continue to process wasted electric and electronic equipment as stipulated in the EU directives.

5.4 Containment strategy - Cleaner recycling

Toxicity is the main driver for lead elimination. For a number of lead-containing products, a better end-of-life management of products could reduce the toxicity hazards as well. In addition, Schoenung et al. 2003 argue that recycling policies and different waste management practices are more cost effective than the EU (RoHS) directive. Although lead is a known toxicant, the alternative solder metals also present a variety of environmental impacts, especially when the entire life cycle is considered. For many of the alternative materials, data on environmental fate and regulatory standards are not available; silver appears to be of particular concern (Ogunseitan et al. 2003). In addition, the replacement materials may also lead to higher resource depletion values (silver, copper and tin). From a metallurgical point of view, lead is an essential metal that enables an economical and environmentally sound production and recovery of a number of other metals. A phase out of lead can have a dramatic affect on the recovery potential of the metallurgical infrastructure, and on the supply of raw materials for, among others, silver, bismuth, copper and zinc. The investigation of lead free solders above already pointed out that substitution of lead by bismuth and tin could be problematic if no alternative sources for bismuth can be found, as lead is the main supplier of the raw materials for bismuth, and is also important for its recycling. As many uses of lead are (in theory at least) recyclable uses, industrial ecology suggests that the goal of lead management can also be containment instead of phase-out.

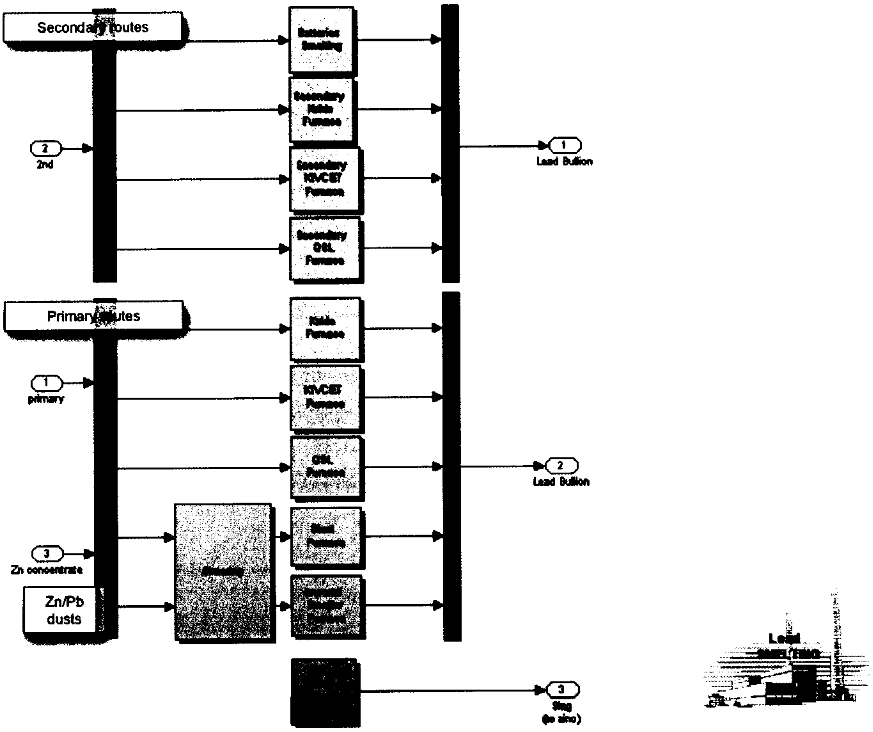

Figure 5.9: Primary and secondary lead smelting routes in Simulink^{TM}.

Socolow and Thomas' study (1997) on lead batteries showed two complementary implications for what they call 'clean recycling'. First, unless primary production is dirtier than secondary production, secondary production should be the principal focus of clean recycling. Second, a clean recycling system can be achieved only if both primary and secondary smelters meet stringent environmental standards. The first implication points to lead mining and disposal as major environmental concerns; increased recycling avoids disposal and mining and thus reduces leaks from the industrial system. The recycling and primary production processes are both a source of environmental concern, because in both cases largely the same equipment is used. Except for mining processes, primary and secondary lead (and zinc) concentrates are smelted to lead bullion and subsequently refined to produce lead metal in the same processes. The overlap in primary and secondary lead smelting routes is schematically depicted in Figure 5.9. Secondary lead resources – apart from the recycling of lead from obsolete lead-acid batteries, which is carried out in dedicated processes - are typically smelted in the KIVCET, the QSL and the Kaldo processes along with the primary concentrates. Ore concentrates but also secondary materials containing zinc are processed in the ISF, which produces lead bullion and impure zinc and cadmium, which are further refined in zinc processes. The blast furnace also accepts some secondary lead raw materials. Thus, production of lead from secondary resources is no dirtier than from primary resources, as both are mostly carried out in the same processes; the main differences between the two routes are mainly the mining and ore concentration processes.

5.4.1 Policy-maker and Legislator

To promote clean recycling, legislators and policy-makers have to enable the reduction of environmental impact of lead processes. To reduce process emissions, there are basically two options: further increase the (end-of-pipe) off-gas treatment or stimulate new technology and phase-out old. Investigations of the interconnected metal cycles by Scholte (2003) showed that in particular the efficiency of flue dust capture has a strong influence on the total environmental impact, expressed as Eco-Indicator '99. The effect of a five per cent increase in capture efficiency on the Eco-Indicator '99 scores is shown in Figure 5.10.

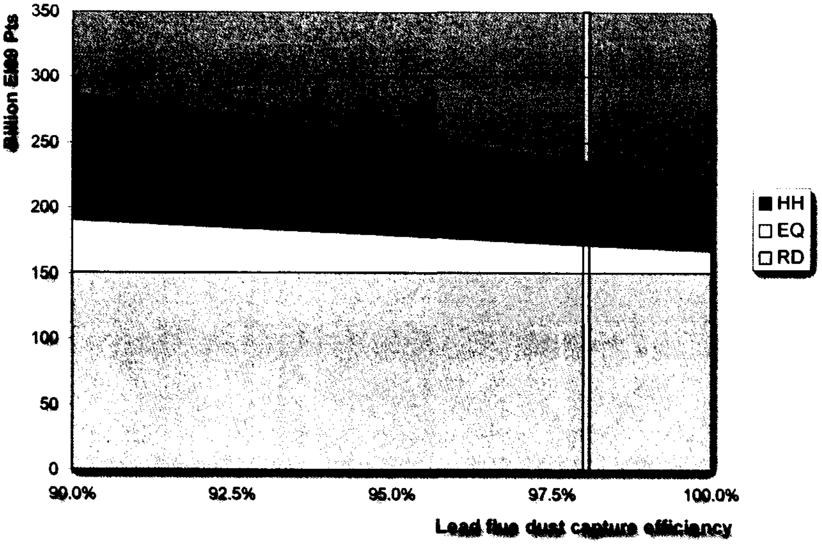

Figure 5.10: The effect of different lead flue dust capture efficiencies on the Eco-Indicator '99 scores of the interconnected metal production system. The highlighted represents a five percent increase in flue dust capture.

Over past decades lead production processes in the Western world have installed more and more advanced off gas treatment, which reduced emission significantly (see e.g. Nriagu and Pacyna (1988), Pacyna (1996), TNO (1998), and Thornton et al. (2001)). Outside the western world, control measures are not always enforced to the same degree and still leave a considerable margin for improvement particularly in Asia and South America (Greenpeace 1994, Pacyna and Pacyna 2001). It should be emphasized that the metallurgical system operates at a *global* scale. A large amount of 'Western' scrap is processed in developing countries for instance. A reduction of the environmental impact of lead use would be most effective if targeted at the countries with the largest margin for improvement: investment in the developing countries, rather than improving the already advanced facilities in the Western world. In addition, it was argued in the previous chapter that applying too strict environmental standards, without proper consideration of the function of the process in the industrial network, may render some critical recycling processes unprofitable.

Traditionally, lead is smelted in a blast furnace (BF) or the imperial smelter furnace (ISF). These two-stage processes (sintering–smelting) have higher risks for hazardous dust and fume to be released, than the direct smelting processes. This necessitates the use of extensive and expensive exhaust ventilation. This than would lead to large volumes of lead-laden exhaust gases, which must be cleaned before they can be discharged into the atmosphere. Over recent years five of the world's twelve ISF smelters have closed or were converted to accept alternative raw materials (Xstrada 2003, USGS 2003). Modern smelting operations have therefore been developed that apply direct melting operations and avoid the sintering operation. The KIVCET, the QSL and the Kaldo processes are the most abundant examples of the new processes.

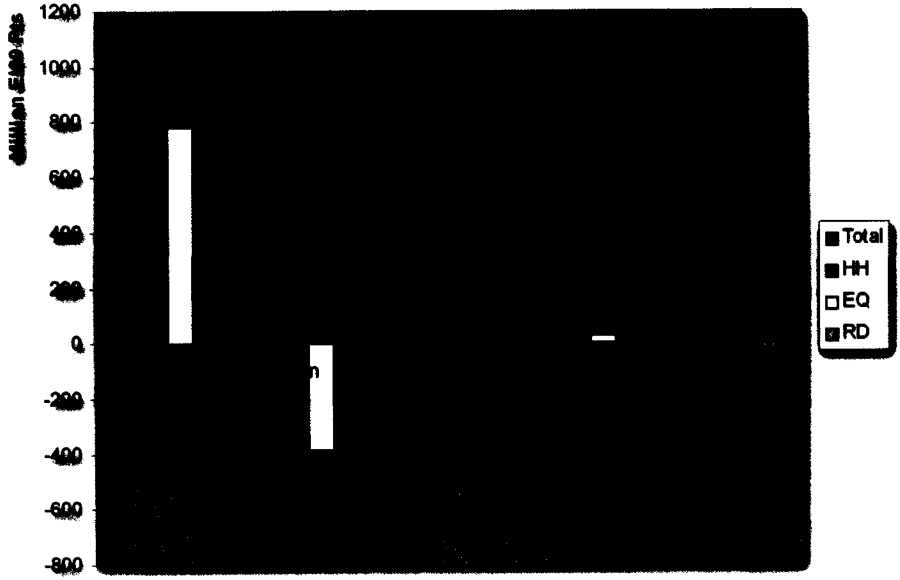

Figure 5.11: The effect of a phase-out of sintering-based lead processes on the Eco-Indicator '99 scores for the interconnected metal resource cycles, and for the lead, zinc, bismuth, silver and gold cycles individually.

Simulation of the phase-out of the two-stage processes shows that this leads to reduced emissions of carbon dioxide, nitrous oxide and sulfur dioxide, as well as to a decrease of the total amount of flue dust. In contrast to what may be expected, a phase-out of sintering processes leads to an overall *increase* in environmental impact. The combined environmental burden of the lead and zinc production alternatives (direct smelting process and hydrometallurgical zinc process respectively) is higher than the burden of the ISF process which simultaneously produces lead and zinc.

Figure 5.11 shows that it leads to a decrease of the overall zinc impacts, and a increase of the lead impact. When the environmental burden is distributed over by lead and zinc production (based on their production volumes), the ISF has lower emissions per ton of lead produced than its direct smelting alternatives. Per ton zinc production, phase-out of the ISF leads to a decrease of environmental burden, even when part of the burden of ISF is allocated to lead. This is because emissions to air in the Eco-Indicator method lead to higher impacts, than impact to soil and water from residue disposal and the hydrometallurgical generates less emissions to air, but more to soil and water.

Figure 5.11 also shows that the phase-out leads to a small increase in lead production efficiency and a decrease of zinc production efficiency. The hydrometallurgical zinc production has a smaller capacity to process lead-zinc concentrates, complex flue dusts and residues. Some of these complex resources can currently only be refined at plants employing the increasingly rare ISF extraction process. In the model, complex zinc and lead concentrates and residues, such as EAF dust, copper flue dust, hydrometallurgical residues or pyrometallurgical slags from lead smelters, are first processed in the slag-fuming process or in the Waelz Kiln. Part of the Waelz oxide is directly sold as product (20%), the remainder is further refined together with slag-fuming product in the lead blast furnace process, the ISF process and the hydrometallurgical zinc process. The simulated phase-out leads to change in the recycling routes for complex zinc and lead resources. Without these processes, the Waelz oxide arising from the recycling of secondary resources with a low zinc and lead content must be treated in the hydrometallurgical zinc process. This partly counters the increase the efficiency of lead production arising from the use of the advanced direct-smelting processes. The lead production efficiency of the interconnected metal production system decreases because the zinc hydro-metallurgical route can process the Waelz oxide[7] but doe not produce lead (a small decrease in resource depletion in Figure 5.11). The phase out of ISF processes may lead to problems for processing of certain ore types. In the simulation, therefore, also the average composition of the zinc and lead ores changes. For zinc production, the phase out of the ISF leads to a small decrease in zinc production efficiency due to a decreased efficiency of the recovery of zinc in lead concentrates (an increase in resource depletion in Figure 5.11).

As can be expected, emission reduction leads to substantial improvement of the environmental performance of lead production. The improvement of the system through phase-out of old technology, however, is less obvious due to the interdependency of metallurgical processes. This illustrates the need for understanding the metallurgical network in order to control it. The changes in the composition of the feedstock of the reactors have a significant impact products, intermediates and residues/emissions - and thus on the performance of the metallurgical network as a whole - that are difficult to predict with the linear models of the process steps. One should thus be careful to draw conclusions form the simulation results whether of the phase-out of old technology is an improvement or not, but the results are an excellent starting point for discussion with industry the role of old technology in metallurgical production network, and improvement to the model.

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[7] See the appendix A for a more detailed description of the production routes of zinc and lead.

5.4.2 Waste manager

The principal focus of clean recycling is stimulating the use of secondary resources. This also implies considering the chemical and physical composition of these secondary materials. Lead is an important carrier metal for the recycling of a number of other metals, such as copper, arsenic, silver, cadmium and bismuth. These metals are concentrated in intermediates and by-products, which enables the refining to recover the pure metals. In the recycling process in addition to lead, thus a number of other valuable metals are produced. If additional materials are collected and pre-treated to increase lead recycling, waste managers need to consider this: Which metals can be recycled, and which metals (and other impurities) results in problems for the downstream recycling? Is separation necessary, and do the current pre-treatment and separation processes collect the co-recyclable metals in the 'right' fraction? Moreover, because of this overlap and the interdependence between the production routes of metals, changes in the recycling of lead also affect production of other metals.

To investigate the effect of increased recycling on the metallurgical system, a ten per cent increase in old lead scrap recovery is stepwise introduced, which reduces the environmental pressure from waste disposal to the same extent. A problem for simulation of increased recycling is estimating the composition of the extra old scrap recovered, and the waste fraction in which it reports to the metallurgical processes[8]. Because of the difficulty of providing reliable estimates of the composition, it is assumed that only lead recovery increases while the recovery of all other metals remains constant. It can be seen easily that this would slightly reduce the concentration of the co-elements in the old lead scrap, while their absolute recovery remains constant.

5.4.3 Metallurgist

Increased recycling leads to a smaller demand for lead ore concentrates and to a change in the utilization of the different lead smelters. Consequently, it reduces the emissions of sulfur dioxide, carbon dioxide, nitrous oxides and flue dusts from the lead resource cycle. Moreover, the total emissions of lead into the environment are reduced. Thus, as can be expected, the environmental impact of the industrial lead resource cycle is reduced. Figure 5.12 shows the change in emissions due to the increased lead recycling. Almost all emissions are reduced, excluding a few emissions to air and soil. Due to the decreased lead disposal on landfills, lead emissions to soil and water are significantly reduced. The decrease in environmental impact may be less than expected, due to a slight increase in the emissions of lead to air, and a subtle decrease in lead production

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[8] In general, the law of the diminishing returns would suggest that it would be increasingly difficult to recover more lead at the same or higher composition or grade. This relation between grade and recovery is also observed in mineral separation processes in industry (Digre 1960, Thwaites 1986) and can also be used to describe separation of wastes (Van Schaik 2002, Verhoef et al. 2004a). Following this train of thought, the extra recovered lead scrap would be of a lower grade. However, the grade/recovery interdependence is determined by the chemical composition and physical structure of the disposed products, and the employed liberation and separation processes. Product consumption, waste infrastructure and waste management practice differ significantly between countries, or even regions. Thus, dependent where the lead scrap is recovered, increased lead recycling could also lead to scrap of a higher grade.

efficiency, following from the change in process routes employed. Because airborne emissions of lead are assigned a higher impact on 'Ecosystem Quality' in de Eco-Indicator'99 than those to water and soil, this leads to an increase in damage to Ecosystem Quality. Figure 5.13 shows the impact of increased lead recycling on the different metal resource cycles. As more lead is produced via secondary routes, the 'primary' ISF route becomes less used (Figure 5.9). As mentioned before, the environmental costs of ISF operation are allocated to lead and zinc (and to a smaller degree also to the other minor metals), this leads to an increase in impact for the lead resource cycle, and a decrease for the zinc resource cycle.

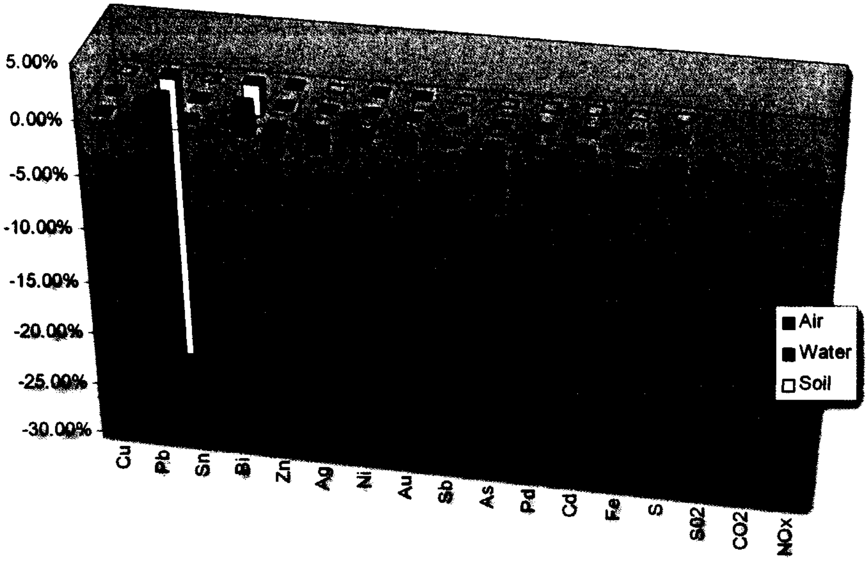

Figure 5.12: Change in emissions of the global interconnected metal cycles due to increased lead recycling.

The increased recycling also affects the production of other metals. Figure 5.13 shows that these effects, expressed as environmental impact, are in the same order of magnitude as the effect on the lead resource cycle itself. Primary copper concentrates are partly obtained from the processing of lead(zinc) ores. An increase in lead recycling leads to a decreased demand for in lead, and thus to decreased production of copper concentrates in processing of lead ores. As a consequence, this leads to increase in copper mining and thus to a higher environmental impact. Similarly, because secondary lead scrap contain less silver and bismuth - even when compensating for the assumptions for lead recycling above - increased lead recycling reduces their recovery in Parkes crust, Kroll Betterton dross and anode slimes. As a consequence the present surplus of these intermediates is reduced, leading decreased disposal of intermediates, higher system-wide efficiencies for silver and bismuth, and thus lower overall environmental impact. Moreover, the change in silver production indirectly also affects the gold production since silver production processes provide raw materials for gold production.

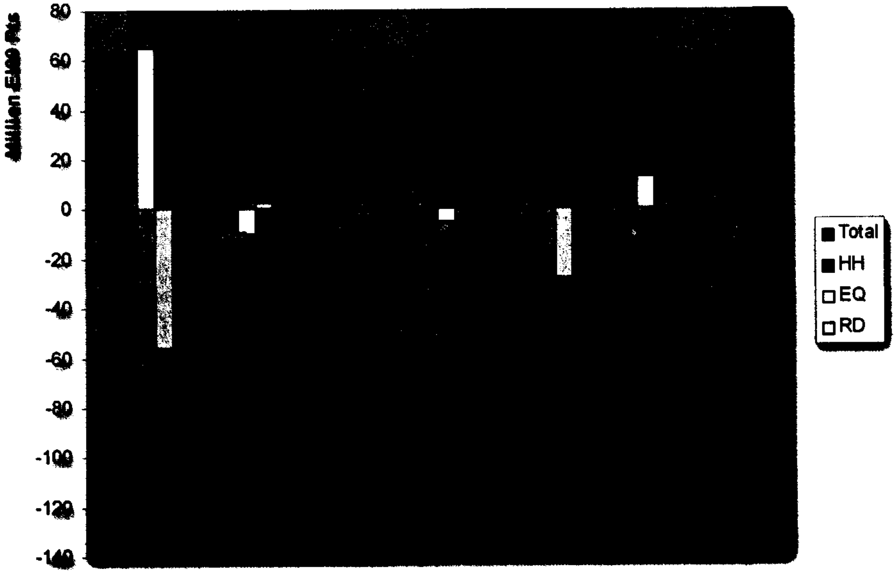

Figure 5.13: Eco-Indicator'99 score of the increase in lead recycling allocated to lead, gold, silver and zinc resource cycles.

5.4.4 Product designer and manufacturer

Lead prevention is particularly important for products that can not be recycled, or are recycled to a limited extent. In the selection of the alternatives, the status-quo on toxicity of possible substitutes throughout the life-cycle of the solders must be compared to that of lead. The lead prevention and containment strategies are thus complementary, but their benefits do not simply add up.

Increased recycling affects the dynamic interdependence between the metal production circuits: the stocks or surpluses of intermediates, which act as a buffer to change in the upstream production systems, are reduced. As a result, a subsequent change in the carrier metals has a stronger effect on the production of other metals, than it would have without the increased lead recycling. Lead recycling thus may influence the environmental impact or feasibility of lead-free solders (see Figure 5.14). To show the effect of cleaner recycling strategies on lead-free solder substitution, a cleaner recycling strategy (5 % increase in flue dust capture and 10 % increase in lead recycling) is combined with the substitution of lead-free solders in Table 5-2.

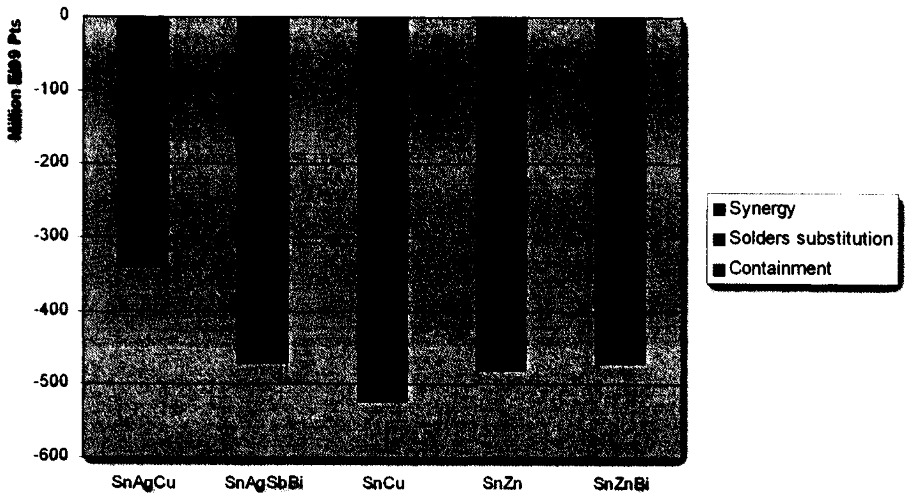

Figure 5.14: The effect of cleaner recycling on the impact of lead-free solder on Ecosystem Quality (Eco-Indicator '99).

The combination of containment with substitution of lead-solders affects the environmental impact of the lead substitution, and the availability of metals for the substitution:

- *Environmental impact*: Figure 5.14 shows three effects: the effect of cleaner recycling, the effects of lead substitution (both compared to the base situation) and the synergetic effects of the combination of both strategies. In particular because of the decrease in flue dust emissions the effects of containment are larger than the human health (HH) and ecosystem quality (EQ) effects of lead substitution. In particular flue dust capture has a large influence on environmental impact in terms of HH and EQ (see figure 5.9). The effects of lead-free solder substitution on HH and EQ differ per solder (see also figure 5.5). Compared to lead free solder substitution alone, these synergetic effects are significant in terms of human health and ecosystem quality[9] (the 'synergy' benefits in Figure 5.14).
- *Resource availability*: The increased recycling of lead reduces the production of bismuth and silver from the lead intermediates. As a consequence, bismuth content in lead-free solder alloys is reduced from 15% to 14 %.

This illustrates that both strategies affect one another: increased recycling leads to larger benefits for the lead-free solders in terms of human health and ecosystem quality, but to a decreased availability of bismuth. The simulation showed that lead substitution is a dynamic problem: actual benefits and availability of metals are dependent on the actual configuration of stock and flows between the different processes. This illustrates the

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[9] The effects on resource depletion are small (~1%) as can be expected, but the human health and ecosystem quality of lead substitution increase by approximately 10 %, except for the human ecosystem quality benefits of SnAgCu, which is almost doubled 76 % increase.

importance of understanding the dynamics in the metallurgical system underlying the different abatement strategies for lead exposure.

5.5 Discussion

In the previous chapters, it was argued that quantitative models are essential to link different efforts, such as product design, process improvement and legislative and policy instruments, in a meaningful way to the impact and operation of the metal production/recycling system. These models must connect the dynamics at process level to the development of the global resource cycles. In this section, the model is evaluated as an example of such bottom-up construction to assist decision-making in complex, interdependent systems.

5.5.1 Linking decision-making

The efficacy of many of the IE strategies is determined by the flows, transformations and accumulations at process level. Bottom-up models, such as the one presented in this chapter, can provide for a 'common ground' to discuss the implications of different strategies with industry, and can assist selecting the appropriate industrial partners to be included in the policy development process. The hierarchical method of modeling and representation provides a transparent overview of the interconnected metallurgical resource cycles, and would be suited to initiate further development of the products, or the production network by the stakeholders involved. As such, the model could assist in making the metallurgical knowledge available for waste management, formulation of policy, development of legislation, or product design and realize a more sustainable production and use of metals.

The most important contribution of the case study on lead production is that the dynamic model of the interconnected metallurgical processes allows one to investigate the impact of a shift in product composition or process configuration on the operation and environmental performance of the industrial metal metabolism. The simulations quantified how the interdependence in the metallurgy can affect policy-making, development of legislation or product design. This would assist co-ordinated decision-making across different organizational levels, and between processes in different resource cycle stages.

5.5.2 Capturing interdependence

Neglect of metal cycle linkages and dynamics in policy formulation or product design may lead to a shortage of lead-substitutes or errors in estimated environmental benefits. The model shows how lead substitution in solders disturbs the flows and stocks in the metal production system and that the effect of some solder compositions on the larger metal system is much greater than of other compositions, and thus their effect on the environmental impact or availability of raw materials. For some solders, the transition results in a reduction of the amount of intermediates that is disposed of, and thus in higher production efficiencies of some metals. For other solders, it can result in significant changes in consumption of energy and raw materials, and in shortage of the raw materials.

The production of some lead-free solder alloy components, such as bismuth or silver, can not independently be changed: their production is closely linked to the production of lead and copper. The simulations showed bismuth production can increase to 453% without changes in the raw materials consumption pattern or without having to find new bismuth sources. This corresponds to a Bi percentage of 15% (holding all other factors constant). The amount of change is dependent on the actual configuration of stock and flows between the different processes: the maximum percentage becomes even lower (viz. 7%) for the SnAgSbBi solder, when considering that anode slimes are also consumed by the silver production processes.

The case study illustrated that the interdependence in metal processing must be considered in order to adequately estimate the environmental impact. The model can assist Lucas on metals, or metal-containing products by estimating these effects. However, the simulations show that the environmental performance of lead free solders is strongly dependent on the perception of environmental problems. The difference in these perspectives and in impacts assessment methods in general, hinders direct adoption of the results in terms of environmental impact of metals, which can drastically reduce to effort for LCA studies to include the interdependence and dynamics in the metal resource cycles, rather than the detailed inventories of the underlying flows and accumulations.

5.5.3 Closing the resource cycles, a dynamic problem

The simulations show that during the transition period metal production efficiencies, emissions and waste generated and raw materials consumption continuously change. As a result, the environmental impact of producing some metals, as well as their production/recycling capacity in the system changes. The long time periods required (approximately three decades) to achieve model convergence after lead substitution illustrated that, under these dynamic conditions, the system will virtually never be in a steady-state: it is continuously affected by new product designs, development of legislation and policy, new technology or increased recycling.

For metallurgists this means that metal processes must be capable of continuous adaptation to changes in their primary and secondary raw materials. For legislators this means that to effectively tackle 'non steady-state' problems, somewhere a balance between the room for technological adaptation and innovation, and the protective constraints of legislation must be found: too strict legislation may fix technological solutions, and hinder the processes to react adequately to external changes. In addition, it must be realized that other measures to abate lead exposure, such as increased lead recycling, also affect the configuration and thus the success of lead substitution strategies.

5.5.4 A further phase-out of lead

All of these aspects become even more important if a further phase-out of lead is considered. In case of an extended ban on lead, both the availability and recovery of a range of metals will be affected. In line with the waste prevention principle, lead substitution has become an increasingly popular approach to reduce lead emissions into the environment at the source in Europe. The proposed EU directives on electrical and electronic equipment (2000b) are an example of this approach. Other bans on the use of lead are in place, or are taking effect in the near future (e.g. in vehicles, with certain exemptions, EU 2000a). In Denmark, bans on most uses of lead compounds not covered by EU legislation, and on many uses of metallic lead are already imposed (see 5.1.3).

The Oslo Paris Commission recommends that lead should be further substituted where appropriate. The commission, however, adds that 'a detailed investigation of the use of lead in such products, including the effectiveness and safety of proposed substitutes and an appraisal of the advantages and disadvantages of carrying out specific substitutions will need to be carried out in order to assess the practicability of phasing out lead in products' (OSPAR 2002).

Figure 5.15 shows the possible effect of a near complete lead substitution (90%) based on status of lead alternatives (reviewed by LDAI 1992, ILZSG 1992, Thornton 2001, OECD 1993, Nordic Council of Ministers 2003)[10].It can be seen flows and accumulations in interconnected metal production/recycling circuits will be drastically altered, leading to shortages in raw materials for silver and bismuth, but to an increased supply or raw materials for nickel and gold. Due to increased production of silver, the demand for gold ore may decrease with 15%. The phase-out of lead will also lead to a reduced recycling capacity for a number of metals: First, the smaller lead production automatically results in smaller co-recycling of other metals through the lead route. Second, due to the decreased lead production with considerable amount of lead still in economic stocks, lead processes will be able to select old scrap to be recycled. Old scrap that is high in impurities may be refused, and consequently these impurities are not recovered. In addition, as old scrap composition is typically not the same as ore composition, this may also lead to shortages and underscores the importance of the metallurgical understanding for product design.

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[10] Lead substitution will affect many different metals, in particular bismuth. Bismuth is an important substitute for lead. Apart from its possible applications as lead substitute in lead-free solders, bismuth is important for lead substitution in ammunition, fishing weights, tools and anchors, and lead compounds in glazes and enamels. If bismuth were to be used in all of these applications, it would dramatically increase the demand for bismuth (as much as 25 times based on average composition of lead-free solders in Table 5-2). Silver is also important as substitute for lead in alternative batteries[10], bearings and solders and lead substitution could increase the demand for silver more than six fold. Copper is also important as lead substitute in a number of applications: including joints in drain and water pipes solders, balance and wheel weights, and roofing plates. However, because of the relatively large production compared to lead, only a marginal change in the demand for copper can be expected. This holds also true for iron which may be used to substitute lead in among others flashing (around chimneys, windows etc.) ammunition, bearings, lead weights (fishing tools anchors and balance weights for vehicles) plating of gasoline tanks, yacht keels, lead tubes and joints (for drain and water pipes etc.). A small increase in the demand for zinc can also be expected.

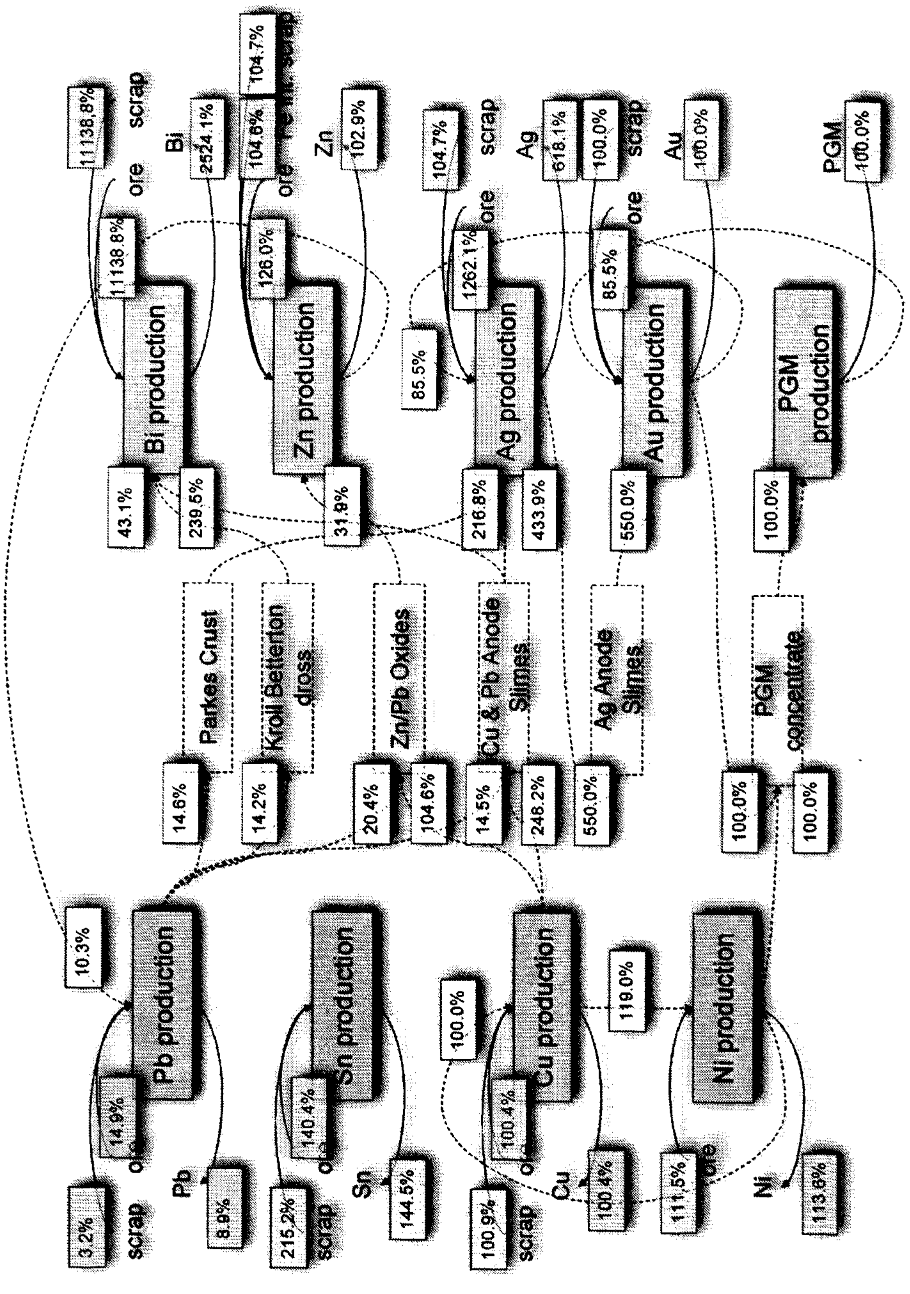

Figure 5.15: Estimated disturbance of the metal production system due to a near complete lead substitution.

5.6 Conclusion

In the previous chapter it is shown that the current metallurgic knowledge and industrial infrastructure have the capacity to realize industrial ecology strategies, but only if the metallurgic constraints of metals production and recycling are taken into account in waste management, policy development, and product design (and vice versa).

Adequate modeling and presentation of modeling results of the metal production network are required to assess the consequences of existing and new regulation, product innovations, and process improvements. The model of the interdependent industrial metal resource cycles presented meets these criteria. It can be used to estimate the effect of regulatory, product and process changes system-wide, and identify possible bottlenecks at process level. In such a way, the model can be used to co-ordinate decision-making across the different systems levels by identifying possible (technological) bottlenecks.

The system of metal production and recycling processes is too complex to fully predict the environmental consequences of technological changes or new policy and legislation. The effects of changes to the metal metabolism can not be completely modeled using mass balances only, among others due to the complex interdependence between feed composition and product quality in metallurgical processes – partly controlled by the tacit knowledge in the processes.

The model can sufficiently predict system-wide changes in the system, to assist in initiating stakeholder assessments. The combined (partly tacit) knowledge of the stakeholders can be feed back into the model and further develop the model. This is why and where industrial ecologists and metallurgists must join forces. In short, metallurgical process technology know-how must complement a sound understanding of economics and regulation to bring to fruition industrial ecology concepts. Without a sound technological and scientific basis, industrial ecology will remain in theory and philosophy books.

6 Synthesis and Conclusions

Summary
In the synthesis (6.2 –6.4), the approach chosen and results obtained are evaluated based on the research questions as formulated in chapter 1. Subsequently, important concepts, and ideas derived from this study are summarized (6.5). Finally recommendations for future research are given (6.6).

6.1 Sustainability of industrial ecology

In order to answer the central research question, one needs to understand and define the concept of sustainability. This lead to the first research question: What are 'sustainability' and 'industrial ecology'? Below the concepts and their relation are briefly described.

Sustainability

The concept of sustainability refers to continued welfare of human life on earth. It is an emerging system quality, which means that sustainability is a property of the system as a whole and that one can not know that the system is sustainable until in fact sustainability has been reached. The web of environmental processes upon which the present industrial society and thus human welfare is built, is robust with respect to perturbations, but only within distinct limits. Overstressing these limits may lead to a (partial) collapse of the natural systems, and have dire consequences for human welfare. As a consequence, sustainability of human welfare would also call for a level of 'welfare' for the environmental processes. The extent to which the current consumption-based society has reached these limits or the effectiveness of measures to avoid reaching these limits is unknown.

Given the expected growth in population the present definition of welfare will most likely overstress the boundaries of natural systems at some point in time. Above all, sustainability requires a redefinition of the concept of welfare. To date welfare is measured using the 'having' paradigm: it is almost universally defined in terms of ability to appropriate goods and materials. An alternative definition of welfare based on the 'being' paradigm is necessary to ensure the sustainability of human welfare. Considering the complex dynamics of environmental processes and human activities, sustainability is probably not a specific system configuration that can be accomplished, but more of a continuous co-evolution of human and natural systems.

Industrial ecology

The role of technology in this process is very ambivalent. Depending on how technology is used, it can either be part of the problem or the solution. It is therefore essential to take a critical attitude towards technology. Industrial ecology – the discipline that focuses on the sustainability of industrial activities – would appear a good analytic framework to investigate critically the role of technology and technological knowledge in achieving sustainability.

The review of the concept showed that by itself implementation of the principles of industrial ecology will not lead to sustainability. Industrial ecology is a systems approach that, based on sustainable examples in nature, strives to achieve a deliberate (r)evolution of industrial activities within the boundaries set forth by natural systems they are founded on. The industrial ecology approach contains two essential elements. The descriptive element describes industrial activities in the context of other processes, both in the 'technosphere' and the 'biosphere'. Since in the end, the industrial system interacts with nature at the physical level, the industrial activities are described in terms of flows, transformations and accumulations. The prescriptive element aims to inform the decision-makers about the (un)sustainability of industrial activities, in order to realize the desired evolution of industrial systems.

The sustainability of industrial ecology

The approach of industrial ecology excludes some of the basic components of sustainability. Sustainability of any of the (industrial) subsystems can not be considered without the larger systems context, whereas industrial ecology focuses on the industrial subsystem. Industrial ecology strives to be objective, not normative, and social, psychological and economic issues are evaluated as objective dimensions of the problem. These issues are critical dimensions of sustainability – they determine the perception (and distribution) of human welfare and thus the extent of the technological change required. Since industrial ecology concentrates on just a part of the problem and possible solutions, its implementation can not lead to a sustainable society. The desired evolution does provide the necessary 'breathing space' to address the core issues. Moreover, industrial ecology-approaches can visualize the limits of such industrial ecological evolution and thus constrain the possible definitions of welfare. While industrial ecology does not really address the question whether technology is a problem or solution, it does investigate the boundaries for industrial/technological systems that the different, possible sustainable system configurations would pose. This makes industrial ecology an essential tool for any deliberate advance towards sustainability, or investigation of the role of technological knowledge in this process.

6.2 Technological knowledge, a bottleneck for sustainability?

The second research question concerned to what extent technological knowledge (know-how and know-to) has been recognized and appreciated as essential ingredient for sustainability in industrial ecology?

A deliberate evolution towards sustainability requires co-ordinated efforts of decision-makers across all system levels. Many of the industrial ecology strategies require solutions at the bottom-level of technological processes. At top-level, the industrial system can be seen as a compartment in the global metabolism, in which materials are converted into products, products are accumulated and recycled into materials again. This system of resource cycles is not closed as materials leak into the environment. The resulting impact of the industrial compartment on the environment is a function of the amount of material and energy that is used in the system, and the efficiency by which they are used and recycled. The industrial metal production system constitutes a key component in the metal cycles: it performs the chemical transformations necessary to introduce or feed metals back into the material cycle.

The changes in the supply and composition of secondary materials resulting from product manufacturing require that metallurgical processes must be able to produce and recycle metals efficiently under continuously changing conditions. In a system of closed metal cycles, the rate of change for the individual product flows or processing components is determined by the dynamics of the slowest components. If product designs change faster than the production/recycling infrastructure, this could result in problems with availability of raw materials from the interconnected metal production systems downstream, in a reduced efficiency of recycling, or in undesired environmental impacts in metal recycling upstream. This is the case at present, products change fast and their manufacture introduces new metal-metal and metal-non-metal combinations for which no recycling technology is available. As a consequence, recycling contaminates the produced metals. Currently, the utility of metals is maintained through addition of high amounts of clean primary (virgin) materials. On the long term, however, this would prevent closure of the material cycles. A critical obstacle for the successful implementation of industrial ecology strategies is the co-ordination of the different efforts themselves: a design for cleaner production that aims for minimum emissions and residues may as a consequence produce residues that can not be further processed and do not contribute to the closure of the material cycle.

The current metallurgic knowledge and industrial infrastructure have the capacity to recycle many different metal combinations at limited environmental impacts, and thus to close material cycles. Because of the long life spans and development times of metallurgical processes, this capacity and knowledge can only be exploited if the metallurgic constraints of metals production and recycling are taken into account in waste management, policy development, and product design. Thus a condition for industrial strategies on metals is the proper appreciation of these bottom-level constraints. However, in industrial ecology studies and models the industrial process routes are often oversimplified; many interconnectivities and interdependencies are neglected. Consequently, many real impediments to closing the material cycles and other strategies may be overlooked and the contribution of industrial ecology inventories as tools to invoke improvement for metals processing and recycling systems may be questionable. This leads to the conclusion that in the body of knowledge of industrial ecology technological knowledge has not really been recognized and appreciated as essential ingredient for sustainability or industrial ecology.

6.3 The role of models to co-ordinate decision-making

The fourth research question was how a better understanding of technology and communication of technological knowledge can assist an advance to sustainable metal production and recycling systems. The metallurgical bottlenecks to recycling are difficult to pinpoint since metals participate in a system of linked cycles and can not be produced or recycled independently from one another. Moreover, much of the operational knowledge controlling the material transformations in the processes is tacit.

The concept of the metal wheel was developed to visualize the constraints and capacities in a simple manner: Based on the ore compositions for which the metallurgical system was developed, it illustrates the interconnectivity in metals processing and shows which metal combinations in products or waste fractions can be effectively recycled into metals again. The wheel indicates which impurities are recovered and which are problematic and are disposed of through process residues. As such it can assist product designers in selecting which combinations of metals can be used, which should be avoided and for which new technology may be required, and thus in designing recyclable products.

The metal wheel visualizes the capacity of metallurgical systems, but provides no information on the dynamic behavior of the system, necessary for effective control of the system. The industrial ecological evolution aims to approach a (type III) ecosystem configuration. In nature, organisms consume and dispose of large amounts of materials continuously. These organisms are bottom-up organized into ecosystems to efficiently recycle these materials. The type III ecosystems are robust in a sense that they are able to keep this efficiency under changing conditions by continuous adaptation. This adaptability is a consequence of multiple feedback loops. These tend to bring the ecosystem back into balance, whenever there is a deviation from the norm due to changing environmental conditions. Industrial ecosystems are controlled by feedback as well in a similar fashion as ecosystems. If a process becomes less economically fit for one reason or another, the technology is less likely to be reproduced in new processes and its 'population' declines unless of course it is able to adapt. Because processes have distinctive material transformation functions, which often can only be partially replaced by other processes, a declining population affects the capacity of total industrial system.

There are also significant differences between natural and industrial ecosystems. Perhaps most important of these is the capacity of humans to consciously plan their activities. It is this planning capacity, which in principle allows one to make the industrial system compatible and meet the needs of present and future generations and the present and future needs of the natural processes. Economics, policy and legislation translate the global environmental objectives into requirements at process level, and thus govern materialization of technological solutions and configurations. Today, much of the environmental policy and legislation is reactive: when a problem arises, measures are taken to solve or reduce it. The complex web of interactions and feedback on these interactions may induce a significant delay in the effect of changes to either system. Technological solutions that may appear to be sustainable may have detrimental effects on the longer run due to long delay in the feedback in the natural processes. Natural ecosystems are robust within distinct limits and it often takes time to reach these limits. This is a problem as some damages to nature are irreversible, and technological configurations may prove very difficult to alter because of the so-called technological lock-in. At process level, delay in feedback control systems is known to result in instability and thus in deviation from the control parameters such as product quality or emissions.

An important lesson that can be learned from ecosystems that have to deal with the same issues is feedforward control. In addition to feedback control, natural systems also exhibit feedforward control. Where feedback control is reactive, feedforward control is pro-active. As in feedforward control possible changes are measured in advance, in theory perfect control is possible: no offsets in the control parameters. The effect of these changes is anticipated based on a quantitative model of the controlled system, and is compensated for by altering the system parameters. Feedforward control could avoid the problems of feedback control, but can not compensate for non-measured disturbances or non-modeled parts of the system. Not all disturbances can be measured and the process dynamics are often too complex to capture in quantitative models. In industrial practice, both feedforward and feedback control are used; part of the feedforward control in metallurgical control is based on the tacit, mental models of the operators. Similarly, dealing with complex systems implicit in the industrial ecology approach will require both mechanisms as well.

The concept of feedforward control clearly illustrates the need for communication and the provision of comprehensive information to all stakeholders on industrial activities.

One needs to understand the interactions in the technological system and take timely action: for example in order to establish whether changes in technological configuration may have undesired by-products; or whether changes in environmental requirements or material throughput result in problems for the current configuration. This particularly holds true for metals, because of the strong interdependence and overlap in metal production routes. As a consequence, the effects of changes to the system can not intuitively be predicated. Therefore quantitative models are needed to provide knowledge to decision-makers: to minimize emissions and maintain metal utility, environmental policy and legislation must shift from today's mainly reactive approaches to more pro-active approaches.

6.4 Can industrial ecology models provide the necessary knowledge?

The last research question adressed whether industrial ecology models can provide the necessary knowledge to support decision-making of metal resource management, based on the current status-quo of the models and available data on system.

The adjective 'deliberate' in the industrial ecology goal of an industrial development towards sustainability implies at least in part feedforward control. Therefore, it is not surprising that most of the industrial ecology studies involve quantitative descriptions of industrial activities in terms of flows, transformations and accumulations. These descriptions should provide for a 'unifying core' of industrial ecology connecting the different prescriptive efforts at different systems levels: from process/product level to the metabolism at national or global level. Through such a co-ordinated effort a deliberate advance towards sustainability could be made. Present models and studies in industrial ecology are not sufficient to realize its potentially valuable concepts and ideas: industrial ecology tools are available for distinct time and spatial scales. Due to the dynamically linked metal cycles, the system is no longer intuitively understandable – e.g. small changes can have large effects – and tools emphasizing distinct parts of the system can not easily be combined to predict system-wide changes.

In particular, the production of metals is so interdependent that they can hardly be considered separately, and their control spans various organizational levels. Therefore, a further convergence in the current trends in research and modeling of environment related flows in the physical economy is essential. Such convergence could yield significant benefits with respect to the underlying data collection, access and conformity, and the analytical conformity. In addition, it could considerably reduce the effort of modeling such complex systems. For this reason, the data underlying the quantitative description is reported in detail in the appendices. The data can serve as a solid basis for other studies on metals processing and recovery. In addition, if a model methodology is well defined, data can be collected and published in a structured way.

