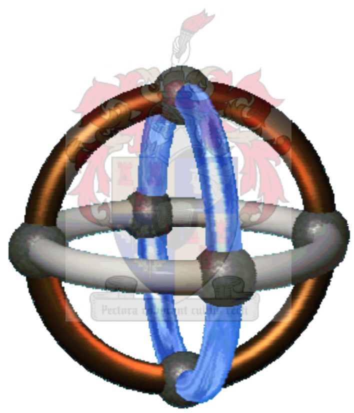
THE FUNDAMENTAL LIMITS OF RECYCLING

From minerals processing to computer aided design of automobiles and other consumer goods

by

MARKUS ANDREAS REUTER



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Declaration

I hereby certify that this dissertation is my own original work, except where specifically acknowledged in the text. Although the published papers contained in this submission have been produced in collaboration with co-workers, my own contribution has been generally as the originator of the work unless otherwise explicitly stated. Where it is claimed that the primary intellectual origin of such work is not duly recognized, the author withdraws his rights. Some of the research has been submitted in part as theses by co-workers, but the collection of papers in their published form have not been submitted at any other University.

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Markus A. Reuter *(PhD, Dr. habil, Pr. Eng.)*
22 November 2006

Abstract

My applied engineering research and industrial application work of the past 20 years is presented in this dissertation. It is the conjecture of my work that only if thorough first principles knowledge of the depth of process metallurgy and recycling is available, can meaningful first principles environmental models be developed. These models can then evaluate technology, provide well argued and first principles environmental information to our tax paying consumer society as well as to legislators and environmentalists. Only through this path can one estimate the limits of recycling and its technology, hence evaluate the true boundaries of sustainability.

My work with students has presently culminated in the detailed modelling and simulation of recycling systems for post-consumer goods. Notably the models are finding an application in the prediction of legally required recycling rates for automobiles. The models provide first principles arguments for less stringent EU recycling legislation and the integration of the first principles models in computer aided design tools of the automotive industry as part of a large EU 6th Framework (project managed by Volkswagen and the other European car producers). Presently these models are also being converted to model the Waste Electric and Electronic Equipment (WEEE) as well as water recycling systems respectively, both for industry in The Netherlands.

This unique rigorous integration of systems engineering, reactor technology and process control theory is the basis of all my work to describe recycling systems as dynamic feedback control loops. My large body of acquired industrial knowledge renders these models practical and can hence be used by the automotive and recycling industries.

The origins of this work may be found in the various cited publications and reports to industry by myself (due to my close association with industry as well as industrial experience) over the past 20 years as well as the work of my students, covering topics such as:

- *system optimization models for flotation, mineral beneficiation and recycling systems and applying these for design for recycling and argue for better/improved first-principles based legislation,*
- *industrial measurement, modelling and simulation of industrial extractive process pyrometallurgical reactors as well waste incinerators and recycling plants,*
- *various activities in other areas such as hydrometallurgy, clean and new breakthrough technology, and*
- *process control of industrial metallurgical reactors by among others the application of artificial intelligence techniques.*

All the ideas of the last years have been worked out with students and have been summarized in our book: "The Metrics of Material and Metal Ecology, Harmonizing the resource, technology and environmental cycles".

Opsomming

My ingenieursnavorsing en die toepassing daarvan in die industrie die afgelope 20 jaar word in hierdie proefskrif beskryf. My werk huldig die veronderstelling dat sinvolle omgewingsmodelle slegs ontwikkel kan word met 'n breë kennis van die teorie van prosesingenieurswese en hersirkulasie. Hierdie modelle het die vermoë om tegnologie te evalueer, om sinvolle inligting te verskaf aan ons belastingbetalende samelewing en aan mense en wetgewers gemoeid met kwessies rakende die omgewing. Alleen deur hierdie weg te volg kan die huidige, begrensende aspekte van hersirkulasie bepaal word, die beperkinge van die huidige tegnologie ontbloot word en dus ook die limiet van duursaamheid vasgestel word.

My navorsing, ondersteun deur die navorsing van my studente, het ontwikkel tot die modellering en simulasie van hersirkulasiesisteme van konsumentafvalprodukte. Ons modelle word huidiglik hoofsaaklik toegepas in die voorspelling van hersirkulasiepersentasies t.o.v. motorkarre. Die modelle lewer fundamenteel teoretiese argumentasie wat aantoon dat wetgewing met betrekking tot motorkar-hersirkulasie (soos tans in Europa van toepassing is) minder streng moet wees. Verder is die modelle fundamenteel genoeg om met die rekenaarondersteunde ontwerpsagteware van die motorkarindustrie integreer te word (as 'n deel van 'n groot 6th Framework EU projek gelei deur Volkswagen en ander Europese motorkarvervaardigers). Die modelle word ook toegepas in ander industrieprojekte, o.a. die modellering van die "Waste Electric and Electronic Equipment (WEEE)" hersirkulasiesisteem asook 'n water hersirkulasiesisteem van 'n groot watergraafskap, beide in Nederland.

Die unieke integrasie van sisteemingenieurswese, reaktortegnologie en prosesbeheer vorm die fundamentele basis van my beskrywing van hersirkulasiesisteme as dinamiese terugvoerlusse. My breë kennisbasis van die industrie maak hierdie modelle prakties en bruikbaar vir die motorkar- en hersirkulasieindustrië.

Verskeie persoonlike publikasies en industrieverslae ('n gevolg van my lang verhouding met die industrie) vorm die basis van hierdie werk:

- *sisteemoptimeringmodelle vir flottasie, mineraalprossesering en hersirkulasiesisteme,*
- *datameting in die industrie, modellering en simulasie van reaktore in die prosesmetallurgiese industrie en afvalverwerking,*
- *verskeie aktiwiteite in ander navorsingsgebiede soos hidrometallurgie en nuwe deurbraaktegnologie, en*
- *prosesbeheer van industriële metallurgiese reaktore deur die gebruik van kunsmatige intelligensie.*

Saam met my studente het ek die laaste jare hierdie in diepte ontwikkel en opgesom in die boek: "The Metrics of Material and Metal Ecology, Harmonizing the resource, technology and environmental cycles".

Preface

The figure and the written message photographed by the author in the town Real de Catorce in Mexico (elevation 2700m) best and succinctly describe the objectives of all this work.

"We do not inherit the Earth from our Ancestors; we borrow it from our Children"

Acknowledgements

In Udo Boin I found a unique colleague! Two generations meeting with identical ideas, opening up a field and permitted me to apply and harmonize all my past work into the simulation of recycling systems. Udo's wisdom, long industrial experience also as board member of a large metallurgical company and intuitive knowledge on recycling have been the single most inspiring source of creativity for me. I am deeply indebted and very grateful of having had such a Master Guide in my life. In addition to so much general information on recycling systems, I learnt through Udo to appreciate the complexity of aluminium recycling. The section on aluminium recycling in the book can mainly be attributed to him, I being part of it through supervision of joint master students.

The many fruitful and creative discussions with Kari Heiskanen have contributed to the theory of recycling and the creation of our book. Also the new ideas we developed on how to teach and convey the knowledge we were creating on recycling to the new generation of students were exhilarating! Our many discussions on how to use classical minerals processing theory in the field of recycling has been the leitmotiv for most of the work done in the creation of a unique European Recycling Course.

At the same time as having had the formidable peer Udo working so closely with me, I had had the good fortune to work together with so many exceptional PhD and Master Students (see Appendix C), all contributing in various ways to this work. Dr. Antoinette van Schaik, MSc Olga Ignatenko and Dr. Ewoud Verhoef may be singled out for contributing so significantly to the ideas we were and still are developing between us on the modelling of recycling systems, bridging the gap from my past in primary metallurgy and minerals processing systems and control to recycling systems of the modern consumer society. The so creative discussions and so many long hours of work between us are still part of me and are still the source of continuing fruitful creation of knowledge.

I thank my *alma mater* for the invitation and opportunity to write this dissertation, especially also to Prof. Burger for his helpful suggestions and comments in its preparation.

The various companies mentioned in Appendix C and their financial and intellectual support made it all possible, made it real. Thank you!

Finally thank you for the loving patience of my family for the many hours they had to share with the work described in this dissertation. If considered carefully, the work discussed in this dissertation has such deep philosophical roots in the old Scriptures. It therefore remains true to the philosophy of life we share as a family and thus is so inherently part of us, part of sustainable life. I have always had a home to return to, to share the most creative moments in my life but also the most difficult. This dissertation is dedicated to you as it is also to my parents, sisters and brother and others close to me.

Glossary of terms

AMPL	A mathematical programming language
CAD	Computer aided design
ELV	End-of-life vehicle
EoL	End-of-life
EU	European Union
LCA	Life cycle assessment
LIBS	Laser induced breakdown spectroscopy
MFA	Material flow analysis
NGO	Non-governmental organization
OEM	Original equipment manufacturer
WEEE	Waste electric and electronic waste

Format of Dissertation

- **Chapter 1** provides the necessary background and briefly discusses indicates how the various research projects of the author contribute to the theme of this dissertation i.e. the fundamental limits of recycling.

- **Chapter 2** is devoted to the discussion of the bigger picture of Material and Metal Ecology and indicates the author's significant contribution questioning the applicability of current environmental analysis methodologies.

- **Chapter 3** discusses the author's developments in the system engineering aspects of recycling, starting from the system models developed for minerals processing and culminating in the present models in use for recycling systems, which are also being linked to computer aided design tools for cars.

- **Chapter 4** discusses the detail of each technology within the recycling system by referring to my experimental research work on metallurgy as well as on the modelling, simulation and control of metallurgical reactors, which are the real closers of the material cycle. This is done with reference to the large scale recycling systems.

- **Chapter 5** shows how this work has flown into the discussion and formulation of recycling legislation.

- **Chapter 6** briefly highlights the important insights developed by the author's research and provides an outlook to where things are heading to in view of recycling, product design and fundamental investigations to develop process technology that closes material cycles, which could possibly bring some "sustainability" to our anthropogenic behaviour.

- **References** provides only those references cited within the text, referring to the list of publications, theses, and selected industry reports by the author as well as the book.

Various other details are provided in the five Appendices:

- **Appendix A** contains my curriculum vitae.

- **Appendix B** provides the list of publications not cited in the main text of this dissertation but in general contributes to the main theme of this dissertation.

- **Appendix C** lists all the theses (PhD and Master) the author has supervised as well as a list of the various companies the author has done projects for or that have sponsored the student PhD and Master projects.

- **Appendix D** provides a copy of the book *(Copyright with Elsevier, Amsterdam)*.

- **Appendix E** contains reprints of all the encyclopaedia, journal, conference, plenary and key note lectures as cited in this dissertation (and as categorised under References).

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Chapter 1

Introduction

This dissertation describes a contribution by the author to harmonize the philosophy of Industrial Ecology with the theory and technology of minerals processing, metallurgy, recycling and computer aided product design, providing a basis for the estimation of some of the metrics of sustainability. This evolved into our book that discusses Material and Metal Ecology and provides some detail on how to colour in the three pillars of sustainability: social, environment and economy [1 and Figure 1.1].

Metals and Materials [1] are used in a wide range of products and applications ranging from consumer products (cars, electronics, white and brown goods, etc.) to constructions (buildings, roads) and agriculture (fertilisers) etc. The social, economic and ecological value of the materials in these applications is not only determined by the 'in-use value' of these applications such as functionality, durability, safety, reduced energy consumption, aesthetics, etc. but also by the possibility of these materials to return from their original application into the resource cycle after their functional lives/use at the lowest environmental and social impact. The design of the product determines the selection of materials to be applied in the products as well as the complexity of the material combinations and interactions within this product (e.g. welded, glued, alloyed, and layered). These actions directly affect the recyclability of the materials i.e. whether the material cycle can be closed and whether one can speak of an Industrial Ecological system.

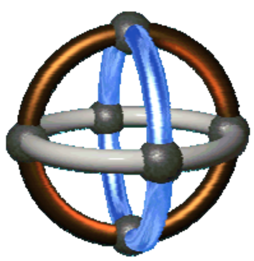


Fig. 1.1: Approaching sustainability by linking and harmonizing the three depicted cycles [1]. The three cycles also coincide with the three pillars of sustainability viz.: environmental, social and economic.

Figure 1.1 indicates that the social/environmental value of materials and metals can only be properly determined if both the material/resource cycle and the design/technology cycle are fundamentally understood and described, but more important that tools are available to link these three inseparable disciplines. The interconnectivity between the resource cycle (i.e. the primary and secondary material cycles), the design cycle (i.e. product design, recycling technology, materials processing, etc.) and the social/environmental cycle is depicted by Figure 1.1.

This dissertation shows how complexly linked (nano-/micro-) metals (with their associated materials, plastics, etc.) are related to products, production and manufacturing technology; and the product designer depicted by the Technology and Design; and Resource cycles respectively. Ultimately these cycles intersect with nature i.e. the "Nature" cycle, but this is not discussed in this dissertation. However, the link to geology, ores and metal containing minerals is considered as is the environmental impact of waste and residues from anthropogenic activity.

All these aspects compose the complex Web of Metals and Materials from an anthropogenic point of view – the focus of this dissertation. This web depicts the flow of metals/materials into consumer products; subsequently as consumer products into most regions of the world and finally either recycled back into consumer products and/or into nature and/or humans (Figure 1.2 provides a simplistic overview). Central to this is the metallurgical processing technology, which constitutes the "ecological organism" in this Industrial Ecological; the "organism" that closes the anthropogenic material and metal cycle.

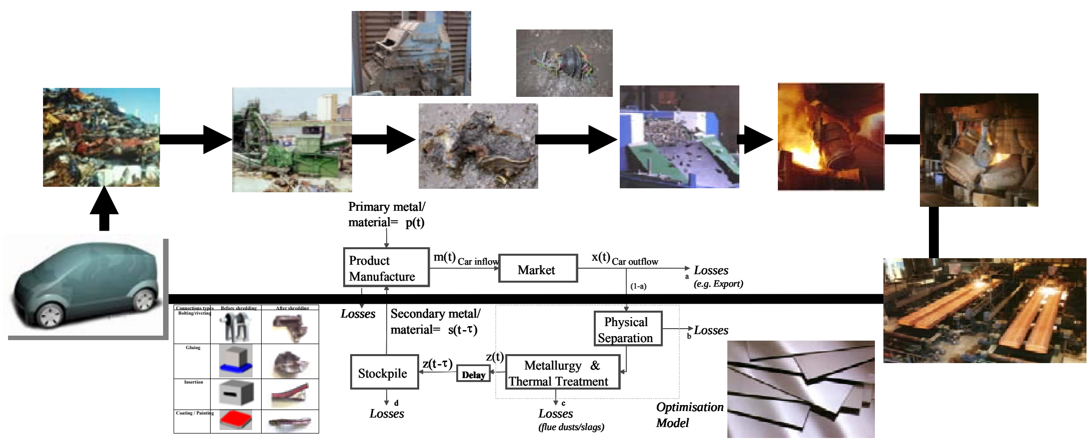


Fig. 1.2: The anthropogenic material and metal cycle: Understanding its beauty requires a system perspective, in-depth knowledge of all technology, an understanding of legislation and society as well as a thorough understanding of process control, thermodynamics as well as physics.

The Web of Metals and Materials or Industrial Ecological Metal and Material System depicts how metals and associated materials flow through the resources industry as well as the consumer product and waste system. In order to describe and make any legislative claim on the flows in Figure 1.2 requires the following detailed expertise:

- **System engineering** [1-5] of recycling and metal production systems in order to establish a detailed overview of all the intricacies of the Web of Metals in order to be able to realistically describe the flow on the basis of the first principles of recycling technology, metallurgical processing technology theory and the market.

- Knowledge of **product design** [1].

