Environmental assessment of metals

through dynamic modelling of the metal life cycle system
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Summary

The metal production system is complex and has many interconnections between the production of individual metals. As such it is not easy to do an environmental assessment on metals. Raw materials, ore or recycled material, are usually a mix of several metals.

There are several methods developed for environmental assessment, here a combination of Life Cycle Assessment (LCA) and Substance Flow Analysis (SFA) is used. LCA is a method developed to support decision making on environmental issues. LCA is widely used and therefore well developed, there are several existing methods that convert environmental emissions, like CO2, to environmental impacts, like carcinogenic effects. As this translates a lot of data into a few fairly simple to understand data points it is ideal to use to simplifying things. On the other hand the simplification also removes information. Therefore SFA is used complementary to LCA. SFA focuses on the flows of one or more substances through a system. As a method SFA is less developed than LCA, but can be used very good in complex systems. Combining LCA and SFA allows for a greater understanding of the system and environmental impacts of the scenario change to the system.

One of the major problems of using LCA in a complex system like the metal life cycle system is how to allocate the environmental burdens in processes that have multiple functions. There are several methods to solve allocation problems, in the case of the metal life cycle system causal allocation and system expansion are both valid methods. Non-causal allocation is a possibility but not preferable, division of multiple function systems is impractical.

The model of metal life cycles models the mining, production, manufacturing, consumption and waste management of eight metals, lead, zinc, tin, bismuth, copper, silver, nickel and gold. Each phase in the metal life cycle is modelled as detailed as possible. The production phase is modelled down to the unit operating level. Each unit operation is abstracted as having one or more inputs, one or more outputs, off gas and energy consumption. The outputs can be end products, products need to be further processed in the same production chain, products that need to be processed further in another production chain (intermediates) or wastes. Unit processes in a production chain are connected with each other in flow sheets. Different production chains are connected through intermediates. In the manufacturing and consumption phases metals are grouped into five different groups according the estimated consumption lifetime of the way that particular metal is produced. In the waste management phase metals are grouped into five different types of waste, each with different recycling rates; municipal solid waste, end of life vehicles, waste of electrical and electronics equipment, construction and demolition waste and other wastes. The recycled material is fed back into the production phase.
To illustrate the use of the model three case studies were made. The first case study involved the comparison of three DVDs. The causal allocation method and the system expansion method gave similar LCA scores, the non-causal allocation gave a smaller LCA score. There were no changes to the flow sheet due to the relative small size of the change. The second case study involved lead-free solders, this is based on the WEEE directives that ban the use of lead-based solders in electronics. Several alternative lead-free solders were examined, some of those gave a lower impact on the environment, others not. All alternatives did show to give a strain on the metal production system due to changes in total demand. The third case study involved a hypothetical scenario of replacing 16.5% of the copper consumption, namely the copper pipes used in construction. The scenario shows that even though copper is a metal that is produced with relative few dependent metals it already gives strains on the metal production system.
1 Introduction

The metal production industry can be considered a relative environmental friendly industry. Although the production of metals itself produces large amounts of environmental emissions the industry is at the forefront of recycling, constantly reducing the need for resources and reducing the amount of waste discarded. This environment friendly side of the metal production industry is however not always apparent. As such it is not easy to do an environmental assessment of a metal. Especially not as one metal is not produced in isolation.

1.1 Metal production and recovery system

The metals production system is a very complex system. The raw materials for the production of metals, ore and scrap, are usually a mix of metals and other materials. Ores contain, besides the main metal that is locked in some sort of chemical bond with other elements, other chemically bonded metals and waste product such as silica or magnesia. Scrap usually consists of a mix of metals, plastics, and other materials. This variety in raw materials means that each metal has several types of production processes to obtain the final metal and that several metals are produced from one raw material source. Figure 1-1 gives a good overview of the connections between the production of metals. The carrier, or bulk, metals are those metals for which the raw materials are processed. The co-elements are side benefits of the production of the carrier metals; consequently the production of these co-elements is limited by the production of the carrier metals.

![Figure 1-1: Interconnected carrier metal cycles](image-url)
Figure 1-2 is another illustration of the interconnectivity of metal production. The figure shows the sources of primary silver. Only 25% of the silver produced from ores comes from silver ores, the other 75% comes from lead, zinc, copper and gold ores. A change in the production of lead will influence the availability of silver that in turn influences the demand of silver from other sources. Thus if we want to examine silver production we also need to examine lead, zinc, copper and gold production.

![Figure 1-2: Sources of primary silver](image)

### 1.2 Assessment of the metal production system

Once the metal life cycle is modelled an environmental assessment of the system can be made. Several methods have been developed to assess complex systems within an environmental context; these methods can be grouped under the term of Material Flow Analysis (MFA). In this study two methods that fall under the umbrella of MFA methods are used: Life Cycle Assessment (LCA) and Substance Flow Analysis (SFA). LCA is a widely acknowledge tool to support decision making on environmental issues in complex systems. LCA however is designed to assess the environmental impacts in a ceteris paribus system; it cannot adequately deal with changes in a dynamic system. SFA focuses on the material flow of one or more substance in a specific geographical region. SFA is a method that can handle complex and dynamic systems but its environmental assessment methods are less developed compared to LCA. As LCA and SFA are similar methods in use they are used in this study to compliment each other.

### 1.3 Objectives

The main objectives of this study are:

i. Construct, based on solid technological data, a dynamic model of the metal life cycle of nine metals using the work already done by Albert Scholte

ii. Through the use of the model get a better knowledge of the working of the metal life cycle system, how the production of the different metals depend on each other.

iii. To have an easy accessible tool with which people less knowledgeable on the metal life cycle can gain an overview of the metal life cycle and how certain decisions impact the whole system

iv. Use the model to make good environmental assessments of scenario changes to the system not only through the use of the LCIA method but also by examining the impact of change on the flows within the system
1.4 *The structure of the report*

The next chapter describes the environmental assessment methods used in this study. The differences and similarities between LCA and SFA are described and the application of these two methods to the metal life cycle system is discussed. In chapter 3 the model of the metal life cycle is described including the mathematical calculations and assumptions behind the model. The model of the metal production system is built up of the combination of several flow sheets that are described in chapter 4. The results of the model are discussed in chapter 5 using three case studies. A sensitivity analysis on the model is done in chapter 6. The report ends with the conclusions and recommendation in chapter 7.
2 Environmental assessment

In this chapter the approach to environmental assessment of the metal life cycle system is discussed. Paragraph 2.1 introduces the general framework under which environmental assessment methods are grouped, material flow analysis. Paragraph 2.2 and 2.3 describe the two methods used in this study, Life Cycle Analysis and Substance Flow Analysis. The differences and similarities between these two methods are discussed in paragraph 2.4. The application of these methods to the metal life cycle is discussed and described in paragraph 2.5.

Environmental assessment of products or systems is done for several reasons. For instance to get an idea of the environmental impact of that product or system, to gain knowledge of what the environmental impacts of the product or system cause and how this environmental impact can be minimized, to compare similar systems or products on their environmental impact so the environmentally best alternative can be identified.

In the last couple of decades several environmental assessment methods have been developed which can be grouped under the general name of Material Flow Analysis (MFA), in this study two specific methods are used: Life Cycle Analysis and Substance Flow Analysis

2.1 Material Flow Analysis

Material Flow Analysis (MFA) is a methodological framework concerned with the analysis of the throughput of process chains compromising the extraction or harvest, chemical transformation, manufacturing, consumption, recycling, accumulation and disposal of materials (Bringezu 2000). Through careful accounting of the inputs and outputs of the system of process chains, the interaction of the system with the environment can be estimated and possible methods of decreasing the impact a system has on the environment identified.

Within the MFA framework a domain of environmental assessment methods exist (Daniels and Moors 2002, Bringezu 2000). The MFA methods vary in the way they describe the system, the detail level, the function and region. SFA and LCA are two of these methods. The methods within the MFA framework have only a limited domain of application, therefore there is an increasing effort to converge and combine several methods for wider applicability (e.g. Assefall et al 2002, Tukker et al 1997, Van der Voet and Van Oers 1999, Daniels and Moore 2002).

2.2 Life Cycle Assessment

Life cycle analysis (LCA) examines the whole life cycle of a product accounting all phases in the life cycle. The development of a standardized framework for LCA started in 1989 at SETAC (the Society of Environmental Toxicology and Chemistry) followed by ISO (International Organization for Standardization), a worldwide organization, which aims to standardize a wide range of products and activities. The 14000 series of ISO standards includes the standard 14001 on Environmental Management Systems, as well as a series of standards relating to LCA, the 14040 series. These ISO activities began in 1994 and aimed to produce the first complete series of LCA standards (Guinée 2001).
Today there is worldwide consensus on most of the methodology; it is structured in a framework that forms the basis of a number of ISO standards (Guinée 2001). This framework divides the LCA procedure into four distinct phases.

- Goal and scope definition
- Inventory analysis
- Impact Assessment
- Interpretation

Below a brief description of each step is given.

2.2.1 Goal and scope definition
The goal definition should explain the goal, specify the intended uses of the result, the initiator and practitioner of the study, the target audience. The scope definition establishes the main characteristics of a LCA study. It covers the temporal, geographical and technological coverage, the mode of analysis applied and the level of sophistication of the study. Finally the products that are analysed are described in terms of function, functional unit and reference flows.

2.2.2 Inventory analysis
During the inventory analysis phase the system of investigation is further defined. This includes setting the systems boundary, designing the flow diagrams with unit processes, collecting data for each of these processes and performing allocation steps for multifunctional processes. The result of the inventory phase is a list quantifying the inputs from and the outputs to the environment associated with the functional unit.

2.2.3 Impact assessment
In the impact assessment phase the results from the inventory analysis are processed and interpreted in terms of environmental impact and societal preferences. Therefore a list of impact categories is defined and models relating environmental emissions to the suitable impact categories. Optionally, these impact categories can be grouped and weighted to include societal preferences of the various impact categories.

In LCA, the assessment methodology is well developed and some standardized methods have been developed, for instance the CML’02 (Guinée 2001) the EDIP ’97 (Wenzel et al 1997) and the Eco-Indicator ’99 (Goedkoop 2000). The first and second methods are problem orientated or bottom up approaches; The Eco indicator ’99 is a damage oriented or top down approach. Each of these methods could be used for assessment, though the outcome can differ for each method (Dreyer 2003).

The Eco-Indicator ’99 aggregates the results of the assessment in one or a few points, so called endpoints, through weighting. CML ’02 and EDIP ’97, on the other hand, make use of so called midpoints to present the results of the assessment; the impact categories are not weighted. Midpoints have the advantage that more information is given on the impacts; endpoints have the advantage that the result is easy to interpret for non-experts. Both types of assessment methods cannot be used together as they use different assumption to get to the results. There is some work done to integrate the two types of LCIA (Heijungs et al 2003, Hertwich and Hammit, 2001, Bare et al 2000)
2.2.4 Interpretation

The main elements of the interpretation phase are an evaluation of the results in terms of consistency and completeness, an analysis of the results in terms of e.g. robustness and the formulation of the conclusions and recommendations.

2.3 Substance Flow Analysis

A Substance Flow Analysis (SFA) focuses on the material flow of one substance, or a limited group of substances, in a specific geographical region. The aim of a SFA is to provide information for an overall management strategy with regard to the studied substances (van der Voet 2002). A SFA is also based on mass balance of all in- and outputs of the substances.

Unlike LCA no standardized framework has been made to set-up a SFA. A framework that is similar to the LCA approach is suggested (Udo de Haes 1997). The outline of that framework is given below.

