Product Centric Simulation Based Design for Recycling (DfR) and Design for Resource Efficiency (DfRE)

10 Fundamental Rules & General Guidelines for Design for Recycling & Resource Efficiency

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MARAS
Material Recycling and Sustainability

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Summary

Metals and materials play a pivotal role in Electric and Electronic Equipment (EEE) as their properties impart unique functionality to consumer products. Through mindful product design, closely linked to recycling technology, Design for Recycling (DfR) can contribute to the recovery of metals and materials following a Product Centric Approach. This Product Centric approach (Reuter et al., 2013) [1] implies that EEE products are considered are complex minerals, taking into account the complex interactions of metals and minerals and recycling process technologies during pre-processing and metallurgical recycling.

MARAS has performed a study on DfR for NVMP to develop 10 DfR rules taking into consideration the possibilities and limits of Recycling (Van Schaik et al., 2013). This report will discuss and illustrate how a Product Centric approach to recycling (with its roots in minerals processing) is core to Design for Recycling/Resource Efficiency (DfR/DfRE)[1, 2]. This permits the pinpointing of the "mineralogical" interactions and effects of functional design considerations (material choice/combinations) in combination with recycling processing infrastructures/routes on material recovery, losses and emissions and hence Resource Efficiency. Ten DfR rules will be presented, which have been developed by the authors in a study performed for NVMP/Wecycle (The Netherlands) on DfR of E-waste. These consider the possibilities and limits of recycling. Rigorous recycling process simulation models, based on the richness of tools available from minerals and metallurgical processing, have been applied to reveal the depth required to derive useful DfR rules and guidelines. This includes in depth knowhow of recycling technology and physical limits due to functional linkages and combinations of materials in a product.

Various recyclers have provided their input on design related issues in recycling to develop these rules. Numerous recyclates have been investigated by the authors to this end. These have helped to understand the relationship between design and recyclate quality and link this to modelling of liberation as a function of product design, being integrated part of the recycling systems simulation models.

These rules include simple guidelines and material (in) compatibility tables to detailed recycling system based DfR rules based on simulation. The rules address the technological and economical possibilities and limits in the entire recycling system from design to metallurgy in relation to material interactions, recovery, losses and emissions and resource efficiency. It is crucial to realise that DfR is product and recycling system specific and that no general rules can be defined. DfR rules/guidelines have to be derived based on rigorous recycling process simulation and differ per product and recycling system. The presented rules will clearly illustrate this.

[1] Reuter et al. (2013). UNEP report: Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Reuter, M. A.; Hudson, C.; van Schaik, A.; Heiskanen, K.; Meskers, C.; Hagelüken, C., 320p.

[2] Worrell, E. and M.A. Reuter (2014). Handbook of Recycling – State-of-the-art for practitioners, analysts and scientists. Elsevier. ISBN 978-0-12-396459-5. 581 p. (In press).

Recycling process simulation tools are crucial to pinpoint and quantify the critical DfR rules for a particular product as these differ for different products. Simulation models developed by the authors are based on the commercial HSC Sim 7.1 software and provide a rigorous basis for DfR. These models are also applied by the authors for calculation of Recycling Indices, and reveal the recoverability and losses of all individual metals/materials in a product. Linking of Process Simulation and rigorous simulation based Recycling Indices to Design tools is a necessary step forward to realize realistic and economically viable DfR.

This report will present the 10 Design for Recycling Rules (5 Rules and 5 Derived Guidelines)[3]. The background and physics based Product/Mineral Centric principles on which the 10 Design for Recycling Rules have been defined will be discussed and explained.

This study has also resulted in a "Manifesto for the Sustainable design of electronics - Recommendations for product design with efficient use of raw materials", which was presented to Paulus Jansen, Chairman of the Infrastructure & Environment Commission in the Dutch Lower Chamber, at the Design for Recycling symposium held on 29 August 2013, in The Hague, The Netherlands[4].

Fundamental Design for Recycling (DfR) Rules

1. DfR rules are product and recycling system specific; oversimplification of recycling by defining general DfR rules will not produce the intended goal of resource efficiency.
2. DfR needs model and simulation based quantification.
3. Design data should be accessible and available in a consistent format which is compatible with the detail required to optimise and quantify recycling performance of products for all metals, materials and compounds present.
4. Economically viable technology infrastructure and rigorous tools must be in existence for realizing industrial DfR rules and methodology.
5. CAD, Process and System Design tools must be linked to recycling system process simulation tools to realise technology based, realistic and economically viable DfR.

[3] Schaik, A. van, M.A. Reuter and NVMP/Wecycle (2013). 10 Design for Recycling Rules. Presented at the Design for Recycling symposium held on 29th August 2013, The Hague, The Netherlands (available from: http://producenten-verantwoordelijkheid.nl/uploads/pdf/nieuws/2013/2013%2010%2011%20Summary%20MARAS%20def3.pdf).

[4] NVMP/Wecycle (2013). Manifesto for the sustainable design of electronics : Recommendations for product design with efficient use of raw materials. Presented to Paulus Jansen, Chairman of the Infrastructure & Environment Commission in the Dutch Lower Chamber, at the Design for Recycling symposium held on 29 August 2013 (available from: http://producenten-verantwoordelijkheid.nl/uploads/pdf/nieuws/2013/2013%2008%2030%20NVMP%20Manifesto%20DfR.pdf)

Possible Design for Recycling Guidelines - Derived from the Fundamental DfR Rules (Iteratively checked by simulation and for validity, while being subject to a mindful consideration of product/component functionality)

6. Identify and minimize the use of materials which will cause losses and contaminations in recycling due to material characteristics and behaviour in sorting.

7. Identify components/clusters in a product, which will cause problems and losses in recycling due to combined and applied materials.

8. Design clusters or sub-units in products that can be easily removed and which match with the final treatment recycling options (i.e. Metal Wheel – see report).

9. Labelling (including carefully considered standardisation) of products/components based on recovery and/or incompatibility so that they can be easily identified from recyclates and waste streams. Thus Design for Waste stream sorting or Design for (Automated) Dismantling/Sorting are important.

10. Be mindful of liberation of materials in design (Design for Liberation).

Note : All DfR rules/guidelines are subject to a mindful consideration of product/component functionality and should not impair these

Policy targets for Recycling and Ecodesign

Some policy targets and recommendation have been derived from these rules with regard to recycling and eco-design. These have been translated into a Manifesto which was handed over to the Dutch Lower Chamber (NVMP/Wecycle, 2013):

- design rules should remain within what is physically, technologically and thermodynamically possible and hence be based on recycling process simulation tools and knowledge;
- must be set in ways that account for the loss of metals due to mixing in products (for product functional specifications);
- should reflect the interest and expertise of all stakeholders in the product and recycling system and stimulate interaction;
- should respect the dynamic (time-varying) product characteristics and hence recycling profile over time[5]; and
- should be set aligning with economic drivers.

[5] A. van Schaik, and M.A. Reuter (2004). The time-varying factors influencing the recycling rate of products. Resources, Conservation and Recycling, Vol. 40(4), pp. 301-328.

Conclusions

It is clear from the above discussion and presented DfR rules and guidelines, that Design for Resource Efficiency (DfRE), of which Design for Recycling (DfR) is a sub-set, demands knowledge of liberation behaviour, of the particulate quality of recyclates, of the separation efficiency linked to the compatibility and thus recovery and/or loss of material in metallurgical processing, and of the modelling thereof, all as a function of design choices, connection type and connected materials. Insight into this provides a technology- and industrial-process driven basis for DfR to optimize resource efficiency and closure of material cycles for both commodity and critical and scarce elements in complex consumer products, such as cars and e-waste/WEEE products. This all should be read in line with the recent UNEP Metal Recycling report (Reuter et al., 2013), which gives a detailed overview over metal recycling and also links recycling to Urban Mining and (Enhanced) Landfill Mining. In view of the discussion on DfR in this report and the UNEP report, some points can be kept in mind when advancing the field of Design for Resource Efficiency and Design for Recycling and its suggested more product centric view to it. With reference to the such diverse number and complexities of E-waste products, but also for any other complex End-of-Life (EoL) product from the Urban Mine and forms of materials and spatially distributed diverse, heterogeneous, reacted/decayed, fines containing excavated waste from the landfills being a source for metals and materials to be obtained through recycling, the following should be considered:

- develop as far as possible the description of the system on the basis of the theory that is already available from minerals and metals processing in order to optimise the systems as rapidly as possible, while also further innovating and advancing the theory and deeper understanding;
- base the DfRE and DfR efforts and descriptions on rigorous process simulation as done for recycling;
- this will help also to further develop a Product Centric approach to mining landfill and products from the Urban Mine, very much like mining classical minerals and processing these in a minerals (product) centric manner;
- ensure that data structures are developed in accordance with standard minerals processing standards and sampling is done in accordance with rigorous available techniques, which enables the calibration of rigorous simulation models;
- ensure that the complete system is modelled from landfill to metallurgy to ensure a decent economic CAPEX and OPEX analysis can be made to ensure the developed ideas make economic sense;
- the rigour suggested by the DfR rules also ensures that research is focussed on the issues that are of true value and will lead to true innovation;
- understand the thermodynamics of the system as well as kinetic issues that may affect the outcome;

- understand the distributed nature of all variables in the system in order to obtain an indication of the risk involved in the urban mine "ore body", thus the use of Kriging techniques and sampling theory are of paramount importance; and
- understand the dynamics of the market as well as the available metallurgical infrastructure as these are key to extract metal value.

Obviously this list can be extended or perhaps even shortened, but is a basis for a rigorous discussion on resource efficiency, which is ultimately the goal of DfR, DfRE and also Urban and landfill Mining. Fundamental rigour and theory is the common language, which is important to harmonise discussion and bridge the gap between the waste processing, metallurgical, OEM, resource recovery, materials science, recycling and other silos. This should be a pressing outcome for our exciting but urgent innovation ahead of us. Society and the taxpayers demand that of us.

Structure of report

The Introduction gives a brief overview of the background and relevant developments in e.g. European policy on Resource Efficiency and Design for Recycling as part of this. Chapter 2 discusses the principles of Resource Efficiency as the foundation for Design for Recycling by explaining the analogy between existing and well advanced theory of minerals and metal processing systems and recycling. This chapter discusses how this provides the rigorous basis for recycling and residue processing and Design for Recycling. Chapter 3 explains the Product ('Mineral') Centric Approach providing the framework for the recycling of complex products cq. 'man-made minerals'. Chapter 4 positions the Product Centric Simulation Based Design for Recycling (DfR) approach of this research relative to general, often too simplistic DfR approaches coming from a Material (single material) Centric point of view, which are not applicable for the complexity of WEEE products and their recycling. In Chapter 5 the Ten DfR rules and Guidelines are presented and extensively explained by referring to the preceding chapters. Many examples are given for the Rules and Guidelines resulting from this study. Policy recommendation and targets for DfR and Eco-design as derived from this study are presented in Chapter 6. Chapter 7 provides the Conclusions of this research. The report is accompanied by Appendices (A and B) which give detailed background of the theory and models discussed (Appendix A) as well as some illustrative examples and results of the application of Recycling Process Simulation Models developed in HSC Sim 7.1 for Design for Recycling (Appendix B).

1. Introduction

1.1 A resource efficient Europe

“Natural resources underpin the functioning of the European and global economy and our quality of life,” declares *A resource efficient Europe—Flagship initiative under the Europe 2020 strategy* (COM, 2008). Reliable access to critical raw materials is a persistent challenge for resource-dependent countries, and this initiative supports smarter use of natural resources to achieve sustainable growth.

1.2 EU2020 vision

The objective of the Societal Challenge 'Climate action, environment, resource efficiency and raw materials' of the Horizon 2020 Work Programme 2014-2015 (EC, 2013) is “To achieve a resource – and water – efficient and climate change resilient economy and society, the protection and sustainable management of natural resources and ecosystems, and a sustainable supply and use of raw materials, in order to meet the needs of a growing global population within the sustainable limits of the planet's natural resources and eco-systems”. It is stated that “A smart economy minimizes the production of waste and reuses waste as a resource’ and that “Resource constraints and environmental pressures will accelerate the transformation from a linear extraction-use-throw away model of production and consumption to a circular one”. The need for the decoupling of economic growth from resource use has been clearly identified. One of the areas for investigation and improvement in the H2020 focuses on waste, i.e. resources, recycling, reuse and recovery of raw materials by addressing the whole production and consumption cycle, from waste prevention and the design of processes and products for recyclability to reuse and waste management.

1.3 Association NVMP, recycling and Design for Recycling

Association NVMP (the Dutch Association for the Disposal of Metalelectro Products) has established that the environmentally-friendly processing of most of our electronic waste in the Netherlands is well-organised and that we are recovering most of the steel, copper, plastic and other commonly-used substances in our e-waste. At the same time, NVMP has also ascertained that high-quality raw materials that we use in small amounts and in complex compounds, which are essential for the functionality of our modern electronics, are lost during the recycling process. Those high-quality metals are either rare or their supply is critical because producers are dependent on just a few suppliers or on geopolitical constraints. It is essential that we recover these critical metals from discarded electronic devices in order to guarantee their availability in the future. However, new recycling techniques are not the solution. After all, those technologies cannot overcome the limitations as imposed by the laws of nature (physics and thermodynamics) that affect the recycling of critical substances. The solution is to adapt the product design so that these materials can be recovered using the best available recycling technology. In order to investigate Design for Recycling options for E-waste, NVMP has commissioned research to MARAS, resulting in a number of workable empirical Product Centric Simulation Based Design for Recycling rules so that the necessary adjustments can be made in the choice of materials and in the construction and design processes.

The Product Centric simulation based approach of this research, allows moving away from general and simplistic DfR rules and approaches, which have, also according to the recycling industry, not led to significant improvements in recyclability and recovery of metals/materials.

2. Principles of Resource Efficiency as the foundation for Design for Recycling

Metals, their compounds and alloys have unique properties that enable sustainability in innovative modern infrastructures and through modern products (Reuter et al., 2013). Through mindful product design and high (end-of-life) collection rates, the metals and their compounds in sustainability enabling and other products can be recovered well, thus recoveries and therefore recycling of metals can be high. However, limitations on the recycling rate, in particular of minor or critical elements, can among others be imposed by the (functionality driven) linkages and combinations of metals and materials in products. The resource efficiency of the recycling system and recovery and losses of metals/materials/elements from this can only be optimized by exploring these limits and restrictions on a rigorous basis, while addressing the interactions between design, particulate and recyclate quality and recycling/recovery/losses in metallurgical processing as a consequence. Figure 1 shows various factors that can affect the Resource Efficiency of metal processing and recycling (Reuter et al., 2013; Worrell and Reuter, 2014). The interaction therefore of primary and secondary recovery of metals drives not only the sustainable recovery of elements from (ore) minerals but also provides the recycling infrastructure that recovers metals/materials from complex products and therefore enables the maximum recovery of all elements from 'designer minerals' i.e. our modern complex multi-material products such as EEE, automotive applications, etc.

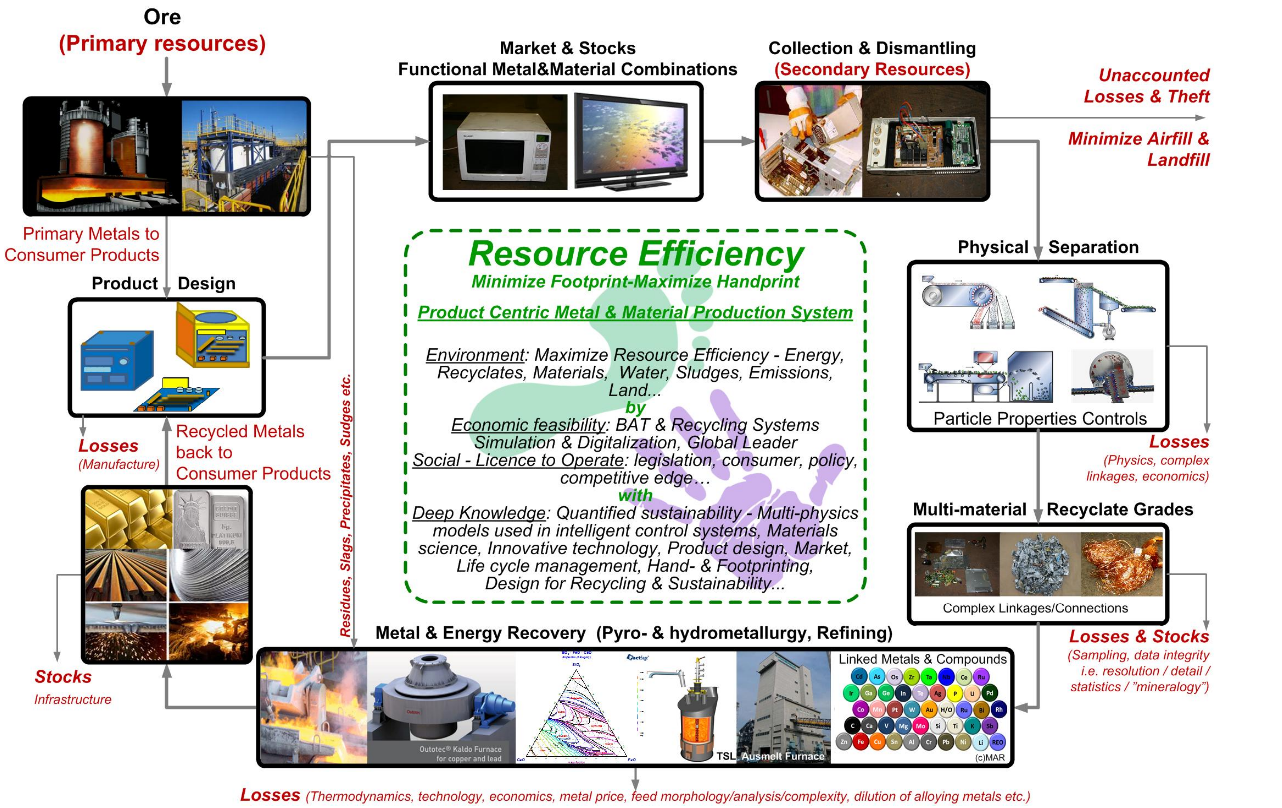


Figure 1 Overview of the various factors affecting Resource Efficiency, which have to be addressed in DfR if it reaches the depth required to innovate the system architecture, technology and policy on a rigorous techno-economic basis (Reuter et al., 2013; Worrell and Reuter, 2014).

