KU LEUVEN

Proceedings of the
THIRD INTERNATIONAL

SLAG VALORISATION SYMPOSIUM

THE TRANSITION TO SUSTAINABLE MATERIALS MANAGEMENT

19-20 March 2013
Leuven, Belgium

Editors Annelies Malfliet, Peter Tom Jones, Koen Binnemans, Özlem Cizer, Jan Fransaer, Pengcheng Yan, Yiannis Pontikes, Muxing Guo, Bart Blanpain

REVIEW OF METAL RECYCLING END-OF-LIFE PRODUCTS, RESIDUES, WASTES, SLAGS, DESIGN FOR SUSTAINABILITY, ECO-LABELLING

Markus A. REUTER[1], Antoinette VAN SCHAIK[2]

[1] Outotec Oyj, Riihitontuntie 7, Espoo, Finland & Aalto University, Helsinki, Finland.
[2] MARAS - Material Recycling and Sustainability, Rijsbes 47, The Hague, The Netherlands.

markus.reuter@outotec.com, a.vanschaik@marasustainability.nl

Abstract

Metals are an essential and critical component of today's society: a moment's reflection on their ubiquitous presence in virtually all energy and material production processes, products, infrastructure, confirms this. Metals play a key role in Enabling Sustainability through societies various high-tech applications. However, the resources of our planet are limited, as is the strain to which we can subject it in terms of emissions, pollution, and disposal of waste. For these reasons, finding ways to lower the environmental footprint of our collective existence and therefore lowering greenhouse gas emissions and help mitigate climate change is a vital priority[1,2]. The maximisation of resource efficiency[3] is the principal theme of this contribution. It will be shown what depth and detail that is required to systemically fully understand resource efficiency in the context of material use. Specifically the understanding of Product-Centric recycling is highlighted (setting it apart from the usual Material-Centric recycling approaches, which focus more on bulk materials), which maximises the economic recovery of especially technologically critical elements but also bulk metals. Design for Resource Efficiency is elaborated on with on the basis of physics rather than simplistic material flow analysis approaches which provide no basis to improve resource efficiency. In support of this, the detailed data that are required, the technological understanding and design rules are among others implicitly highlighted that impact on resource efficiency. The required physics basis for Eco-Labelling of products for eco friendliness of design and recycling is briefly mentioned.

Introduction

This paper discusses briefly the requirements for increasing metal recycling from various sources. A particular focus will be the recycling of the high-value, lower-volume metals that are essential elements of today's and tomorrow's high tech products, as applied in complex multi-material design such as electronics and vehicles to aircrafts or generation and storage of renewable energy. These metals,

such as gallium, rare Earths, platinum group elements and indium, are often scarce, essential to sustainable growth and yet typically lost in current recycling processes. The important role of slag chemistry and its role in enabling resource efficiency will be alluded to.

The physics based systemic approach showing the various factors that optimise metal recycling, while embracing Best Available Technology (BAT), can only be discussed briefly in this paper (for more details refer to Reuter/Van Schaik[4,5] and UNEP[6]). It requires optimising and deep knowledge and understanding on what flows through the interconnected system. Therefore deep systemic thinking as well as deep metallurgical process knowledge is paramount as well as a thorough understanding of the process technology as well its economic drivers. Currently, also valuable metals are lost because of poor collection of end-of-life (EoL) devices or within the recycling chain, and this limits achieving goals of high-resource efficiency, resource security as well as higher recycling rates. Another reason for loss of these valuable metals is the lack of a systemic physics based link between product design, material applications and combinations with final treatment process technology in the entire recycling system or chain. Much will be done if the often too simplified and linear approaches (*e.g.* MFA type methods) are replaced by more rigorous approaches that embrace and recognise the complex interlinked and non-linearity of recycling physics.