This framework is a three-step procedure:

- System definition
- Quantification of the overview of flows and stocks
- Interpretation of the results for policy makers

2.3.1 System definition

The most important part is the establishment of the objective of the study. From this objective the substances to be studied and the system boundaries, usually a certain geographic region, are established. It can be useful to differentiate the system into subsystems. Two subsystems are typically used; a) the societal subsystem which contains the stocks and flows mainly controlled or caused by humans; and (b) the environmental subsystem containing the stocks and flows in the environment that can be described as biologically available. The environmental subsystem can be further subdivided into a number of environmental media: atmosphere, hydrosphere, pedosphere, biosphere and lithosphere. The lithosphere is sometimes regarded as a separate subsystem as it is the part of the environment that has no interaction with the other components of the given substance.

2.3.2 Quantification of the overview of flows and stocks

The substance flows can be modelled in different ways; three distinctive ways are described.

- Accounting
- Static modelling
- Dynamic modelling

Accounting

In this method a flowchart for the system with all the stocks, flows and processes is made. For a given period of time empirical data on the flows and stocks are collected. This method allows policy makers to spot trends and evaluate effects of certain changes.

Static modelling

With static modelling the process network is translated into a set of linear equations that describe the flows and accumulations as dependent on one another. Thus the inputs can be computed from the outputs, or vice versa. With static modelling a stationary situation is described, apart from possible changes in the immobile stocks and change from outside the system. Data from the accounting method can be used, but it is preferable to use data regarding the distribution characteristics of the processes itself. This way a consistent mathematical structure is developed. Static modelling is used to analyse specific problem flows with regards to their origins. Another use of this method is to measure the effectiveness of certain developments by comparative analysis.

Dynamic modelling
The output of a SFA can be used without further treatment of the data. With this method not only the long-term equilibrium can be studied but also the road towards that equilibrium and the time it takes to reach the equilibrium. This method is the most suitable for real scenario analysis, however as the data requirement of dynamic modelling is very high the accuracy of the model and of the projection might be limited.

2.3.3 Interpretation of the results
The output data of a SFA inventory can be used without further treatment if the case studied is relative simple. If the SFA is more complex, i.e. it studies several materials at the same time; the output data needs to be aggregated for interpretation. Specific key streams can be selected for monitoring, or efficiencies of processes can be examined.

The data of a SFA can be used without further treatment of the data. However, if the output of the inventory phase is complex, for instance if several substances are studied, further elaboration of the results is needed. The output data needs to be aggregated in one way or another to enable further interpretation by non-experts. A common approach is to aggregate the output in indicators. Indicators can be simple selected flows and stocks that are key to the flow of the substances studied or indicate critical accumulation of a substance within the system. They can also be used in reference to a value, e.g. a minimum value or an average value. Indicators can deal with the physical economy (recycling rate, efficiency etc.), the environment (total emission, environmental accumulation etc.) and with the system as a whole (pollution export, disruption rate etc.)

2.4 Differences and similarities in LCA and SFA
It can be seen that the methodological frameworks of LCA and SFA, as well as the typical problems encountered in these methods, are similar. However as the goal of both methods is quite different the implementation of the methods differs. LCA is generally focussed on products and their environmental impact to give information to product designers on how to environmentally improve a product. SFA on the other hands focuses on the impact that one substance, or a group of substances, has on a region to give information to policy makers.

LCA considers the change to a system while everything else remains equal, also it only considers the interaction between the technosphere and the ecosphere, not how
both spheres are changed. SFA on the other hand examines both the flows between the ecosphere and the technosphere as well as the flows and accumulations within those spheres. This makes it more difficult to conduct a SFA, but SFA is better suited for the use in complex dynamic systems than LCA.

In a SFA the results of an inventory are assessed in terms of trends, either changing of flows or stocks, 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 an ideal or normal value; deviation from this reference value can indicate problems. The indicators can be difficult to interpret for those that are not experts in that particular field. The impact analysis in LCA is far more developed than in SFA. Several methods have been developed for the assessment phase that convert the output into environmental impacts and one or a few environmental scores. However to aggregate the results assumptions need to be made which makes the results less scientifically based. Moreover, as they are used on highly aggregated level information is lost; analysing impact assessment results should thus not be done without the context in which they are conducted.

2.5 Impact assessment in the metal life cycle

When conducted an impact assessment of a scenario change to the metal production system many problems are encountered that are typically for LCA and SFA. Difficulties like limited data availability and quality, determining allocation rules, system boundaries and detail, and temporal and spatial characteristics (e.g. Heijungs 1996, Ekvall and Finnveden 2001, Burgess and Brennan 2001, Björklund 2002). Due to the iterative nature of SFA and LCA these problems are interrelated. For instance study scope, resolution and boundaries establish the need for data, while data availability can affect scope, resolution and system boundaries. This is especially true in the metal production and recycling system because of the interdependencies between the metals; often it can only be established afterwards if the choices made were right for the study.

2.5.1 Goal and scope

Determining the goal and scope of a SFA or LCA basically involves five choices: Goal, system boundaries, geographical coverage, subsystem and level of detail.

Both LCA and SFA can be used to study the metal production system. As mentioned before they have different types of goals: LCA can be used to assess for example which scenario alternative has the lowest environmental impact, SFA can be used for example to investigate how the supply of raw materials is affected by the scenario change.

It is important to realize that the metal production system is a global system; ores are mined all over the world, shipped to smelters in other parts of the world, consumed and recycled everywhere. The metal production system should always be considered in a global context.

After selection of the goal of the study, the first choice in both methods is the selection of the system boundaries. According to the ISO 14041 system boundaries should be selected so that all the inputs and outputs are elementary flows, i.e. flows that are directly affected by a change to the system. In this context it is useful to
distinguish between a foreground and a background system (Azapagic and Clift 1999). 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 very small the system can be regarded as in status quo and there is no need to model it detailed.1 If however, the background system is more affected by the changes in the foreground system it cannot be regarded as a status quo, equilibrium, system.

Background systems like the energy requirements of processes, off gas produced during the process and emissions during transporting metals over the world are linearly dependent on the production of metals and do not need a detailed level of modelling. Due to the complexity and interdependency of the metal production system it is difficult to estimate which processes can be regarded as foreground systems and which as background systems. Figure 1-1, which shows the interdependence of metal production and recovery system, can serve as a guideline in determining the system boundaries.

One of the main limitations in modelling systems is the data availability. Data for the unit processes in the metal production system is typically scarce and scattered, which leads to problems of data gaps, data inaccuracy and unrepresentative data (Huijbregts 2001, Bjorklund 2002, Danius and Burstrom 2002). Data gaps can be filled through the use of expert knowledge and inaccurate or unrepresentative data can be dealt with using data reconciliation (Reuter 2001). Although more detailed modelling might give more problems with data availability it can sometimes be very necessary to accurately model the system due to interactions within the system at the lower level.

2.5.2 Inventory

When constructing an inventory for a LCA or SFA it should be considered that although the ISO standards for LCA provide a starting point for constructing a LCA or SFA it does not regulate all methodological choices, consequentially virtually any result could be produced (Ekvall and Finnveden 2001). Using different, equally suitable and acceptable, assumptions and choices can give different a totally different inventory outcome.

The inventory of the metal production system needs to incorporate the dynamics and interdependency of that system. As demand for metals and recycling rate change over time the interdependencies within the metal production system adept to the new situation. A dynamic model will also allow the assessment of not only the end result of a change to the system but also the path towards the new equilibrium and what possible problems will be on that path. Dynamics of a system are usually modelled in SFA through the use of stocks, accumulation ‘nodes’, in the model.

Due to the dependencies between metals there are many multiple function processes in the metal production system. Multiple function processes are in this context processes that generate more than one usable output. The problem is to assign to each

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1 Which background systems should be examined can be determined by cut-off criteria, these determine how much influence the background system has on the foreground system. However often such a cut-off criteria can only established afterwards.
of the substances or products only those environmental burdens that are produced due to that substance or product. The LCI-ISO 14042 standard prescribes the following allocation hierarchy:

(i) Avoidance of allocation through division of the multifunction process or through expansion of the system investigated until the same functions are delivered by all systems incorporated.

(ii) Allocation based on causal relationships between the environmental burdens and the functions.

(iii) Allocation based on non-causal relationships between the environmental burdens and the functions, e.g. economic value.

Allocation based on non-causal relationships may not provide accurate information on the consequences of an action. Non-causal relationships are however relatively easy to establish and this method is often used in LCA; if possible however it should be avoided. Avoiding allocation through subdividing processes rarely solves allocation problems but can reduce the problem. However, it can be a time consuming process and the needed higher data resolution can be difficult to acquire.

Solving allocation problems through causal relationships and avoiding allocation through system expansion both are good methods to solve allocation problems, which should be used depends on the situation (Ekvall and Finnveden 2001, Azapagic and Clift 1999). Expansion of the system should be used if the indirect effects of a change to the process are important. Allocation based on causal relationships should be used when the effects on the production of the exported function of a process are expected to not be important. In the ideal case solving allocation through causal relationships will have the same result as system expansion. The choice between the different methods to tackle emissions from multiple function processes is difficult to make due to the complexity and non-linearity of the system. Besides these considerations data availability and ease of applicability decide how to handle allocation problems. Due to the interdependencies in the metal production system expansion of the system is usually the best method of solving allocation problems, it is however also the most time consuming method and relies more on data availability and quality.

When the best allocation method has been chosen the original choices in the goal and scope may have to be reviewed and adjusted if needed. It should also be recognized that only after the inventory and inventory assessment is made it can be established if the choice made were right, e.g. if the system boundaries should have been different or if the level of detail was good.

2.5.3 Impact assessment

The result of the inventory phase is a long list of very different entries that can be difficult to interpret. To assist in interpreting the data both LCA and SFA have come up with assessment methods that represent the data in easy to interpret decision parameters.

The LCIA assessment method Eco-Indicator '99 is very useful to compare different scenarios as it provides a single score, which makes comparison of different scenarios
easy. However, as noted in paragraph 2-4 with this method a lot of the information from the inventory is lost.

The assessment methods used in the SFA methodology, which are generally less developed, compared to LCA, examine the system more closely through the use of indicators to assess the inventory results. These indicators are usually compared to a reference value. Indicators include flow rates, production efficiency, stock level, and recycling rate and indicate what the cause and effect are of changes to the system (Van der Voet et al 1997). These types of indicators are especially useful in a dynamic system.

Both assessment methods are complementary. The LCA assessment method gives an easy result which is relative good to relate to the problem, but as it uses assumptions and additionally models, the end results can vary depending on the assessment method chosen. SFA assessment methods on the other hand are good to examine the relationships between effects and the causes and thusly give more information where changes have greater effect.
3 Modelling of the metal life cycle

This chapter describes the model of the metal life cycle as it is used in this study. The first paragraph briefly describes the software used for the model. Paragraphs 3.2 to 3.6 describe each of the five phases in the metal life cycle: mining, production, manufacturing, consumption and waste management. The production phase is described extensively as this is the emphasis of my work on the model. Paragraph 3.7 shortly describes the various scenarios implemented in the model. Finally in the last paragraph has a description of the inventory analysis and environmental assessment as it is in the model.

![Interactive map of the metal life cycles](image)

*Figure 3-1: The overview of the metal life cycle model*

3.1 Software for constructing the model

The model is constructed in Simulink. Simulink is an interactive tool for modelling, simulating and analysing dynamic systems (Mathworks Inc 2002). It is a software package that enables a user to model, simulate, and analyse systems whose outputs change over time.