- **Process control** [2] in order to dynamically model, monitor, control and improve the system (and on this basis its economics), but also linking this information back to product design. The best manner in which to map the complex interactions between metals is by the application of dynamic modelling, which is more advanced than Material Flow Analysis (MFA) and provides valuable insights into the dynamic interaction and movement of metals and materials linked to consumer products. This is crucial to ensure that valuable minor elements find their way back into products, hence visualizing and controlling the distribution of these elements onto the surface of the earth due to the action of consumer society and Original Equipment Manufacturers (OEMs).

- **Process engineering and metallurgy** [2-5] in order to optimally operate each of the unit operations in the feedback flow loop of Figure 1.2.

- **Legislation and knowledge transfer** is a crucial aspect to all this work.

With reference to Figure 1.2 and various plenary and keynote papers the following aspects will be discussed in this dissertation, hence providing an overview of the contribution the author made to establish some Metrics of Material and Metal Ecology [1]:

- **System Engineering:** Resource efficiency and future availability of materials / minor elements are of environmental, economic and societal concern. Therefore, the recovery of material and metals within the highly connected Web of Metals and Materials in the resource cycles of both base metals and especially environmentally relevant and valuable minor elements for automobiles, consumer electronics, miniaturization applications and nano-technology is of crucial importance from a sustainability perspective.

  My contribution is the methodologies developed for the analysis of these large recycling systems, which is finding application in for example the recycling and automotive industries respectively [1 and 6-12].

- **Product Design:** The role of product design is demonstrated by discussing the Design Wheel, which shows how Computer Aided Design (CAD) is linked to recycling, metal and energy recovery and waste creation/prevention. Often materials are connected to each other, alloyed, welded, glued, etc., which makes it impossible to consider the Ecology of Metals and Materials only on an elemental basis.

  The author has managed with these models to link the materials processing and metallurgical process engineering fields to product design, which is a unique contribution [1, 6 and 7].

- **Process Control:** Time dependencies as well process dynamics often have a crucial impact on the Web of Metals and Materials and hence on the impact these metals and materials have on the environment. This is important since it takes time for consumer products and their associated metals and materials to flow through the system. Also the complex connection between the linked primary ore and secondary recycled materials chains and rapidly changing product compositions has an important effect on determining where metals and materials report to. Social aspects such as the concentration of labour in certain parts of the world associated with metal production and recycling could be dynamically illustrated by such a dynamic visualization.

Various contributions in the process control field of process metallurgy have developed the skills to integrate these aspects into the modelling methodologies [1, 2, 7 and 9].

- **Process Engineering:** Energy and climate change effects are directly connected to recycling as many of the environmental impacts are dominated by the energy needed and produced CO_2 to extract materials or by the prevention of this by proper recycling activities. Recycling is therefore of extreme importance to lower the consumption of energy during their production, hence directly having an impact on greenhouse gas emissions.

  The contribution of the author has been to show how the Web of Metals and Materials can be arranged to maximize energy recovery, support light-weight design, minimize toxic emissions by basing the system and reactor models on the first principles of process engineering. The theoretical basis for this and its roots in classical minerals processing and metallurgy has been developed by the author and his students [1, 9, 10 and 14-18].

- **Legislation:** The rigorous approach provides a basis for quantifying legislation on a more technological and fundamental basis (i.e. physics, chemistry and thermodynamics), hence providing a first principles basis for recycling targets and a solid legal basis which the OEMs can safely operate on and manufacture products (e.g. future energy-efficient recyclable light-weight cars). The link to legislation and how the fundamental approach can be used for the formulation of environmental legislation is discussed.

  The author applied these techniques in discussions on car recycling at EU level [13].

- **Knowledge Transfer:** The link to industrial practice is discussed through various contributions by the author. The author has managed to attract project partners from the classical processing metallurgy field, to process control, recycling and the automotive industry [6, 7 and 14-18].

  This dissertation discusses how the theory from minerals processing was adapted and applied to model recycling systems. It is further shown how this basis makes it possible to link to product design as is now done in a €M20 EU project, to design a super light car (www.SuperLightCar.com).

This dynamic and technological detailed first principles approach, when integrated into more simplified tools and translated to single score methodologies such as Life Cycle Assessment (LCA), provides the consumer with transparent information on all issues surrounding the ecological safe production and use of the product until its end-of-life phase and subsequently its recycling back into metals, materials and energy. In summary, in order to realize a "sustainable" Material and Metal Ecology, the system depicted by Figure 1.2 should be in balance with the material and metal cycles in nature. Linking these two worlds is a key to achieving "sustainability" in our present consumer society.

In the subsequent chapters the author will discuss his contributions to address the various key areas mentioned above to show where the key ideas originated from and how these were filled in by various PhD and Master Theses.

The key outcome of all this work is to show the limits of recycling. This is proven by having developed new theories for recycling systems based on extensive industrial experience and knowledge of the materials and metals processing as well as consumer product manufacturing industries respectively [28].

Chapter 2

Material and Metal Ecology

In the present time and age it is not possible to conduct research anymore if the role of the research within the bigger picture is not known, if the social and environmental consequences are not made visible. This is most certainly valid for materials research for consumer applications; not knowing the effect that materials within consumer products have on the environment and their impact on society is not permitted anymore. A larger systemic picture and view should always be at hand to evaluate the consequences of the actions of Engineers throughout the life of the product and its contained materials and associated energy. The basis for this work is to be found in reference [79].

Consumer products are a complex mixture of closely associated metals, plastics, chemicals, inorganic compounds and materials. These complex connections are often difficult to separate due to the limitations of the applicable separation physics as well as incompatible thermodynamics, which sometimes renders the complete recycling chain uneconomical subject to product type. The result could be that these end-of-life products are then shipped to low cost countries where these are hand-processed (often more efficiently than present technology permits) and/or dumped or even re-used but then eventually finding their End-of-Life (EoL) on an unsafe dump in an uncontrolled economic environment. The result is obviously that hazardous materials could report to the ground water with all its subsequent consequences to health.

Therefore, any modelling and assessment approaches should provide valuable information to the legislator to provide a fundamental basis for global environmental legislation based on achievable technology, energy and economics incorporating the dynamics of market flexibility and consumer behaviour. Mapping of materials will inform the original equipment manufacturers (OEMs) on a technology basis where materials and elements in their products are reporting to, ensuring that a solid legal and environmental basis is maintained for marketing these products. On the other hand the consumer can be transparently informed of all benefits and risks of using the products of the OEM, as well as providing the legislator the means to monitor the (likely) movement of end-of-life products across the globe to ensure that nature and humans do not ultimately come to harm. Thus, a first principles modelling and simulation approach ensures that the recycling loop can be mapped and subsequently “closed” for metals and related materials in relation to design. Such an approach that quantifies the material and metal flows is the only way to ensure that sustainability is approached for resource usage.

Therefore, judicious management and understanding of the plight of valuable (and also possibly toxic) minor elements is a matter of extreme importance to OEMs, legislators, recyclers, ecologists, environmentalists as well as sociologists, general population, non-governmental organizations (NGOs), to name but a few. Therefore, to discuss the Ecology of Metals and Materials, a fundamental understanding of the size and nature of resource cycles over time is needed. This enables the quantification of environmental impacts in addition to formulation of policy, design, technology and system organizational strategies for more sustainable global resource cycles.

Figure 2.1 shows that each carrier commodity metal is associated in nature (geology) by a unique blend of valuable minor elements (with or without own processing infrastructure) as well as harmful and worthless elements are lost due to unfavourable thermodynamic and other conditions within the processing chain. The carrier element can in some cases be only the secondary material being recovered since the minor elements are of much higher economic value. Therefore, the disruption of the production of the carrier elements could in the end adversely affect the production of the valuable minor elements. Green processing, therefore, implies minimizing the losses of elements to the green outside band of Figure 2.1.

The intricate and unique blend of elements within each ore has led to metallurgical processing being honed to effectively recover and contain most elements economically. This complex link of materials, processing of ores, metals and end-of-life products has led the creation of a complex Web of Metals and Materials, in which each element has a unique position. Hence eliminating or disrupting the production of one element will have an effect over all other connected elements within the Web of Metals[1].

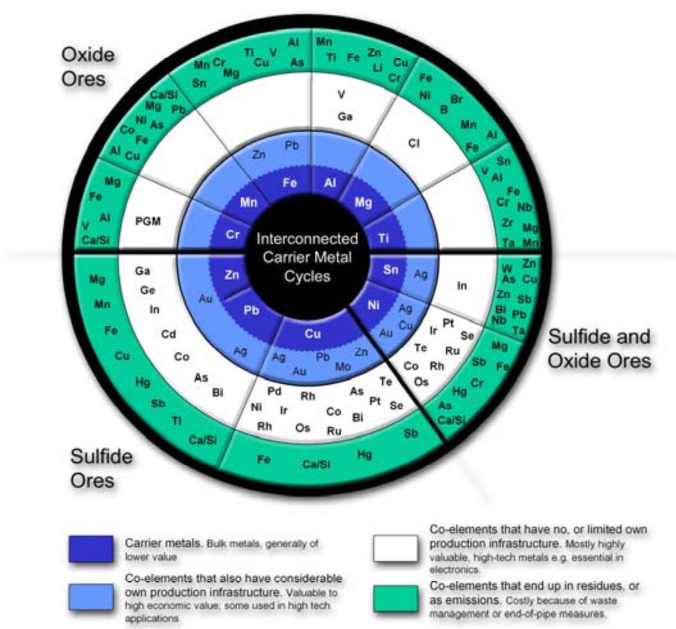


Fig. 2.1: The ‘Metal Wheel’ showing the complex interactions between different metals as well as the economically and thermodynamically recoverability of (co-)elements [44].

[1] An interesting example is Indium that is used in flat TV panels. The question is how much is required, where, when and how this changes dynamically due to the metal (especially zinc) market? For example a specific country requires around 160t per annum at the moment but can only obtain a fraction of this via primary ore sources. Therefore, recycling has to supply the rest, but this is only achieved partially i.e. in total primary and secondary recovery only reaches around 100t.

2.1 Dynamic simulation model

Figure 2.2 shows a model that simulates this complex link between various elements and predicts their global flow over time through the complete metal and material chain, the link visualized by the unique Figure 2.1 [11]. Also for example the passage of the metal Indium (used in flat panel displays) can be simulated through the complete material and metal system in time. Environmental indicators have been linked to the output in order to quantify the environmental performance of the complete global anthropogenic system.

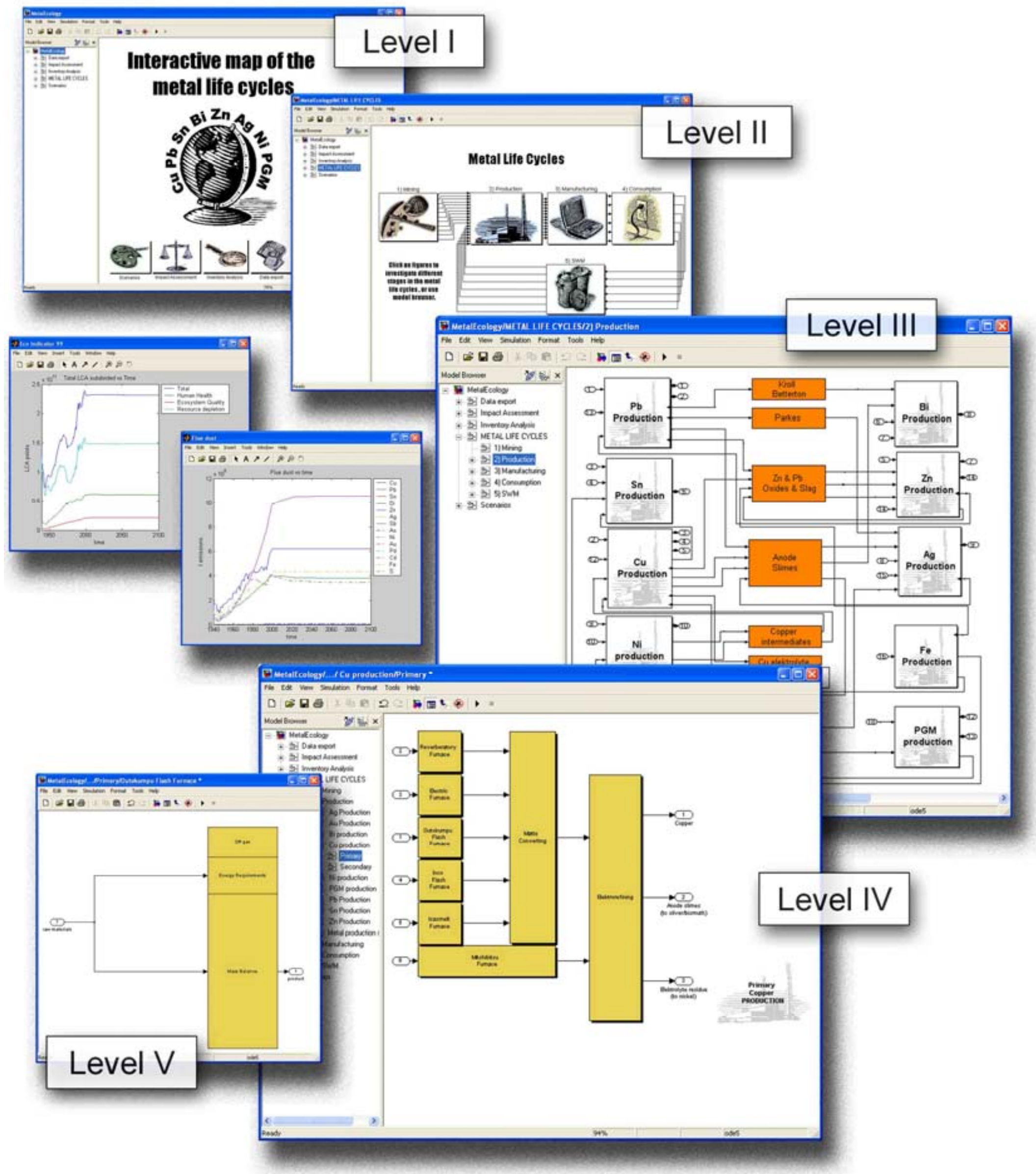


Fig. 2.2: The various levels of the dynamic Simulink® (The Mathworks) model that dynamically links the metal flow of various metals as shown in the Level III slide, producing a dynamic LCA environmental score for the complete system (two small grey windows left middle) [1, 37].

The complex interactions between the various reactors for the production of the various metals can only be produced with extensive industrial metallurgical process knowledge. The complex web of interactions can only be created in such a model if metallurgy is known. My extensive industrial and theoretical experience made it possible to have developed this type of model as well as to create the Figure 2.1 to instruct non-metallurgists on the complexity of metallurgy [9, 40]. The various publications listed in this dissertation (also in Appendix B) as well as numerous reports to industry are evidence of this.

2.2 The development of theory

The basis for this dissertation started when the author was associated with the Aachen University of Technology (Germany) [81, 83-85]. Here the extent of the environmental impact of metals and the effect this could have on the viable future of the metallurgical industry in Germany but also in Europe as a whole became clear. The projects mostly focused on base metal industry of Germany all in view of maximizing metal production and minimizing energy consumption.

2.2.1 The simulation of industrial ecological systems

Metal flow networks are complex and highly connected and not modelled easily. This has been discussed in detail [1]; however, the origin of multi-level modelling of industrial ecology systems was first done by Reuter, in which it was shown how intricate metallurgy is:

- A model was developed to show the intricacies of metal production and the dense web of metals it creates [42, 54 and 79].

- This work was extended in a project for Phillips (the producer of consumer products and electronics) in which it was proven that it could be quite problematic to sustain the intricate interconnected metal cycle if lead (an integral important part) is removed from solder or hence from primary production [30, 37].

- The link of this work to Industrial Ecology was discussed while also highlighting the importance of tacit process operational knowledge within the metallurgical industry – the knowledge that often makes it possible for operations to survive, run safely, environmentally friendly, to name a few [44].