In addition, an industrial ecology (Substance Flow Analysis) model of the interdependent industrial metal resource cycles is developed that can provide a frame to other industrial ecology models, as it connects the different system levels. It has been demonstrated that by founding the model on reconciled mass balances of the underlying networks of processes, the model is capable to be able to largely capture the dynamic interdependence of metal production and recycling in models. In this way the flows between the different circuits, but also from and into the environment could be sufficiently estimated to identify possible problems and support decision-making. For the further development of such models it is essential that the metallurgical industry (and the manufacturing and waste industries as well) collects and presents data on the different stages in the metal cycles. Availability of recent data is important considering that the metal ecology is an evolving system.

6.5 Conclusions

How can the metal ecology be analyzed, modeled and communicated to stakeholders to facilitate dissemination and correct use of sound technological information and systemic know-how? Using the findings of this study, this central research question can be answered. Each of the headings below summarizes an important argument.

The first the context for analysis, modeling and communication is defined (6.5.1). Secondly, the analytic framework must be investigated on its potential to analyze the metal ecology in this context (6.5.2). Thirdly, the requirements for models to effectively capture and communicate the metal ecology were investigated (6.5.3 and 6.5.4). Finally, it was investigated whether such models could facilitate dissemination and correct use of sound technological information and systemic know-how (6.5.5).

6.5.1 Sustainability, an emerging system property

Sustainability, the continued welfare of human and other life on earth, is an emerging system property. The designation refers to the fact that sustainability is a property of the system as a whole and that one can not know that the system is sustainable until in fact sustainability has been reached. Sustainability is not a specific system configuration that can be achieved, but rather a property that emerges from the continuous co-evolution of human and natural systems. ***<Chapter 2>***

6.5.2 Connecting the industrial and ecological thinking in industrial ecology

The intent of the field of industrial ecology is to provide the technological and scientific basis for a path towards global sustainability. However, the technological basis in the body-of-knowledge of industrial ecology hampers the realization of its objective. Many in the field of industrial ecology share the view that industrial progress is the central means for environmental progress and advance towards sustainability, but industrial ecology so far has not or only partly bridged the gap between its holistic concepts and the different industrial practices. This obscures technological problems and opportunities in the system analyses and thus their consideration by decision-makers at other levels. Since many of the relationships between industrial activities are determined at process level, the current lack of a solid technological footing in the industrial ecology models, studies and literature inhibits the successful implementation of its strategies and concepts. ***<Chapter 2>***

Industrial ecology is an ecological or systems approach that focuses on a part of sustainability. Based on sustainable examples in nature, ecosystems, it strives to achieve a deliberate (r)evolution of industrial activities within the boundaries set forth by natural systems they are founded on. This deliberate development of industrial systems towards sustainability requires (i) the co-ordination of industrial activities mutually, and with the other activities in the resource cycles, and therefore (ii) the support of decision-making across various organizational levels that influence industrial activities. Two elements can be distinguished in industrial ecology approach: descriptive and prescriptive elements. The descriptive element describes the industrial system at and across system levels. The prescriptive element aims to stimulate decision-making based on considerations of sustainability. To co-ordinate decision-making across system levels descriptive approaches should be able to show a consistent picture of the industrial system at the various levels.

6.5.3 The dynamic interdependence of the metal metabolism

Present Material Flow Analysis studies on metals are insufficient as tools to invoke improvement in their industrial systems. Neither in the industrial ecology literature, nor in metallurgical literature have (SFA) models been reported that showed the dynamics and interconnectivity of the metal resource cycles at the proper resolution. Because the metal production and recycling capacity is realized by a dynamic network of reactors, tools to invoke improvement in this capacity also require modeling at level of reactors. ***<Chapter 3>***

The metal production/recycling system can be considered as an example of industrial ecology in practice. Consequently, the production, use and recycling of different metals (the metal metabolism) is so interconnected that they can not be considered independently and the effectiveness, feasibility and environmental impacts of the different industrial ecology strategies are not intuitively predictable.

This capacity is realized by a dynamic network of reactors. Modeling at this level of detail requires the use of statistical methods to increase reliability. In particular, data reconciliation methods from engineering practices are essential tools to model at this resolution: to obtain reliable closed mass balances around each reactor type from data sources in literature. The metal wheel is developed to visualize the interdependence in metal production and recycling in a simple manner. It represents the combined capacity of the metallurgical industry to soundly produce high-grade metals from different raw materials and assists in the appreciation of the effect of metal groupings. As such, it can be a valuable tool for industrial ecology models, studies or product designs.

6.5.4 Feedforward control in the metal ecology

Predictive, quantitative models of the system are required to promote feedforward control of the system. These models must be rooted in a solid understanding of technological infrastructure (i.e. representing the metallurgical system as a dynamic network of reactors) to be able to predict the effect of changes, and introduce the tacit industrial knowledge and the detailed engineering models into the various levels of decision-making. ***<Chapter 4>***

For co-ordination of the production, use and recycling of different metals, two types of control can be distinguished: the reactive feedback and the predictive feedforward control. Feedback control is necessary, because the system of metal production and recycling processes is too complex to fully predict the environmental consequences of technological changes or of new policy and legislation. Feedforward control is to be preferred, however, because it enables control without offsets in the control objectives. It requires a predictive model that links transformations and flows of materials and energy to the dynamics of the metal metabolism. The effects of changes to the metal metabolism can not be completely modeled using mass balances only, among others due to the complex interdependence between feed composition and product quality in metallurgical processes – partly controlled by tacit knowledge. Striving towards such a model not only provides valuable insights about how the processes interact and how this might affect the environment, but also provides for a basis to include the industrial tacit knowledge (and the detailed engineering models) into the decision-making process.

6.5.5 A predictive dynamic model to control the metal metabolism

At present MFA studies are not sufficient to communicate sound technological information and systemic know-how and thus to invoke improvement, a new type of SFA model was developed. Because this new multi-level dynamic model is rooted in the metallurgical network of reactors, it can estimate the effect of changes in the metallurgy of one metal on the metallurgy of other metals. Through identification of the potential metallurgical constraints in advance, it enables feedforward decision-making at higher system levels. The model developed can invoke improvement by visualizing the constraints of cyclic use of metals and facilitate the inclusion of metallurgical process technology know-how into industrial ecology strategies and concepts. ***<Chapter5>***

The case on lead production demonstrated that dynamic bottom-up modeling of the interconnected metal production and recycling systems can quantify the dynamic interdependence sufficiently to assist the pro-active evaluation of strategies. The model developed bridges the gap between the detailed process engineering and the holistic industrial ecology models, and provides a basis for feedforward control of metal production system across its system levels. Due to the dynamic interdependence of metal production and recycling, a non-linear, dynamics system results. Consequently, the benefits and constraints of either containment or prevention approaches are not intuitively predictable, neither can they be adequately estimated with linear LCA (or MFA) methods. The model provides a scientific backing to evaluate impact of changes in the resource cycles on the metallurgical system.

The model showed quantitatively how bismuth production is linked to the production of lead and copper, and that its production can not independently be changed. The simulations for tin-zinc-bismuth solder showed bismuth production can increase to 453% without changes in the raw materials consumption pattern or without having to find new bismuth sources. This corresponds to an average Bi percentage of 15% in the substituting solder alloys. The models showed that lead substitution is a dynamic problem: the maximum change is dependent on the actual configuration of stock and flows between the different processes. If 10% more lead is recycled this can reduce average bismuth percentage to 14%. The maximum percentage becomes even lower (viz. 7%) for the SnAgSbBi solder, when considering that anode slimes are also consumed by the silver production processes.

Feedforward control will become even more important if a further phase-out of lead is considered. In line with the waste prevention principle, lead substitution has become an increasingly popular approach to reduce lead emissions into the environment at the source in Europe. In case of an extended ban on lead, both the availability and recovery of a range of metals will be affected. The phase out of lead can affect not only the containment of lead in the resource cycles, but also the containment of a number of other metals.

6.6 Recommendations

To bring industrial ecology concepts out of the philosophy books and into reality, I recommend that industrial ecologists further expand on this more detailed methodology. Industrial ecologists need to take particular care to ensure sufficient depth in their models. The complex interdependence of industrial systems can not be captured with present 'superficial' MFA methods. The model developed in this study represents a first attempt to connect the underlying details of metallurgical processes to industrial ecology strategies such as closing the materials cycles or detoxification.

As the model has sufficient technological depth to model for feedforward control, recommendations for improvements must lie in the scope of the model. Economic models should be added to the technological model since the price for instance determines the (economic) selection of secondary resources, or the recycling of residues. I recommend that the model should be further expanded to include interconnection with other (groups of) metals, as their production system shows similar characteristics to that of the metals selected for this study.

Moreover, the approach taken is not unique for the metallurgical industries. The chemical industries for instance, can also be considered a complex network of interrelated processes, which have to cope with comparable problems. Individual processes typically rely on other manufacturing processes for raw materials, and as markets for their products. As a consequence, there are a variety of production routes available for different chemical products. To support decision-making without neglecting the technological constraints and opportunities, the development of these predictive models can be used for series of interdependent chemical processes.

Another challenge is to incorporate electricity and other utility sectors in these predictive models and interface them with the metal and chemical industry sector parts. The value of these detailed quantitative models can be expected to increase with the implementation of industrial ecology. This will direct the development of society to arrive at a type III ecosystem – the goal of industrial ecology. As a result it will require coping with increasingly interconnected industrial systems, such as the metal production and recycling system, and development of quantitative models as unifying cores for multi-level decision-making involved.

Since this is a very data-intensive process, I recommend that industrial ecologists clearly define their data requirements and methodologies. Only if a methodology is well defined, data can be collected and published in a structured way. For representative modeling of metallurgical systems, industry must ensure that the data and flowsheets represent industrial practice and that these are published in literature available to industrial ecologists rather than in specialist literature alone.

The proposed model also can be used to complement other industrial ecology approaches that typically do not go into much detail, such as LCA. To facilitate the use of the results obtained with the proposed model, I recommend an alignment of the various impact assessment methods to ensure conformity of the results of the proposed model with requirements of the less detailed approaches.

Positions added to the Thesis 'The Ecology of Metals'

by Ewoud V. Verhoef

1. Metals are often promoted as being infinitely recyclable (*e.g. ICME 2004*), but this only holds true when plant (process) and product design prevent the dilution of metals, and avoid 'foreign' combinations of metals. (*This thesis, chapters 3 en 4)*

2. The labeling of products and materials as waste limits their potential for recovery. (*This thesis, chapters 1 en 4)*

3. Only in combination with a solid footing in technology can the current body-of-knowledge of industrial ecology offer guidance to decision-making on sustainability. (*This thesis, chapter 2)*

4. Sound technological models and representation of modeling results of the metal production network are required to assess the consequences of existing and new regulation, product innovations, and process improvements in the context of sustainability. (*Verhoef et al. 2004*).

5. Although the smell of money was often spoken about ('pecunia non olet'), it was the sound (and bite) that really counted.

6. In the study chemical technology - as a rule - too little attention is given to the design and control of systems of interdependent industrial processes.

7. The reuse of metals under Louis XIV was critical for financing the expansion of France to its natural borders.

8. The shortage of General Practitioners in the Netherlands (*Nivel 2004*) has more to do with the organization of the Doctor's offices than with the number of General Practitioners.

9. For a good interpretation of measurements it is not sufficient to know the basic operation of the equipment used; this holds particularly true for electrochemical experiments with metals.

10. The primary task of the police is maintaining (legal) order in the society. While fining of offenders sometimes can be useful in the process, requiring a minimum number of fines per annum is in direct violation with this primary task.

These positions are considered defendable and as such have been approved by the supervisor, prof. dr. M.A. Reuter.

Stellingen behorend bij het proefschrift 'The Ecology of Metals'

door Ewoud V. Verhoef

1. Metalen worden vaak naar voren geschoven als oneindig recyclebare grondstoffen (*e.g. ICME 2004*), maar dit is slechts juist wanneer fabrieks-(proces) en productontwerp de verdunning van metalen voorkomt en 'vreemde' mengsels van metalen vermijdt. (*Dit proefschrift, hoofdstukken 3 en 4*)

2. Het brandmerken van producten en materialen als afval beperkt het hergebruik. (*Dit proefschrift, hoofdstukken 1 en 4)*

3. Slechts in combinatie met een 'solid footing' in technologie kan de thans ontwikkelde 'body-of-knowledge' van industriële ecologie een duurzame ontwikkeling van de industriële systemen leiden. (*Dit proefschrift, hoofdstuk 2*)

4. Het goed modelleren van het industriële metaalproductienetwerk en duidelijke presentatie van de resultaten, zijn vereisten om de consequenties van de huidige en nieuwe wetgeving, productontwerpen of procesverbeteringen te kunnen evalueren in de context van duurzaamheid. (*Verhoef et al. 2004*).

5. Tegenwoordig wordt niet meer betaald met klinkende munt.

6. In de opleiding tot ingenieur wordt als regel veel te weinig aandacht besteed aan het ontwerpen en beheren van systemen van onderling afhankelijke industriële processen.

7. Bij de financiering van de expansie van Frankrijk tot zijn natuurlijke grenzen onder Lodewijk XIV was het hergebruik van metalen doorslaggevend.

8. Huisartsentekort (*Nivel 2004*) heeft niet zozeer te maken met het aantal huisartsen als wel met de organisatie van de huisartspraktijken.

9. Voor een goede interpretatie van meetresultaten volstaat het niet de globale werking van de toegepaste meetapparatuur te kennen. In het bijzonder geldt dit voor elektrochemische experimenten met metalen.

10. De primaire taak van de politie is het handhaven van de (rechts)orde in onze maatschappij. Hierbij kunnen bekeuringen soms een dienstig, maar lang niet altijd een optimaal instrument zijn. De eis dat een bepaald aantal bekeuringen per jaar moet worden gerealiseerd is hiermee in strijd.

Deze stellingen worden verdedigbaar geacht en zijn als zodanig goedgekeurd door de promotor, prof. dr. M.A. Reuter.

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A - Metal production flowcharts

Summary
In this appendix a detailed inventory of interconnected metal production system is presented, that allows modeling the metal production system as a dynamic network of interdependent process steps, which are interconnected through the exchange of intermediates. The sections B-2 to B-10 contain an overview of the different end-uses, a description and flowsheet of the production of each metal and the reconciled mass balances of the processes in the flowsheet Section B-11 contains the assumptions necessary to model the stocks of metal in consumption and calculate the old scrap composition, as well as the mass balances for the different waste management processes.

A.1 Introduction

In comparison with the well-known examples of eco-industrial parks, the interconnected metal production and recycling systems are a less recognized example of industrial ecology in practice. The metallurgical industries have minimized the use of resources and production of wastes by interchanging resources, intermediates and residues between processes. As a result the production of metals is so interdependent that they can hardly be considered separately. To date industrial ecology studies on metals production and recycling lack a sufficient depth to invoke improvement for metal processing and recycling systems.

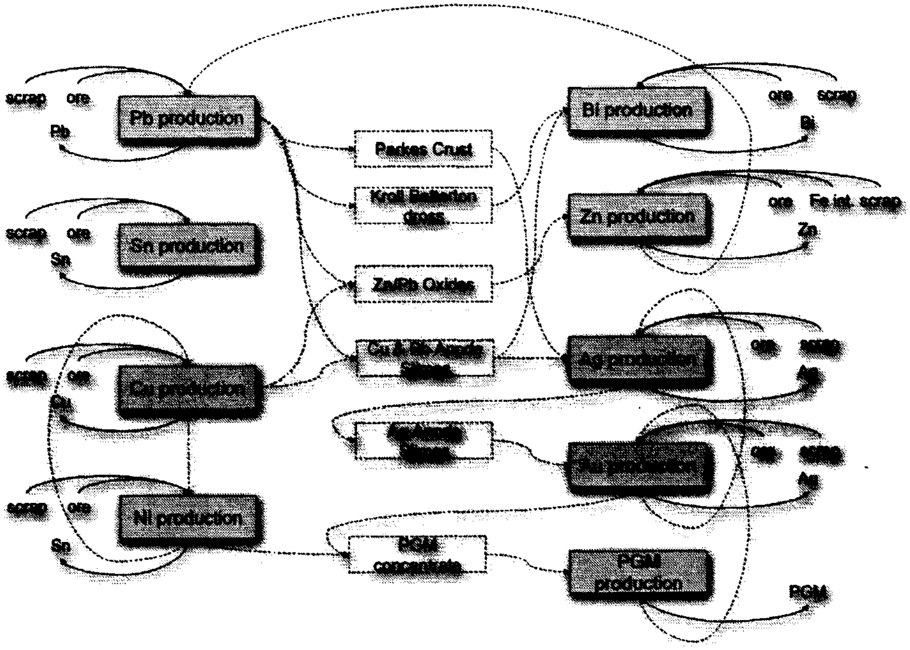

Figure 1: Overview of the interconnected production system of eleven metals. The dotted squares represent important intermediates connecting the metal production circuits.

To model the metal production system at sufficient depth, it must be seen as a dynamic network of interdependent process steps that are interconnected through the exchange of intermediates. To enable modeling the system at a sufficient depth, section B-2 to B-10 contain:

1. The applications of eleven metals (Cu, Pb, Sn, Bi, Zn, Ag, Au, Ni and the PGMs Pt,Pd, and Rh) in different end-uses
2. The description and flowsheet of the production of each metal
3. The reconciled mass balances of the processes in the flowsheet

Data reconciliation is a method from the engineering toolbox to adjust the experimental data to reduce and possibly eliminate discrepancies in the mass balance by using the standard deviation as a measure for the reliability of the data. In the reconciliation of the mass balances of process steps, the data is not based on measurements as common in process engineering, but on processing data of plants around the world found in the literature. Note that all this information can also be directly obtained from the model; for example by clicking on any the Simulink flowchart components, using the data explorer in Simulink, or by browsing through the data 'M-files'.

In the tables of the reconciled mass balances, the product outputs are given as percentage of the total input. The outputs can be divided into three categories:

1. *Fluxes*: These are extra inputs usually consisting of SiO_2, CaO and other similar minerals. Although fluxes are inputs they are listed under outputs for mathematical reasons. The need for flux is dependent on the input of metal sources (ore, etc). Note that the sum of recoveries of the other outputs can exceed 100% if fluxes are used in the process.
2. *Products and intermediates*: One or several outputs which are processed further or are the end product (metal)
3. *Wastes*: Consisting of off gas, flue dust, residues and slag. These are the emissions to the environment which are often further processed before finally to be emitted to the environment. If not included in the table recovery to slag follows from: 100% - {the recovery of all other streams in %}.
4. In addition the energy requirements (coal, oil, gas, electricity) and air are listed and, if applicable, the amount of off gas produced in terms of NO_X, CO, CO_2 and SO_2.

Section B-11 contains the assumptions necessary to model the stocks of metal in consumption and calculate the old scrap composition, as well as the mass balances for the different waste management processes.

A.2 Bismuth production and recycling profile

A.2.1 End uses

In 2000, about 4370 tons of bismuth was produce globally. Based on U.S. consumption patterns, it is estimated that currently about 42% of bismuth is used in bismuth alloys, 40% in pharmaceuticals and chemicals, 16.5% as metallurgical additives, and 1.5% for other uses. In recent years, several new uses for bismuth have been developed as non-toxic substitutes for lead in various applications. These included the use of bismuth in brass plumbing fixtures, ceramic glazes, crystal ware, fishing sinkers, lubricating greases, pigments, and solders. Because data on the end uses of bismuth covered only the last decade, the figure below is constructed using extrapolation.

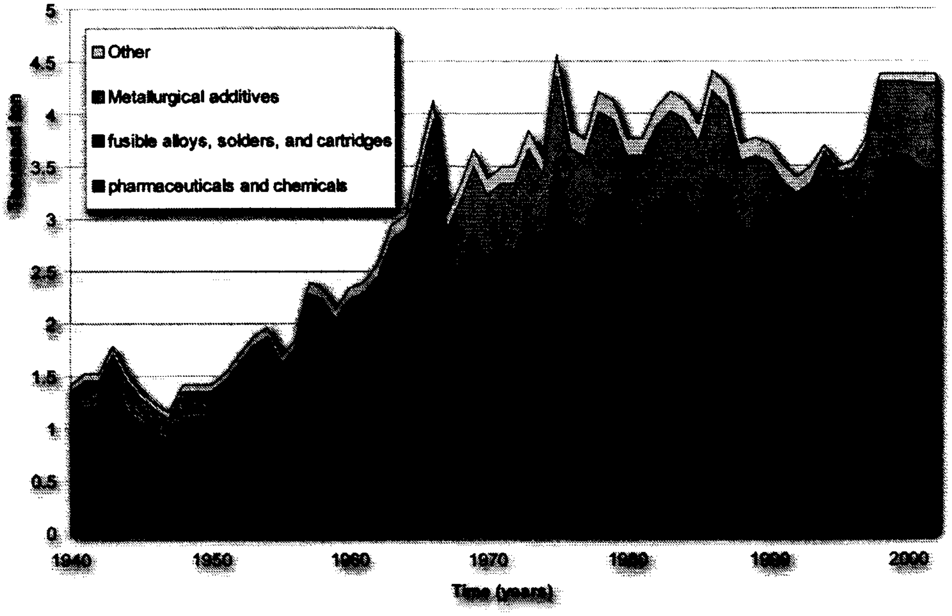

Figure 2: Bismuth production and estimated end uses from 1940-2000 (USGS 2003, Roskill 1993).

A.2.2 Production

Bismuth is mostly recovered as by-product from lead and copper production, viz. the copper and lead anode slimes (18%) and the Kroll Betterton dross (61%) from lead production. Only in very rare occasions ores are rich enough in bismuth to treat them separately. The world's only significant potential source where bismuth could be the principal product is the Tasna Mine in Bolivia, which was closed in 1985 and is now for sale (Doorn 2000). Bismuth is also obtained from other bismuth rich concentrates. These concentrates exhibit great variety and there is no standard procedure for treating them, however, a distinction can be made between special refinery (16%) and other (5%) operations.

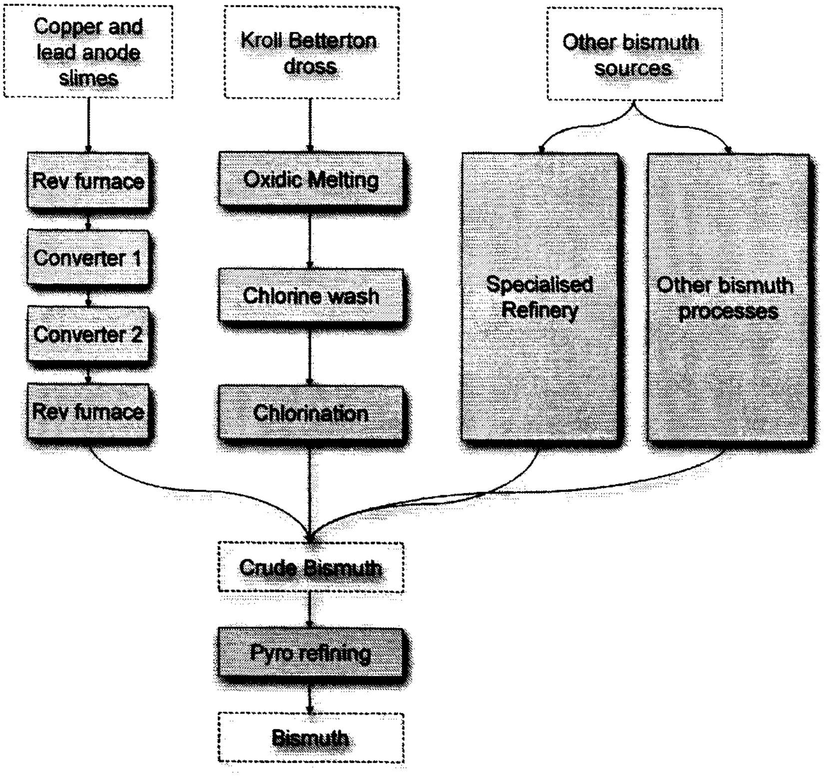

Figure 3: Simplified bismuth production flowchart.

Bismuth is separated from lead during the Kroll-Betterton process as the *Kroll-Betterton dross*. The dross is mixed with tar oil to oxidize the magnesium and calcium present, while some of the lead is melted and separated (oxidic melting). In subsequent chlorine wash and chlorination steps, the remaining solid dross is melted and chlorinated. This converts the residual lead to lead-chloride leaving crude bismuth as product.

Anode slimes from lead and copper refining can contain significant amounts of bismuth (see BA.5 and BA.3 respectively). The anode slimes from both processes are treated in a similar way. First, the anode slimes are melted in a reverberatory furnace to partially evaporate the antimony present. Then the metal is air oxidized in a converter in two stages. The resulting product is treated in a second reverberatory furnace to obtain crude bismuth. Refining of bismuth is almost identical to lead refining. Refining is done in five steps:

(i) de-copperization by liquation and sulfuring,
(ii) tellurium, arsenic and antimony removal with the Harris process,
(iii) removal of precious metals by zinc addition,

(iv) lead and zinc removal by chlorination, and

(v) the final oxidation with air in the presence of sodium hydroxide (NaOH).

Only a small amount of bismuth is obtained by recycling old scrap. In the recycling of old scrap bismuth is recovered as in the Ferro and non-Ferro fractions. Bismuth in Ferro fractions typically remains in the steel cycle. Part of the bismuth from the non-Ferro fractions returns to bismuth production through the copper and lead anode slimes, and the Kroll Betterton dross.

A.2.3 Reconciled mass balances

	Anode slimes processing											
	Oxidic melting				Chlorine washing				Chlorination			
	Input		Output		Input	Output			Input	Output		
	Copper anode slimes	Lead anode slimes	Deleaded	Lead	Deleaded	PbBi	PbCl2	CaMg	PbBi	CrBi	PbCl2	Cl
Total	2882	2437	38.7%	61.3%	2061	89.7%	10.3%	0.0%	1847	25.4%	32.6%	42.0%
Cu	61	48	99.8%	0.2%	109	99.8%	0.0%	0.2%	109	100.0%	0.0%	0.0%
Pb	437	380	33.1%	66.9%	270	90.3%	9.7%	0.0%	244	0.2%	0.0%	99.8%
Sn	0	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Bi	965	840	98.0%	2.0%	1768	100.0%	0.0%	0.0%	1768	100.0%	0.0%	0.0%
Zn	0	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Ag	531	462	80.0%	20.0%	794	100.0%	0.0%	0.0%	794	100.0%	0.0%	0.0%
Sb	794	691	0.6%	99.4%	9	99.8%	0.2%	0.0%	9	99.0%	0.1%	0.9%
As	91	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Ni	0	13	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Au	0	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Pd	0	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Cd	0	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Fe	3	3	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
S	0	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%

KWh/t refined Bi	2220
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

	Kroll Bretterton crust processing														
	Reverberatory furnace 1			Converter 1				Converter 2				Reverberatory furnace 2			
	Input	Output		Input	Output			Input	Output			Input	Output		
	Kroll Bretterton crust	Slag	Flue dust	Slag	Metal	Flue dust	Slag	Metal	Bismuth slag	AgBiPb	Flue dust	Bismuth slag	Crude bismuth	Copper matte	slag
Total	5319	88.5%	11.5%	4706	68.5%	2.9%	28.6%	3222	61.5%	32.5%	6.0%	1983	42.1%	14.5%	43.3%
Cu	110	96.6%	3.4%	106	82.9%	4.2%	12.9%	88	100.0%	0.0%	0.0%	88	31.6%	68.4%	0.0%
Pb	817	79.2%	20.8%	648	57.9%	4.0%	38.2%	375	68.3%	23.5%	8.1%	256	24.3%	9.8%	66.0%
Sn	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Bi	1805	96.2%	3.8%	1736	85.5%	1.8%	12.6%	1485	62.7%	30.1%	7.2%	931	89.5%	1.1%	9.4%
Zn	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Ag	992	93.7%	6.3%	930	81.4%	1.7%	16.9%	757	5.5%	91.6%	2.8%	42	84.3%	8.9%	6.8%
Sb	1485	76.4%	23.6%	1134	12.6%	4.3%	83.1%	143	40.7%	0.0%	59.3%	58	0.3%	29.4%	70.3%
As	91	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Ni	13	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Au	0	5.8%	94.2%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Pd	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Cd	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Fe	7	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
S	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%

KWh/t refined Bi	4530
Electricity	0%
Oil/Gas	70%
Coal	0%
Air	30%

KWh/t refined Bi	386
Electricity	72%
Oil/Gas	0%
Coal	28%
Air	0%

KWh/t refined Bi	386
Electricity	72%
Oil/Gas	0%
Coal	28%
Air	0%

KWh/t refined Bi	4530
Electricity	0%
Oil/Gas	70%
Coal	0%
Air	30%

	Pyrorefining					
	Input	Output				
	Crude bismuth	Bismuth	Zinc residue	Ag residue	Pb residue	Cu residue
Total	4023	82.2%	3.7%	8.4%	3.2%	2.4%
Cu	28	0.0%	0.1%	0.3%	0.1%	99.5%
Pb	78	0.0%	0.1%	0.1%	20.9%	78.9%
Sn	0	0.0%	0.0%	0.0%	0.0%	100.0%
Bi	4406	96.8%	0.0%	2.9%	0.0%	0.3%
Zn	0	0.0%	52.2%	38.3%	9.5%	0.0%
Ag	35	0.0%	0.0%	91.6%	0.0%	8.4%
Sb	75	4.2%	18.7%	42.8%	16.2%	18.1%
As	0	0.0%	0.0%	0.0%	0.0%	100.0%
Ni	0	0.0%	0.0%	0.0%	0.0%	100.0%
Au	0	0.0%	0.0%	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	0.0%	100.0%
Fe	0	0.0%	0.0%	0.0%	0.0%	100.0%
S	0	0.0%	0.0%	0.0%	0.0%	100.0%

KWh/t refined Bi	694
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

	Other and special refinery			
	Input	Output		
	Bismuth concentrates	Bismuth	Slag	Flue dust
Total	10627	82.2%	3.7%	8.4%
Cu	28	0.0%	0.1%	0.3%
Pb	8365	0.0%	0.1%	0.1%
Sn	0	0.0%	0.0%	0.0%
Bi	1425	96.8%	0.0%	2.9%
Zn	4	0.0%	52.2%	38.3%
Ag	303	0.0%	0.0%	91.6%
Sb	475	4.2%	18.7%	42.8%
As	22	0.0%	0.0%	0.0%
Ni	5	0.0%	0.0%	0.0%
Au	0	0.0%	0.0%	0.0%
Pd	0	0.0%	0.0%	0.0%
Cd	0	0.0%	0.0%	0.0%
Fe	2	0.0%	0.0%	0.0%
S	0	0.0%	0.0%	0.0%

KWh/t refined Bi	694
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

A.3 Copper production and recycling profile

A.3.1 End uses

In 2000, about 14.9 million t tons of copper were produced globally (USGS 2003). Copper is an essential metal for electronic appliances, because of its excellent electrical conductivity. Electrical uses of copper, including power transmission and generation, building wiring, telecommunication, and electrical and electronic products, account for about three quarters of total copper use. Building construction is the single largest market, followed by electronics and electronic products, transportation, industrial machinery, and consumer and general products.

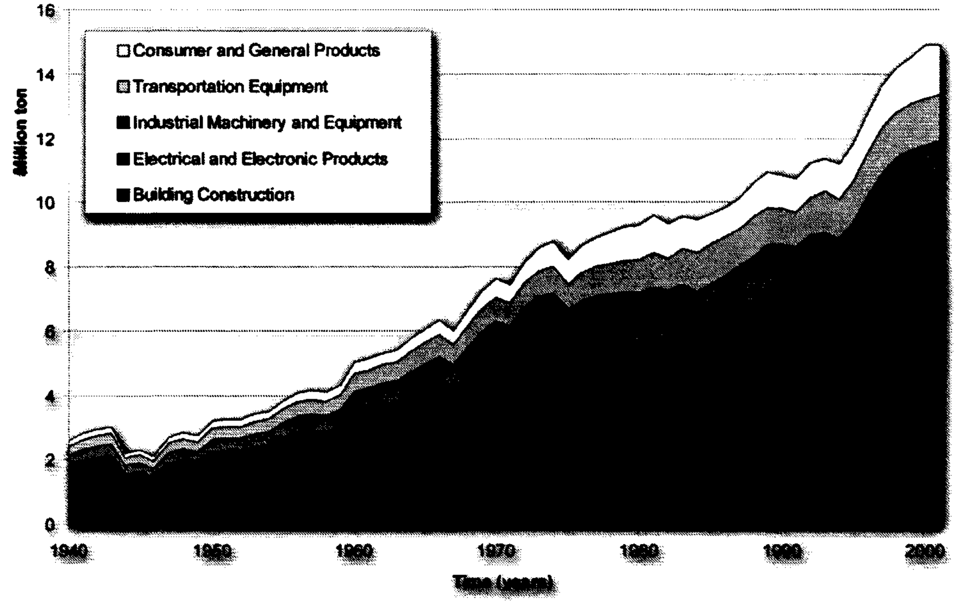

Figure 4: Copper production and estimated end uses from 1940-2000 (USGS 2003, WBMS 2000, NATO 1976, CDA 2002).

A.3.2 Production

Copper is produced from sulfuric and oxidic ores that are obtained from lead, zinc, nickel and copper mining. A copper ore has often a low copper content, 0.8 - 4%, and is crushed, ground and concentrated by flotation to 25 -35% Cu (Ullmann 1996, Bruch et al. 1995, Biswas and Davenport 1994[1]). The resulting tailings have a very low copper

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[1] 20-30%

content (ca. 0.05% Cu), and are discarded. Dependent on ore composition, copper is produced from the ore concentrates through different routes.

About 80% (Ullman 1999) of the primary copper originates from low-grade sulfide ores (containing ca. 0.5-2% Cu, Biswas and Davenport 1994). These are usually converted into copper in two main steps: (i) the concentrate is smelted to a matte, and then converted to crude (blister or converter) copper, and (ii) the crude copper is pyrometallurgical refined to fire-refined copper and subsequently electrolytically to high purity copper. Prior to smelting the copper concentrate to "matte" in the pyrometallurgical route, roasting may be necessary to decrease the sulfur content to an optimum level for smelting. In many modern processes, the roasting step is combined with matte smelting. In matte smelting the concentrate, or roasting product, is converted into a copper matte that consists of approximately 55% copper, 20% sulfur, 15% iron and some minor elements.

Globally, six different processes are used for matte smelting, viz. reverberatory furnace smelting (27%), electric furnace smelting (8%), Outokumpu flash smelting (48%), Inco flash smelting (8%), Isa or Ausmelt (5%), and the Mitsubishi process 5% (USGS 2003).The *reverberatory furnace* is a classic, rectangular furnace with burners at one side of the furnace. In the furnace, two zones can be distinguished: the smelting and settling zones. The concentrate, flux and fuel (coal, heavy fuel oil or natural gas) are fed into the furnace at the smelting zone located at the burner side. After smelting, the reactor mixture flows to the opposite side of the furnaces, the settling zone, where matte and slag separate. The atmosphere in the furnace is slightly oxidizing, or neutral. The reverberatory furnace has the highest energy consumption of all copper matte-smelting operations. The reverberatory furnace is an old technique for copper smelting; new furnaces of this type will probably not be built. The *electric furnace* process is similar to the reverberatory furnace, but the feed is dried before charging and the furnace is heated by up to six carbon electrodes with alternating currents. As it uses significant amounts of electricity this furnace is usually used only when electricity is inexpensive. The use of electrodes allows higher temperatures, which has the advantage that magnetite can be easier slagged off compared to the reverberatory furnace. In addition, the volume of off gas is smaller and the heat loss is much smaller than in the reverberatory furnaces. The off gas is more easily cleaned.

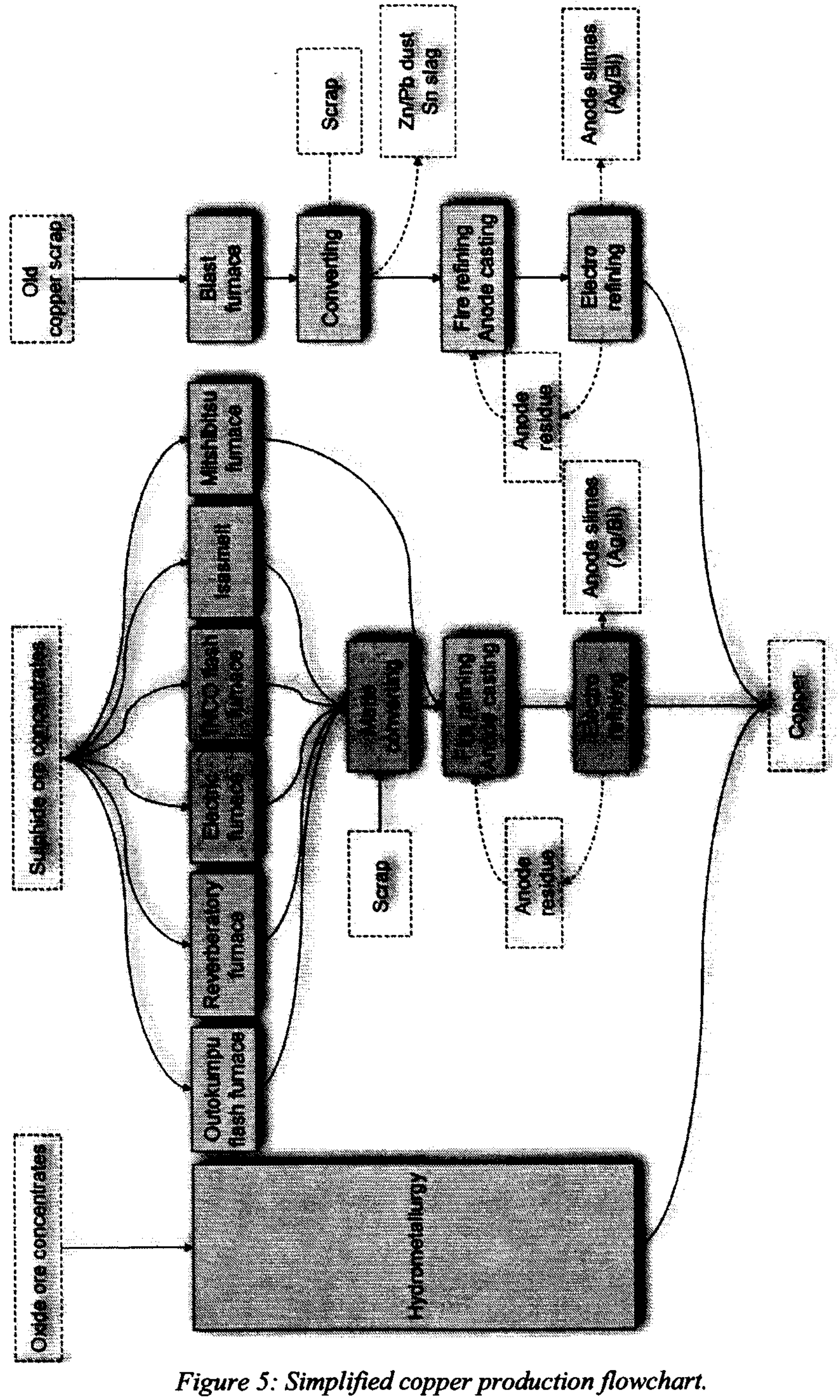

Figure 5: Simplified copper production flowchart.

The Inco Flash furnace, the Outokumpu flash furnace and the Isasmelt are modern autogenous smelters that use the heat generated by the oxidation of iron sulfides for the smelting process. Not only does this save energy input, it also reduces the offgas volumes, moreover the rate of reaction in autogenous smelters is higher which increases production rate. A typical disadvantage is higher copper content in the slag. The *Outokumpu flash furnace* consists of three distinct sections: (i) a circular reaction shaft for roasting and smelting of the dried concentrate, (ii) a settling hearth for the collection of the molten droplets, and separation of the matte from the slag and (iii) a rectangular uptake shaft for off gas. In the Outokumpu flash furnace air or oxygen enriched air is used. The *Inco Flash smelting process* is very similar to the Outokumpu flash smelting, but is less common. The main difference between the two processes is the use of pure oxygen in the Inco Flash smelting process. The *Isasmelt furnace* is a tall cylindrical furnace. The feed is heated, and converted by blowing oxygen-enriched air through a lance submerged into the slag. Additional energy can be fed to the process by adding coal to the charge or blowing oil or gas through the lance.

The smelted matte from these processes must be further processed in a *convertor,* to produce a crude copper with 98-99% copper suitable for refining (e.g. Ullmann 1996, Biswas and Davenport 1994). In this process, the matte is blown with air in two stages. First, the iron is oxidized to iron oxide and dissolved the slag by adding silica. Second, the copper sulfide is converted to copper metal. Because these reactions are highly exothermic, copper scrap is added during the process as a coolant.

The last matte smelting process is the *Mitsubishi process.* The three-step continuous Mitsubishi process combines matte smelting and matte converting. Unlike the other smelting processes, the Mitsubishi process produces crude copper suitable for refining. In the first step, the concentrate is smelted together with fluxes and coal to produce matte, in the second step the matte is separated from the slag in an electric furnace by adding coke and some pyrite, and finally in the last stage the matte is converted into crude copper by oxidation of the obtained high-grade matte.

The crude copper metal is further refined through fire refining and electrolysis. The *fire refining* process has three purposes: (i) to remove impurities by dissolving in the slag and volatilization, (ii) to reduce the sulfur content by oxidation, and (iii) decrease the oxygen content by reduction. After fire refining the main impurities consists of precious metals, and the copper can be cast into anodes. Fire refining is a batch process using either a reverberatory furnace, or a rotary furnace. The copper concentrate obtained from fire refining is typically further refined by *electrolysis*. By running a current from the anode to the cathode, a 'clean' copper sheet, the copper dissolves and is deposited at the cathode. Base metals, mainly nickel, dissolve into the electrolyte and will be treated to remove the metals. Precious metals do not dissolve and report to the anode slimes; these are treated to remove the precious metals.

Approximately 15% of the primary copper originates from low-grade oxidized or mixed ores (Ullman 1999). Copper is generally produced from these ores through the *hydrometallurgical route.* The route consists of four steps. In the first step, the ore concentrate is pre-treated, either physically or chemically. In the second step, the concentrate is leached with sulfuric acid or ammoniacal solutions. Subsequently, this solution is cleaned by precipitation of impurities or by selective enrichment of copper by solvent extraction or ion exchange. In the fourth step, the cleaned solution is precipitated to copper metal.

The remaining primary copper comes from high-grade ores and is processed in shaft furnaces. Copper from secondary material, which often has a high copper content and low sulfur content, is usually recovered through this route. A blast or shaft furnace is fed with alternating layers of copper containing materials and coke. The blast furnace can be divided into three zones:

(i) the heating zone where the water is evaporated,
(ii) the reduction zone where reactions between gases and solids take place,
(iii) the smelting zone where the liquid phases react with each other.

The furnace produces black copper with approximately 75% copper, copper rich slag and if there are high concentrations of arsenic or antimony a third phase, speiss, can form. The black copper is converted to crude copper in a similar way to primary converting. Lead, tin and nickel report to the slag phase, zinc and some lead report to the flue dust.

Some 12.7 % of copper is obtained by recycling old scrap (USGS 2003). The bulk of the old copper scrap is recovered for its copper value. The Ferro fractions and old lead scrap resulting from the waste separation processes also contain small amounts of copper. Copper in Ferro fractions is typically removed from the steel cycle in the iron production slag. The copper from the old lead scrap fractions can be recovered. Low-grade old copper scrap is typically recovered in a blast furnace, an Ausmelt reactor, and high grade copper scrap can directly be processed in a converter, or even directly refined[2]. In addition, also old and new scrap is added to control the temperature in the ('primary') convertors. Tin is a valuable by-product of secondary copper production. The tin can be recovered in a silicate slag (at the copper convertors) which is sold to tin producers (up to 17-25% Sn, Moore 1978). Zinc and lead are recovered as the oxides in the blast furnace and convertors. The refining of the convertor scrap is similar to the 'primary' refining.