It is self-evident that "classical" minerals processing and metallurgy play a key role in maximizing resource efficiency and ensuring that metals are true enablers of sustainability. Thus key to recycling of complex consumer goods is:

- Mineral Processing and Metallurgy – The Foundation of Recycling
    - The link Minerals to Metal has been optimized through the years by economics and a deep physics understanding.
    - There is a good understanding between all actors from rock to metal.
- Product Centric vis-à-vis Metal Centric Recycling
    - Designer Minerals (e.g. cars, mobiles etc.) are far more complex than geological minerals; complicating recovery.
    - To "close" the loop requires a much deeper understanding between all actors of the system than is the case presently. Resource Efficiency will improve if this Product Centric depth is achieved and provide the basis for Design for Recycling and Resource Efficiency.
- This deeper understanding of recycling will help to develop sensible physics-based policy (Reuter et al., 2013).

The use of available minerals processing and process metallurgical theoretical depth to describe the system shown in Figure 1 is required to understand the Resource Efficiency of the complete system. A fundamental description of the system also shows what theory and methods still have to be developed to innovate the primary and recycling fields further. It is evident from Figure 1 that the use of the rigorous theory developed in the classical minerals and metallurgical processing industry over the years and more recently adapted for recycling are very useful to quantify the various losses shown in Figure 1 as well as to maximize resource efficiency. Both "classical" minerals processing and process metallurgy therefore have a significant role to play in a modern resource constrained society. Identifying the detailed metal, compound, etc., contents in all flows will help optimizing the recycling system, as is already the case for the maximum recovery of metals in concentrates from known ore and product streams, giving a rather precise mass balance for all total, compound and elemental flows.

Minerals processing and extractive metallurgy has evolved to a high level of sophistication through the past decades, providing the rigorous and well developed basis for recycling systems and Design for Recycling/Resource Efficiency, in which for example:

- particle systems are described in terms of detailed particle descriptions, their properties and their liberation (Andrews and Mika, 1976; Metha et al., 1989; Heiskanen, 1993);
- fundamental phenomena, physical and chemical separation and concentration of minerals have been modelled to various degrees of detail (King,1994; Gay, 2004);

- complete plants and systems can been simulated (King, 2001) and optimised (Reuter and Van Deventer, 1990);
- systems can be characterised with sophisticated measurement such as Mineral Liberation Analysis (MLA) (Sutherland and Gottlieb, 1991; Bonifazi, 1995; Goodall, 2008) to help calibrate simulation models and understand the mineralogy of materials;
- sophisticated sampling of materials can be performed as described by Gy's sampling theory to assist in characterising materials as well as provide statistical relevance to analysis of streams (Gy, 1976;1981); and
- ore bodies can be characterised and quantified by for example Kriging (Matheron, 1963; Cressie, 1993).

These techniques have been applied in various ways in software (HSC and HSC Sim 7.1, 1974-2012). For example Figure 2 shows software that can model by the use of the aforementioned theory and simulate and control complete systems e.g. from rock to copper metal as depicted.

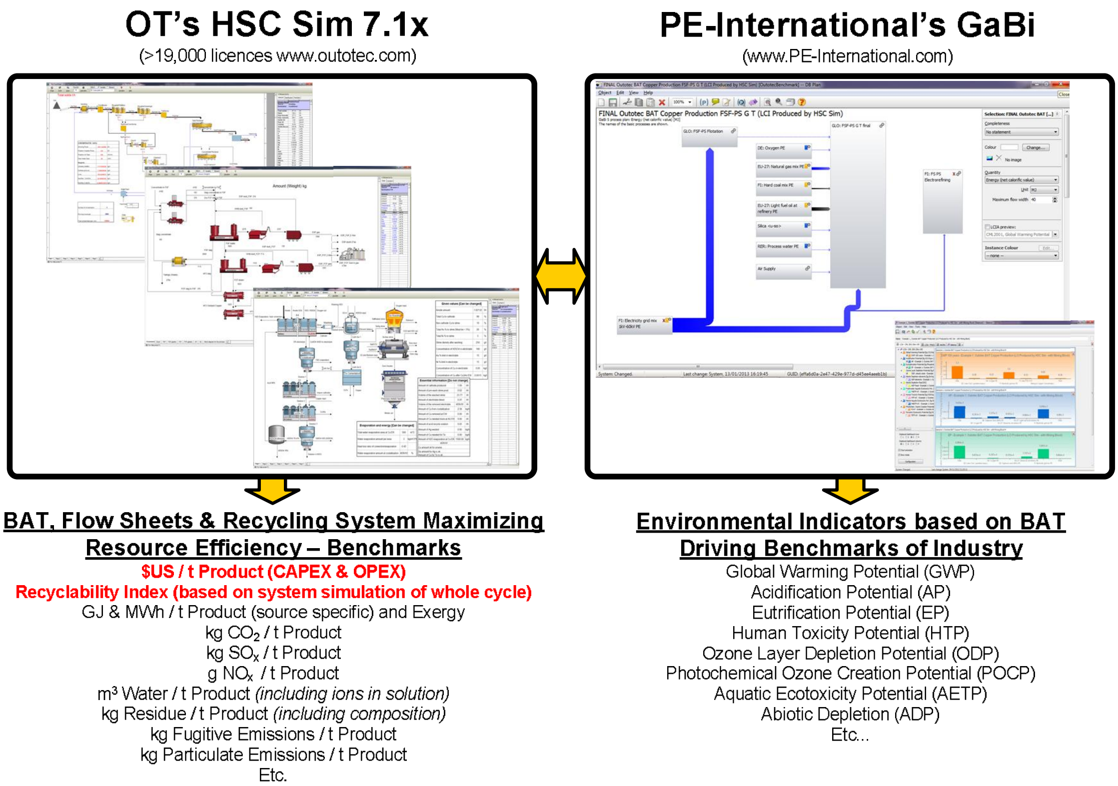


Figure 2 A complete rock to metal flowsheet for copper as provided by Outotec (www.outotec.com) (HSC and HSC Sim 7.1, 1974-2012) showing the link of physical separation with metallurgical processing as represented by the HSC Sim process simulator with the link to GaBi (www.pe-international.de).

Furthermore these systems are supported and linked by sophisticated environmental software (PE: GaBi6, 1992-2013). In addition Gibbs free energy minimization may be used to quantify equilibrium systems to assist in the simulations and understanding of the behaviour of species if they undergo chemical change in hydro- and pyrometallurgical reactors and complete plants (HSC and HSC Sim 7.1, 1974-2012; FACT Sage 6.4, 1976-2013). It is self-evident that there is much to be learnt and used from these techniques in classical minerals and metals processing. This report will describe briefly how this theory has been used to develop 10 Design for Recycling rules and apply Design for Resource Efficiency based on this detail. This is done on the basis of describing, simulating recycling and residue processing systems, while highlighting a Product Centric description of materials and EoL products and simulation of complete product to recycling systems on this fundamental basis with existing well advanced tools.

3. Product Centric Recycling of complex products / 'man-made minerals'

Understanding the existent minerals and metallurgical processing fundamental basis well, has been the basis for the authors to use this well developed theory to describe recycling and residue processing systems. This provides a rigorous basis for Design for Recycling as part of Design for Resource Efficiency (Reuter, 1998; Van Schaik and Reuter, 2004; Van Schaik et al., 2004; Richard et al., 2005; Castro et al., 2005; Van Schaik and Reuter, 2010).

3.1 Product Centric Recycling

In order to be able to fundamentally describe the system requires a key understanding that EoL products, waste materials etc. and should be considered very much like minerals as shown in Figure 3, taking account of the complex and non-linear interactions between different metals/materials/compounds as applied for product functionality, performance, design and/or aesthetic reasons. We coined that Product Centric recycling (Reuter and Van Schaik, 2012a). This is identical way to considering a Mineral Centric description of systems, which is standard in minerals processing. This then by default brings into play the richness of all the theory and tools available through classical minerals and metals processing. A Product Centric approach to recycling is core to Design for Recycling/Resource Efficiency, as it allows pin pointing the interactions and effects of design considerations (material choice/combinations) in combination with recycling processing infrastructures/routes on material recovery, losses and emissions and hence Resource Efficiency.

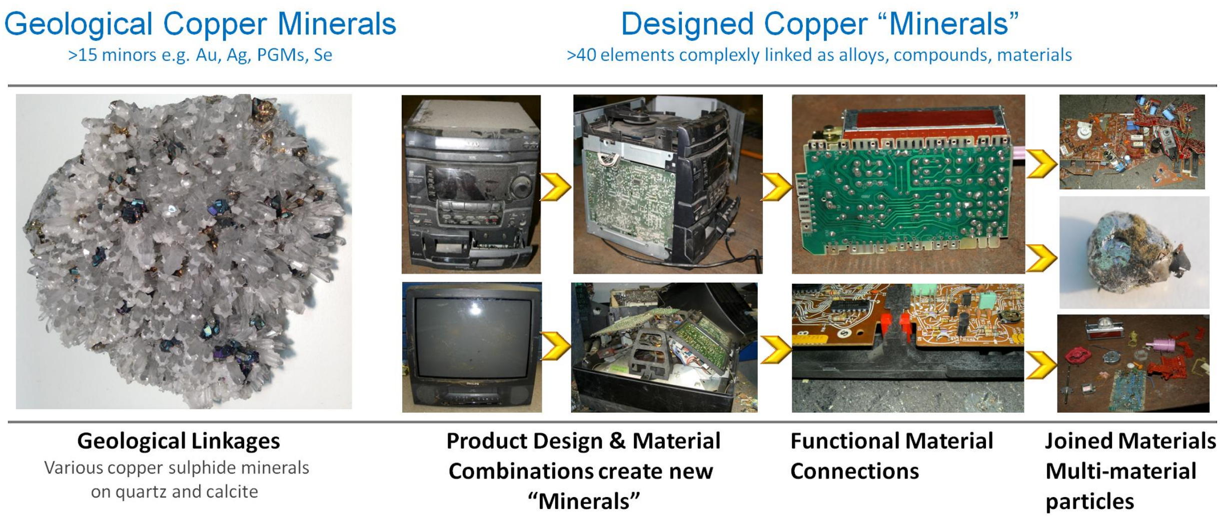


Figure 3 Learning from the simulation of complex primary minerals (figure left) processing and metallurgical plants to quantify the processing of complex "designer" minerals i.e. consumer products, which may have even more complex "mineralogies" as shown by the figure (right).

Crucial to this understanding of recycling and residue processing is the inclusion of ('design determined') liberation and particulate quality as a function of design and comminution and hence recyclate quality in the description of recycling system and its effect on recovery, losses and emissions during recycling (Figure

4). Figure 3 reflects some of the complexity of EoL materials and the possible issues that describe and affect the liberation behaviour and thus the losses from the system. Figure 2 suggests that the deportation of all elements in chalcopyrite can be simulated well and a process can be designed on this simulated basis. This is common practice in for example Outotec (www.outotec.com) when we design plants as shown in this figure. However, the complexity of EoL products and often the lack of good sampling data for scrap, lack of detailed "mineralogies" of EoL products, lack of understanding of liberation behaviour etc. make the simulation of recycling systems significantly more difficult. Nevertheless, by the systematic used and also description of recycling systems on the basis of well-established minerals processing and further developments of this theory, some steps have been made to better understand EoL recycling systems and support consistent data collection on WEEE recycling input streams and products.

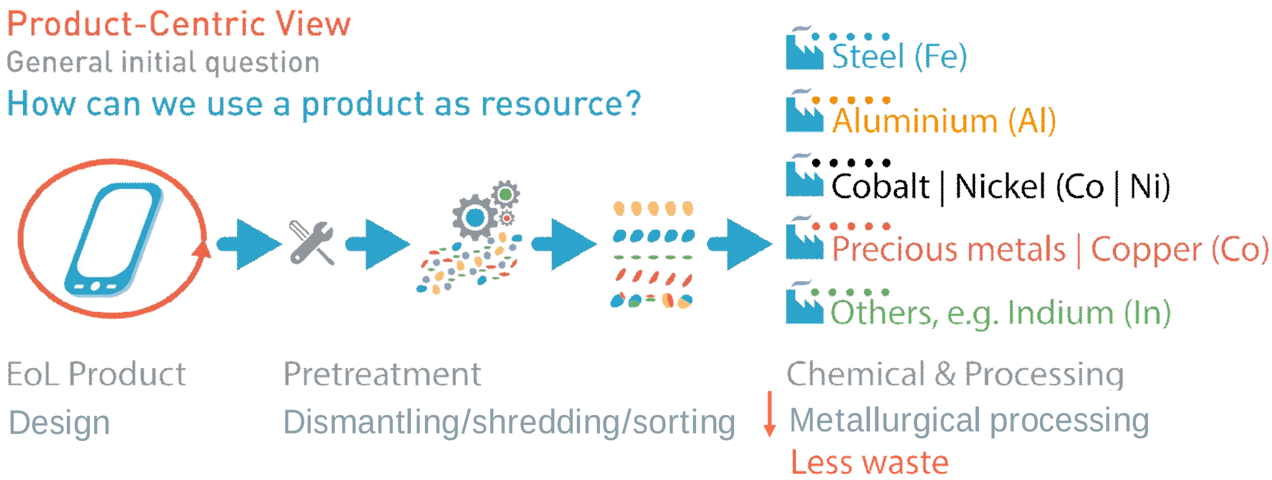


Figure 4 A key message concerning Product-Centric recycling: Product design (for Recycling) must be linked to liberation, separation efficiency, and quality of both recyclate and of final output streams, based on the thermodynamic limits and non-linear interlinkages of recycling (Reuter et al., 2005; Reuter and Van Schaik, 2008, 2012a&b; Van Schaik and Reuter, 2012).

Figure 5 shows, that by the use of the same tool as shown in Figure 2 for classical copper rock to metal simulation, EoL systems can be simulated and scrap particle systems appropriately calibrated.

The reader is referred to Appendix A, which gives a detailed description and formulation of the recycling process models and the modelling of liberation, pre-processing and metallurgical processing on a physics and thermodynamics basis.

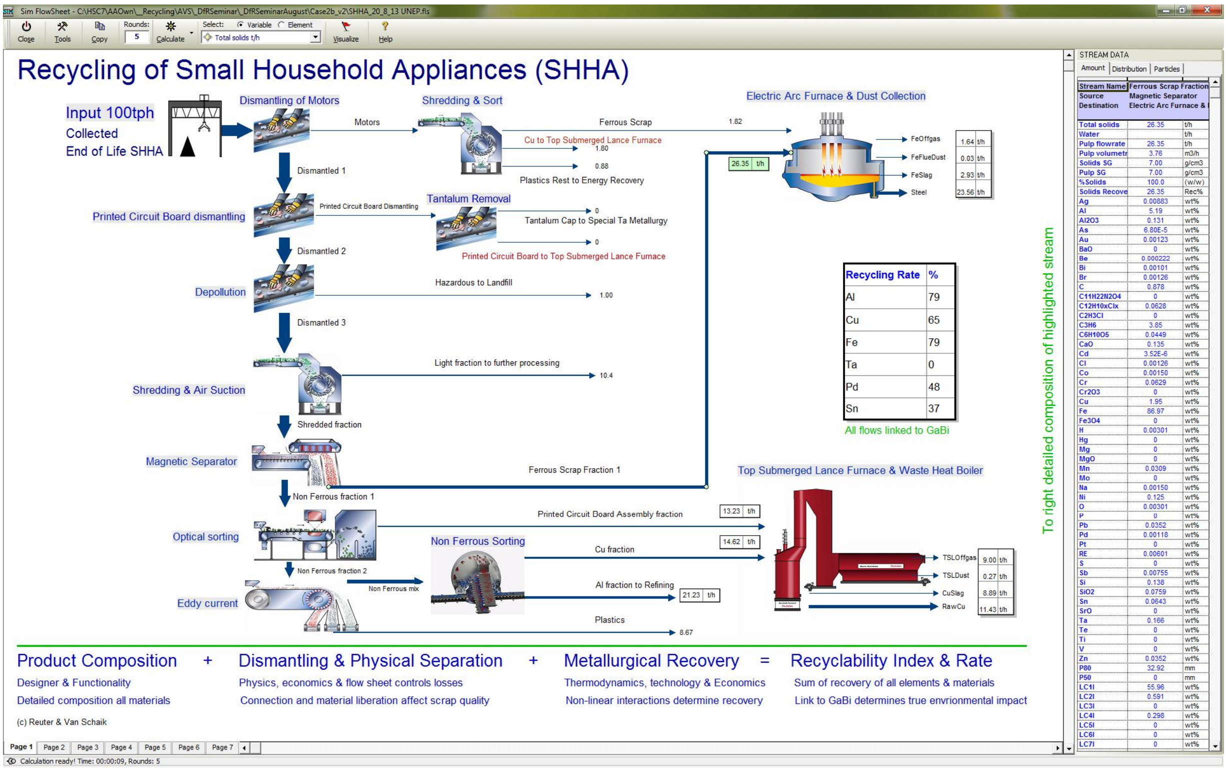


Figure 5 Adaptation of minerals processing simulation to "designer" minerals and simulating and providing Recyclability Index for products on a rigorous simulated basis using HSC Sim 7.1 – thus true quantified sustainability and recycling rate calculations.