This knowledge hence makes Industrial Ecology possible; if it is destroyed by for example legislation the Industrial Ecological system could collapse!

2.2.2 The involvement within the zinc and lead industries

The strong attack by The Netherlands' Environmental Protection Agency on zinc as a metal product due to its perceived poor environmental impact at that time, sparked a large body of this work, not only to show how wonderful this and other metals really are, but also to illustrate the principles of Industrial Ecology. My involvement in the International Zinc Association as a lecturer for the six Zinc Colleges held between 1997 and 2006 for senior members and executives of the metallurgical industry [5], has led to the various applications discussed in our book [1] given in Appendix D. A typical example, showing the intricacy and interlinked system of zinc and lead metallurgy, is depicted in Figure 2.3.

In order to bring some rational into the zinc discussion my first large system optimization was done for this base metal. I attempted to prove and show with this work that the system is far more complex than the environmentalists were portraying it at the time. As a function of various objective functions we could show how the system behaves as a function of different optimizing objective functions [81, 83-85].

This work laid the foundation for describing the larger and more complex recycling systems of EoL consumer products.

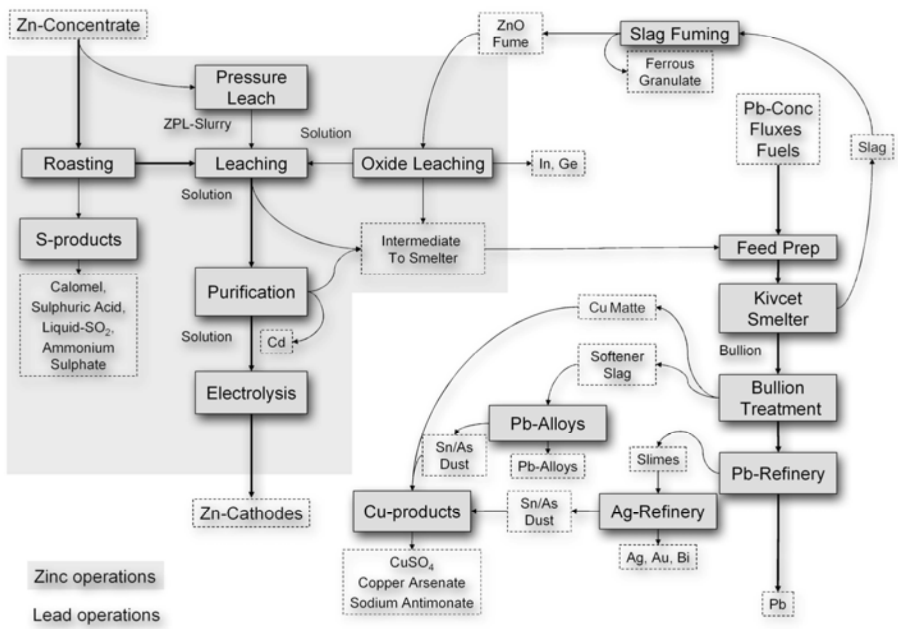


Fig. 2.3: A schematic flowsheet of the Cominco zinc-lead plant at Trail in Canada [5].

2.2.3 Metallurgical reactor technology

End-of-life consumer goods are a valuable resource of metals. Processing these is key to recycling and "closure" of material cycles; contributing to the sustainable use of metals. Rapidly changing metal combinations in consumer products challenge the current boundaries of thermodynamics and kinetics and their use to recover these metals from post-consumer products in reactors. Hence the distribution behaviour of key elements in these reactors has a key impact on where these metals report to in the recycling system. Therefore, to optimize the recycling system requires detail knowledge and control of metallurgical reactors. This will be discussed in more detail in Chapter 4. In this regard a large body of work was done to model and control metallurgical furnaces:

- Aluminium recycling furnaces were modelled and optimized to maximize recovery in industrial furnaces in Germany [25, 33 and 39],
- The general modelling and simulation of metallurgical reactors [87, 92],
- Submerged arc furnaces for processing phosphorous containing materials [21, 26], and
- Control of submerged arc furnaces [80, 82].

2.2.4 Waste management

The work within industrial ecology has been extended to the waste processing industries as well as waste infrastructure. Various research projects expanded the zinc system models to waste processing models:

- We developed a roadmap for the Dutch waste management system [29],
- Processed bottom ashes of waste incinerators to investigate the required technology and system necessary to process the bottom ash [48], and
- We developed a new paradigm for waste management based on system thinking [69].

In order to optimize the waste processing system, detailed knowledge is required on the waste processing technology. A large body of simulation work and industrial measurement was done on the optimization of an industrial chemical waste incinerator in Rotterdam (The Netherlands), which will be discussed in more detail in Chapter 4 [32, 33 and 56].

2.3 Significance of contribution

The intricacy of the Metal Web [1] led to a body of work that involved the system modelling of zinc and lead industries to show which options for processing lead and zinc containing materials are best. It was demonstrated in [11, 30] that a LCA analysis of the metal production and recycling system is too simple to describe a highly interconnected dynamic complex flow of materials. This work has discussed with proof the applicability of LCA methodology to evaluate the environmental impact of metallurgical systems.

This work forms the basis for the system modelling for recycling, which will be discussed in the following Chapter 3, exploring the depth required to accurately describe the recycling of EoL consumer goods and also to estimate the limits of the recycling.

Chapter 3

Product Design and Fundamental Recycling Optimization Models

Product design has a crucial influence on the closure of the material cycles and hence the efficient use of resources. System modelling is a key tool to evaluate the performance of the material cycle and is hence indispensable to provide information on the impact of consumer behaviour. These system models therefore not only provide an important input to the economic dimension of sustainability, but perhaps more important, to the social dimension. Furthermore, these system models are the basis evaluating Industrial Ecolcogy and hence provide an important input to the environmental dimension of sustainability. Minerals processing plant optimization carries a wealth of knowledge that can be applied with adaptation to the recycling field and the system models within Industrial Ecology. This chapter will discusses the author's involvement in a present project with the automotive industry to link recycling models to computer aided design of cars laying the link to the theory of minerals processing. The origin of this work can be found in the publications by the author for modelling mineral processing and metallurgical systems [83-84, 90-91 and 93-94].

The design of a product is linked to recycling as depicted in Figure 3.1. The design does affect how materials are liberated during shredding, how efficient materials can be separated and what the composition and quality of the recyclates will be. This determines if these recyclates can be recycled or not, but also therefore determines what the losses will be from the recycling chain. The control of the recycling chain determines what the qualities of the streams are and whether or not the recycling rate is high. This in essence determines whether materials and metals can be recycled, hence the pivot of industrial ecology of the materials and metals within the car. This chapter discusses the various influencing factors for the Material and Metal ecology of consumer products.

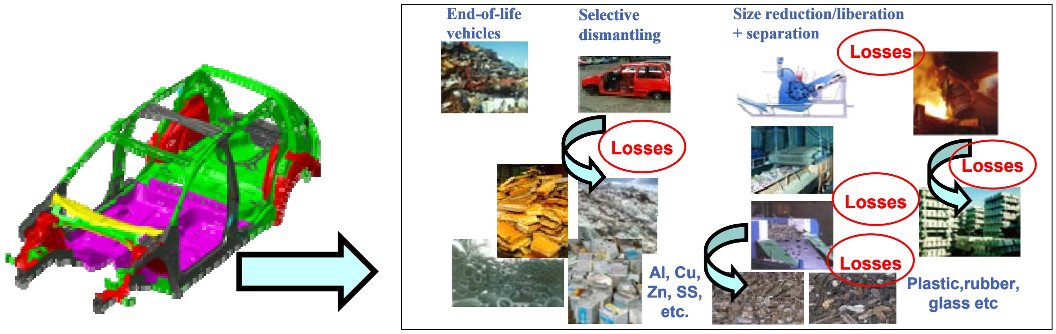


Fig. 3.1: The link of a car design to the recycling chain, which includes selective dismantling, size reduction and subsequent separation [1].

3.1 The 'Metal Wheel' and recycling technology

Product designers select the produced metals and materials from (primary) resources as depicted by Figure 2.1 and apply them in products and applications. The product designers determine which interconnected materials are to be separated and recovered from primary ores. During the design of the product a range of materials/elements are once again mixed and complexly connected (gluing, welding, alloying, etc.). Modern products contain a combination of metals that are not necessarily linked in the natural resource systems as shown in Figure 2.1 [1]. As a consequence, these materials are not always compatible with the current processes in the metals production network, that was developed and optimized for the processing of primary natural resources and associated minor elements. This was discussed in more detail in Chapter 2.

In general an increased complexity of recycling pyrometallurgy has arisen through the development and design of modern consumer products (such as passenger vehicles and consumer electronics). The consequence is the formation of complex residue streams or undesired harmful emissions that cannot be handled in the current system (thus the processing and recycling of those products at their end-of-life). This can be prevented by linking product design with optimized recycling technology, therefore minimizing the loss of valuable material and prevent the decrease of both quality of recyclates and recycling rates of these products as discussed below.

3.2 The roots of recycling system models in minerals processing

A number of papers by the author progressed and developed towards the modelling of recycling systems as will be discussed in this chapter. These included:

- The modelling and optimization of flotation circuits without and included regrind milling as shown in Figures 3.2 and 3.3 respectively [93, 94], developed also with a theoretical understanding of flotation chemistry [78]. Note that the author also spent some time running an industrial flotation plant as a foreman for Anglo American Corporation (South Africa) providing the so important industrial experience and understanding to the modelling and simulation activities described in the cited papers.

- These ideas were expanded to other circuit types e.g. gravity separation circuits such as for heavy mineral sands [90]. Gravity separation technology is also typical for recycling systems, this knowledge from the past therefore being invaluable.

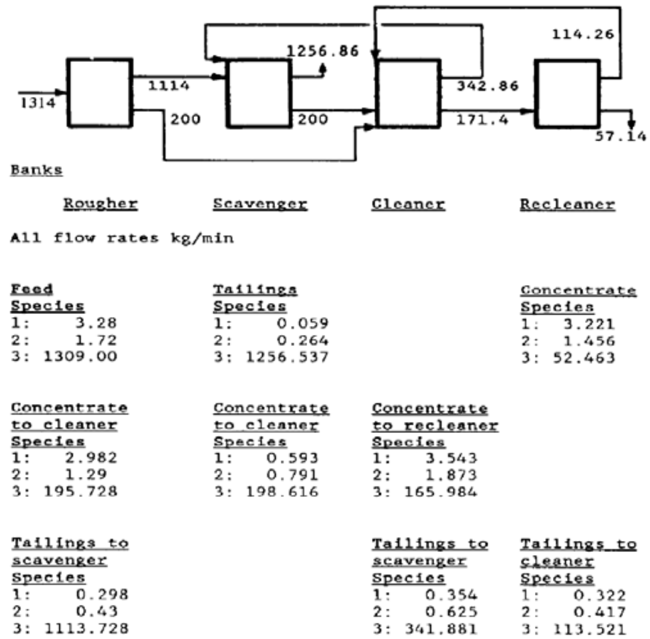


Fig. 3.2: Optimal flotation circuit structure in a system without a regrind mill [94].

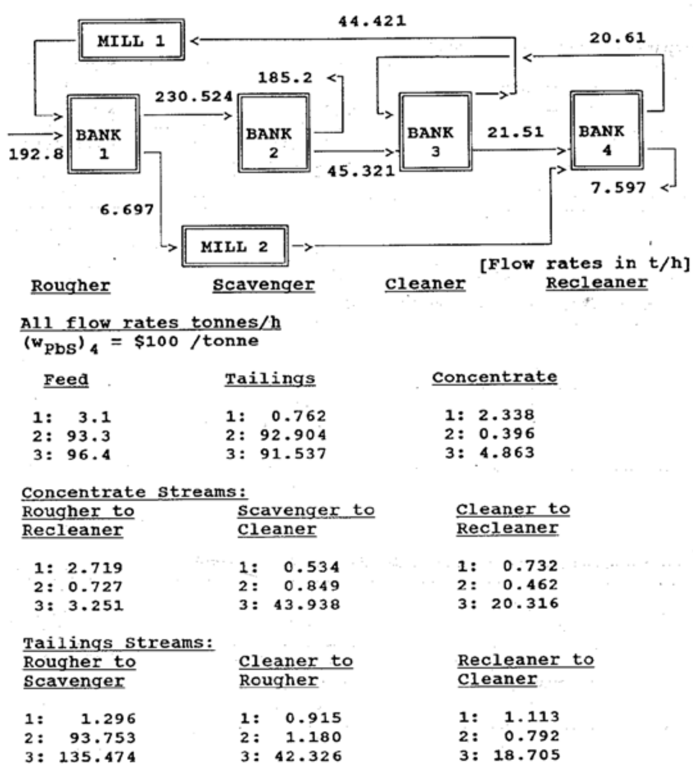


Fig. 3.3: Optimal flotation circuit structure in a system including regrind mills [93].

- In order to introduce and include the ill-defined aspects of mineral separation circuits, artificial intelligence methodologies were integrated with the system models for the optimisation of minerals processing plants [90, 91].
- Subsequently these approaches were adapted to synthesis large metallurgical processing flowsheets in order to optimize metal and material recovery on a regional as well as continent scale. Most of these applications focused here on the processing of zinc and lead containing materials [81, 83-85] but also included copper and aluminium [1].

3.3 Recycling optimization models

Commercial recycling systems never create pure material streams (see Figure 3.4 for materials from end-of-life vehicles (ELVs) recycling collected from various shredder plants, never achieves 100% material recovery (recycling) during physical separation (dictated by separation physics), neither achieves 100% material recovery (recycling) during high temperature metal production (dictated by thermodynamics) and nor achieves 100% energy recovery (dictated by thermodynamics). The recyclability of a product is not only determined by the intrinsic property of the different materials used, but very much by the quality of the recycling streams (see Figure 3.4), which is determined by the mineral classes (combination of materials due to design, shredding and separation), particle size distribution and degree of liberation (multi-material particles defined into liberation classes) (see Figure 3.5). These all affect the physical separation efficiency, metallurgical and energy recovery, which all in turn determine the quality and economic value of the recycling (intermediate) products in the recycling system, which can be applied as secondary resources. These determine the limits of the recycling system!

Fig. 3.4: Impure quality materials created during physical separation of shredded ELV's (clockwise top left: steel, wires, Mg/Al/Zn/Cu/SS, steel/Cu, Mg/Al/Zn/Cu/SS, and plastics) [24].

Fig. 3.5: The ‘mineral’ aluminium in its different appearances (liberation and particle size classes) as a high quality liberated fraction (top left) to un-liberated radiator (bottom left) and various un-liberated mixed fractions that cannot necessarily be recycled directly [96].

Since the quality of recyclates and the recycling rate of a product is largely affected by the design of the product (see Figure 3.6), it is required that tools are available that link computer aided design (CAD) software and recycling models in order to predict recyclability of the car during the design phase. In addition this predicts and determines the social and environmental value of the materials applied in the product. Fundamental knowledge of recycling processes, such as shredding, mechanical separation processes and metallurgy, and material characteristics of recycling (intermediate) products (material type, liberation, etc.) have to be combined with that of the design of the product (material combinations and connections). In order to optimise the material/resource cycle and maximise the recycling rate of (future) products all the parameters determining the recovery rate for each of the materials present in the multi-material designs and applications of the present and future have to be fully understood. This should all embrace the dynamics and statistically distributed nature of the resource cycle system.

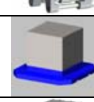
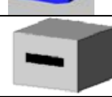
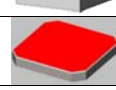
Connections types	**Before shredding**	**After shredding**
Bolting / riveting		
Gluing		
Insertion		
Coating / Painting		

Fig. 3.6: Possible connection types in car design with distinctive liberation behaviour [97].