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[2] Some copper scrap (e.g wire, cable and copper tubing) can be separated in relatively pure copper, and needs only to be remelted and cast. For instance, copper wire is chopped into short pieces for easy disposal of insulation, and finally melted in a convertor (typically a reverberatory furnace) and cast. Brass and bronze scrap are generally remelted without refining as well, provided they can be sorted into composition categories

A.3.3 Reconciled mass balances

	Mining		
	Input	Output	
	Copper ore	Copper concentrate	Tailings
Total	931420000	3.8%	96.2%
Cu	11177000	90.2%	9.8%
Pb	5215900	30.3%	69.7%
Sn	0	0.0%	100.0%
Bi	0	0.0%	100.0%
Zn	5215900	30.3%	69.7%
Ag	0	0.0%	100.0%
Sb	0	0.0%	100.0%
As	0	0.0%	100.0%
Ni	18628000	1.9%	98 1%
Au	0	0.0%	100.0%
Pd	0	0.0%	100.0%
Cd	0	0.0%	100.0%
Fe	29805000	28.8%	71.2%
S	158340000	6 9%	93.1%

KWh/t refined Cu	8027
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

	Hydroprocessing		
	Input	Output	
	Copper concentrate	Copper	Residue
Total	6566300	26.8%	73.2%
Cu	1855600	95.0%	5.0%
Pb	52060	0.0%	100.0%
Sn	266	0.0%	100.0%
Bi	656630	0.0%	100.0%
Zn	289560	0.0%	100.0%
Ag	2627	0.0%	100.0%
Sb	9317	0.0%	100.0%
As	0	0 0%	100.0%
Ni	5927	0.0%	100.0%
Au	1	0.0%	100.0%
Pd	0	0.0%	100.0%
Cd	0	0.0%	100.0%
Fe	1788000	0.0%	100.0%
S	2004100	0.0%	100.0%

KWh/t refined Cu	860
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

	Primary smelting 1																
	Electric furnace						Outokumpu flash furnace					Inco flash furnace					
	Input	Output					Input	Output				Input	Output				
	Copper concentrate	Flux	Matte	Flue dust	Offgas	Slag	Copper concentrate	Matte	Flue dust	Offgas	Slag	Copper concentrate	Flux	Matte	Flue dust	Offgas	Slag
Total	2393000	3.7%	46.1%	14.9%	10.9%	31.7%	14657000	42.8%	6.1%	12.4%	38.8%	2093900	14.1%	46.4%	2.3%	9.5%	56.0%
Cu	673640	0.0%	89.4%	10.6%	0.0%	0.0%	4126100	82.8%	5.3%	0.0%	11.8%	589440	0.0%	89.9%	1.8%	0.0%	8.3%
Pb	14358	0.0%	39.8%	0.1%	0.0%	60.1%	102600	31.5%	62.0%	0.0%	6.5%	9004	0.0%	55.6%	42.1%	0.0%	2.3%
Sn	718	0.0%	1.6%	0.0%	0.0%	98.5%	0	42.8%	6.1%	0.0%	51.2%	0	0.0%	18.5%	0.0%	3.8%	77.7%
Bi	239	0.0%	16.1%	0.0%	0.0%	83.9%	1466	42.8%	6.1%	0.0%	51.2%	209	0.0%	34.4%	0.0%	8.4%	57.2%
Zn	105530	0.0%	13.6%	0.0%	0.0%	86.4%	646390	12.6%	10.7%	0.0%	76.7%	92342	0.0%	13.6%	11.4%	0.0%	75.0%
Ag	957	0.0%	100.0%	0.0%	0.0%	0.0%	5863	95.0%	5.0%	0.0%	0.0%	838	0.0%	100.0%	0.0%	0.0%	0.0%
Sb	239	0.0%	6.7%	0.0%	0.0%	93.3%	14657	42.8%	6.1%	0.0%	51.2%	2094	0.0%	50.0%	0.0%	8.5%	41.5%
As	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Ni	239	0.0%	7.7%	0.0%	0.0%	92.3%	1466	7.1%	0.0%	0.0%	92.9%	209	0.0%	7.7%	0.0%	0.0%	92.3%
Au	0	0.0%	100.0%	0.0%	0.0%	0.0%	0	98.0%	2.0%	0.0%	0.0%	0	0.0%	100.0%	0.0%	0.0%	0.0%
Pd	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Fe	606400	0.0%	30.3%	8.8%	0.0%	60.9%	4104100	25.4%	2.4%	0.0%	72.2%	607230	0.0%	26.6%	1.0%	0.0%	72.3%
S	734430	0.0%	32.7%	4.7%	32.0%	30.6%	4470500	30.5%	2.5%	40.7%	26.4%	638640	0.0%	33.1%	1.1%	27.5%	38.3%

KWh/t refined Cu	3290
Electricity	72%
Oil/Gas	0%
Coal	28%
Air	0%
CO	0.00.E+00
CO2	0.00.E+00
SO2	1.60.E+08
NOX	5.72.E+08

KWh/t refined Cu	1854
Electricity	0%
Oil/Gas	65%
Coal	0%
Air	35%
CO	0.00.E+00
CO2	0.00.E+00
SO2	6.20.E+08
NOX	2.89.E+09

KWh/t refined Cu	640
Electricity	0%
Oil/Gas	74%
Coal	0%
Air	35%
CO	0.00.E+00
CO2	0.00.E+00
SO2	1.20.E+08
NOX	4.94.E+08

	Primary smelting 2										
	Isasmelt						Reverberatory furnace				
	Input	Output					Input	Output			
	Copper concentrate	Flux	Matte	Flue dust	Offgas	Slag	Copper concentrate	Matte	Flue dust	Offgas	Slag
Total	119650	4.1%	46.1%	8.8%	20.6%	28.6%	7777400	46.1%	13.3%	12.0%	28.6%
Cu	328090	0.0%	91.7%	7.0%	0.0%	1.3%	2213400	88.4%	11.1%	0.0%	0.5%
Pb	26922	0.0%	10.6%	89.4%	0.0%	0.0%	18666	98.5%	0.1%	0.0%	1.4%
Sn	0	0.0%	58.1%	11.0%	0.0%	30.8%	0	46.1%	25.3%	0.0%	28.6%
Bi	120	0.0%	58.1%	11.0%	0.0%	30.8%	778	46.1%	13.3%	0.0%	40.6%
Zn	52767	0.0%	13.6%	15.5%	0.0%	71.0%	342980	13.6%	0.0%	0.0%	86.4%
Ag	47861	0.0%	99.0%	1.0%	0.0%	0.0%	3111	100.0%	0.0%	0.0%	0.0%
Sb	14239	0.0%	0.0%	0.0%	0.0%	100.0%	7777	13.9%	3.6%	0.0%	82.4%
As	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%
Ni	120	0.0%	7.7%	0.0%	0.0%	92.3%	778	7.7%	0.0%	0.0%	92.3%
Au	0	0.0%	100.0%	0.0%	0.0%	0.0%	0	100.0%	0.0%	0.0%	0.0%
Pd	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%
Fe	279510	0.0%	32.9%	6.1%	0.0%	61.1%	1870500	31.9%	12.8%	0.0%	55.3%
S	364940	0.0%	32.9%	3.1%	63.9%	0.0%	2379100	32.8%	4.2%	35.4%	27.6%

KWh/t refined Cu	0
Electricity	0%
Oil/Gas	65%
Coal	0%
Air	35%
CO	0.00.E+00
CO2	0.00.E+00
SO2	1.59.E+08
NOX	4.80.E+08

KWh/t refined Cu	4527
Electricity	11%
Oil/Gas	6%
Coal	83%
Air	0%
CO	0.00.E+00
CO2	0.00.E+00
SO2	5.73.E+08
NOX	1.93.E+09

	Primary converting														
	Mitsibishu process							Matte smelting							
	Input	Output						Input		Output					
	Copper concentrate	Flux	Blister copper	Flue dust	Offgas	Converter slag	Smeltin slag	g Matte	Copper scrap	Flux	Blister copper	Flue dust	Offgas	Slag
Total	1794800	11.9%	28.2%	4.2%	29.4%	10.1%	39.9%	12482000	3769900	12.7%	62.5%	0.4%	24.4%	25.3%
Cu	538080	0.0%	92.6%	1.8%	0.0%	4.8%	0.8%	6807400	3769600	0.0%	96.8%	0.1%	0.0%	3.1%
Pb	22614	0.0%	9.0%	80.2%	0.0%	0.0%	10.9%	64278	4	0.0%	52.9%	20.8%	0.0%	26.3%
Sn	179	0.0%	28.2%	29.7%	0.0%	10.1%	32.0%	11	2	0.0%	62.5%	24.4%	0.0%	13.0%
Bi	179	0.0%	49.1%	29.8%	0.0%	10.1%	11.0%	1166	3	0.0%	99.0%	1.0%	0.0%	0.0%
Zn	79096	0.0%	9.0%	80.2%	0.0%	0.0%	10.9%	161920	1	0.0%	52.9%	20.8%	0.0%	26.3%
Ag	718	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	11243	26	0.0%	100.0%	0.0%	0.0%	0.0%
Sb	179	0.0%	61.0%	13.4%	0.0%	7.7%	18.0%	8420	4	0.0%	99.0%	1.0%	0.0%	0.0%
As	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0	3	0.0%	99.0%	1.0%	0.0%	0.0%
Ni	17948	0.0%	16.9%	0.0%	0.0%	0.0%	83.1%	208	4	0.0%	100.0%	0.0%	0.0%	0.0%
Au	2	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0	0	0.0%	59.0%	0.0%	0.0%	41.0%
Pd	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0	0	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0	0	0.0%	0.0%	0.0%	0.0%	100.0%
Fe	430390	0.0%	0.0%	2.2%	0.0%	19.4%	78.4%	2078600	5	0.0%	0.0%	0.4%	0.0%	99.6%
S	547410	0.0%	0.2%	1.6%	90.4%	0.4%	7.4%	2718000	24	0.0%	1.0%	0.3%	90.8%	8.0%

KWh/t refined Cu	2566
Electricity	11%
Oil/Gas	6%
Coal	83%
Air	0%
CO	0.00.E+00
CO2	0.00.E+00
SO2	3.37.E+08
NOX	8.76.E+08

KWh/t refined Cu	385
Electricity	0%
Oil/Gas	70%
Coal	0%
Air	30%
CO	0.00.E+00
CO2	0.00.E+00
SO2	1.68.E+09
NOX	5.02.E+09

	Refining										
	Anode Furnace				Electrolysis						
	Input		Output		Input	Output					
	Blister copper	Anode reste	Copper anode	Flue dust	Copper anode	Anode rest	Copper	Anode slimes	Elektrolyte	Residue
Total	10666000	1363700	91.1%	8.9%	10957747	12.4%	86.6%	0.9%	0.0%	0.0%
Cu	10734000	1383500	91.7%	8.3%	11106904	12.5%	87.5%	0.0%	0.0%	0.0%
Pb	36007	1038	22.5%	77.5%	8342	12.4%	0.3%	87.3%	0.0%	0.0%
Sn	59	8	100.0%	0.0%	67	12.4%	1.7%	0.0%	0.0%	85.8%
Bi	1245	116	68.3%	31.7%	930	12.4%	0.5%	86.2%	0.0%	0.9%
Zn	92678	0	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Ag	11986	1343	100.0%	0.0%	13329	10.1%	0.4%	88.7%	0.0%	0.9%
Sb	8369	903	78.2%	21.8%	7253	12.4%	0.2%	86.5%	0.0%	0.9%
As	3	0	99.8%	0.2%	3	12.4%	0.1%	0.0%	0.0%	87.5%
Ni	3269	61	100.0%	0.0%	3330	1.8%	6.7%	1.2%	90.2%	0.0%
Au	2	4	100.0%	0.0%	6	65.5%	1.0%	0.0%	0.0%	33.6%
Pd	0	0	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	0	0	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Fe	148	21	100.0%	0.0%	169	12.4%	1.4%	86.2%	0.0%	0.0%
S	27244	171	5.0%	95.0%	1371	12.4%	4.7%	82.9%	0.0%	0.0%

KWh/t refined Cu	303
Electricity	0%
Oil/Gas	100%
Coal	0%
Air	0%

KWh/t refined Cu	847
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

	Secondary processing												
	Blast Furnace						Converter						
	Input	Output					Input		Output				
	Copper scrap	Flux	Black copper	Offgas	Oxides	Slag	Black copper	Copper scrap	Rough copper	Flue dust	Offgas	Tin recovery	Slag
Total	4474900	11.5%	55.3%	1.0%	5.8%	49.4%	2472968	1256200	63.8%	6.9%	0.4%	0.0%	28.0%
Cu	1297300	0.0%	99.9%	0.0%	0.1%	0.0%	1295993	671350	80.1%	1.0%	0.0%	0.0%	18.9%
Pb	358720	0.0%	72.0%	0.0%	25.1%	2.9%	258265	309	6.8%	35.5%	0.0%	0.0%	57.7%
Sn	19455	0.0%	94.1%	0.0%	3.2%	2.8%	18299	17	1.7%	10.9%	0.0%	87.4%	0.0%
Bi	488	0.0%	41.1%	0.0%	0.0%	58.9%	201	0	43.1%	0.0%	0.0%	0.0%	56.9%
Zn	1003000	0.0%	40.0%	0.0%	20.1%	40.0%	400893	2173	0.2%	99.8%	0.0%	0.0%	0.0%
Ag	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0	0.0%	0.0%	0.0%	0.0%	100.0%
Sb	11365	0.0%	0.0%	0.0%	4.8%	95.2%	0	0	0.0%	0.0%	0.0%	0.0%	100.0%
As	339	0.0%	0.0%	0.0%	1.6%	98.4%	0	0	0.0%	0.0%	0.0%	0.0%	100.0%
Ni	109070	0.0%	100.0%	0.0%	0.0%	0.0%	109070	227	12.8%	4.5%	0.0%	0.0%	82.7%
Au	34	0.0%	0.0%	0.0%	0.0%	100.0%	0	10	0.0%	0.0%	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	4075	0.0%	0.0%	0.0%	0.0%	100.0%	0	1144	0.0%	0.0%	0.0%	0.0%	100.0%
Fe	13252	0.0%	0.0%	0.0%	0.0%	100.0%	0	3720	0.0%	0.0%	0.0%	0.0%	100.0%
S	619000	0.0%	29.0%	62.9%	6.9%	1.2%	179262	1215	1.3%	22.5%	76.3%	0.0%	0.0%

KWh/t refined Cu	1518
Electricity	1%
Oil/Gas	0%
Coal	97%
Air	2%
CO	1.56.E+08
CO2	2.70.E+08
SO2	2.66.E+08
NOX	1.86.E+09

KWh/t refined Cu	866
Electricity	0%
Oil/Gas	70%
Coal	0%
Air	30%
CO	7.12.E+07
CO2	1.21.E+08
SO2	9.32.E+07
NOX	7.78.E+08

A.4 Gold production and recycling profile

A.4.1 End uses

In 2000, about 3660 tons of gold were produced globally (USGS 2003). Gold is a valuable, yellow-colored scarce metal that has been the inspiration for innumerable conquests, wars, and provided impetus for the discovery and exploration of the Western Hemisphere. The voyages of Columbus, Magellan, and other explorers were motivated at least in part by the expectation of finding gold. Spanish conquistadors plundered the sixteenth century Latin American empires, and later other European settlers began to tap the resources in the northern part of the continent. Since the gold decorated the Egyptian life and afterlife, coins, jewelry, and ornaments have always been the most important applications of gold.

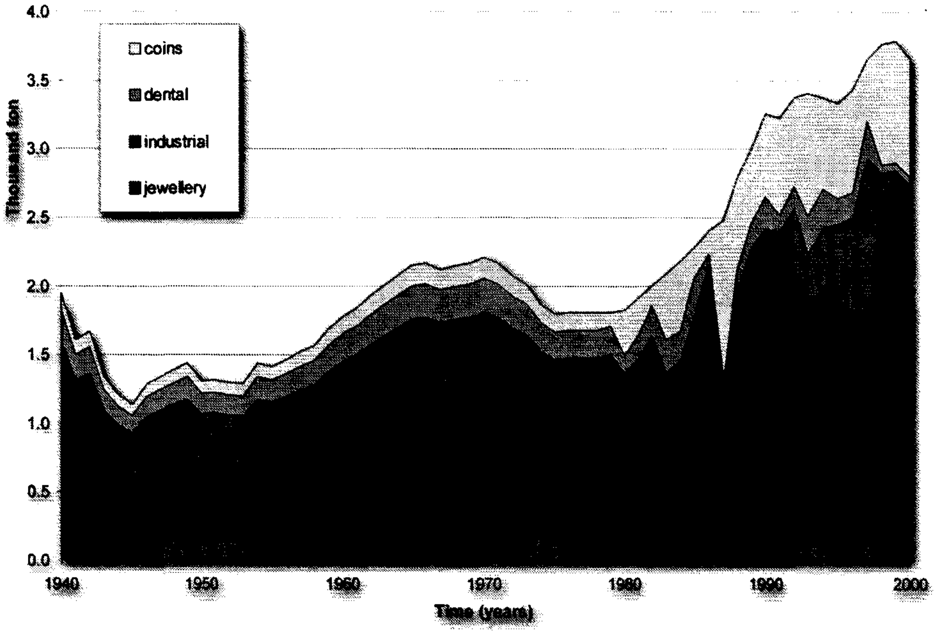

Figure 6: Gold production and estimated end uses from 1940-2000 (USGS 2003).

Still today, they consume most of the gold. In addition to aesthetic characteristics, gold is increasingly valued for its other characteristics, such as malleability, high electrical conductivity, and resistance to oxidation and most chemical agents. Other important end uses for gold are industrial and dental applications. In the 90s about a quarter of the gold was used for industrial applications on average, and less than 10% for dental applications. Because of the use of gold for durable goods such as jewelry and coins, gold can be expected to have an average long residence time in the consumption phase.

A.4.2 Production

The bulk of the gold is obtained from gold ores (76%). A small amount of gold is produced through silver production; this gold originates from copper, lead, silver and nickel ores. Gold concentration processes usually consist of gravity concentration, flotation, cyanidation, or a combination of these processes.

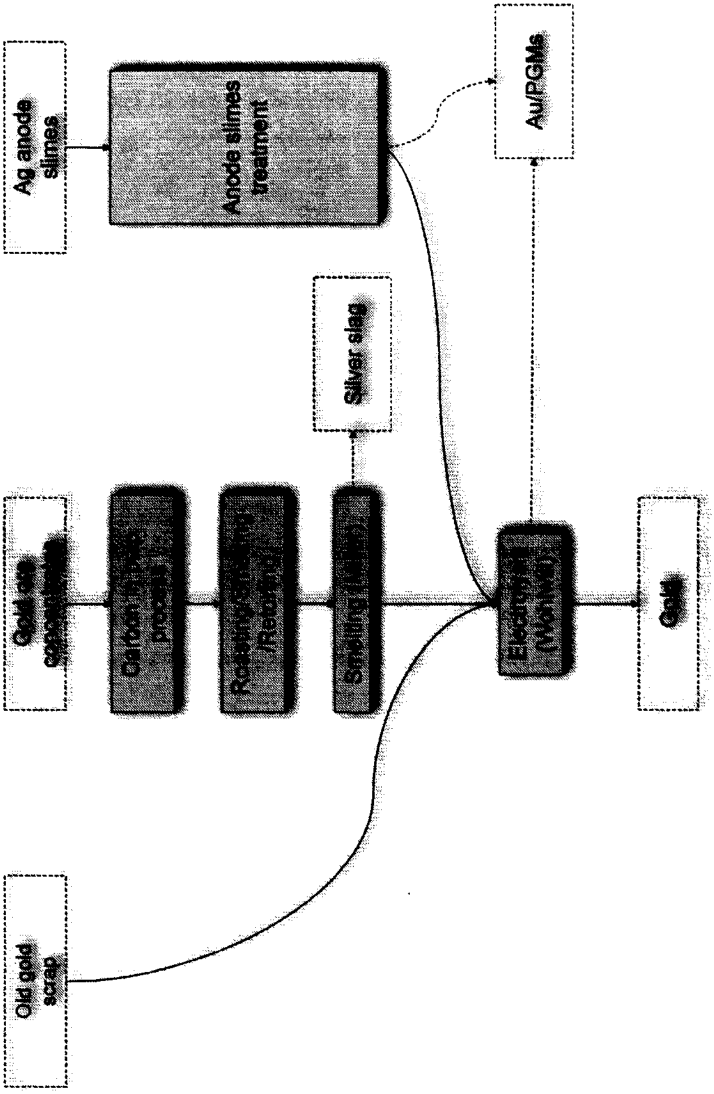

Figure 7: Simplified gold production flowchart.

Gold ores are mainly treated with the carbon-in-pulp process (Marsden and House 1992). In this process, the gold in ore is dissolved by leaching with cyanide, and subsequently selectively absorbed by active carbon. In the next step, the gold is separated from the carbon, by a second cyanide leach but at a lower pH. Gold is recovered from the leach solution by either electrowinning or precipitation with zinc. The resulting gold concentrate is treated with roasting, smelting or retorting to remove residual impurities, and a suitable feedstock, gold bullion, for the refining process is obtained.

The gold bullion is refined in the Miller process to a grade of 99.5%. The process is based on the low reactivity of gold with chloride at 1100°C: gold chlorides do not form, while silver and base metals react with chlorine to form stable chlorides. As a consequence, copper and silver are liquid at 1100°C and can be collected in the added borax slag; other base metals vaporize and report to the off gas. The borax slag is treated to recover the silver.

In the Wohlwill electrolysis process gold is further refined to a quality of 99.99%. Palladium and platinum are recovered from the electrolyte, a hydrochloric acid/tetrachloroauric acid. Other platinum group metals and silver accumulate in the anode slime. These are further treated to obtain the precious metals.

A significant amount of gold is produced from old gold scrap (24%, USGS 2003). Gold's main applications, such as jewelry, require it to be in an almost pure state. Recycling of gold, therefore, usually only involves remelting, or sometimes an additional refining step. Gold from electronics is recovered with the non-Ferro fractions from WEEE and ELVs, and is returned to gold circuit via copper recycling.

A.4.3 Reconciled mass balances

	Mining										
	Gravity concentration			Sulphide concentration			Carbon in leach process				
	Input	Output		Input	Output		Input			Output	
	Gold ore	Gravity conventrate	Tailings	Gold ore	Sulfide concentrate	Tailings	Gold ore	Gravity conventrate	Sulfide concentrate	Concentrate	Tailings
Total	3738700	14.4%	85.6%	5551800	8.0%	92.0%	49954042	540034	443923	0.0%	100.0%
Cu	0	0.0%	100.0%	0	0.0%	100.0%	0	0	0	0.0%	100.0%
Pb	0	0.0%	100.0%	0	0.0%	100.0%	0	0	0	0.0%	100.0%
Sn	0	0.0%	100.0%	0	0.0%	100.0%	0	0	0	0.0%	100.0%
Bi	0	0.0%	100.0%	0	0.0%	100.0%	0	0	0	0.0%	100.0%
Zn	0	0.0%	100.0%	0	0.0%	100.0%	0	0	0	0.0%	100.0%
Ag	0	0.0%	100.0%	0	0.0%	100.0%	0	0	0	0.0%	100.0%
Sb	0	0.0%	100.0%	0	0.0%	100.0%	0	0	0	0.0%	100.0%
As	0	0.0%	100.0%	1887600	84.7%	15.3%	0	0	1598114	0.0%	100.0%
Ni	0	0.0%	100.0%	0	0.0%	100.0%	0	0	0	0.0%	100.0%
Au	243	100.0%	0.0%	247	93.7%	6.3%	1678	243	231	94.0%	6.0%
Pd	0	0.0%	100.0%	0	0.0%	100.0%	0	0	0	0.0%	100.0%
Cd	0	0.0%	100.0%	0	0.0%	100.0%	0	0	0	0.0%	100.0%
Fe	0	0.0%	100.0%	0	0.0%	100.0%	0	0	0	0.0%	100.0%
S	0	0.0%	100.0%	9818000	100.0%	0.0%	0	0	9814780	0.0%	100.0%

KWh/t refined Au	860
Electricity	50%
Oil/Gas	0%
Coal	0%
Air	50%

KWh/t refined Au	860
Electricity	50%
Oil/Gas	0%
Coal	0%
Air	50%

KWh/t refined Au	860
Electricity	50%
Oil/Gas	0%
Coal	0%
Air	50%

	Smelting						Miller process			
	Input	Output					Input	Output		
	Concentrate	Flux	Gold bullion	Offgas	Flue dust	Slag	Gold bullion	Gold (99.9%)	Offgas	Slag
Total	4532	30.0%	56.4%	4.4%	6.9%	62.3%	2555	84.6%	0.0%	15.4%
Cu	517	0.0%	83.7%	0.0%	3.2%	13.1%	433	0.0%	0.0%	100.0%
Pb	181	0.0%	77.9%	0.0%	22.1%	0.0%	141	0.0%	4.6%	95.4%
Sn	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Bi	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Zn	382	0.0%	0.1%	0.0%	9.3%	90.6%	0	0.0%	0.0%	100.0%
Ag	2266	0.0%	92.6%	0.0%	7.4%	0.0%	2097	0.0%	0.0%	100.0%
Sb	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
As	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Ni	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Au	2027	0.0%	99.5%	0.0%	0.2%	0.3%	2018	100.0%	0.0%	0.0%
Pd	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Fe	54	0.0%	1.3%	0.0%	15.6%	83.1%	1	0.0%	31.2%	68.8%
S	199	0.0%	0.0%	87.5%	11.2%	1.2%	0	0.0%	0.0%	100.0%

KWh/t refined Au	860
Electricity	50%
Oil/Gas	0%
Coal	0%
Air	50%
CO	0.00.E+00
CO2	0.00.E+00
SO2	1.19.E+05
NOX	1.10.E+06

KWh/t refined Au	860
Electricity	50%
Oil/Gas	0%
Coal	0%
Air	50%

	Wohlwill refining		
	Input	Output	
	Gold (99.9%)	Gold (99.99%)	PGM concentrate
Total	3094	99.7%	0.3%
Cu	0	0.0%	100.0%
Pb	0	0.0%	100.0%
Sn	0	0.0%	100.0%
Bi	0	0.0%	100.0%
Zn	0	0.0%	100.0%
Ag	0	0.0%	100.0%
Sb	0	0.0%	100.0%
As	0	0.0%	100.0%
Ni	0	0.0%	100.0%
Au	3068	100.0%	100.0%
Pd	0	0.0%	100.0%
Cd	0	0.0%	100.0%
Fe	0	0.0%	100.0%
S	0	0.0%	100.0%

KWh/t refined Au	860
Electricity	50%
Oil/Gas	0%
Coal	0%
Air	50%

	Silver anode slimes						
	Anode slimes cleaning			Elektrolysis			
	Input	Output		Input	Output		
	Silver anode slimes	Cleaned anode slimes	Residue	Cleaned anode slimes	Gold (99.9%)	Elektrolyte	Anode slimes
Total	559	36.6%	63.4%	204	60.3%	25.2%	14.5%
Cu	0	0.0%	0.0%	0	0.0%	0.0%	100.0%
Pb	16	100.0%	100.0%	16	0.0%	100.0%	0.0%
Sn	0	0.0%	0.0%	0	0.0%	0.0%	100.0%
Bi	0	0.0%	0.0%	0	0.0%	0.0%	100.0%
Zn	0	0.0%	0.0%	0	0.0%	0.0%	100.0%
Ag	275	0.0%	0.0%	0	0.0%	0.0%	100.0%
Sb	0	0.0%	0.0%	0	0.0%	0.0%	100.0%
As	0	0.0%	0.0%	0	0.0%	0.0%	100.0%
Ni	0	0.0%	0.0%	0	0.0%	0.0%	100.0%
Au	268	100.0%	100.0%	268	90.0%	0.0%	10.0%
Pd	0	0.0%	0.0%	0	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0	0.0%	0.0%	100.0%
Fe	0	0.0%	0.0%	0	0.0%	0.0%	100.0%
S	0	0.0%	0.0%	0	0.0%	0.0%	100.0%

KWh/t refined Au	860
Electricity	50%
Oil/Gas	0%
Coal	0%
Air	50%

KWh/t refined Au	860
Electricity	50%
Oil/Gas	0%
Coal	0%
Air	50%

A.5 Lead production and recycling profile

A.5.1 End uses

In 2000, about 6.65 million tons of lead was produced globally (USGS 2003). Lead has been used for centuries to make water pipes and to cover roofs. It is very easy to cast, and is extremely corrosion resistant. Lead pipes dating from Roman times are still in use (NATO 1976). In addition, lead is a good sound and radiation absorber and is attractive in its appearance. In past century, other uses for lead have been developed. Today, lead is used in a large number of applications as metallic lead in batteries and accumulators, lead shots, boat keels, building materials but also in products such as paint, leaded petrol, glass, electronic and electric equipment, plastic, ceramic products. Applications are being developed for lead and lead compounds in a number of new areas: microelectronics, superconductors, earthquake damping materials and radon gas shielding, and for retrievable storage or permanent disposal of nuclear waste, to name a few (OSPAR 2002). Major new applications are also being developed for traditional uses, notably lead-acid batteries, which are increasingly being used for emergency power applications, for powering electric and hybrid-electric vehicles and for energy storage in remote areas without access to electricity mains.

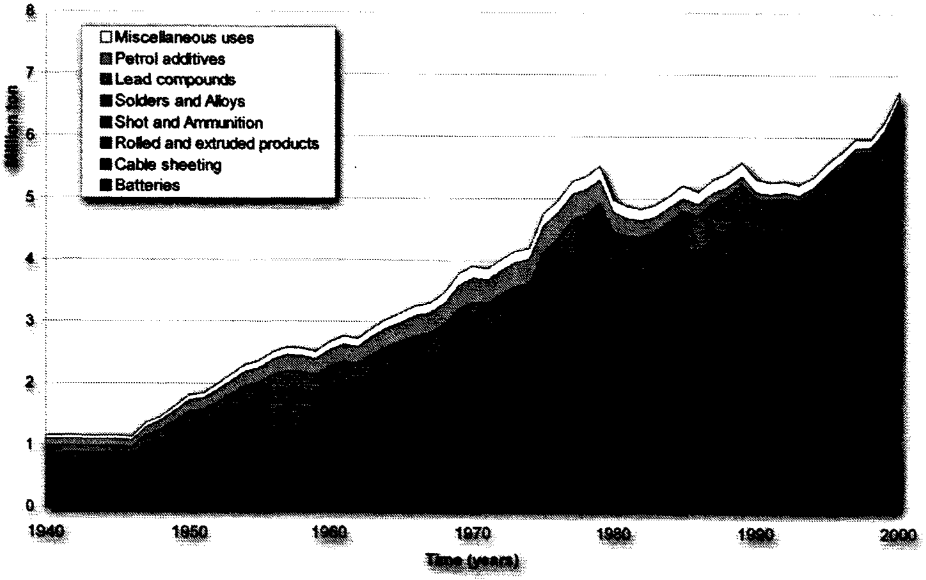

Figure 8: Lead production and estimated end uses from 1940-2000 (USGS 2003, WBMS 2000).

A.5.2 Production

Lead (typically 6%) is often found together with zinc (typically 9%), and copper (typically 0.5 %) (other valuable elements associated with (zinc-)lead ores are silver, cadmium and bismuth). Some 20% of the lead is obtained form lead mines (Ullmann 1996). The zinc, lead and copper concentrates are separated at the mines, but considerable amounts of zinc can remain in the lead concentrate.

This zinc is recovered from the lead smelting slags in zinc processes, or directly in the ISF process. After ore beneficiation, the lead concentrates typically contain 50-60% lead (Ullmann 1996). Lead production can be divided into two steps: (i) production of crude lead, the lead bullion, and (ii) refining of lead bullion to lead. Secondary lead is processed as part of the feed to primary smelters, only the lead in lead-acid batteries is recovered in dedicated processes. Five most common furnaces for lead smelting are the blast furnace (52%), the Imperial Smelting furnace (24%), the QSL furnace (12%), the Kaldo Boliden furnace (7%) and the Kivcet furnace (5%) (Siegmund 2000).

Traditionally, lead is produced with the blast furnace process or the imperial smelter process. Both processes use a sintering step to oxidize the sulfide concentrate and to obtain a lumpy and strong agglomerate suitable for use in the furnace. The *Blast Furnace* (BF) is *the* traditional metal production furnace. The furnace is a steel stack lined with refractory bricks, where sinter, coke and limestone are fed into the top in alternating layers. Preheated air is blown into the bottom. The sinter is reduced and the liquid reaction products are drained from the bottom of the furnace at regular intervals. The lead content of the sinter, mainly lead oxide is reduced to metallic lead. Other metal oxides present in the sinter, such as copper, antimony, arsenic and noble metals, are also reduced to their metallic state. Other constituents such as zinc and cadmium, report to the slag phase as oxides. If the zinc content of the slag is high, it is treated to remove the zinc. The *Imperial Smelting Furnace* (ISF) is similar to the Blast Furnace, but produces lead bullion and crude zinc simultaneously. The charge of the furnace is a mixed lead–zinc concentrate. The difference with the Blast Furnace is that the top of the furnace is closed to maintain a higher temperature in the top part of the furnace. As a consequence, the zinc remains as a gas, which is condensed in a lead metal bath, the spray condenser. The condensed, crude zinc needs is further refined by distillation (see the zinc profile).

The flue dust production in the sintering step is a major environmental problem of the traditional routes. In order to avoid environmental problems, proper ventilation and dust cleaning equipment is required (e.g. Ullmann 1996). Modern smelting operations have been developed that apply direct smelting operations and avoid the sintering operation. The KIVCET, the QSL and the Kaldo processes are the most abundant examples of the new processes.

The *KIVCET furnace* consists of two sectors; an oxidation section and a reduction section. In the oxidation section, the blended charge together with fluxes, recycle flue dust and oxygen are fed through burners. Combustion of the different charge products at a temperature of 1400°C results in almost a complete desulphurization before the reaction products collect in the slag bath. The lead monoxide from the charge combustion is reduced by a layer of floating coke particles on the slag bath under the combustion shaft. The reduced slag and the lead bullion flow to the reduction section where the remaining lead oxide is reduced and a slag with a typical lead content of 2-3 % is produced. The Kivcet or KIVCET process can also smelt oxidic charge materials such as zinc leach residues (Ullmann 1996).

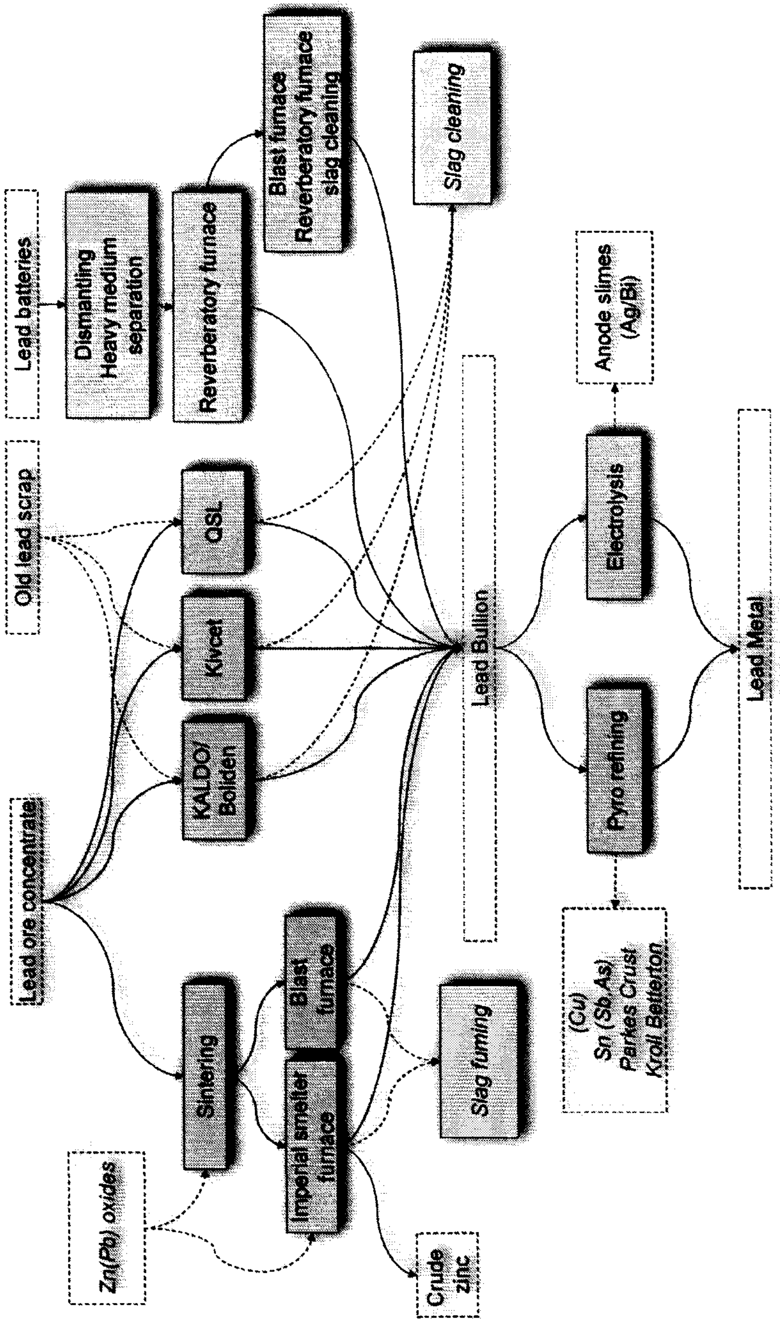

Figure 9: Simplified lead production flowchart.

The *QSL furnace* is a horizontal refractory lined vessel, which is divided into an oxidation section and a slag reduction section, similar to the KIVCET process. The input of the QSL process is a mixture of lead concentrate, fluxes, coal, flue dusts and other recycle streams. The oxidation products of the QSL process are a high lead slag, sulfur dioxide gas, flue dust and lead bullion. The *Boliden Kaldo Process* melting furnace is a top blown converter. A (batch) melting cycle starts with the combustion of the charge with oxygen in a preheated empty vessel. The combustion of the charge continues until the lead bullion and the high lead slag reach the top of the converter; from this point on the slag reduction starts. Lead sulfide concentrate is used recover a major portion of the lead monoxide produced in the oxygen charge combustion, followed by reduction with coke particles. The Boliden Kaldo process can handle a variety of scrap and recycling streams, such as flue dusts. The slags from all three processes can contain considerable amounts of zinc and lead. Depending on the lead and zinc content, they are either processed in zinc processes, or treated and recycled back to lead smelting.

The lead bullion as produced in the melting operations still contains significant amounts of impurities, such as copper, arsenic, silver and bismuth, and needs to be refined. Worldwide, the two dominant lead refining operations are pyrometallurgical refining (72%) and electrorefining (28%) (Siegmund 2000). In the *Pyrometallurgical Refining* of lead impurities are separated into individual residue streams using batch processes: (i) de-copperization, (ii) removal of arsenic, tin and antimony with the Harris process, (iii) removal of noble metals with Parkes process, (iv) dezincification and finally (v) bismuth removal with the Kroll-Betterton process. The Parkes crust is processed to recover silver and other precious metals; the Kroll-Betterton dross is processed to recover bismuth. In *Electrorefining* lead bullion is cast into anodes, which are dissolved in an electrolyte, typically a fluosilicate electrolyte. The lead is selectively precipitated on the cathode. Metals with a higher electrochemical potential than lead remain in solution, and accumulate in the anode slimes. These anode slimes are treated to recover the precious metals. Metals with a lower potential, such as iron, nickel and zinc, dissolve in the electrolyte, but will not deposit on the cathode. The main advantage of the pyrometallurgical lead refining is the sequential separation of impurities. In the electrorefining most impurities accumulate in the anode slimes and require complex separation processes for their recovery.

Lead is the most recycled non-ferrous metal in the world. Production from recycled materials has risen steadily. It surpassed primary output for the first time in 1989. In 2000, about 60% of lead was produced from secondary material (USGS 2003). The steady growth of the amount of recycled lead is primarily due to its increased use in recyclable applications (in particular batteries) and a declining consumption for disperse uses such as leaded petrol. Also, general increases in the recycling rates of lead containing products such as vehicles and electrical and electronic equipment will result in increased secondary lead production.

The main (old) scrap source for lead is batteries. Lamm (1998) estimated that about 90-96% of the lead acid batteries are recovered. Before battery melting and producing lead bullion, the batteries are dismantled and mechanically separated using shredders and grinding mills, and the heavy medium separation. The metal fraction resulting from mechanical recycling is further processed in a reverberatory furnace producing lead bullion. The slag, still containing significant amounts of lead, is cleaned in either a single step, or in a two steps process, using reverberatory and blast furnaces (Ullmans

2000). Battery recycling is a dedicated process; other lead containing products are recycled in the modern lead smelters such as the QSL, KIVCET and Kaldo furnaces. These other sources include lead dismantled during demolition wastes, and the old lead scrap, Ferro and non-Ferro fractions from the different waste recovery routes. The old lead scrap can be used directly in lead smelters, the Ferro fractions are typically recovered in electric arc furnaces in the iron production circuit. In the recycling of iron, lead, zinc and cadmium are recovered as flue dust. The electric arc furnace dust returns to the lead(-zinc) circuit by processing in Waelz kilns, or ISF processes. Whereas the ISF process produces lead bullion, the Waelz oxide must be further processed into lead bullion, in a Blast furnace for instance. Lead in the non-Ferro fractions can also be recovered.

A.5.3 Reconciled mass balances

	Mining				
	Input	Output			
	Lead-zinc ore	Lead concentrate	Zinc concentrate	Copper concentrate	Tailings
Total	78778000	7.6%	13.8%	0.6%	78.0%
Cu	369850	28.6%	27.7%	26.5%	17.2%
Pb	4562100	81.0%	4.4%	0.8%	13.8%
Sn	0	0.0%	0.0%	0.0%	100.0%
Bi	0	0.0%	0.0%	0.0%	100.0%
Zn	6845000	4.4%	87.0%	0.3%	8.2%
Ag	6778	53.9%	13.9%	9.7%	22.4%
Sb	0	0.0%	0.0%	0.0%	100.0%
As	0	0.0%	0.0%	0.0%	100.0%
Ni	0	0.0%	0.0%	0.0%	100.0%
Au	47	22.5%	8.0%	4.1%	65.4%
Pd	0	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	100.0%
Fe	10930000	3.1%	7.2%	0.0%	89.7%
S	16365000	5.1%	21.2%	0.9%	72.8%

KWh/t refined Pb	3752
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

	Slag cleaning			
	Input	Output		
	Slag	Fume	Offgas	Slag
Total	976180	15.6%	6.3%	78.1%
Cu	445	0.4%	0.0%	99.6%
Pb	20290	85.1%	0.0%	14.9%
Sn	395	4.3%	0.0%	95.7%
Bi	5	29.9%	0.0%	70.1%
Zn	84067	65.7%	0.0%	34.3%
Ag	6309	0.0%	0.0%	100.0%
Sb	164	100.0%	0.0%	0.0%
As	13	100.0%	0.0%	0.0%
Ni	0	0.0%	0.0%	100.0%
Au	3	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	100.0%
Fe	57749	2.9%	0.0%	97.1%
S	132	2.4%	96.6%	1.1%

KWh/t refined Pb	130
Electricity	50%
Oil/Gas	0%
Coal	0%
Air	50%
CO	0.00.E+00
CO2	0.00.E+00
SO2	8.69.E+04
NOX	8.09.E+05

	Imperial Smelter Process												
	Sintering							Smelting					
	Input			Output				Input	Output				
	Lead concentrate	Zinc concentrate	Oxides	Flux	Calcine	Offgas	Flue dust	Calcine	Crude zinc	Lead bullion	Flue dust	Offgas	Slag
Total	857000	2162100	104970	9.5%	71.5%	23.5%	14.5%	2233710	40.6%	20.7%	3.6%	1.4%	33.6%
Cu	15125	19997	0	0.0%	99.0%	0.0%	1.0%	34771	2.3%	60.1%	0.6%	0.0%	37.0%
Pb	523950	52599	0	0.0%	81.0%	0.0%	19.0%	467005	3.0%	93.6%	3.2%	0.0%	0.2%
Sn	0	0	0	0.0%	81.0%	0.0%	19.0%	0	1.1%	84.2%	12.6%	0.0%	2.1%
Bi	1894	0	0	0.0%	81.0%	0.0%	19.0%	1534	1.5%	93.3%	0.4%	0.1%	4.7%
Zn	44190	1171400	11671	0.0%	100.0%	0.0%	0.0%	1227261	90.8%	0.0%	3.8%	0.0%	5.3%
Ag	20396	175	0	0.0%	81.0%	0.0%	19.0%	16663	3.0%	93.6%	3.2%	0.0%	0.2%
Sb	10786	20	0	0.0%	25.0%	1.0%	74.0%	2702	0.3%	99.5%	0.0%	0.0%	0.1%
As	0	0	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Ni	0	0	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Au	2	1	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Pd	0	0	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	0	113	0	0.0%	33.0%	0.0%	67.0%	37	94.7%	0.2%	4.8%	0.0%	0.3%
Fe	24236	158410	0	0.0%	100.0%	0.0%	0.0%	182646	0.3%	0.2%	0.0%	0.0%	99.4%
S	118250	589600	0	0.0%	2.0%	95.0%	3.0%	14157	0.0%	5.7%	3.4%	73.6%	17.3%

KWh/t refined Pb	569
Electricity	80%
Oil/Gas	20%
Coal	0%
Air	0%
CO	0.00.E+00
CO2	0.00.E+00
SO2	7.66.E+07
NOX	2.73.E+09

K Wh/t refined Pb	11100
Electricity	11%
Oil/Gas	6%
Coal	83%
Air	0%
CO	4.08.E+07
CO2	3.51.E+08
SO2	7.11.E+06
NOX	3.66.E+09

	Blast Furnace											
	Sintering						Smelting					
	Input	Output					Input	Output				
	Lead concentrate	Oxides	Flux	Calcine	Offgas	Flue dust	Calcine	Lead bullion	Offgas	Flue dust	Matte	Slag
Total	3500800	1043100	10.4%	86.4%	13.5%	10.5%	3926975	45.3%	1.3%	3.4%	1.7%	48.3%
Cu	61786	0	0.0%	99.9%	0.0%	0.1%	61714	40.7%	0.0%	0.0%	56.2%	3.1%
Pb	2167500	18593	0.0%	99.9%	0.0%	0.1%	2183557	93.5%	0.0%	4.0%	0.8%	1.7%
Sn	0	0	0.0%	99.9%	0.0%	0.1%	0	99.4%	0.0%	0.0%	0.0%	0.6%
Bi	12813	0	0.0%	99.9%	0.0%	0.1%	12798	99.2%	0.0%	0.1%	0.0%	0.7%
Zn	192640	2328	0.0%	98.4%	0.5%	1.1%	191897	0.0%	0.0%	3.3%	0.6%	96.1%
Ag	83317	0	0.0%	99.9%	0.0%	0.1%	83220	0.0%	0.0%	0.0%	0.0%	100.0%
Sb	352	0	0.0%	99.9%	0.0%	0.1%	352	99.9%	0.0%	0.0%	0.0%	0.1%
As	0	0	0.0%	0.0%	0.0%	100.0%	0	55.7%	0.0%	0.0%	44.0%	0.3%
Ni	0	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Au	6	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Pd	0	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	0	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Fe	200250	1	0.0%	100.0%	0.0%	0.0%	200227	0.4%	0.0%	0.8%	0.5%	98.3%
S	484130	0	0.0%	26.7%	73.1%	0.2%	129185	9.6%	49.3%	9.1%	9.1%	23.0%

KWh/t refined Pb	569
Electricity	80%
Oil/Gas	20%
Coal	0%
Air	0%
CO	0.00.E+00
CO2	0.00.E+00
SO2	2.41.E+08
NOX	3.87.E+10

KWh/t refined Pb	1440
Electricity	11%
Oil/Gas	6%
Coal	83%
Air	0%
CO	1.77.E+08
CO2	2.08.E+08
SO2	4.34.E+07
NOX	3.92.E+09

	Primary Direct smelting														
	Kaldo					Kivcet					QSL				
	Input	Output				Input	Output				Input	Output			
	Lead concentrate	Lead bullion	Offgas	Flue dust	Slag	Lead concentrate	Lead bullion	Offgas	Flue dust	Slag	Lead concentrate	Lead bullion	Offgas	Flue dust	Slag
Total	471260	54.3%	12.9%	14.2%	18.6%	336620	61.4%	11.3%	4.5%	22.9%	807880	64.2%	12.8%	10.0%	12.9%
Cu	2664	99.5%	0.0%	0.0%	0.4%	5565	38.5%	0.0%	60.8%	0.7%	5492	98.0%	0.0%	0.0%	2.0%
Pb	287630	85.9%	0.0%	12.7%	1.3%	206130	96.9%	0.0%	1.4%	1.7%	552390	90.8%	0.0%	8.5%	0.7%
Sn	382	99.9%	0.0%	0.0%	0.1%	305	99.9%	0.0%	0.0%	0.1%	874	91.1%	0.0%	0.0%	8.7%
Bi	306	99.9%	0.0%	0.0%	0.0%	243	99.9%	0.0%	0.0%	0.1%	617	99.9%	0.0%	0.0%	0.1%
Zn	37698	7.8%	0.0%	40.4%	51.8%	16831	7.8%	0.0%	40.4%	51.8%	40389	7.8%	0.0%	40.4%	51.8%
Ag	11216	44.5%	0.0%	0.0%	55.5%	8011	100.0%	0.0%	0.0%	0.0%	19227	100.0%	0.0%	0.0%	0.0%
Sb	1607	100.0%	0.0%	0.0%	0.0%	112	99.7%	0.0%	0.0%	0.3%	3257	100.0%	0.0%	0.0%	0.0%
As	429	96.9%	0.0%	0.2%	2.8%	0	0.0%	0.0%	0.0%	100.0%	818	99.9%	0.0%	0.0%	0.1%
Ni	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%
Au	1	0.0%	0.0%	0.0%	100.0%	1	0.0%	0.0%	0.0%	100.0%	1	0.0%	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%
Fe	31026	1.0%	0.0%	6.5%	92.4%	7081	3.7%	0.0%	0.0%	96.3%	22904	2.8%	0.0%	0.0%	97.1%
S	63461	2.1%	91.0%	6.9%	0.0%	41042	2.6%	92.4%	5.0%	0.0%	109140	2.4%	90.3%	7.2%	0.1%

KWh/t refined Pb	860
Electricity	50%
Oil/Gas	0%
Coal	0%
Air	50%
CO	2.15.E+07
CO2	0.00.E+00
SO2	3.94.E+07
NOX	5.61.E+08

KWh/t refined Pb	6640
Electricity	0%
Oil/Gas	20%
Coal	70%
Air	99%
CO	1.92.E+07
CO2	0.00.E+00
SO2	2.59.E+07
NOX	4.15.E+08

KWh/t refined Pb	1340
Electricity	0%
Oil/Gas	20%
Coal	70%
Air	99%
CO	5.15.E+07
CO2	0.00.E+00
SO2	6.72.E+07
NOX	1.09.E+09

	Secondary direct smelting														
	Kaldo					Kivcet					QSL				
	Input	Output				Input	Output				Input	Output			
	Lead scrap	Lead bullion	Offgas	Flue dust	Slag	Lead scrap	Lead bullion	Offgas	Flue dust	Slag	Lead scrap	Lead bullion	Offgas	Flue dust	Slag
Total	1179500	54.3%	12.9%	14.2%	18.6%	884590	61.4%	11.3%	4.5%	22.9%	2211500	64.2%	12.8%	10.0%	12.9%
Cu	4322	99.5%	0.0%	0.0%	0.4%	9480	38.5%	0.0%	60.8%	0.7%	9745	98.0%	0.0%	0.0%	2.0%
Pb	221730	85.9%	0.0%	12.7%	1.3%	166840	96.9%	0.0%	1.4%	1.7%	465740	90.8%	0.0%	8.5%	0.7%
Sn	1318	99.9%	0.0%	0.0%	0.1%	1103	99.9%	0.0%	0.0%	0.1%	3292	91.1%	0.0%	0.0%	8.7%
Bi	0	99.9%	0.0%	0.0%	0.0%	0	99.9%	0.0%	0.0%	0.1%	1	99.9%	0.0%	0.0%	0.1%
Zn	25498	7.8%	0.0%	40.4%	51.8%	11953	7.8%	0.0%	40.4%	51.8%	29879	7.8%	0.0%	40.4%	51.8%
Ag	0	44.5%	0.0%	0.0%	55.5%	0	100.0%	0.0%	0.0%	0.0%	0	100.0%	0.0%	0.0%	0.0%
Sb	11095	100.0%	0.0%	0.0%	0.0%	811	99.7%	0.0%	0.0%	0.3%	24600	100.0%	0.0%	0.0%	0.0%
As	0	96.9%	0.0%	0.2%	2.8%	0	0.0%	0.0%	0.0%	100.0%	0	99.9%	0.0%	0.0%	0.1%
Ni	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%
Au	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%
Fe	1	1.0%	0.0%	6.5%	92.4%	0	3.7%	0.0%	0.0%	96.3%	1	2.8%	0.0%	0.0%	97.1%
S	208	2.1%	91.0%	6.9%	0.0%	141	2.6%	92.4%	5.0%	0.0%	391	2.4%	90.3%	7.2%	0.1%

KWh/t refined Pb	860
Electricity	50%
Oil/Gas	0%
Coal	0%
Air	50%
CO	1.65.E+07
CO2	0.00.E+00
SO2	1.29.E+05
NOX	1.51.E+08

KWh/t refined Pb	6640
Electricity	0%
Oil/Gas	20%
Coal	70%
Air	99%
CO	1.56.E+07
CO2	0.00.E+00
SO2	8.90.E+04
NOX	1.42.E+08

KWh/t refined Pb	1340
Electricity	0%
Oil/Gas	20%
Coal	70%
Air	99%
CO	3.48.E+07
CO2	0.00.E+00
SO2	2.41.E+05
NOX	3.18.E+08

	Batteries smelting														
	Reverberatory smelting					Slag cleaning					Blast Furnace				
	Input	Output				Input	Output				Input	Output			
	Batteries	Lead bullion	Offgas	Flue dust	Slag	Slag	Lead bullion	Offgas	Flue dust	Slag	Slag	Lead bullion	Offgas	Flue dust	Slag
Total	3287344	35.8%	4.5%	27.9%	31.8%	1044380	40.3%	0.6%	3.4%	55.7%	581786	66.0%	0.2%	0.0%	33.8%
Cu	9675	100.0%	0.0%	0.0%	0.0%	0	0.0%	0.0%	0.0%	100.0%	0	36.2%	0.3%	0.0%	63.5%
Pb	3030600	48.2%	0.0%	21.1%	30.7%	930042	56.7%	0.0%	2.6%	40.7%	378606	98.8%	0.0%	0.0%	1.2%
Sn	22693	6.9%	0.0%	5.3%	87.8%	19931	0.0%	0.0%	0.2%	99.8%	19885	71.8%	0.0%	0.0%	28.2%
Bi	2093	94.9%	0.1%	0.0%	5.0%	104	84.9%	0.0%	0.1%	15.0%	16	21.9%	0.2%	0.0%	78.0%
Zn	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%
Ag	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%
Sb	13981	7.9%	0.0%	0.0%	92.1%	12873	11.7%	0.0%	0.0%	88.3%	11367	91.9%	0.0%	0.0%	8.1%
As	1105	18.1%	0.0%	0.0%	81.9%	905	0.8%	0.0%	0.0%	99.2%	898	76.2%	0.0%	0.0%	23.8%
Ni	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%
Au	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%
Fe	8686	16.6%	0.0%	83.4%	0.0%	1	0.0%	0.0%	0.0%	100.0%	1	28.3%	0.2%	46.6%	24.9%
S	198510	2.7%	64.6%	25.6%	7.1%	14132	4.9%	41.1%	13.8%	40.2%	5679	0.0%	19.7%	0.1%	80.2%

KWh/t refined Pb	20200*
Electricity	0%
Oil/Gas	20%
Coal	70%
Air	99%
CO	3.88.E+08
CO2	1.48.E+08
SO2	8.74.E+07
NOX	5.69.E+09

CO	1.11.E+08
CO2	5.27.E+07
SO2	3.96.E+06
NOX	1.53.E+09

CO	2.40.E+07
CO2	4.26.E+07
SO2	7.61.E+05
NOX	6.16.E+08

*Energy requirements for the three unit operations involved in batteries smelting.