Through this *Product-Centric* approach (Reuter and Van Schaik, 2012a), which simultaneously considers all metals, alloys, materials etc. in an EoL product, recycling and Design for Recycling have the potential to capture much greater value from waste streams, extracting the metals now lost. Thus resource efficiency is captured, much in the way as we capture the losses of all metals in classical minerals and metals processing system.

This contrasts with a rather more simplistic *Material (& Metal)-Centric* approach. This approach is favoured more by the waste processing field and has its root from the bulk recycling industry that would try to increase recycling of a specified metal, focuses on this, while forgetting all other connected materials and the related thermodynamics and physics. This Material Centric approach would be similar if one would just consider ONLY the copper in the chalcopyrite of Figure 3 and neglect all non-linear effects of all other included minor elements and compounds. Considering that a Printed Circuit Board Assembly (PCBA), which is only part of a product, can contain over 50 different elements, compounds and alloys, clearly points out the complexity of WEEE products and component 'mineralogies' and the need to address recycling on a Product Centric basis. It is therefore extremely important for resource efficiency to step away from the Material Centric perspective to the product perspective when considering EoL products, waste streams, residues etc. This requires a deep understanding of extractive metallurgy, slag chemistry, separation physics and systems engineering as well as the techno-economic (CAPEX & OPEX) aspects of processes and systems.

Figure 4 and Figure 5 furthermore provide a brief glimpse of some of the actors and aspects that have to be understood in a *Product-Centric* systemic and physics based manner in order to optimise resource efficiency e.g. through Design for Recycling. Also a clear understanding of the various losses that occur is imperative (many governed by physics, chosen technology and linked economics), which also requires a deep compositional understanding of all residues, obviously related to a deep data availability of product compositional data, but also the understanding of unaccounted flows (poor statistics, data as well as collection) and the economics of the complete system are critical.

If we consider that liberation, sorting (in) efficiency during pre-processing, recyclate and particulate quality as depicted by Figure 3, which all complicate the picture even further, it should be clear that no average recycling rates (UNEP, 2011) can be applied to predict the recycling of complex products and the recycling rates of their composing materials/elements/compounds. The recyclate and particulate quality as well as the dispersion of the elements and components (such as parts of the PCBA) over the various recyclate fractions determine in which metallurgical commodity metal infrastructure, depicted by the different sections of the Metal Wheel (see Figure 6; Reuter et al., 2013) the recyclates and contained materials/elements will end up and can be recovered or will go lost.

3.2 Metal Wheel

The Metal Wheel reflects based on primary metallurgy the destination of different elements in commodity/base metal minerals (base or carrier) processed in hydro- and pyrometallurgy and electrorefining/winning infrastructure as a function of interlinked metallurgical process technology and different intermediates and products such as dross, sludges, slimes, precipitates, speiss, slag, metal, matte, flue dust etc. Each slice represents the complete infrastructure for a carrier base metal refinery. This basic metallurgical know-how, based on the processing of concentrates originating from mineral ores (the elements are typical to the different ores), should be in place also for recycling in order to maximize resource efficiency (Reuter et al., 2013; Reuter et al., 2005; Reuter and Van Schaik, 2012a&b; Ullmann's Encyclopaedia, 2005).

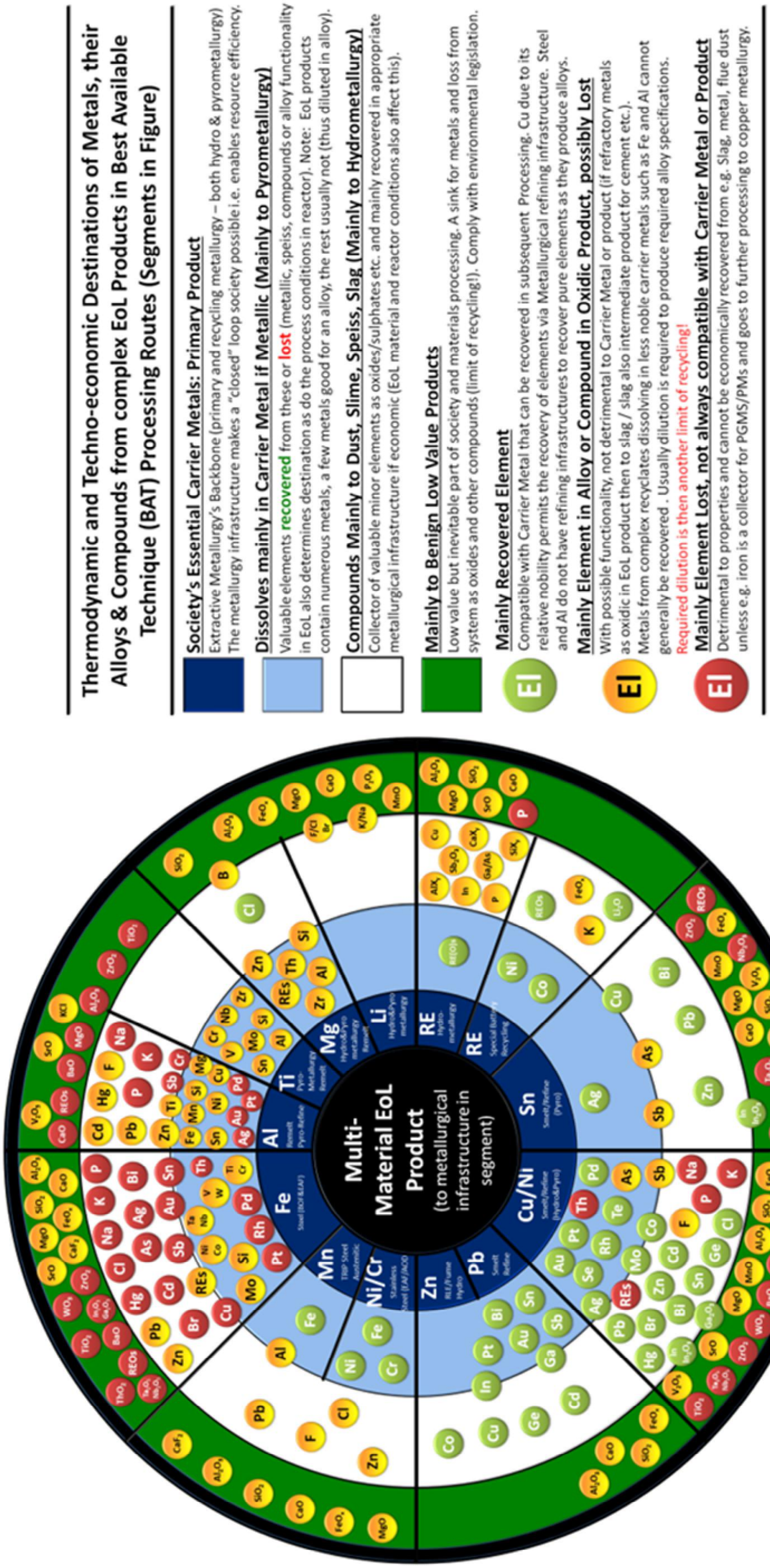


Figure 6 A generalized Metal Wheel, showing in each sector a complete carrier metal industry to recover efficiently in a product centric way as many as possible the elements, metals and compounds.

3.2 Metal Wheel : an example

A PCBA or part of it, being connected by a steel bolt to the product structure, will most likely end up in the ferrous fraction finding its way to the steel recycling infrastructure, rather than to the preferred Cu/Pb route as depicted by Figure 5 and Figure 6. The recovery and losses within this steel route, will be entirely different. On the other hand the Cu recycling infrastructure due to copper's relative nobility has the capability to capture these technology elements from PCBAs and other EoL products acting as a solvent. Through refining, it releases these in a sophisticated refining infrastructure. These (valuable) minor elements are thus not diluted to produce the correct alloy types as is the case for the less noble alloys such as steel and aluminium (Reuter and Kojo, 2014).

4. From Material to Product Centric Simulation based Design for Recycling and Resource Efficiency

The recycling of bulk waste is relatively easy and fits into simplified circular economy discussions, following a Material Centric approach. Challenging is the recycling of modern products, the complex designed "minerals" characterized by numerous specialty materials at their functional heart. Product Centric recycling provides the platform optimizing the recovery of materials and energy from these designer "minerals" in System Integrated Metallurgical Processing (SIMP), hence linked to collection and pre-processing (including dismantling/depollution/disassembly). Thus platforms exist for the recovery of metals from geological and designer minerals. Policy must provide the wise policy that cements these systems (i.e. internet-of-things) as key pillars into a RE aware society.

Simplified circular economy discussions, based on a single material (Material Centric) approach stimulate the notion that DfR-rules are the golden bullet solve recycling hurdles. Complex products such as WEEE fundamentally challenge the development of too simple rules that suppress innovation.

The depth and flexibility required to understand, improve and optimise resource efficiency, cannot be captured by the general and too simplistic DfR rules, which for example suggest (Hultgren, 2012; Balkenende, 2013): (i) the avoidance of certain material combinations (e.g. ferrous and non-ferrous metals), (ii) use of lesser (weight) materials; (iii) use of a limited number of materials; (iv) use of compatible materials; to name a rules few as applied currently in many DfR approaches. These rules reflect the earlier attempts to perform Design for Recycling as described by Graedel and Allenby (1998), including e.g. trivial and non-functional suggestions on the use of easy to open click connections for manufacturing, which would not pass e.g. product safety tests. Such general rules do not find their basis in a physics and thermodynamics driven recycling system approach. No rigorous process simulation basis is supporting these simplistic approaches, which allows for quantification and specification of these rules in order to be applied and selected respecting product (functional) demands. The same discussion applies to linear recovery rating methodologies intending to support and direct DfR. These lack the physics and thermodynamics based depth and insights to deal with the non-linearities and complexities of recovery of materials from complex products. Important also to realize is that these simplistic but often extended DfR 'rules' do not support and consider the industrial reality of product design and product functional demands and are often not effective from a recycling point of view. Such large lists of rules restrict creativity and requirements for product design. General rules just give the "do not's" rather than the "do's" and prevent consideration of all material combinations and connections for functionality reasons, presenting a precarious situation.

Colledani and Tolio (2013) claim to have defined a multi-level recycling system model that integrates process physics and system dynamics, by indicating that design of multi-stage mechanical recycling systems has never been tackled from a system engineering perspective. It should however be realised that these models only present a part of the recycling system, do not include and neglect the vital role of metallurgy, nor the effect of design and modelling of liberation, particulate and recyclate quality and its effect on recovery and losses in the system as addressed in discussed in rigorous detail in the Product Centric based models as briefly discussed above. Lu et al. (2014) discuss the influence of disbanding techniques on recycling in view of rapid disassembly. VDI (2002) has defined a 'Fastener Selection Table' in which qualitative (good/average/bad) ratings are given for different connection types including detaching behaviour and recyclability. Detaching and disassembly should however be considered in the entire picture of product material composition, component composition and connections as these factors all contribute to recyclate quality and hence recycling/recovery. Masanet and Horvath (2007) have assessed the benefits of DfR for plastics in electronics. Although this work pretends to define quantitative metrics for EoI cost and environmental impacts, the work is based on Material Centric approach in which the interactions between plastics and the other materials, affecting recyclate quality and recovery rates are ignored. The study of Fan et al. (2013) on notebook recycling presents a cost and environmental analyses for re-design. In this study, the parts are considered as separate materials, taking default values for 'recycling', whereas the complex non-lineair interactions of materials in components after disassembly, which affect recycling values, have been disregarded. This provides a very debatable basis for environmental analysis and will not result in re-design options in which the entire product to recycling chain, and the interplay between disassembly, disassembled component composition and final material/metal recovery can be taken into account. Froelich et al. (2007) discuss the feedback of a survey on industrial and innovative recycling technologies into a methodology for car design integrating plastic recycling constraints.

Challenging the RE playing field in this study, we derived DfR-rules and policy that:

- are based on and aligned with robust system integrated pre-processing and metallurgy technological platforms that are thermodynamically, technologically and economically viable;
- based on recycling system simulation, rigorously quantifying the recycling profile of product and/or recycling route and accounting for the recovery and loss of metals from functional combinations;
- reflect the interest and expertise of all stakeholders in the resource system, stimulating dynamic interaction; and
- respect the time-varying product "mineralogy", innovation and recycling profiles of different products.

This DfR-rules and policy basis allows for product specific DfR directions, which apply for the particular product and can be quantified in terms of need and effectiveness which have been derived on a rigorous Product Centric basis. Only these will guide the designer towards more resource efficient product specific design improvements for resource efficiency, rather than having to deal with a long and restricting list. In view of the detail discussed above, it is clear that each product, each situation must be calculated and checked to reveal fully the complexity and requirements of (Design for) Recycling. This demands very rigorous modelling to reveal the opportunities and limits of recycling and quantify recycling/recovery rates as well as losses and emissions in the EoL phase in relation to product design and recycling options as illustrated in Figure 5. Design for Recycling and Resource Efficiency on a Product Centric basis captures this detail, as discussed by Reuter and van Schaik (2012a&b, 2013a&b). It should be realized that even these have limitations as all thermodynamic data is not yet available. Efforts should be focused on this rather than develop simplistic approaches that have not link to reality. This implies that forcing recycling rates quotas for especially the minor metals would be a fallacy; rather a focus should be to maximize recovery of the elements. Given the correct economic basis, BAT infrastructure and market driven policy forcing for example zero landfill will help to maximize recovery and recycling rates. It is has always been the case on any metallurgical plant to recover valuable elements. If there is an economic incentive to do so, recovery will happen.

5. Ten Fundamental Rules & General Guidelines for Design for Recycling & Resource Efficiency

Based on and using the theory and simulation tools as explained and described in the previous paragraphs, a set of 10 Design for Recycling Rules are proposed (Van Schaik et al., 2013). These are grouped into 5 fundamental design rules and 5 derived guidelines.

In this section these 10 DfR rules and guidelines are presented. A detailed explanation for the various rules is given, by referring to the above background and by providing examples. Examples and illustrative results of the applied simulations tools (HSC Sim 7.1) are given to further detail the rules and guidelines.

5.1 Fundamental Design for Recycling (DfR) Rules

1. DfR rules are product and recycling system specific; oversimplification of recycling by defining general DfR rules will not produce the intended goal of Resource Efficiency

   Figure 1, Figure 3, and Figure 5 shows the different facets and complexity of recycling complex multi-material products such as WEEE and reveals all details which should be considered in DfR (Design for Recycling) & DfRE (Design for Resource Efficiency).

   - Due to its functional and unique mix of materials each product has a unique recyclability profile. This implies that every product has a unique set of DfR guidelines which are product and recycling system specific.

     The ‘Recycling Matrix’ of Table 1 (Van Schaik, 2011; Reuter and Van Schaik, 2012a) reveals the unique recycling fingerprint of some of precious/critical metals. It illustrates where they can be recovered using best current BAT practices. Although different appliances may all have similar suites of functional materials loosely called “mineralogies” i.e. contained elements and the functional connections, their recovery is not the same and hence their recycling rates are different. This table shows that, depending on the product and the combinations of materials, the recovery of metals may be different due to chemistry, concentration and metallurgical processes being incompatible.

     This Recycling Matrix has been developed as a preliminary DfR tool for designers, together with the Design for Resource Efficiency Metal Wheel from Figure 6. They capture the physics of recycling on the basis of the discussed simulation models that link product design to the complete recycling system as shown in Figure 5.

Table 1 Recyclability matrix as a function of pre-processing and metallurgical recovery showing the unique recycling fingerprint of different 'critical' materials as a function of product and recycling routes (developed from experience and estimations from tools such as shown by Figure 2, Figure 5 and Figure 6) (Van Schaik, 2011; Reuter and Van Schaik, 2012a).