The prediction of the recyclability and recoverability of products already in the design stage requires the exploration of the limits of recycling on a fundamental basis as has been discussed by Reuter *et al.* (2006) [28]. Recycling models have been developed over the last number of years by Reuter and van Schaik evolving from the theory developed in the classic minerals processing and metallurgical processing fields [83, 93]. These recycling models take into consideration (i) material quality (physical and chemical) and calorific values of the (intermediate) recycling streams being a function of material/mineral classes, particle size classes, liberation classes (degree of liberation); (ii) the value of intermediate streams; (iii) separation physics and thermodynamics; (iv) losses and emissions; (v) harmonisation of plant / flowsheet architecture with changing product design; and (vi) distributed and dynamic properties of present and future product designs (see Figure 3.8 for a detailed flowsheet of the recycling optimisation model).

The progression of modelling followed a path, starting from [93, 94] and incorporating my (industrial) experience in process control [2], metallurgical reactor simulation [56] and minerals processing modelling and plant optimization [91].

- With the knowledge of minerals processing and from observation of particles created in recycling systems (Figures 3.4 and 3.5) we could define the fundamental basis of the recycling systems in terms of (i) mineral classes, (ii) particle size classes, (iii) liberation classes, (iv) the link between these and (v) the definition of the minerals for a consumer product [which we developed through the sequence of publications 58, 46, 43 and 28].

    - First we explored the dynamic nature of recycling systems, gleaning from experience in process control, showing the effect of time delays in the system on recycling rate [58].

    - Knowing that all properties are highly distributed in time in recycling systems, we investigated the effect of this on the recycling rates of cars [46].

    - Subsequently we started to realize that we could prove that there are fundamental limits to recycling as a function of all the highly distributed properties, which culminated in a number of papers used to argue against the rigidity of recycling legislation [28, 43].

- Liberation, physical and chemical separations are key to the production of pure recyclates within the recycling system. We investigated these aspects by modelling the separation thermodynamics during metallurgy [38] and quantifying the quality loss within the recycling system in terms of Exergy [23].

- Furthermore, LCA studies were performed on cars [55] to evaluate the environmental impact of the use phase.

- We investigated the effect of particle size reduction and liberation on the recycling rate of cars to show what the key cause was for losses in the recycling system and hence the reason for low recycling rates [47].

- Also, we started linking design and liberation of materials during shredding to our recycling models to estimate recycling rates [19, 31].

- In order to calibrate our models we became involved in large industrial scale recycling experiments to estimate real recycling rates for cars [14-15, 17, 36 and 100].

- Furthermore we published some significant papers, which showed that recycling legislation was violating thermodynamic laws [24].

- In order to complete the flow sheet of recycling, extractive metallurgy was always uniquely added, whereas most flow sheets in environmental analysis do not consider or simplify this highly important aspect. These aspects I modelled in Aachen when investigating the optimization of metallurgical flowsheets for the optimal recovery of base metals [83, 84].

Figure 3.7 shows how after shredding, shredded particles have different degrees of liberation, therefore creating streams of different quality. This is partially caused by imperfect separation in the physical separation stage of these particles and also by the design choices as shown in Figure 3.7, which affect particle composition after shredding. The quality of the recyclate streams ultimately determines in which processing steps, depicted in the detail flowsheet in Figure 3.8, these materials can be processed and hence how much material of sufficient quality and economic value can be recycled. This determines the closure of the material cycle and ultimately the "sustainability" of the system, of society!

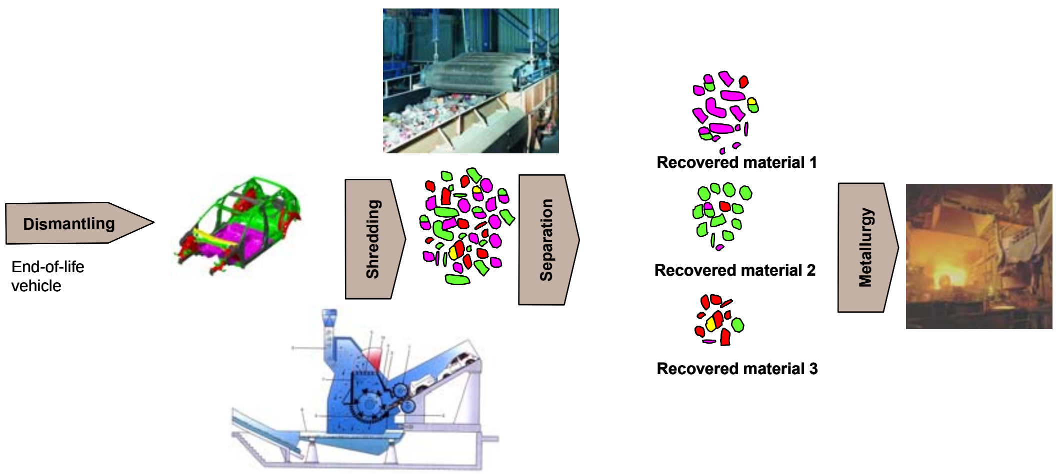


Fig. 3.7: Shredding of a car and the creation of liberated and un-liberated materials [97].

Figure 3.9 depicts how product design selects materials from the primary metal and material cycles and combines them into a complex multi-material design, in which the various materials (metals and non-metals) are complexly integrated. The combination and connection of the materials in the product design is linked (on the basis of the discussed recycling models) to the quality of recyclates as a function of the degree of liberation of the various particles after shredding. The colours in the 'Design Spectrum' of Figure 3.9 reflect the (in)compatibility of material combinations in the recyclates (either due to imperfect liberation or separation) based on the material combination matrix given in Figure 3.10, in which the (in)compatibility of material combinations is based on the thermodynamics and kinetics of metallurgical processing (see also Figure 2.1).

Figure 3.9 reflects the knowledge and modelling detail captured by the developed recycling optimisation tools and provides feedback to the designer on desired and undesired material combinations in the design. The wheel acts as a preliminary design for recycling tool, reflecting the complexity and detail of the developed recycling models to ensure a proper reflection of the reality of recycling system behaviour and the quality and value of produced recyclates. The wheel enables real design for recycling based on the limits and possibilities of recycling technology and recyclates quality as a function of design and separation efficiency.

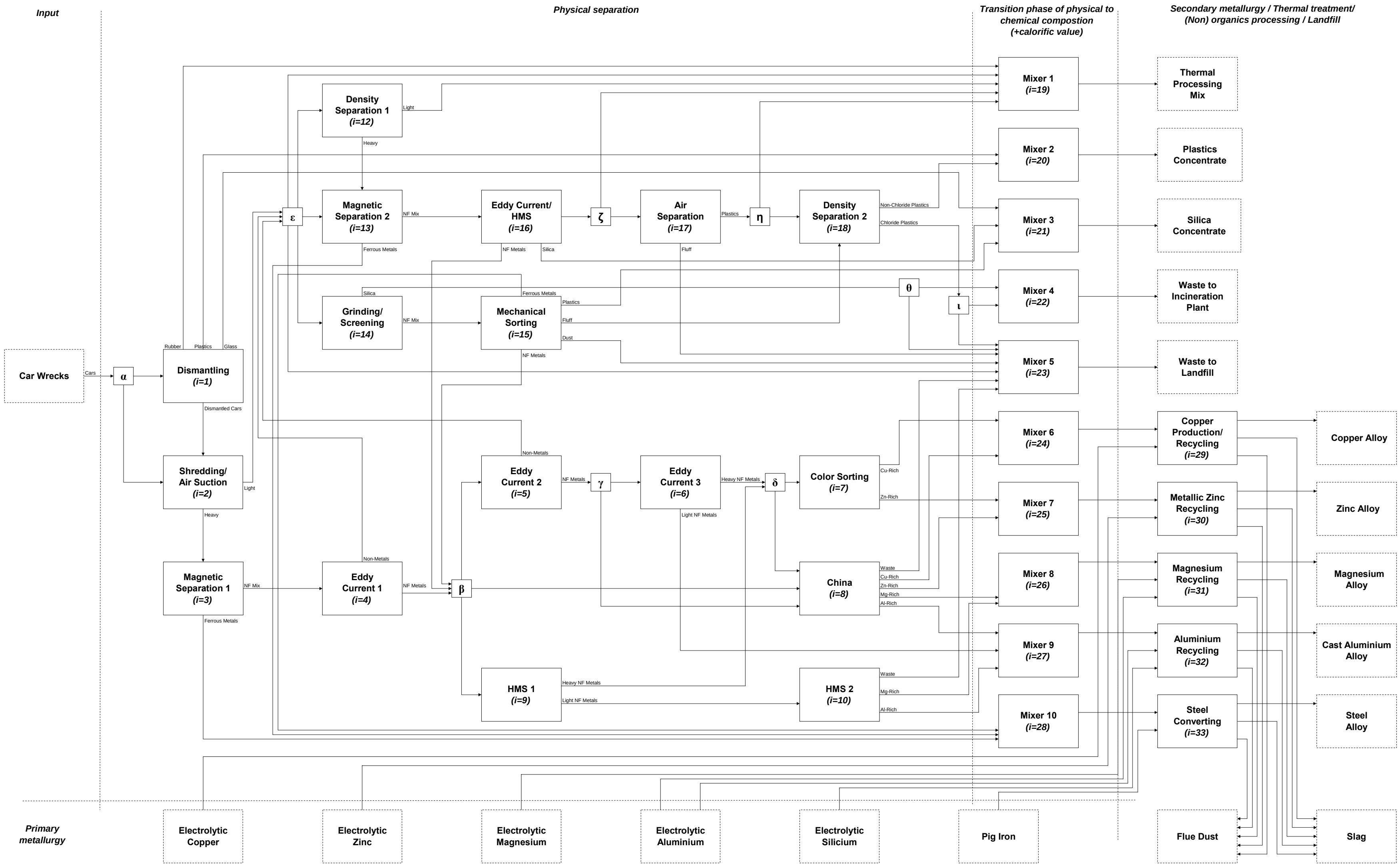


Fig. 3.8: Flowsheet of detailed recycling system optimisation model (programmed in AMPL) [28].

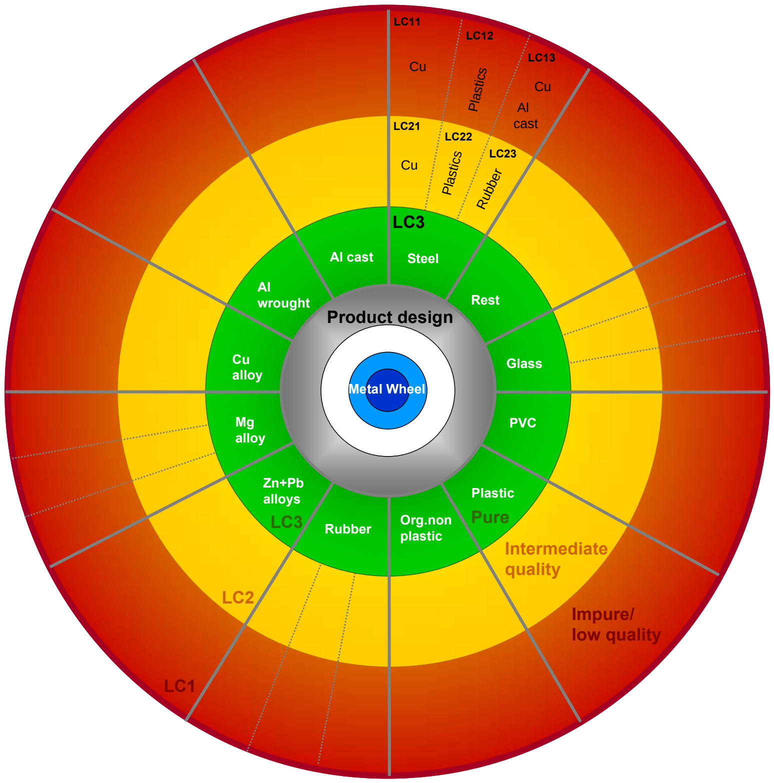


Fig. 3.9: The 'Design Spectrum' illustrating the underlying liberation classes that are created as a function of product design as predicted by the recycling model depicted in Figure 3.8. It also shows that poor design shifts recycled particles into the red band, while it is desirable for high recycling rates to have shredded particles being well-liberated and hence land in the green band. This figure also suggests an intimate link to the Metal Wheel (Figure 2.1).

	Industrial streams (metals)								
Input streams (secondary)	Aluminium cast	Aluminium wrought	Copper	Lead	Magnesium	PGM's	Stainless steel	Steel+cast iron	Zinc
Aluminium cast	green	red	yellow	yellow	red	yellow	yellow	yellow	red
Aluminium wrought	yellow	green	yellow	yellow	red	yellow	yellow	yellow	red
Copper	yellow	red	green	yellow	red	green	red	red	green
Lead	red	red	green	green	red	green	green	green	green
Magnesium	yellow	yellow	yellow	yellow	green	yellow	yellow	yellow	yellow
PGM's	red	red	green	green	red	green	yellow	yellow	yellow
Stainless steel	red	red	yellow	yellow	red	yellow	green	red	yellow
Steel+cast iron	red	red	yellow	yellow	red	yellow	yellow	green	green
Zinc	yellow	red	green	green	yellow	yellow	green	green	green
Glass	yellow	red	yellow	red	red	yellow	yellow	yellow	red
Elastomers	yellow	yellow	yellow	yellow	red	yellow	yellow	yellow	yellow
Natural Fibres	yellow	yellow	yellow	yellow	red	yellow	yellow	yellow	yellow
Natural Rubber	yellow	yellow	yellow	yellow	red	yellow	yellow	yellow	yellow
Porcelain	yellow	red	yellow	red	red	yellow	yellow	yellow	red
Thermosets	yellow	yellow	yellow	yellow	red	yellow	yellow	yellow	yellow
Thermoplastics	yellow	yellow	yellow	yellow	red	yellow	yellow	yellow	yellow

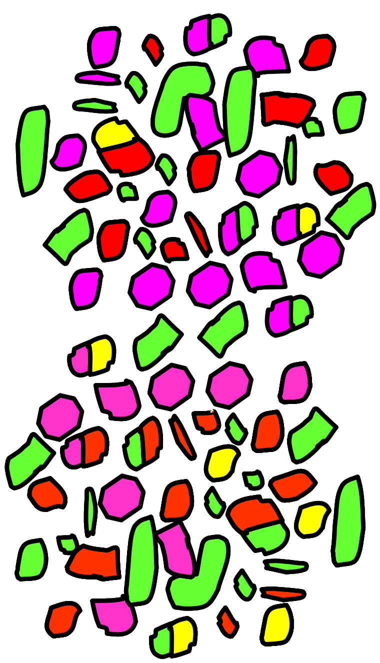
- green: can be combined
- yellow: limited combination possible
- red: avoid combination-non compatible

Fig. 3.10: Material combination matrix: permitted connections and non-permitted connections [38] also used within the automotive industry.

3.3 Linking design and recycling

Figures 3.1, 3.7 and 3.8 respectively depict a simple scheme for car recycling and a complex optimization model for recycling of end-of-life products. Figure 3.11 depicts the (un)liberated particles after shredding (Figure 3.4 to 3.6) which determines its recyclability due its quality (and hence its economic value). This determines whether or not the material chain can be closed.

Table 3.1 explains how and why certain fractions can be fully recycled if they are liberated. For example copper connected to steel will dissolve in steel. Since copper is more noble (less reactive to oxygen) than steel it cannot readily be removed from the steel. This affects the steel quality (e.g. its mechanical properties) and therefore it is given a red colour in Table 3.1. Note, that this is dependent on the amount of the one material connected to the other (the concentration of the contaminant). In many cases, although red material combinations exist, shredding liberates the materials, which are subsequently separated during physical processing and hence they are recyclable. Figure 3.11 and Table 3.1 are only true if there are reasonable amounts of materials connected in the recyclates (exceeding the contamination limits), hence producing alloys outside their normal definitions. The type of models as discussed above can predict the recyclate quality and therefore link design to recycling possibilities and restrictions as indicated in Table 3.1.