In Simulink a dynamic system is modelled through selection and interconnection of appropriate blocks representing the elementary units. Each block is compromised of one or more of the following: asset of inputs, a set of states and a set of outputs. The
output of a block is a function of time, the blocks inputs and states. The blocks used in this model are however stateless. The input signal of each block, a 15 elements vector consisting of the total mass and the masses of fourteen key metals from the previous unit operation, is multiplied by a constant split factor for each element. Each Simulink block type is associated with a set of system functions that specify the time dependant relationships. A simulation invokes the system functions to compute the values of the systems states and outputs. A Simulink model specifies the time derivatives of its continuous states but not the values of the states themselves. The continuous states are computed by numerical integration.

### 3.2 Mining

The mining block calculates how much ore is needed, also mining and concentrating at the mine is modelled. In figure 1-2 the calculation of the ore demand is depicted for copper. The demand for copper ore is calculated at (1); it is the total world demand for copper minus the demand satisfied by the recycling of copper as calculated by (2). The mining and concentration of copper ore is calculated in block (3) through the use of unit operations, which are explained in paragraph 1-3.

The outputs of each of the five blocks need to be transported for processing at the next size. Copper concentrate needs to be transported form the mine to the smelter. The distance between each site can vary a lot and can span half of the globe. The emissions of these transports are calculated at (4) based on the average distances between the mine sites and the smelter locations. The transportation between the other blocks is calculated in a similar fashion.

![Figure 3-2: The mining block](image-url)
3.3 Metal Production

In this paragraph the application of metal production in Simulink is explained. This is the most important part of the model and most extensive modelled. The actual flow sheets of the metal production are thoroughly described in chapter 4.

3.3.1 Modelling unit operations

The approach to model unit processes is extensively described by (Scholte 2002). Here a short summary of the method is given. The production of a metal can be represented by a flow sheet, a series of connected processes. Each of these processes, unit operations, has certain inputs, outputs and energy requirements. In literature data about the unit operations were searched. The data found originates from different sources, from different years and were used for different purposes. Therefore these data can be inconsistent, i.e. the mass balance does not fit. To correct the data inconsistencies data reconciliation is applied; data reconciliation is a tool with which the in- and outputs are adjusted to get balanced mass while minimizing the adjustments made. Mathematically equation 3-1 needs to be minimized, while the constraints, global flow rate (equation 3-3), global and elements flow rate (equation 3-4) and data integrity (equation 3-5), need to be adhered (Reuter 2001).

$$J(Y) = \sum_{p} \sum_{i} J_{pi}(Y)$$  \hspace{1cm} \text{Equation 3-1}

$$J_{i}(Y) = \left( \frac{Q_{pi} - \bar{Q}_{pi}}{\sigma_{pi} \cdot \bar{Q}_{pi}} \right)^2 + \sum \left( \frac{P_{pik} - \bar{P}_{pik}}{\sigma_{pik} \cdot \bar{P}_{pik}} \right)^2$$  \hspace{1cm} \text{Equation 3-2}

$$\sum_{i} m_{ji} \bar{Q}_{pi} = 0$$  \hspace{1cm} \text{Equation 3-3}

$$\sum_{i} m_{ji} \bar{Q}_{pi} \bar{P}_{pik} = 0$$  \hspace{1cm} \text{Equation 3-4}

$$\sum_{k} \bar{P}_{pik} = 1$$  \hspace{1cm} \text{Equation 3-5}

Where:

- $\bar{Q}_{pi}$ = Measured flow rate of phase p in stream i
- $Q_{pi}$ = Estimated flow rate of phase p in stream i
- $\bar{P}_{pik}$ = Measured fraction of component k of phase p in stream i
- $P_{pik}$ = Estimated fraction of component k of phase p in stream i
- $\sigma_{pi}$ = Possible estimated measurement error in $Q_{pi}$ (%)
- $\sigma_{pik}$ = Possible estimated measurement error in $P_{pik}$ (%)

After a unit process is mass balanced the recovery of all outputs is calculated based on the main input. The data reconciliation and calculation of recoveries can all be done in simple calculating programs; in this case Microsoft Excel was used.
After the data reconciliation the unit operations are put into the Simulink. Figure 3-3 is an example of a unit operation in Simulink. Each unit operation is depicted in two or three blocks: (a) a mass balance block, (b) an energy requirement block and, if applicable, (c) an off gas block.

In the mass balance block the outputs of the process are calculated using the recoveries obtained from the data reconciliation.

The energy requirements of a process are calculated using equation 3-6:

\[ E_{Total} = Q_{in} \times E_{process} \times R_{process} \]

Equation 3-6

Where:

- \( E_{Total} \) = Total energy requirements of the process (kWh)
- \( E_{process} \) = Energy requirements of the process based on the amount of end product that is produced (kWh/t)
- \( R_{process} \) = Tonnes of end product that can be produced from the input (kWh/t)

The composition of the off gas is calculated using equations 3-7 to 13-18.
**CO₂ and CO production**

CO₂ and CO are produced through reduction of metals in processes and burning fuels during processes.

\[
CO_2,\text{total} = CO_2,\text{process} + CO_2,\text{fuel} + CO_2,\text{transport}
\]

*Equation 3-7*

Where:

- \(CO_2,\text{total}\) = Total CO₂ production (m³)
- \(CO_2,\text{process}\) = CO₂ production due to reduction of metals (m³)
- \(CO_2,\text{fuel}\) = CO₂ production due to burning fuels during processes (m³)
- \(CO_2,\text{transport}\) = CO₂ production during transport (m³)

Metal oxides are usually reduced to metals using carbon; the amount of CO and CO₂ created during this reduction process is calculated with formulas 2-5.

\[
CO_p = Q_{in} \times X_{\text{carbon}} \times \frac{10^6}{M_c}
\]

*Equation 3-8*

\[
CO_2' = \sum_{i=0}^{14} Q_{ip} \times X_{\text{ton/mol}} \times X_{\text{oxides/metal}}
\]

*Equation 3-9*

\[
CO_2,\text{process} = CO_2' \times \frac{M_{CO_2}}{\rho_{CO_2}}
\]

*Equation 3-10*

\[
CO = (CO_p - CO_2') \times \frac{M_{CO}}{\rho_{CO}}
\]

*Equation 3-11*

Where:

- \(CO_p\) = Theoretical CO production (mol)
- \(Q_{in}\) = Total input quantity (t)
- \(X_{\text{carbon}}\) = Carbon input as a percentage of the total input
- \(M_c\) = Mol mass of carbon (kg/mol)
- \(CO_2'\) = Moles CO₂ produced
- \(Q_{ip}\) = Tonnes of produced metal i (t)
- \(X_{\text{ton/mol}}\) = Conversion factor tonnes of moles for metal oxides
- \(X_{\text{oxides/metal}}\) = Moles of O needed to oxidize one mole of metal i
- \(CO_2,\text{process}\) = Actual CO₂ production (m³)
- \(M_{CO_2}\) = Mol mass of CO₂ (kg/mol)
- \(\rho_{CO_2}\) = Density of CO₂ (m³/kg)
- \(CO\) = Actual CO production (m³)
- \(M_{CO}\) = Mol mass of CO (kg/mol)
- \(\rho_{CO}\) = Density of CO (m³/kg)

Oil, gas and coal burned for energy during the process also generates CO₂ dependent on the carbon content of the fuels (Table 3-1). It is assumed that no CO is produced, only CO₂.

\[
CO_2,\text{fuel} = \sum_{i=0}^{f} X_{CO_2,i} \times Q_i
\]

*Equation 3-12*

Where:

- \(CO_2,\text{fuel}\) = CO₂ produced through burning fuel (kg)
- \(X_{CO_2,i}\) = CO₂ produced per quantity of fuel burned (kg/kg)
\[ Q_i = \text{Quantity of fuel I used (kg)} \]

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>CO2 emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy fuel oil</td>
<td>3.129 kg/l</td>
</tr>
<tr>
<td>Natural gas</td>
<td>1.77 kg/m(^3)</td>
</tr>
<tr>
<td>Coal</td>
<td>2.73 kg/kg</td>
</tr>
</tbody>
</table>

*Table 3-1: CO\(_2\) production for different types of fuels*

**SO\(_2\) production**

SO\(_2\) is produced from oxidizing metal sulphides; SO\(_2\) production from fuels is neglected.

\[
SO_2' = Q_{S, offgas} \times X_{S, ton/mol} \quad \text{Equation 3-13}
\]

\[
SO_2 = \frac{SO_2'}{M_{SO_2}} \times \rho_{SO_2} \quad \text{Equation 3-14}
\]

Where:

- \(Q_{S, offgas}\) = Tonnes of sulphur in the off gas (t)
- \(X_{S, ton/mol}\) = Conversion factor converted tonnes to moles for sulphur
- \(M_{SO_2}\) = Mol mass of SO\(_2\) (kg/mol)
- \(\rho_{SO_2}\) = Density of SO\(_2\) (m\(^3\)/kg)
- \(SO_2\) = Moles SO\(_2\) produced
- \(SO_2'\) = Cubic meters of SO\(_2\) produced (m\(^3\))

It is assumed that 99\% of the SO\(_2\) produced is captured and converted to H\(_2\)SO\(_4\) with an efficiency of 97.49\%.

**NO\(_x\) production**

The NO\(_x\) emissions of a process are determined by the formation and capture of the NO\(_x\):

\[
E_{NO_x}(t) = C_{NOX} \cdot \sum_{i=1}^{n} F_{NOX,i}(t) \quad \text{Equation 3-15}
\]

Where:

- \(E_{NOX}(t)\) = Emission of NO\(_X\) (ton/a)
- \(C_{NOX}\) = Capture efficiency of NO\(_X\) (ton/ton)
- \(F_{NOX,i}(t)\) = NO\(_X\) formation through mechanism \(i\) (ton/a)
- \(n\) = Number of NO\(_X\) formation mechanisms

There are three different formation mechanisms for NO\(_X\) (Sloss 1992):

- **Thermal formation** from N\(_2\) in the air,
- **Prompt NO\(_X\) formation**, which converts N\(_2\) into NO in the flame front, and
- **Fuel NO\(_X\) formation**, in which the nitrogen in the fuel is oxidised to NO\(_X\).

Thermal formation typically starts at 1300\(^\circ\)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. Based on (Sloss 1992), the thermal NOX formation can be estimated as follows:

\[ N_2 = \left( CO_p + SO_2 \right) \frac{M_{O_2}}{\rho_{O_2}} \frac{C_{Air,N_2}}{C_{Air,O_2}} \]  \hspace{1cm} \text{Equation 3-16}

\[ F_{NOX,\text{thermal}}(t) = N_2 \left( 1 - O_{2,\text{excess}}^{-1} \right) \frac{C_{Air,N_2}}{C_{Air,O_2}} \times 100 \]  \hspace{1cm} \text{Equation 3-17}

Where:
- \( C_{Air,O_2} \) = Oxygen concentration in the air
- \( C_{Air,N_2} \) = Nitrogen concentration in the air
- \( O_{2,\text{excess}} \) = Excess oxygen during the process,
  - Reductive processes \( O_{2,\text{excess}} = 1.025 \)
  - Oxidative processes \( O_{2,\text{excess}} = 1.1 \)

According to the (Sloss 1992) prompt NOX formation is negligible (\( F_{NOX,\text{prompt}}(t) \approx 0 \)).