A.6 Nickel production and recycling profile

A.6.1 End uses

In 2000 globally about 1.12 millions tons were produced (USGS 2003). Nickel is produced as nickel metal (ca. 56-64%), as nickel oxide (ca. 10-18%) and as ferronickel (ca. 22%, NIDI 2000)[3]. Nearly 90 % of all nickel is consumed in the production of different stainless and alloy steels, other nickel alloys and foundry products. The steels and other nickel alloys are processed into commercial products in a number of industrial applications. These applications include building and construction materials; chemicals production; process equipment; petroleum refining, power generation, and other industrial processes components and machinery; automotive, railway, marine, aerospace, and other transportation equipment; electronics; and consumer and other products. About 9 % is used in plated products, and the remaining two percent is used in a number of other relatively small applications, including chemicals, catalysts, batteries, coins, pigments, and powders (including powder metallurgy).

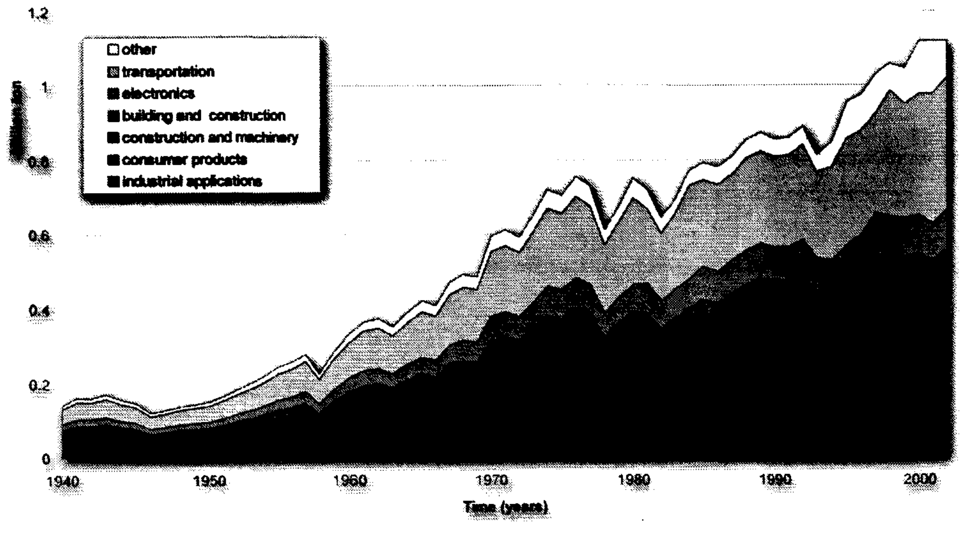

Figure 10: Nickel production and estimated end uses from 1940-2000 (USGS 2003, INSG 2004, WBMS 2000).

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[3] These data are 1998 estimates from Norilsk Nickel (www.nornik.ru) as used in the Ecobalance (2000) *Life cycle assessment of nickel products* (final report), prepared for Nickel Industry LCA Group of the Nickel development institute.

A.6.2 Production

The complex metallurgy of producing nickel from these ores is reflected in the wide range of extraction and refining processes in operation. Nickel is produced from both sulfide (86%) and oxide (14%) ores[4], that both have different production routes (Figure 11). Nickel sulfides are often found together with economically recoverable amounts of copper, cobalt, gold, silver, platinum group metals and several other metals. The nickel content of sulfide ores usually can be concentrated several times (up to 25% Ni) by the relatively economical ore dressing techniques before the concentrate is smelted and refined to nickel products (EU 2000). Oxidic ores, in contrast, are amenable to only limited beneficiation by physical methods e.g. magnetic or heavy media techniques, and therefore almost the entire volume of ore must go directly to metallurgical plants. Thus, oxidic processing tends to be more cost intensive, but mining costs are usually much lower than for sulfide ores. These differences, plus the availability of by-product value, can have an important influence on the viability of a specific deposit and whether refined metal or Ferro-nickel is produced from it: most oxidic ores are used for the production of ferronickel.

The production of nickel from sulfide ores can be divided into two steps: (i) smelting and converting the sulfide ore to matte that contains 35-70% Ni (ii) processing the matte to nickel. The treatment of sulfide ores is similar to the treatment of copper sulfides. The process can be divided into three steps, viz. roasting, smelting and converting. In the roasting step, sulfur and iron are partly oxidized. In the smelting step, the roasting product is smelted together with a siliceous flux to produce two immiscible phases: an iron-silicate slag and a matte containing mainly nickel and copper sulfides. The last step is to convert the matte into a high-grade nickel copper matte by oxidation, sulfide is driven off as sulfur dioxide and the remaining iron is oxidized and removed in a silicate slag. If the slag contains high amounts of nickel or copper, the slag can be treated to recover the nickel and copper. In most of the modern operations the roasting step has been eliminated, the concentrate is fed directly into the smelter. Globally three furnaces are used to convert the sulfide ore into matte: the reverberatory (14 %), electric (56%) and (Outokumpu and INCO) flash smelting furnace (30%). In Europe, only the Outokumpu flash furnace is used (EU 2000). As nickel smelting is similar to copper smelting, the operation of these furnaces is more or less the same as in copper production. Both flash furnaces were initially developed for the treatment of copper concentrates. (The concentrates are roasted and melted in suspension in the furnace and fall into the settler in the same manner. The Inco furnace use commercial oxygen, however, while the Outokumpu furnace uses oxygen enriched air.)

The *reverberatory furnace* is a long rectangular structure with an arched roof. The burners are located at one end in the roof. The charge is fed through pipes mounted on the roof along the side of the furnace. As an additional charge, molten converter slag can be introduced into the furnace. As the charge melts, it flows to the centre. The matte is tapped from the side; the slag is tapped from the end opposite to the burners. Fossil fuel is burned separately from the material that is being smelted. The reverberatory furnace has low energy efficiency, because the off gas stream carries nearly 50% of the

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[4] These data vary in literature, for instance the NF BREF (EU 2000) about 60% of the nickel comes from sulfide deposits and 40% from oxide deposits.

heating value of the fuel. In the *electric furnace* electric energy is the heating source and is used if the cost of electric energy is low. The electric furnace is heated by passing a three-way current through a circuit consisting of carbon electrodes immersed in the slag. The concentrate and flux are charged from the top. As there is no fuel combustion, the quantity of off gas is much smaller compared to the reverberatory furnace, and heat and dust recovery is easier. In a *flash smelting furnace*, the process heat is supplied by (partial) oxidation of the sulfur and iron in the charge. In the current practice, which uses oxygen-enriched air, the process is autogenous. This process usually generates less off gas and is more energy efficient than the other two processes.

The subsequent *matte converting* is usually performed in a Peirce-Smith converter, a horizontal side blown converter. Air or oxygen-enriched air is blown through the matte to oxidize the iron and remove some of the sulfur. The iron oxides are 'slagged off' through the addition of silica fluxes. The matte is a melt of nickel (50-60%) and copper sulfides with small amounts of cobalt sulfides, iron, precious metals and other impurities. Because nickel in many applications is used as an alloying element, highly refined metals are not necessary for these applications; in other applications, high purity nickel is essential and the matte must be refined (Ullmann 1996). The object of the refining process is not only to remove the impurities form the nickel, but also to recover those that have economic value (e.g. copper and PGMs). There are six different processes to treat nickel matte: Hydrochloric Acid Leach, Atmospheric Acid Leach, Acid Pressure Leach, Ammonia Pressure Leach, Direct Electrolysis and Matte Separation. In addition to nickel matte, nickel ore, or nickel products from other operations are used as feed as well. Which process is used depends on the characteristics of the nickel matte, most importantly the copper and sulfur content of the matte.

In the *matte separation process* (19%), the matte is slowly cooled. The matte segregates into three phases during cooling: a copper sulfide (Cu_2S) phase, a nickel sulfide (Ni_3S_2) phase and a nickel-copper alloy phase. Precious metals will collect in the latter phase. After solidification, the three phases are crushed and ground and are separated by magnetic separation and flotation. The nickel-copper alloy is refined using the carbonyl process, in which nickel is separated from the impurities using carbon monoxide. Under the process condition only Ni volatilizes as $Ni(CO)_4$. As other metals do not react with the carbon monoxide, or react at a much lower pace, this produces a very pure nickel. The nickel sulfide is roasted to nickel oxide in a fluidized bed roaster.

Alternatively, the matte can leached to dissolve the nickel. The nickel in the leach solutions is recovered by electrolysis. Globally, four different leach processes are employed to leach the nickel matte. In *the ammonia leach process* (20%) matte is leached in a two-stage counter current process. Nickel, copper and cobalt form complexes with ammonia and are dissolved. *The atmospheric acid leach process* (11%) treats high copper, low sulfur nickel matte. In the process leaching is carried out in trains of air agitated Pachuca tanks. *The acid pressure leach process* (11%) is also used for nickel mattes that contain high concentrations of copper. The process is carried out in horizontal multi-compartment autoclaves and allows very high extractions of nickel, copper and sulfur. In addition, it can also be employed to extract PGMs from the matte, and is used by the platinum producers in South Africa for this reason. The PGMs are concentrated in the leach residue, producing a high-grade PGM concentrate (dependent on the feed).

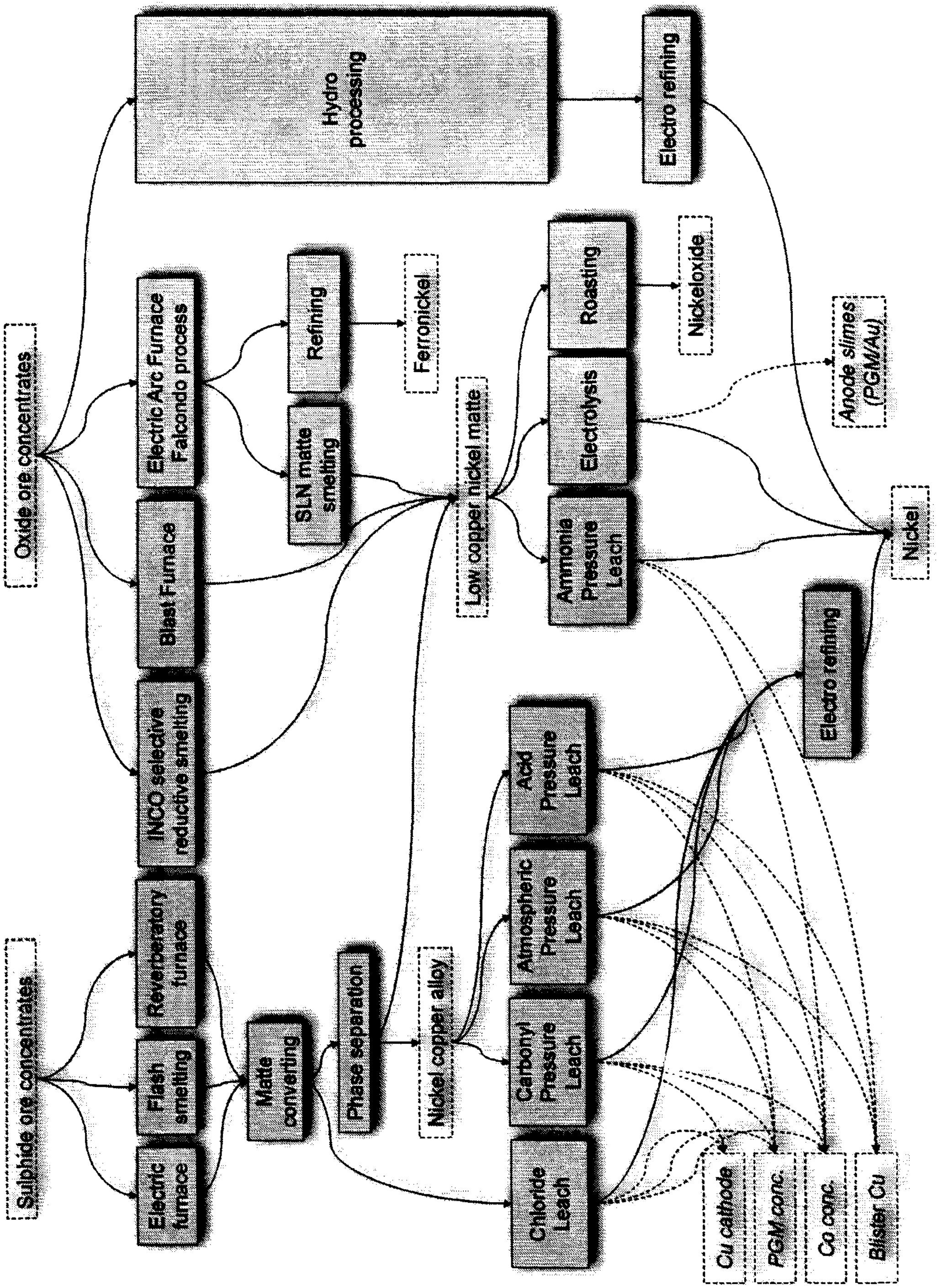


Figure 11: Simplified nickel production flowchart.

The concentrate can be directly treated in a platinum refinery. In the *chloride leaching process* (18%), the matte is leached under atmospheric pressure at the boiling point of the leach solution. In case the matte contains low concentrations of copper, the leaching step can be skipped. In this *direct electrolysis process* (21%), the matte is cast into anodes; the nickel is dissolved in the sulfate electrolyte and deposited on the cathode. The precious metals do not dissolve and will collect in the anode slimes. This process is mainly used by the Russian PGM producers.

Oxide nickel ores typically contain large amounts of iron, and small amounts of copper. The oxide ores can be processed hydrometallurgically into nickel, or pyrometallurgically into ferronickel or nickel matte. The nickel matte is treated analogous to the matte from sulfide ores. Oxide ores are more abundant and easier to extract than sulfide ores, however the energy requirements for oxide ore processes are much higher than for sulfide ore processes. Three pyrometallurgical processes exist to treat the oxide ores.

In *the rotary kiln – electric furnace process* (48%) the ore is dried and partial reduced in a rotary kiln at temperatures of 900-1000°C; as fuel coal or coke is used. The produced calcine is fed into an electric furnace and heated to 1400- 1650°C. Dependent on the magnesia and silica content of the ore flux is added. The carbon electrodes that are submerged into the slag layer reduce the nickel and iron oxides to metals.The Falcondo process (8%) is a process similar to the rotary kiln-electric arc furnace process, the calcination of the ore however is done with a shaft furnace instead of a rotary kiln. This process has a lower energy consumption compared to the common route to produce ferronickel; this is only possible due to the special composition of the ore. Virtually all nickel and approximately 65% of the iron are reduced to metal producing a crude ferronickel. The crude ferronickel is further refined in a similar way as steel refining: First the ferronickel is treated under reducing conditions to remove the sulfur, then refined under oxidizing conditions with suitable fluxes to remove carbon, silicon and phosphorous. The ferronickel is used to produce stainless steel. Ferronickel can also be converted to nickel matte using the *SLN matte converting process*. In this process, the ferronickel is converted into a matte by mixing it with elemental sulfur in a Peirce-Smith converter. After 'sulfidizing' the matte is blown with air in order to oxidize the iron. In the *blast furnace* (or shaft furnace, 5%) oxide ore is converted to nickel matte. The ore is blended with coke, limestone and pyrite and sintered in a sinter machine. The resulting sinter is smelted in the furnace using oxygen-enriched air to produce furnace matte. This matte is blown in a Peirce-Smith converter to a high-grade converter matte. In the *Inco selective reduction smelting process* (26%) oxide ores are directly converted into nickel matte. The ore is first dried and partially reduced in a rotary kiln by adding coal and high sulfur oil into the ore bed. The hot calcine is smelted in an electric furnace. To produce the matte elemental sulfur is added. The resulting matte is further upgraded in an air blown converter.

Finally, nickel can be produced from oxide ores in two hydrometallurgical processes: the Moa bay process and the Caron process (13%). In the Caron process, partially reduced ore is leached in ammoniacal solution. The Moa Bay process applies a direct sulfuric acid pressure leach.

The main source of secondary nickel is stainless steel. This is usually remelted and refined to produce new stainless steel (Ullmann 1996). It is estimated that around 80 per cent of the nickel is recycled from new and old stainless steel scrap and returns to that end use (EU 2000). Other nickel bearing materials (e.g. electronics, precipitates and residues) are recycled to primary production through production processes of other metals. Industrial applications, construction and machinery applications, large transportation applications (aerospace and marine) and the 'other' applications are assumed to be recovered through other routes.

A.6.3 Reconciled mass balances

	Sulfide Mining			
	Input	Output		
	Sulfide nickel ore	Nickel concentrate	Copper concentrate	Tailings
Total	23235000	20.1%	0.9%	79.0%
Cu	230500	73.4%	26.1%	0.5%
Pb	0	0.0%	0.0%	100.0%
Sn	0	0.0%	0.0%	100.0%
Bi	0	0.0%	0.0%	100.0%
Zn	0	0.0%	0.0%	100.0%
Ag	0	0.0%	0.0%	100.0%
Sb	0	0.0%	0.0%	100.0%
As	0	0.0%	0.0%	100.0%
Ni	394990	92.9%	0.6%	6.5%
Au	0	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	100.0%
Fe	3580400	40.6%	0.5%	58.9%
S	6970400	18.7%	0.2%	81.2%
Co	0	0.0%	0.0%	100.0%

KWh/t refined Ni	6944
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

	Sulfide smelting																	
	Electric furnace						Flash furnace						Reverberatory furnace					
	Input	Output					Input	Output					Input	Output				
	Nickel concentrate	Flux	Furnace matte	Off gas	Flue dust	Slag	Nickel concentrate	Flux	Furnace matte	Off gas	Flue dust	Slag	Nickel concentrate	Flux	Furnace matte	Off gas	Flue dust	Slag
Total	604200	58.3%	30.0%	19.8%	8.5%	100.0%	3439300	3.0%	31.7%	21.4%	0.2%	49.7%	604200	10.0%	29.5%	19.7%	7.5%	53.2%
Cu	21147	0.0%	99.0%	0.0%	0.0%	1.0%	120720	0.0%	83.7%	0.0%	10.6%	5.6%	21147	0.0%	98.8%	0.0%	0.0%	1.2%
Pb	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Sn	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Bi	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Zn	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Ag	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Sb	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
As	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Ni	47490	0.0%	81.8%	0.0%	18.2%	0.0%	270330	0.0%	93.6%	0.0%	0.9%	5.5%	47490	0.0%	87.4%	0.0%	10.7%	1.9%
Au	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Fe	186330	0.0%	36.0%	0.0%	0.3%	63.7%	1092700	0.0%	35.7%	0.0%	0.0%	64.3%	186330	0.0%	35.1%	0.0%	0.2%	64.6%
S	168330	0.0%	27.2%	70.9%	1.9%	0.1%	963340	0.0%	27.2%	72.7%	0.0%	0.0%	168330	0.0%	26.8%	70.8%	2.2%	0.2%
Co	1631	0.0%	81.8%	0.0%	18.2%	0.0%	9286	0.0%	93.6%	0.0%	0.9%	5.5%	1631	0.0%	87.4%	0.0%	10.7%	1.9%

KWh/t refined Ni	4820
Electricity	72%
Oil/Gas	0%
Coal	28%
Air	0%
CO	0.00.E+00
CO2	0.00.E+00
SO2	2.40.E+02
NOX	2.53.E+07

KWh/t refined Ni	2620
Electricity	0%
Oil/Gas	65%
Coal	0%
Air	35%
CO	0.00.E+00
CO2	0.00.E+00
SO2	4.78.E+08
NOX	1.34.E+09

KWh/t refined Ni	8333
Electricity	11%
Oil/Gas	6%
Coal	83%
Air	0%
CO	0.00.E+00
CO2	0.00.E+00
SO2	8.13.E+07
NOX	2.29.E+08

Nickel-copper alloy processing

Carbonyl pressure leach

	Input	Output					
	Nickel copper alloy	Ni	NiFe	Cu	Co	PGM concentrate	Residue
Total	67900	53.6%	12.6%	19.6%	5.3%	0.0%	8.9%
Cu	13751	0.0%	0.0%	99.9%	0.0%	0.0%	0.0%
Pb	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Sn	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Bi	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Zn	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Ag	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Sb	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
As	0	99.0%	0.0%	0.0%	0.0%	0.0%	1.0%
Ni	46180	92.9%	6.9%	0.2%	0.0%	0.0%	0.0%
Au	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Fe	972	0.4%	80.7%	8.8%	0.1%	0.0%	9.9%
S	6518	2.8%	0.2%	0.1%	1.3%	0.0%	95.6%
Co	2810	1.8%	1.5%	0.1%	96.7%	0.0%	0.0%

KWh/t refined Ni	1388
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

Atmospheric acid leach

	Input	Output			
	Nickel copper alloy	Ni	CuS	CoS	Residue
Total	36480	45.8%	45.0%	1.3%	7.9%
Cu	7388	0.0%	98.0%	1.6%	0.4%
Pb	0	0.3%	99.3%	0.0%	0.4%
Sn	0	0.0%	0.0%	0.0%	100.0%
Bi	0	0.0%	0.0%	0.0%	100.0%
Zn	0	0.0%	0.0%	0.0%	100.0%
Ag	0	0.0%	0.0%	0.0%	100.0%
Sb	0	0.0%	0.0%	0.0%	100.0%
As	0	80.1%	15.4%	0.0%	4.5%
Ni	24811	98.0%	0.1%	0.3%	1.7%
Au	0	0.0%	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	100.0%
Fe	522	0.2%	5.3%	2.7%	91.7%
S	3502	0.0%	87.5%	2.9%	9.6%
Co	1510	16.3%	0.9%	83.1%	0.2%

KWh/t refined Ni	927
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

Acid pressure leach

	Input	Output				
	Nickel copper alloy	Ni	CuS	PGM	Co	residue
Total	13298	51.0%	28.3%	0.1%	1.7%	18.9%
Cu	2693	0.0%	99.3%	0.0%	0.0%	0.7%
Pb	0	3.3%	99.0%	0.0%	0.1%	0.0%
Sn	0	0.0%	0.0%	0.0%	0.0%	100.0%
Bi	0	0.0%	0.0%	0.0%	0.0%	100.0%
Zn	0	0.0%	0.0%	0.0%	0.0%	100.0%
Ag	0	0.0%	0.0%	0.0%	0.0%	100.0%
Sb	0	0.0%	0.0%	0.0%	0.0%	100.0%
As	0	13.2%	89.3%	0.0%	0.0%	0.0%
Ni	9044	93.8%	0.3%	0.0%	0.9%	4.9%
Au	0	0.0%	0.0%	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	0.0%	100.0%
Fe	190	0.3%	0.5%	0.5%	0.0%	98.7%
S	1277	0.0%	0.0%	0.1%	5.0%	94.9%
Co	550	18.2%	0.9%	2.7%	51.5%	26.8%

KWh/t refined Ni	927
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

	Hydrochloric acid leach					
	Input	Output				
	Converter matte	Ni	Cu	Co	PGM	Residue
Total	53271	49.8%	28.4%	0.4%	0.1%	21.3%
Cu	13575	0.0%	88.3%	0.0%	0.1%	11.6%
Pb	0	2.9%	92.2%	0.2%	0.0%	4.7%
Sn	0	0.0%	0.0%	0.0%	0.0%	100.0%
Bi	0	0.0%	0.0%	0.0%	0.0%	100.0%
Zn	0	0.0%	0.0%	0.0%	0.0%	100.0%
Ag	0	0.0%	0.0%	0.0%	0.0%	100.0%
Sb	0	0.0%	0.0%	0.0%	0.0%	100.0%
As	0	12.5%	87.6%	0.2%	0.0%	0.0%
Ni	31323	93.8%	0.3%	0.0%	0.0%	5.9%
Au	0	0.0%	0.0%	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	0.0%	100.0%
Fe	629	0.2%	0.4%	0.0%	0.9%	98.5%
S	7473	0.0%	0.0%	0.0%	0.1%	99.8%
Co	879	12.2%	0.6%	50.0%	0.1%	37.1%

KWh/t refined Ni	927
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

	Copper elektrolyte treatment			
	Input	Output		
	Copper elektrolyte residue	Ni	Cu	Residue
Total	31323	63.0%	37.0%	0.0%
Cu	30	0.1%	99.9%	0.0%
Pb	0	32.9%	67.1%	0.0%
Sn	0	0.0%	0.0%	100.0%
Bi	0	0.0%	0.0%	100.0%
Zn	0	0.0%	0.0%	100.0%
Ag	0	0.0%	0.0%	100.0%
Sb	0	0.0%	0.0%	100.0%
As	0	3.2%	96.8%	0.0%
Ni	31322	100.0%	0.0%	0.0%
Au	0	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	100.0%
Fe	0	0.0%	100.0%	0.0%
S	0	0.0%	100.0%	0.0%
Co	0	15.3%	84.7%	0.0%

KWh/t refined Ni	927
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

	SLN matte smelting				
	Input	Output			
	Crude FeNi	Flux + sulfur	Matte	Off gas	Slag
Total	41564	22.2%	44.7%	0.5%	32.7%
Cu	0	0.0%	0.0%	0.0%	100.0%
Pb	0	0.0%	0.0%	0.0%	100.0%
Sn	0	0 0%	0.0%	0.0%	100.0%
Bi	0	0.0%	0.0%	0.0%	100.0%
Zn	0	0.0%	0.0%	0.0%	100.0%
Ag	0	0.0%	0.0%	0.0%	100.0%
Sb	0	0.0%	0.0%	0.0%	100.0%
As	0	0.0%	0.0%	0.0%	100.0%
Ni	11842	0.0%	95.8%	0.0%	4.2%
Au	0	0.0%	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	100.0%
Fe	21519	0.0%	3.5%	0.0%	96.5%
S	111	3824 9%	3739.5%	185.0%	0.0%
Co	32	0.0%	61.2%	0.0%	38.7%

KWh/t refined Ni	30
Electricity	10%
Oil/Gas	90%
Coal	0%
Air	0%
CO	0.00.E+00
CO2	0.00.E+00
SO2	1.02.E+06
NOX	9.55.E+06

	Hydroprocessing			
	Input	Output		
	Oxide nickel ore	Acid	Matte	Slag
Total	3484300	6.2%	1.8%	92.0%
Cu	0	0.0%	0.0%	100.0%
Pb	0	0.0%	0.0%	100.0%
Sn	0	0.0%	0.0%	100.0%
Bi	0	0.0%	0.0%	100.0%
Zn	0	0.0%	0.0%	100.0%
Ag	0	0.0%	0.0%	100.0%
Sb	0	0.0%	0.0%	100.0%
As	0	0.0%	0.0%	100.0%
Ni	76305	0.0%	96.7%	3.3%
Au	0	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	100.0%
Fe	810440	0.0%	0.0%	100.0%
S	348	49356.9%	0.5%	0.0%
Co	2439	0.1%	7.3%	92.5%

KWh/t refined Ni	1193
Electricity	10%
Oil/Gas	90%
Coal	0%
Air	0%
CO	0.00.E+00
CO2	0.00.E+00
SO2	4.98 E-01
NOX	2.97.E+00

	Nickel matte processing															
	Nickel sulfide roasting				Ammonia pressure leach					Matte anode refining						
	Input	Output			Input	Output				Input	Output					
	Nickel matte	Nickel oxide	Off gas	Residue	Nickel matte	Ni	CuS	Co	Residue	Nickel matte	Ni	Cu	Co	PGM	Residue
Total	535450	81.6%	18.4%	0.0%	251140	59.9%	1.1%	0.6%	38.5%	292770	62.5%	4.2%	0.6%	0.0%	32.7%
Cu	3742	1.0%	2.4%	96.6%	1755	0.2%	16.2%	0.0%	83.6%	2046	0.1%	98.9%	0.0%	0.0%	1.0%
Pb	0	0.9%	12.0%	87.1%	0	0.1%	0.4%	0.0%	99.5%	0	41.1%	0.2%	0.0%	0.0%	58.6%
Sn	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Bi	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Zn	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Ag	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Sb	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
As	0	1.0%	2.1%	96.9%	0	0.4%	0.0%	0.0%	99.6%	0	2.8%	10.1%	0.0%	0.0%	87.0%
Ni	291250	100.0%	0.0%	0.0%	136600	96.3%	0.0%	0.0%	3.6%	159250	99.9%	0.1%	0.0%	0.0%	0.0%
Au	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Fe	206680	1.0%	4.6%	94.4%	96937	0.0%	3.2%	0.0%	96.8%	113010	0.1%	7.4%	0.1%	0.0%	92.5%
S	40775	0.0%	100.0%	0.0%	19124	0.0%	1.1%	0.0%	98.9%	22295	0.0%	0.0%	0.0%	0.0%	100.0%
Co	2369	1.0%	0.1%	98.9%	1111	16.6%	0.0%	83.2%	0.3%	1295	16.0%	0.1%	80.0%	0.0%	4.0%

KWh/t refined Ni	200
Electricity	0%
Oil/Gas	100%
Coal	0%
Air	0%
CO	0.00.E+00
CO2	0.00.E+00
SO2	5.32.E+11
NOX	1.33.E+12

KWh/t refined Ni	927
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

KWh/t refined Ni	927
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

A.7 Platinum Group Metals

Platinum groups metals (PGMs), viz. platinum, palladium, rhodium, iridium, osmium, ruthenium, are produced as by-products from production of other metals.

A.7.1 End uses

In 2000 approximately 19 tons of rhodium, 182 tons of platinum and 227 tons of palladium (USGS 2003) were produced. Figure 13 shows production and the end-uses of the PGMs as a function of time.

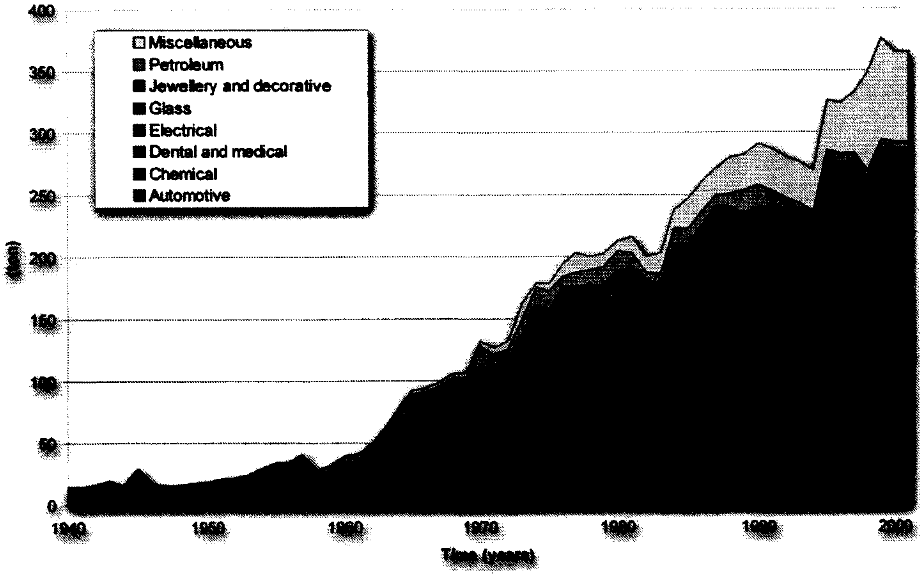


Figure 12: PGM production and estimated end uses from 1940-2000 (USGS 2003).

A.7.2 Production

The main sources for primary PGMs are ores that are associated with nickel-copper sulfides. As such, these ores are first processed to extract the nickel and copper also producing a PGM rich intermediate. PGMs are also produced from gold by-products.

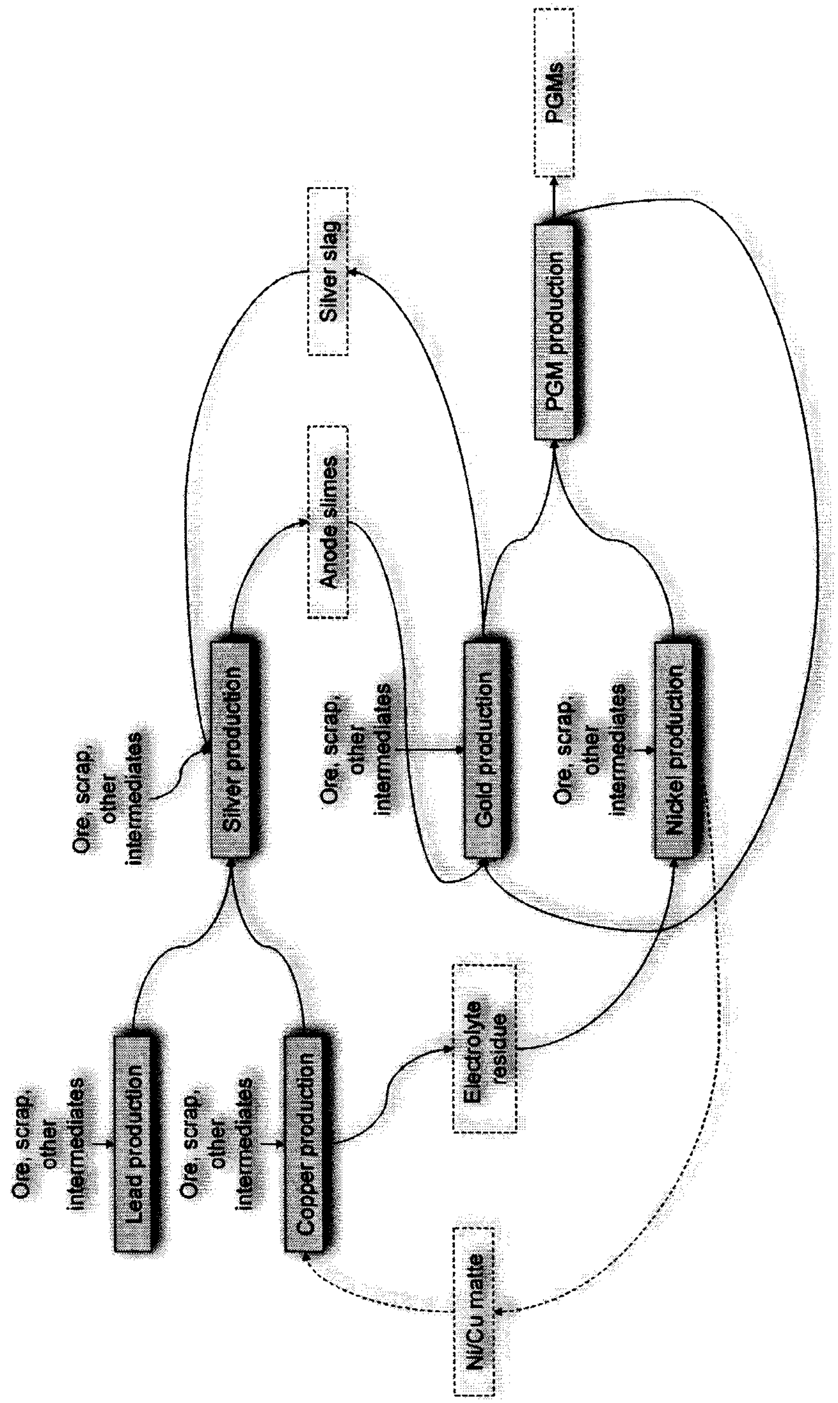


Figure 13: Simplified PGM production flowchart.

PGMs are circulated between different metal production circuits before the recovery is feasible. The PGM rich concentrates are separated and refined with a variety of complex hydrometallurgical processes sometimes combined with gold production. PGM refining is complex and individual process stages may have to be repeated to achieve the required purity. The number and order of the stages also depends on the contaminants to be removed and the specific mix of PGMs to be separated from any one batch of feedstock. The exact process combinations employed depends on the raw materials mix processed in the refinery. Being of high value, all process routes have high internal recycling rates, and yield recoveries of almost 100%.

PGMs are generally recycled at high rates (e.g. car catalysts if they are dismantled from cars). Secondary PGMs can be very concentrated and directly refined to pure PGMs, or are part of complex materials and are processed in different base metal smelters routes and typically concentrated in gold or nickel production to PGM rich residues or precipitates.

A.8 Silver

A.8.1 End uses

In 2000, approximately 23 thousand tons of silver were produced globally. Silver is produced from lead-zinc ores (38%), copper ores (23%), gold ores (15%) and silver ores (24%, World Silver Survey 2002). Silver has been known since ancient times; there is evidence that mankind separated silver from lead as early as 3000 BC (NATO 1976). For centuries, silver has traditionally been used for coinage. Only in the last century, it has been replaced by other metals in most countries because of its increased price and industrial usage. Silver is still used for coinage and other traditional applications (jewelry, silverware etc), but is mainly used for its chemical and electronic properties. Particularly, the use of silver for brazing alloys, solders, electrical equipment and electronics has decreased. The ban on lead in electronics in Europe, however, may (partially) reverse this trend as silver is one the potential substitutes for lead in solders. The use of silver for other applications has remained more or less constant. The use of silver for photographic uses may be expected to decrease in the future, as digital photography gains more and more ground.

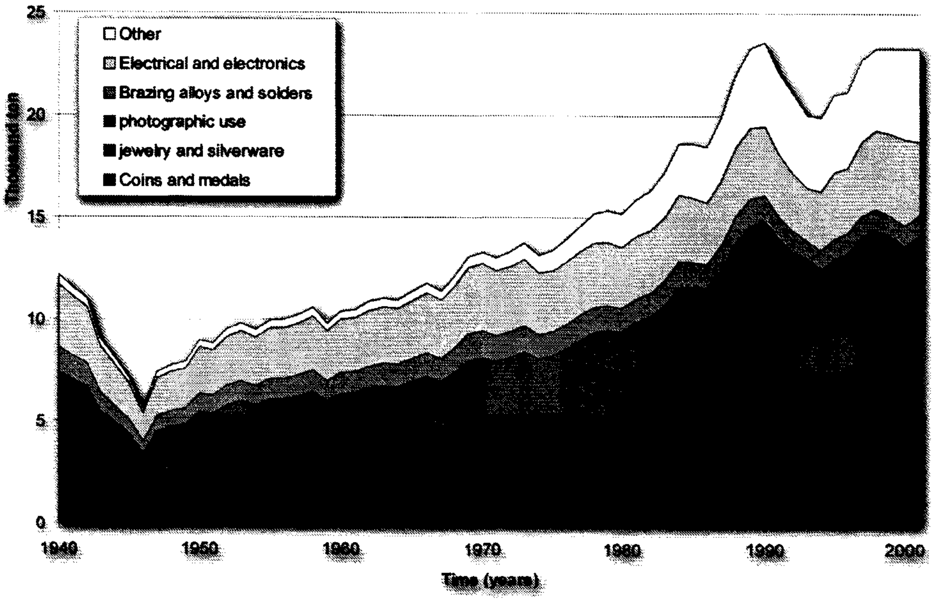


Figure 14: Silver production and estimated end uses from 1940-2000 (USGS 2003, Silver World Survey).

A.8.2 Production

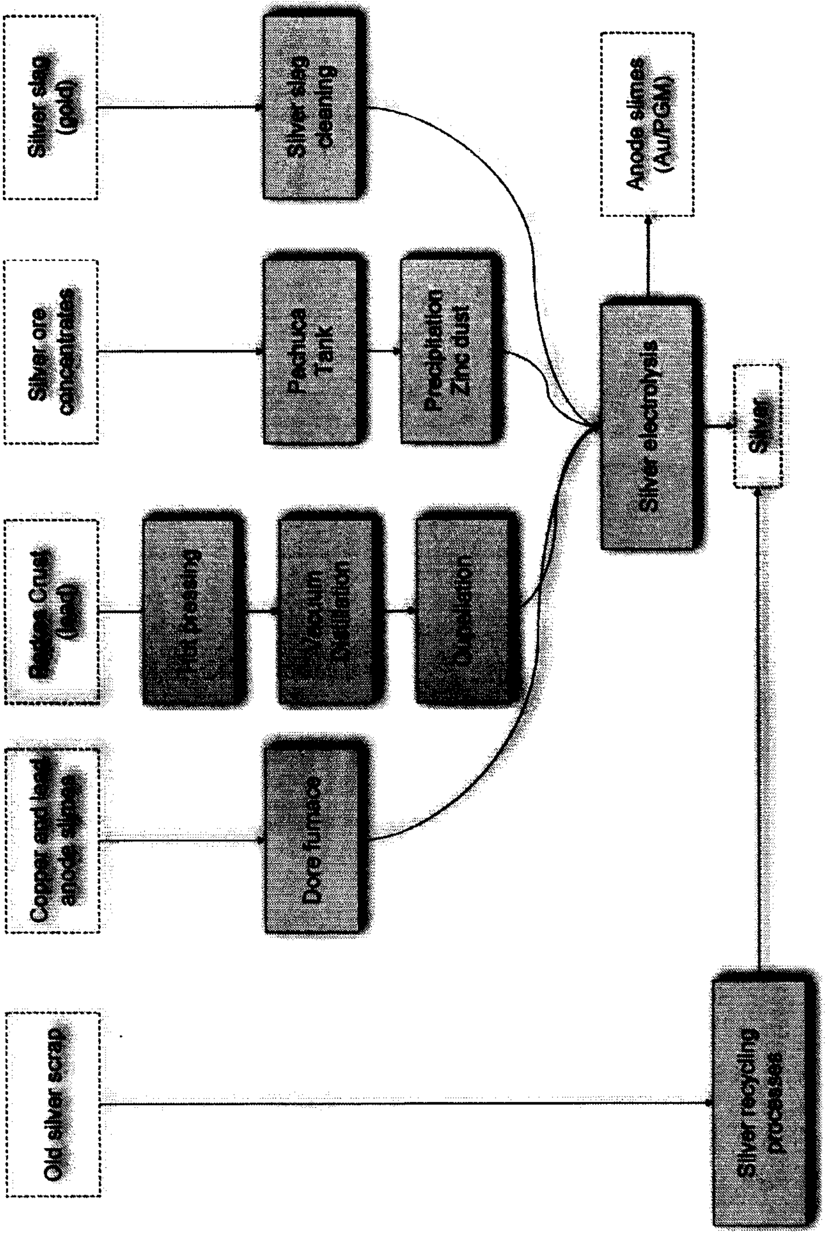


Figure 15: Simplified silver production flowchart.

Each ore or intermediate has its own process to produce crude silver. Silver ores can be treated in several ways. The common practice is to leach the ore in a *Pachuca tank* with sodium cyanide (co-dissolved from gold ores). The solids are filtered out the solution and the silver is *precipitated* by cementation with zinc dust. Another process involves the adsorption of the silver cyanide complex on active carbon together with gold cyanide, similar to the carbon-in-pulp process for gold. The silver present in lead-zinc ores follows lead, and is recovered in the refining of lead. Silver is either recovered as Parkes crust in the pyrometallurgical refining, or as anode slimes in the electrolytical refining (see lead).

The Parkes crust is processed in the *Cupellation process*. In the Cupellation process, the smelt is blown with air in order to oxidize the lead, while silver and other precious metals do not react. The lead oxide, litharge, is continuously removed. The produced crude silver is further refined. Anode slimes from copper (BA.3) and lead electrolysis can contain large amounts of silver and other precious metals. The anode slimes are typically treated in the *Doré process*. In the Doré furnace fluxes, sodium carbonate, lime, cullet and sand are added to the anode slimes. During melting, these fluxes form a silicate slag that takes up iron, arsenic, antimony, lead, nickel and tin. If the starting materials have a high selenium and tellurium content, also a selenium phase will form between the slag and the matte.

Silver is produced from approximately 30% from secondary materials. These secondary materials come from jewelry, photo materials and from industrial applications and other sources. These materials are treated to extract their silver content. Many routes for silver recovery exist:

Photographic film, papers and sludges are incinerated. The ash is recovered and treated with other silver bearing material, the gases are filtered and the dust that is collected is also treated to recover silver. A chemical stripping process in which the silver salts are leached from the emulsion layer is also used. Silver is recovered from waste solutions from the photographic and other industries by chemical precipitation as sulfide to form a powder, which is dried, melted and refined. Alternatively, silver thiosulfate solutions are electrolyzed to produce silver sulfide, which is insoluble and can be recovered. Jewelry can often be recovered by direct remelting. The silver in electronic appliances is typically recovered for the copper value, and return as anode slimes.