Recoverability *	PMs		PGMs		Rare Earths (Oxides)			Other					©MARAS
(per equipment/application)	Ag	Au	Pd	Pt	Y	Eu	Other REs	Sb	Co	In	Ga	W	Ta
Washing machine													
Large Household Appliances (ex Fridge)													
Video recorder													
DVD player													
Hifi unit													
Radio set													
CRT TV													
Mobile telephone													
Fluorescent lamps													
LED													
LCD screens													
Batteries (NiMH)													

*Recovery is a function of processing route, product design etc. The table gives the recovery for the present most likely route, but could change if suitable technology exist.

Recovery possible	If separately recovered and/or if there is appropriate technology and recovery available.
Limited recovery/recovery under certain conditions	If seperately recovered. Partial or substantial losses during separation and/or processing/metallurgy. Recovery if appropriate systems exist.
No separate recovery	Pure recovery not possible. Lost in bulk recyclates during separation and/or during metallurgy into different non-valuable phases.
For a combination of colours	Depending on process route followed high recovery or high losses possible. Needs careful attention to design, infrastructure, legislation etc. This is especially possible for metals closlet linked where one metal can be recovered while the other due to this selection of recovery then goes lost. This is driven by the thermodynamics, technology, design etc.

A clear example taken from this Table is the recycling/recovery of PMs and PGMs from PCBAs and electronics from washing machines versus complex small household appliances or mobile phones. Steel, stainless steel, copper, glass, and plastics make up over 95 % of the current mass of EoL devices like washing machines. PCBAs and electronic components amount to less than 5 %. Thus under existing, mass-based recycling targets their recycling is often neglected and PCBAs and their contained specialty and precious metals, the recovery of which should be increased, disperses mainly to the commodity material fractions such as steel and plastics. Their recovery is hence low for these type of products. This differs from the recovery of these elements from e.g. mobile phones. The average weight share of precious metals lies around 3000 ppm for Silver (Ag), 320 ppm for Gold (Au) and 120 ppm for Pd (Palladium) (Hagelücken et al., 2009; Van Schaik, 2011). These high quantities (economically) justify their recovery, as mobile phones including their PCBAs and electronic parts are directly sent to an integrated copper/precious metal smelter and refinery which allows for the recovery of these elements.

This example also makes clear that weight based recycling targets are not supporting the recovery of these specialty/critical materials. The definition of recycling targets should hence be refined using a Product Centric approach.

- These DfR guidelines are to be derived and iteratively refined for each product/product group separately by the application of recycling simulation models that can map any (BAT - Best Available Technique) recycling system and its opportunities and limits.

Figure 1 shows the complexity of the various factors affecting Resource Efficiency, which have to be addressed in DfR if it reaches the depth required to innovate the system architecture, technology and policy on a rigorous techno-economic basis. DfR should embrace system simulation, rigorously digitalizing the recovery, losses and fugitive emissions of metals and materials from functional combinations as applied in different and time changing product designs. An example of such simulation tool as developed in HSC Sim 7.1 is given in the previous section by Figure 5.

Appendix B provides more examples of the application and results of the use of the developed recycling process simulation models for Design for Recycling. These examples illustrate in more detail the depth reached by this (Product Centric based) approach allowing for Design for Recycling, which is capable of addressing and pin pointing the issues of importance in optimisation of both recycling technology (on a rigorous physics basis), recycling infrastructure, and design considerations for improvement of recovery of materials.

2. DfR needs model and simulation based quantification.

- DfR demands a tool (process simulation models) that is capable of quantifying the product's recycling profile and performance to pinpoint DfR issues of importance and to give priority within Design adjustments to be implemented and insight in the effect of improved design on Resource Efficiency (Recycling Rate, toxicity, scarce material recovery/losses, environmental impact, etc.).

Crucial in the understanding and optimisation of recycling and resource efficiency is the understanding and model based prediction of the effect of product design (material choices and connections) on liberation behaviour and particulate quality (mono or multi-material particle composition) as a function of design and comminution technologies and settings (e.g. shredding, cutting, etc.). Figure 7 shows as an example different types and levels of material combinations (both physically and chemically connected) for PCBAs in different WEEE appliances. Design determined particulate quality, directly affects recyclate quality (see Figure 8) and the dispersion of materials/elements over the different produced recyclate fractions/streams (e.g. steel recyclate, copper recyclate, aluminium recyclate, plastic recyclate, PCBA recyclate, etc. etc). It is of crucial importance for recycling optimisation and DfR to be able to quantify the product's recycling profile (including liberation, recyclate quality, etc.) as the mix of metals and materials in design and recyclates determines the recovery, losses and fugitive emissions of all materials/elements in final treatment processing (such as metallurgy). This is shown above in Figure 4.

Figure 7 Different levels of material connections and material combinations (both physical and chemical) of Printed Circuit Board Assemblies in E-waste.

(a) (b) (c) (d) (e)

Figure 8 Recyclate quality from WEEE product due to inevitable imperfect separation & liberation - particles, distributions in which (a) ferrous recyclate; (b) aluminium recyclate; (c) plastics recyclate.; (d) Printed Circuit Board recyclate; (e) residue fraction.

The process simulation models as presented in Figure 5 provides the tool to quantify recovery, losses and emission of all elements and material in a product, hence providing a basis to quantify the effect of design on recycling, allowing for quantified, well directed DfR suggestions. Due to the rigorous (physics and thermodynamics based) nature of the process simulation models, this can be done for any product, any processing route and any recycling infrastructure alternative. The simulation models provide a full mass balance for all materials/elements in the product over the entire recycling system/flow sheet. On this basis, defined by the rigorous modelling of liberation, physics of separation and process thermodynamics, these models allow to determine the qualities and quantities of all (intermediate) recyclate and recycling products in the recycling system and predict recoveries, losses and emissions of all materials/elements in a product/recycling input flow. This fundamental rigour provides the relative basis, the so important baseline, to which things are measured and on which things can be compared and potentials and limits for improvement can be identified, much as has already been developed in minerals and metals processing.

As an example of the results of recycling process simulation models, material flow or Sankey diagrams can be derived from these full material mass balances, based on the product centric driven simulations. Figure 9 illustrates as an example of simulation outcomes the flow (recovery and dispersion) of gold (Au) over the entire recycling system. The flow of any other element/material/compound is simultaneously predicted by including the complex non-linear interactions between different material (mixtures) and can be derived from these simulations. This basis is very different from the Sankey diagrams which are tried to set up in order to visualise the material 'flows' in and from the Urban Mine. The latter are lacking a rigorous process simulation basis, which accounts for the non-linear and product and processing route dependent interactions affecting recoveries and losses as Figure 9. Appendix B provides more examples of the truly quantified predictions and results of these models. Some examples of the quantification of changing recycling performance as a results of recycling processing routes (i.e. yes/no dismantling of PCBAs and Ta capacitors) or design adjustments (design for improved liberation) are given in this Appendix B.

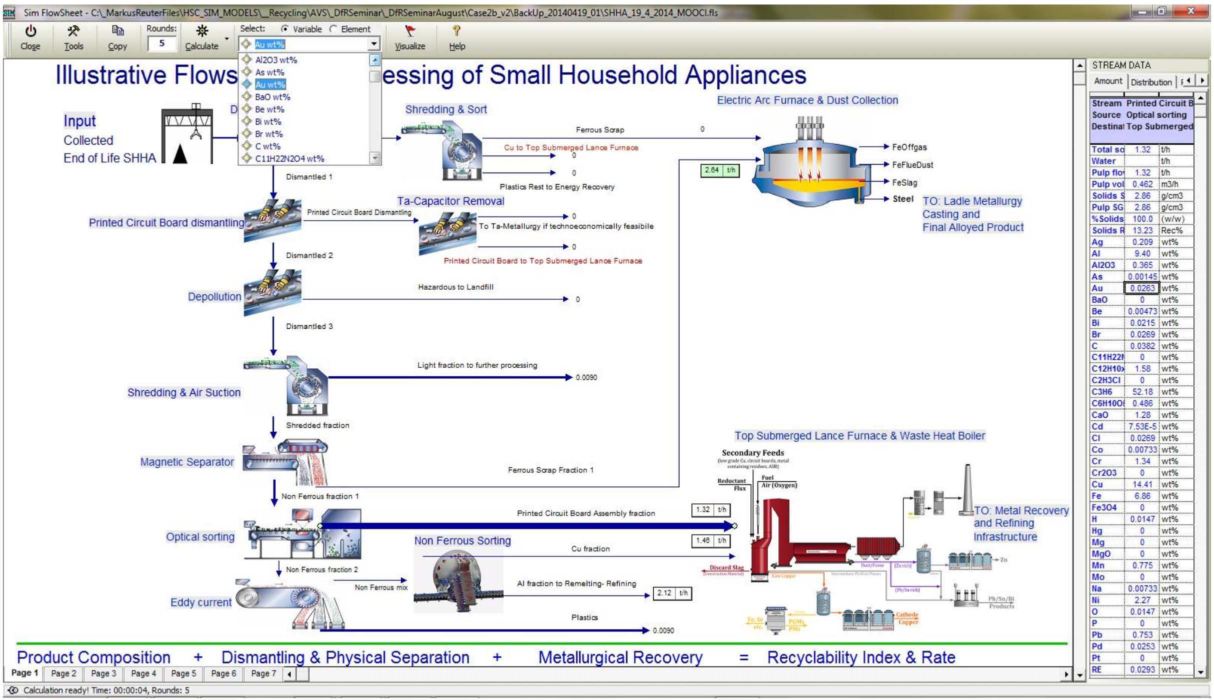


Figure 9 Example of recycling process simulation model (developed in HSC Sim, see also Figure 5) supporting Design for Recycling; showing as an example the distribution/dispersion of Au over all (intermediate) recyclate flows and recycling products (results are equally derived for any of the other materials/elements in the product/input). This provides a true basis for Design for Recycling by pin pointing critical issues/losses, as well as for the calculation of recycling rates, environmental assessment etc.

3. Design data should be accessible and available in a consistent format which is compatible with the detail required to optimise and quantify recycling performance of products for all metals, materials and compounds present.

   ➢ Detail and format of the product data on product material composition (including chemical compounds) and construction should have the resolution to quantify, identify and localise the commodity/critical/disturbing materials (see Figure 2).

   The fundamental rigour of the Product Centric and physics based simulation approaches, provide a basis to define a rigorous data structure for data collection adjusted to the detail required for Design for Recycling. It allows for further developing of sampling systems, data acquisition and storage, data resolution and depth in terms of analysis and composition (grade), etc. This standardisation of data will help much to provide the detail that can help enable resource efficiency. This is common practice for example in minerals and metals processing system design and optimisation. It is also common practice in metallurgy in which all data is measured in such a way that it can calibrate standard polynomials for heat capacities (c_p), solution models etc. The recycling field still has much to learn from this as WEEE 'flow', product and recycling data is collected and gathered with random detail and often inconsistent and incompatible, making it of no use to truly understand, simulate and optimise resource efficiency. Figure 10 shows and example of the different levels of data and data resolution required to capture the recycling profile of a product and pin point critical DfR issues to identify and quantify potential improvement, which can be achieved through DfR. It also shows the limits thereof, determined by functional product specifications.

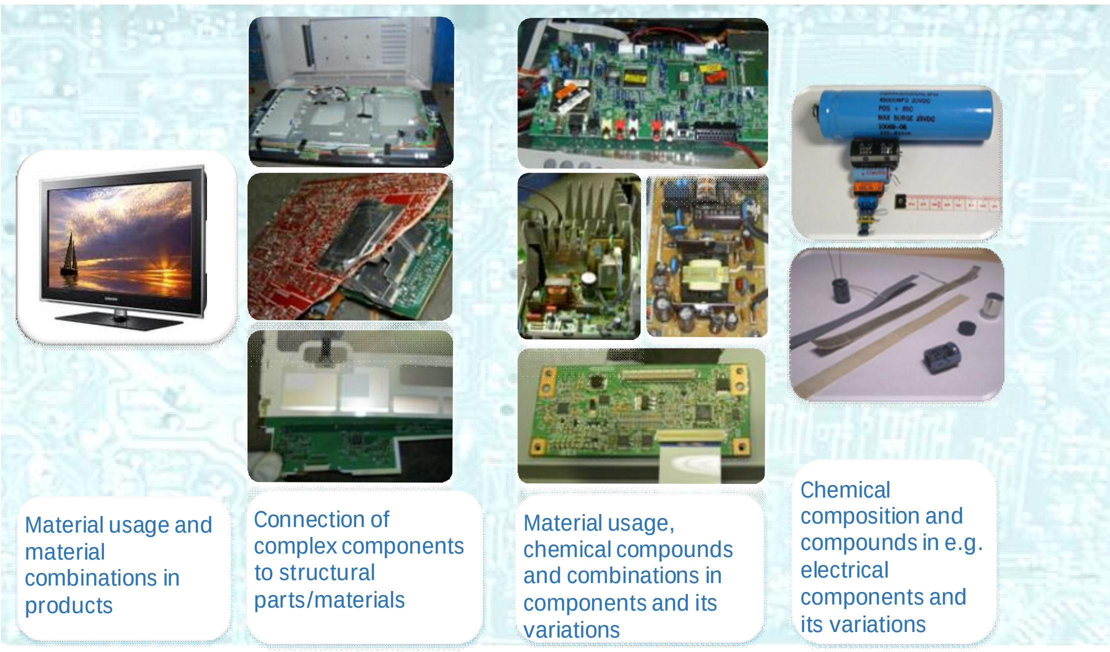


Figure 10 Example of different levels and details of data required (from BOM/FMD/chemical content analyses etc.) to capture the recycling profile of a product and pin point critical DfR issues.

4. Economically viable technology infrastructure and rigorous tools must be in existence for realizing industrial DfR rules and methodology.

   - Design must be based on a robust physical separation and sorting infrastructure that is minimally capable of producing economically valuable recyclates.

   - A robust metallurgical infrastructure and system must be in place to ensure maximum recovery of all “critical” materials from complex recyclates and dismantled functional sub-units of a product.

Figure 4 and Figure 5 illustrate the role of the metallurgical processing infrastructure as integrated part of the recycling system, which takes up the different recyclates from dismantling and sorting. The Metal Wheel of Figure 6 (Reuter et al., 2005) shows the destination (recovery/losses) of the different elements contained in an EoL product and different recyclates of physical recycling (of which the quality is design and pre-processing / sorting determined). The carrier metallurgical infrastructure (segment in the Metal Wheel) in which the recyclate will end up determines the recovery, losses and fugitive emissions of product recycling.

In the UNEP report on Metal Recycling (Reuter et al., 2013) we show that Resource Efficient recycling requires a robust high-tech interconnected metallurgical infrastructure as a crucial enabler of the EU2020 vision (EC, 2013). Companies such as Outotec (www.outotec.com) 3rd globally most sustainable corporation have a long history of supplying such high-tech mineral centric metallurgical processing technology. Figure 11 shows briefly some of the infrastructure that is required to recover high purity metals and materials from various inputs. Figure 9 shows where this whole refining flowsheet fits into the bigger recycling picture.

At the heart of Product Centric recycling is deep knowledge of this metallurgical infrastructure linked to design, collection (product mixtures/categories collected in a stream) and pre-processing (including dismantling); a brief explanation of what is meant by this is given below by discussing the complexity and detailed knowledge of extractive metallurgy and thermodynamics required to understand and predict the complex interactions and interlinkages between metals/materials for the example of the recovery of metals from a complex PCBA. Recycling/recovery of the metals on a PCBA (including all active and passive components) have been assessed by simulations of the metallurgical smelting using Pb- & Cu-metallurgy as basis (FACT Sage 6.4, 1976-2013). Figure 12 shows the recovery of different metals present on the PCBA into the metal phase (from which they can be recovered) in a TSL furnace as a function of temperature (T) and partial oxygen pressure (pO_2) as well as the solution thermodynamics of each phase. Note that a wide range is given, while in reality furnace operation, smelting campaigns, feed mixes, furnace type, etc. determine which oxygen partial pressure prevails in a narrow window. Thus it is incorrect to take a specific window that looks good for one metal only (which is a tendency of simplistic DfR approaches to do so). One tries to operate in a window that maximizes recovery of many elements at the same time into the phases from which they are best recovered downstream during refining.