Fuel NOX formation depends on the nitrogen content of the fuel used (Table 3-2) and the combustion method used. It is assumed that 50% of the nitrogen in the fuel is oxidized to NOX.

\[ F_{NOX,\text{fuel}}(t) = 0.5 \sum_{i=1}^{n} F_i(t) C_i \]  \hspace{1cm} \text{Equation 3-18}

Where:
- \( F_i(t) \) = Consumption of fuel i
- \( C_i \) = \( N_2 \) concentration of fuel i
- \( n \) = Number of fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Nitrogen content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>0.5-2%</td>
</tr>
<tr>
<td>Heavy oil</td>
<td>0.5%</td>
</tr>
<tr>
<td>Light oil</td>
<td>Trace</td>
</tr>
<tr>
<td>Natural gas</td>
<td>Trace</td>
</tr>
</tbody>
</table>

\text{Table 3-2: Nitrogen content of selected fuels}

Finally, NOX emissions are reduced by selective catalytic reduction, in which NOX is reduced to \( N_2 \). The efficiency of this reaction ranges from 60% to 90% (Sloss 1992). An average capture of NOX (\( C_{NOX} \)) of 0.75% is assumed.

In appendix 1 the recovery numbers, the energy requirements and the off gas of each unit process is listed as they are used in the model.
3.3.2 Flow sheets

The production of a metal is usually described using a flow sheet. In a flow sheet all options of producing a metal are displayed through connecting the relevant unit operations. Figure 3-4 shows the flow sheet of lead production.

![Figure 3-4: The flow sheet of lead production](image-url)

The flow sheet of lead production shows that lead is produced along several processing routes. These production processes are incorporated into the whole flow sheet using splitters, which define the connection between the unit operations. A splitter, for instance the block lead bullion in Figure 3-4, accommodates a number of inputs and splits these in all relevant unit operations, in this example electrorefining and pyrorefining. The mathematical representation of a splitter is depicted in Figure 3-5

### Input from other unit operations to splitter A

\[
\sum_{j=1}^{n} X_{i,j} \cdot \alpha_{i,j,k} \cdot \beta_{i,j,k} = A_{i,k}
\]

**Total mass of k reporting to unit i**

**Fraction of k reporting to unit j**

**Decision variable between 0 and 1**

**Decision variable between 0 and 1**

### Mass Balance equation for splitter A:

\[
A_{i,k} - \sum_{j=1}^{n} X_{i,j} \cdot \alpha_{i,j,k} \cdot \beta_{i,j,k} = 0
\]

\[
\sum_{j=1}^{n} \beta_{i,j,k} = 1
\]

**Figure 3-5: Mathematical representation of a splitter**

In the model the splitter is calculated as in Figure 3-6, which depicts a splitter for lead concentrate. Notice that the feed for the Imperial Smelter Furnace is calculated dependant on the zinc input; all other processes use a constant amount of the rest of the lead concentrate.
3.3.3 Intermediates

Once the flow sheets of the production of individual metals have been made the links between those flow sheets needs to be implemented. Flow sheets are linked through intermediates; intermediates are by products of a process that can be further processed to produce another metal. In the model intermediates are stored in stocks. This ensures that the consumption of an intermediate is not directly affected by the production of the intermediate. In general the production of an intermediate is greater than the consumption of the intermediate; there is an overproduction of the intermediate. It is assumed that this overproduction is because not all intermediate is economical feasible to process. A decrease of the stock level means that economic less viable intermediates need to be processed, while an increase of stock indicates that only the more concentrated intermediates are processed. A deviation of a stock could indicate that there can be problems, either in the supply of the intermediate or in the consumption of the intermediate.

Mathematically this is calculated with the following formulas:

\[ \text{Stock}(t) = \int (P(t) - \text{Disposal}(t) - \text{Consumption}(t)) \, dt + \text{Stock}(t - 1) \quad \text{Equation 3-19} \]

\[ \text{Disposal}(t) = \text{Stock}(t) - \text{Consumption}(t) \quad \text{Equation 3-20} \]

\[ \text{Consumption}(t) = \min(C(t), \text{Stock}(t)) \quad \text{Equation 3-21} \]

With:

- Stock(t) = Stock of intermediate
- Disposal(t) = Intermediate disposed (to waste incinerator or landfill)
- Consumption(t) = Actual consumption of intermediate
- P(t) = Production of intermediates
- C(t) = Calculated consumption of intermediate, depends on the demand for metal
3.4 Products Manufacturing

Metals are produced into a wide variety of products; copper for instance can be used in electronics, brass, copper wiring and many other applications. As the model tries to follow the flow of the metal and not the exact use an abstraction of the products was chosen. Five basic product groups were chosen and categorized on the lifetime, the time before the products are discarded, of the products in that group.

- Life time of 1 year
- Life time of 8 years
- Life time of 15 years
- Life time of 20 years
- Life time of 50 years

Each product was assigned into a different group according to their expected lifetime, e.g. tin cans in the first group, jewellery the last group. In the course of years the use of metals in each product group can change. Such changes can have considerable impact on the distribution of the metals over the five product groups.
During the manufacturing of products some metal waste is produced. This waste, sometimes named new scrap, is relative pure metal and usually only needs to be remelted to use it again.

### 3.5 Consumption

In the consumption block the time it takes till products are discarded is modelled. The consumption model combines two concepts.

1. The actual lifetime. A time distribution over the product group is applied with the median being the average lifetime.
2. The composition of the output. The consumption phase is considered to be a plug flow; the composition that enters the consumption phase first will leave the consumption phase first.

The composition of the total output of a product group is thus a mix of different input compositions.

### 3.6 Solid Waste Management

In the waste management block the collection, separation and discarding of products is modelled. An overview is depicted in figure 3-8. In the three collection blocks the collection percentage for the product groups is calculated and grouped in five types of waste.

- Municipal Solid Waste (MSW)
- End of Life Vehicles (ELV)
- Electrical and Electronics Equipment Waste (WEEE)
- Construction and Demolition waste (CDW)
- Other wastes

The other wastes group contains all wastes that cannot be categorized in the first four groups.
The first four waste categories are usually separated into several valuable fractions and a waste fraction. The waste fraction is sent to either a landfill, where nothing will happen to it, or to a municipal solid waste incinerator where the waste is burned, sometimes with energy recovery, and some metals are recovered. All recovered metals are collected in the scrap dealer block where the metals are sorted into the appropriate categories.

3.7 Scenarios
In the model several standard scenarios are built in affecting parameters with which the model calculates, e.g. the demand for metals. Additionally several scenarios can be used to examine the influence of a scenario change on the metal life cycle.

The quasi dynamic uses the parameters of the year 2000 as a starting point and calculates the whole simulation with the same parameters.

The dynamic scenario uses historic data for the parameters to simulate the metal life cycle from 1940 to 2000, after 2000 it uses a prediction of the development of the parameters (Van Vuuren et al 1999).

- Egalitarian. This scenario assumes that humans will recycle a lot, and consumption is low
- Hierarchist. This scenario assumes that humans recycle moderately and consumption is moderate
- Individualist. This scenario assumes that human recycling is low and consumption is high
- 2000. This scenario assumes that after the year 2000 nothing changes to the metal demand

3.8 The Inventory Analysis and the Life Cycle Assessment
In paragraph 2-5 the application of assessment methods in this study is discussed. In this paragraph the indicators used for LCA assessment are explained and the Eco-indicator’99 is explained.

The indicators used in SFA assessment are quite simple and easily calculated indicators. Examples include process efficiency, recycling rate, the quantity of each stream can be easily accessed in the form of graphs in the inventory analysis block. This allows for a quick assessment of the material flows and identification of problem flows. There are also a few indicators incorporated like production efficiency, recycling rate and recycling efficiency.

The Life Cycle Impact Assessment is applied using the ECO-Indicator’99 method, a method that is explained below. The results from the LCIA are shown in midpoints and in endpoints.

3.8.1 Eco-indicator’99 method
The assessment method most commonly used by product designers in the Netherlands is the Eco-indicator’99 (Goedkoop 2000). The Eco-indicator ’99 is a SETAC method. In the Eco-indicator’99 all environmental impacts are expressed in a single score. The general outline of this method is depicted in figure 3-9. After the inventory phase the damages the environmental emissions cause to human health, ecosystem quality and resources is calculated. For this purpose a series of damage models are developed. The results for the three impact categories are weighted to produce one figure.
Damage model for emissions
For the calculation of the damages caused by emissions four steps are needed.

Fate analysis
Chemical substances released to the environment find their way through the environmental compartments air, water and soil. Where a certain substance will go depends on the substance. With the fate analysis the transfer between compartments and degradation of substance is calculated.

Exposure
Based on the calculation with the fate analysis the amount of substance taken in by people, plants or other life forms can be calculated.

Effect analysis
Once the exposure to a certain substance is derived the types and frequencies of diseases and other effects can be calculated.

Damage analysis
The prediction of diseases can now be expressed into LCA damage units. E.g. the years of lives lost due to cancer caused by a chemical substance. These damages are subdivided into different categories see Figure 3-10.
**Damage model for land use**
Mankind is occupying large areas for urban, industrial and agricultural purposes. This is an important reason why many species are threatened with extinction. The effect depends on the type of land use: e.g. a paved parking lot will have less plant species than an organic meadow. These effects are included in a LCA study.

**Damage model for resources**
Extraction of minerals will reduce the quality of the remaining resources. The damage to resources will be experienced by future generations, as they will have to increase the effort to extract the remaining resources. The extra effort is expressed as “surplus energy”. For the extraction of fossil fuels a similar model is used.

The damage models will result in the three environmental impacts shown in Figure 3-10
- Damage to human health
- Damage to ecosystems
- Damage to resources

**Weighting**
The weighting step is the most critical and controversial step in the methodology. Through weighting the three impact categories can be put into a single score. A panel weights the damages caused by the impacts categories and assesses the seriousness of the three impact categories.
- Damage to human health expressed as the number of year life lost and the number of years lived disabled.
- Damage to the ecosystem quality expressed as the loss of species over a certain area during a certain time.
- Damage to resources, expressed as the surplus energy needed for future extractions of minerals and fossil fuels.
4 Metal production flow sheets

In this chapter the metal production flow sheets are explained. These are the flow sheets as applied in the metal production model and are a simplification of the reality. Some processes that are very similar in operation are grouped; other processes have an insignificant throughput and are left out. Each paragraph handles one metal and includes a general overview of the metal production, a description of the unit processes and a description of the solid waste management of the metal. This chapter was written together with Ewoud Verhoef. Of each chapter Ewoud Verhoef has written the waste management and the manufacture and consumption paragraphs; the mining and production paragraphs are written by me. For this chapter various sources are used, the main sources are (Ullmann 2000, Rosenqvist 1983, Pawlek 1983, USGS). In appendix 1 the input of and recoveries in each unit process described here are quantified.

4.1 Bismuth

4.1.1 Mining & Production

In 2000, about 4370 tonnes of bismuth were produce globally. Bismuth is mostly recovered as by-product from lead and copper 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. 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.

![Figure 4-1: Global bismuth production](image-url)

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.
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 lead and copper production). 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 sulphuring (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 was obtained by recycling 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 obtained from the non-Ferro fractions returns to bismuth production through the copper and lead anode slimes and the Kroll Betterton dross.

Figure 4-2: Simplified flow sheet of bismuth production
4.1.2 Manufacture and consumption

Based on U.S. consumption patterns, it is estimated that currently about 42% of bismuth was 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. Data on the end uses of bismuth covered only the last decade.

4.1.3 Solid waste management

Only a small amount of bismuth was obtained by recycling 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.

4.2 Copper

4.2.1 Production

In 2000, about 14.9 million tonnes of copper were produce globally. Copper is produced from sulphuric and oxidic ores that are obtained from lead, zinc, nickel and copper mining. About 80% of the primary copper originates from low-grade sulphide ores, 0.8 - 4%, and is crushed, grinded and concentrated by flotation to 25 -35% Cu. The resulting tailings have very low copper content (ca. 0.05% Cu), and are discarded.