Combinations in design

- Green/pink – steel/plastics
- Green/yellow – steel/copper
- Red/Green –aluminium cast/steel
- Pink/red – plastics/aluminium cast
- Pink/yellow – plastics/copper
- Red/yellow – aluminium cast/copper

	Industrial streams (metals)		
Input streams (secondary)	Aluminium cast	Copper	Steel+cast iron
Aluminium cast			
Copper			
Steel+cast iron			
Plastics			

Fig. 3.11: A selection of liberated and un-liberated particles from the car body-in-white given in Figure 3.1. A section from the compatibility matrix is also given *(Table 1 and Figure 3.10 - please note that colours of particles are randomly chosen and do not coincide with the colours of the matrix)* [47].

Table 3.1: The reasons why certain materials are compatible (also see Figures 3.10 and 3.11) explained on a thermodynamic basis [European car industry is using this, based on 38].

	Industrial streams (metals)		
Input streams (secondary) = recyclates	**Aluminium cast**	**Copper**	**Steel + cast iron**
Aluminium cast	Similar material	During copper processing Al is lost to slag	Loss of Al; Al less noble
Copper	Cu is more noble than Al cast; a certain % of Cu is allowed being one of the alloying elements for Al cast	Similar material	Cu is more noble than steel
Steel + cast iron	Steel+cast iron more noble than Al cast	Creates excessive slags, loss of steel to slag	Similar material
Plastics	Limited due to reaction of Al with C and subsequent loss of Al (Al_4C_3)	Affects energy balance of processing; fillers affect slag properties; possible dioxine creation	Affects energy balance of processing; fillers affect slag properties; possible dioxine creation

The optimization model of which the flowsheet basis is depicted by Figure 3.8 is too complex to link to CAD directly. Therefore fuzzy logic models, which represent (mirrors) this complex model, have been developed from the numerical results of the recycling models. These are presently being linked to CAD software and hence to the design of the product (Figure 3.12). Not only can these fuzzy logic models be linked to CAD software, but they can also be integrated into LCA tools, in order to ensure that environmental models are provided with fundamental information on the end-of-life behaviour of products (which include (i) physics and thermodynamics of separation processes, (ii) the quality and value of recyclates as a function of physical design choices (material combinations and connections) and (iii) physical separation and metallurgical and thermal processing technology on a statistical basis). This modelling originates from my detailed knowledge of artificial intelligence [80, 82, 89 and 91].

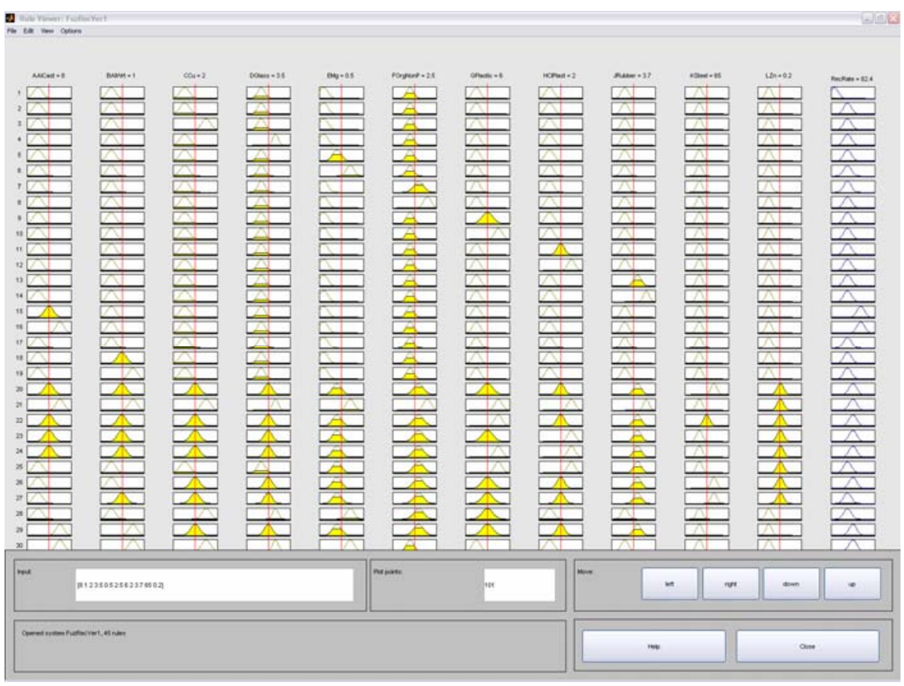


Fig: 3.12: Fuzzy logic model that includes all detail of the fundamental recycling model and statistics; which creates the link to the computer aided design model [This is being linked to CAD of the car industry www.superlightcar.com.].

3.4 A theoretical basis for Material and Metal Ecology

The theory summarized above and discussed in the various publications within Appendix E provides some fundamental basis for Material and Metal Ecology and hence for the metrics to measure the social, economic and environmental sustainability of our consumer society. Figure 3.13 summarises this i.e. application of material and metal ecology, in which fundamental models link material choices in product design to recycling and interconnected material cycles. This provides fundamental knowledge and data for environmental models (LCA and MFA), therefore linking the various disciplines related to the ecological value of materials in our society. It is still required to link these material and metal ecology models to the environment so that the effect of a product design on the environment can be directly determined. This would then constitute the final objective of true metal and material ecology in the present industrialized society. Figure 2.2 already shows a model that shows the way, however Figure 3.13 shows how the Metal Wheel (Figure 2.1) is linked to product design, hence how primary metal production is related to design and ultimately to product recycling. This is a key issue in controlling the anthropogenic material and metal cycle, ensuring that the interaction with the environmental cycles as shown in Figure 2.1 is minimized.

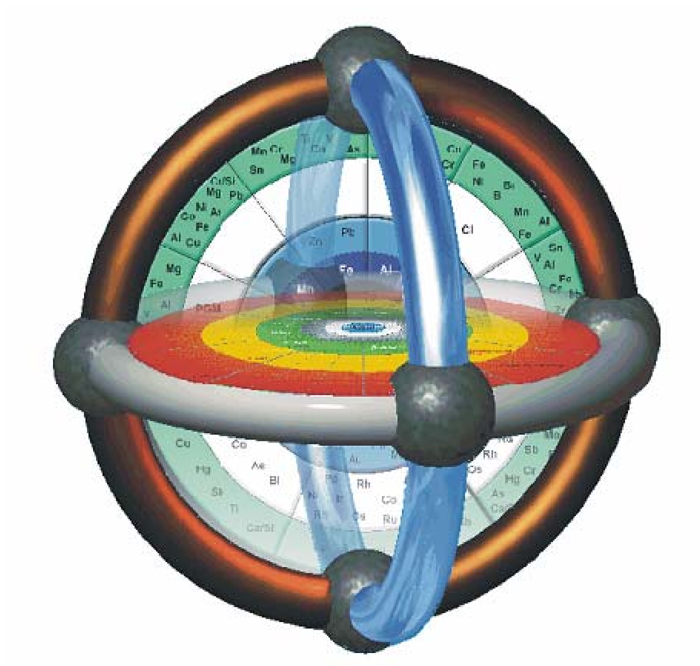


Fig. 3.12: The interlinked disciplines – applying fundamental models in order to link design to recycling and interconnected metal cycles providing fundamental knowledge and data to LCA based environmental models.

This rigorous modelling of recycling systems reveals the limits of recycling systems on a first principles basis [28], the key message of this dissertation. This fundamental basis was shown to be rigorous enough to be linked to the design tools of the automotive industry [www.superlightcar.com].

Chapter 4

From Theory to Practice

Closing the material and metal cycle is not possible without a thorough knowledge of the technology that creates and recycles the metals and materials used in consumer products. Not only does this require a good fundamental description and understanding of the technology but it also requires sufficient measured data to calibrate models and also to predict environmental performance. This chapter shows that the principles of process engineering have an important and necessary role to play within any sustainability discussion. It is also crucial to understand the bigger system in which this technology is residing of which process control is a fundamental ingredient. High temperature process reactors will be the focus of the discussion since it is conjectured that these are crucial for closing of the material cycle – they are the closers of the material cycle. Pyrometallurgical reactors facilitate sustainability in metals and materials processing [2, 7 and 14].

The developed systems theory as described in the previous chapter provides a fundamental basis for proper collection of data, supported by a good mass balance based on data reconciliation, and the corresponding statistics and how this should be performed when carrying out experiments or auditing a plant. This theory is essential to characterise and control the material and element flows in recycling plants and through the complete recycling and metal and material processing system. This is extremely important for good metal/material accounting, the calculations of recycling rate on a sound statistical basis, as well as quality control of recycling streams. In fact this is the basis of any meaningful discussion on material and metal ecology. It should also, in fact, be the only basis on which to argue environmental legislation.

Experimental and industrial data on the composition of the car, the separation efficiency of the various processes, liberation and particle size reduction in the shredder, the quality (or grade) of the recycling (intermediate) material streams are typical of the information that becomes available as a result of good understanding of the theory of recycling and metallurgy as discussed in Chapter 3. Furthermore, the collection of industrial data on recycling based on best available technology is essential to predict and calculate the recyclability of consumer products, using the developed system models. This is of extreme importance for a realistic definition of the type approval and end-of-life legislation of vehicles or any other consumer product. This type of data hence underpins the viability of Metal and Material ecology.

The theory is applied to provide a procedural basis from which the recycling rate can be calculated from an industrial experiment, in which 1153 end-of-life vehicles were recycled, the largest in the world to date. This experiment was executed at a large scale industrial recycling plant and clearly illustrates how statistically sound recycling rates can and therefore should be calculated from data collected from recycling experiments based on the developed theory and classical sampling theory and statistics.

This work was done for the automotive industry and some information is provided in the first pages of a report placed in the collection of papers [14, 15].

4.1 Practical procedures for recycling 1153 ELVs

Mass balances of plants based on measured data mostly do not close due to inevitable weighing and sampling errors, as is also the case for the shredding and PST trial as discussed here. Data reconciliation has been applied to close total and element/compound mass balances over the plant and its unit operations. A large body of data renders the mass balance more accurate and makes it possible to calculate the recovery and grade for each of the different materials over the various process steps. The data are used to calibrate the models in the optimisation and dynamic models mentioned above. Classical sampling theory has been applied to calculate statistically correct sample sizes for analyses of the various material flows throughout the plant (see Figure 4.1). The mass flows and composition of the streams were measured and analysed over all unit operations in the plant, i.e. on the input, intermediate and output streams, in order to increase the amount of data available for data reconciliation, which increases the accuracy of the mass balance and its statistics [36, 43].

4.1.2 Calculation of recycling/recovery rate

Based on the mass balance and its statistics, the recycling rate of end-of-life vehicles based on the discussed test could be calculated for best available technology as shown in Figure 4.1. For the first time a test was therefore concluded in which the recycling rate was calculated within a statistical framework, crucial to proving the validity of the recycling rate calculation. Ultimately the recycling rate is determined by the possibility of the market to absorb the produced output streams (either for direct application or in metallurgical or thermal processes) and is therefore determined by the quality of the recycling (intermediate) products as well as by the geographic location of the plant (due to local environmental legislation).

4.1.3 Statistical approaches to measuring recycling rates

Only data reported within a statistical and theoretical framework can have a legal basis and can find their way into design software for cars in order to perform Design for Recycling and hence real Metal and Material Ecology on a large industrial scale. Moreover the statistics around the calculation of the recycling rate based on plant data indicates that the (calculations for the) recycling rates and requirements for type-approval of cars as imposed by legislation in Europe should also be based on a statistical basis and are meaningless if represented by a single value as is required at the moment. Any methodology to assess end-of-life systems has to take into account the statistics of design and end-of-life technology.

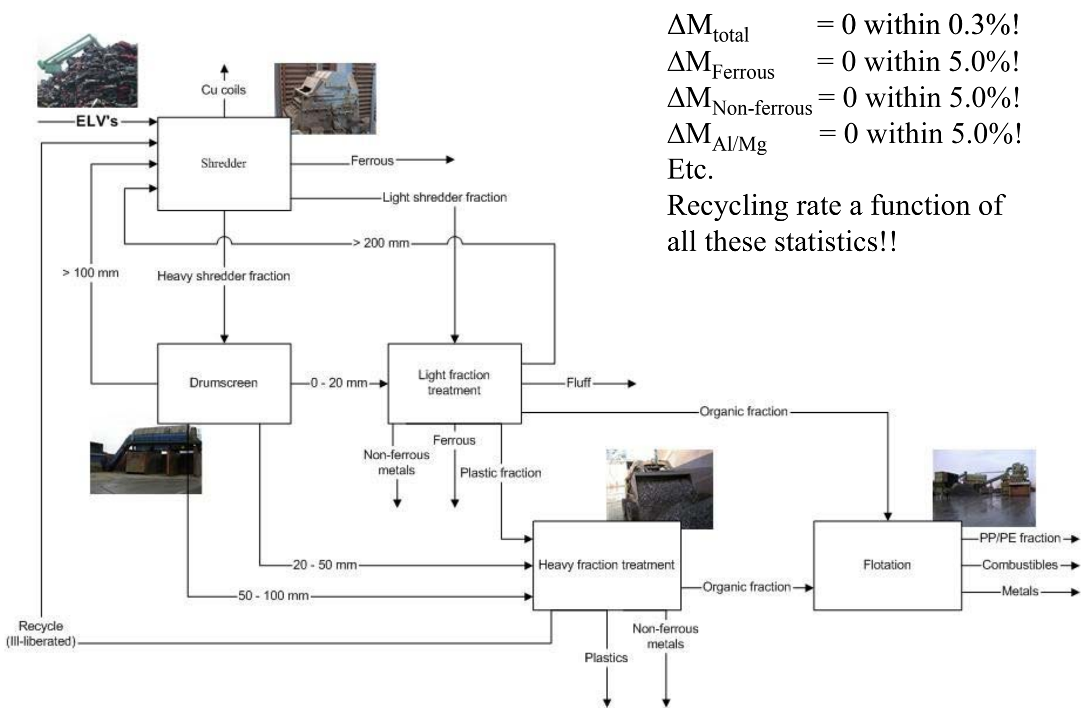


Fig. 4.1: A simplified flowsheet of the shredding and Post Shredding Technology (PST) plant at Comet Sambre, Belgium [36, 43].

4.2 Metallurgical reactors - closers of the material cycle

A topic of my keynote lectures [7-9] has in some instances been to show how metallurgical reactors play a key role in closing the material cycle. For these reactors to optimally do this one requires a thorough knowledge of metallurgical process engineering and technology as well as the associated knowledge of thermodynamics. At the same time process control is a key to achieving optimal reactor performance, minimal energy consumption, minimal residue creation, maximal production of metal.

Over the years I always had some activities in hydrometallurgy [70, 72 and 77], which permitted me to also consider hydrometallurgical projects to solve certain waste problems in the metallurgical industry.

If one considers the flow sheet (Figure 3.8) for the recycle of end-of-life products (e.g. cars), it is clear that metallurgy does play a significant role, also to an extent end-of-pipe solutions to waste abatement. Therefore, in order to be able to produce optimal system models for the recycling chain, detail process and fundamental knowledge of metal processing is required. This section will discuss various activities that support and provide detail to the system models for recycling and design for recycling. Without this knowledge endeavours into quantifying the sustainability of metal production, recycling and product manufacture could be dangerous.

4.2.1 High temperature reactor process development and modelling

It is clear from the discussion so far that high temperature reactors are a key to closing of metal and material cycles [7-9]. The following summarizes some of this work; much of this work is to be found in confidential reports, master theses as well as numerous conference proceedings publications with the various companies listed in Appendix C. In the following an excerpt is given.