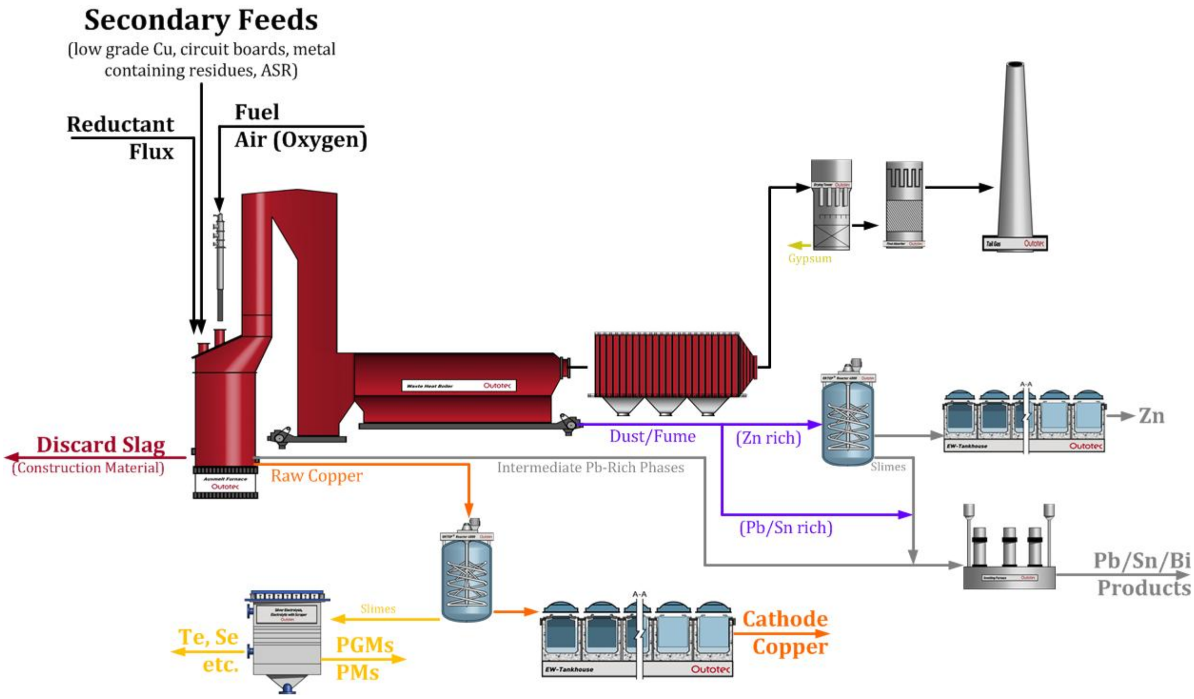


Figure 11 A company such as DOWA Japan (http://www.dowa-eco.co.jp/en/recycle.html), exploits fully the refining metallurgy of at least 4 segments of Figure 6 i.e. that of Copper, Lead, Zinc and Nickel to produce various refined high quality metal products and compounds from various inputs (also see Figure 5 where this fits into the bigger system).

It is self-evident from Figure 12 (Van Schaik and Reuter, 2014) that in order to recover metals from complex mixtures of recyclates, very careful control and understanding of the theory of metallurgical reactor technology is required to obtain metals that report to fractions from which these can be economically recovered. It reveals that recycling is clearly a complex thermodynamic and resulting economic puzzle to solve, obviously with no one answer or one set of Design for Recycling rules, and not solvable with beautiful credos such as cradle-to-cradle. It would also be self-evident that "mining" the urban mine, which has the sound of hype to it, will be rather a complex and even (economically) impossible task as reflected by the nonlinear effects (see Figure 12) and the complexity of the urban "ore body" and its "mineralogy" (Figure 3).

MARAS Material Recycling and Sustainability

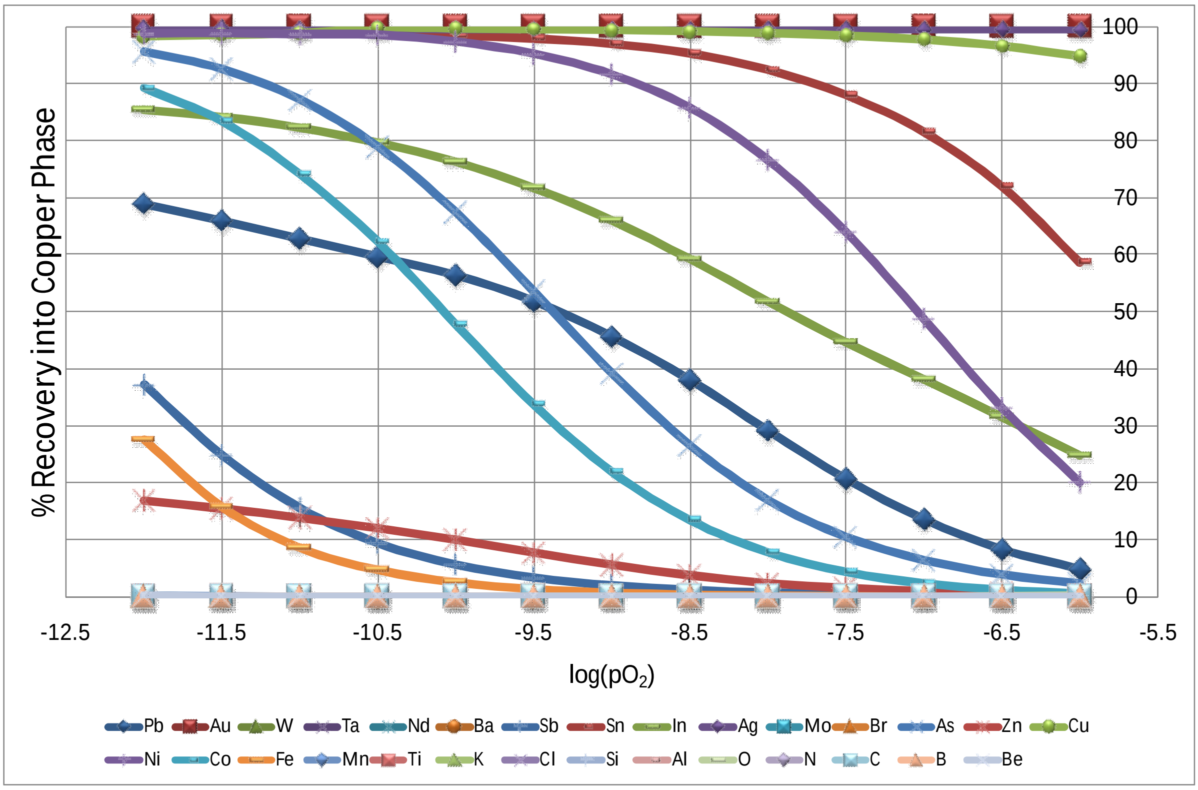


Figure 12 Recovery of a selection of the many elements present in the PCBA into the copper phase of PCBA smelting at 1300°C as is with copper present as solvent – temperature too low to melt all oxide species – thus the slag is under these conditions in some pO_2 ranges not totally molten with various spinels and other precipitates present. Note that many of the metals report to other phases and/or thus crowded close to the 0% recovery level and thus only visible on a logarithmic scale. As also mentioned above, the solution models in FACT also do not fully cover the complete range of elements in the PCBA and the above is also to be considered only indicative. Filling the gaps in the solution models is the real challenge in DfR and NOT simplistic DfR rules.

It is clear that for each new mixture and each condition this separation as presented in Figure 12 will be different (please refer to DfR rule 1), which is also a function of the activity coefficients of elements in copper as shown by Figure 13.

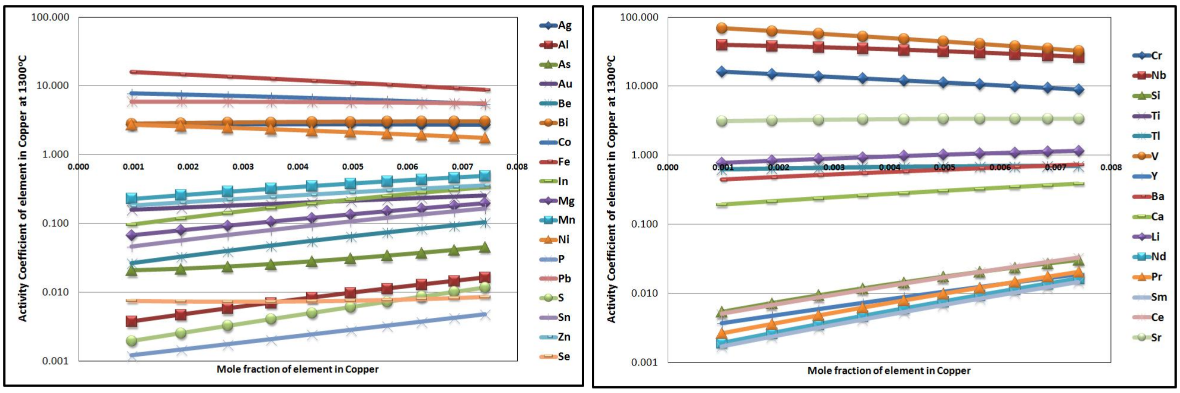


Figure 13 The activity coefficients of various elements at 1300°C in copper that define their possible recovery into copper or into other phases during smelting and refining.

These simple examples imply that general (Material Flow Analyses/Life Cycle Assessment/DfR) methodologies, that do not address this depth of mineralogy (i.e. compounds, alloys, transformations, etc.) and solution thermodynamics will obviously and inevitably lead to false conclusions and uneconomic and unrealistic technological and policy (including eco-design) recommendations for recycling. This discussion also suggests clearly that all the figures in this report are snapshots and will be different for each new situation. The figures reveal that is extremely tricky and nonsensical if the metallurgy is disregarded in recycling/recovery rating and DfR approaches.

- Environmental footprint and eco-design should include the whole chain of processing to ensure that all materials, residues, fugitive emissions are tracked (Figure 2). This requires suitable global policy to be in place.

5. CAD, Process and System Design tools must be linked to recycling system process simulation tools to realise technology based, realistic and economically viable DfR.

Linking of existing and industry applied Process Simulation tools to CAD/Design tools is a necessary step forward to realize realistic and economically viable DfR (see Figure 2). This is a rigorous basis for industrial useful DfR rules and methodology. The example in Figure 2, Figure 5 and Figure 9 shows that based on rigorous recycling process simulation and detailed product compositional data derived from CAD/Design tools Recycling performance indicators and Recycling Indices including Environmental Analyses can be derived. The simulated Recovery rates for commodity and minor/critical materials and Recycling indicators provide the basis for DfR. Ecolabels for a product can be derived on this basis, which provide the depth to rigorously distinguish differences in product designs and identify the most Resource Efficient designs. This approach rigorously incorporates the detailed product design and recycling system dependent composition (grade) of all streams, residues, effluents etc. (see Figure 9) into the evaluation for DfR. The mass flow models provide a rigorous basis for any 'add-on' analyses such as environmental and/or economical analyses. See Figure 2 illustrating the software based link between HSC Sim and Gabi which allows for the link of process simulation tools with environmental assessment software.

In the EU 6th framework project SuperLightCar (SLC, 2005-2009; Krinke et al., 2009) a software based link between CAD, recycling process models, Life Cycle Costing tools and Life Cycle Assessment Software (PE Gabi6, 1992-2013) was realised, proving the capability of linking these different types of tools for DfR for large international OEM's and their complex and highly sophisticated and functional, safety and energy consumption demanding product requirements.

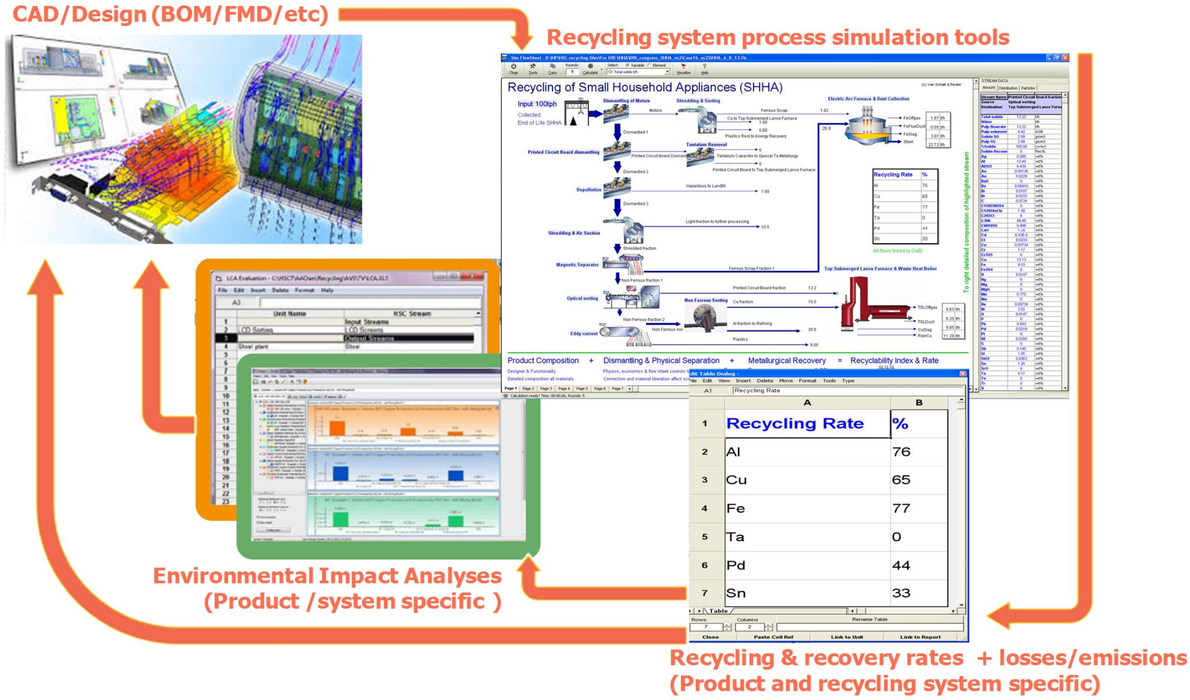


Figure 14 Example of linking existing Process simulation software (including process flow sheet design), with compositional data for a product derived from CAD/Design tools (BOM/FMD/etc) (here example on LCD screens), which lead to simulated resource efficiency data that, in turn, lead to a recyclability index based on environmental analysis as the basis for DfR (a physical and metallurgical processing infrastructure is prerequisite (Reuter et al.,2013; Van Schaik and Reuter, 2014).

5.2 Possible Design for Recycling Guidelines–Derived from the Fundamental DfR Rules (Iteratively checked by simulation and for validity, while being subject to a mindful consideration of product/component functionality)

Various Design for Recycling Guidelines can be derived by applying the above listed Fundamental DfR rules and principles. Recycling process simulation tools are used to define, validate and quantify the set of guidelines per product (of which the list below shows some possible guidelines). This physics based approach also can set priorities between the different guidelines and quantify the necessity and potential result of DfR.

Examples of the below guidelines can be found in general DfR approach, however by the implementation of the Fundamental Rules and simulation as a basis to derive and refine these, unique sets of guidelines are derived per product as a function of material mix and (BAT) recycling systems, including a mindful consideration of product functional demands (whereas a fixed set of all possible guidelines will leave no room for the designer to design/construct a product).

Input from recyclers (pre-processing plants) has also been used in defining examples for the certain guidelines.

6. Identify and minimize the use of materials which will cause losses and contaminations in recycling due to material characteristics and behaviour in sorting.

   Some examples are:

   - Use and construction of concrete in washing machines, which is difficult to dismantle and distributes over different recyclate streams;
   - Use of glass plates in fridges, which is considered as process waste and hence decreases recyclability;
   - Application of isolation materials which are difficult to sort and will contaminate different recyclate fractions and hence lead to losses; and
   - Use of coloured (other than brown, green) Printed Circuit Boards, which will lead to contamination of PCB fraction with e.g. coloured plastics or losses of PWB to other recyclates.

Figure 15 Some examples of materials applied in WEEE and the problems arising in sorting/separation as a consequence.

7. Identify components/clusters in a product, which will cause problems and losses in recycling due to combined and applied materials.

   - A compatibility matrix can be derived per product based on the knowledge behind the Metal Wheel and is useful for a quick first screening. It is important to realise that compatibility tables are no DfR tool on their own, since this gives no quantitative indication of resource efficiency, material recovery, losses and fugitive emissions. Figure 16 gives an example of derived compatibility matrices for a complete LCD display (including PCBA) and a PCBA in a Large Household Appliance (e.g. washing machine).

The Metal Wheel (Figure 6) indicates the consequences whereas simulation quantifies these in terms of recoveries, losses and emissions capturing the complexities and depth of recycling technology, its physics, chemistry and economics.

(a) (b)

Figure 16 Example of a material (in) compatibility matrix for (a) LCD display (including PCBA) and (b) a PCBA in Large Household Appliances showing the (in)compatibility of elements in the product/component with the various carrier metal processing routes (Metal Wheel). Aggregated product data originating from different sources is presented. Product/component compositional data can also differ for different designs.

8. Design clusters or sub-units in products that can be easily removed and which match with the final treatment recycling options (i.e. Metal Wheel Figure 6) e.g.:

   - Design products in such a way that critical components are present on separable or removable parts or components (see Figure 17).
   - Examples are the use or removal of Al applied as heat sinks on a PCBA; separate PCBAs for different functions e.g. power boards (high Fe content, which will be lost in PCBA processing route), control boards; removal of Ta capacitors, etc.