![Copper production graph](image-url)

**Figure 4-3: Global copper production**

These copper concentrates are usually converted into copper in two 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 sulphur content to an optimum level for smelting. In many modern processes, the roasting step is combined with matte smelting, however. In matte smelting the concentrate, or roasting product, is converted into a copper matte that consists of approximately 55% copper, 20% sulphur, 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%.

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 will probably not be built.

![Figure 4-4: Simplified flow sheet of copper production](image)

*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. Consequently the off gas is more easily cleaned.
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 as the rate of reaction in autogenous smelters is higher, it increases the 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 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 smelted matte from these processes, must further processed in a convertor, to produce a crude copper with 98-99% copper suitable for refining. In this process, the matte is blown with air in two stages. First, the iron is oxidized to iron oxide and dissolved in the slag by adding silica. Second, the copper sulphide is oxidized to copper metal. Because these reactions are highly exothermic, copper scrap is added during the process as a coolant.

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 volatilisation, (ii) to reduce the sulphur content by oxidation, and (iii) to decrease the oxygen content by reduction. After fire refining, the main impurities consist 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 (see Nickel production). 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. 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 sulphuric 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 high copper content and low sulphur content, is usually recovered through this route as well. 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.

4.2.2 Manufacture and consumption

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.

4.2.3 Solid waste management

Some 13% of copper is obtained by recycling old scrap. 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 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. 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 converter (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. (However, this is not modelled.)

In addition, also new scrap (and to some extent old scrap as well) is added to control the temperature in the ‘primary’ converters. Tin is a valuable by-product of secondary copper production. The tin is recovered in a silicate slag (at the copper convertors) which is sold to tin producers (up to 17-25% Sn). 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.

### 4.3 Gold

#### 4.3.1 Production

In 2000, about 3660 tonnes of gold were produced globally. The bulk of the gold is obtained from gold ores (76%). A small amount of gold is produced from by-products of the 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 4-5: Global gold production](image)

Gold ores are mainly treated with the carbon-in-pulp process. 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/tetrachloroaauric acid. Other platinum group metals and silver accumulate in the anode slime. These are further treated to obtain the precious metals.
4.3.2 Manufacture and consumption

Gold is a valuable, yellow-coloured scarce metal that has been 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, jewellery, and ornaments have always been the most important applications of gold. 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 90’s 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 jewellery and coins, gold can be expected to have an average long residence time in the consumption phase.

4.3.3 Waste management

A significant amount of gold is produced from old gold scrap (24%). Gold’s main applications, such as jewellery, 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.
4.4 Lead

4.4.1 Production

In 2000, about 6.65 million tonnes of lead were produced globally. 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 from lead mines. 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.

![Lead production graph](image_url)

Figure 4-7: Global lead production

After ore beneficiation, the lead concentrates typically contain 50-60% lead. 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, except for 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%). Traditionally, lead is produced with a blast furnace or the imperial smelter process. Both processes use a sintering step to oxidize the sulphide concentrate and to obtain a lumpy and strong agglomerate suitable for use in the furnace.

The **Blast Furnace 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 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 zinc).

The flue dust production in the sintering step of these two furnaces is a major environmental problem of the traditional routes. In order to avoid environmental problems, proper ventilation and dust cleaning equipment is required. Modern smelting operations have 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.

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 desulphurisation 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 process can also smelt oxidic charge materials such as zinc leach residues.

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, sulphur 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 sulphide concentrate is used to reduce 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 slag from direct smelting 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 (see silver production); the Kroll-Betterton dross is processed to recover bismuth (see bismuth production).

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 (see silver and bismuth production). 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.

### 4.4.2 Production and manufacture

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. 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. 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.

4.4.3 Waste management

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. 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 a two steps process, using reverberatory and blast furnaces. 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 further processed into lead bullion, in a Blast furnace for instance. Lead in the non-Ferro fractions can also be recovered.
4.5 Nickel

4.5.1 Production

In 2000 globally about $1.12 \times 10^6$ tonnes were produced (USGS 2000). Nickel is produced as nickel metal (ca. 67%), as nickel oxide (ca. 10%) and as ferronickel (ca. 23%, USGS 2000).

Nickel is produced from both sulphide (48%) and oxide (52%) ores, that both have different production routes. The production of nickel from sulphide ores can be divided into two steps: (i) smelting and converting the sulphide ore to matte (ii) processing the matte to nickel. Oxide ore is processed in a variety of processes; most oxide ores are used to produce ferronickel.

The treatment of sulphide ores is similar to the treatment of copper sulphides. The process can be divided into three steps, viz. roasting, smelting and converting. In the roasting step, sulphur and iron are partly oxidized. In the smelting step, the roasting product is melted together with a siliceous flux to produce two immiscible phases: an iron-silicate slag and a matte containing mainly nickel and copper sulphides. The last step is to convert the matte into a high-grade nickel copper matte by oxidation. More sulphide is driven off as sulphur 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 sulphide ore into matte: the reverberatory (13 %), electric (13%) and flash smelting furnace (74%). As nickel smelting is similar to copper smelting, the operation of these furnaces is more or less the same as in copper production.
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 heating value of the fuel.

The electric furnace uses electric energy as heating power 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 sulphur 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 oxidise the iron and remove some of the sulphur. The iron oxides are

Figure 4-10: Simplified flow sheet of nickel production
'slagged off' through the addition of silica fluxes. The matte is a melt of nickel (50-60%) and copper sulphides with small amounts of cobalt sulphides, iron, precious metals and other impurities. This matte is slowly cooled which allows the matte to segregate into three phases: (i) copper matte (ii) nickel matte (iii) copper-nickel alloy containing the precious metals. After solidification, the three phases are crushed, ground and are separated by magnetic separation and flotation. The copper matte is converted to copper in the copper matte converting process (paragraph 4.2).

The nickel matte can be treated with three different processes to refine nickel and extract cobalt and copper. In the ammonia leach process (26%) matte is leached in a two-stage counter current process. Nickel, copper and cobalt form complexes with ammonia and are dissolved. In case the matte contains low concentrations of copper, the leaching step can be skipped. The ammonia leach process can also be used for ore concentrates. In the direct electrolysis process (26%), the matte is cast into anodes; the nickel is dissolved in the sulphate electrolyte and deposited on the cathode. Precious metals do not dissolve and will collect in the anode slimes. The nickel matte can also be roasted (48%) in a fluidised bed roaster to nickel oxide. The nickel oxide can is either used as such or further processed to nickel.

The nickel-copper alloy can be treated in three hydrometallurgical processes to refine nickel and extract PGM, cobalt and copper concentrates. In the carbonyl pressure process (58%) nickel is separated from the other metals using carbon monoxide. The residue contains copper, cobalt and the precious metals and is treated hydrometallurgically to recover those metals. In the atmospheric acid leach process (31%) leaching is carried out in trains of air agitated Pachuca tanks. The acid pressure leach process (11%) is carried out in horizontal multi-compartment autoclaves and allows very high extractions of nickel, copper and sulphur. 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). The concentrate can be directly treated in a platinum refinery.

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 sulphide ores. Oxide ores are more abundant and easier to extract than sulphide ores, however the energy requirements for oxide ore processes are much higher than for sulphide ore processes. Three pyrometallurgical processes exist to treat the oxide ores.

In the rotary kiln – electric furnace process (38%) 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. Virtually all nickel and approximately 65% of the iron is 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 sulphur, then refined under oxidizing conditions with suitable fluxes to
remove carbon, silicon and phosphorous. The ferro nickel 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 sulphur in a Peirce-Smith converter. After ‘sulphidizing’ the matte is blown with air in order to oxidize the iron.

In the *blast furnace* (or shaft furnace, 7%) 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* (13%) 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 sulphur oil into the ore bed. The hot calcine is smelted in an electric furnace. To produce the matte elemental sulphur 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 (38%). In the Caron process, partially reduced ore is leached in ammoniacal solution. The Moa Bay process applies a direct sulphuric acid pressure leach.

### 4.5.2 Manufacture and consumption

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).

### 4.5.3 Waste management

The main source of secondary nickel is stainless steel. This is usually remelted and refined to produce new stainless steel. It is estimated that around 80 percent of the nickel is recycled from new and old stainless steel scrap and returns to that end use (NF BREF 2000). Other nickel bearing materials such as electronics, precipitates and residues are recycled to primary production through production processes of other metal. Industrial applications, construction and machinery applications, large transportation applications (aerospace and marine) and the ‘other’ applications are assumed to be recovered through other routes.
4.6 Platinum Group Metals

4.6.1 Production

Platinum groups metals (PGMs), viz. platinum, palladium, rhodium, iridium, osmium, ruthenium, are produced as by-products from production of other metals. In 2000 approximately 19 tonnes of Rhodium, 182 tonnes of platinum and 227 tonnes of palladium were produced. The main sources for primary PGMs are ores that are associated with nickel-copper sulphides. As such, these ores are first processed to extract the nickel and copper, and in the process produce a PGM rich intermediate. PGMs are also produced from gold by products.

![Figure 4-11: Global PGM production](image)

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. Because their high values, all process routes have high internal recycling rates, and yield recoveries of almost 100%.
4.6.2 Waste management

Because of their high values, 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.

4.7 Silver

4.7.1 Production

In 2000, approximately tonnes of silver were produced globally. Although silver can be found uncombined in nature, most silver used today is obtained from its ores. The metal is prepared in various ways depending upon the nature of its occurrence. The greatest quantity is obtained in connection with the refining of lead and copper. Silver is produced from lead-zinc ores (38%), copper ores (23%), gold ores (15%) and silver ores (24%).
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 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. After removal of the silicate slag, the selenium phase is blown with air and treated with sodium carbonate and sodium nitrate to produce a selenium and tellurium slag, which is tapped off as well. If the feed has low selenium and tellurium content, sodium nitrate is added to the matte molten reacts to remove the remaining copper, lead, selenium and tellurium and yield crude silver.

Figure 4-14: Simplified flow sheet of silver production
The gold Miller process (see gold) produces a silver chloride in a borax slag. In the slag cleaning process, the slag is leached with a solution of sodium chlorate in hydrochloric acid. This dissolves the base metals and leaves silver chloride as residue. This silver chloride is reduced with zinc dust to precipitate crude silver.

The crude silver from the four processes is mainly refined using the Mobius electrolysis process. This process uses a silver nitrate-sodium nitrate-nitric acid electrolyte. Silver and base metals are dissolved from the crude silver anode and the silver is deposited on the cathodes. The remainder of the anode that has not dissolved is collected in anode slimes. The anode slimes contain silver, gold, selenide, telluride and PGMs and are further processed to extract the gold and PGMs (see gold).

4.7.2 Manufacture and consumption

Silver has been known since ancient times; there is evidence that mankind separated silver from lead as early as 3000 BC. 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 industrial usage. Silver is still used for coinage and other traditional applications (jewellery, silverware etc), but is mainly used for its chemical and electronic properties. Particularly, the use of silver for ??? grown over the past three decades, at the expense of silver used in brazing alloys, solders, electrical equipment and electronics. 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.

4.7.3 Waste management

Silver is produced from approximately 30% from secondary materials. These secondary materials come from jewellery, 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 sulphide to form a powder, which is dried, melted and refined. Alternatively, silver thiosulphate solutions are electrolysed to produce silver sulphide, which is insoluble and can be recovered. Jewellery can often be recovered by direct remelting. The silver in electronic appliances is typically recovered for the copper value, and return as anode slimes.

4.8 Tin

4.8.1 Production

In 2000 about 2.97 \(10^5\) tonnes were produced globally. Unlike the other metals, the global production of tin remained more or less constant from 1940 to 2000.
Figure 4-15: Global tin production

Tin is mainly produced from sulphide (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. Sulphide ores are first roasted to an oxidic concentrate. In the roasting process, the tin sulphides are oxidised, and major oxidic impurities, such as arsenic, are volatised. 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 (26%), 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 oxidised to a flue dust that is also recycled back to the tin smelting.