A.8.3 Reconciled mass balances

	Silver ore					
	Mining			Processing		
	Input	Output		Input	Output	
	Silver ore	Silver Concentrate	Tailings	Silver Concentrate	Silver bullion	Leach residue
Total	1271400000	4.9%	95.1%	72180000	0.0%	100.0%
Cu	0	0.0%	100.0%	0	0.0%	100.0%
Pb	0	0.0%	100.0%	0	0.0%	100.0%
Sn	0	0.0%	100.0%	0	0.0%	100.0%
Bi	0	0.0%	100.0%	0	0.0%	100.0%
Zn	0	0.0%	100.0%	0	0.0%	100.0%
Ag	5047	98.1%	1.9%	5774	99.4%	0.6%
Sb	0	0.0%	100.0%	0	0.0%	100.0%
As	0	0.0%	100.0%	0	0.0%	100.0%
Ni	0	0.0%	100.0%	0	0.0%	100.0%
Au	7	87.9%	12.1%	722	52.5%	47.5%
Pd	0	0.0%	100.0%	0	0.0%	100.0%
Cd	0	0.0%	100.0%	0	0.0%	100.0%
Fe	0	0.0%	100.0%	0	0.0%	100.0%
S	0	0.0%	100.0%	0	0.0%	100.0%

KWh/t refined Ag	2780
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

KWh/t refined Ag	2220
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

	Parkes crust								
	Hot pressing			Vacuum destillation			Cupellation		
	Input	Output		Input	Output		Input	Output	
	Parkes crust	Deleaded silver bullion	Pb intermediate	Deleaded silver bullion	Refined parkes crust	intermediate	Refined parkes crust	Silver bullion	Litharge
Total	30208	68.7%	31.3%	20765	42.5%	57.5%	8822	59.3%	40.7%
Cu	0	95.1%	4.9%	0	99.9%	0.1%	0	22.2%	77.8%
Pb	11557	19.8%	80.2%	2284	100.0%	0.0%	2284	0.3%	99.7%
Sn	0	0.0%	100.0%	0	0.0%	100.0%	0	0.0%	100.0%
Bi	0	0.0%	100.0%	0	0.0%	100.0%	0	0.0%	100.0%
Zn	12989	97.0%	3.0%	12595	1.8%	98.2%	228	0.0%	100.0%
Ag	5470	98.1%	1.9%	5368	100.0%	0.0%	5368	99.3%	0.7%
Sb	192	0.0%	100.0%	0	0.0%	100.0%	0	0.0%	100.0%
As	0	0.0%	100.0%	0	0.0%	100.0%	0	0.0%	100.0%
Ni	0	0.0%	100.0%	0	0.0%	100.0%	0	0.0%	100.0%
Au	0	0.0%	100.0%	0	0.0%	100.0%	0	0.0%	100.0%
Pd	0	0.0%	100.0%	0	0.0%	100.0%	0	0.0%	100.0%
Cd	0	0.0%	100.0%	0	0.0%	100.0%	0	0.0%	100.0%
Fe	0	0.0%	100.0%	0	0.0%	100.0%	0	0.0%	100.0%
S	0	0.0%	100.0%	0	0.0%	100.0%	0	0.0%	100.0%

KWh/t refined Ag	1440
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

KWh/t refined Ag	4530
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

	Copper and lead anode slimes								
	Input		Output						
	Copper anode slimes	anode slimes	Flux	Silver bullion	Offgas	NaO3 slag	Se slag	Si slag	Residue
Total	16643	9958	9.5%	12.9%	15.1%	7.8%	13.8%	38.4%	12.0%
Cu	48	278	0.0%	5.8%	0.0%	63.3%	24.7%	0.0%	6.2%
Pb	4263	1987	0.0%	0.1%	0.0%	5.9%	45.4%	36.1%	12.5%
Sn	0	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Bi	840	1243	0.0%	0.2%	0.0%	10.0%	20.4%	47.1%	22.3%
Zn	0	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Ag	5175	2412	0.0%	87.7%	0.0%	1.6%	0.0%	0.0%	10.6%
Sb	6141	3609	0.0%	0.0%	0.0%	2.0%	6.4%	81.4%	10.2%
As	0	413	0.0%	0.0%	0.0%	18.7%	0.0%	62.6%	18.7%
Ni	141	0	0.0%	0.0%	0.0%	0.0%	95.0%	0.0%	5.0%
Au	0	0	0.0%	7.9%	0.0%	5.0%	11.6%	75.5%	0.0%
Pd	0	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	0	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Fe	34	16	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
S	0	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%

KWh/t refined Ag	4530
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

	Wohlwill refining		
	Input	Output	
	Gold (99.9%)	Gold (99.99%)	PGM concentrate
Total	3094	99.7%	0.3%
Cu	0	0.0%	100.0%
Pb	0	0.0%	100.0%
Sn	0	0.0%	100.0%
Bi	0	0.0%	100.0%
Zn	0	0.0%	100.0%
Ag	0	0.0%	100.0%
Sb	0	0.0%	100.0%
As	0	0.0%	100.0%
Ni	0	0.0%	100.0%
Au	3068	100.0%	100.0%
Pd	0	0.0%	100.0%
Cd	0	0.0%	100.0%
Fe	0	0.0%	100.0%
S	0	0.0%	100.0%

KWh/t refined Au	860
Electricity	50%
Oil/Gas	0%
Coal	0%
Air	50%

A.9 Tin production and recycling profile

A.9.1 End uses

In 2000 about 297 thousand tons were produced globally. Unlike the other metals, the global production of tin remained more or less constant from 1940 to 2000. Tin has been known to mankind since at least 3500 BC (NATO 1976). Tin has the lowest melting point (232°C) of the common metals, is corrosion resistant, and readily forms a wide range of useful alloys. Cans and containers are its main end use. It is also used for the production of electrical appliances, construction, transportation and a large number of other, smaller end uses. These include paints, toothpaste, plastics, tin chemicals, tin foil, collapsible tubes, organ pipes, liners for valves and pipes, molten baths for float glass, and tin powder for lowering the sintering temperature of powder metallurgy pads. Figure 17 shows the trends in the end uses of tin from 1972 to 2002. The use of tin for cans and containers is slowly decreasing, due to a falling proportion of tin in tinplated steel, and the rise of substitutes for tinplated steel such as aluminum, plastics and tin-free steel (e.g. coated with a thin film of chromium/chromium oxide). In addition, the combination of a thin film of plastic and tin reduces the use of tin. Particularly, food and drink cans are increasingly made of aluminum, or other substitutes. The substitution of lead in electronics and electrical equipment (in the EU) may lead to an increased use of tin for electronics, as many lead-free solders contain higher amounts of tin than the conventional lead-tin solders.

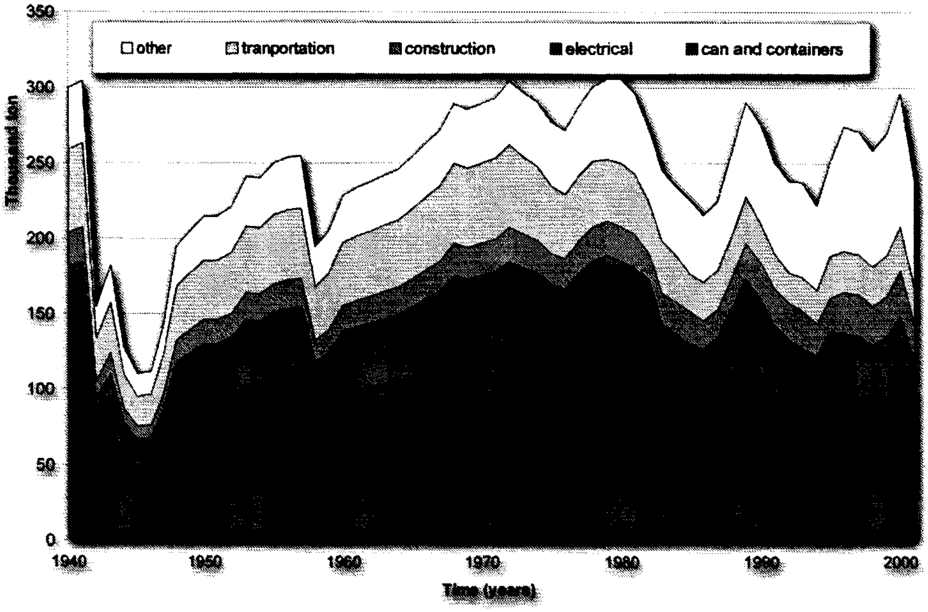


Figure 16: Tin production and estimated end uses from 1940-2000 (USGS 2003, NATO).

A.9.2 Production

Tin is mainly produced from sulfide (25%) and oxide ores (75%), a small fraction is produced from the intermediates of the production of other metals (e.g. from secondary copper production). A head grade for both ores of 0.7 - 2 % is common, usually concentrated to 40-70% prior to shipment for metal production (e.g. Ullmann 1996, Wright 1982, Hassan 1983). Sulfide ores are first roasted to an oxidic concentrate. In the roasting process, the tin sulfides are oxidized, and major oxidic impurities, such as arsenic, are volatized. Roasting is usually carried out in rotary kilns. The roast product and the concentrated oxidic ore are reduced in two steps to crude tin. The first stage gives a relative pure metal and a tin rich slag. This slag is treated in a second stage to extract the tin. Various kinds of furnaces are used for treating tin concentrates, each with its advantages and disadvantages. The most commonly used furnaces are the reverberatory furnace (48%), the rotary air furnace (26%), the electric furnace (8%), and the Ausmelt furnace (18%).

A *reverberatory furnace* is a rectangular furnace with burners located at the narrow sides of the furnace. The furnace, operated in batches, is charged with concentrate, carbon and flux. The carbon reduces the tin oxide to tin. The partial pressure of carbon monoxide in the furnace determines the efficiency of the furnace. *Rotary kiln furnaces* are horizontal smelting units that also operate batch wise, and are based on the same metallurgy. In comparison to reverberatory furnaces, they have larger melting capacities, but also higher stress on the refractory lining and higher energy requirements. *Electric furnaces* are circular furnaces that reduce the tin oxide to tin by electrical current. The three-phase electric arc currents through carbon electrodes reduce the tin oxides and provide for the process heat. When the concentrate has low levels of iron, the electric furnace can produce a crude tin in a single stage. The *Ausmelt* is a cylindrical furnace in which a vertical lance is mounted. The furnace is heated by submerging the lance in the bath, and feeding fuel and air through the lance. This also provides for rigorous mixing and thus good interaction between the different phases in the melt. The slag produced in the tin smelting contains 10-20% tin. The tin in the slag is recovered either by employing a strongly reducing smelt process producing a tin-iron alloy, hardhead, which is recycled to the tin smelting process, or by a blowing process, in which the tin is oxidized to a flue dust that is also recycled back to the tin smelting.

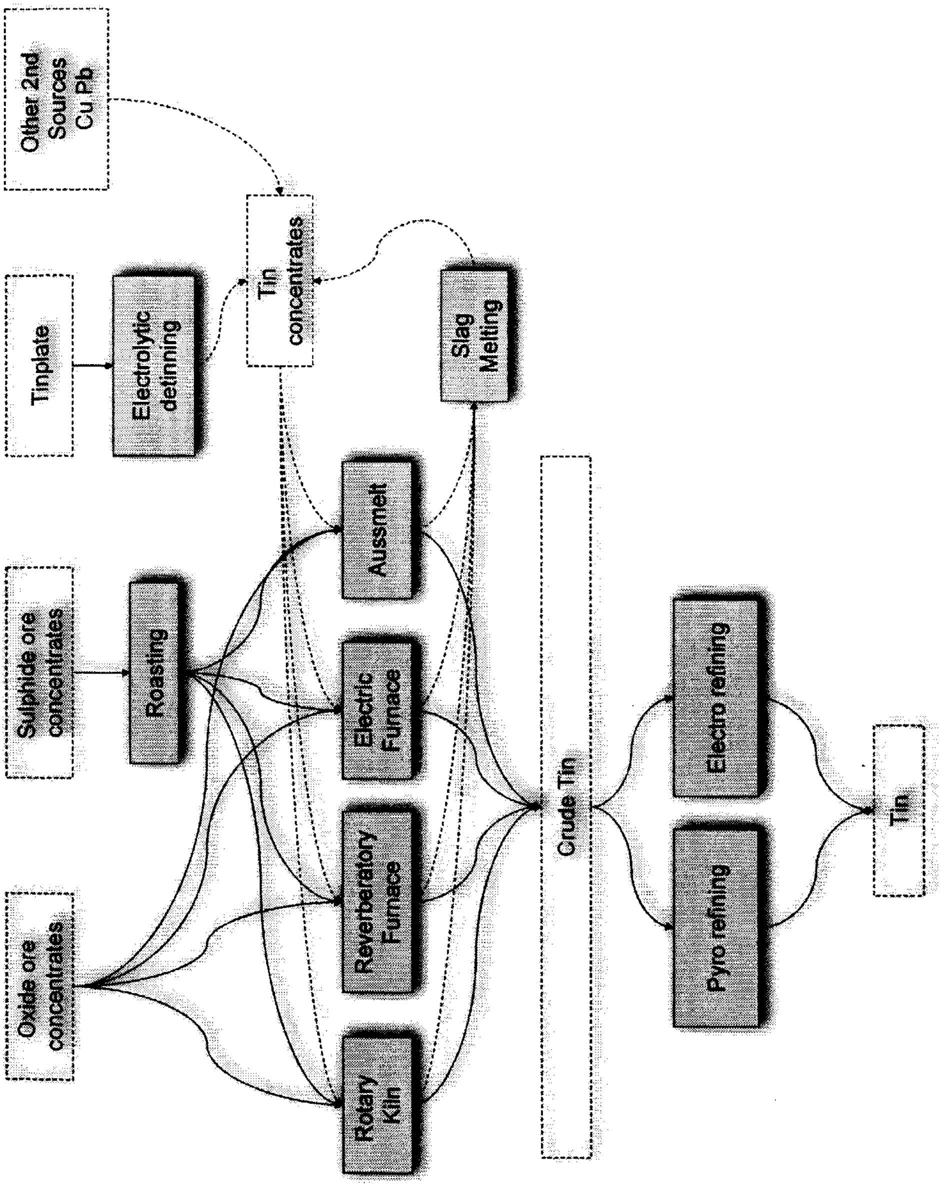


Figure 17: Simplified tin production flowchart.

Tin is the most difficult of the common metals to refine. For many years pure tin has only been available from very pure ores, and refining has been practiced only by countries with impure ores and secondary smelters (Halsall 1989). The crude tin is purified by pyrometallurgical methods (an estimated 40%) or through electrorefining (an estimated 60%). In *pyrometallurgical refining* iron, copper, arsenic, lead and bismuth are stepwise removed: (i) iron is removed by liquation and the precipitated iron is separated from the tin by passing steam, or air through the melt, (ii) copper is removed by reaction with elemental sulfur and skimming off the resulting copper dross, (iii) arsenic is removed, together with some nickel, copper and iron, by formation of intermetallic compounds with aluminum, (iv) lead is removed by treatment with chlorine, which will convert it into lead dichloride, (v) in the last step bismuth is removed by precipitation with calcium or magnesium. *Electrorefining* of tin is only employed when the crude tin contains high concentrations of noble metals: The process can only be operated at low current densities, and has a relatively low efficiency. As electrolyte both an acid, sulfate electrolyte, or an alkaline, sodium hydroxide (NaOH) electrolyte, medium can be used.

Approximately 27 % of the global tin production is produced from secondary materials. New scrap accounts for 11 %, and old scrap for 16 %. Tin is used as a coating on other metals, alloying metal with one or more other metals. Tin containing products (old scrap) are typically recycled for their content of other metals. The major end use and source of secondary tin is tin-plated steel. In the recycling, the steel is treated electrolytically to remove the tin in de-tinning facilities. Similarly, tin in electronics (e.g. solders) is typically recycled in copper processes.

A.9.3 Reconciled mass balances

	Mining					
	Sulphide ore			Oxide ore		
	Input	Output		Input	Output	
	Sulfide ore	Sulfide ore concentrate	Tailings	Oxide ore	concentrate	Tailings
Total	17393000	2.4%	97.7%	26089000	1.1%	98.9%
Cu	91776	1.3%	98.7%	122310	0.1%	99.9%
Pb	428280	4.2%	95.8%	125120	4.1%	95.9%
Sn	295830	56.3%	43.7%	197050	94.3%	5.7%
Bi	87002	0.0%	100.0%	122330	0.1%	99.9%
Zn	0	0.0%	100.0%	0	0.0%	100.0%
Ag	0	0.0%	100.0%	0	0.0%	100.0%
Sb	3730	97.4%	2.6%	140600	1.5%	98.5%
As	209370	1.4%	98.6%	122300	0.1%	99.9%
Ni	0	0.0%	100.0%	0	0.0%	100.0%
Au	0	0.0%	100.0%	0	0.0%	100.0%
Pd	0	0.0%	100.0%	0	0.0%	100.0%
Cd	0	0.0%	100.0%	0	0.0%	100.0%
Fe	1450500	2.5%	97.5%	2432700	0.3%	99.7%
S	1803500	1.4%	98.6%	0	0.0%	100.0%

KWh/t refined Sn	569
Electricity	80%
Oil/Gas	20%
Coal	0%
Air	0%

KWh/t refined Sn	569
Electricity	80%
Oil/Gas	20%
Coal	0%
Air	0%

	Roasting			
	Input	Output		
	Sulfide ore concentrate	Calcine	Offgas	Fume
Total	406710	94.6%	5.1%	0.3%
Cu	1195	99.9%	0.0%	0.1%
Pb	1778	93.1%	0.0%	6.9%
Sn	165840	100.0%	0.0%	0.0%
Bi	1	90.4%	26.7%	17.1%
Zn	8338	0.0%	0.0%	100.0%
Ag	102	0.0%	0.0%	100.0%
Sb	3619	98.0%	0.0%	2.0%
As	2987	96.6%	0.0%	3.4%
Ni	0	0.0%	0.0%	100.0%
Au	0	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	100.0%
Fe	36121	99.5%	0.0%	0.5%
S	25694	26.4%	73.4%	0.2%

KWh/t refined Sn	569
Electricity	80%
Oil/Gas	20%
Coal	0%
Air	0%
CO	6.19.E+06
CO2	0.00.E+00
SO2	3.77.E+04
NOX	6.94.E+08

	Slag cleaning			
	Input	Output		
	Slag	Hardhead	Fume	Slag
Total	302320	47.5%	2.5%	50.0%
Cu	2	39.0%	0.0%	61.0%
Pb	38141	98.3%	1.7%	0.0%
Sn	46380	70.3%	5.7%	24.0%
Bi	46	1.8%	96.3%	1.9%
Zn	7060	69.9%	0.0%	30.1%
Ag	67	0.0%	0.0%	100.0%
Sb	11596	98.9%	1.0%	0.1%
As	137	98.6%	0.0%	1.4%
Ni	20	0.0%	0.0%	100.0%
Au	0	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	100.0%
Fe	33713	66.9%	0.5%	32.7%
S	14	0.0%	0.0%	100.0%

KWh/t refined Sn	569
Electricity	80%
Oil/Gas	20%
Coal	0%
Air	0%
CO	1.06.E+07
CO2	1.74.E+07
SO2	0.00.E+00
NOX	4.06.E+07

	Primary smelting 1										
	Ausmelt					Electric furnace					
	Input	Output				Input		Output			
	Concentrate + calcine	Tin bullion	Flue dust	Offgas	Slag	Concentrate + calcine	Flux	Tin bullion	Flue dust	Offgas	Slag
Total	117310	44.8%	9.6%	5.7%	40.0%	175630	6.8%	42.4%	13.4%	2.7%	48.2%
Cu	184	100.0%	0.0%	0.0%	0.0%	276	0.0%	94.7%	5.3%	0.0%	0.0%
Pb	1456	21.6%	6.4%	0.0%	72.0%	2180	0.0%	20.5%	79.5%	0.0%	0.0%
Sn	65989	76.0%	9.8%	0.0%	14.2%	98795	0.0%	71.9%	19.1%	0.0%	8.9%
Bi	42	30.4%	0.0%	0.0%	69.6%	63	0.0%	28.8%	71.3%	0.0%	0.0%
Zn	1511	0.0%	0.0%	0.0%	100.0%	2262	0.0%	0.0%	70.1%	0.0%	29.9%
Ag	15	0.0%	0.0%	0.0%	100.0%	22	0.0%	0.0%	100.0%	0.0%	0.0%
Sb	962	21.8%	33.9%	0.0%	44.3%	1	0.0%	20.6%	10.6%	0.0%	68.8%
As	387	82.1%	3.3%	0.0%	14.6%	579	0.0%	77.7%	22.3%	0.0%	0.0%
Ni	4	0.0%	0.0%	0.0%	100.0%	5	0.0%	0.0%	0.0%	0.0%	100.0%
Au	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Fe	6425	7.4%	0.0%	0.0%	92.5%	9620	0.0%	7.0%	0.0%	0.0%	93.0%
S	3003	0.3%	0.0%	99.6%	0.1%	4496	0.0%	0.3%	0.0%	99.7%	0.0%

K Wh/t refined Sn	569
Electricity	80%
Oil/Gas	20%
Coal	0%
Air	0%
CO	2.47.E+04
CO2	8.50.E+06
SO2	2.04.E+06
NOX	1.56.E+08

K Wh/t refined Sn	569
Electricity	80%
Oil/Gas	20%
Coal	0%
Air	0%
CO	2.57.E+06
CO2	1.20.E+07
SO2	3.06.E+06
NOX	7.57.E+08

	Primary smelting 2											
	Reverberatory furnace						Rotary kiln furnace					
	Input	Output					Input	Output				
	Concentrate + calcine	Flux	Tin bullion	Flue dust	Offgas	Slag	Concentrate + calcine	Flux	Tin bullion	Flue dust	Offgas	Slag
Total	319760	2.1%	44.8%	12.7%	17.3%	27.3%	58321	13.1%	43.7%	7.8%	2.8%	58.8%
Cu	502	0.0%	99.9%	0.1%	0.0%	0.0%	92	0.0%	97.7%	0.0%	0.0%	2.3%
Pb	3968	0.0%	21.7%	19.8%	0.0%	58.5%	724	0.0%	21.1%	14.1%	0.0%	64.8%
Sn	179870	0.0%	76.0%	14.9%	0.0%	9.1%	32806	0.0%	74.2%	5.6%	0.0%	20.2%
Bi	115	0.0%	30.4%	68.7%	0.0%	0.9%	21	0.0%	29.7%	1.0%	0.0%	69.4%
Zn	4119	0.0%	0.0%	0.0%	0.0%	100.0%	751	0.0%	0.0%	0.0%	0.0%	100.0%
Ag	40	0.0%	0.0%	0.0%	0.0%	100.0%	7	0.0%	0.0%	0.0%	0.0%	100.0%
Sb	2623	0.0%	21.8%	77.9%	0.0%	0.3%	478	0.0%	21.3%	1.4%	0.0%	77.3%
As	1055	0.0%	82.1%	17.8%	0.0%	0.1%	192	0.0%	80.1%	0.3%	0.0%	19.5%
Ni	10	0.0%	0.0%	0.0%	0.0%	100.0%	2	0.0%	0.0%	0.0%	0.0%	100.0%
Au	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Fe	17514	0.0%	7.4%	0.0%	0.0%	92.5%	3194	0.0%	7.3%	10.6%	0.0%	82.1%
S	8186	0.0%	0.3%	0.0%	99.6%	0.1%	1493	0.0%	0.3%	0.0%	99.5%	0.2%

K Wh/t refined Sn	569
Electricity	80%
Oil/Gas	20%
Coal	0%
Air	0%
CO	5.21.E+04
CO2	2.32.E+07
SO2	5.56.E+06
NOX	1.46.E+09

K Wh/t refined Sn	569
Electricity	80%
Oil/Gas	20%
Coal	0%
Air	0%
CO	1.34.E+06
CO2	4.12.E+06
SO2	1.01.E+06
NOX	2.59.E+08

	Secondary smelting																
	Ausmelt					Electric furnace						Reverberatory furnace					
	Input	Output				Input	Output					Input	Output				
	Tin scrap	Tin bullion	Flue dust	Offgas	Slag	Tin scrap	Flux	Tin bullion	Flue dust	Offgas	Slag	Tin scrap	Flux	Tin bullion	Flue dust	Offgas	Slag
Total	26362	44.8%	9.6%	5.7%	40.0%	39474	6.8%	42.4%	13.4%	2.7%	48.2%	72046	2.1%	44.8%	12.7%	17.3%	27.3%
Cu	0	100.0%	0.0%	0.0%	0.0%	0	0.0%	94.7%	5.3%	0.0%	0.0%	0	0.0%	99.9%	0.1%	0.0%	0.0%
Pb	14787	21.6%	6.4%	0.0%	72.0%	22142	0.0%	20.5%	79.5%	0.0%	0.0%	40412	0.0%	21.7%	19.8%	0.0%	58.5%
Sn	9879	76.0%	9.8%	0.0%	14.2%	14792	0.0%	71.9%	19.1%	0.0%	8.9%	26998	0.0%	76.0%	14.9%	0.0%	9.1%
Bi	0	30.4%	0.0%	0.0%	69.6%	0	0.0%	28.8%	71.3%	0.0%	0.0%	0	0.0%	30.4%	68.7%	0.0%	0.9%
Zn	1	0.0%	0.0%	0.0%	100.0%	1	0.0%	0.0%	70.1%	0.0%	29.9%	2	0.0%	0.0%	0.0%	0.0%	100.0%
Ag	1	0.0%	0.0%	0.0%	100.0%	2	0.0%	0.0%	100.0%	0.0%	0.0%	4	0.0%	0.0%	0.0%	0.0%	100.0%
Sb	6615	21.8%	33.9%	0.0%	44.3%	9905	0.0%	20.6%	10.6%	0.0%	68.8%	18078	0.0%	21.8%	77.9%	0.0%	0.3%
As	286	82.1%	3.3%	0.0%	14.6%	428	0.0%	77.7%	22.3%	0.0%	0.0%	780	0.0%	82.1%	17.8%	0.0%	0.1%
Ni	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Au	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Pd	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%
Fe	0	7.4%	0.0%	0.0%	92.5%	0	0.0%	7.0%	0.0%	0.0%	93.0%	0	0.0%	7.4%	0.0%	0.0%	92.5%
S	0	0.3%	0.0%	99.6%	0.1%	0	0.0%	0.3%	0.0%	99.7%	0.0%	0	0.0%	0.3%	0.0%	99.6%	0.1%

KWh/t refined Sn	569
Electricity	80%
Oil/Gas	20%
Coal	0%
Air	0%
CO	4.86.E+04
CO2	1.59.E+06
SO2	0.00.E+00
NOX	4.76.E+07

KWh/t refined Sn	569
Electricity	80%
Oil/Gas	20%
Coal	0%
Air	0%
CO	2.01.E+05
CO2	2.26.E+06
SO2	0.00.E+00
NOX	1.90.E+08

KWh/t refined Sn	569
Electricity	80%
Oil/Gas	20%
Coal	0%
Air	0%
CO	1.30.E+05
CO2	4.35.E+06
SO2	0.00.E+00
NOX	3.67.E+08

	Elektrorefining							Pyrorefining						
	Fe drossing			Elektrolysis										
	Input	Output		Input	Output			Input	Output					
	Tin bullion	Anode	Fe dross	Anode	Tin	Anode rest	Anode slimes	Tin bullion	Tin	Bi intermediate	intermediate	SbAs intermediate	Cu intermediate	intermediate
Total	213980	94.1%	5.9%	201355	75.5%	21.9%	2.7%	142650	88.0%	0.1%	0.3%	0.0%	2.0%	9.7%
Cu	210	91.9%	8.1%	193	3.0%	22.3%	74.7%	827	0.1%	0.0%	0.0%	0.0%	79.1%	20.8%
Pb	15444	98.4%	1.6%	15195	2.2%	22.3%	75.5%	2820	3.2%	0.0%	1.6%	0.0%	0.0%	95.2%
Sn	193030	96.0%	4.0%	185289	77.3%	21.8%	0.9%	128010	92.1%	0.1%	0.3%	0.0%	0.9%	6.6%
Bi	25	100.0%	0.0%	25	78.9%	21.1%	0.0%	47	65.3%	34.7%	0.1%	0.0%	0.0%	0.0%
Zn	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Ag	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Sb	3882	100.0%	0.0%	3882	4.3%	22.3%	73.4%	4731	0.8%	0.0%	0.0%	0.1%	0.0%	99.1%
As	1538	28.0%	72.0%	431	1.7%	22.3%	76.0%	1459	2.3%	0.0%	0.0%	0.0%	0.0%	97.6%
Ni	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Au	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Pd	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Fe	1853	4.7%	95.3%	87	3.7%	22.3%	74.0%	841	0.8%	0.0%	0.0%	0.0%	0.0%	99.2%
S	0	0.0%	100.0%	0	0.0%	0.0%	100.0%	51	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%

KWh/t refined Sn	569
Electricity	80%
Oil/Gas	20%
Coal	0%
Air	0%

KWh/t refined Sn	569
Electricity	80%
Oil/Gas	20%
Coal	0%
Air	0%

KWh/t refined Sn	569
Electricity	80%
Oil/Gas	20%
Coal	0%
Air	0%

A.10 Zinc production and recycling profile

A.10.1 End uses

In 2000, 6.65 million tons of zinc was produced. Increasingly, the most important use of zinc is the galvanizing of steel, which consumes approximately half of the zinc produced. About two third of the zinc for galvanizing is used in transport (automobiles, trucks, and ships) and construction (infrastructure, buildings and factories). Other important galvanizing end uses are electrical equipment, air condition and heating. The balance is used for wire, fencing, tanks, pipes and other smaller end uses such as nails and fasteners. Zinc-based alloys (excluding brass and bronze) are the second largest end use. These alloys are mainly used in automobiles and trucks, construction, electrical components and (industrial, agricultural and commercial) machinery and some general appliances. A small amount is used for sporting goods, toys, and scientific equipment and sound and television products. The third largest end use of zinc is brass, and bronze (and some other alloys). About two third is used in electrical and electronic products, industrial machinery, and transportation equipment. The remainder is used in consumer and general products, and in building and construction. The 'other' end uses of zinc in Figure 19 consist of rolled zinc, zinc dust and chemicals. Zinc chemicals are mostly used in rubber production and agriculture. Paints and pigments are also an important application. To a lesser extent, zinc chemicals are also used in ceramics, electronics, photocopying, chemicals (processing), and pharmaceutical and consumer products. The most important application of zinc dust and rolled zinc is coinages, followed by batteries and consumer items. Rolled zinc and zinc dust is also used in metallurgical processes and chemicals production, for printing plates, paints and pigments, the dying of textiles, concrete roofing and gutters.

A.10.2 Production

Zinc is found as sulfide ore, in open pit (8%), underground mines (80%) and combined mining operations (12%). A head grade of zinc ore of 3-9% is common, typically concentrated to about 50%. The majority of the zinc ore (80%) is processed with the hydrometallurgical Roasting-Leach-Electrowinning (RLE) route. The balance is produced via the pyrometallurgical route, the Imperial Smelter process. The pyrometallurgical routes are generally used to process complex ores, or other zinc containing materials (secondary materials), with a high lead content. Zinc-containing residues from lead smelting or other processes, or secondary material with low zinc content are processed in a Waelz kiln or a slag fuming process (Figure 20) to zinc oxide. The zinc oxide can be sold directly, or further refined in the ISF or hydrometallurgical route. The pyrometallurgical route has higher fuel consumption and emissions than the hydrometallurgical route, but (often) produces a waste product that is environmentally easier to discard.

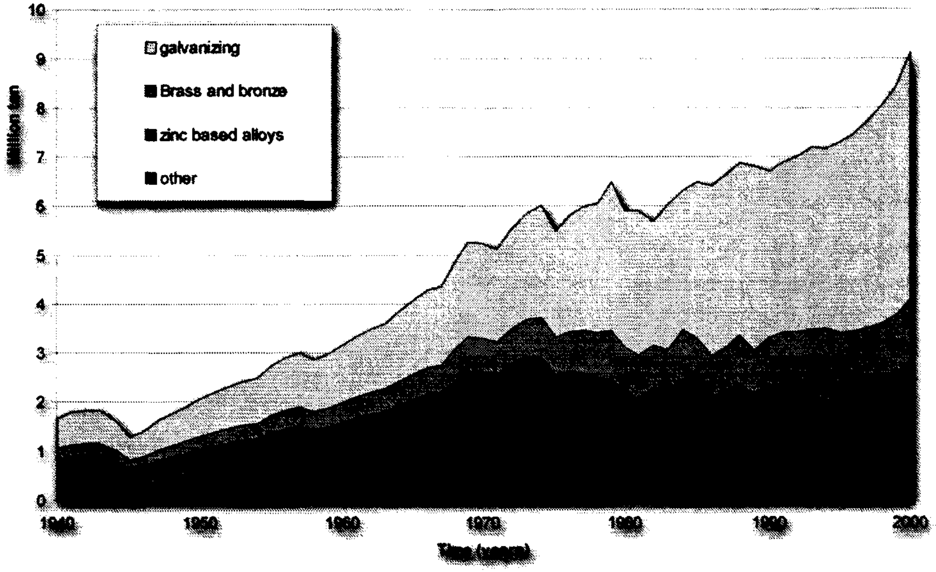


Figure 18: Zinc production and estimated end uses from 1940-2000 (USGS 2003, WBMS 2000).

The *hydrometallurgical RLE route* can be divided into three steps: (i) roasting, (ii) leaching, (iii) electrolysis. In the roasting step, the concentrate is calcined (oxidized) in a fluid bed roaster. Next, the calcine is leached in a neutral leach: the oxides are dissolved in a dilute sulfuric acid solution. The residue is further leached to recover the remaining zinc and to remove iron as a residue. Depending on the leach processes, different iron-containing residues are produced, viz. jarosite (84%), hematite (12%) or goethite (4%). These residues are a major environmental problem, as a good treatment of these residues has not been found. The zinc recovered in the second leach is fed back to the neutral leach. The zinc solution from the neutral leach is purified using zinc dust. In most cases, the removed metals (copper, cadmium, nickel and cobalt) can be sold as a by-product. The zinc in the purified solution is finally recovered as high purity zinc by electrolysis.

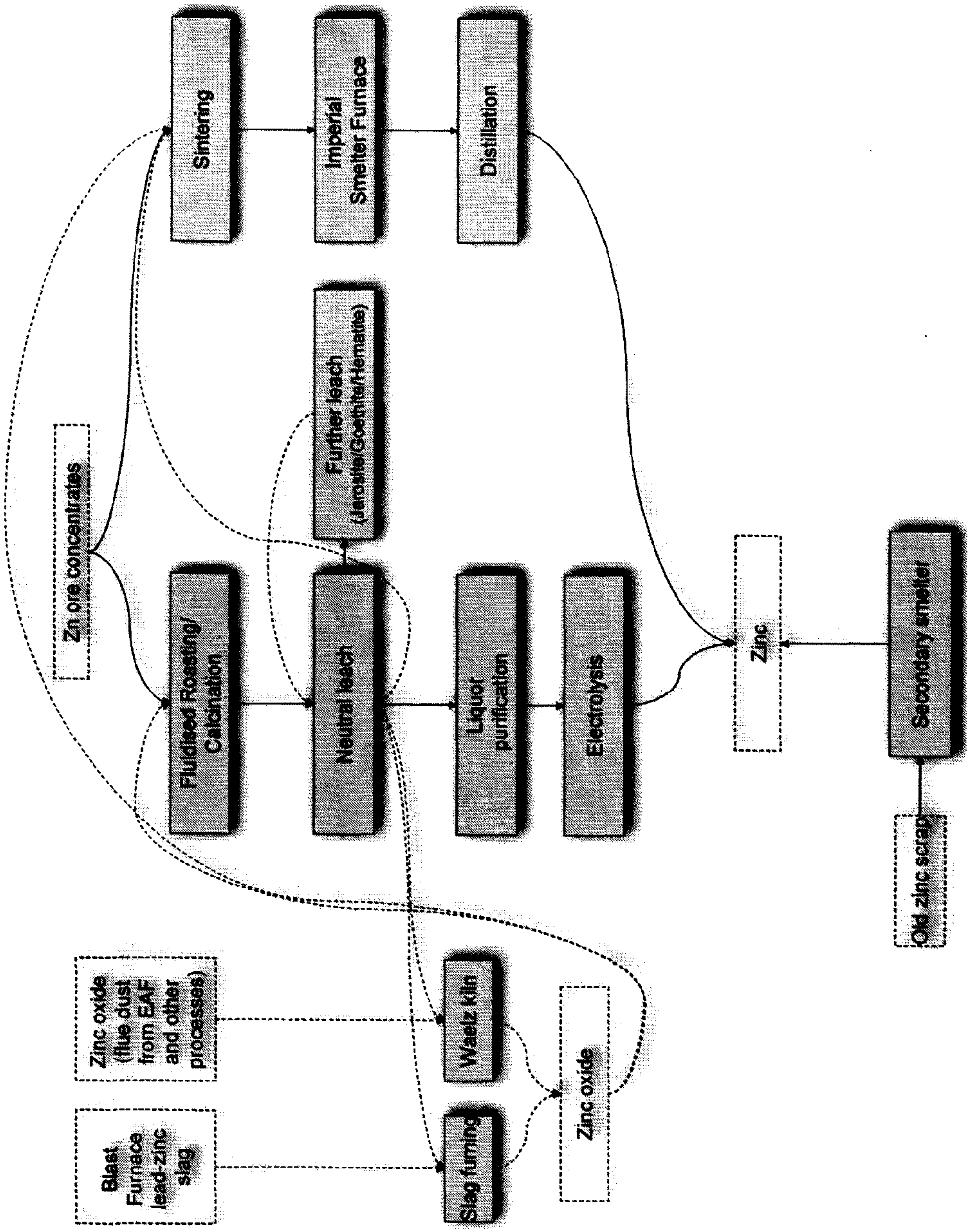


Figure 19: Simplified zinc production flowchart.

The reductive smelting in the *Imperial Smelter Furnace* produces crude zinc, as well as impure cadmium and lead bullion (BA.5). The crude zinc is refined by *distillation* to obtain a high purity product. The crude zinc contains typical impurities such as lead, cadmium and iron, as well as some copper, arsenic and other impurities, depending on the composition of the ore. The distillation process is based on the difference in boiling points of the species: zinc has a relatively low boiling point (906° C) compared to the boiling points of the main impurities, lead (1740° C) and iron (2735°C). Cadmium has a lower boiling than zinc, namely 767°C. The distillation is usually carried out in a system of two columns and a condenser. The molten feed is introduced to the middle of the first column, which is externally heated at the bottom to a temperature of about 1100°C, evaporating zinc and cadmium, which are withdrawn at the top and led to the condenser. The melt, at the bottom, exists mainly of zinc, but with about twice as much lead as in the crude zinc. This can be sold as such, or can be treated to obtain two molten phases, a zinc rich phase (the hard zinc), and a lead rich phase (which can be recycled). Iron and copper also report to the molten phase of the first column. The molten zinc/cadmium mixture from the condenser is fed to the second column with a lower temperature (ca. 950°C), allowing zinc to remain in the condensed state and evaporating cadmium. An impure cadmium canister is obtained at the top of the tower. The final product is high purity zinc.

About 31% of the world's zinc supply (nearly 2.9 million tons) comes from recycled zinc, including new scrap (22%). An estimated 80% of the old and new zinc scrap available for recycling is currently recycled (Reuter et al. 2001). Consumer products containing zinc are mostly treated for their iron content by steel plants (typically electric arc furnaces). Secondary zinc can also be obtained from products treated for their lead or copper content. Brass has a high copper content (> 60%) and is recycled almost exclusively by the (brass and) copper industries, which is financially the most attractive route (Reuter et al. 2001). Some old zinc scrap is obtained directly, such as scrap zinc sheet from building applications.

As secondary material can contain impurities that would cause severe problems in electrolytic zinc production, they are typically processed in pyrometallurgical processes. The Waelz kiln process is used to enrich and purify (lead and) zinc materials to a product with over 45% of zinc. The raw material for a Waelz kiln can be the slags, flue dusts and sludges arising from zinc production, the slag from lead production, if the zinc content is high enough, the flue dust from the electric arc furnace (EAF). Most of the secondary zinc arises from recycling galvanized steel in an EAF, where the zinc is captured as an oxide in the flue dust. The ISF can also treat flue dusts from EAFs or copper processes (up to 15%). The Waelz kiln is a slightly inclined rotary kiln. In the reactor, zinc oxide is vaporized and reacted with carbon to form zinc vapor. This zinc vapor is collected in the dust bags. The product is an impure grade of zinc oxide containing 50 to 60% zinc that is usually calcined in a rotary kiln to produce clinker oxide. In slag fuming, slag from lead smelting - containing up to 20% zinc oxide - is processed to produce a high-grade zinc oxide. The zinc oxide from these processes can either be sold as a product, or used as a feed to other zinc processes.

A.10.3 Reconciled mass balances

	Mining				
	Input	Output			
	Lead-Zinc ore	Lead concentrate	Zinc concentrate	Copper concentrate	Tailings
Total	78778000	7.6%	13.8%	0.6%	78.0%
Cu	369850	28.6%	27.7%	26.5%	17.2%
Pb	4562100	81.0%	4.4%	0.8%	13.8%
Sn	0	0.0%	0.0%	0.0%	100.0%
Bi	0	0.0%	0.0%	0.0%	100.0%
Zn	6845000	4.4%	87.0%	0.3%	8.2%
Ag	6778	53.9%	13.9%	9.7%	22.4%
Sb	0	0.0%	0.0%	0.0%	100.0%
As	0	0.0%	0.0%	0.0%	100.0%
Ni	0	0.0%	0.0%	0.0%	100.0%
Au	47	22.5%	8.0%	4.1%	65.4%
Pd	0	0.0%	0.0%	0.0%	100.0%
Cd	0	0.0%	0.0%	0.0%	100.0%
Fe	10930000	3.1%	7.2%	0.0%	89.7%
S	16365000	5.1%	21.2%	0.9%	72.8%

KWh/t refined Zn	3752
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

	Imperial Smelter Process																		
	Sintering							Smelting						Destillation			
	Input			Output				Input	Output					Input	Output		
	Lead concentrate	Zinc Concentrate	Oxides	Flux	Calcine	Offgas	Flue dust	Calcine	Crude zinc	Lead bullion	Flue dust	Offgas	Slag	Crude zinc	Zinc	Cadmium intermediate	Residue
Total	857000	2162100	104970	9.5%	71.5%	23.5%	14.3%	2233710	40.6%	20.7%	3.6%	1.4%	33.6%	907745	97.9%	0.2%	1.9%
Cu	15125	19997	0	0.0%	99.0%	0.0%	1.0%	34771	2.3%	60.1%	0.6%	0.0%	37.0%	790	0.0%	0.0%	100.0%
Pb	523950	52599	0	0.0%	81.0%	0.0%	19.0%	467005	3.0%	93.6%	3.2%	0.0%	0.2%	14177	0.1%	0.0%	99.9%
Sn	0	0	0	0.0%	81.0%	0.0%	19.0%	0	1.1%	84.2%	12.6%	0.0%	2.1%	0	0.0%	0.0%	100.0%
Bi	1894	0	0	0.0%	81.0%	0.0%	19.0%	1534	1.5%	93.3%	0.4%	0.1%	4.7%	23	0.0%	0.0%	100.0%
Zn	44190	1171400	11671	0.0%	100.0%	0.0%	0.0%	1227261	90.8%	0.0%	3.8%	0.0%	5.3%	1114398	99.6%	0.0%	0.4%
Ag	20396	175	0	0.0%	81.0%	0.0%	19.0%	16663	3.0%	93.6%	3.2%	0.0%	0.2%	506	0.0%	0.0%	100.0%
Sb	10786	20	0	0.0%	25.0%	1.0%	74.0%	2702	0.3%	99.5%	0.0%	0.0%	0.1%	8	0.0%	0.0%	100.0%
As	0	0	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Ni	0	0	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Au	2	1	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Pd	0	0	0	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	100.0%	0	0.0%	0.0%	100.0%
Cd	0	113	0	0.0%	33.0%	0.0%	67.0%	37	94.7%	0.2%	4.8%	0.0%	0.3%	35	0.4%	74.6%	25.0%
Fe	24236	158410	0	0.0%	100.0%	0.0%	0.0%	182646	0.3%	0.2%	0.0%	0.0%	99.4%	594	1.3%	0.0%	98.7%
S	118250	589600	0	0.0%	2.0%	95.0%	3.0%	14157	0.0%	5.7%	3.4%	73.6%	17.3%	3	0.0%	0.0%	100.0%

K Wh/t refined Zn	1390
Electricity	80%
Oil/Gas	20%
Coal	0%
Air	0%
CO	0.00.E+00
CO2	0.00.E+00
SO2	7.66.E+07
NOX	2.73.E+09

K Wh/t refined Zn	11100
Electricity	11%
Oil/Gas	6%
Coal	83%
Air	0%
CO	2.72.E+08
CO2	3.51.E+08
SO2	7.11.E+06
NOX	8.17.E+08

K Wh/t refined Zn	1940
Electricity	11%
Oil/Gas	6%
Coal	83%
Air	0%

	Hydroprocessing														
	Roasting						Hydroprocessing								
	Input			Output			Input	Output							
	Zinc concentrate	Zincoxides	Recycled flue dust	Calcine	Offgas	Flue dust	Calcine	Zinc	HAL residue	SAL residue	Jarosite residue	Goethite residue	Hemathite residue	Purification residue	NL leach
Total	8648200	259050	1069200	61.5%	27.2%	11.3%	6130827	59.7%	10.9%	5.5%	13.5%	2.0%	0.6%	1.4%	6.4%
Cu	79989	22	165600	28.7%	0.0%	71.3%	70395	0.0%	0.0%	0.6%	5.8%	7.2%	0.0%	69.8%	16.6%
Pb	210400	381	1989	99.0%	0.0%	1.0%	210642	0.0%	31.7%	36.3%	18.2%	0.7%	0.0%	1.0%	12.1%
Sn	0	0	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Bi	0	0	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Zn	4685500	1374000	2866700	66.1%	0.0%	33.9%	5896304	95.4%	0.8%	0.3%	0.8%	0.3%	0.0%	0.5%	1.9%
Ag	701	0	84	61.5%	27.2%	11.3%	482	0.0%	40.5%	49.4%	8.5%	1.6%	0.0%	0.0%	0.0%
Sb	81	0	10	61.5%	27.2%	11.3%	56	0.0%	39.9%	10.9%	9.0%	0.1%	0.0%	0.0%	40.1%
As	0	0	0	0.0%	0.0%	100.0%	0	0.0%	14.5%	4.3%	28.4%	4.4%	0.0%	0.0%	48.4%
Ni	0	0	0	0.0%	0.0%	100.0%	0	0.0%	18.1%	9.1%	0.0%	0.0%	0.0%	0.0%	72.8%
Au	3	0	0	61.5%	27.2%	11.3%	2	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Pd	0	0	0	0.0%	0.0%	100.0%	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
Cd	450	132	70	61.5%	27.2%	11.3%	401	0.0%	1.3%	0.2%	0.8%	0.3%	0.0%	87.6%	9.8%
Fe	633660	0	174910	77.1%	0.0%	22.9%	623601	0.0%	19.8%	2.2%	44.2%	9.4%	3.6%	1.1%	19.7%
S	2758400	0	85497	5.4%	91.4%	3.2%	154499	0.0%	0.0%	0.0%	65.8%	3.1%	0.0%	0.0%	31.1%

KWh/t refined Zn	1940
Electricity	18%
Oil/Gas	10%
Coal	74%
Air	0%
CO	7.85.E+06
CO2	0.00.E+00
SO2	2.91.E+14
NOX	2.70.E+15

KWh/t refined Zn	5470
Electricity	100%
Oil/Gas	0%
Coal	0%
Air	0%

	Zinc oxide processing													
	Waelz Kiln						Slag Fuming			Calcining				
	Input			Output			Input	Output		Input		Output		
	Copper converter dust	EAF dust	NL residue	Flux	Zincoxide	Slag	Slag cleaning fumes	Zincoxide	Slag	Zincoxide (Waelz)	Zincoxide (Fuming)	ZnO product	Zincoxide, input for other processes	Residue
Total	1730200	821510	-1572100	29.2%	37.6%	33.2%	2800700	22.6%	77.4%	368119	632958	19.4%	77.8%	2.8%
Cu	0	20954	11659	0.1%	0.1%	99.9%	14785	0.2%	99.8%	23	33	10.0%	40.0%	50.0%
Pb	166310	181680	25449	0.0%	49.1%	50.9%	55873	96.9%	3.2%	183228	54113	2.0%	8.0%	90.0%
Sn	0	2616	0	0.0%	0.0%	100.0%	17	0.0%	100.0%	0	0	10.0%	40.0%	50.0%
Bi	0	0	0	0.0%	0.0%	100.0%	165	0.0%	100.0%	0	0	10.0%	40.0%	50.0%
Zn	1563400	603360	112560	0.0%	73.3%	26.7%	305250	86.3%	13.7%	1670475	263339	18.0%	72.0%	10.0%
Ag	0	0	0	0.0%	0.0%	100.0%	2134	0.0%	100.0%	0	0	10.0%	40.0%	50.0%
Sb	0	547	22	0.0%	0.0%	100.0%	168	0.0%	100.0%	0	0	10.0%	40.0%	50.0%
As	0	6	0	0.0%	0.0%	100.0%	127	0.0%	100.0%	0	0	10.0%	40.0%	50.0%
Ni	0	4918	0	0.0%	0.0%	100.0%	0	0.0%	100.0%	0	0	10.0%	40.0%	50.0%
Au	0	0	2	0.0%	0.0%	100.0%	0	0.0%	100.0%	0	0	10.0%	40.0%	50.0%
Pd	0	0	0	0.0%	0.0%	100.0%	0	0.0%	100.0%	0	0	10.0%	40.0%	50.0%
Cd	430	0	39	0.4%	70.5%	29.2%	0	0.0%	100.0%	330	0	10.0%	40.0%	50.0%
Fe	0	0	122840	0.0%	0.0%	100.0%	380060	0.0%	100.0%	2	7	10.0%	40.0%	50.0%
S	0	83133	48013	0.0%	0.0%	100.0%	32454	0.0%	100.0%	0	0	10.0%	40.0%	50.0%

KWh/t refined Zn	130
Electricity	50%
Oil/Gas	0%
Coal	0%
Air	50%
CO	9.31.E+06
CO2	0.00.E+00
SO2	0.00.E+00
NOX	8.45.E+07

KWh/t refined Zn	130
Electricity	50%
Oil/Gas	0%
Coal	0%
Air	50%
CO	2.08.E+06
CO2	0.00.E+00
SO2	2.21.E+06
NOX	3.95.E+07

A.11 Calculation waste composition

A.11.1 Method

In the modeling of waste flows from consumption stocks, Klein et al. (2000) suggest to model the stock as a 'time buffer'. Metals in use (economic stocks) and waste generation can then be approximated using general metal statistics that report on the different end uses of metals as function of time, and estimates of life span distributions for these end uses or rather end use categories (A1 in *Figure 20*). The total economic stocks of metals can than be determined by integration over the longest life span.