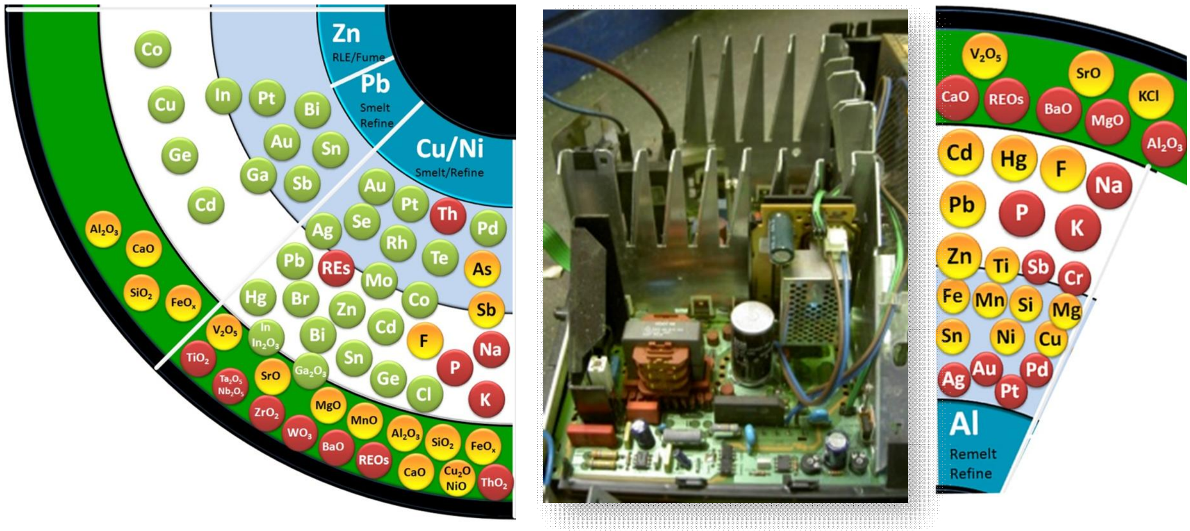


Figure 17 PCBA material cluster or sub-unit (middle) and example of 2 segments of the Metal Wheel, i.e. Cu/Ni infrastructure (left) and Al smelting infrastructure (right) showing the (in)compatibility (and hence recoveries and losses) in final treatment options (metallurgical infrastructure – see Metal Wheel in Figure 6).

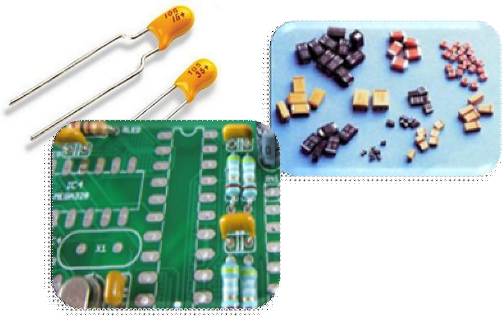
9. Labelling (including carefully considered standardisation) of products/components based on recovery and/or incompatibility so that they can be easily identified from recyclates and waste streams. Thus Design for Waste stream sorting or Design for (Automated) Dismantling/Sorting are important.

   Examples are (see Figure 20):

   - Use of colour or identification based labelling & easy to break connections for Ta capacitors. Of crucial importance is metallurgical knowledge as captured in Process Simulations tools to understand what the quality requirements are for the existing industrial Ta production/recycling infrastructure
   - Labelling/identification based Waste Stream sorting of CFL from LED lamps;
   - Standardisation of marking & identification (e.g. type of marking and position) of cooling liquid & gas and marking of type of liquid & gas applied in fluid system and foam (these might be different); and

➢ Marking of tapping point on compressors.

Design for Waste Stream sorting provides a close link to the organisation of collection system and product mixtures as derived through collection. Knowledge on the behaviour of material mixtures in recycling and in particular metallurgical processing, can provide insight on the 'Redesign' of collection categories (i.e. by pin pointing undesired products/materials).



Ta capacitors – color/identification based labelling & easy to break connections

CFL versus LED lamps

Compressors - Marking of tapping point

Standardisation of marking/identification (incl. position) of cooling liquid/gas for fluid system and foam

Figure 18 Some examples of requirements and suggestions for labelling and marking for Waste stream Sorting and (Automated) Disassembly & Sorting (including input from recyclers/pre-processors).

10. Be mindful of liberation of materials in design (Design for Liberation)

Simulation and knowledge on liberation behaviour in relation to design, particulate and recyclate quality and recycling (metallurgical) efficiency is crucial. Examples are:

➢ Avoid bolts/rivets of dissimilar materials (e.g. Fe bolts to Al, PCBA, plastics, etc.) as these produce generally a liberation problem therefore creates cross-contamination of the different recyclate fractions (see Figure 19);

Figure 19 Some examples of bolts/rivets from dissimilar (incompatible) materials.

- ➢ Minimize the use of non-reversible adhesives for incompatible & undesired material combinations (see Figure 20);
- ➢ Examples are gluing of glass on steel mask of CRT TV, shrink films on tube lamps, sealed batteries, PUR foam glued to steel/aluminium/plastic, wood glued to plastic, etc..

Figure 20 Non-reversible adhesives for incompatible & undesired material combinations causing problems and material losses during liberation, sorting and final treatment processing.

Crucial to the understanding of recycling and residue processing and Design for Recycling is the inclusion of liberation and particulate quality as a function of design and comminution and hence recyclate quality in the description of recycling system and its effect on recovery, losses and fugitive emissions in metallurgical processing (see Figure 4 and Figure 12). EoL products and their "mineral" structure have been linked by simple "mineral" liberation data structures gathered from extensive data collection and analyses of pre-processing recyclate fractions and contained particles (see Figure 21), while at the same time linking this to metallurgical processing (see Appendix A for more detail).

Figure 21 Particulate quality (determining recyclate quality and recovery/losses) as a function of design. An impression of unliberated and multi-material particles as found in various WEEE recyclates.

In the modelling of liberation parallels were drawn between classical minerals processing and the shredding/size reduction of EoL products (Richard et al., 2005). As an example Table 2 compares various aspects of relevance between crushing and grinding from classical minerals processing and EoL shredding. Understanding this well; makes it possible to better quantify losses in the system through physical phenomena as well as through dissolution of metals in inappropriate phases. This is the true basis for quantifying sustainability, which lies at the basis of the presented system models (see Figure 5 and Figure 9). This table shows that significant work still has to be done on the description on how particles are liberated in residue and EoL processing systems, although some work is available that has attempted to better to understand these phenomena (Van Schaik and Reuter, 2010; Richard et al., 2005; Castro et al., 2005; Van Schaik et al., 2004) (see Appendix A for more detail on the modelling of liberation and modelling of recycling systems).

Table 2 Comparative elements between comminution modelling in minerals processing and End-of-Life shredding/cutting modelling with often non-brittle materials and complex joining.

Minerals processing	EoL Shredding/Cutting
Mineralogical Texture: Size of mineral grains in the particles, the grade or analysis, their shape, orientation and position, liberation (may be > 15).	*Design:* Materials choices, size and shape of the elements of the product, the joints between these different elements, complexity of product, the detailed analysis of many elements (may be >40).
Minerals properties: Minerals are generally considered as brittle and hard materials.	*Materials properties:* Since the large range of elements composing cars, different materials behaviours have to be considered, from brittleness to very ductile.
Liberation: Detachment by comminution (particle size reduction) of one or more species of mineral from the complex in which it is bound in a larger fraction of gangue material of little economic value.	*Liberation in End-of-Life products, waste, residues:* To be further developed on the basis of the complexity of modern products, where all materials can be valuable

6. Policy recommendations

Some policy targets and recommendation have been derived from these rules with regard to recycling and eco-design. These have been translated into a Manifesto which was handed over to the Dutch Lower Chamber (NVMP/Wecycle, 2013):

- design rules should remain within what is physically, technologically and thermodynamically possible and should hence be based on recycling process simulation tools and knowledge;
- must be set in ways that account for the loss of metals due to mixing in products (for product functional specifications);
- should reflect the interest and expertise of all stakeholders in the product and recycling system and stimulate interaction;
- should respect the dynamic (time-varying) product characteristics and hence recycling profile over time; and
- should be set aligning with economic drivers.

Stimulation of the use of certified BAT/P (Best Available Technology/Techniques and Processes) is essential to achieve the best results in a recycling chain that uses raw materials efficiently. It must cover the collection, sorting and mechanical recycling right up to the metallurgical final processing. This requires the definition of a level playing field for all actors in the field. In order to realise the efficient use of raw materials, it is crucially important to safeguard recycling and high-tech metallurgical infrastructures and the knowledge required to operate these processes on an international playing field. Stimulating knowledge and training young people in the relevant technical areas of expertise are important activities in an international context. Also consult the UNEP report on Metal Recycling: Opportunities, Limits, Infrastructure (Reuter et al., 2013) for more policy recommendations.

7. Conclusions

It is clear from the above discussion and presented DfR rules and guidelines, that Design for Resource Efficiency (DfRE), of which Design for Recycling (DfR) is a sub-set, demands knowledge of liberation behaviour, of the particulate quality of recyclates, of the separation efficiency linked to the compatibility and thus recovery and/or loss of material in metallurgical processing, and of the modelling thereof, all as a function of design choices, connection type and connected materials. Insight into this provides a technology- and industrial-process driven basis for DfR to optimize resource efficiency and closure of material cycles for both commodity and critical and scarce elements in complex consumer products, such as cars and e-waste/WEEE products. This all should be read in line with the recent UNEP Metal Recycling report, which gives a detailed overview over metal recycling and also links recycling to Urban Mining and (Enhanced) Landfill Mining. In view of the discussion on DfR in this report and the UNEP report, some points can be kept in mind when advancing the field of Design for Resource Efficiency and Design for Recycling and its suggested more product centric view to it. With reference to the such diverse number and complexities of E-waste products, but also for any other complex EoL product from the Urban Mine and forms of materials and spatially distributed diverse, heterogeneous, reacted/decayed, fines containing excavated waste from the landfills being a source for metals and materials to be obtained through recycling, the following should be considered:

- develop as far as possible the description of the recycling system on the basis of the theory that is already available from minerals and metals processing in order to optimise the systems as rapidly as possible, while also further innovating and advancing the theory and deeper understanding;
- base the DfRE and DfR efforts and descriptions on rigorous process simulation as done for recycling;
- this will help also to further develop a Product Centric approach to mining landfill and products from the Urban Mine, very much like mining classical minerals and processing these in a minerals (product) centric manner;
- ensure that data structures are developed in accordance with standard minerals processing standards and sampling is done in accordance with rigorous available techniques, which enables the calibration of rigorous simulation models;
- ensure that the complete system is modelled from landfill to metallurgy to ensure a decent economic CAPEX and OPEX analysis can be made to ensure the developed ideas make economic sense;
- the rigour suggested by the DfR rules also ensures that research is focussed on the issues that are of true value and will lead to true innovation;
- understand the thermodynamics of the system as well as kinetic issues that may affect the outcome;

- understand the distributed nature of all variables in the system in order to obtain an indication of the risk involved in the urban mine "ore body", thus the use of Kriging techniques and sampling theory are of paramount importance; and
- understand the dynamics of the market as well as the available metallurgical infrastructure as these are key to extract metal value.

Obviously this list can be extended or perhaps even shortened, but is a basis for a rigorous discussion on resource efficiency, which is ultimately the goal of DfR, DfRE and also Urban and landfill Mining. Fundamental rigour and theory is the common language, which is important to harmonise discussion and bridge the gap between the waste processing, metallurgical, OEM, resource recovery, materials science, recycling and other silos. This should be a pressing outcome for our exciting but urgent innovation ahead of us. Society and the taxpayers demand that of us.

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Appendix A - Modelling of recycling in HSC Sim

A.1 Modelling design characteristics and shredding (liberation and particle composition)

The modelling of design characteristics and liberation has been extensively described by Van Schaik and Reuter (2010). Three basic matrices are defined that (i) describe design in terms of materials and connections and related connected masses as well as link design to (ii) resulting material connections after shredding and (iii) material liberation by the modelling of shredding behaviour using these matrices.

The product design characteristics and material clusters as derived from and identified by design data (either collected by dismantling or from CAD data) are in the model translated into a *'Design table'* $D^{l,k}$, which describes the mass of the individual materials *'k'* and combinations in the product as derived from the data collection on material composition and material connections in the product/component as described above (or derived from CAD software). Each material cluster is represented in this *'Design table'* by separate 'liberation or material connection classes' for the un-liberated classes *l* = $LC1_1$, $LC2_1$ to LCM_1, in which *'M'* represents the number of different material clusters present in the design, roughly equivalent to the major components of a product. Material clusters consisting of one material are defined by the definition of liberated classes, for which *l*= $LL_{1\text{ to }x}$. The liberation/connection classes *'l'* contains the information on the masses of the materials *'k'* connected in the unique combinations of connected physical materials representing a material cluster. A material *'k'* can be present in different clusters; the mass of the material *'k'* is hence spread over different clusters and hence allocated and defined accordingly in the 'Design table' to ensure closing of mass balances. The mass of the individual materials *k* as derived from the material analysis of the product and present in different clusters is hence distributed over the different $LC1_1$, $LC2_1$ to LCM_1 classes defined in the *'Design table'*. Each design will be represented by a unique '*Design table'*.

The liberation behaviour of a product during shredding is characterised by two different key principles:

(i) Liberation of '*design-defined material clusters'* into non-liberated particles. These particle can either contain the material combinations as initially defined in the design (containing equal or different mass ratios between the various materials 'k') and/or can liberate into newly created non-liberated binary, ternary and/or multi-material particles (liberation/connection classes), which are sub-sets of the initial material combinations classes as defined in the *'Design table'*; and

(ii) Liberation of materials into fully liberated (pure) particles.

The shredding process is modelled in based on these two principles, by the definition of two different 'matrices' (in fact shredding equations) by which the particle compositions and degree of liberation of the output stream of the shredding process can be calculated:

(i) 'Shredder Connection Table' $SC^{l,k}$ – models the liberation of the individual materials *'k'* for the different material clusters of the design into similar and newly created non-liberated particles (liberation/connection classes) and hence provides the basis to calculate the masses of the different materials present in the different material connection/liberation classes (original and new) after shredding.

(ii) 'Shredder Liberation Table' $SL_i^{l_d,l_y}$ – models the distribution of the different material clusters of the design l_d into liberated and un-liberated particles of the output l_y and hence provides the basis to calculate the mass of the liberated materials *'k'*.

Since each material cluster can in theory remain connected during shredding (containing equal or different mass ratios between the various materials 'k') and/or liberate into each possible binary, tertiary or multi-material combination of the initially connected materials and can liberate into their pure components, liberation/connection classes will be created in the model for each of the non-liberated (sub-)classes l = $LC1_{1\text{ to }a}$, $LC2_{1\text{ to }b}$ to $LCM_{1\text{ to }z}$, as well as fully liberated materials for which l= $LL_{1\text{ to }x}$. The indices a to z represent the number of connection/liberation sub-classes which can be created from each of the original clusters and are determined by the amount of elements k present in one cluster. The number of liberated materials is defined by the number of materials *'k'* present in the product, hence *'x'='k'*. In order to facilitate calculation of liberation behaviour during shredding, these shredding-created liberation/connection classes and liberated classes are added to the *'Design table'*. Since these classes are not present before shredding, the masses of the different materials *'k'* in these classes in the *'Design table'* are zero.

The degree to which the different material connections are liberated, and the new connection classes created are determined by the connection characteristics of the product/component. The re-distribution of the materials k in the non-liberated design connection classes l = $LC1_1$, $LC2_1$ to LCM_1 over the non-liberated design defined and newly created sub-classes l = $LC1_{1\text{ to }a}$, $LC2_{1\text{ to }b}$ to $LCM_{1\text{ to }z}$ is defined in the model by the '*Shredder Connection table'* $SC^{l,k}$. The degree to which the different materials in the initial connection classes are fully liberated or remain un-liberated is described by a *'Shredder Liberation table'* $SL_i^{l_d,l_y}$ for each material connection class as defined in the *'Design table'* $D^{l,k}$ (or intermediate recyclate stream entering a next liberation process $f_i^{l,k}$). To guarantee the closure of material mass balances, the sum of the fractions reporting to the original and sub-classes as defined in the *'Shredder Connection Table'* must be 1.

The same applies to the sum of the materials reporting to the non-liberated and liberated classes as defined in the *'Shredder Liberation Table'*.