- A complete flow sheet was developed for the production of ferro-niobium from the slag of Baotou (China), together with the company Lurgi (Germany – now Outokumpu, Finland). This process involved pre-reduction of pellets and subsequent smelting in an arc-furnace. Tests were performed in lab-scale furnaces, bench-scale rotary kilns, induction furnaces as well as on pilot scale in a 300kW plasma furnace [86]. It was possible to create FeNb from the slag by this process.

- In addition to investigations into the production of ferro-alloys, I conducted investigations on the recovery of metals from sulphide ores e.g. molybdenum from its sulphide ores [62].

- A large body of work was done on submerged arc furnaces for the production of ferro-alloys [2]. The ideas for a large body of this works started while working at Mintek and observing how difficult it is to model these furnaces [also see list of publications in Appendix B]. Much of this work originated from the observations I published [75] observing that the operation of the furnace can be divided into a equilibrium part and a dynamic part [also see 2].

    - An intelligent decision support system (Furnstar^{TM}) was developed for ferro-alloy submerged arc furnaces, while the author was at Mintek (South Africa) [2, 80]. It supports the low-level control of the Minstral^{TM} electrode control system, installed internationally on FeCr, FeMn, FeSi, Si, CaC_2 furnaces [82].

    - Over a period of 9 years various modelling and experimental work was and still is being done on the optimization of the three 60MW phosphorous submerged arc furnaces at Thermphos International (The Netherlands) [21, 26].

    - Various modelling activities have also been done on FeCr furnaces submerged arc and plasma furnaces, which included fundamental slag chemistry [65], solid state reduction of chromite [102] as well as identifying the variability within various FeCr furnaces [22, 63 and 103].

    - The various transport properties within the submerged arc furnaces were analyzed for ferro-chrome production furnaces in view of simulating these [101].

- Various projects were done for Corus plc, IJmuiden, The Netherlands *(some of these papers have been added in Appendix E for information and details but also consult appendix B to get a true overview of all the work done)*:

    - modelling and control of the blast furnace to predict ahead silicon and sulphur concentration in pig iron as a function of furnace operation [see MSc projects and various conference papers (Appendix B) - Little of this work is published due to the confidential nature of the work.],

    - fundamental work was done to understand the stochastic flow of slag and metal through the carbon bed within the blast furnace [34, numerous MSc theses],

    - simulation work showing the flow modelling that has been performed in the hearth of the blast furnaces at Corus (IJmuiden) [105, 106 and numerous MSc theses], and

    - also the heat treatment of long steel products was investigated [53].

- As a part of the Hydrogen Economy project in The Netherlands we investigated the use of hydrogen in metallurgy. Since the blast furnace is a large producer of CO_2 the use of hydrogen could reduce this emission. We started creating a model for the smart design of iron ore pellets to be able to theoretically predict their behaviour as a function of new gas compositions in the blast furnace, which could include higher hydrogen concentrations in future [20, 27].

- A range of other metallurgical furnaces have been modelled and simulated for various companies including the Outokumpu furnace, a tin smelter, Imperial Smelting Furnace [35], to mention a few [see details of various publications in Appendix B].

- The modelling and simulation of the chemical waste incineration furnace at the Afval Verbranding Rijnmond (AVR), Rotterdam, The Netherlands, has been an intensive activity over the last number of years. The main objective of all this work was to lengthen the refractory life as well as to ensure that the off-gas composition was within the limits as required by legislation

    - Combustion behaviour was modelled inside the kiln as well as the incineration of chemical waste [32, 61], and

    - Controlling the combustion within the kiln [56].

- Understanding the aluminium losses during melting and refining of aluminium scrap, has been a long activity with the company Konzelmann (Hannover, Germany). The work ranged from experimental work in the laboratory:

    - measuring the loss of metal in salt slags as a function of molten salt properties [16],

    - investigation of environmental issues of salt slags [33], and

    - modelling the recovery aluminium as a function of different scrap types [63],

  to data driven modelling on the industrial plant [39] and subsequently computational fluid dynamic modelling of the heat flow within the rotary furnace [25, 99]. Also data collection of aluminium of buildings in Europe was done to estimate the scrap inventory within the built environment [41].

- In addition to the recycling of aluminium, work is being performed on the recycling of magnesium [95] as well as EoL consumer products such as laptops [98].

- A unique approach was followed when modelling the Isasmelter of Umicore (Hoboken, Belgium) in that classical process modelling techniques were linked to environmental impact assessment [18]. This approach was followed to assess the environmental impact of the pre-processing intensity of electronic scrap on the environmental performance of the Isasmelter. Classical thermodynamics and dynamic modelling were linked in the Ausmelt reactor at Impala Platinum (South Africa) to predict the matte composition in the reactor [64], the idea originating from the observations I made in reference [75], also gleaning from the approach of using neural nets to approximate thermodynamic data by the use of neural nets [88, 89: at the time the first paper in metallurgy to use neural nets!].

- Various projects were completed in the modelling of ill-defined metallurgical reactors. Some of this theory eventually was used, for example, to model and control submerged arc furnaces. This work included the following:

- In the early days of neural net technology the author applied these techniques in modelling various processes within metallurgy. The first paper to integrate thermodynamics into this neural net technology was published in 1992 [89] and the first to approximate kinetics with neural nets in 1993 [87]. This was followed by various applications [64, 82 and 86].
- These techniques were integrated into reactor kinetic and dynamic modelling as well as reactor diagnosis [73, 88 and 91-92].
- Diagnosis of reactor operation by the use of artificial intelligence techniques [35].

4.2.2 Furnace process control

The author was invited to write the metallurgical process control chapter in Smithells Metals Reference Book (8th Edition) [2, 80 and 82].

Most of the modelling and simulation work mentioned above found its way into the control strategy of the furnaces discussed [2]. It is one of the reasons for doing this type of work. Notable was the work on the Minstral/Furnstar™ controller [80, 82], which was installed on submerged-arc furnaces. The work on the phosphorous submerged-arc furnaces as well as the aluminium rotary furnaces has led to improved control and production. Some aspects can be mentioned here:

- Artificial intelligence modelling tools have been integrated and combined with dynamic process modelling and computational fluid dynamic simulation tools to improve the control of a range of furnaces as discussed under section 4.2.1. Most notably are the submerged arc furnaces for ferro-chrome production [80, 104] as well as thermal phosphorous production [21].
- The Imperial Smelting furnace has been modelled in order to stabilise the furnace operation, which is rendered rather dynamic due to the fast changing and varied feed compositions of various waste materials [see various publications in Appendix B, e.g. 72].
- The ISA smelting furnace for the recycling of electronic waste is crucial within the complete recycling system. Work done with Umicore integrated environmental impact scoring with the process control of the furnace to show under which conditions the furnace is running optimally, not only economically, but also environmentally.
- Work on the modelling of the Outokumpu flash furnace at the Norddeutsche Affinerie (Hamburg, Germany) led to the installation of a plant wide process control system [e.g. 129 in Appendix B].

4.2.3 New metal production technology

The author has been involved in the development of new technology of which three can be mentioned here.

- The first involved the investigation of an Al_2S_3 route for the production of aluminium, which could show a 30% reduction in energy consumption [40]. A world-wide patent had been submitted by Corus (IJmuiden, The Netherlands) for this process for which the author is a co-inventor [51].

- The electrolysis of zinc from zinc chloride molten salt has also been investigated together with industry [50, 76] as an alternative to the classical hydrometallurgical route.

- Magnesium is an element that negatively influences the electrolysis of zinc from zinc sulphate solutions. Membrane and electrodialysis technology was developed by my student to remove this from zinc sulphate electrolytes to produce a more manageable residue [49, 52, 67 and 71].

4.2.4 Waste abatement technology

High pressure reactor technology reaching supercritical conditions have been applied to treat heavy metal containing organic materials and waste streams. These end-of-pipe solutions included:

- Waste organic materials have been mixed with heavy metal containing solutions for example to create copper metal from effluents from the electronic printing plate industry [59, 74]. It could be shown that micron sized copper powder could be created with a very narrow particles size distribution and good shape factor.

- Arsenic is a major by-product of any sulphide base metal smelter. The processing of arsenic containing materials at supercritical temperatures has been the object of a number of studies with the company Ceramic Oxides International BV (The Netherlands) to produce crystalline products [57, 66 and 68]. This work is important especially in view of all sulphide ores containing arsenic, which creates an environmental hazard in many cases. A precipitated crystalline iron arsenate is the most stable form into which arsenic can be precipitated.

- The recovery of molybdenum from effluent streams from chemical companies is an issue [45]. This residue is created due to catalysts reporting in low molybdenum concentrations during polymerization reactions to the watery effluent stream.

4.3 Design for Recycling

With all the detail of the reactor technology discussed above, as well as a thorough understanding of the thermodynamics, kinetics and technology of waste abatement, it is possible to create sufficiently accurate system models that predict the recycling performance of the complete system.

In other words, it is impossible to create suitable design for recycling and sustainability tools if all the above knowledge is not known and integrated within the models that predict recycling, sustainability, environmental performance!

An important outcome of all the work discussed in this dissertation is that it is being applied to predict the recyclability of newly designed super light cars on a first principles basis. This is an important step into the model-based sustainable design of products, which the automobile industry has realized and has taken up into their design strategies.

Fig. 4.2: All the companies involved in the design of a super light car.

Our first principles approaches are the only way to continue to evaluate environmental impact of product designs, especially in view of incorporating first principles into the predictions of environmental outcomes. The less rigorous environmental impact methodologies cannot do this [55].

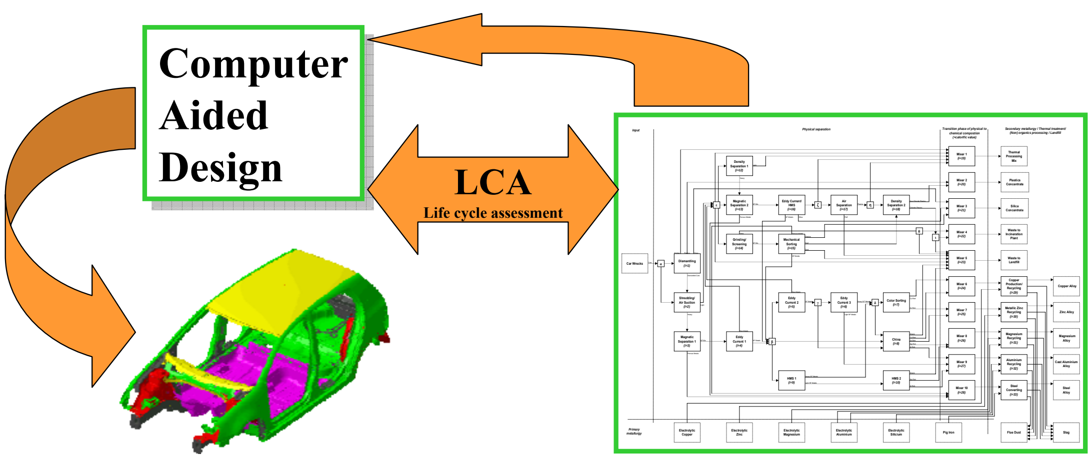


Fig. 4.3: Our contribution into the design of a super light car viz. the module that calculates the recyclability of newly designed automobiles. This is being integrated into the computer aided design software of the automotive industry (Figure 3.8 connected to computer aided design).

4.4 Significance of contribution

This chapter clearly shows one simple fact: If environmental impact modelling and simulation is going to have any technological meaning, one has to include sufficiently detailed and fundamental understanding of the complete material cycle, its technology and the manufacturing industry into these. This requires that all stakeholders should work very closely together to realize this!

Above all, it requires a detailed understanding of all the technology, thermodynamics, physics of all the reactors and the system depicted by Figure 3.8 and integrates this into CAD as shown by Figure 4.3. This is a rather significant contribution, at the moment being implemented in industry in the www.superlightcar.com EU project.

Similar principles and approaches are implemented to optimize a WEEE recycling system of a particular European country as well as evaluate optimal water recycling strategies for water boards.

Chapter 5

Society and Legislation

Engineering has always had a strong societal role and impact. The present global situation requires more than ever a leading role from Engineers by the application of their unique design skills and engineering approach to the creation of technology but also the strong practical problem solving abilities to solve the daunting problems ahead of us. European legislation plays an important role in recycling, environmental control etc., contributing to rendering our future more sustainable. Engineers can contribute significantly to this debate, enhancing the quality of the legislation, identifying its flaws and subsequently assisting in the creation of legislation that inherently contribute and enhance sustainability. This chapter discusses a few contributions of the author in this regard.

The work discussed in this dissertation provides fundamentally based approaches to questions of crucial importance to the industry and environmentalists such as the magnitude of the legally required recycling rate of presently designed products, emissions of processes and end-of-life products to nature, environmental performance of processing technology, etc. This approach is being adopted by the automobile industry to ensure among others that recycling rates have the fundamental basis that challenges, but also provides the legal basis for recycling legislation. It can also provide the basis for risk analyses for new car designs.

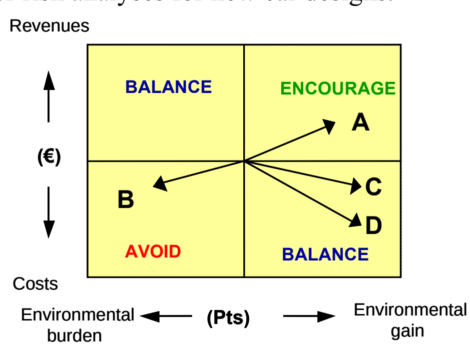


Fig 5.1: Metallurgic, recycling system and product design will in future measure all activities into the metrics shown in the figure – all metrics will be reduced to simple numbers, which are based on detailed models as discussed in this dissertation.

5.1 Underpinning legislation by first principles modelling

Any evaluation of the economic and/or environmental consequences and calculation of environmental scores of material applications can only be conducted if the interconnectivity of material/metal cycles is recognized and recycling rate calculations are based on fundamental recycling models. The model structure should be linkable to CAD product design activities, material choices, joints, etc. This is not possible with a life cycle assessment approach on its own, since it is not a simulation or predictive tool, it only represents the present and does not give technological advice about the future, how technology should be controlled and adapted, how the physical design of products have to be changed to ensure that economic recyclates can be created. The author has argued in various documents, keynote lectures, papers as well as work on a European Union level for this:

- In the largest recycling experiment for automobiles to date it was shown how recycling rates should be determined, measured, calculated and how the system should be monitored [14-15, 36 and 43].

- The author was involved in a stakeholder discussion on the modification of the EU legislation on the recycling of automobiles in Brussels. This included representatives from the automotive industry, recyclers, environmentalists etc. The complete report (written by Bill Duncan in which our work is cited) is given in Appendix D [13], which shows that our work has flown into it, using our conclusions given in the many papers cited above.

- A key message that has been given in various papers is the importance of understanding the process technology within the recycling system. It is key for engineers to be part of this legislative and political discussion, bringing into it the rigorous engineering and technological method [13, 24].

- An objective of all this work is for engineers to keep society informed so that clarity exists (Figure 5.2)! For this reason papers such as Reuter *et al.* [28] questioning recycling rate calculations or the paper by Reuter and van Schaik [24] that shows that recycling legislation violates thermodynamic laws are of extreme importance. These papers have been written and published in trade journals not generally highly regarded by the academic community. These articles are, however, of crucial importance to inform general public.