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 practised only by countries with impure ores and secondary smelters. 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 sulphur and skimming off the resulting copper dross, (iii) arsenic is removed, together with some nickel, copper and iron, by formation of intermetallic compounds with aluminium, (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, sulphate electrolyte, or an alkaline, sodium hydroxide (NaOH) electrolyte, medium can be used.

4.8.2 Manufacture and consumption
Tin has been known to mankind since at least 3500 BC. 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. 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 aluminium, 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 aluminium, 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.

4.8.3 Waste management
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.

4.9 Zinc

4.9.1 Production
In 2000, 9.14 million tonnes of zinc were produced. Zinc is found as sulphide 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%.
Figure 4-17: Global zinc production

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 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.

The hydrometallurgical RLE route can be divided into three steps: (i) roasting, (ii) leaching, (iii) electrolysis. In the roasting step, the concentrate is calcined (oxidised) in a fluid bed roaster. Next, the calcine is leached in a neutral leach: the oxides are dissolved in a dilute sulphuric acid solution. The residue is further leached to recover the remaining zinc and to remove iron as a residue. Depending on the leach processes residues 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.
The reductive smelting in the Imperial Smelter Furnace produces crude zinc, as well as impure cadmium and lead bullion. 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 among others 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. The hard zinc can be recycled to the process. 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.

4.9.2 Manufacture and consumption
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 wire, fencing, tanks,
pipes and other smaller end uses such as nails and fasteners. Consequently, zinc used for galvanizing has a relatively long delay in the consumption phase. It is mostly partitioned to products IV and V due to large share of zinc used for transport and construction.

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, scientific equipment and sound and television products. Zinc-based alloys have a somewhat shorter average lifespan. They are also largely partitioned to products IV and V because of the large share of automotive and construction applications. 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 (product II, III and IV). The remainder is used in consumer and general products, and in building and construction. The average delay of bronze and brass products is, therefore, shorter than the delay of the preceding two zinc uses. The ‘other’ end uses of zinc consist of rolled zinc, zinc dust and chemicals. Zinc chemicals mostly are 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. The other zinc uses are mostly partitioned to products I, II and III.

4.9.3 Waste management

About 31% of the world’s zinc supply (nearly 2.9 million tonnes) comes from recycled zinc, including new scrap (22%). An estimated 80% of the old and new zinc scrap available for recycling is currently recycled. 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 (IZA 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 Waelp 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 Waelp 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, or 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 Waelp kiln is a slightly inclined rotary kiln. In the reactor, zinc oxide is vaporized and reacted with carbon to form zinc vapour. This zinc vapour 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 as used as a feed to other zinc processes.
5 Results

This chapter discussed the results. In the first paragraph the three different calculation methods for the LCA score are explained. In the second paragraph the LCA score for individual metals is calculated using the non-causal and causal allocation methods. Paragraphs 5.3 to 5.5 discuss the three case studies: DVDs, Lead-free solders and copper pipes.

As argued in paragraph 2-5, the metals participate in cycles that cannot be considered independently. However, the system of interconnected metal cycles is too complex to be intuitively understood. Oversimplification of the system in life cycle assessments can therefore lead to considerable errors in predicted environmental impact of changes. The model of the metal life cycles was built to provide insight into the environmental impact of changes to metal production infrastructures, the demand for metals or changes in metal recycling.

In this chapter three types of scenarios are used to investigate the effect of interdependence in metal production and recycling:

1. Marginal changes in product composition (slow evolution of product design): DVD scenarios. In these scenarios the environmental impact of replacing older types of DVDs with newer types of DVDs is calculated. These replacements have a small impact on the metal life cycle system.
2. Larger changes in product composition/product substitution (part of the product, or product as a whole is redesigned)
   a. Lead free solder scenarios. In these scenarios the lead-tin solders used in electronics is completely replaced with an alternative lead-free solder. These scenarios are based on the WEEE directives which ban the use of lead based solders in electronics. The change to lead-free solders has, dependent on the lead free solder alternative used, a moderate influence on the metal life cycle system.
   b. A copper pipes replacement scenario. This is a hypothetical scenario to test the model on extreme situations. In this scenario copper pipes used in building and construction (accounting for 16.5% of the copper usage) are replaced with plastic pipes. As copper is an important base metal in the metal life cycle system it will likely have a large affect on the system.

5.1 Calculation of the environmental impact

In the model the Eco-Indicator’99 is used to calculate the environmental impact, this method is explained in paragraph 3-8. One of the major difficulties in calculating the environmental impact of a scenario change is in the allocation of environmental burdens in multiple function processes. As explained in paragraph 2-5 there are four methods to allocate the burdens from those processes:

1. Avoidance of allocation through
   a. Subdividing the multifunction process; or
   b. Expansion of the system;
2. Allocation based on causal relationships; and
3. Allocation based on non-causal relationships.

Avoidance of allocation through subdividing the process is not done here as the current model of metal production system is already subdivided down to process level, further subdivision will be very time consuming and it is not sure it is possible at all. Examples of the other three methods are examined; methods 1b and 2 were identified in paragraph 2.5 as the best methods to solve allocation problems, method 3 is included as it is the most common method in the LCA practice. Each method will be discussed in reverse order in the next paragraphs.

5.1.1 LCA calculation with allocation based on non-causal relationships

The third category in the ISO 14042 LCA framework, the non-causal allocation, includes allocation based on relationships that do not directly link the environmental burdens of a process to the functions of the process; allocation is based on other relationships like mass, economic value or volume of the flows going in and out the process. The relationship upon which the allocation is based should be determined by the ‘function’ of the process in question.

In the metal production system raw materials are processed to create metals, in each process step the valuable metals in the input are concentrated into one or several outputs; the function of the process is to concentrate as much of the valuable metals in the input into one or more outputs. Common practice in the LCA is, when using mass, to allocate on the mass of the output (Ullmann 2000). In waste (recycling) processes however allocation is done on the flows going into the process (Clift et al 2000, Finnveden and Ekvall 2000). Based on the description of the function of metal production processes it is logically to also use the input masses to allocate environmental burdens. This is best explained by an example.

Figure 5-1 shows two processes, process 1 produce a product containing A and B; This is further processed to produce a separate product A and product B. Process 2 is an improved version of process 1 where the recovery of B is increased, which decreases the total emissions from the process. The calculation of the allocation of the environmental burdens for both processes is done with equations 5-1 and 5-2, the first for allocation on the output mass, the second for allocation on the input mass.

![Figure 5-1: Example of allocation in multiple function processes](image)

*Allocation on the output: \( I_A = \frac{m_{A,\text{output}} * E_{A,\text{Total}}}{m_{\text{Total,\text{output}}} * m_{A,\text{output}}} \) Equation 5-1*
Allocation on the input: \( I_A = \frac{m_{A,input} \cdot E_{A,Total}}{m_{Total,input} \cdot m_{A,output}} \) \hspace{1cm} \text{Equation 5-2}

<table>
<thead>
<tr>
<th>Process</th>
<th>Allocation on the output</th>
<th>Allocation on the input</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Allocated to A</td>
<td>Allocated to B</td>
</tr>
<tr>
<td>1</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>0.71</td>
<td>0.71</td>
</tr>
<tr>
<td>2</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Table 5-1: Emissions per kg allocated to A and B

Table 5-1 shows the emissions allocated to A and B per kg of produced A and B. With allocation on the output an increasing efficiency of the recovery of B leads to an equal reduction of the environmental burdens allocated to A and B. Using allocation on the input an increasing recovery leads to a much larger reduction of environmental emission allocated to B than to A.

As mentioned earlier the function of a metallurgical process is to concentrate as much of the valuable metals in the input into one or more outputs. With an increase in the efficiency of B recovery a larger decrease of the environmental emission allocated to B than to the decrease of the environmental emissions allocated to A is expected. This is the case with allocation on the input. With allocation on the output the decrease is exactly the same for both metals.

Equations 5-3 to 5-9 are used to calculate LCA score with non-causal allocation. The equations can be used for both allocation on the input and allocation on the output, see the added notes.

\[
I_{Scenario} = \sum_i \left[ (D_{i,S} - D_{i,Base}) \cdot I_i \right] \hspace{1cm} \text{Equation 5-3}
\]

With:
- \( I_{scenario} \) = Environmental impact of the scenario change
- \( D_{i,Base} \) = Demand for metal i, in the base situation
- \( D_{i,S} \) = Demand for metal i, in the scenario
- \( I_i \) = Environmental impact of metal i

\[
I_i = I_{production,i} + I_{manufacturing,i} + I_{consumption,i} + I_{SWM,i} + I_{transportation,i} \hspace{1cm} \text{Equation 5-4}
\]

With:
- \( I_{production,i} \) = Environmental impact of the production of metal i
- \( I_{manufacturing,i} \) = Environmental impact during the manufacturing of metal i into products
- \( I_{consumption,i} \) = Environmental impact during the consumption of metal i containing products
- \( I_{SWM,i} \) = Environmental impact during the waste treatment of metal i containing products
\( I_{\text{transportation},i} \) = Environmental impact during the transportation of products containing metal \( i \)

\[
I_{\text{production},i} = \sum_{p} \left[ \frac{M_{i,p}}{\sum M_{i,p}} * I_{p} \right]
\]

*Equation 5-5*

With
\( I_{p} \) = Environmental impact of process \( p \)
\( M_{i,p} \) = Mass of valuable metal \( i \) in process \( p \)

\[
I_{\text{manufacturing},i} = \sum_{p} \left[ \frac{M_{i,p}}{\sum M_{i,p}} * I_{p} \right]
\]

*Equation 5-6*

With
\( I_{i} \) = Environmental impact during the manufacturing of product group \( i \)
\( M_{i,p} \) = Mass of metal \( i \) in the input of process \( p \)

\[
I_{\text{consumption},i} = \sum_{p} \left[ \frac{M_{i,p}}{\sum M_{i,p}} * I_{p} \right]
\]

*Equation 5-7*

With
\( I_{i} \) = Environmental impact during the consumption of product group \( i \)
\( M_{i,p} \) = Mass of metal \( i \) in the input of process \( p \)

\[
I_{\text{SWM},i} = \sum_{p} \left[ \frac{M_{i,p}}{\sum M_{i,p}} * I_{p} \right]
\]

*Equation 5-8*

With
\( I_{i} \) = Environmental impact during the processing of waste group \( i \)
\( M_{i,p} \) = Mass of metal \( i \) in the input of process \( p \)

\[
I_{\text{transportation},i} = \sum_{p} \left[ \frac{M_{i,p}}{\sum M_{i,p}} * I_{p} \right]
\]

*Equation 5-9*

With

\(^2\) Valuable metals in this case are metals that are further concentrated in a process to eventually make a metal out of it. For each process the valuable metals can differ, see the flow sheets in chapter four to identify which are the valuable metals.

\(^3\) When allocating on the input the aggregate of the inputs is used; when allocating on the output the aggregate of the outputs that are processed further is used.
\[ I_i = \text{Environmental impact during the transportation of product } i \]
\[ M_{i,p} = \text{Mass of metal } i \text{ in the input of process } p \]

### 5.1.2 LCA calculation with allocation based on casual relationships

The second category of allocation, causal relationships, allocates emissions using relationships that directly link the environmental burdens of a process with the functions of a process. Allocation based on causal relationships will thus reflect how a change in the functions of a process affects the environmental burdens.