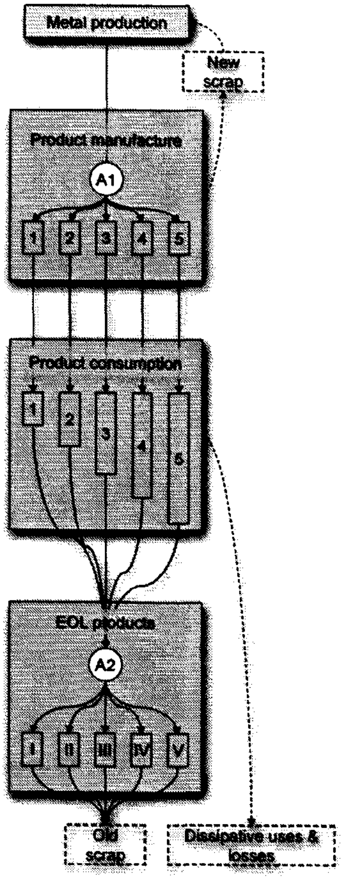
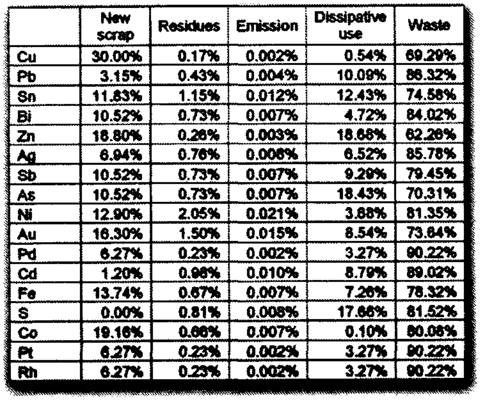


Figure 20: Estimation of metals in stock and waste generation using metal statistics on the different end uses of metals.

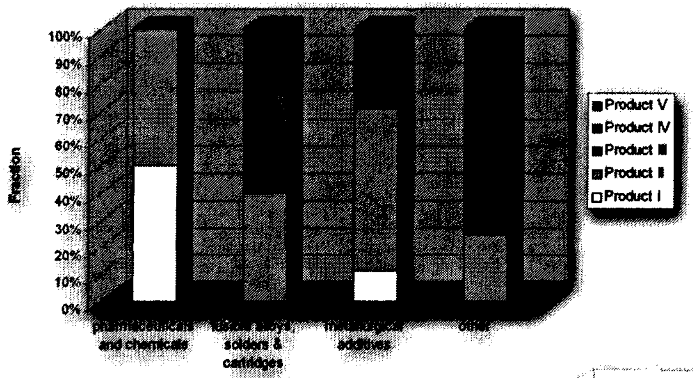
The actual composition of the old scrap from separation processes can be estimated (A2 in Figure 20) similarly by partitioning the end use categories to standardized routes for typical waste categories (Municipal Solid Waste, Wasted Electric and Electronic Equipment or End-of-Life Vehicles etc.). The data on the manufacture, consumption and solid waste management stages is given below. Further detail this approach can be found in appendix B.

A.11.2 Consumption

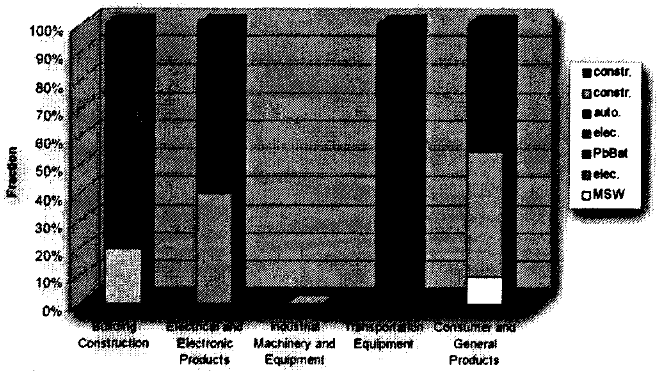


	New scrap	Residues	Emission	Dissipative use	Waste
Cu	30.00%	0.17%	0.002%	0.54%	69.29%
Pb	3.15%	0.43%	0.004%	10.09%	86.32%
Sn	11.83%	1.15%	0.012%	12.43%	74.58%
Bi	10.52%	0.73%	0.007%	4.72%	84.02%
Zn	18.80%	0.28%	0.003%	18.66%	62.26%
Ag	6.94%	0.76%	0.008%	6.52%	85.78%
Sb	10.52%	0.73%	0.007%	9.29%	79.45%
As	10.52%	0.73%	0.007%	18.43%	70.31%
Ni	12.90%	2.05%	0.021%	3.68%	81.35%
Au	16.30%	1.50%	0.015%	8.54%	73.64%
Pd	6.27%	0.23%	0.002%	3.27%	90.22%
Cd	1.20%	0.98%	0.010%	8.79%	89.02%
Fe	13.74%	0.67%	0.007%	7.26%	78.32%
S	0.00%	0.81%	0.008%	17.66%	81.52%
Co	19.16%	0.66%	0.007%	0.10%	80.08%
Pt	6.27%	0.23%	0.002%	3.27%	90.22%
Rh	6.27%	0.23%	0.002%	3.27%	90.22%

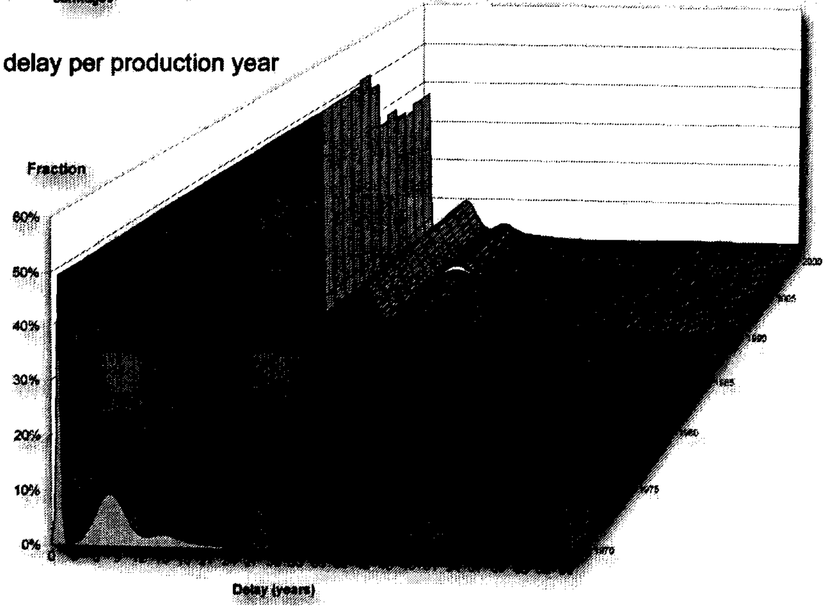
A1 - Partitioning to product catagories



A2 - Partitioning to waste catagories

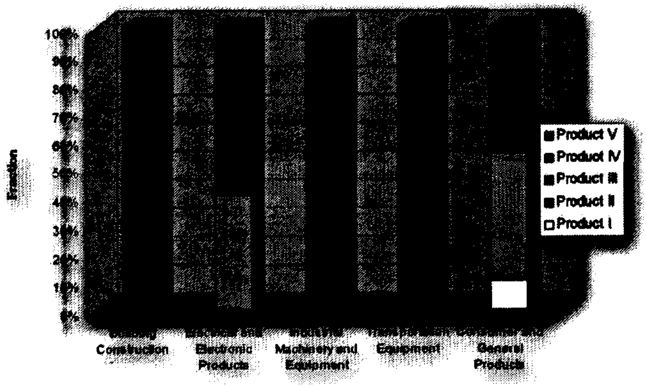


Distributed delay per production year

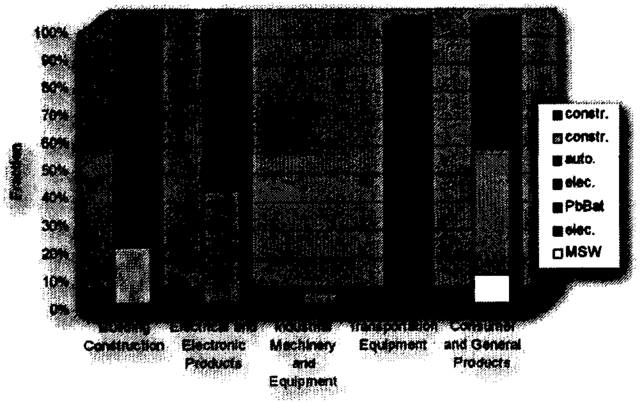


Bismuth

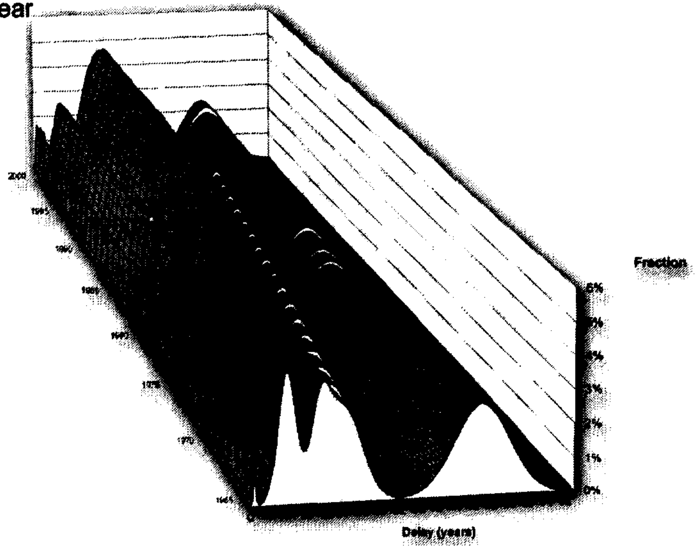
A1 - Partitioning to product catagories



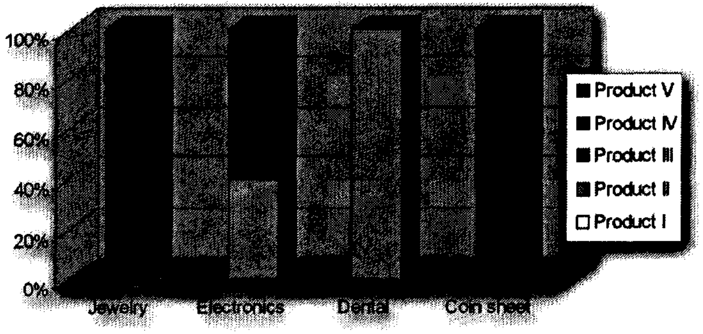
A2 - Partitioning to waste catagories

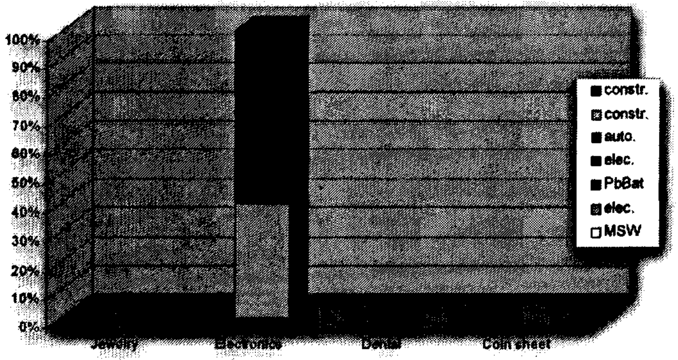


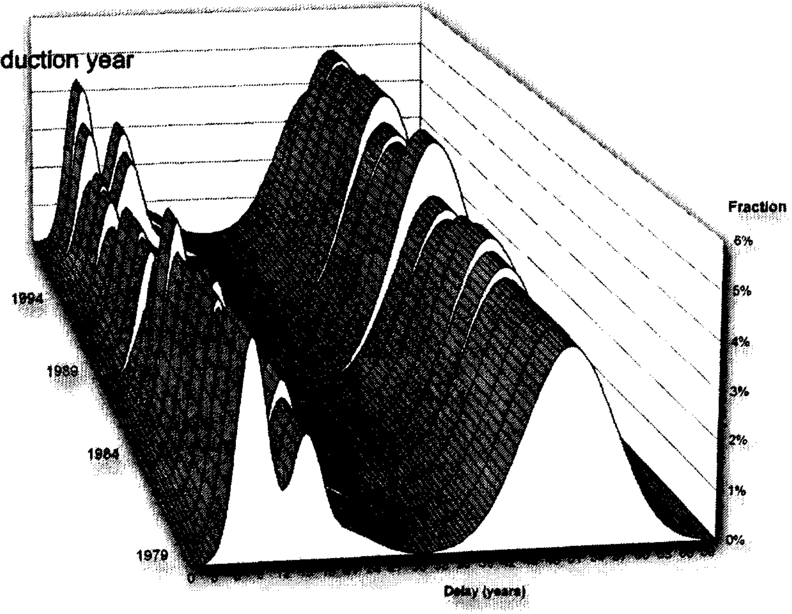
Distributed delay per production year



Copper

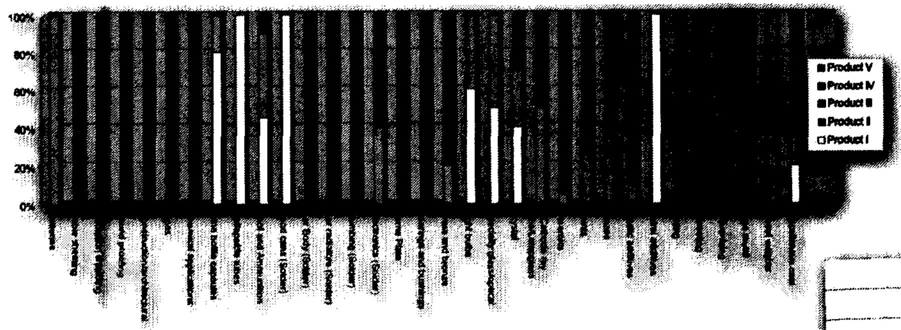

A1 - Partitioning to product catagories


A2 - Partitioning to waste catagories

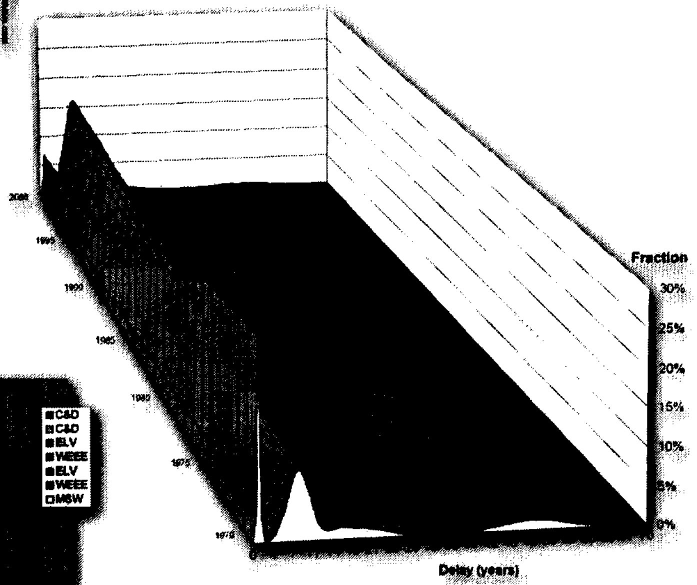

Distributed delay per production year

Gold

A1 - Partitioning to product catagories



Distributed delay per production year



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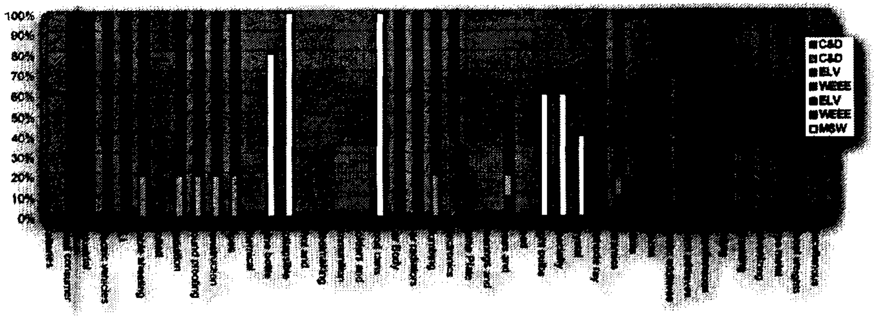
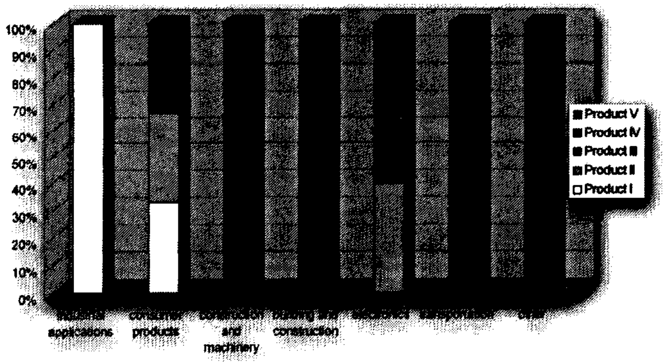
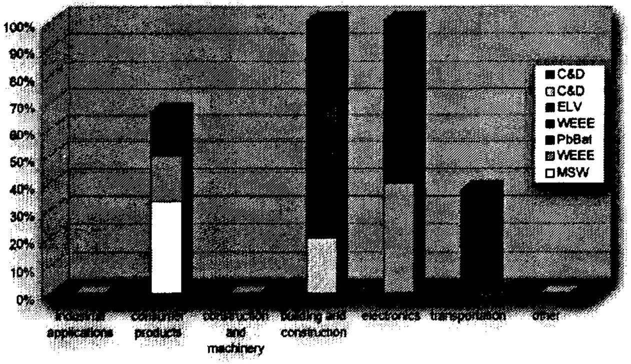
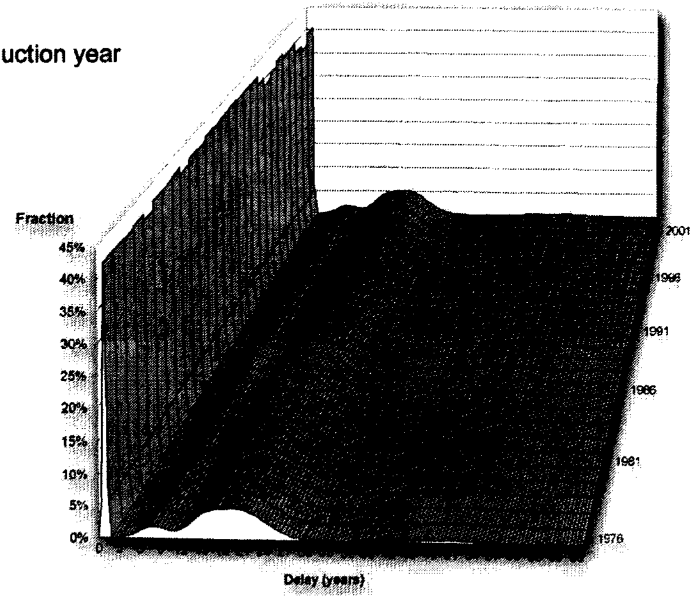


Lead

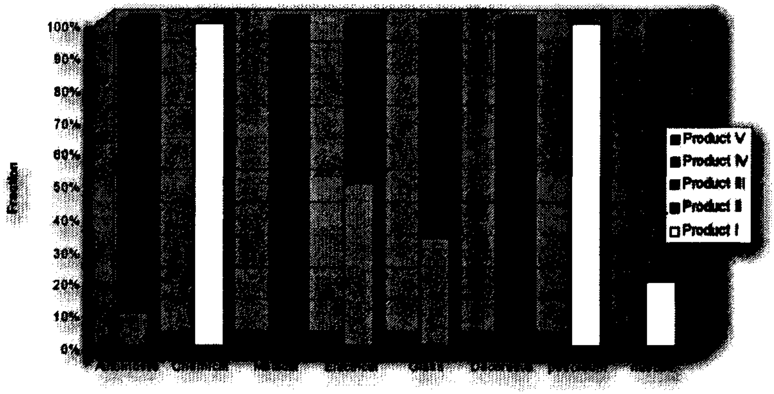

A1 - Partitioning to product catagories

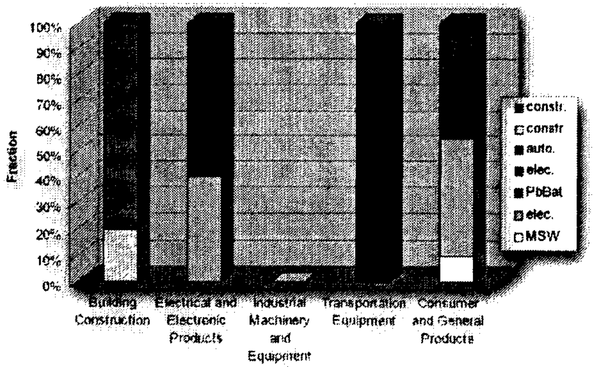

A2 - Partitioning to waste catagories

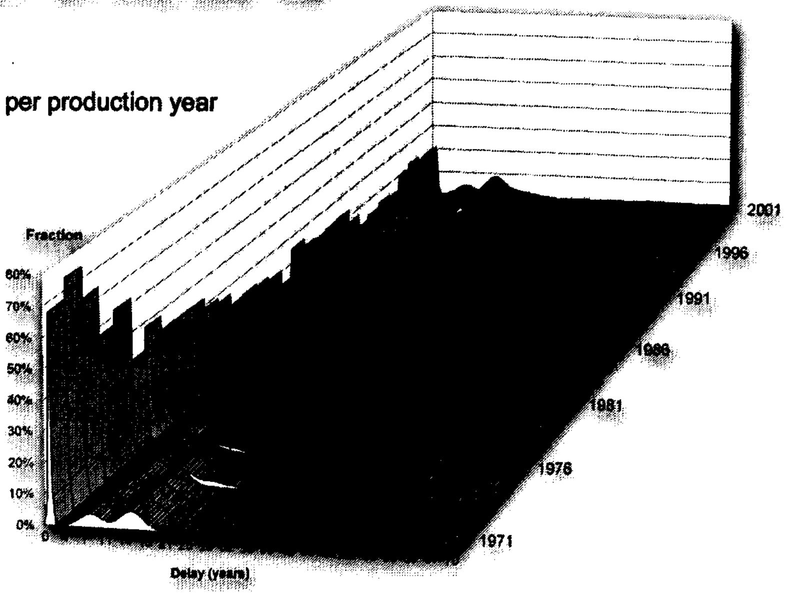
Distributed delay per production year



Nickel

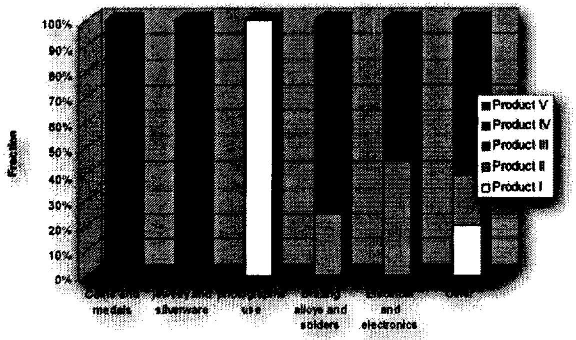

A1 - Partitioning to product catagories


A2 - Partitioning to waste catagories


Distributed delay per production year

PGMs

A1 - Partitioning to product catagories



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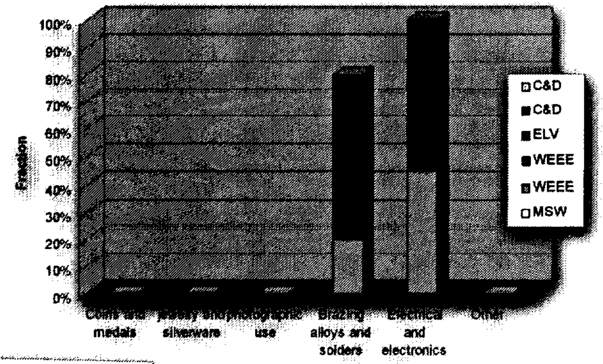
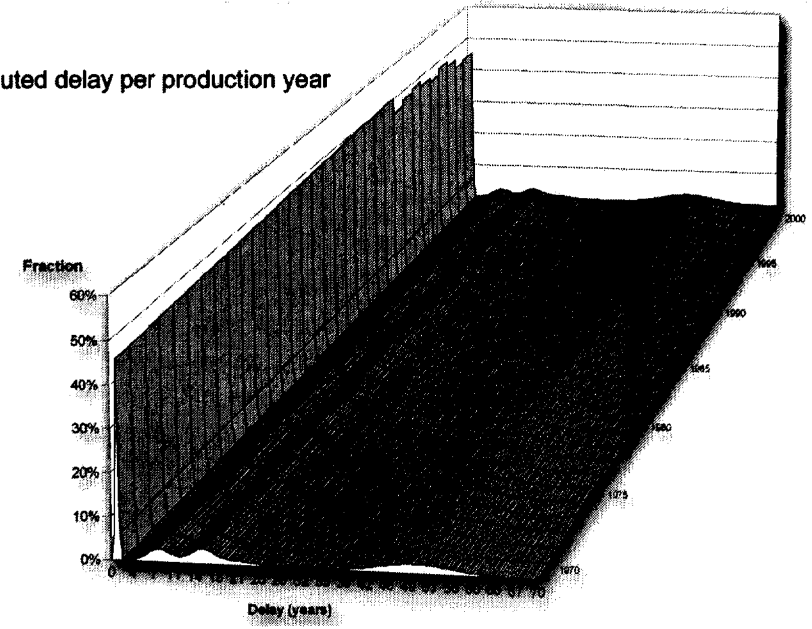
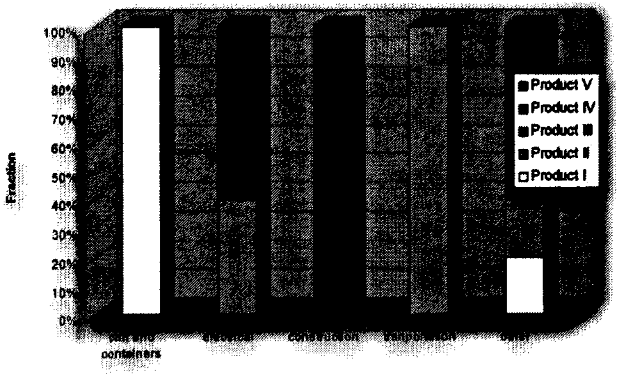


Distributed delay per production year

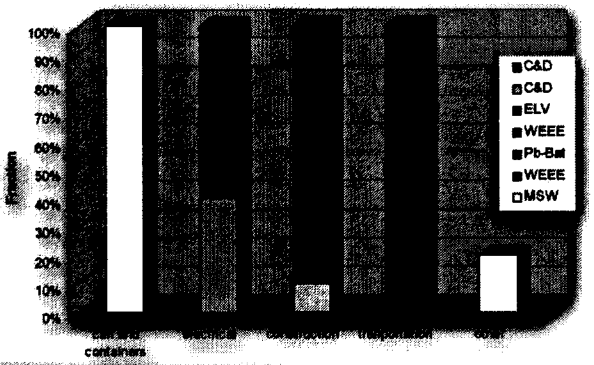


Silver

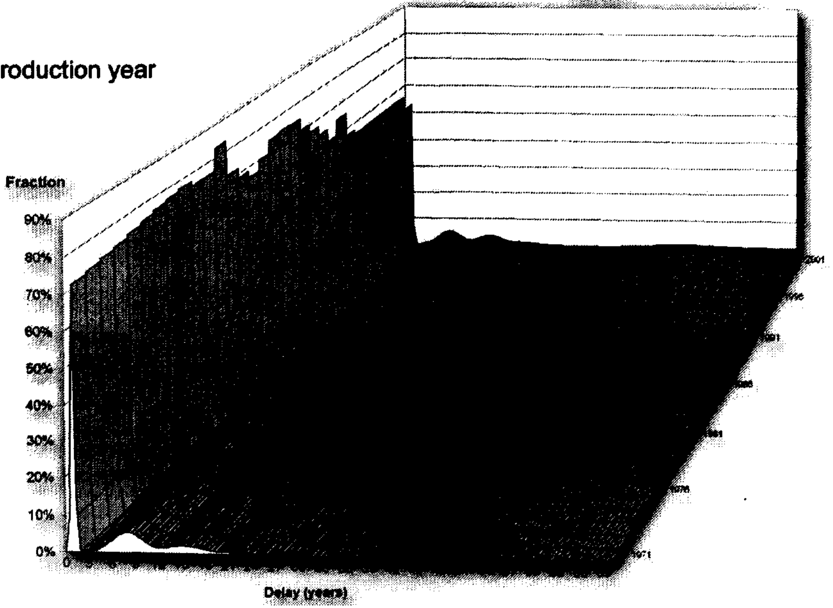
A1 - Partitioning to product catagories



A2 - Partitioning to waste catagories



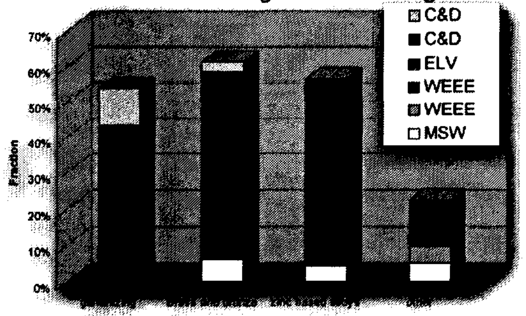
Distributed delay per production year



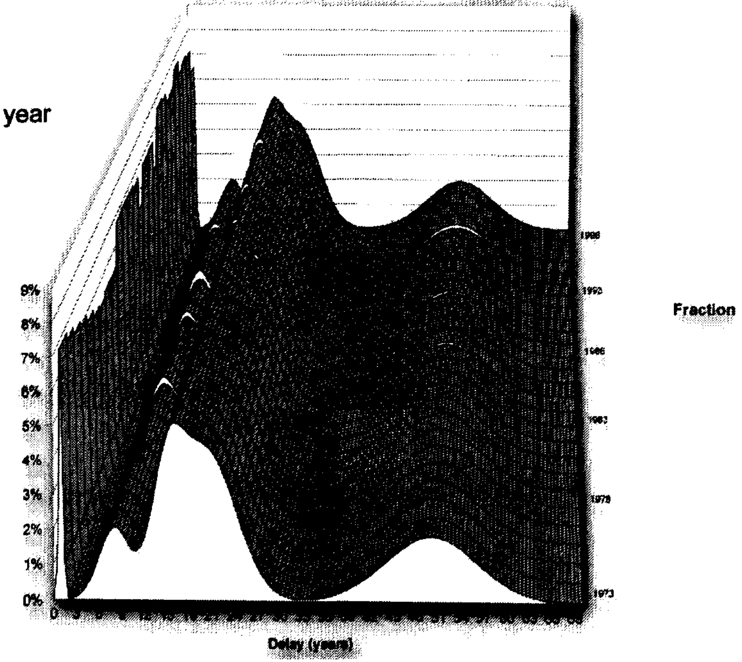
Tin

A1 - Partitioning to product catagories

A2 - Partitioning to waste catagories



Distributed delay per production year



Zinc

A.11.3 Solid waste management

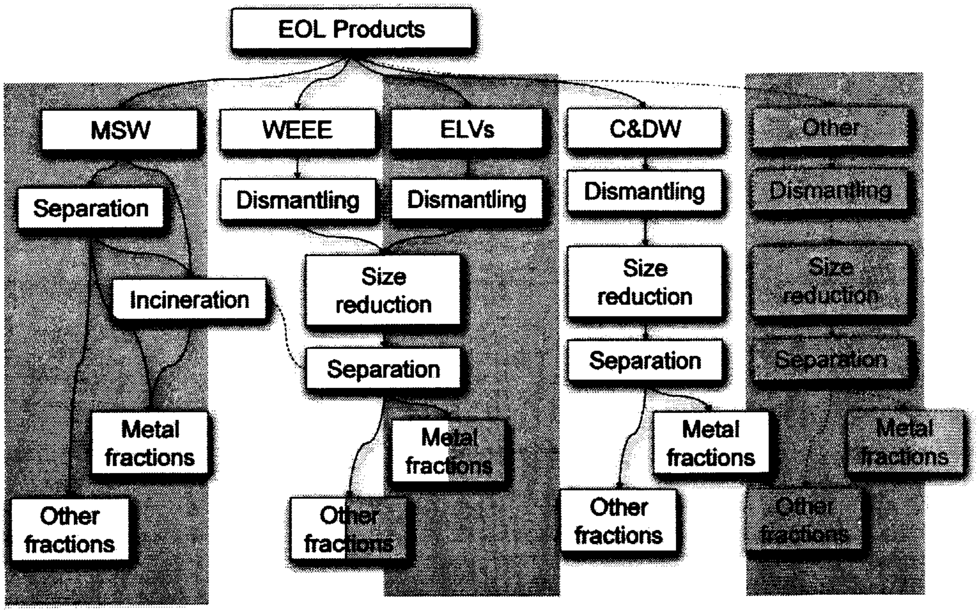


Figure 21: Simplified solid waste management flowchart.

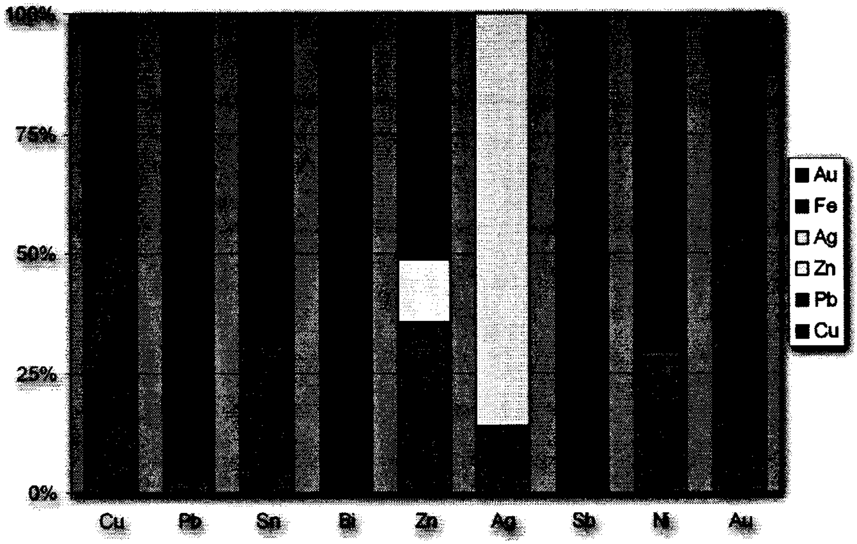
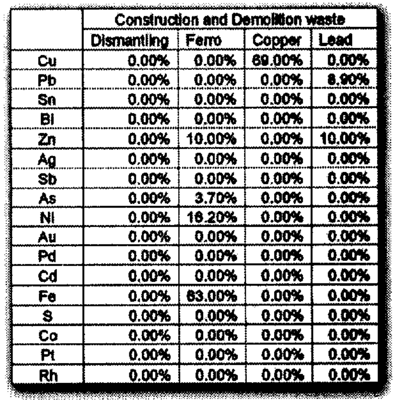


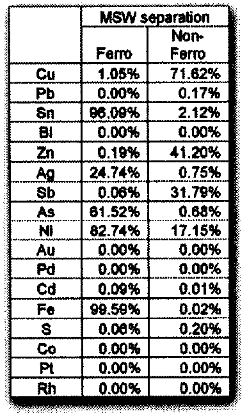
Figure 22: Partitioning of 'other' waste to carrier metals: Au, Fe, Ag, Zn, Pb and Cu.

	Grate Furnace				Bottom Ash Separation	
	Filter	Residue	Emission	Bottom Ash	Ferro	Non-Ferro
Cu	14.16%	0.96%	0.00%	84.88%	5.31%	1.29%
Pb	28.06%	12.13%	0.06%	59.75%	0.77%	0.03%
Sn	5.57%	36.23%	0.09%	58.11%	0.00%	0.00%
Bi	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Zn	27.29%	17.67%	0.02%	55.02%	2.24%	1.93%
Ag	13.70%	0.70%	0.02%	85.58%	0.00%	0.00%
Sb	9.01%	49.67%	0.09%	41.23%	0.00%	0.00%
As	9.46%	13.05%	0.10%	77.39%	0.00%	0.00%
Ni	4.20%	1.77%	0.05%	93.98%	0.00%	0.00%
Au	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Pd	8.37%	3.38%	0.01%	88.24%	0.00%	0.00%
Cd	57.33%	25.99%	0.04%	16.64%	0.00%	0.00%
Fe	0.19%	0.47%	0.01%	99.33%	60.00%	0.00%
S	28.20%	34.65%	5.78%	31.37%	0.00%	0.00%
Co	2.71%	6.73%	0.10%	90.46%	0.00%	0.00%
Pt	8.37%	3.38%	0.01%	88.24%	0.00%	0.00%
Rh	8.37%	3.38%	0.01%	88.24%	0.00%	0.00%

	MSW separation	
	Ferro	Non-Ferro
Cu	1.05%	71.82%
Pb	0.00%	0.17%
Sn	96.09%	2.12%
Bi	0.00%	0.00%
Zn	0.19%	41.20%
Ag	24.74%	0.75%
Sb	0.06%	31.79%
As	61.52%	0.68%
Ni	82.74%	17.15%
Au	0.00%	0.00%
Pd	0.00%	0.00%
Cd	0.09%	0.01%
Fe	99.59%	0.02%
S	0.06%	0.20%
Co	0.00%	0.00%
Pt	0.00%	0.00%
Rh	0.00%	0.00%



	Construction and Demolition waste			
	Dismantling	Ferro	Copper	Lead
Cu	0.00%	0.00%	69.00%	0.00%
Pb	0.00%	0.00%	0.00%	8.90%
Sn	0.00%	0.00%	0.00%	0.00%
Bi	0.00%	0.00%	0.00%	0.00%
Zn	0.00%	10.00%	0.00%	10.00%
Ag	0.00%	0.00%	0.00%	0.00%
Sb	0.00%	0.00%	0.00%	0.00%
As	0.00%	3.70%	0.00%	0.00%
Ni	0.00%	16.20%	0.00%	0.00%
Au	0.00%	0.00%	0.00%	0.00%
Pd	0.00%	0.00%	0.00%	0.00%
Cd	0.00%	0.00%	0.00%	0.00%
Fe	0.00%	63.00%	0.00%	0.00%
S	0.00%	0.00%	0.00%	0.00%
Co	0.00%	0.00%	0.00%	0.00%
Pt	0.00%	0.00%	0.00%	0.00%
Rh	0.00%	0.00%	0.00%	0.00%



	MSW separation	
	Ferro	Non-Ferro
Cu	1.05%	71.62%
Pb	0.00%	0.17%
Sn	96.09%	2.12%
Bi	0.00%	0.00%
Zn	0.19%	41.20%
Ag	24.74%	0.75%
Sb	0.06%	31.79%
As	61.52%	0.68%
Ni	82.74%	17.15%
Au	0.00%	0.00%
Pd	0.00%	0.00%
Cd	0.09%	0.01%
Fe	99.59%	0.02%
S	0.06%	0.20%
Co	0.00%	0.00%
Pt	0.00%	0.00%
Rh	0.00%	0.00%

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B - Model description

Summary

In this appendix, the model construction is explained. It is described how a model of interconnected material cycles can be founded on a solid technological base by building the model on a network of process steps that define the functional relationships between the different processes. It is described how the networks of reactors can be aggregated into the global resource cycles using simple assumptions about the dynamic relationships between processes, and between the various stages in the resource cycle. It is shown, how the effect of changing compositions and lifespans of products on waste generation can be modeled.

In this way, the model can visualize the dynamics at process level and its effect on the total resource cycles in an understandable way at different organizational levels, and vice versa. Due to its modular architecture economical, legislative or environmental factors can be included in the model as constraints, and evaluated at process level.

B.1 General model framework

Substance Flow Accounting (SFA) is used as basis for the model. SFA models belong to the family of Material Flow Accounting (MFA) models, with which the physical aspects of human activities can be mapped (Baccini and Brunner 1991, Baccini and Bader 1996). As discussed in chapter 2, a MFA model is based on the principle of mass preservation and describes flows, accumulations of materials in the economy and the environment. As there is no standardized framework for SFA, as there is for LCA, the LCA framework is used. The Leiden University Centre for Environmental Science adopted and modified the LCA framework for SFA (e.g. Van der Voet 1996, Udo de Haes et al. 1997, Udo de Haes and Van der Voet 1997, Huppes et al. 1997). This framework consists of three distinct phases, which structure the analysis, and are based on the technical framework of LCA (ISO 14040):

1. *Objective and system definition*: This first phase corresponds to the first phase in LCA, Goal and scope, and involves four choices. The first step SFA modeling is the choice of the objective of the study. According to the goal of the study, the second step is to establish whether the studied system should correspond to a certain region, the regional approach, or a certain function, the functional approach. This also involves the definition of subsystems. The third step is the time span. Often, in MFA studies a one year period is chosen, and the accumulated flows for the region or the function are determined for that period. The fourth step concerns the materials and flows to be studied. An SFA can be carried out for a single substance, or a number of related materials (e.g. connected to a function).
2. *Inventory and modeling*: This phase correspond to the second phase in LCA, the inventory phase and involves identifying, collecting and organizing relevant data. This data can be organized in one of three different types of modeling, all three types having there own data requirements, viz. bookkeeping, static modeling and dynamic modeling.
3. *Interpretation*: The last stage of an MFA study is to interpret the quantitative results on flows and stocks. For an MFA study where only one substance or group of substances is studied, the interpretations of the result might be relatively simple. This is not the case for complex MFA studies with several materials. In these studies, the result may be interpreted by using environmental issues, or environmental impact categories, such as global warming, eutrophication, or acidification (Udo de Haes and Van der Voet 1997). This is the same procedure as in LCA, where it is called classification and characterization.

In the following sections, the general layout of the model is discussed based on these three phases.

B.1.1 Goal and system definition

An SFA can be used for quite different purposes: as a support for data acquisition, for the analysis of trends and their causes, for the identification and the prediction of the effectiveness of environmental measures, and as a screening tool, identifying issues for further investigation by other tools (Udo de Haes et al. 1997a). In the identification or evaluation of potential policy measures SFA offers the possibility to predict the emergence of new or unexpected problems. In the SFA model developed, the objective is to investigate the consequences of policy measures, viz. replacing lead in solder for electronic and electrical appliances on the global metal cycles. The specific focus of the study is on the effects on the production and recovery of metals.

Often an SFA deals with one substance only. If measures are taken to reduce the use of the substance under study by replacing it by another substance, problems connected with this other substance are outside the scope of such studies. Rather than a single substance the model therefore deals with a group of metals that are related to the production of lead (free) solder, as well as a representative selection of the co-elements associated with those metals. The metals investigated in this study are copper, lead, tin, bismuth, zinc, nickel, silver, gold and three platinum group metals (PGMs: platinum, palladium and rhodium). In addition, the following co-elements are considered: sulfur, arsenic, antimony, cadmium, iron, and cobalt. In the determination of emissions of the different processes involved in the production and recovery of the metals, also nitrogen, oxygen and carbon are included. The selection of elements allows a good representation of the compositions of the material flows through the system.

The choice of the materials investigated sets the system boundaries of the modeled system. The market for metal production is global; the concentrate, scrap, metal and valuable intermediates are transported and traded worldwide. Consequently, metals are produced by an entangled network of interconnected production routes, rather than by geographically isolated production centers. The system boundaries of the SFA are function based; the focus of the analysis is the global metal production system.

The time span of the study is determined by the dynamics of the global metal production system. The study focuses on the global lead production system, and investigates the effects of the introduction of a number of lead-free solders in the present global metal production system. Because of the delays in the system, it takes time before the substitution of lead in solder has trickled through the global system, and the effects can be evaluated. The time span of the study is therefore at least the life span of electrical and electronic appliances in which the lead is substituted. Moreover, to estimate the waste flows returning to the metal production system (and partially replacing the virgin ore concentrates) the historical metal production must be integrated over a maximum of roughly 60 years, obviously dependent on assumptions for the average life spans of the different metals considered.

With respect to the definition of subsystems, it is usual to make a distinction between the ‘society’ and the natural environment. Within society, the attention is generally focused on the physical economy. SFAs and MFAs refer to accounts in physical units comprising the extraction, production, transformation, consumption, recycling, and disposal of materials (e.g. ores, raw materials, base materials, products, wastes, and emissions). In the model, therefore, the physical economy is further divided into mining, metal production, product manufacture, consumption and solid waste management compartments. The environment is often split into a number of environmental media such as lithosphere (i.e. the earth’s crust), atmosphere, hydrosphere, soil (or ‘pedosphere’) and biosphere. Metal production processes directly affect the atmosphere, soil and part of the hydrosphere (mainly groundwater), which in turn influence the other parts of the hydrosphere and the biosphere. In the model the environment is split into only these first four compartments, the induced changes are considered in the interpretation phase. Note that in contrast to LCA, the definition of the borderline between society and environment in SFA is not so much a critical issue. The core issue in LCA concerns the transgression of substances over this borderline, either as the extraction of resources or as the emission of hazardous substances. SFAs consider both the accumulations within the environment and the economy; therefore, the possible effects are considered, independent from the precise definition of the borderline between the two subsystems (Udo de Haes and Van der Voet 1997).

B.1.2 Inventory and modeling

This step involves identifying, collecting and organizing relevant data. Udo Haes and Van der Voet (1997) distinguish at least three types of models for the modeling of flows and stocks: (i) book keeping, (ii) stationary modeling and (iii) dynamic modeling. Considering the interdependent dynamics of the metal production systems, the dynamic model seems the logical choice for the SFA model developed. The modeling approach and the modeling of the five stages that together represent the life cycles of a metal will be discussed in more detail in sections B.2-B.3.

B.1.3 Interpretation

The last stage of an MFA study is to interpret the quantitative results on flows and stocks. In most SFA studies, the output is defined in terms of flows and accumulations of the material under study. The relevance of the analysis is generally directly related to the hazardous character of the chosen material and will need no further specification (Udo de Haes et al. 1997). In some cases, there is an explicit need for further elaboration of the SFA results, for example, if a group of substances is studied. Here it is difficult to make a comprehensive interpretation of such an amount of data without some form of aggregation. A possible way to interpret the outcome of SFA studies is the specification of the contributions of the substances to a number of environmental issues or environmental impact categories, such as global warming, ozone depletion, and acidification. This approach links up with the development of LCA impact assessment methodology. An example of such approach is the recent SFA study on chlorinated hydrocarbons in The Netherlands (Kleijn et al. in: Udo de Haes et al. 1997) that used environmental impact categories such as global warming, ozone depletion and ecotoxicity. Other examples include the studies on chlorine and PVC for the Dutch government and Norsk Hydro that also combined elements of SFA and Life Cycle Impact Assessment (LCIA) (Kleijn et al. 1997, Tukker et al. 1995 and 1996). Based on the studies Tukker and Klein (1997) conclude that environmental evaluation methods like SFA and LCA can successfully be used in combination. Obviously, the output of an SFA of the complex, global interconnected metals cycles requires aggregation in some way to enable interpretation. The SFA model is therefore combined with elements of LCIA. This is discussed in more detail in section B.4.

B.2 The inventory and modeling approach

The focus of the study is on the operation of the interconnected metal cycles, more specifically on the production and recovery of metals. In order to properly assess the environmental aspects of metallurgy, or to adequately capture the interdependent dynamics of the global system, modeling is required that is based on the fundamental thermodynamics in each metallurgical reactor, of waste processing step. For that reason, the dynamic inventory has been constructed by employing a bottom-up approach, where the interconnected circuits for metal production and recovery are represented by a series of individual processes and/or reactors. The SFA inventory is modeled in Simulink^{TM}, an interactive graphical interface for modeling, simulating and analyzing dynamic systems in Matlab (®Mathworks Inc. 2000). The equations that constitute the dynamic system model are input by the selection and connection of the appropriate blocks that represent elementary mathematical operators. In the dynamic simulation, Simulink calculates all blocks in a given order for each time step.

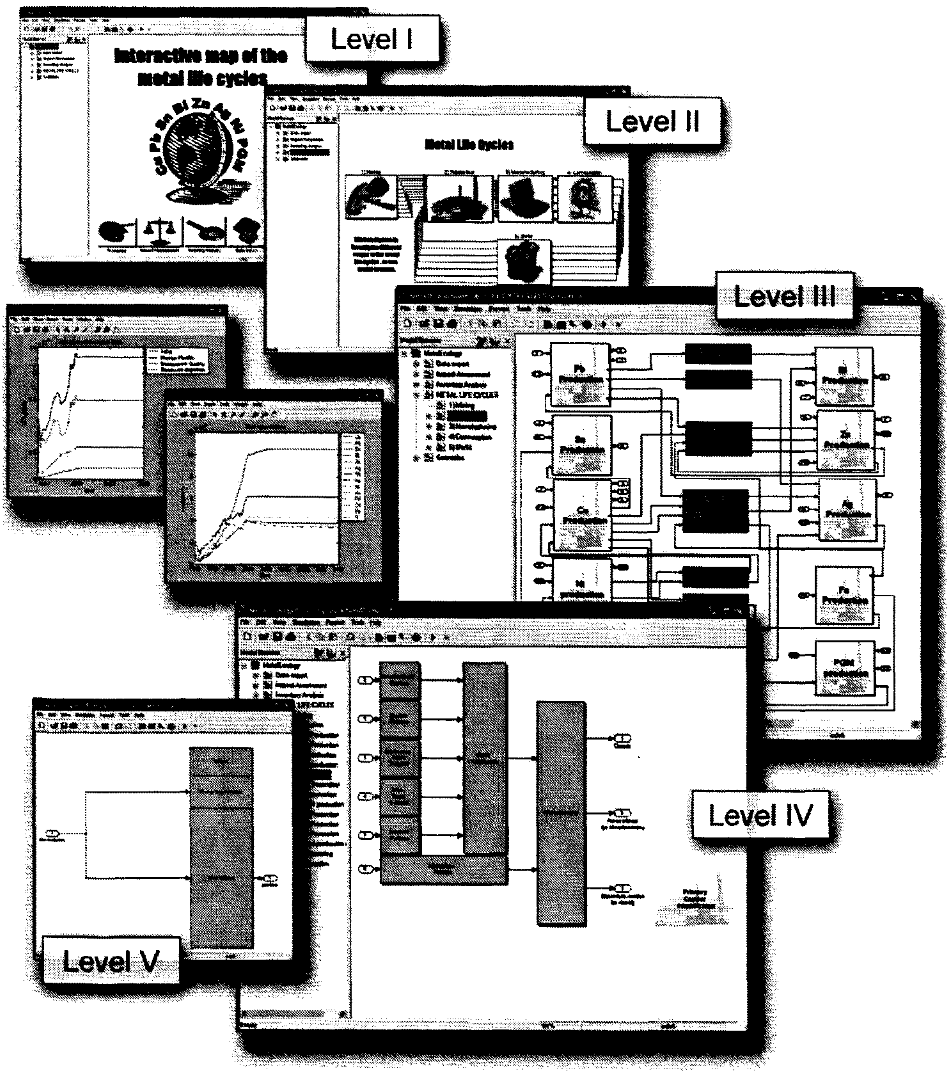


Figure 1: Hierarchical structure of the Simulink model.