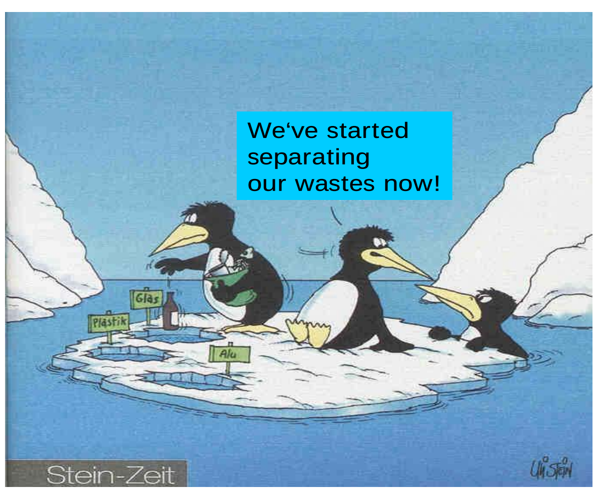


Fig. 5.2: Waste management?

5.2 Societal impact of this work

It is clear that recycling plays a crucial part in the complete resource cycle. Not only does it save primary mineral resources but it also decreases the energy consumption per ton of produced metal.

In a future which will be marked by ever increasing oil and energy prices recycling will play an extremely important role due to the large saving in energy that are achieved during recycling. Recycling technology will come of age, it will move in general to more sophisticated sorting technology as depicted by Figure 5.3 since material and metal prices will permit this.

Fig. 5.3: Recycling by hand or automatically by Laser Induced Breakdown Spectroscopy (LIBS)?

Only those companies that control the complete material and metal cycle will in future survive i.e. companies that have as their mission to take part in the complete cycle as depicted in Figure 1.2. Resource companies will probably in the short term make money due to increase in the resource prices but their linear product portfolio i.e. mine to mill, or well to refinery is inherently not sustainable and will in the long term not survive in their present structure.

Acknowledging the fact that metals and their associated Industrial Ecology are probably presently the only anthropogenic system that can hesitantly be labelled “sustainable” opens very attractive perspectives for resource and metal producing companies. A rethink and shift in resource company vision will contribute significantly to ensuring a sustainable future for the planet!

The resource companies are excellently positioned to contribute significantly to the “sustainability” discussion since metals have the unique property that they are atoms which can be recycled indefinitely.

In summary, there is no time left to delay research and development work that has a significant positive environmental impact, or that comes to the benefit of the tax payers who are paying for publicly funded research!

Chapter 6

Summary

The author's work discussed in this dissertation provides a framework to define Material and Metal Ecology, elucidating the limits of recycling on a first principles basis. On this basis the following may be asserted and/or demonstrated:

- Only a thorough technological as well as fundamental knowledge of the physics and thermodynamics of the recycling system permits the quantification of the limits of recycling! Through this a fundamental basis is created for the formulation of environmental legislation for the process industry, while it also improves and underpins recycling legislation.

- System modelling should be developed for the large material and metal processing systems to ensure global optima are obtained. This would ensure that sub-system optimization is not a goal, since this does not ensure sustainability!

- The fundamental nature of the developed recycling models for interconnected metals and materials render these generic so that they can be applied for various product categories and applications, for example the models are being applied by the authors for the recycling of waste electric and electronic equipment (WEEE) as well as for other waste/material systems such as recycling of automobiles.

- Fundamental recycling models (developed on a statistical basis) are linked to environmental LCA tools/software in order to provide a fundamental technological and a statistical basis for the calculations of recycling rates, prediction of quality of recyclates, the process operation, recycling system architecture, as well as environmental impact. All environmental models should in future be underpinned by the developed rigorous process models to be of any use in the future.

- A fundamental/technological basis for real Design for Recycling guidelines is provided; including the influence of material combinations and connections, liberation, particle size and physical/chemical/thermodynamic process efficiency on the quality of recyclates and the maximum achievable recycling rate. This therefore improves significantly on the present rather fuzzy design for recycling methodologies. Thus, these models support Eco-design by providing fundamental knowledge on recycling systems and design for recycling. Fuzzy logic models are derived from our complex recycling models. These map fundamental recycling models and link these on a simplified (but rigorous) basis to design tools and material choices. This rigorous basis is the future of Design for Recycling!

- Process control of recycling and metallurgical companies should be optimal to ensure that technology within the cycle is optimally operated, creating minimal waste, minimize energy consumption, maximize metal and material recovery throughout the complete system.

- All this work gives some basis for the formulation of Metrics of Sustainability by the inclusion of engineering methodology and first principles. It is creating a fundamental basis to define and realise material and metal ecology. Fundamental knowledge of technology must be available, and must be integrated into the cycle of metals and materials thinking in order to reach sustainability.

- Companies that incorporate the large recycling picture (Figure 1.2) will most likely survive in the long term. They will be able to manage the supply and demand of raw materials and balance this with recycling since they will have in their portfolio iron ore mines, coking coal, blast furnaces, converters and arc furnaces that also process recycled scrap. Furthermore, these companies are usually also closely associated with the OEMs. This strategy will become especially relevant if energy prices are high. Hence, it will be envisaged that steel companies will only become larger, especially also to counter the impact of the Chinese market.

In summary, it is presently extremely urgent to conduct research and development work that does have a significant positive environmental impact. It is our task as academics and engineers to do this research and development work for the benefit of Mother Earth, Mankind and for the tax payers who are paying for publicly funded research. In the end more so for our Children and I refer the reader back to the message in the Preface:

"We do not inherit the Earth from our Ancestors; we borrow it from our Children"

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Appendix A

Curriculum Vitae

Markus A. Reuter (1959) is a professor of Sustainable Technology at the University of Melbourne (UoM) in Australia. He received his B. Eng. at the Department of Chemical Engineering, M. Eng. and PhD. at the Department of Metallurgical Engineering, University of Stellenbosch, South Africa. In 1994 he obtained his Dr. habil. at the Aachen University of Technology (RWTH-Aachen, Germany) for which he was awarded the "Friedrich Wilhelm Prize".

He has worked as a senior lecturer at the University of Stellenbosch, in the Measurement and Control Division as group leader, Mintek, Randburg, South Africa, also for Anglo American Corporation in South Africa. Until June 2005 he was Professor at the Delft University of Technology, his group rated "Excellent" by an international visitation commission organised by the Dutch Government Committee for Universities in 2002, a level bestowed on ca. 10% of professors in The Netherlands.

He has written 1 book, (co-)authored over 114 publications in refereed international journals and over 149 publications in International Conference Proceedings. He has also (co-)authored various chapters in encyclopaedias (e.g. Ullmann's Encyclopaedia of Industrial Chemistry, and the Control Chapter in Smithells Metal Reference Book *(8th Edition)*) and books in metallurgical engineering (14). He has presented over 200 plenary, keynote, invited and major conference papers as well as lecturer for the International Zinc Association's (Brussels) "Zinc College". *(Total publications ca. 270)*

He serves on the editorial board of three journals: Minerals Engineering, IChemE Journal (Sustainability) and Erzmetall. He has served on various technical and scientific advisory boards of conferences and was Chairman of TMS' Lead Zinc Committee.

He is a registered Professional Engineer (PE) in Engineering Council of South Africa (ECSA). Main areas of interest are process control in extractive metallurgy as well as associated environmental control; and system and design engineering. His over 104 master students and 16 PhD (+4 new in Melbourne) students are (have been) involved in projects with the metallurgical and recycling industries in Europe but also with the car industry (VW, Daimler, GM, Ford, Volvo) on issues related to linking car design (CAD) and recycling. He is also been involved in a workgroup at in Brussels on recycling legislation, projects relating to the recycling of electronic and electric (WEEE) goods recycling agency NVMP in The Netherlands. Also he is involved in a project in The Netherlands on predicting water quality for the water board.

At UoM he holds the Chair of "Sustainable Technology" from August 2005, a joint chair between civil and chemical engineering, with the objective to create course and research content in engineering that extends further than the boundaries of engineering. He will in December 2006 commence working for Ausmelt as Chief Executive Technologist while still being an adjunct professor at UoM.

Appendix B

Publications not cited in this dissertation are listed in this appendix, as well as publications submitted (these are added to show that the work is still continuing).

General book and seminar publications

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3. M.A. Reuter and W.L. Dalmijn (2001): Course notes for the recycling short course, Held at the CIM Annual Meeting, Toronto, Canada.
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164. W. van der Merwe, M.A. Reuter and J.S.J. van Deventer (1990): A Knowledge-Based System for the Simulation of Gold Leaching. Proceedings: Minerals Processing Conference CMMI, July 1990, Edinburgh, Scotland, pp. 147-160.

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166. D.J. Nieuwoudt, J.S.J. van Deventer, M.A. Reuter and V.E. Ross (1989): The Influence of Design Parameters on the Efficiency of Pyrite Flotation in Air-Sparged Hydrocyclones. Proceedings: International Symposium on The Developments in Froth Flotation, 3-4 August 1989, Gordon's Bay, South Africa.

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Appendix C

This appendix contains a list of the dissertations and theses (PhD and Master) the author has supervised as well as a list of the various companies the author has done projects for or that have sponsored the student PhD and Master projects.

Companies for which the author completed larger projects

Many of these companies also supported my MSc and PhD projects.

1. Arcelor *(France - Steel recycling)*,
2. AVR *(Netherlands-Waste processor in Rotterdam)*,
3. Auto Recycling Netherlands *(Netherlands - Car recycler)*,
4. Berzelius *(Stolberg, Germany - Lead),*
5. BHP-Billiton *(South Africa - Fe-alloys production)*,
6. Breda Water board *(The Netherlands - Water purification),*
7. Corus *(GB/NL – Steel production)*,
8. Ford *(USA)*,
9. Glencore *(Italy/Swiss-Zn/Pb - now Xtrata)*,
10. Kerr McGee *(USA - Titanium production)*,
11. Konzelmann *(Germany - Aluminium production)*,
12. Lurgi *(was in Germany),*
13. Norddeutsche Affinerie *(Germany – Cu production)*,
14. NVMP *(The Netherlands - WEEE recycler)*
15. Pasminco *(Australia – Zinc production - (now Zinifex))*,
16. Philips *(Netherlands - Consumer electronics producer)*,
17. Remag *(Germany – Magnesium production)*,
18. Ruhr Zinc *(Germany – Zinc production)*,
19. SMS DEMAG *(Germany - Metallurgical plant producer)*,
20. Sudamin Duisburg *(Germany - Zinc and lead recycler)*,
21. Thermphos *(Netherlands – Phosphorous)*,
22. Umicore *(Belgium - 24 metals)*,
23. Volkswagen, Fiat, Daimler, Volvo *(European Union - Car industry)*,
24. Wieland *(Ulm, Germany – Copper products), and*
25. Development / commercialisation / marketing / installation / servicing of process control equipment e.g. (i) Minstral control system for submerged arc furnaces in Zimbabwe, Australia, Tasmania, India and Brazil as well as (ii) process control in minerals processing *(Mintek, South Africa)*.

PhD and MSc theses completed under my supervision

PhD – projects

1. S. Sudhoelter: Optimisation of zinc metallurgy with a system model (Aachen, Germany - 1999).
2. D. Bernhard: Optimisation of a thixocasting machine (Aachen, Germany - 2000).
3. J. Booster: Magnesium removal in the electrolytic zinc industry (Pasminco/EET, Netherlands - 2003).
4. W. Husslage: Dynamic distributions: Sulphur transfer and flow in a high temperature packed coke bed (CORUS, Netherlands - 2004).
5. S. Lans: The limiting phenomena at the anode of the electrowinning of zinc from zinc chloride in a molten chloride electrolyte (Umicore, Belgium - 2004).
6. C. Mambote: Hydrothermal metallurgy: concept and case studies (Ceramics International, Netherlands - 2004).
7. A. van Schaik: The theory of recycling systems: Applied to car recycling; ("Smart Product Systems", Netherlands - 2004).
8. E. Verhoef: The Ecology of Metals ("Waste infrastructures", Netherlands - 2004).
9. B. Castro: Modelling for the liberation of materials from complex end-of-life products ("Smart Product Systems", Netherlands - 2004).
10. J. Eksteen: A generic, semi-empirical approach to the stochastic modelling of bath-type pyrometallurgical reactors (FeCr and Ti-slag, South Africa - 2004).
11. B. Zhou: Modelling the melting of post-consumer scrap within a rotary melting furnace for aluminium recycling (EET, Netherlands - 2005).
12. J. Post: Modelling of melt flow in the non-homogeneous coke-bed of a blast furnace hearth (CORUS, Netherlands - 2006).
13. E. Scheepers: CFD Modelling of a thermal phosphorus submerged-arc furnace (Thermphos, Netherlands - 2007).
14. G. Georgalli: Use of hydrogen for reduction in a hydrogen economy (EET, Netherlands - 2007).
15. O. Ognatenko: Physical and high temperature processing of the shredder waste fraction – development of a system model for Auto recycling Netherlands. (ARN, Netherlands - 2007).
16. C. Meeskers: Recycling of coated magnesium materials (Senter/Remag, Netherlands - 2008).
17. Georgie Mead: Environmental Performance Parameters (Orica, Australia).
18. Jill Fagan: System modelling of water systems (Australia).
19. Waven Zhou: Titanium production with molecular hydrogen (Australia).
20. B. Abedi Tari: Bubble bursting above molten metal baths in electric arc smelters (Smorgons, Australia).

MSc – titles of projects

21. B. Länger: Die Modellierung der Zinklaugung mit einem hybriden Expertensystem (Diplom thesis, RWTH-Aachen).
22. X. Xu: Extraktion von Niob aus Baotou Einsenerzkonzentraten bzw. niobangereicherten Zwischenprodukten ' (Diplom thesis, RWTH-Aachen).
23. G. Rombach: Untersuchungen zur Niobverteilung zwischen Einsenschlacken und Roheisen (Diplom thesis, RWTH-Aachen).

24. S. Sudhölter: Verfahrenstechnische Auswertung von Zinkgewinnungsanlagen (Diplom thesis, RWTH-Aachen).
25. W. van der Merwe: Knowledge based simulation of gold leaching processes (M.Sc., University of Stellenbosch, South Africa).
26. D. Niewoudt: Optimization of an airsparged hydrocyclone for the recovery of pyrite ores (M.Sc., University of Stellenbosch, South Africa).
27. B. Heinen: A soft sensor for estimating the production of P in a submerged arc furnace.
28. R.A. Devilee: Selective removal of iron contaminations from zinc chloride melts by cementation with zinc.
29. S. Lans: Sulfurization of aluminium (Fundamental study and Aspen modelling of proposed reactor).
30. J. Mahabir: Pressure precipitation of copper from copper sulphate solution with carbohydrates.
31. R. Ruitenberg: Fundamental research in leaching e.g. ferric leaching of arsenopyrite - kinetic and modelling studies in bioleach systems (project at the University of Cape Town).
32. Q. Wesseldijk: The Behaviour of Chromite in the Flotation of UG2 ore (project at the University of Cape Town).
33. B. van Dorp: Diagnostic leaching of arsenopyritic gold ores (project at the University of Stellenbosch).
34. A.S. Verburg: The simulation of the aluminium cycle.
35. F. Severens: The simulation of metal cycles for sustainable development of metals production on plan(e)t earth -Zn,Pb,Sn-.
36. J-P. van Hall: The simulation of metal cycles for sustainable development of metals production on plan(e)t earth -Cu-.
37. D.A. Wijmans: Synthesis and thermodynamical properties of pentlandite.
38. P. Ehren: Lithium recovery from brine (BHP).
39. C.M. Verbaan: Removal of cobalt and manganese from sulphate solutions by oxidative precipitation (McGill, Canada).
40. R. Kuivenhoven: Pressure precipitation of zinc from zinc sulphate solution with carbohydrates.
41. E. Zuidervaart: A study into the reasons behind the improved transfer of oxygen in aqueous slurries containing pyrite and quartz using air sparging.
42. K. Buist: Oxygen transfer in agitated silica and pyrite slurries.
43. R.A.G. Janssen: Control of Sn-furnace, Kayser Luenen (Germany).
44. R.A. Dumoulin: Distillation of Titanium Tetrachchloride ($TiCl_4$) (Kemira/Kerr Mc Gee, Netherlands).
45. M.K. Keegel: Project to optimise the $TiCl_4$ to TiO_2 burner (Kemira/Kerr Mc Gee, Netherlands).
46. A.J.W. de Jong: Modelling of the mass and heat transfer phenomena in the CCF Melt cyclone Hoogovens IJmuiden (Netherlands).
47. S. van der Born: Quality control system for a material separation process.
48. M. Kock: Effects of the reduction conditions on dilation during conversion of hematite to magnetite.
49. M.V. Pieterse: Is the pyrometallurgical recovery of inorganic material an option for automobile shredder residue?
50. L.N. de Boer: Image processing to control the eddy-current separator.
51. M. van Kesteren: Mass balance calculation of the Oxysteel process using statistical data manipulation for optimalisation of the COCON process model at Hoogovens (Netherlands).