Each process in the model is associated with one major metal, the metal that is the primary focus of concentrating in the process. If a process has multiple outputs the output containing most of the main metal is processed further in the same process chain, the output containing other concentrated metals are processed in other process chains, these outputs are labelled as intermediates. Intermediates in the model are represented as stocks. The input of intermediates into the stock is usually higher than the demand for intermediates; the remainder is discarded and is an environmental burden. If the demand of a downstream metal increases less of the intermediate is discarded, if the demand of an upstream metal increases more of the intermediate is discarded. Thus in the model the intermediate stocks represent the link between process chains and are a causal relationship between output and environmental burdens.

In the model the equations 5-10 and 5-11 are used to calculate the LCIA using causal relationships to allocate environmental burdens in multiple output process.

\[ I_{\text{scenario}} = \sum_i \left( (D_{i,S} - D_{i,\text{Base}}) * I_i \right) \quad \text{Equation 5-10} \]

With:
\[ I_{\text{scenario}} = \text{Environmental impact of the scenario change} \]
\[ D_{i,\text{Base}} = \text{Demand for metal } i \text{, in the base situation} \]
\[ D_{i,S} = \text{Demand for metal } i \text{, in the scenario} \]

\[ I_i = \frac{I' - I}{D_i'} \quad \text{Equation 5-11} \]

With:
\[ I_i = \text{Environmental impact metal } i \]
\[ I' = \text{Environmental impact of the total system with slightly increased demand for metal } i \]
\[ I = \text{Environmental impact of the total system} \]
\[ D_i' = \text{Slightly increased demand for metal } i \]
\[ D_i = \text{Demand for metal } i \]

### 5.1.3 LCA calculation with avoided allocation through system expansion

Allocation can be avoided in multiple function systems through system expansion. This can be achieved by examining all relevant systems at the same time, allowing for the interactions of the different processes with each other. In the metal production
system as it is modelled the production of eight relevant metals is modelled. The
different metals are connected with each other through intermediates.

The approach of examining the system as a whole gives information on the
environmental impact of a scenario change at different time periods after the change
allowing for the system to react to the change.

Mathematical the calculation of the environmental impact is done with equation 5-12

\[ I(t) = I(t)_S - I(t)_{Base} \]

*Equation 5-12*

Where:
- \( I(t) \) = Environmental impact of the scenario at time \( t \)
- \( I(t)_S \) = Total environmental impact of scenario \( S \) at time \( t \)
- \( I(t)_{Base} \) = Total environmental impact of the base scenario at time \( t \)

Non-causal allocation and causal allocation provide LCA scores for individual metals.
These LCA scores can be used to calculate the total LCA score of a scenario change.
Once the individual LCA scores are obtained there is no more need to run the model
again. With system expansion on the other hand the model needs to be run for each
scenario. Although this provides more work it also gives more information. The LCA
score after different time intervals can be examined as the system adjust to the
changes made. Moreover, the dynamics in the system itself can be examined, for
instance changes to the flows of materials.
5.2 Results for individual metals

The first two methods used to deal with emissions in multiple function processes, causal allocation and non-causal allocation, give a LCA number for individual metals which can be used to calculate the LCA of a scenario change.

Table 5-2 compares the results for non-causal allocation with allocation on the input and allocation on the output. There is not much difference between the two calculation methods.

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Pb</th>
<th>Sn</th>
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<th>Zn</th>
<th>Ag</th>
<th>Ni</th>
<th>Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
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<td>3.81</td>
<td>20.71</td>
<td>10.77</td>
<td>1.79</td>
<td>81.87</td>
<td>4.08</td>
<td>37324.77</td>
</tr>
<tr>
<td>Output</td>
<td>2.60</td>
<td>4.18</td>
<td>20.75</td>
<td>12.80</td>
<td>1.41</td>
<td>85.00</td>
<td>4.29</td>
<td>37324.79</td>
</tr>
</tbody>
</table>

Figure 5-2: LCA score for metals using non-causal allocation on the input and non-causal allocation on the output

Table 5-3 and table 5-4 give the LCA score for non-causal allocation and causal allocation. The LCA score is broken down into the twelve subcategories to be able to further differentiate between the scores and see where the differences between scores lie. These categories are:

- Carcinogenic effects on humans (HHcarc)
- Human health effects caused by toxicity (HHtox)
- Respiratory effects on humans caused by organic substances (HHresporg)
- Respiratory effects on humans caused by inorganic substances (HHrepiorg)
- Damage to Human Health caused by climate change (HHclim)
- Human health effects caused by ozone layer depletion (HHzon)
- Human health effects caused by ionising radiation (HHion)
- Damage to ecosystem quality caused by ecotoxic emissions (EQecotox)
- Damage to ecosystem quality caused by the combined effect of acidification and eutrophication (EQacid)
- Damage to ecosystem quality caused by land occupation and land conversion (EQland)
- Damage to resources caused by extraction of minerals (RDmineral)
- Damage to resources caused by extraction of fossil fuels (RDfossil)

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Pb</th>
<th>Sn</th>
<th>Bi</th>
<th>Zn</th>
<th>Ag</th>
<th>Ni</th>
<th>Au</th>
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</thead>
<tbody>
<tr>
<td>Total</td>
<td>2.55</td>
<td>3.81</td>
<td>20.71</td>
<td>10.77</td>
<td>1.79</td>
<td>81.87</td>
<td>4.08</td>
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</tr>
<tr>
<td>HHcarc</td>
<td>0.02</td>
<td>0.05</td>
<td>0.50</td>
<td>0.48</td>
<td>0.04</td>
<td>0.91</td>
<td>0.29</td>
<td>176.74</td>
</tr>
<tr>
<td>HHtox</td>
<td>0.26</td>
<td>1.88</td>
<td>1.67</td>
<td>4.01</td>
<td>0.24</td>
<td>10.26</td>
<td>0.30</td>
<td>262.04</td>
</tr>
<tr>
<td>HHresporg</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.37</td>
</tr>
<tr>
<td>HHrepiorg</td>
<td>1.14</td>
<td>0.55</td>
<td>0.59</td>
<td>2.79</td>
<td>0.76</td>
<td>13.81</td>
<td>2.29</td>
<td>326.70</td>
</tr>
<tr>
<td>HHclim</td>
<td>0.02</td>
<td>0.07</td>
<td>0.03</td>
<td>0.13</td>
<td>0.05</td>
<td>5.27</td>
<td>0.16</td>
<td>156.51</td>
</tr>
<tr>
<td>HHion</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.02</td>
</tr>
<tr>
<td>HHzon</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.16</td>
</tr>
<tr>
<td>EQecotox</td>
<td>0.59</td>
<td>1.05</td>
<td>1.04</td>
<td>3.12</td>
<td>0.40</td>
<td>18.09</td>
<td>0.45</td>
<td>26.94</td>
</tr>
<tr>
<td>EQacid</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>0.02</td>
<td>0.10</td>
<td>0.03</td>
<td>36.93</td>
</tr>
<tr>
<td>EQland</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
<td>0.02</td>
<td>0.05</td>
<td>0.03</td>
<td>26.19</td>
</tr>
<tr>
<td>RDmineral</td>
<td>0.46</td>
<td>0.09</td>
<td>16.83</td>
<td>0.00</td>
<td>0.05</td>
<td>32.98</td>
<td>0.29</td>
<td>36000.09</td>
</tr>
<tr>
<td>RDfossil</td>
<td>0.03</td>
<td>0.09</td>
<td>0.05</td>
<td>0.18</td>
<td>0.22</td>
<td>0.40</td>
<td>0.24</td>
<td>311.07</td>
</tr>
</tbody>
</table>

Table 5-2: LCA score for metals with non-causal allocation
<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Pb</th>
<th>Sn</th>
<th>Bi</th>
<th>Zn</th>
<th>Ag</th>
<th>Ni</th>
<th>Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>3.15</td>
<td>1.94</td>
<td>20.92</td>
<td>1.76</td>
<td>1.69</td>
<td>-105.72</td>
<td>4.96</td>
<td>56806.80</td>
</tr>
<tr>
<td>HHcarc</td>
<td>0.04</td>
<td>0.02</td>
<td>0.48</td>
<td>0.41</td>
<td>0.04</td>
<td>0.02</td>
<td>0.24</td>
<td>269.95</td>
</tr>
<tr>
<td>HHTox</td>
<td>0.22</td>
<td>0.80</td>
<td>0.54</td>
<td>0.62</td>
<td>0.20</td>
<td>7.90</td>
<td>0.04</td>
<td>399.39</td>
</tr>
<tr>
<td>HHresporg</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.57</td>
</tr>
<tr>
<td>HHrespinorg</td>
<td>1.54</td>
<td>0.42</td>
<td>0.52</td>
<td>0.02</td>
<td>0.77</td>
<td>14.08</td>
<td>3.78</td>
<td>496.90</td>
</tr>
<tr>
<td>HHclim</td>
<td>0.05</td>
<td>0.02</td>
<td>0.03</td>
<td>0.01</td>
<td>0.05</td>
<td>6.84</td>
<td>0.09</td>
<td>237.97</td>
</tr>
<tr>
<td>HHion</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.01</td>
<td>0.00</td>
<td>1.56</td>
</tr>
<tr>
<td>HHozon</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.24</td>
</tr>
<tr>
<td>EQecotox</td>
<td>0.45</td>
<td>0.50</td>
<td>0.37</td>
<td>0.69</td>
<td>0.29</td>
<td>23.07</td>
<td>0.34</td>
<td>39.12</td>
</tr>
<tr>
<td>EQacid</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>0.02</td>
<td>-0.14</td>
<td>0.01</td>
<td>56.42</td>
</tr>
<tr>
<td>EQland</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.02</td>
<td>-0.15</td>
<td>0.00</td>
<td>40.02</td>
</tr>
<tr>
<td>RDmineral</td>
<td>0.76</td>
<td>0.16</td>
<td>18.93</td>
<td>0.00</td>
<td>0.07</td>
<td>-155.54</td>
<td>0.40</td>
<td>54789.30</td>
</tr>
<tr>
<td>RDfossil</td>
<td>0.07</td>
<td>0.02</td>
<td>0.05</td>
<td>0.03</td>
<td>0.23</td>
<td>-1.74</td>
<td>0.05</td>
<td>475.34</td>
</tr>
</tbody>
</table>

Table 5-3: LCA score for metals with causal allocation

Metals that have little or no interaction with the other metals in the system, tin, nickel, copper and zinc, show little difference between the two LCA score calculations. For the other metals, lead, bismuth, gold and silver the difference is substantial; in the case of silver it even becomes negative, which is mainly due to resource depletion. As the primary silver mainly not comes from silver ores but from lead, zinc, copper and gold ores, see figure 1-2, an increase in silver production will come from a greater usage of the silver associated with these ores, thus less silver resources wasted. The big difference between the LCA scores for lead, bismuth, silver and gold is due to the dependency of these metals on the production of other metals, this is accounted for with causal allocation and not accounted for with non-causal allocation. As argued in paragraph 2-5 the causal allocation method is preferred above the non-causal allocation method.
5.3 Marginal changes: DVDs

Many products slowly evolve over the years, as functionality, durability and usage change the composition of those products change accordingly. A good example is consumer products; here the specific example of DVDs is used. DVDs are relative new products and therefore the change of product composition is fairly big with each new type. In Table 5-4 the compositions of three DVD models are listed, several materials in that list are not modelled; those get a standard LCA value.