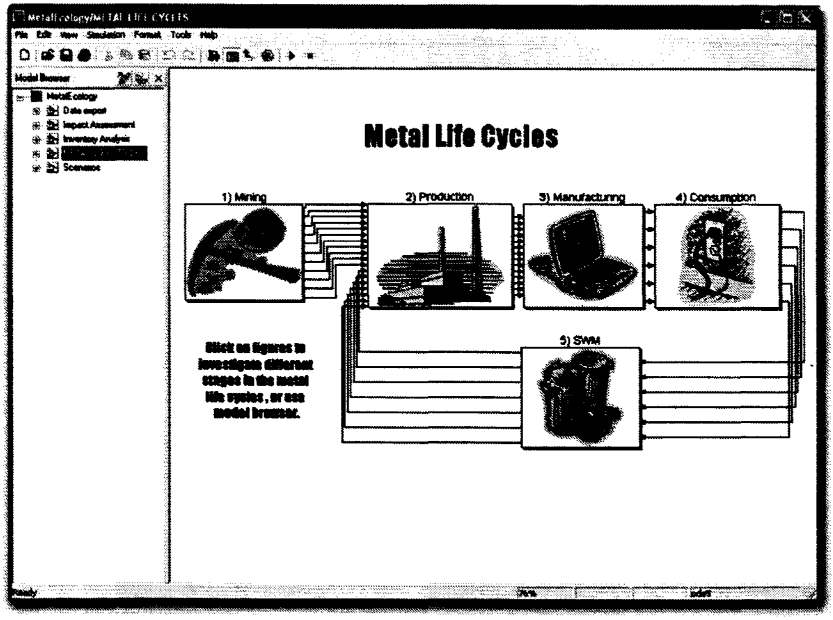
The first level shows the general menu to access the mass balances, impacts assessment, dynamic inventory or different scenarios. The second level incorporates the five phases in the life cycle of a metal: mining, metal production, product manufacturing, consumption, and waste management. The third level shows the interconnected metal production systems. The higher levels show increasing technical detail: the different process steps in the production of these metals, and interconnections between the metal production processes in more detail. At all levels of detail, a description of the flowsheets and flowsheet components is given, which can be accessed by clicking on the info button (general information) or on each of the different flowsheet components. As mentioned in chapter five, this hierarchical method of modeling and representation provides a transparent overview of the interconnected metallurgical production circuits, and would be suited to initiate further development of the products, or the production network by the stakeholders involved. As such, the model could assist in making the complex metallurgical knowledge available for waste management, policy and product design.

Mass-balance calculations based on data reconciliation allow simulation of system change and track the effect on the system performance. In addition, the model is structured such that emissions can be traced down to individual processes or reactors. The modeling approach allows the investigation of a wide range of scenarios, because all parameters can either be fixed over time or given a scenario for change over time. For instance, the effect of the development of new products can be modeled by a change in the metal production rates, distribution of the metals concerned over products and waste categories. Alternatively, a new technology or process step can easily be included in the model because of the bottom up modeling approach combined with the modular structure of Simulink™, the Matlab™ programming environment. By using the options available for parameter manipulation, the effects of a shift in employed technology can be analyzed.

B.2.1 Modeling of the metal life cycles

As discussed in chapter three, the environmental impact and efficiency of metal production is dependent on the total demand for the metal, but also on the demand for other metals via intermediates, and the availability of other metal resources, viz. new and old scrap. In particular secondary materials are increasingly important raw materials for the production of metals. The rate of generation of the secondary raw materials and their compositions, are a function of the combination of metals and other materials into different products, and the lifespan of these products (see chapter three and five). Level two of the model (Figure 2) shows this interdependence between the different stages in the metal life cycle.

An important aspect of the Simulink model developed is that it allows dynamic simulations of the operation of the interconnected metal cycles, in particular the changing interdependencies in the production and recovery of metals. Until recently, quantitative descriptions of the physical economies have concentrated mostly on flows without considering the build-up of stocks in the economies (Klein et al. 2000). During the past few years, researchers have realized that the delay of materials in the consumption phase is an essential component of such descriptions, for example in the prediction of future emissions and waste flows (Bergbäck and Lohm 1997, Guinée et al. 1999, Klein et al. 2000, Müller 2001 and 2002). Today's stocks are tomorrow's emissions and waste flows. Moreover, because of the time lag introduced by the buffering function of the stock of materials and products in society flows, which seem to be under control, can easily rebound. Large stocks of metals have accumulated in the economic system, which must be dealt with in some way or the other. An increasing fraction of secondary raw materials in metal production may significantly reduce the grade of the produced metals (see chapter 4). To develop an adequate waste and metallurgical infrastructure to recycle the wasted metals into high-grade raw materials, information on the amount of wastes, and material combinations flowing from the economic stocks is required. Figure 2 shows the different stages of dynamic mass balance of the interconnected metal life cycles, which form the basis of the model.



Click on figures to investigate different stages in the metal life cycles, or use model browser.

Figure 2: Level two of the Simulink model shows the different stages in the metal life cycle.

B.2.2 Mining

The efficiency and environmental impact of metal mining and extraction is not constant but is a function of the mining and extraction route. The mining and extraction route for each ore is modeled separately. The demand for ore is dependent on the total demand for a metal and the availability of other metal resources, viz. new and old scrap, and intermediates. For each ore follows:

$$D_{ore,i}(t) = \left(f_{air,ore,i} + \sum_{j=1}^{j=n} f_{ore,i,j} + f_{tailings,i} \right) \cdot D_{ore,i}(t) \tag{1}$$

And for each ore concentrate:

$$P_{ore,j}(t) = \sum_{i=1}^{i=k} f_{ore,i,j} \cdot D_{ore,i}(t) \tag{2}$$

In which:

$D_{ore,i}(t)$ = Demand for ore i (ton/a)
$f_{air,ore,i}$ = Fraction of ore i emitted into air (ton/ton)
$f_{ore,i,j}$ = Fraction of ore i processed into ore concentrate j (ton/ton)
$f_{tailings,i}$ = Fraction of ore i processed into tailings (ton/ton)
n = Number of ore concentrates i produced
$P_{ore,j}$ = Production of ore concentrate for metal j
k = Number of ores that produce ore concentrate for metal j

The leaching model that connects the tailings disposal of tailings to emissions into soil and water (as well as the slag and residues from other life cycle stages) is discussed in section B.4.4. The ore extraction and concentration modules underlying equation 1 are discussed in more detail in section B.3.4.

B.2.3 Metal production

Dependent on the availability of metals resources (new and old scrap, intermediates and ore) the metals are produced through the different processing routes, and as a consequence the efficiency of metal production, $f_{metal,i}(t)$, is not constant but a function of time:

$$R_i(t) = \left(f_{air,metal,i}(t) + f_{metal,i}(t) + \sum_{j=1}^{j=n} f_{inmed,i,j}(t) + f_{slag,i}(t) \right) \cdot R_i(t) \tag{3}$$

$$R_i(t) = P_{ore,i}(t) + S_{inmed,i}(t) + S_{new,i}(t) + S_{old,i}(t) \tag{4}$$

$$P_{metal,i}(t) = f_{metal,i}(t) \cdot R_i(t) \tag{5}$$

$$P_{inmed,j}(t) = \sum_{i=1}^{i=k} f_{inmed,i,j}(t) \cdot R_i(t) \tag{6}$$

In which:

$R_i(t)$ = Supply of resources for metal i (ton/a)
$f_{air,metal,i}(t)$ = Fraction of resources emitted into air (ton/ton)
$f_{metal,i}(t)$ = Fraction of resources processed into metal i (ton/ton)
$f_{inmed,i,j}(t)$ = Fraction of resources processed into intermediate j (ton/ton)
$f_{slag,i}(t)$ = Fraction of resources processed into slag (ton/ton)
n = Number of intermediates produced
$P_{ore,i}(t)$ = Production of ore concentrate for metal i (ton/a)
$S_{inmed,i}(t)$ = Supply of intermediates for metal i (ton/a)

$S_{new,i}(t)$ = Supply of new scrap for metal *i* (ton/a)
$S_{old,i}(t)$ = Supply of old scrap for metal *i* (ton/a)
$P_{metal,i}$ = Production of metal *i* (ton/a)
$P_{inmed,i,j}(t)$ = Production of intermediates for metal *j* (ton/a)

The dynamic efficiency of metal production can be included by modeling bottom up, starting from individual process steps. The different metal production flowcharts presented in appendix A were modeled as described in sections B.3.1 to B.3.3. The relation between the production of intermediates in one production circuit and the supply of intermediates to another is discussed in section B.3.3 (see equations 4 and 6). Note that the different production routes for the metals are not constrained by a maximum capacity; an increase in the production volumes of the metals does not affect fraction of metal produced through a production route. Because of the modular structure these constraint can easily be added.

B.2.4 Manufacture and consumption

To estimate composition and quantity of the generated waste at a point in time, or the dynamics in the metal cycles in case of disturbance, the delays in the consumption (life spans of the products) need to be estimated. In the model the delays in the production of metals are assumed negligible compared to delays in the consumption phase, that vary from less than one year to well over fifty years. The metals are manufactured into five hypothetical products to estimate the average delays of the metal in the consumption phase. Energy consumption during manufacturing or consumption is not included in the model. Equations 7 to 9 describe the manufacturing and equation 10 the consumption phase respectively:

$$P_i(t) = \left(f_{air,man,i} + \sum_{j=1}^{j=m} f_{man,i,j}(t) + f_{new,i} + f_{res,i} \right) \cdot P_i(t) \tag{7}$$

$$P_{man,j}(t) = \sum_{i=1}^{i=n} f_{man,i,j}(t) \cdot P_i(t) \tag{8}$$

$$P_{new,i}(t) = f_{new,i} \cdot R_i(t) \tag{9}$$

In which:

n = Number of substances considered in manufacturing
$P_i(t)$ = Production of substance *i* (ton/a)
$f_{air,man,i}(t)$ = Fraction of substance *i* emitted into air (ton/ton)
m = Number of products produced *(m=5)*
$f_{man,i,j}(t)$ = Fraction of substance *i* processed into product *j* (ton/ton)
$f_{new,i}(t)$ = Fraction of substance *i* processed into new scrap *i* (ton/ton)
$f_{res,i}(t)$ = Fraction of substance *i* processed into residue (ton/ton)
$P_{man,j}(t)$ = Manufacture of product *j* (ton/a)
$P_{new,i}(t)$ = Generation of new scrap *i* (ton/a)

$$\sum_{j=1}^{j=m} P_{man,j}(t) = \sum_{i=1}^{i=n} \frac{1}{(1-f_{diss,i})} \cdot \frac{dC_i(t)}{dt} + \frac{1}{(1-f_{diss,i})} \cdot P_{waste,i}(t) \tag{10}$$

In which:

$f_{diss,i}$ = Fraction of i lost through dissipative uses (ton/ton)
$C_i(t)$ = Stock of i in consumption (ton)
$P_{waste,i}(t)$ = Discarding of substance i (ton/a)

The modeling of new scrap generation, the composition of the products, the accumulation in consumption phase and the emissions from dissipative use of metals are discussed in section B.2.4.

B.2.5 Solid waste management

As a function of the final products of metals and other substances collected as waste j, waste is disposed and recovered through the different processing routes, and the efficiency of waste recovery, $f_{old,i,j}(t)$, is thus a function of time:

$$P_{waste,i}(t) = \left(f_{air,waste,i}(t) + \sum_{j=1}^{j=n} f_{old,i,j}(t) + f_{fres,i}(t) \right) \cdot P_{waste,i}(t) \tag{11}$$

$$S_{old,j}(t) = \sum_{i=1}^{i=n} f_{old,i,j}(t) \cdot P_{waste,i}(t) \tag{12}$$

In which:

$P_{waste,i}(t)$ = Discarding of substance i (ton/a)
$f_{air,waste,i}(t)$ = Fraction of waste i emitted into air (ton/ton)
n = Number of substances considered in manufacturing
$f_{old,i,j}(t)$ = Fraction of substance i processed into old scrap j (ton/ton)
$f_{fres,i}(t)$ = Fraction of waste i disposed of as final residue (ton/ton)
$S_{old,j}(t)$ = Supply of old scrap for metal i (ton/a)

The solid waste management phase is modeled in a similar way as the metal production phase. The different solid waste management routes as presented in Appendix A were modeled as described in sections B.3.1 and B.3.6. The energy consumption is mainly a function of the energy required for the transport of the waste in the collection, processing and delivery to the metal production facilities.

B.3 Bottom-up approach

In the next section, the bottom up modeling approach used to model metal production and recycling is further elaborated starting from the modeling of individual processes to the interconnected metal production and recovery flowcharts. Subsequently, the modeling of the mining, consumption, and manufacturing stages is discussed.

B.3.1 Level V: Individual processes

Figure 3 shows a process model in Simulink, consisting of mass balance, energy and emission (Off gas) calculations blocks. The calculations in these three blocks are discussed in the sections below.

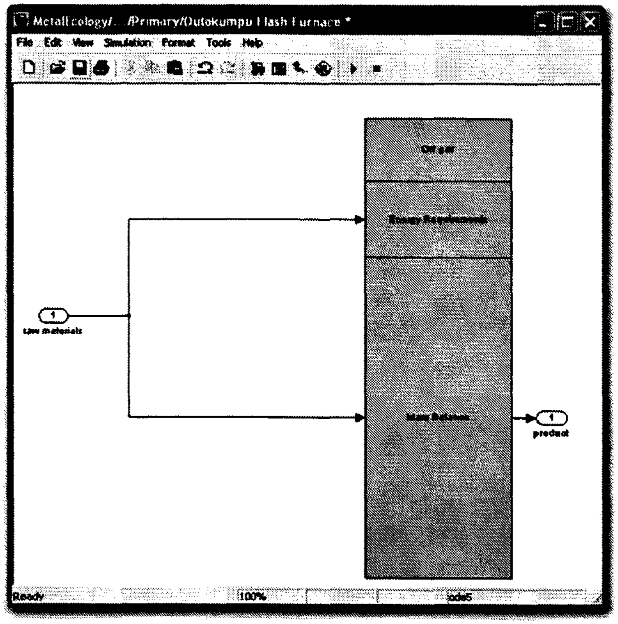


Figure 3: An individual process in Simulink

B.3.1.1 The mass balance of a process

The core of both the stationary and dynamic model is the development of a consistent mathematical structure, which renders it possible to specify relations between the different flows and stocks within the system. In this way, specific problem flows can be analyzed with regard to their origins. In addition as argued above, for an assessment the environmental aspects of metallurgy, or the modeling of the impact of a system change on the pattern and the balance of relationships between processes, dynamic modeling of the total system is required. Such modeling has to be based on the fundamental thermodynamics of each metallurgical reactor, its geographical distribution and the prevalent knowledge. To meet these criteria, literature reports of the individual process steps in the production of metals were reviewed to obtain input and output data for each process step in the network (in the mining, metal production and solid waste management stages). This is consistent with the preferred use of data regarding the distribution characteristics of the processes themselves. After Reuter (1998) linear relationships (split-factors) between feed and process outputs were used to approximate the fundamental thermodynamics in each production step.

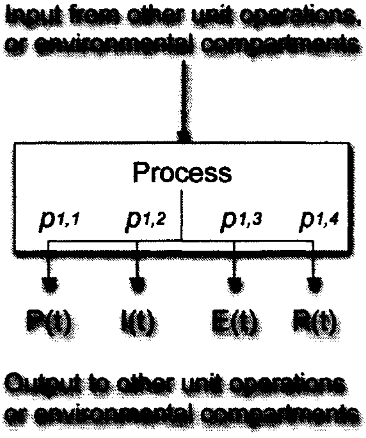


Figure 4: Schematic representation of a unit operation model. Legends: P= product, I=intermediate, E=emission, and R=residue.

The process split-factors (the vector of distribution fractions of the feed over the product, by-product, emission and residue streams respectively) are calculated by mass balancing the total mass flows in and out the process (eq. 13), as well as the mass flows of 14-17 chemical elements individually, dependent of the processes considered (eq. 14). Elements considered were copper, lead, tin, bismuth, zinc, silver, antimony, arsenic, nickel, gold, palladium, cadmium, iron, sulfur, cobalt, platinum and rhodium. In such a way dependent on feed quantity, amounts and compositions of products, by-products and residues can be calculated as a function of time. Mathematically Figure 4 can be written as:

$$\varphi_{in}(t) = \sum_{j=1}^{j=m} \varphi_{out,j}(t) \qquad (13)$$

$$\varphi_{in,j,i}(t) = p_{j,i} \cdot \varphi_{in,i}(t) \qquad (14)$$

In which:

m = Number of output streams
φ_{in} = Process feed
$\varphi_{out,j}$ = Output stream *j*
$\varphi_{in,j,i}$ = Element *i* of output stream *j*
$\varphi_{in,i}$ = Element *i* of feed,
$p_{j,i}$ = Element *i* of split factor for output stream *j*

A problem of the modeling approach adopted is that detailed information on the compositions of products, by-products and waste is needed to calculate split factors for each process in the network. These compositions could be obtained from literature reports on different plants, however, data was often not consistent and mass balances could often not be closed. This is a common problem in engineering, where mass balances based on measured data often are not complete. This is usually caused by inaccuracy of the measurements because of the sampling, measurement and analysis errors as well as the very lack-of-measurements. Madron (1992) and later Veverka and Madron (1997) gave overviews of data reconciliation: a set of methods used to adjust the experimental data to reduce and possibly eliminate discrepancies in the mass balance. Data reconciliation is basically minimizing a sum of errors (the difference between each measured data and its reconciled value) weighted by the standard deviation of the measurement, *J(Y)*, subject to a number of constraints (the mass balance equations). The mathematical denotation for the data reconciliation is as follows:

$$J(Y) = \sum_{p} \sum_{i} J_{pi}(Y) \tag{15}$$

$$J_i(Y) = \left[\frac{Q_{pi} - \bar{Q}_{pi}}{\sigma_{pi} \cdot Q_{pi}} \right]^2 + \sum \left[\frac{P_{pik} - \bar{P}_{pik}}{\sigma_{pik} \cdot P_{pik}} \right]^2 \tag{16}$$

In which

Q_{pi}, P_{pik} = Estimated Magnitudes
$\sigma_{pi}, \sigma_{pik}$ = Error
$\bar{Q}_{pi}, \bar{P}_{pik}$ = Measured Magnitudes
$\bar{Q}_{pi}, Q_{pi}$ = Flow rate of phase *p* in stream *i*
$\bar{P}_{pik}, P_{pik}$ = Fraction of component *k* of phase p in stream *i*
σ_{pi} = Possible estimated measurement error in Q_{pi} (%)
σ_{pik} = Possible estimated measurement error in P_{pik} (%)

Adjustments to experimental data are subjected to a number of restrictions, viz. the conservation of global flow rate (eq. 17), the conservation of global and elements flow rates (eq. 18) and the data integrity constraint (eq. 19):

$$\sum_{k} P_{pik} = 1 \tag{17}$$

$$\sum_{i} Q_{pi} \cdot P_{pik} = 0 \tag{18}$$

$$\sum_{i} Q_{pi} = 0 \tag{19}$$

In the reconciliation of the mass balances of processes for the dynamic modeling, the data is not based on measurements, but on processing data of plants around the world found in the literature. The essentials of the data reconciliation technique, however, remain the same. Calculation of the average compositions as a basis for constructing the mass balance normally does not result in a completed mass balance of the unit operation employing linear algebra. Using the standard deviation in the data as a measure for the accuracy of the data, a closed mass balance can be obtained using data reconciliation.

Because the thermodynamics and physics of the processes are not always fully understood, and process outputs are partially controlled with the tacit knowledge of the process crew, these split-factors are difficult to determine and can vary between different processes, or with feed composition. The work of Reuter (1998) showed that the approach taken provides for a good representation for average process operation. The software used for data reconciliation is Excel 2000. The maximum number of elements that can be reconciled is limited by the computational capacity of Excel's standard solver, and therefore only critical elements were included in the mass balance. Further details of the reconciliation process and the raw data can be found in Scholte (2002) and Van Tweel (2004). The reconciled mass balances for all metals are given in appendix A, sections A-2 to A-10.

B.3.1.2 The emissions of a process

Based on the mass balance emissions, material and energy consumption of the process are calculated. Solid wastes are not considered emissions, however their subsequent disposal on landfills does lead to the leaching the metals, which results in environmental hazards to soil and groundwater (see Impact assessment). One percent of the flue dusts was assumed to leave the process together with the off gas. The bulk (90%) of the captured flue dust is recycled internally or externally (e.g. in zinc plants) and the remainder is disposed off on landfills. Gaseous emissions are calculated based on the mass balance and the addition of reagents.

SO_2 is produced from oxidizing metal sulfides; SO_2 production from fuels is neglected. This gives:

$$E_{SO_2}(t) = \varphi_{SO_2}(t) \cdot 1000 \cdot \frac{M_{SO_2}}{M_S \cdot \rho_{SO_2}} \tag{20}$$

In which:

$E_{SO2}(t)$ = Emission of SO_2 produced (m^3)
$\varphi_{SO2,offgas}(t)$ = Sulfur in the off-gas (ton/a)
ρ_{SO2} = Density of SO_2 (kg/m^3)
M_{SO2} = Molar mass of SO_2 (kg/mol)
M_S = Molar mass of S (kg/mol)

The bulk of the sulfur in the feed reports to the off gas: in the process sulfur in the feed is oxidized to sulfur dioxide. The produced sulfur dioxide is then converted to sulfuric acid in a sulfuric acid plant. Based on literature survey (Van Tweel 2004) it is assumed that 99% of the SO2 produced is captured and converted to H_2SO_4 with an efficiency of 97.49%.

The coke and oxygen required in pyrometallurgical reduction processes leave the furnace together with the off gas as carbon dioxide. The amount of carbon dioxide was calculated using literature values carbon feed (as cokes) and simple chemistry: Cokes are added for two reasons: (i) as a fuel; in the presence of oxygen part of the carbon in the cokes is oxidized to carbon dioxide, which is an exothermic reaction generating energy, and (ii) as a source for carbon monoxide, the reducing agent to convert metal oxides into their metallic from. The carbon monoxide is produced by the reaction of the solid carbon particles to carbon monoxide, or by partial reduction of carbon dioxide. Reduction of the metal oxide produces carbon dioxide. The remaining carbon monoxide in the off gas is mostly oxidized to carbon dioxide both to restrain carbon monoxide emissions and to recover energy. Although in practice efficiency will be lower than 100%, a full conversion was assumed. This gives:

$$E_{CO_2,total}(t) = E_{CO_2,process}(t) + E_{CO_2,fuel}(t) \tag{21}$$

In which:

$E_{CO2,\,total}(t)$ = Total CO_2 emission (m^3)
$E_{CO2,\,process}(t)$ = CO_2 emission due to reduction of metals (m^3)
$E_{CO2,fuel}(t)$ = CO_2 emission from fuel combustion (m^3)

Metal oxides are usually reduced to metals using carbon; the amount of CO and CO_2 created during this reduction process is calculated as follows:

$$E_{CO_p}(t) = \varphi_{in}(t) \cdot f_c \cdot \frac{10^3}{M_C} \tag{22}$$

$$E^{*}_{CO_2}(t) = \sum_{i=1}^{i=n} \varphi_{i,p}(t) \cdot X_{i,ton/mol} \cdot X_{oxides/metal} \tag{23}$$

$$E_{CO_{2,process}}(t) = E^{*}_{CO_2}(t) \cdot \frac{M_{CO_2}}{\rho_{CO_2}} \tag{24}$$

$$E_{CO}(t) = \left(E_{CO_p}(t) - E^{*}_{CO_2}(t)\right) \cdot \frac{M_{CO}}{\rho_{CO}} \tag{25}$$

In which:

$E_{COp}(t)$ = Theoretical CO emission (mol/a)
$\varphi_{in}(t)$ = Total input (ton/a)
f_c = Carbon input as fraction of total output
M_c = Molar mass of carbon (kg/mol)
$E^{*}_{CO_2}$ = CO_2 emission (mol/a)
$\varphi_{i,p}$ = Production metal *i* (ton/a)
$X_{i,ton/mol}$ = Conversion factor ton metal-*i*-oxide to mol (ton/mol)
$X_{oxides/metali}$ = Oxygen demand for the oxidation of 1 mol metal *i* (mol/mol)
M_{CO2} = Molar mass of CO_2 (kg/mol)
ρ_{CO2} = Density of CO_2 (m^3/mol)
$E_{CO}(t)$ = Actual CO emission (mol/a)
M_{CO} = Molar mass of CO (kg/mol)
ρ_{CO} = Density of CO (kg/mol)

Oil, gas and coal burned for energy during the process also generates CO_2 dependent on the carbon content of the fuels (Table 1). The type of liquid fuel used in processes can be any of the four in Table 1, an average for oil was taken ($X_{CO2,oil} = 2.83$). It is assumed that no CO is produced, only CO_2.

$$E_{CO_{2},fuel}(t)=\sum_{i=1}^{i=n}X_{CO_{2},i}\cdot\varphi_{fuel,i}(t) \tag{26}$$

In which:

$X_{CO2,i}$ = CO_2 produced per unit fuel (kg/kg)
$\varphi_{fuel,i}(t)$ = Fuel consumption (kg/a)
n = Number of fuels

Table 1: CO_2 production for different types of fuels (Jantzen and van der Woerd 2003)

Fuel type	CO_2 emission per unit
Gasoline	2.39 kg/l
Diesel	2.67 kg/l
Light fuel oil	3.128 kg/l
Heavy fuel oil	3.129 kg/l
Natural gas	1.77 kg/m^3
Coal	2.73 kg/kg

The NO_x emissions of a process are determined by the formation and capture of the NO_x:

$$E_{NO_x}(t)=C_{NO_x}\cdot\sum_{i=1}^{i=n}F_{NO_x,i}(t) \tag{27}$$

In which:

$E_{NOx}(t)$ = Emissions of NO_x (ton/a)
C_{NOx} = Capture efficiency NO_x (ton/ton)
$F_{NOx,i}(t)$ = NO_x formation through mechanism i (ton/a)
n = Number formation mechanisms.

There are three different formation mechanisms for NO_X (Sloss 1992):

1. *Thermal formation* from N_2 in the air,
2. *Prompt NO_X - formation*, which converts N_2 into NO in the flame front, and
3. *Fuel NO_X - formation*, in which the nitrogen in the fuel is oxidised to NO_X.

Thermal formation typically starts at 1300°C depending on the oxygen concentration. The amount of excess oxygen depends on the process. A distinction is made between reductive or oxidative processes, where the latter obviously have higher excess of oxygen than the former. According to Sloss (1992) thermal NO_X formation can be estimated as follows:

$$F_{NO_x,thermal}(t)=N_2(t)\cdot\left(1-O_{2,excess}{}^{-1}\right)\cdot\frac{C_{Air,N_2}}{C_{Air,O_2}}\cdot 100 \tag{28}$$

$$N_2(t)=\left(E_{CO_p}(t)+E_{SO_2}(t)\right)\cdot\frac{M_{O_2}}{\rho_{O_2}}\cdot\frac{C_{Air,N_2}}{C_{Air,O_2}} \tag{29}$$

In which:

$C_{air,O2}$ = Oxygen concentration in the air
$C_{air,\,N2}$ = Nitrogen concentration in the air
$O_{2,\,excess}$ = Excess oxygen in process:
- Reductive processes: 1.025
- Oxidative processes: 1.1

M_{O2} = Molar mass of O_2 (kg/mol)
ρ_{O2} = Density of O_2 (m^3/mol)

According to the Sloss (1992) prompt NO_X formation is negligible ($F_{NOx,prompt}(t)$ ~0). The fuel NO_x formation depends on the nitrogen content of the fuel used and the combustion method used. It is assumed that 50% of the nitrogen in the fuel is oxidized to NO_x.

$$F_{NO_x,fuel}(t) = 0.5\cdot\sum_{i=1}^{i=n} F_i(t)\cdot C_i \qquad (30)$$

In which:

$F_i(t)$ = Consumption of fuel
C_i = N_2-concentration in Fuel i
n = Number of fuels

Finally, NO_X emissions are reduced by selective catalytic reduction, in which NO_X is reduced to N_2. The efficiency of this reaction ranges from 60% to 90% (Sloss 1992). An average capture of NO_x (C_{NOx}) of 0.75 % is assumed.

Oxygen demand for the different reduction and oxidation reactions were obtained by the construction of phase diagrams (1000°C) of the metals in an environment of sulfur and oxygen. Because furnaces are generally working at atmospheric pressure, only metal oxides and sulfides likely to occur at the lowest sulfur dioxide and oxygen pressures were included in the calculations. In the calculations of the oxygen demand, the oxygen consumed in the oxidation of the nitrogen was not considered. It was assumed that oxygen is not present in the off gases (oxygen is assumed not be added in excess). Although in reality this is not the case, the assumption does not affect the environmental score of the processes.

B.3.1.3 The energy consumption of a process

Metal production requires considerable amounts of energy, viz. electricity and fossil fuels, such as coal, oil products and natural gas. The energy requirements of the unit operations were obtained from literature sources and were expressed as kWh per ton refined metal in the model. Using the mass balance and taking the efficiencies of the unit operations into account, the energy consumption per ton throughput could be determined. The energy needed for the production of reagents, fluxes etc. used is included in the total energy demand of the process.

$$E_{Total}(t) = \varphi_{in}(t) \cdot E_{process} \cdot R_{process} \qquad (31)$$

In which:

φ_{in} = Process input in ton of metal (ton/a)
E_{total} = Energy requirements of the process (KWh/a)
$E_{process}$ = Energy requirements based the amount of end product produced from input
$R_{process}$ = End product produced from unit input (ton/ton)

B.3.2 Level IV: Metal production flowcharts

The efficiency of the production and recycling of a certain metal - as well as the amount of waste and emissions produced in the process - is not constant, but is dependent on the production and recovery of other metals. To estimate environmental impacts, or the effects of dynamics, these interconnections must be taken into account. As the metal cycles are connected at the level of processes, the mining of metal ores, metal production and solid metal waste management stages in the model are constructed bottom-up.

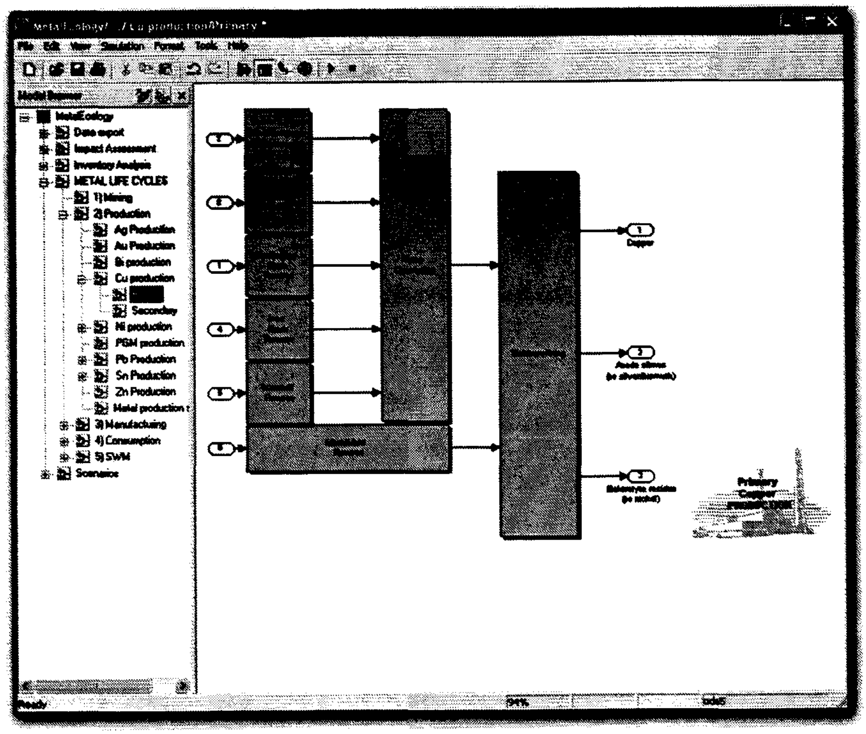


Figure 5: Copper production flowchart in Simulink.

According to the quantitative description of production and recovery of metals in appendix A, the flowcharts for mining, production and solid waste management were constructed by interconnecting the input and output streams of the processes involved in the mining, production and recovery of that metal. As discussed in chapter 5, two types of parameters determine dynamic material flows through flowcharts: process parameters and structural parameters (Figure 6).

The *process parameters* ($p_{j,i}$) determine which part of the raw material is converted to product, intermediate, residue or emission in process step *j*. As described in the previous section, linear relationships between feed and process outputs were used to approximate the fundamental thermodynamics and physics in each production and process step. The output *i* of a process *j* as function of time is given by process parameter, $p_{j,i}$, multiplied by its the feed.

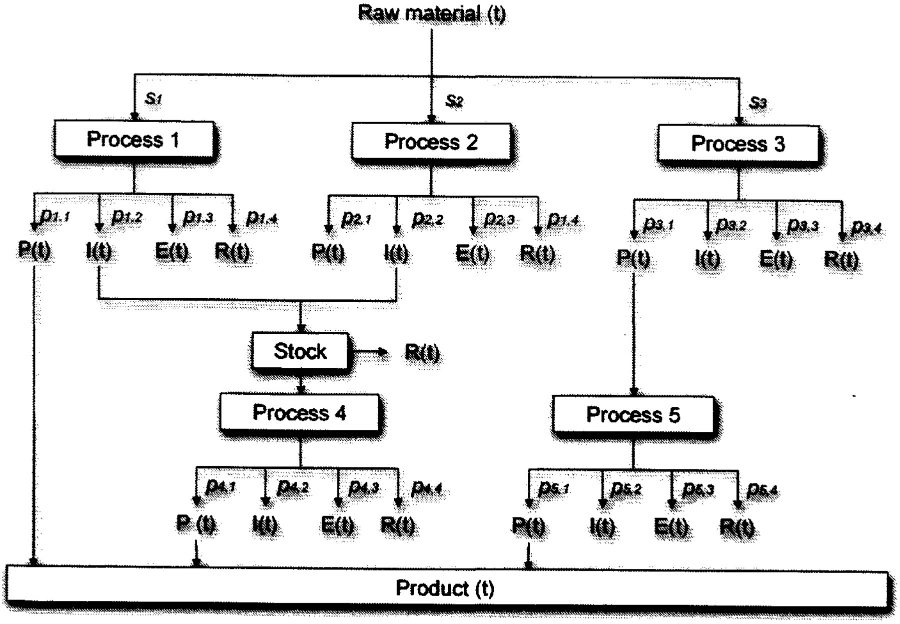


Figure 6: Hypothetical flowchart for the production of a metal; Legends: P = product, I= intermediate, E= emissions, R= residue, $p_{j,i}$ = process parameter, and s_j = structural parameter

Because metals are often produced through more than production route, a raw material, such as ore concentrate or crude metal, can be used in more than one process (the raw material in Figure 6 is used by three processes). The *structural parameters* (s_j) determine the flow of material through the different processing routes and thus the feed of the different processes. At any point in time, the feed of process *j* is given by multiplication of the supply of raw material at that time by structural parameter s_j. Distribution of the mass flows over the process routes was based on the literature. The partitioning of the elements over the mass flows was determined by dividing the average (reconciled) feed compositions by the total composition of raw materials (eq. 32). Note that for primary material, new scrap and old scrap routes the structural parameters differ.

$$s_j = \frac{C_j \cdot f_j}{\sum_{j=1}^{j=n} C_j \cdot f_j} \tag{32}$$

In which:

C_i = average reconciled feed composition of process i (ton/ton)

f_i = average use of raw materials of process i (ton/a)

Data reconciliation and extensive industrial knowledge obtained through reliable personal industry contacts, as well as extensive in-house knowledge ensured that the data is of high quality and reflects the current state-of-the-art.

B.3.3 Level III: Interconnected process flowcharts

After construction of the flowcharts for the individual metals, the flowcharts are linked through intermediates. The main intermediates are represented as orange blocks in Figure 7.

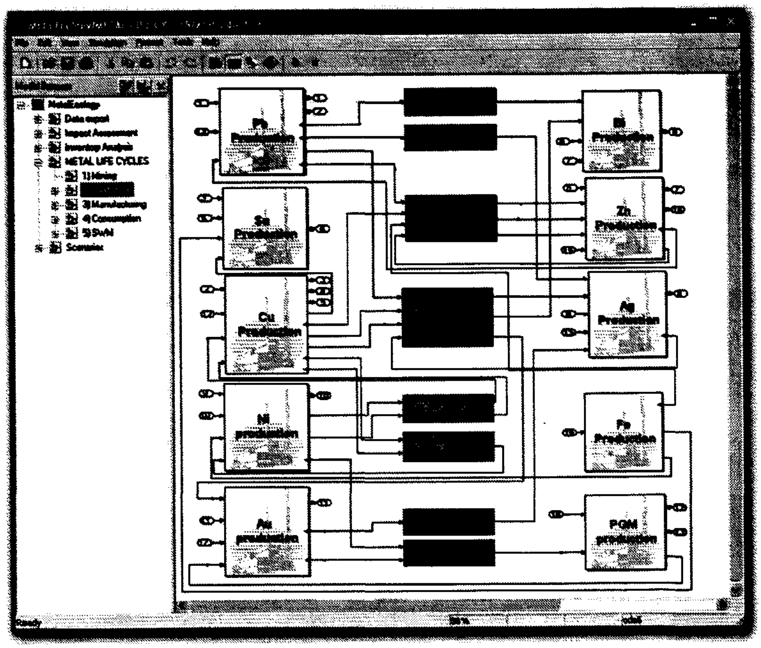


Figure 7: Interconnected metal production flowcharts in Simulink.

The amount of intermediate disposed of (R in the hypothetical flowchart, Figure 6) is determined by the demand for, and supply of intermediate. In order to avoid convergence problems that arose when using direct connection of the processes the interconnections between the material cycles were modeled as stocks. This ensures that the consumption of an intermediate is not affected by the (small) fluctuations in the production of the intermediate and allows for better (faster) convergence. Klein et al. (2000) distinguish two basic types of relations between stocks and flows:

(i) The stock as a *size buffer*: In this approach, the outflow is proportional to the stock's magnitude. This is the case for the leaching of materials into groundwater from stocks such as heavy metals in landfills, or nitrate in soil. Modeling this type of flow-stock relation is relatively straightforward. First, the magnitude of the stock has to be determined, for example, by measurements or by mass balance calculation based on records of past inflows and outflows. The outflow can then be calculated as a simple fraction of the stock leading to a geometric distribution. Most environmental stocks conform to this type (e.g. leachate models see B.4), and some emissions from economic stocks as well (e.g. dissipative use B.3.5). This type of model is also quite common in process design as an ideal 'Continuously Stirred Tank Reactor' (CSTR) model, or as first order kinetics in chemical process control.

(ii) The stock as a *time buffer*: In this approach, the outflow is a delayed inflow. An example is the modeling of waste flows from stocks of goods in society (see B.3.5). Contrary to the nitrate example mentioned above, in this case it does make a difference at what point in time a certain product has entered the stock. Each individual product has a certain life span, and on average the older specimens will enter the waste stage earlier than the newer ones. Thus, not only the magnitude of the stock but also the age distribution of products in the stock determines the outflow.

For the modeling of the intermediates, it does not make a difference at what point in time a certain intermediate has entered the stock, it is rather its composition that determines its outflow: In general, the production of an intermediate is greater than the consumption of the intermediate. It is assumed that this overproduction is because not all intermediates are economically feasible to process. A decrease of the stock level means that economic less viable intermediates need to be processed as well, while an increase of stock indicates that only the economically attractive intermediates are processed. Moreover, a relatively short residence time (one year) in the stocks is assumed. For the total mass flow and each element this gives:

$$R(t) = \sum_{i=1}^{i=n} S^{*}_{inmed,i}(t) - S_{inmed,i}(t) \qquad (33)$$

$$S_{inmed,i}(t) = \begin{cases} S^{*}_{inmed,i}(t) & if \quad S^{*}_{inmed,i}(t) < D_{I,i}(t) \\ D_{inmed,i}(t) & if \quad S^{*}_{inmed,i}(t) \geq D_{I,i}(t) \end{cases} \qquad (34)$$

$$S^{*}_{inmed,i}(t) = St_{inmed,i}(t) \cdot \frac{1}{\tau} \qquad (35)$$

$$S_i(t) = \int_0^t P_{inmed,i}(t) - St_{inmed,i}(t)\cdot\frac{1}{\tau}\cdot dt \qquad (36)$$

In which:

n = Number of elements considered
$P_{inmed,i}(t)$ = Intermediate production (ton/a)
$S_{inmed,i}(t)$ = Supply of intermediate to metal production process(ton/a)
$S^{*}_{inmed,i}(t)$ = Outflow of intermediate stock (ton/a)
$R_i(t)$ = Disposal of residue vector element i (ton/a)
$D_{inmed,i}(t)$ = Demand for intermediate element i (ton/a)
τ = Average residence time in intermediate stock (a)
$St_{inmed,i}(t)$ = Quantity of i in intermediate stock (ton)

In the model, the primary raw material mix used for the production of a metal is fixed. However, if the supply of an intermediate decreases, this means the supply of other raw materials for the production must increase to meet the demand for that metal. It is assumed that the demand for the *other* raw materials increases, but their relative share remains constant. In case of a decreased supply of intermediate i, the total increase in other raw materials can de determined from:

$$\Delta_{inmed,i}(t) = (D_{inmed,i}(t) - S_{inmed,i}(t))\cdot E_{inmed,i} \qquad (37)$$

$$\Delta D_{inmed,j}(t) = \frac{f_j}{1-f_i}\cdot\Delta_{inmed,i}(t) \qquad (38)$$

In which:

$\Delta_{inmed,i}(t)$ = Shortage of intermediate i (ton/a)
$D_{inmed,i}(t)$ = Demand for intermediate i (ton/a)
$S_{inmed,i}(t)$ = Supply of intermediate i (ton/a)
$E_{inmed,i}$ = Efficiency of metal production from intermediate i (-)
$\Delta D_{inmed,j}(t)$ = Increase in demand for intermediate j (ton_{metal}/a)
f_i = Share of metal produced from intermediate i (-)
f_j = Share of metal produced from other intermediate j (-)

B.3.4 Level III: Mining and concentration flowcharts

In the model, the demand for ore, D_{ore}, is determined by the total demand for metal, D'_{ore}, and the secondary material supplied to the market, S_{sec}. It is assumed that all of the secondary material is used (eq. 39). The amount of ore required is calculated using the efficiency of the primary production routes and the efficiency of the ore processing process (eq. 40). The supply of secondary materials is expressed in ton ores according to equation 41.

$$D_{ore}(t) = D^{*}_{ore}(t) - S_{old}(t) \qquad (39)$$

$$D^{*}_{ore}(t)=\frac{D_{metal}(t)}{\sum_{i=1}^{i=n_i}\left(f_{op,i}(t)\cdot R_{op,i}\right)\cdot\sum_{j=1}^{j=n_j}\left(f_{pp,j}(t)\cdot R_{pp,j}\right)} \tag{40}$$

$$S_{old}(t)=\frac{S^{*}_{old}(t)\cdot\sum_{k=1}^{k=n_k} f_{sp,k}(t)\cdot R_{sp,k}}{\sum_{i=1}^{i=n_i} f_{op,i}(t)\cdot R_{op,i}\cdot\sum_{j=1}^{j=n_j} f_{pp,j}(t)\cdot R_{pp,j}} \tag{41}$$

In which:

$D_{ore}(t)$ = Demand for ore (ton_{ore}/a)
$S_{old}(t)$ = Supply of secondary material (ton_{ore}/a)
$D^{*}_{ore}(t)$ = Demand for metal expressed in ore (ton_{ore}/a)
$D_{metal}(t)$ = Demand for metal (ton_{metal}/a)
$f_{op,i}(t)$ = Fraction of ore processed through route i
$R_{op,i}$ = Efficiency of ore processing route i ($\text{ton}_{concentrate}/\text{ton}_{ore}$)
$f_{pp,i}(t)$ = Fraction of concentrate processed through route j
$R_{pp,i}$ = Efficiency of primary production route j ($\text{ton}_{metal}/\text{ton}_{concentrate}$)
$S^{*}_{old}(t)$ = Supply of secondary material (t_{waste}/a)
$f_{sp,k}(t)$ = Fraction of concentrate processed through route k
$R_{sp,k}$ = Efficiency of primary production route k (t_{metal}/t_{waste})

The processing of the ores converts the ores into concentrates and tailings (residues). The concentration (or 'beneficiation') of the ores generally includes crushing of the rock followed by dense medium separation in which the light gangue material is separated from the more heavy pieces. Subsequently the separated materials are ground and further processed through flotation, in which the minerals are separated on their tendency to attach to air bubbles (Ullmann 1996). Because of the low concentration of the metals in the ores, each ton of metal concentrate involves the removal and processing of seven (zinc) to more than sixty tonnes of ore (tin). The ore processing is described with linear models based on reconciled mass balances (see B.3.1.1).

The processing of a single ore may produce different types of concentrates. As illustrated in the metal wheel (chapter 3), ores typically contain more than one metal. Lead, zinc and copper are all often present both in lead and zinc ores. Lead is predominately mined from combined lead-zinc ores. Seventy per cent of lead is mined together with zinc, and only twenty per cent of the lead concentrate production comes from dedicated lead mines. The remainder is produced as by-product from zinc mining. In the model, therefore, it is assumed that all lead and zinc are produced from the same ore, which also produces a copper concentrate. In some cases, 'co-metals' are not separated in the mining and concentration of ores, but recovered further downstream the metal production chains. Concentrates that contain zinc, lead and cadmium are processed in the Imperial Smelting Furnace that produces lead bullion, and zinc-cadmium concentrate. Silver is produced from dedicated silver ores, but also from by-products of lead (zinc), copper and gold production. For these metals, equation 36 also includes the supply of metals from intermediates (eq. 42). The demand for these intermediates is a fixed fraction of the total demand for the metal (eq. 43).

$$D_{ore}(t) = D^{*}_{ore}(t) - S_{old}(t) - S_{inmed}(t) \tag{42}$$

$$S_{inmed}(t) = \sum_{l=1}^{n_l} \left(\frac{f_{\mathrm{inmed},l}(t)}{R_{\mathrm{inmed},l}} \right) \cdot \frac{D_{metal}(t)}{\sum_{i=1}^{n_i} \left(f_{op,i}(t) \cdot R_{op,i} \right) \cdot \sum_{j=1}^{n_j} \left(f_{pp,j}(t) \cdot R_{pp,j} \right)} \tag{43}$$

In which:

$S_{inmed.}$ = Supply of intermediates (t_{ore}/a)
$f_{inmed.,l}$ = Fraction of intermediate processed through route l
$R_{inmed.,l}$ = Efficiency of intermediate production route l ($t_{metal}/t_{interm.}$)

B.3.5 Level III: Manufacturing and consumption flowcharts

As mentioned in chapter 3, data availability is not sufficient to allow a bottom-up construction of the many product manufacturing routes based on mass balances of individual manufacturing processes involved. As a consequence, product compositions, emissions and energy consumption of the manufacturing stage can not adequately be estimated through bottom-up approaches. For similar reasons, the residence times, energy consumption or the dissipation into the environment during use can not adequately be estimated through a bottom-up approach either. The residence time of metals in the consumption phase, for example, is an aggregate of the lifespans of the many different products the metals are used in. The actual lifespan of each of these products is a distributed property; depending on individual consumer preferences and decisions to discard the products, it shows considerable variation per product and may also change considerably over time.