52. J. Grimmelt: Influence of small amounts of galena on the flotation efficiency of sphalerite (Mc Gill) (Canada).
53. N: Jokanovic: Optimisation of protective slag layers on refractory linings in chemical waste incinerators (AVR-chemie) (Netherlands).
54. J.T. Maatman: Some aspects on the kinetics and mechanisms of the segregation process applied to nickel ferrite.
55. D. van der Pas: Reduction behaviour of pellets in a Phosphorus-furnace at Thermphos (Netherlands).
56. C. Dresen: Optimisation of pellet reduction in a phosphorus furnace at Thermphos (Netherlands).
57. D. Rabelink: Modelling of aluminium hydroxide precipitation–desilication reactions (Billiton) (Netherlands).
58. J.J. Pouw: Identification of temperature in the hearth at Hoogovens/Corus (Netherlands).
59. J.P. van Elten: Optimisation of Pyrohydrolysis at Nedmag Industries (Netherlands).
60. W. Verbeek: Production of Mn-steel using recycled batteries.
61. P.C. Kuiper: Immobilization of Metals in glass and ferrites.
62. H. Sasker: Improvements of the continuous crystallizer for lead processing – Bi removal (Germany).
63. M.A. Hoekstra: Final optimization of a process for the treatment of Cannington concentrates (BHP).
64. J. Rakhorst: Modelling of gas flow in the kiln of a chemical waste incinerator (AVR-chemie) (Netherlands).
65. P. Vonk: Optimisation of secondary aluminium smelting at BUS (Germany).
66. A.J.D. Albornoz: Combined Treatment of Metal (Cu,Ag) and Carbohydrate effluents in a plug flow Reactor and autoclave.
67. I.H. Bonekamp: Quantification of the dynamics of the flash smelter at the Nordeutsche Affinerie (Germany).
68. J.H. Groeneveld: Optimisation of feed chemistry of flash smelter at the Nordeutsche Affinerie (Germany).
69. T.J. Auping: Use of data reconciliation: A zinc plant case study (Ruhr Zinc, Germany).
70. E.A. van Dijk: Research on the influence of slag composition on the reduction rate of zinc-oxide in molten slags.
71. Bayirli: The conversion of MgF_2 to $Mg(OH)_2$ and its thermal decomposition.
72. P. Kengen: Toekomstige beschikbaatheid van staalschroot en de gevolgen voor CO_2-uitstoot bij staalproduksie.
73. B. de Monnink: Chlorination of Ti-Slags at Kerr Mc Gee (Netherlands).
74. W.T.C. Bos: Membrane technology in the cleaning of nitrate leach solutions.
75. C.J.C. Niewold: Study on agglomerate-strength to improve the permeability of a packed bed in a bioleaching operation (Chile).
76. Kroeze: Simulation of transient heating of metals in a heat treatment furnace.
77. D.T.M. Hartman: Simulation of heat transfer inside a rotary kiln waste incinerator at AVR-Chemie (Netherlands).
78. V. Salet: Steady state mass and energy balance of the rotary furnace (Konzelmann, Germany).
79. J.C. Schouten: Factors affecting the CO/CO_2-ratio during the carbo-chlorination of titanium dioxide ores (Kerr McGee - Netherlands).
80. M. de Ouden: Good data: the key to good modelling (Corus, Netherlands).
81. H. van Gelder: Electrode design in a new molten salt process (Belgium-Umicore).

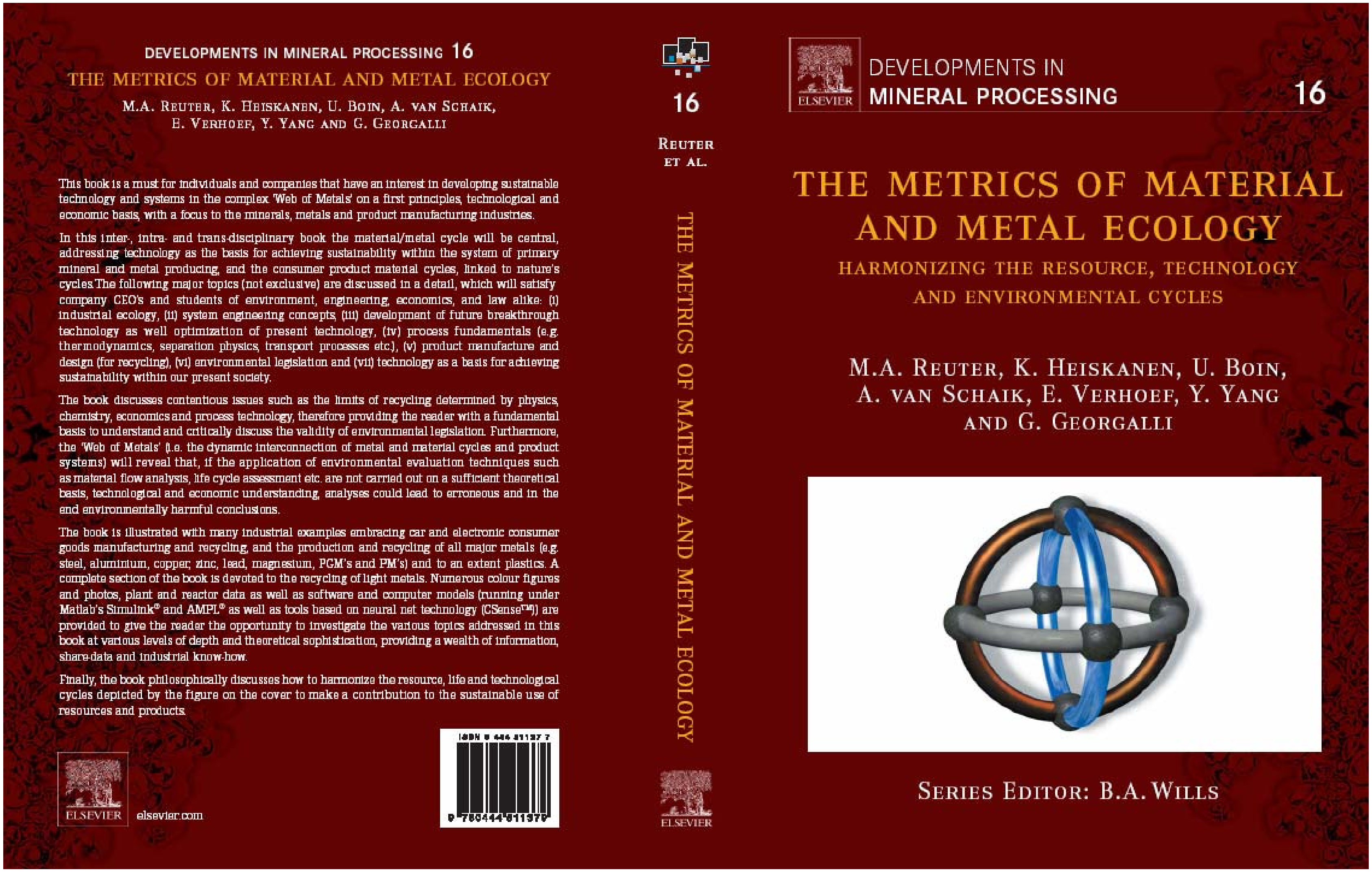
82. F.A. Kamminga: Analysis of an aluminium scrap block (Konzelmann, Germany).
83. Fabiano Maraspin: Il Recupero Dei Metalli non Ferrosi con un separatore a correnti parassite.
84. J.L. Sepúlveda: Copper (II) reduction with carbohydrates from copper sulfate solutions in an autoclave.
85. R.S. Sewdajal: The Solution of Zinc in mixtures of Zinc Chloride with Alkali Chlorides.
86. E. Janson: Optimization of an Industrial Chlorinator at Kerr Mc Gee (Netherlands).
87. M. Doctor: The effect of mineralogy and feed mixing on the Cd-content of Imperial Smelter Sinter at Glencore. Cadmium elimination in lead-zinc sintering (Italy).
88. B.R. Mulderij: Hot model simulation of slag flow in the dropping zone of the blast furnace at (Corus, Netherlands).
89. D. Vera: Simulatie van stroming in de druppelzone van de hoogoven met behulp van een koud model (Corus, Netherlands).
90. M. Pijnenborg: Combustion modelling of a hazardous waste incinerator at AVR-chemie (Netherlands).
91. S. Mareck: Recycling of Automotive Aluminium Application (Germany).
92. H. Oterdoom: From Data to information (Demag, Germany).
93. de Jong: Feasibility study for the application of a data driven model on the Imperial Smelting Furnace at M.I.M. Hüttenwerke Duisburg (Germany).
94. A. Scholte: Static and Dynamic Modelling of Metal Life Cycles (NL-Philips).
95. P. Haeser: Dry Magnus Separation: The modelling, construction and testing of a dry Magnus pilot separator.
96. D.I. de la Fuente: Purification of Zinc-Sodium-Potassium chloride melt in zinc production - removal of copper.
97. H.J.M. Krevel: De invloed van kalium op het sintergedrag van synthetische hematiet.
98. I.W. Schaap: Investigation into the application of the extractant SBX-50 in a process modification in the RLE of Zn.
99. R. de Jong: Simulation of transient heating of dredging pumps and fans.
100. J. Soons: Sulfidation of Al_2O_3 with CS_2 (Corus, Netherlands).
101. J. Bohte: The possibilities of electrowinning Al from Al_2S_3 (Corus, Netherlands).
102. G.A. Schrader: Development and Testing of an electrodialysis reactor with soluble Zinc anode (Netherlands).
103. A. van Heukelem: Modelling of an Isasmelt reactor for the recycling of electronic goods (Belgium).
104. J. Dunselman: A dynamic model for the blast furnace (Corus, Netherlands).
105. Nijssen: The modelling of an imperial smelting process (Duisburg, Sudamin, Germany).
106. C. Meeskers: A mineralogical study of sinters for the blast furnace (Corus, Netherlands).
107. H. van Kooten: Optimization of metal recovery from an aluminium salt slag (Konzelmann, Germany)
108. J. Vandenhoek: Fundamental study into the flouride slag attack to refractories in aluminium recycling furnaces (Konzelmann, Germany).
109. R. Monis: Bubble formation around an anode within $ZnCl_2$ fused salt electrolysis.
110. S. Steeneken: Metal recovery for magnesium scrap – experimental study (Remag, Netherlands).
111. R. Losenoord: WU model for the blast furnace (Corus, Netherlands).
112. A. Hogervoorst: Characterization of coke within the blast furnace (Corus, Netherlands).

113. A.T. Adema: A Dynamic-CFD hybrid model of a submerged arc furnace for phosphorus production (Thermphos, Netherlands).
114. A. Richard: A comparison of the modelling of comminution and liberation in minerals processing and shredding of cars.
115. M. Goense: Measurement of the activities of minor metals in salt slags for Mg production.
116. J. Sernee: The estimation of the distribution of the product quality by the use of stochastic modelling (Konzelmann, Germany).
117. M.S. Ijsselstijn: The liberation of metals during shredding.
118. A. Meskers: Characterization of hazardous components in the end-of-life notebook displays.
119. G.J. de Haan: Fundamental limits of the recycling of cars.
120. V. Roode: Minimizing dross formation on a recycling plant – a theoretical and industrial study (Konzelmann, Germany).
121. M. Mooij: Separation of particles by shape.
122. E. Bakker: Locating and recovering high value components from mother boards.
123. M. Gadziala: Exergy analysis of recycling systems for cars.

Appendix D

This appendix provides an electronic “pdf” copy of the book I prepared in TEX *(Please refer to the CD attached to the inside of the back cover of this dissertation.)*.

Note: *The copyright of this book remains with Elsevier, however, it is provided here so that the reader can get a detailed overview of the work discussed in this dissertation.*


DEVELOPMENTS IN MINERAL PROCESSING 16
THE METRICS OF MATERIAL AND METAL ECOLOGY
M.A. REUTER, K. HEISKANEN, U. BOIN, A. VAN SCHAIK, E. VERHOEF, Y. YANG AND G. GEORGALLI
This book is a must for individuals and companies that have an interest in developing sustainable technology and systems in the complex 'Web of Metals' on a first principles, technological and economic basis, with a focus to the minerals, metals and product manufacturing industries.
In this inter-, intra- and trans-disciplinary book the material/metal cycle will be central, addressing technology as the basis for achieving sustainability within the system of primary mineral and metal producing, and the consumer product material cycles, linked to nature's cycles. The following major topics (not exclusive) are discussed in a detail, which will satisfy company CEO's and students of environment, engineering, economics, and law alike: (i) industrial ecology, (ii) system engineering concepts, (iii) development of future breakthrough technology as well optimization of present technology, (iv) process fundamentals (e.g. thermodynamics, separation physics, transport processes etc.), (v) product manufacture and design (for recycling), (vi) environmental legislation and (vii) technology as a basis for achieving sustainability within our present society.
The book discusses contentious issues such as the limits of recycling determined by physics, chemistry, economics and process technology, therefore providing the reader with a fundamental basis to understand and critically discuss the validity of environmental legislation. Furthermore, the 'Web of Metals' (i.e. the dynamic interconnection of metal and material cycles and product systems) will reveal that, if the application of environmental evaluation techniques such as material flow analysis, life cycle assessment etc. are not carried out on a sufficient theoretical basis, technological and economic understanding, analyses could lead to erroneous and in the end environmentally harmful conclusions.
The book is illustrated with many industrial examples embracing car and electronic consumer goods manufacturing and recycling, and the production and recycling of all major metals (e.g. steel, aluminium, copper, zinc, lead, magnesium, PGM's and PM's) and to an extent plastics. A complete section of the book is devoted to the recycling of light metals. Numerous colour figures and photos, plant and reactor data as well as software and computer models (running under Matlab's Simulink® and AMPL® as well as tools based on neural net technology (CSense™)) are provided to give the reader the opportunity to investigate the various topics addressed in this book at various levels of depth and theoretical sophistication, providing a wealth of information, share-data and industrial know-how.
Finally, the book philosophically discusses how to harmonize the resource, life and technological cycles depicted by the figure on the cover to make a contribution to the sustainable use of resources and products.
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HARMONIZING THE RESOURCE, TECHNOLOGY AND ENVIRONMENTAL CYCLES
M.A. REUTER, K. HEISKANEN, U. BOIN, A. VAN SCHAIK, E. VERHOEF, Y. YANG AND G. GEORGALLI
SERIES EDITOR: B.A. WILLS

Appendix E

This appendix contains a contribution by the author to the Smithells Metals Reference Book (8th Edition). Contributions to the Ullmann's Encyclopedia of Industrial Chemistry are also given. Also presented are the contents of two key reports that address European Union legislation around end-of-life vehicles the author was involved in (in their preparation and execution).

Furthermore, this appendix contains copies of various journal and conference papers presented as plenary, keynote and invited lectures, as referenced in this dissertation. These are listed according to the numbers in the reference list of this dissertation. Each paper has a cover page also giving its reference number within the text.

(*Please refer to the CD attached to the inside of the back cover of this dissertation for electronic pdf copies of these papers. Please follow the links to navigate through the different publications or return to the list of publications*).