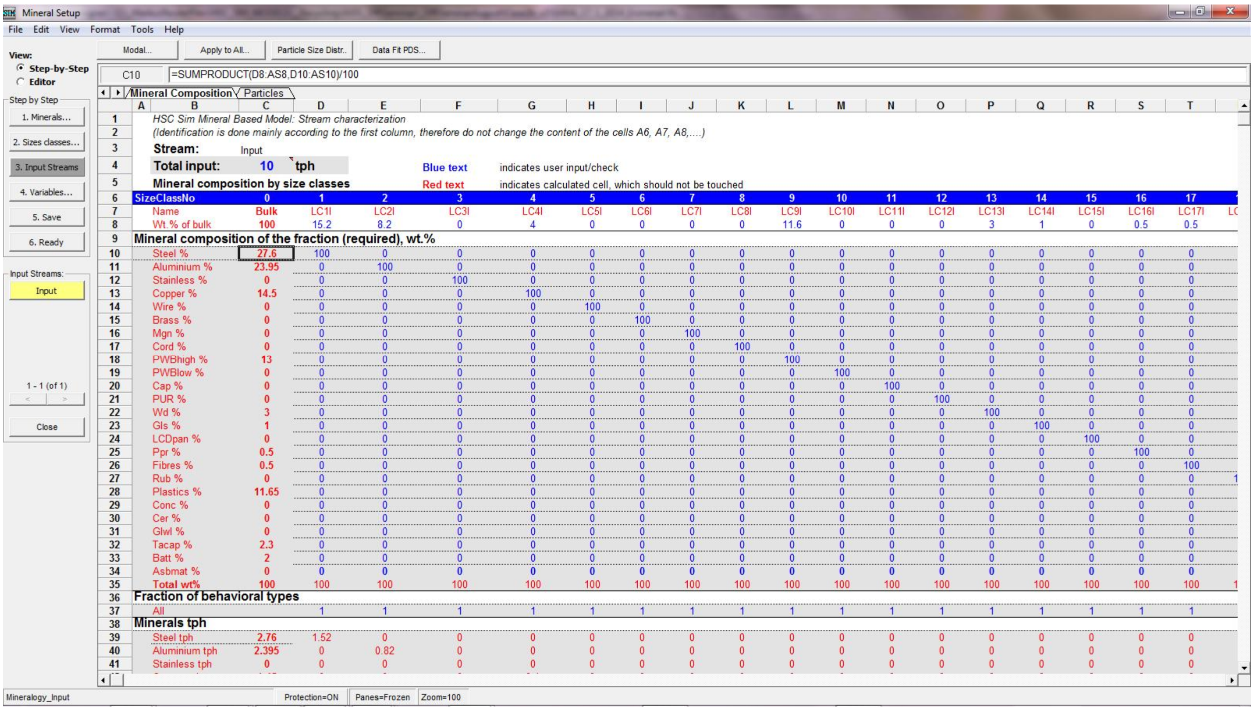
The mass balance over the shredder process *i* and hence the calculation/prediction of liberated materials and connected material masses in the non-liberated classes after shredding is described by the following set of equations (Eq. 1)

$$y_i^{LC1_{1-a},l_y,k} = D^{LC1_1,k} \cdot SC^{LC1_{1-a},k} \cdot SL_i^{LC1_{1-a},l_y}$$
$$y_i^{LC2_{1-b},l_y,k} = D^{LC2_1,k} \cdot SC^{LC2_{1-b},k} \cdot SL_i^{LC2_{1-b},l_y}$$
$$\ldots$$
$$\ldots$$
$$\text{to} \qquad \text{(Eq.1)}$$
$$y_i^{LCM_{1-z},l_y,k} = D^{LCM_1,k} \cdot SC^{LCM_{1-z},k} \cdot SL_i^{LCM_{1-z},l_y}$$

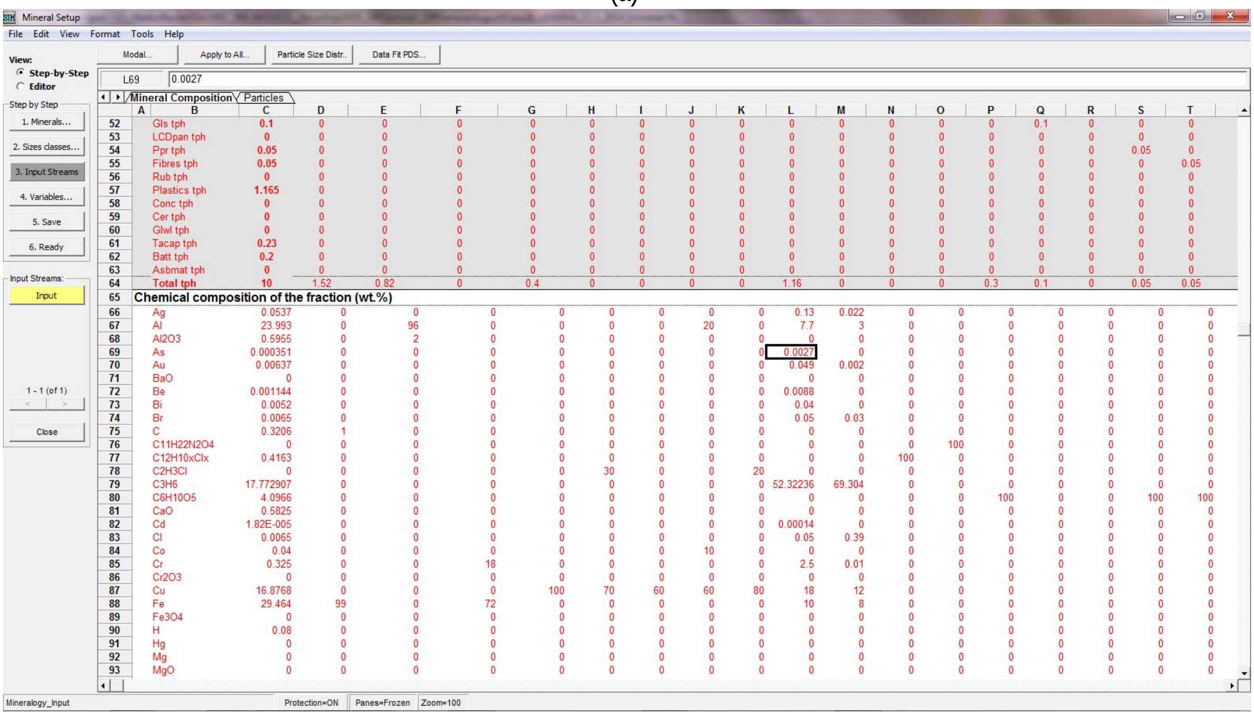
where

$$y_i^{l_y,k} = y_i^{LC1_{1-a},l_y,k} + y_i^{LC2_{1-b},l_y,k} + \ldots. + y_i^{LCM_{1-z},l_y,k}$$

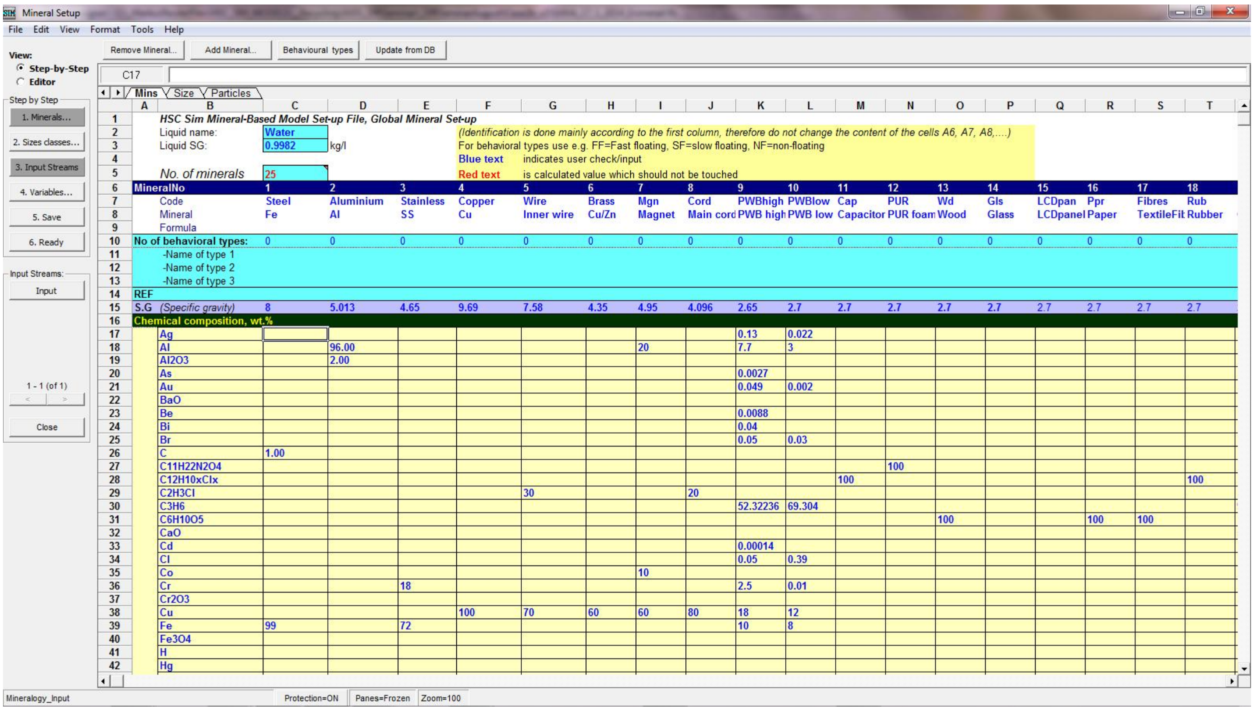
Equation 1 can capture the dynamics of time-varying design, related shredding performance and hence recyclate quality and recycling behaviour for different WEEE products and components. This first principles link between design and recycling facilitates the performance of Design for Recycling as a function of the dynamic characteristics of design and recycling technology. The screen captures from HSC Sim 7.1 as given in Figure 22 give an impression on how the above liberation modelling is captured in the models.


Mineral Setup
HSC Sim Mineral Based Model: Stream characterization
Mineral composition by size classes
Mineral composition of the fraction (required), wt.%
Fraction of behavioral types
Minerals tph

(a)


Mineral Setup
Chemical composition of the fraction (wt.%)

(b)



(c)

Figure 22 Screen capture from HSC Sim showing (a) the modelling of liberation particles LCXX as captured in the models of Figure 5 and (b) some element analysis of the liberation classes as a function of the different materials in the product as listed in (c).

A.2 Modelling of physical separation

Separation efficiency can be described as a function of particle composition in the recycling models (Reuter et al., 2005; Reuter, 2011; Van Schaik et al., 2004; Van Schaik and Reuter, 2010; 2007). This means that separation efficiency calculations of multi-material (unliberated) particles are based on the pure elements in a process, describing the imperfection of separation to achieve recyclate quality and hence recycling performance. The separation efficiencies for multi-material particles are calculated for all physical separation processes and for all multi-material particles (material connection classes) according to a weighted average

$$R_{i,y}^{l} = \frac{\sum_k R_{i,y}^{k} \cdot F_i^{l,k}}{\sum_k F_i^{l,k}}$$

$$R_{i,x}^{l} = \frac{\sum_k R_{i,x}^{k} \cdot F_i^{l,k}}{\sum_k F_i^{l,k}}$$

where

$R_{i,y}^{l}, R_{i,x}^{l}$ recovery factor (separation efficiency) for liberation/connection class l for unit operation i to output streams y, x, etc. (Eq.2)

$R_{i,y}^{k}, R_{i,x}^{k}$ recovery factor of material/element k for unit operation i to stream y, x, etc.

$F_i^{l,k}$ input stream to unit operation i

in which

$$R_{i,y}^{k} + R_{i,x}^{k} + R_{i,z}^{k} = 1$$

and (Eq.3)

$$R_{i,y}^{l} + R_{i,x}^{l} + R_{i,z}^{l} = 1$$

This results in a separation table for each process step in which the separation efficiencies (recovery factors) for each connection/liberation class *l* are defined distributing the input of the process to each of the output streams. These data are based on first principles and tested by the extensive experience and industrial data sources of the authors. Mass balances are defined for each unit operation i and j. The following equations apply to the physical separation processes for connection/liberation class *l* and element *k* between the different unit operations i within the flow sheet of Figure 3 and the structure of the network of processes determined by the structural (or scenario) parameter α, which allows simulation of different recycling flow sheet configurations (Eqs. 4 to 8).

$$y_i^{l,k} - R_{i,y}^{l} \cdot F_i^{l,k} = 0 \qquad \text{(Eq. 4)}$$

$$x_i^{l,k} - R_{i,x}^{l} \cdot F_i^{l,k} = 0 \qquad \text{(Eq. 5)}$$

$$z_i^{l,k} - R_{i,z}^{l} \cdot F_i^{l,k} = 0 \qquad \text{(Eq. 6)}$$

in which

$$F_i^{l,k} = f_i^{l,k} + \sum_{j=1}^{n} \alpha_{ij} \cdot y_j^{l,k} \qquad \text{(Eq. 7)}$$

and

$$0 \le \alpha_{\mathrm{ij}} \le 1 \text{ and } \sum_{i=1}^{n} \alpha_{ij} = 1 \text{ (for each j)} \qquad \text{(Eq. 8)}$$

This description of the physical materials *k* and connection/liberation classes *l* allow that the composition (and therefore quality) of each of the streams in every stage in the recycling system is calculated in the model as a function of separation efficiency of pure materials for the degree of liberation and particle composition determined by product design and shredding efficiency/intensity.

A.3 Modelling of metallurgical, thermal and (non-)organics processing

Chemical description of material streams ('chemical composition of physical materials')

The efficiency and recovery of materials in metallurgical and thermal processing is based on the process thermodynamics of these types of processes and on the chemical components building up the physical materials as defined for physical separation. This requires that the physical materials in the model are translated not only into its corresponding chemical elements, but also its phases.

A *'Chemical Composition table'* $CC^{k,c}$ has been defined in the model, which transposes each physical material into its chemical elements/compounds. The transition of physical to chemical materials is described in the model based on Eq. 9.

$$\sum_l \sum_k CC^{k,c} \cdot y_i^{l,k} - y_i^c = 0 \qquad \text{(Eq. 9)}$$

This crucial information characterizes the effect that design has on recycling efficiency and environmental performance of the system.

Thermodynamics of recycling systems

Mass balances for the metallurgical and thermal processes are defined in the model based on recovery factors for each of these type of processes derived from process thermodynamics and extensive metallurgical industrial experience of the authors and their process/furnace models (Reuter and Van Schaik, 2008; 2013a&b; Anindya et al., 2013 a&b; Creedy et al., 2013; Huda et al., 2012; Chi et al., 2011&2014: the latter discusses metallurgy as part to the informal E-waste recycling system).

$$F_i^c - y_i^c - y_{primary}^c = 0 \qquad \text{(Eq. 10)}$$

$$y_i^c - F_i^c \cdot R_{i,y}^c = 0 \text{ (to metal)} \qquad \text{(Eq. 11)}$$

$$x_i^c - F_i^c \cdot R_{i,x}^c = 0 \text{ (to slag)} \qquad \text{(Eq. 12)}$$

$$z_i^c - F_i^c \cdot R_{i,z}^c = 0 \text{ (to dust)} \qquad \text{(Eq. 13)}$$

for which

$$R_{i,y}^c + R_{i,x}^c + R_{i,z}^c = 1 \qquad \text{(Eq. 14)}$$

The relationship between in- and outputs of metallurgical reactors can be expressed in thermodynamics, the irreversible losses in terms of Exergy, which is also the measure of the increase in entropy of complex (ever smaller) shredded particles lost from the system due to them not being recoverable due to their designed material combinations. These aspects have been addressed by the authors through the quantification of the performance of recycling systems in terms of Exergy (Reuter and Van Schaik, 2008; Ignatenko et al., 2007,) building on work by Szargut (2005) and Ayres (1997).

A.4 Modelling dynamics of the recycling system

The above theory can also be embedded into time dependent simulation models to predict and optimize product recycling systems; all as a function of the recycling system architecture (arrangement and combination of recycling and final treatment processes) and product design (Reuter et al., 2013; Van Schaik and Reuter, 2013; Van Schaik and Reuter, 2010; Van Schaik and Reuter, 2004).

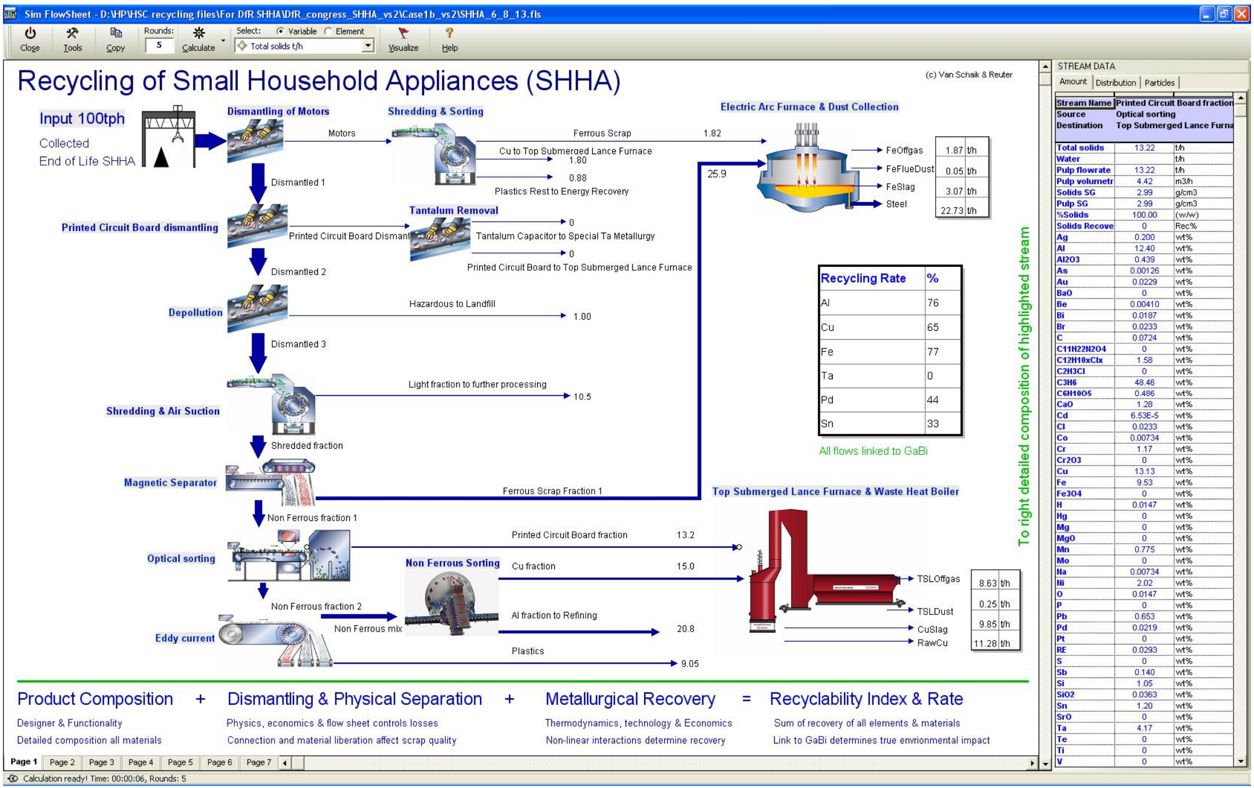
Appendix B - Some simulation examples

This section gives some examples of the application of the HSC Sim recycling process simulation models. Three different application/examples will be shown below for the recycling of SHHA (i) application of the model for (i) quantification and identification of issues in recycling (ii) assessment of redesign of design options and redesign of processing routes (i.e. yes/no dismantling) and (iii) assessment of Design for Liberation. The three different examples refer to the same baseline (i.e. design/input and recycling routes). Results on recycling performance, recyclate qualities, material recoveries and losses can hence be compared between the different simulations/examples. It should be noted that the figures and results do not necessarily represent actual industrial figures. This is to protect confidential process and product information.