To estimate the old scrap from the consumption phase, the stock is modeled as a time buffer (after Klein et al. 2000). Each individual product has a certain life span, and on average the older specimens will enter the waste stage earlier than the newer ones. Thus, not only the magnitude of the stock but also the age distribution of products in the stock determines the outflow. The relation between the present size of the stocks and the future emissions and waste flows is often not straightforward and can not be modeled easily (Huele and Kleijn 1997, Huppes et al. 1997). This is even more true when considering that the societal stock of metals consists of a large number of products with widely varying life spans. The problem with this model type is that to estimate waste flows, product compositions and quantities as well as the life span distribution must be obtained for these products. In some cases - as in the case of cars – detailed data are available in statistics (see e.g. Van Schaik et al. 2004) and input distributions can be *obtained* from real data. However, often this is not the case and *assumptions* are required. Other information then must be used to make such assumptions[1].

---

[1] Klein et al. (2000) see this as an important line of investigation: good estimates are required when data are lacking, but could also very much streamline the procedure because a very limited amount of data may go a long way. This could greatly enhance the applicability for environmental policy.

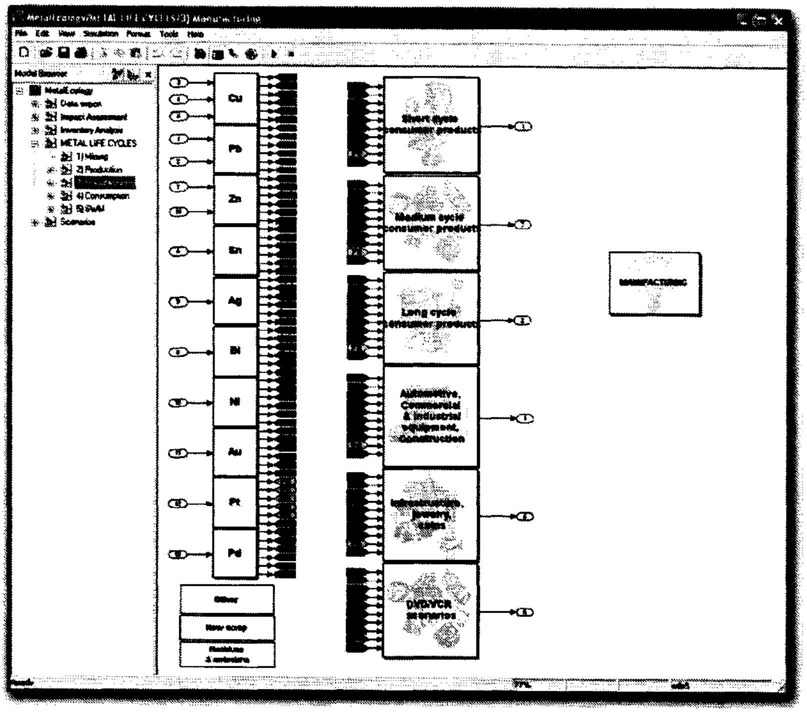


Figure 8: Product manufacture model in Simulink

In the model, five different (hypothetical) products are manufactured that have different average lifespans (see Figure 8[2], chapter 3: section 3.4.2 and appendix A: sections 11-1 and 11-2). In the manufacture of products, all seventeen elements are considered. The distribution of the elements over the five products is estimated based on their end uses. As the end uses change over time, these fractions are a function of time as well. The compositions of the products are calculated by the element-wise multiplication of the vector that contains the total production and the production of individual elements, by the vector containing the distribution fractions for the total and individual elements. The production and composition of the five hypothetical products, $C_{PrI\text{-}V}$, are given by equations 41 and 42:

$$P_{man,j}(t) = \sum_{i=1}^{i=n}\sum_{m=1}^{m=n} f_{j,i}(t) \cdot P_{metal,m,i}(t) \qquad (44)$$

$$C_{man,j,i}(t) = P_{man,j,i}(t) / P_{man,j}(t) \qquad (45)$$

---

[2] Note that that in Figure 8 a sixth product is included; this additional product is only used for DVD/VCR scenarios.

In which

n = Number of elements considered
$P_{man,j,j}(t)$ = Manufacture of product *j* (ton/a)
$f_i(t)$ = Fractions of element i manufactured into product *j* (-/-)
$P_{metal,j}(t)$ = Production of metal (or substance) *m* (ton/a)[3].
$C_{Pr\,j,i}(t)$ = Concentration of element *i* of product *j* (ton/ton)

The generation of new scrap of metal *i* in the manufacture of product *j* is then given by:

$$S_{new,j,i}(t) = P_i(t) \cdot f_{ns,i} \cdot f_j(t) \tag{46}$$

To approximate the lifespan distribution, most commonplace would be to use a normal (or Gaussian) distribution, which is used by Baccini and Bader (1996) as an example of life span distribution. Despite of the fact that the normal distribution is most commonly observed in natural and social behavior, the choice for a normal distribution is arbitrary. In some cases, there are arguments for another type of distribution. Skewed distributions such as Weibull's, which is already used in lifetime modeling (e.g. Van Schaik 2004), might sometimes be more appropriate. Considering that the five hypothetical products consist of many different products that each have distributed life spans, arguments for other distributions are difficult to give. Therefore, the life spans of the products are assumed to be normally distributed around a mean, μ. The generation of waste at time *t* from the discarding of product *j* produced at time t_i is given by:

$$P_{waste,j}(t) = P_{man,j}(t_i) \cdot \frac{e^{\frac{-(t-t_i-\mu_j)^2}{(2\sigma_j)^2}}}{\sigma_j\sqrt{2\pi}} \tag{47}$$

The total waste generated from product *j* produced at time *t* is then given by:

$$P_{waste,j}(t) = \int_{i=t}^{i=0} P_{man,j}(t_i) \cdot \frac{e^{\frac{-(t-t_i-\mu_j)^2}{(2\sigma_j)^2}}}{\sigma_j\sqrt{2\pi}} \tag{48}$$

In which:

$P_{waste,j}(t)$ = The discarded product *j* at time *t* (t)
$P_{man,j}(t_i)$ = Manufacture of product *j* at time t_i (t)
μ_j = Average life span of product *j*
σ_j = Average distribution in the life span of product *j*

Cadre B-1: Simulation in Simulink

For simulation in Simulink, the normal distribution was discretized using the variable delay blocks in Simulink. Hereto, the normal distribution curve from μ-3σ to μ+3σ (representing ca. 99.7% of the total surface of the normal distribution curve) was divided into eleven slices (Figure 9).

---

[3] For substances ('co-elements') for which the production system is not included in the model, $P_{metal,m}$ is equal to the demand, D_m.

The surface of each slice surface was calculated, and normalized so that the sum of all surfaces equals one. In Simulink, the distributed delay system consists of eleven delay blocks with a delay of τ_1 to τ_{11}, to which one of the partitions, $f_{\tau=1}$ to $f_{\tau=11}$, is allocated:

$$P_{waste,j}(t) = \sum_{\tau_{j,n}=\tau_{j,1}}^{\tau_{j,n}=\tau_{j,11}} P_{man,j}(t-\tau_{j,n}) \cdot f_{\tau_{j,n}} \tag{49}$$

$$\tau_{j,n} = \mu_j - (3\tfrac{3}{11} - n \cdot \tfrac{6}{11})\sigma_j \tag{50}$$

$$f_{\tau_{j,n}} = \frac{\displaystyle\int_{\mu_j-3\sigma_j+n*\frac{6}{11}\sigma_j}^{\mu_j-3\sigma_j+(n-1)*\frac{6}{11}\sigma_j} \frac{e^{\frac{-(t-\mu_j)^2}{(2\sigma_j)^2}}}{\sigma_j\sqrt{2\pi}}}{\displaystyle\int_{\mu_j+3\sigma_j}^{\mu_j-3\sigma_j} \frac{e^{\frac{-(t-\mu_j)^2}{(2\sigma_j)^2}}}{\sigma_j\sqrt{2\pi}}} \tag{51}$$

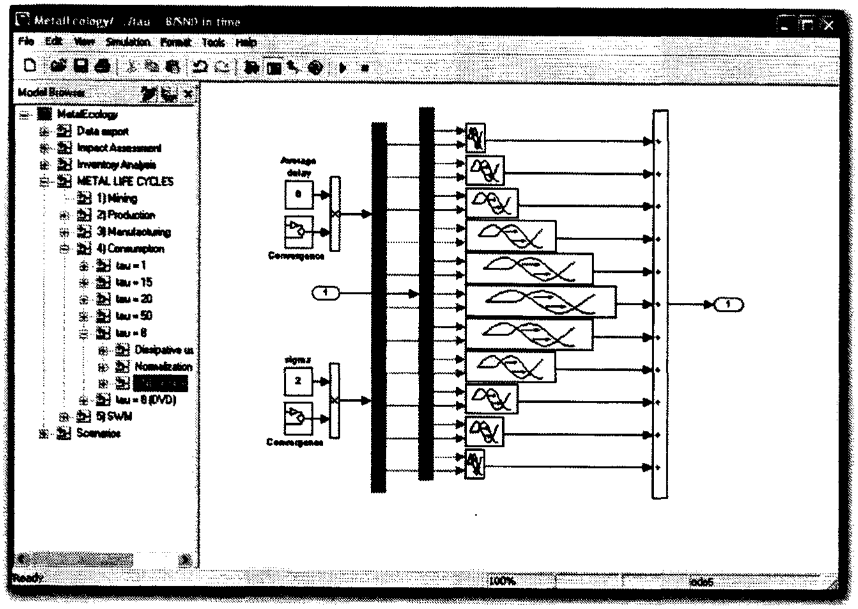


Figure 9: Normally distributed delay in Simulink

New scrap refers to metal discards generated within an industrial setting, either at metal producers ("home scrap") or from product manufacturers ("prompt industrial scrap"). Because new scrap stays within the mill or factory, the quality (i.e. chemical composition) is generally well known and homogeneous. As a result, this metal readily returns to the production loop. Equation 52 shows the new scrap generation calculation:

$$S_{new,i}(t) = P_{metal,i}(t) \cdot f_{new,i} \tag{52}$$

In which:

$S_{new,i}(t)$ = New scrap generation (ton/a)
$P_{metal,i}(t)$ = Production of metal i (ton/a)
$f_{new,i}$ = Fraction metal i rejected as new scrap in product manufacture

Residues from manufacture and consumption include new scrap, other manufacturing residues and emissions due to dissipative use. In the model of the manufacturing process, a fixed fraction of each metal is returned to the metal production system as new scrap with a delay of time step (0.05 year, to 'break' the algebraic loop). It is assumed that the new scrap is remelted without material losses; the composition of the new scrap is identical to the refined metal.

Many of the losses in the metal resource cycle end up in mine wastes (tailings or gangue), metal production slags, or and in metal-containing products and waste processing residues that are disposed of on landfills. Some of this metal could conceivably be recovered in the future as technology improves. However, there are also routes by which metals during consumption are converted into unrecoverable forms and dissipated into the environment. These are via the consumption of food, the use of chemicals, corrosion and erosion. These losses are a deliberate or unavoidable (with current technology) consequence of product use, and are referred to as dissipative use of materials (WRI 2003). Dissipative use comprises two components:

(i) direct dissipative uses such as fertilizers and manure spread on fields, and salt spread on roads, and
(ii) dissipative losses such as rubber worn away from car tires, particles worn from friction products such as brakes and clutches, and solvents used in paints or other coatings.

Dissipative uses can be part of an ultimate throughput (e.g. mineral fertilizer or other agricultural chemicals) or part of recycling (e.g. manure, compost, and sewage applied on fields for nutrient recycling). The discarded product flow must be corrected for dissipative use (eq. 53).

$$P_{waste,j}'(t) = \sum_{i=1}^{i=n} (1 - f_{diss,i}) \cdot P_{waste,j,i}(t) \tag{53}$$

In which:

n = Number of elements considered
$f_{diss,i}$ = Fraction dissipation of element i through use (ton/ton)
$P_{waste,j}'(t)$ = Flow of discarded product j corrected for dissipative use (ton/a)

The fraction of dissipative use of each metal is based on (USGS 2003, and Ayres 2002), and is given in the quantitative description of the metal cycles, and in the appendix A (sections A-11.1 and A-11.2). The losses of direct dissipative use can be considered equally distributed over the average lifespan of a product: fertilizer is spread onto land,

and dissipates into the environment. Once the stock of fertilizer is used, new fertilizer is bought. Dissipative losses, such as corrosion and erosion, can also be assumed to be more or less constant over time (see e.g. discussion on the wear of copper pipes in Ayres 2002). Dissipative use can thus be modeled using the *stock as a size buffer* approach, where the outflow is proportional to the stock's magnitude. The dissipation rate, $D_j(t)$ is a function of the stock dissipated metal $St_{diss,j}$, the fraction dissipative use, f_{diss}, and the average lifespan of product j, τ_j (eq 54 and 55). The consumed stock of metals contained product j, $St_{diss,j}$, is then given by equation 56.

$$D_j(t) = \sum_{i=1}^{i=n} \frac{f_{diss,i}}{\tau_j} \cdot St_{diss,j,i}(t) \tag{54}$$

$$St_{diss,j}(t) = \int_t^0 \sum_{i=1}^{i=n} f_{diss,i} * P_{waste,j,i}'(t) - D_{j,i}(t) * dt \tag{55}$$

$$St_{j,i}(t) = \int_t^o P_{man,j,i}(t) - P'_{waste,j,i}(t) - D_{j,i}(t) \tag{56}$$

In which:

St_j = Stock of product j in use (ton)
τ_j = Average life span of product j (a)

B.3.6 Level III: Solid waste management flowchart

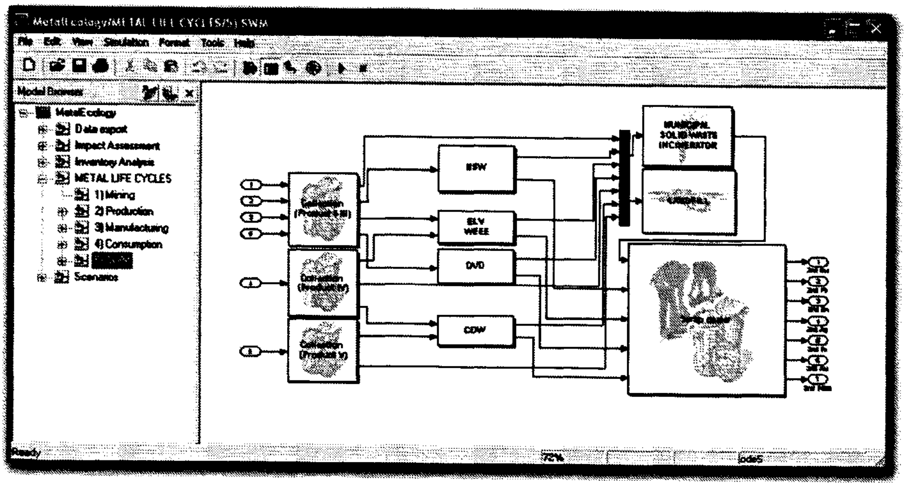


Figure 10: Waste management flowchart in Simulink

Figure 10 shows the different waste management routes included in the model. Mass balance data for the different processes are given in appendix A (section A-11.3). The metals, which are not recovered through the municipal solid waste, electrical and electronic appliances, end-of-life vehicles and construction and demolition waste routes, are partly processed through the 'other' route. As this route is an aggregate of all other routes through which metals are recovered, it is difficult to estimate composition and quantity of the metal concentrates produced in this route. Under the block 'Scrap dealer' all the other routes are included as 'Other routes'.

The composition of the produced secondary resources is dependent on the physical and chemical combinations in the products, and the carrier metal in the recovery. Circuitry boards for example are typically recovered for the copper value. Copper is the carrier metal for these products, and the co-elements in the copper concentrate are typically recovered in the copper production circuit. Based on the distribution of the metals over the different products and information on their subsequent recovery, the distribution of metals over the waste flows was estimated (see appendix A: section A-11.3). The quantity of the metals recovered through this route could be estimated based on the global metal recycling rates. Subtraction of the amount of metals, that are recycled through these four routes, from the global amount recycled metals, gives the recycling of metals through the 'other' route.

B.4 Interpretation and impact assessment

An SFA of the complex, global interconnected metals cycles requires aggregation in some way to enable interpretation (see chapter 3: cadre 3-1). For consistency between different study outcomes, it is stated in the ISO (14042) standard that impact assessment results can not be the only source of information for comparative assertions. Impact assessment is basically viewed as a way to interpret the inventory in the context of the study goal. The SFA model is therefore combined with elements of LCIA; in this way LCIA provides a context to value the different SFA indicators, and vice versa, SFA indicators improve transparency of the LCIA, and provide additional information on the system. Figure 11 shows the three ways of interpretation of the results included in the model:

- Direct assessment of the simulation during and after simulation. Using (among others) the 'Scope' blocks in Simulink all the flows in the model can be tracked. In this way, environmental effects can be traced to the level of reactors.
- SFA-type indicators: these are typically defined in terms of flows and accumulations of the material(s) under study. Indicators can also be more elaborate, by calculating compound indicators relative to the management of the whole chain. For example, one can focus on the efficiency of processes or groups of processes in terms of the ratio between the production of the desired output related to the magnitude of the input of the process, or to the amount of the produced waste.
- LCA-type impact assessment indicators: in these indicators outputs to the environment are assigned to a number of environmental issues or environmental impact categories, such as global warming, ozone depletion, and acidification.

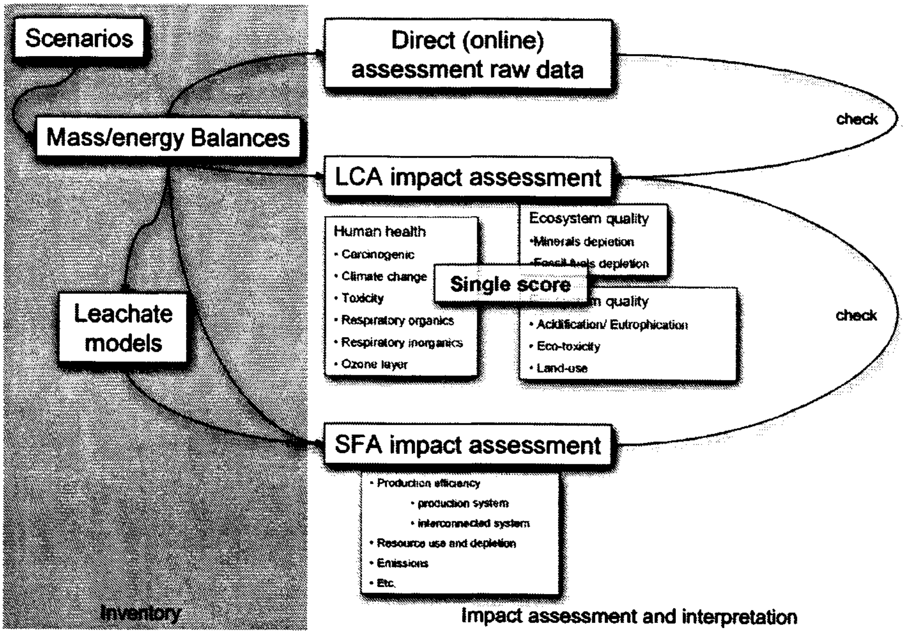


Figure 11: Schematic representation of impact assessment options in the Simulink model.

B.4.1 LCA-type impact assessment

To allow simple interpretation, and because impacts assessment is as yet not well developed in SFA (Udo de Haes and Van der Voet 1997), an LCA impact assessment package was included in the approach.

There is no single package or method preferred to interpret the inventory results under all circumstances, because the translation of human health or ecological impacts is still not well understood and LCA is goal and scope driven. Two basic types of methods can be distinguished: mid-point and end-points (see chapter 3, cadre 3-1). The literature on this topic contains only a few in-depth comparisons of a few methods and there is no consensus on whether results of different methods generally agree, while others have found that the various methods can lead to widely varying results (e.g. Dreyer et al. 2003, Toffel and Marshall 2004). However, there is a growing consensus that both end-points and mid-point methods have complementary limitations and merits (Bare et al. 2000). Endpoints methods (with/without weighed index) can be particularly useful for educational purposes, for decision-support with large groups of stakeholders or product design, while midpoints methods are particularly useful for benchmarking of products, or (single) process monitoring. A damage oriented method, the Eco-indicator 99 (Goedkoop and Spriensma 2000), was selected because of the clear link to environmental concerns, and of conformity with the screening of lead-free solders at

Philips and other lead-free solder LCAs. LCA results per simulation can obtained as single score, as damages (human Health, Ecosystem quality and Resource depletion) or as the various environmental themes (Figure 12).

Methods for LCIA should not only produce a result, i.e. a number of figures, but also present intermediate results, and preferably also the calculations and data; and it should be possible to redo the calculations under slightly different conditions. Therefore, the LCIA calculation is kept as transparent as possible; the different calculations can be accessed by browsing through the different layers, and the values for the parameters can be viewed in the Simulink data explorer. In this way, different parameters in the impact assessment process, such as the weighting of human health, ecosystem quality and resource deletion impacts, can easily changed, or the contribution of the emissions into soil from solid waste incineration to a certain damage for instance.

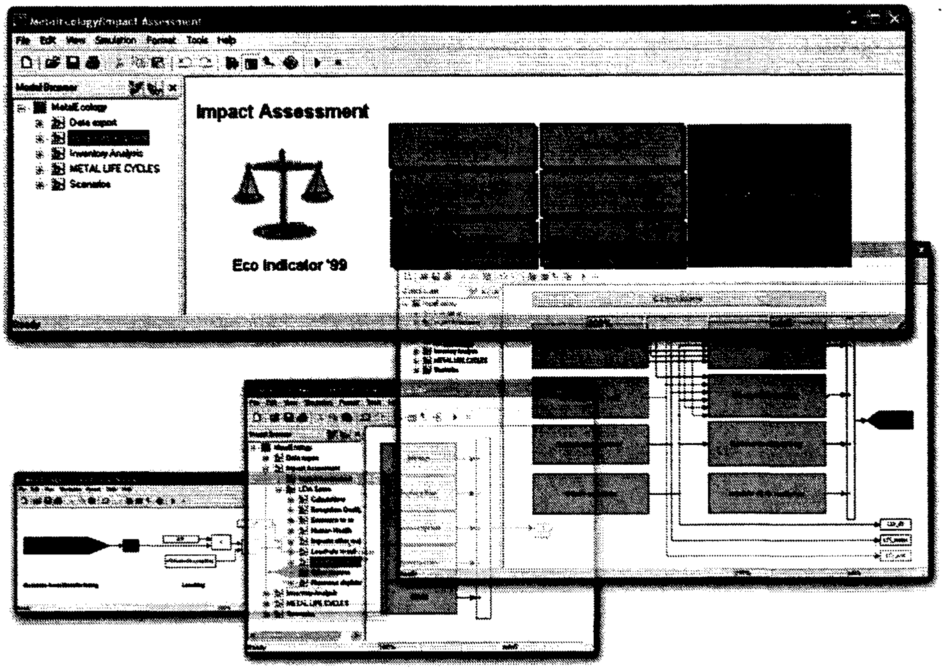


Figure 12: Transparent LCA calculation in Simulink.

It should be noted, that because LCA does not consider time dependency, the effects of the damage over time, e.g. the actual resource depletion, are not accounted for. In other words, if metals ores are mined over time, the available stocks decrease and the seriousness of further depletion increases. In the LCA impact assessment, the increasing damage of resource consumption is not accounted for. After disposal on landfills, metals slowly leach out, which results in environmental hazards to soil and groundwater. In the model, based on leaching numbers, the total amount of metal that leaches out over a time span of 100 years was used to determine the environmental impact of these emissions, rather than simulation of the leach process over time. It was assumed that the bulk, being 90% of the total amount of metal, adheres to the soil, and that 10 % of the total amount of metal leached out reports to the groundwater (after Ansems 2002).

This is an important difference with SFA, which should be realized when interpreting the impact assessment results. The environmental impacts of emissions, depletion etc. measured in EI'99 points during simulation are thus aggregated, weighed and valued based on the situation 'today', even if the change takes many years. Comparisons between two situations in the simulations are thus basically the same as for stationary modeling, which can also compare distinct system steady states.

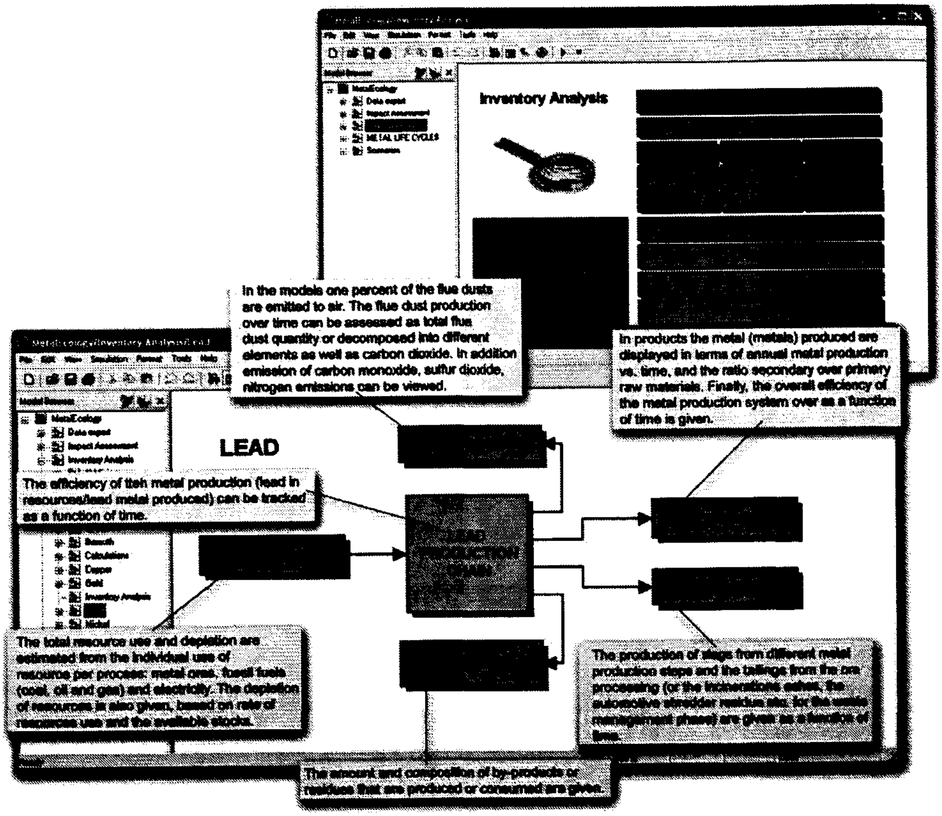
B.4.2 Allocation of burdens

In addition assessment of the total impacts, the model also allows for a more detailed analysis: the environmental impacts of each metal production chain individually. In impacts assessment the environmental burdens, such as wastes and emissions, are allocated to products. Here, a methodological problem arises. Metal production processes can belong to more than one production system, e.g. in copper production also raw materials for silver production are generated. The problem is to decide what share of the environmental burden should be allocated to the metal investigated. The model can calculate the environmental impact of the total interconnected metal life cycles, or each cycle individual based on mass allocation (see Van Tweel (2004) for an extensive description of the allocation procedures).

B.4.3 SFA-type data analysis

While there is a growing consensus that different LCIA methods have complementary limitations and merits, it appears that this observation also holds true for the different LCA and SFA impact assessment procedures. In chapter 5, it was be shown that the underlying dynamics in the metal resource cycles must thus be understood, to evaluate the environmental impact and feasibility of the alternatives under investigation. An SFA simulates the effect of future developments on the system and its environment. For instance, rather than indicating damage scores due to resource depletion alone, the model can shows a decrease of the available resource stock in a given scenario. The results (the stocks and flows in time) of simulations are then available for detailed analysis to support interpretation of the LCIA results. For each simulation, the total inventory as a function of time can be accessed (and saved). In addition, the inventory tables of the subsystems can also be accessed individually (Figure 13).

The SFA-type indicators can add significantly to the transparency of the LCIA values obtained, and better facilitate improvement assessment: changes in intermediate exchanges, emissions or production efficiency can be easily traced. In this way the models not only produces (LCIA) numbers, but also connects these to the related changes in the metallurgical system. There are several procedures included in the model for doing this. At any level of the model, important flows can be analyzed among others by using the scope block (during and after simulation). For each production chain, or resource stage the overall resource use, airborne emissions, residues intermediates and products can be accessed through score cards (Figure 13).



In the models one percent of the flue dusts are emitted to air. The flue dust production over time can be assessed as total flue dust quantity or decomposed into different elements as well as carbon dioxide. In addition emission of carbon monoxide, sulfur dioxide, nitrogen emissions can be viewed.

In products the metal (metals) produced are displayed in terms of annual metal production vs. time, and the ratio secondary over primary raw materials. Finally, the overall efficiency of the metal production system over as a function of time is given.

The efficiency of tteh metal production (lead in resources/lead metal produced) can be tracked as a function of time.

The total resource use and depletion are estimated from the individual use of resource per process: metal ores, fossil fuels (coal, oil and gas) and electricity. The depletion of resources is also given, based on rate of resources use and the available stocks.

The production of slags from different metal production steps and the tailings from the ore processing (or the incinerations ashes, the automotive shredder residue etc. for the waste management phase) are given as a function of time.

The amount and composition of by-products or residues that are produced or consumed are given.

Figure 13: An example of a scorecard for a metal production chain.

B.4.4 Leachate models

For the dynamic analysis, the leaching of materials into the environmental compartment soil and water is calculated as a function of time.

Cadre B-2: Time dependency in landfills

The disposal of wastes leads to emissions into the environment. Some emissions occur directly at the processing of waste, such as the emissions into the air resulting from the incineration of waste. Other emissions typically occur after the disposal processes: when the solid waste comes into contact with water, such as infiltrating rain water or groundwater, metals dissolve and leach out. Due to disposal of EOL wastes, incineration ashes and flue dusts, and production residues on landfills metals and other substances leach into soil and groundwater long after their disposal.

The leaching rate changes over time. For example, Finnveden (1996), and later Finnveden and Nielsen (1999) distinguish between leachate rate during a surveyable period and a (hypothetical) infinite period. The surveyable time corresponds to the time until a pseudo steady state is reached in the landfill, which is probably in the magnitude of 100 years.

Only a small fraction of the landfilled metals is expected to be emitted during the first century, typically between 0.001 and 0.1% of the metal in the landfill body. Emissions from landfills may prevail for a very long time, often thousands of years or longer. It is therefore assumed that material remaining after the surveyable time is completely emitted during the infinite period (Finnveden and Nielsen 1999). This approach is used in the ORWARE waste management model for example. Here the leachate rate is proportional to two stocks, viz. the non steady state stock (surveyable time) and a steady state stock (infinite time). The choice for the distinction between two time frames (and thus stocks in the model) appears somewhat arbitrary. With knowledge of the different decomposition processes in the landfill, a series of typical phases can be distinguished (see e.g. Farquhar and Rovers 1973, Ehrig 1983, Chian et al.1985 and Christensen and Kjeldsen 1989). However, typically five phases are distinguished. In addition, the remaining metals may not only leach out, but can also be immobilized in the landfill. The long-term behaviour of a landfill is strongly influenced by a large number of factors, including content of organic material, moisture, oxygen, and pH. In general the knowledge of the long-term fate of contaminants in landfills and its relation to waste processes is insufficient for detailed modeling (see e.g. Bozkurt et al. 1999, 2000), in particular at global scale considering the differences in local conditions and landfill practice.

In the model, the leachate is simply assumed to be proportional to the stock of materials in landfills (after Klein et al. 2000). The leachate can then be calculated as a simple fraction of the landfill stock.

$$L(t) = R_{leach} \cdot St_{landfill}(t) \qquad (57)$$

$$St_{landfill}(t) = \int_{0}^{t} \sum_{j=1}^{j=V} f_{landfill,j} \cdot P_{waste,j}{}'(t) - L(t) \cdot dt \qquad (58)$$

In which:

$L(t)$ = leachate of metals and other substances (ton/a)
$R_{leachate}$ = leachate rate (ton/ton a)
$St_{landfill}(t)$= Stock of wastes disposed of on landfills (ton)
$f_{landfill,j}(t)$ = Fraction of Waste j disposed of on landfills (ton/ton)

Different leachate rates are included for the different types of waste. In the model, two types of landfills for EOL products are included representing the extremes in landfilling practice around the world: (i) Sanitary landfills that employ leachate containment, collection, and treatment, and (ii) uncontrolled landfills that do not. For uncontrolled landfills, the leachate rate is assumed to be ten times that of sanitary landfills (i.e. collection and containment efficiency of ninety per cent). The slag and tailings produced in the metal production system are separately disposed of on controlled landfills. Emissions into soil and groundwater (the leachate) from slag and tailings differ from those from household waste. In addition, the disposal of fly ash and bottom ash is modeled separately. Metals in fly ash occur mainly as salts, and therefore have higher leachability. The leaching of metals from landfills was obtained from Ansems (2002). The leachate rate is given by the fraction of material leached in the surveyable time divided by the period for which leaching of metals was determined. The metals that leach from the landfill body, distribute over soil and groundwater as 90:10 (Ansems 2002).

Note that the landfill models do not include leachate purification and landfill gas generation. At sanitary landfills, leachate is led to the municipal sewer system and treated in a conventional sewage treatment plant, or the leachate is treated separately, as it often contains higher levels of pollutants than ordinary sewage, and may require special purification methods (Bjorklund 2000). The process of leachate treatment is not included in the model. It is assumed to be disposed of on landfills. The metals flows are considered inert with respect to landfill gas emissions and these are not considered in the model as this emission of metal is very small compared to the other flows to air.

B.4.5 Transport

Metals, metal and ore concentrates, and intermediates are traded globally. Consequently, the distance between ore mining sites, metal production facilities, product manufacturers, consumers and waste processing facilities can be very large. Thus, it can be seen that transport plays an important role in the metal ecology, and is an important source of emissions and consumer of fossil fuels.

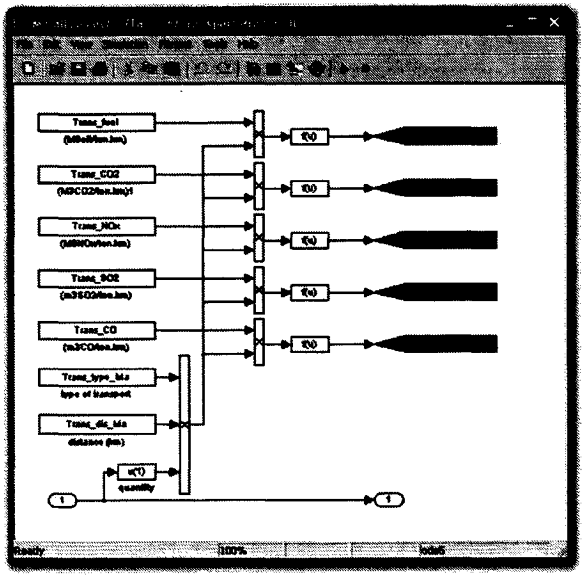


Figure 14: Transport model in Simulink

A simple, linear model was included to estimate resource consumption and emission due to transport was included in the Simulink model (Figure 14). Average figures for emissions and fuel consumption for the different modes of transportation (garbage truck, truck and bulk carrier) were obtained from literature (Rydh and Karlström 2001, Bos 1998, Kristensen 2002, and Weston). It was assumed that the bulk (95%) of intercontinental trade was transported over sea, and half of the intra-continental trade. Trucks with and without trailer equally carried the remaining load. Garbage trucks were only used in the collection of waste in the solid waste management phase.

Data on transport distances of metals, metal and ore concentrates, and intermediates was not found in literature, and had to be estimated. Statistics on the location of mines, metal production facilities and trade of metal and metal scrap was available from metal statistics (UN 1997, MetalEurop 1999, GFMS 2002). A simplified model to estimate the transport distances from this data was used, based on a number of assumptions:

- transport occurs only between different stages in the metal life cycles, and in the waste management stage;
- transport distances can be estimated from the average distances between countries mining metal ore and countries producing the crude metals, and the import and export data of unwrought refined metal and alloys, and of metal scrap;
- metals, metal and ore concentrates, and intermediates are traded first within the continents (Europe, North-America, South-America, Africa, Oceania, and Asia), and second between continents;

The distances between countries were obtained from CEPII 2003. These distances were estimated based on the longitudes and latitudes of the capitals using the great-circle formula from spherical trigonometry. To estimate emissions and fuel consumption resulting from the transport over these distances, transport was assumed to occur only over land or sea. Four modes of transport were considered: hauling with garbage truck, transport by truck, truck and trailer, tanker. The effects of these assumptions on model outcomes were tested in the model sensitivity analysis (Van Tweel 2004, Scholte 2002).

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Summary

Industrial ecology is a promising systems approach that focuses on part of the problem and solution to sustainability: the industrial systems. Based on a detailed investigation of a number of industrial systems, the metallurgical process infrastructure, it is concluded, however, that the current lack of a solid technological footing in industrial ecology (models, studies and literature) prohibits the successful use of this approach (use of the biological analogy, the formulation of workable strategies and the implementation of the concepts postulated). To facilitate the inclusion of metallurgical know-how into industrial ecology strategies, concepts and decision-making processes, the metal resource cycles were analyzed in this thesis, their interdependence summarized in the metal wheel, and their dynamics in response to technology, network and regulatory changes visualized in a versatile simulation model.

A key principle in industrial ecology is the cyclic use of materials, which is a characteristic of natural ecosystems but which realization represents a challenge in industrial systems. Indeed, metal retention - the ongoing use of metal in the economy between the life-cycle stages of resource extraction and final disposal back into the lithosphere - is not completely achieved in society because of the limited grade of recycled metals. Presently, metals of sufficient quality can only be produced from secondary materials when these are mixed with primary (virgin) metals. Short term this practice enables metal recycling, but long term this practice dilutes the total stock of metals with undesired components that can not be removed. A dilemma results: dilution of metals while closing the material cycles threatens to result in a complete loss of suitable metal stock.

Metal ecology and the closure of metal cycles as a long-term solution present a tremendous technical challenge. Current metallurgic knowledge and industrial infrastructure have the capacity to address this challenge, but only if the metallurgic constraints of metals recovery are taken into account in waste management, policy development, and product design (and vice versa). This is complicated because metals circulate in a system of interconnected cycles. Consequently, metals can not be produced or recovered independently from one another. The metal wheel has been developed as a concise but powerful instrument for the communication of available process knowledge in process metallurgy, the science and technology of producing metals from natural ores and the demand for raw materials, residues, and end-of-life products in society. It summarizes the chemical and physical linkages between metals found in ores and the set of metallurgical processes that has been developed to accommodate these linkages. In many products, however, completely new linkages between metals are introduced. When these are alien to the metal wheel, these new linkages may require novel production and recovery processes or innovative

combinations. Alternatively, if an existing link in the wheel is broken, for example through a product or material ban, this will affect all stages in the linked metal cycles, both upstream and downstream of this link. The metal wheel conveys that in the design of products for environment or recycling, a consideration of the metal combinations in the products, their components and the associated waste flows is imperative to enable future recovery of metals.

Adequate modeling and presentation of model results of the metal production network are required to assess the consequences of existing and new regulation, of product innovations and process improvements. The dynamics of the system and available tacit operational knowledge are essential components of the metallurgical infrastructure required to enable the reclamation of metals from complex, heterogeneous virgin materials and waste of rapidly changing composition. A dynamic mass-flow model has been developed that visualizes the dynamic interdependencies in the global metal cycles. This model facilitates the visualization of the evolution of their structure and technological content, in response to product innovation, metals production and recovery development, waste management, and related legislation/policy. To illustrate the interdependency of metal cycles using the metal wheel and the dynamic model, the transition to lead-free solder, the reduction of the emission of lead processes and increased lead recycling have been evaluated in detail. Applying the model, the effect of each lead substitute on the interconnected metal production and recycling system can be quantified in terms of environmental impact and technological feasibility (e.g. availability of raw materials and critical intermediates). The model simulations showed that neglecting metal-cycle linkages and dynamics in policy formulation may lead to a shortage of lead substitutes or a lack of critical processes. In case of an extended ban on lead, both the availability and recovery of a range of metals will be affected. Visualization of the technological problems and opportunities of the metallurgical system in the metal resources cycles at different levels of technological complexity, allows pro-active or feedforward approach in waste management, policy development, and product design to keep metal retention in society at high utility.

This illustrates that the ambitious concepts and models from industrial ecologists should integrate solid footing in process metallurgy and design to ensure that industrial ecology concepts, such as closed material cycles, can become an economic reality. This is where industrial ecologists and metallurgists must join forces. In short, metallurgical process technology know-how must complement a sound understanding of economics and regulation to bring to fruition industrial ecology concepts. Quantitative models can assist this process by visualizing part of this know-how, but only if they are rooted in a solid basis. Because a dynamic network of interrelated reactors realizes the metal production and recycling capacity, tools to invoke improvement in this capacity also require modeling at level of reactors, rather than the oversimplified inventories common in industrial ecology models. Only in this way, the effect of changes can be predicted and translated into concepts and information comprehensible at the various levels of decision-making.

Samenvatting

Industriële ecologie is een veelbelovende systeembenadering van duurzaamheid, die zich richt op de industriële systemen. Deze zorgen voor problemen bij het bereiken van een duurzame samenleving, maar bieden tegelijkertijd ook oplossingen. Door gedetailleerd onderzoek van een aantal industriële systemen in de metallurgische industrie kan geconcludeerd worden dat het huidige gebrek aan voldoende technologische diepgang in industriële ecologie (modellen, studies en literatuur) het succesvolle gebruik van deze systeembenadering verhindert. In dit proefschrift wordt daarom deze grootschalige procesinfrastructuur geanalyseerd van reactor tot wereldwijde metaalkringlopen, zodat technologische beperkingen en mogelijkheden kunnen worden meegenomen in de (verdere) ontwikkeling van concepten, beleid en strategieën. Hiertoe is de samenhang tussen de metaalkringlopen samengevat in het 'metaal-wiel' en de dynamiek van de metaalkringlopen door veranderingen in technologie, netwerkstructuur of wet- en regelgeving gevisualiseerd in een veelzijdig simulatiemodel.

Een belangrijk principe in industriële ecologie is het cyclische gebruik van materialen, karakteristiek voor natuurlijke ecosystemen, maar een grote uitdaging voor industriële systemen. Het probleem van het cyclische gebruik van metalen is de veelal lagere kwaliteit van gerecyclede metalen door vervuiling van de secondaire grondstoffen die uit het afval gewonnen worden. Op korte termijn kan een lagere kwaliteit worden vermeden door de vervuilde secondaire grondstoffen te mengen met schone primaire grondstoffen. Echter op de lange termijn of bij toenemend cyclisch gebruik van metalen kan dit tot grote hoeveelheden onbruikbare metalen leiden. Industriële ecologie staat hierdoor voor een dilemma: het huidige gebruik en verdunning van metalen leidt bij toenemende recycling niet tot duurzamer gebruik van metalen, maar bedreigt juist de gehele voorraad van metalen in circulatie en op stortplaatsen.

Vanuit technologisch oogpunt is het effectief recyclen van metalen op de lange termijn een zware uitdaging. De beschikbare metallurgische kennis en technologische infrastructuur kunnen deze uitdaging aan, mits bij het gebruik van metalen in producten, bij het verwerken van het afval en in de wet- en regelgeving rekening wordt gehouden met de beperkingen en mogelijkheden van metaalrecycling. De beperkingen en mogelijkheden vloeien voort uit het feit dat metalen circuleren in een systeem van onderling sterk afhankelijke materiaalkringlopen. Hierin kunnen twee type's metalen worden onderscheiden: 'carrier'- of dragermetalen en 'downstream' of afhankelijke metalen. De productie en recycling van carrier-metalen leveren belangrijke grondstoffen voor de productie van downstream-metalen. Daarom moet bij de productie en recycling van een eerste type metaal altijd rekening worden gehouden met 'downstream' metalen. Het 'metaal-wiel' is ontwikkeld om deze samenhang in de productie van metalen uit primaire en secondaire grondstoffen op eenvoudige wijze in kaart te brengen. Het vat de mogelijkheden en beperkingen van de metallurgische industrie samen aan de hand van de fysische en chemische combinatie van metalen in ertsen waarvoor de industriële processen ontwikkeld zijn. Het wiel wijst op twee belangrijke voorwaarden voor metaalrecycling. Allereerst, wanneer grondstoffen combinaties bevatten, die buiten het bereik van het wiel vallen, moet voor effectieve recycling nieuwe technologie of anderszins innovatieve oplossingen worden ontwikkeld. Daarnaast kan bijvoorbeeld door een verbod op het gebruik van een bepaald metaal, verbindingen tussen metalen worden verbroken. Hierdoor kunnen problemen worden verwacht in de productie en recycling van de andere metalen. Het metaal-wiel laat dus duidelijk zien dat in het ontwerp van producten, productieprocessen en afvalverwerkings-processen rekening gehouden moet worden met de afhankelijkheid van metaalproductie en -recycling, om het cyclische gebruik van metalen mogelijk te maken.

Om het effect van huidige en nieuwe wet- en regelgeving, productinnovatie of procesverbeteringen op de metallurgische infrastructuur te kunnen bepalen zijn goede kwantitatieve modellen nodig. De variatie en dynamiek in productie routes maken het terugwinnen van metalen uit de steeds veranderende mix van complexe, heterogene primaire en secondaire grondstoffen mogelijk. De keerzijde hiervan is dat de afhankelijkheden tussen metalen niet constant zijn, maar ook veranderen en daarmee het effect van wet- en regelgeving of de milieu-impact van processen en producten. In dit onderzoek is daarom een dynamisch massabalans-model ontwikkeld dat laat zien welke veranderingen in de metallurgische infrastructuur kunnen worden verwacht door veranderingen in productontwerp, metaalproductie/recycling- of afvalverwerkingsprocessen. Als casestudie zijn de introductie van verschillende loodvrije soldeeralternatieven, een reductie in emissie van loodproductieprocessen en een toename loodrecycling onderzocht op milieu impact en technologische haalbaarheid (beschikbaarheid van grondstoffen en kritische bijproducten). De simulaties in het model laten zien dat het negeren van de dynamische afhankelijkheid van metaalproductie/recycling in beleidsformulering kan leiden tot een tekort aan essentiële bijproducten, kritische processen of onverwachte voor- of nadelen in termen van milieuimpact. Een uitgebreid verbod op lood zal daarom de beschikbaarheid en recycling van een groot aantal metalen sterk beïnvloeden.

De analyse, de simulaties en het 'metaal-wiel' demonstreren dat de ambitieuze concepten van industriële ecologie, zoals cyclisch materiaal gebruik, gebaseerd moeten zijn op technologische wetmatigheden om tot ontplooiing te kunnen komen. Kwantitatieve modellen spelen hierbij een belangrijke rol door de complexe en veranderlijke technologische infrastructuur te visualiseren. De huidige studies in industriële ecologie gebruiken te simpele modellen van het industriële systeem om deze veranderingen in kaart te kunnen brengen. Hiervoor moet de metallurgische infrastructuur gemodelleerd worden als een netwerk van afhankelijke reactoren. Hoewel ook deze modellen – de 'stilzwijgende' (niet beschreven, maar wel aanwezige) kennis in metallurgische processen bijvoorbeeld is niet eenvoudig te integreren in deze modellen – niet in staat zijn veranderingen volledig te beschrijven, bieden zij wel een goed uitgangspunt om technologische mogelijkheden en knelpunten mee te nemen in wet- en regelgeving, productontwerp of afvalverwerking. Op deze manier kan een brug worden geslagen tussen de holistische modellen van industriële ecologie en de gedetailleerde modellen uit de procestechnologie. Deze brug maakt een beter gebruik van de veel belovende systeembenadering van duurzaamheid mogelijk.

Curriculum Vitae

On November 14 (1973) Ewoud Vincent Verhoef was born in Newton near Boston (Massachusetts, USA). After a short stay in the 'land of opportunities' he crossed the Atlantic to settle in the Netherlands. He completed the VWO (Grammar school) at the Christelijk Lyceum Delft (1992) and graduated as a chemical engineer from Delft University of Technology (1998). Following graduation he joined the Delft Interfaculty Research Center (DIOC) Design and Management of Infrastructure as a PhD fellow. He initially focused on the design and management of the waste infrastructure. In the course of his PhD project he expanded his focus to include the resource cycles, which eventually resulted in this thesis on the ecology of metals (2004).

In the last decades, sustainable development has become the cornerstone of environmental policy and a leading principle for resource management. Industrial ecology is a promising systems approach that focuses on part of the problem and solution to sustainability: the industrial system.

The (industrial) ecology of metals is the system of the relationships between metals extraction, production, manufacture and recovery processes, as well as the interaction with non-technical factors driving the system such as legislation and the natural environment. Based on a detailed investigation of the ecology of metals, it is concluded, however, that the current lack of a solid [illegible] models [illegible] strategies, and the implementation of the concepts postulated)

To facilitate the inclusion of metallurgical know-how into industrial ecology strategies, concepts and decision-making processes, the metal resource cycles were analyzed in this thesis, their interdependence summarized in the metal wheel, and their dynamics in response to technology, network and regulatory changes visualized in a versatile simulation model.

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