<table>
<thead>
<tr>
<th>Material</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>6.45%</td>
<td>5.58%</td>
<td>6.11%</td>
</tr>
<tr>
<td>Pb</td>
<td>0.09%</td>
<td>0.32%</td>
<td>0.30%</td>
</tr>
<tr>
<td>Sn</td>
<td>0.13%</td>
<td>0.13%</td>
<td>0.12%</td>
</tr>
<tr>
<td>Bi</td>
<td>0.00%</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Zn</td>
<td>2.71%</td>
<td>0.33%</td>
<td>0.32%</td>
</tr>
<tr>
<td>Ag</td>
<td>0.00%</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Sb</td>
<td>0.01%</td>
<td>0.03%</td>
<td>0.02%</td>
</tr>
<tr>
<td>Ni</td>
<td>0.14%</td>
<td>0.05%</td>
<td>0.05%</td>
</tr>
<tr>
<td>Au</td>
<td>0.01%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Fe</td>
<td>63.15%</td>
<td>64.96%</td>
<td>65.70%</td>
</tr>
<tr>
<td>Al</td>
<td>0.60%</td>
<td>1.13%</td>
<td>1.09%</td>
</tr>
<tr>
<td>Glass</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Plastics</td>
<td>21.23%</td>
<td>21.56%</td>
<td>20.60%</td>
</tr>
<tr>
<td>Other</td>
<td>0.00%</td>
<td>4.41%</td>
<td>4.24%</td>
</tr>
<tr>
<td>Br</td>
<td>0.22%</td>
<td>0.05%</td>
<td>0.05%</td>
</tr>
<tr>
<td>Cl</td>
<td>0.01%</td>
<td>0.19%</td>
<td>0.18%</td>
</tr>
<tr>
<td>Cr</td>
<td>0.02%</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Ceramics</td>
<td>0.00%</td>
<td>1.23%</td>
<td>1.18%</td>
</tr>
<tr>
<td>Epoxy</td>
<td>5.22%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

Table 5-4: The composition of DVDs

In Figure 5-3 the results for one specific example are shown, the replacement of 2000 type DVDs with 2001 type DVDs, other results can be found in Appendix 2. The difference between the causal allocation and the expansion LCA score is small. Due to the very marginal changes to the demand of metals the two methods have a hardly noticeable difference. As such the easiest and quickest method, i.e. causal allocation, is better suited for to examine marginal changes to the metal production system. The marginal changes to the flows in the metal production system do not warrant an extra examination.

---

4 The figures show the LCA score show the three different types of calculation methods. NC = Non-causal allocation, C = causal allocation, E(i) = System expansion in year i.
Figure 5-3: LCA score for the replacement of DVD type 200 with DVD type 2001.
5.4 Product Substitution: Lead free soldering

As a part of the WEEE directives of the EU the use of lead based solders in electronics is banned. Therefore several alternative solders have been developed that do not contain lead, see table 5-5 for the solder alternatives used in this case study. The reason for this change is to reduce the amount of lead discarded into the environment. However many of the metals used in the alternatives are more scarce than lead, i.e. silver and bismuth, and many of those metals use lead as a base production system. Examining the impacts of the lead free solders should thus not only be done by looking at the LCA score but also by examining the changes to the metal production system as a whole.

In table 5-5 the composition of the different alternative lead free solders are given.

<table>
<thead>
<tr>
<th>Solders</th>
<th>Sn</th>
<th>Pb</th>
<th>Bi</th>
<th>Cu</th>
<th>Ag</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>SnPb</td>
<td>60%</td>
<td>40%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SnAgCu</td>
<td>95.5%</td>
<td>0.70%</td>
<td>3.8%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SnCu</td>
<td>99.25%</td>
<td>0.75%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SnZnBi</td>
<td>78%</td>
<td>19%</td>
<td>3%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SnZn</td>
<td>91%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9%</td>
</tr>
</tbody>
</table>

*Table 5-5: Composition of different types of solders*

![LCA score SnAgCu, Hierarchist](image)
Figure 5-5: LCA score for the lead free solder alternative SnCu with the hierarchist future prediction for system expansion LCA scores.

The LCA scores for two of the alternatives are depicted in figures 5-4 and 5-5. For SnAgCu the LCA score with causal allocation and expansion, except 2000, are negative, thus this is an improvement in from the LCA perspective. For the SnCu alternative all LCA scores are positive, thus from the LCA perspective this is not a good alternative solder.

Another consequence of the change to lead free solders is the change to the flows within the system; figure 5-6 shows these changes for the SnAgCu solder alternative, figure 5-7 for the SnCu alternative. The figure shows the flows and the percentage change to the flows within the metal production system. Each metal production block can have on the input side primary material (O) secondary material (S) and Intermediates (I), and on the output side metal and intermediate (I). The intermediates connect the metal production block and have an input (left side) and output (right side) with the percentage change to the volumes.

Figure 5-5 shows that using this solder alternative decreases the amount of lead produced with 1.5% at the same time some of the amount of tin produced increased with 30% and the amount of silver produced with 41%. The decrease of lead produced is relatively small while the increase in tin and silver production is quite noticeable. Especially in the case of silver where this increase needs to come from intermediates that depend on the production of base metals like lead and copper this can be troublesome. This increase in demand of metals will likely mean that less economical feasible and less environmentally friendly deposits need to be used.

The SnCu alternative, which is from LCA perspective not that good, shows less of these resource problems. Tin production needs to be increased with 33% while lead...
production is decreased with 1.5%. This change to the metal production system is less likely to cause problems than the SnAgCu.

Figure 5-6: Changes to the flows in the system due to the SnAgCu scenario.
Figure 5-7 Changes to the flows in the system due to the SnCu scenario.
5.5 **Drastic change: 16.5% lower copper demand**

This is a hypothetical scenario; it explores what happens to the metal production system when the production of a base metal is greatly reduced, in this case copper. The example here used is to replace copper pipes used in construction with some other material, for instance plastic pipes. This application of copper is 16% of the total copper consumption (CDA 2003). In this case study the LCA score is not examined as there are no specifics on the type of plastic substitutes, this case study only examines changes to the flow sheet.

Copper is interesting to examine in that regard as it relative little direct dependent metals as the stock levels of intermediates are quite high. This is apparent when examining figure 5-8. The large decrease in copper production decrease the supply of copper anode slimes, the decrease anode slimes consumption is much lower. This is already enough to increase the lead production in order to satisfy the bismuth demand.

Figure 5-8: Changes to the flows within the system due to the copper scenario.


6 Sensitivity Analysis

The model of the metal life cycle uses lots of assumptions. In this sensitivity analysis the effect of some of these assumptions are checked. Paragraph 6-1 examines some variables like flue dust capture efficiency and recycling rate. Paragraph 6-2 examines the influence of changing the flow sheet of metal production on the LCA score.

6.1 Analysis

6.1.1 Emission of gasses

The technology used to reduce the environmental impact of making metals is different around the world. The model uses an assumption that modern technologies are used but that might not be true in the whole world due to ineffective legislation or certain inertia to build new installations. One good example is the flue dust capture efficiency. In the model it is assumed that flue dust is captured with 98% efficiency. If that efficiency however is lower the LCA-score is influenced greatly as is shown in figure 6-1. It shows the LCA score for copper with different flue dust capture efficiency. A reduction of the efficiency with 2% to 96% increases the LCA score with increases the LCA score with 22%.

![Figure 6-1: LCA score of copper dependent on the flue dust capture efficiency](image)

6.1.2 Transportation

Between each phase in the metal life cycle the products need to be transported to another place in the world for further use or processing. The distance material travels between each phase vary for the material being transported but for mining concentrates the average transporting distance is around 4500 kilometres. Changing the average transporting distance has little effect on the LCA score as can be seen from figure 6-2.
6.1.3 Recycling

Recycling of metals is an important part of the metal life cycle. Recycling reduces the amount of waste produced and the amount of ore needed. In the model the metals have been categorized according to their use and for each category an estimate of their recycling rate is made. One of the categories is end of life vehicles (ELV), in figure 6-3 the change to the LCA score of lead is depicted dependent on the recycling rate of ELVs. In the model a recycling rate of 95% is used. If the recycling rate is only 85% the LCA score of lead would increase with 4%
6.1.4 New scrap

During the production of materials out of pure metals scrap is generated that is relative pure, it only needs to be remelted before it can be used again for new product manufacturing. For zinc the model assumes that 18.8% of the zinc produced is discarded as new scrap during manufacturing and can be immediately recycled. Would this percentage decrease to 10% the LCA score of zinc would increase with 11%.
6.2 Changes to the flow sheet

The flow sheet currently implemented in the model is the flow sheet for metal production as it currently is. However, that will change as for instance technology or supply of raw materials changes. Moreover the processes itself can change; a higher recovery efficiency or a different waste material treatment.

Copper production can be used as a good example to examine what happens when the flow sheet changes. In primary copper productions there are six different methods or furnaces to go from copper concentrate to blister copper, see paragraph 4.2 for an explanation of these routes. Which method or furnace is used depends on various things, e.g. the distribution of the copper concentrate and the availability of electricity. As these circumstances change the percentage of copper produced by each route will change.

Changing the distribution of furnaces used does not significantly affect the flows in the other parts of the metal production flow sheet. It does affect the LCA score of copper as is shown in figure 6-5. This figure depicts the LCA score of copper when only using one type of furnace. The differences in LCA score are mainly caused by different flue dust and off gas emission. Using only INCO type furnaces the LCA score is 31% lower compared to using only ISA type furnaces. It is of course not very likely that in the future production will switch to only one type of furnace.

Figure 6-5: LCA score of copper when only one type of furnace is used.

Figure 6-6 explores what happens to the LCA score of copper when only one type of furnace is taken out of production. The difference between the LCA scores is not as significant as in figure 6-5 but still the LCA score difference between not using the Mitsibitshu type furnaces and not using the Reverberatory type furnaces is 5%.
Figure 6-6: LCA score of copper with one furnace off.
7 Conclusions and Recommendations

7.1 Conclusions

The model of metal life cycles provides a good insight in the dynamics of the system. It shows the user of the model what the dependencies are between the metals and allows the user to “play” with scenarios on metal demand and use.

In order to environmentally assess metals such a dynamic model is needed due to the interdependencies of metals. As it is such a complex system assessing the system is not an easy task. It is better to combine several assessment methods, for instance LCA and SFA. LCA assessment can give an insight in the direct environmental impact while SFA gives an insight in the effects on the system, e.g. the flows.

Comparing the LCA score results from causal and non-causal allocation the difference between the two is marginal with metals that have little dependencies on other metals. Metals that do have a big dependency on the production of other metals, lead, gold, silver and bismuth, show a big difference between the causal allocation LCA score and the non-causal allocation LCA score. The results from causal allocation and system expansion are quite similar, only when the LCA score at different time intervals is examined can a large difference occur.

The case studies show where the model can be of use. When only marginal changes to the system are designed there is no need to check the whole model, the changes will not be large enough to significantly affect the system. If however the changes are significant the model is very useful. Not only the check the LCA score after a new equilibrium has settled in the system but also to check if the changes cause strains to the system.
7.2 Recommendations

The model now includes the life cycle of nine metals, as figure 1-1 shows there are several other metals that are highly linked with these metals, like cobalt and cadmium. If a detailed metal life cycle of these metals were also included it would make the model more complete. Additional the model could be built less rigid. Currently it is difficult to change parts of the flow sheet as part of the information is “hard coded” in the model and not flexible.

The data gathered for the model can be improved. For instance the data for the production phase is scarce and not entirely up to date.

The production phase is modelled to a high level of detailed, unlike the other phases, a higher level of detail of the other phases could give better information on the life cycle system. Especially the solid waste management phase where metals are recycled back to the production phase. However an increase in detail would also mean an increase in calculation power needed to run the model.

Currently the model has one LCA scoring method included. As has been argued in paragraph 2-2 there is no LCA scoring method that is objectively better than the other. It would be good to add more methods so LCA values can be compared, sets of results can be better evaluated using more scoring methods etc.
**Literature**