B.1 Simulation example 1 : Quantification

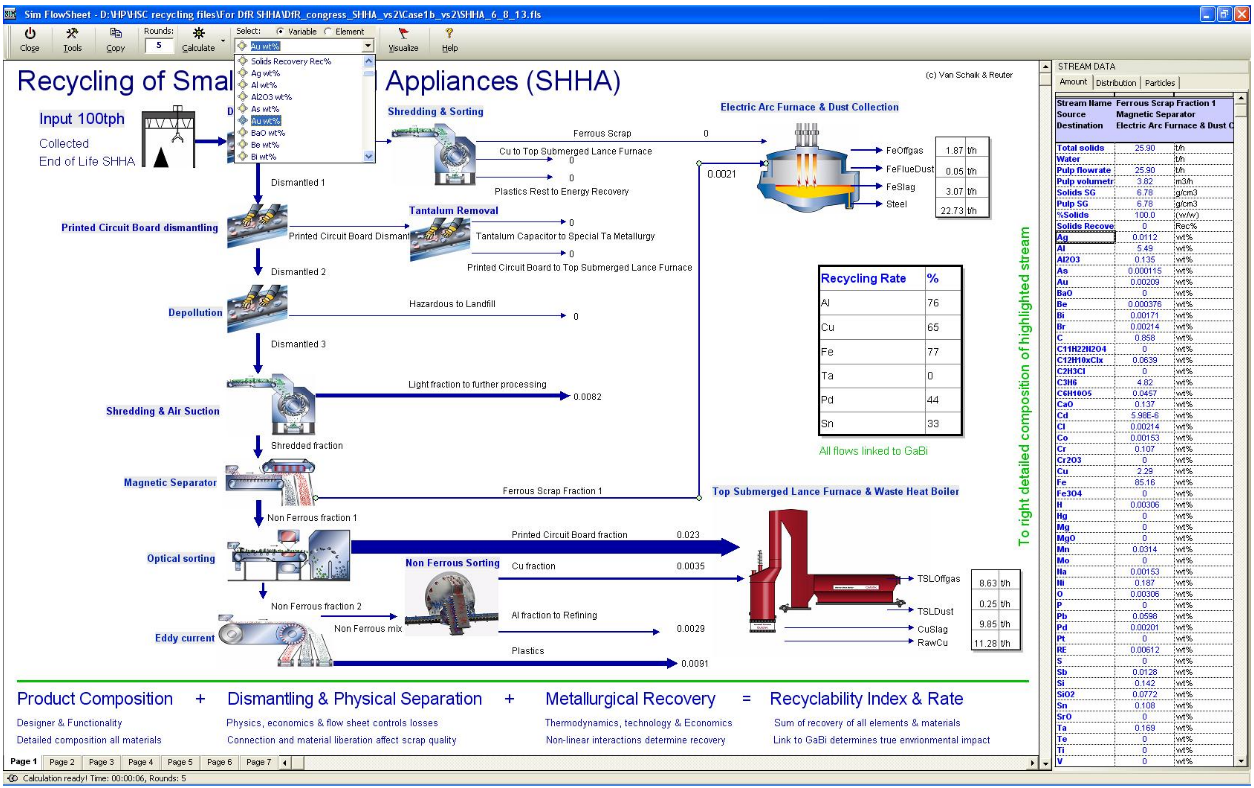
Mass balances, recycling/recovery rates and dispersion of elements/materials

The results of the simulation modeling in Figure 23 show the quantification of Recycling Rate, Mass flows and quality/composition of all (intermediate) recyclate and recycling product flows based on a full mass balance for all elements/materials in the input. Figure 23 (b) details this by illustrating that this provides the information to trace the distribution/dispersion of any element/material/compound over all flows in the recycling system.



(a)

MARAS Material Recycling and Sustainability

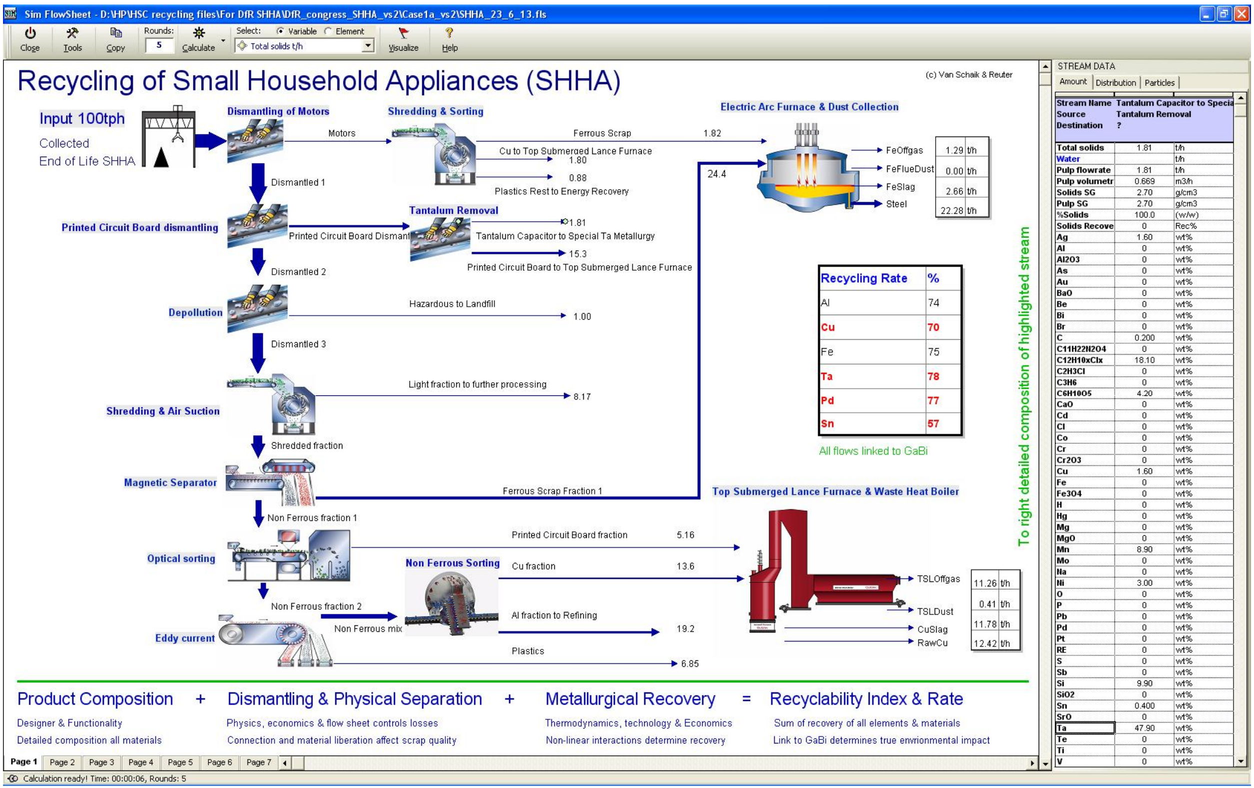


(b)

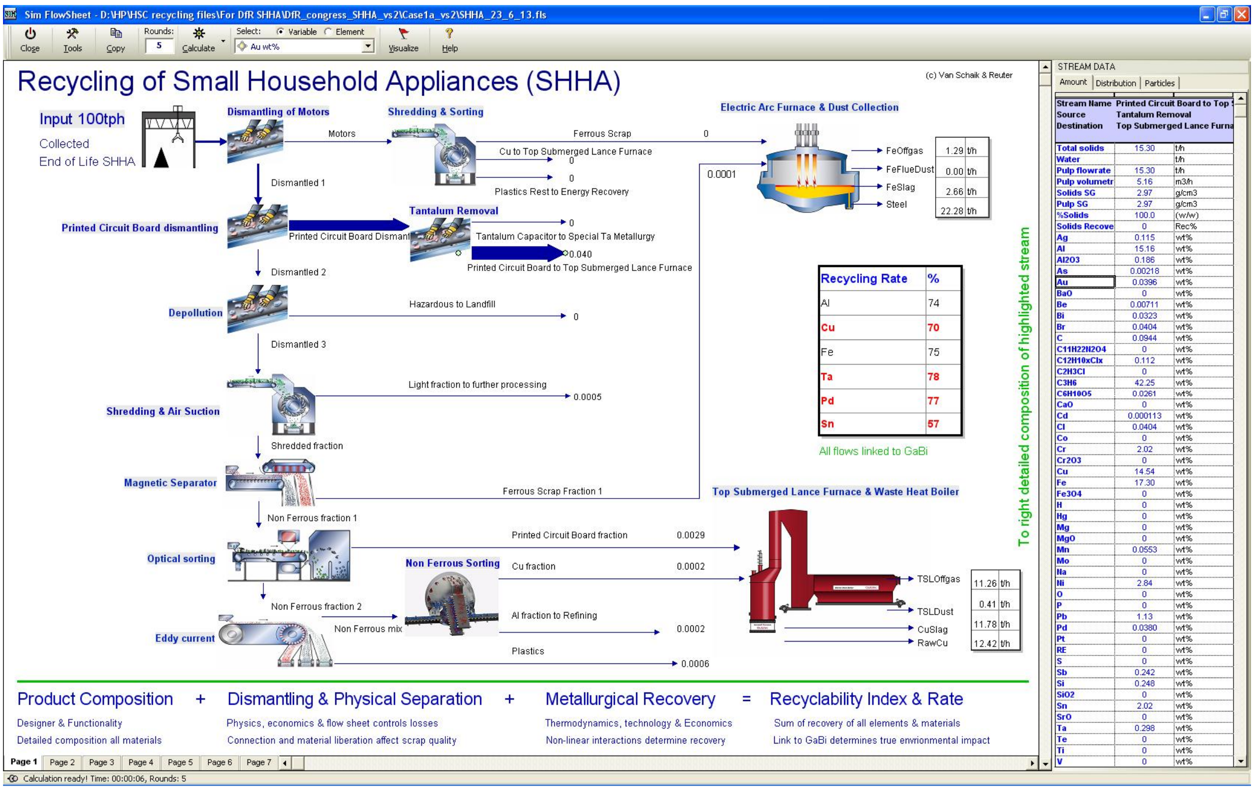
Figure 23 Example of recycling process simulation model (developed in HSC Sim, see also Figure 5) quantifying the recycling rate/performance of SHHA for the given recycling route with (a) showing the mass flows (full mass balance) and quality/composition of all flows based on all elements/materials in the product (box on the right gives the composition/quality of one of the recyclate streams based on all elements/materials - similar results are equally derived for all recyclate and recycling product flows in the recycling system) and (b) illustrates that the distribution/dispersion of elements/compounds can be traced – example on Gold (see Figure 9).

B.2 Simulation example 2 : Redesign and recycling route

The effect of removal/sorting of PCBs & Ta capacitors by dismantling (i.e. change in recycling route) through design changes by e.g. labelling and identification options for sorting have been assessed in this example. The outcomes are relative to the ones presented in Figure 23 and show some clear effects on Recycling Rate for the different metals. This example also proves that 'overall and average' recycling rates for a product or material as presented by Graedel et al. (UNEP, 2011) can reflect the recycling performance of individual materials and the entire product for complex multi-material designs. These change according to design,material combinations, recycling routes, etc. as becomes clear from the simulation results as depicted by Figure 23 and Figure 24.



(a)



(b)

Figure 24 Example of recycling process simulation model showing the effect of redesign (product and recycling route) on the recycling rate/performance of SHHA with (a) showing the mass flows (full mass balance) and quality/composition of all flows based on all elements/materials in the product and (b) distribution/dispersion of Gold relative to the results as shown in Figure 23.

B.3 Simulation example 3 : Design for Liberation

This example quantifies the effect of construction/connections of Printed Circuit Board in a product by improving the design for liberation of Al heat sinks and Fe containing components/bolts. This on the one hand results in a slightly improved recycling rate for both Al and Fe. Interesting to see is that due to improved liberation of PCBA leading to less PCBA part being dragged along to the ferrous fraction, the recycling performance of some minor/critical elements present on the PCBA (e.g. Pd and Sn) have improved.

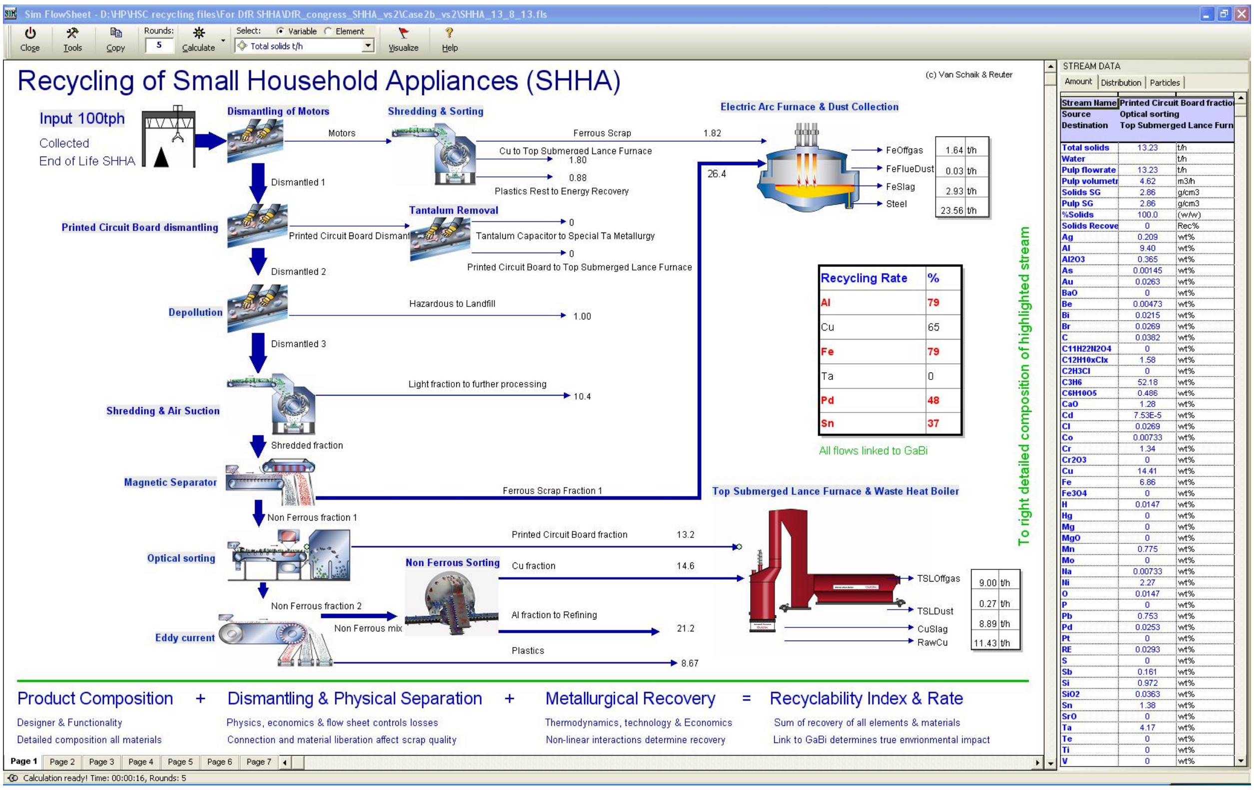


Figure 25 Example of recycling process simulation model showing the effect of design for liberation on the recycling rate/performance of SHHA (note the improved recycling rates of both Fe and Al, as well as of some minor/critical elements as present on the PCBA).