Metals are among others lost because products are not entering an appropriate recycling chain, but instead are typically dumped, exported or go to waste incinerators and are then lost in bottom ashes. But metals are lost as well when (although entering into a recycling chain) they cannot be separated during processing into thermodynamic and economic treatable fractions, often more common than generally assumed. In truth, it is never correct to believe as is so often assumed in simpler material flow models that do not include chemical transitions between different phases *"There is this much metal/element/compound in the waste product, therefore this same amount of recycled metal can be produced."* Metals are lost because the mix of metals brought together in design and during end-of-life 'waste' collection entering metallurgical processes has physical and thermodynamic properties that do not allow the processes used to separate all of them from each other. The valuable metals are often "lost" into process wastes in other recycled metals, residues and intermediate products due to among others economic reasons.

The outcomes from recycling i.e. the range, selection and purity of metals, which are produced are, in turn, a key determinant of the economic profitability - and so viability - of recycling in its entirety.

Recycling has the potential to capture much greater value from waste streams, extracting the metals now lost. It is shown here that the best way to do this in practice is to take a ***Product-Centric***[4-6] perspective to recycling, the classical minerals based approach in which a primary producer will recover as many metals from a concentrate as is technological and therefore also economically possible. This contrasts with a rather more simplistic ***Material (& Metal)-Centric***[7] approach which is favoured more 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. A *Product-Centric* approach considers how to increase the recycling of a product (for example a LCD screen, mobile phone, *etc*.) in its entirety and therefore takes into consideration all the complex thermodynamic and physics aspects and interactions that affect their recovery. This necessarily involves consideration of what will happen to the many different materials within the product, and enables decision makers to more easily look at how the products are collected and how design affects outcomes. However, it is to be noted that Design for Recycling is not the golden bullet it is made to be, as functionality often determines the material connections, overriding their incompatibility for recycling. It more naturally leads to consideration of the interactions in the recycling system, a true systemic consideration, compared to a *Material (& Metal)-Centric* approach that is often a one-dimensional view focusing on one bulk metal or material group.

In summary, it is extremely important for resource efficiency to step away from the Material Centric perspective to the product perspective. This requires a deep understanding of extractive metallurgy, slag chemistry, separation physics and systems engineering. This is still lacking in many areas and should be understood by recycling “experts”.

Three major factors determine the outcomes of recycling (all expressible in monetary terms, the key overarching Key Performance Indicator (KPI)): (i) the way waste streams are mixed or pre-sorted during collection; (ii) the physical properties and (iii) design of the end-of-life products in those waste streams. These factors all affect the final recovery and subsequent production of high quality metal, material and alloy products. These factors interrelate in ways that make it impossible to optimise one without taking into account the others. To get the best results out of recycling, the participants in the recycling system (*e.g.* in design, collection, processing) need to take into account what is happening in the other parts of the system. They also need to consider how to optimise along the chain the recycling of several metals found within one product, rather than only focussing on one, or two major metals (and their alloys and alloying elements), and ignoring the rest of the periodic table.

Figure 1 provides an overview of all the actors and aspects that have to be understood in a ***Product-Centric*** systemic and physics based manner in order to optimise resource efficiency. 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, but also the understanding of unaccounted flows (poor statistics, data as well as collection) and the economics of the complete system are critical. Especially also understanding and controlling the dubious and illegal flows as well as theft *etc*. will help much to maximise recovery, but this is a relatively simple task organised by levelling the playing field by suitable policy. Maximising resource efficiency and therefore Design for Resource Efficiency (DfRE) considers and embraces Figure 1 in its totality. This requires rigorous modelling techniques to pin-point; understand and minimise all losses. It also requires a detailed understanding of the technology of recycling, both physical and metallurgical, as discussed in detail by Reuter and Van Schaik[4,5].

This ***Product-Centric*** approach is an example of the practical application of systems thinking to a complex issue – optimising it requires Design for Resource Efficiency. It is an approach which leads to a set of conclusions that have strong implications for public recycling policy. It suggests that, to optimise recycling and the recovery for various metals and materials from secondary resources such as sludges and slags, the following conditions would have to be in place (refer to Figure 1)[6]:

- **Treatment should happen in Best Available Techniques (BAT) by a certified system of operators:** These techniques can differ between regions, and need not be high tech only, but can also include hand-sorting in the earlier steps of the recycling chain. A deep understanding of slag chemistry to facilitate optimum separation and determine the most optimal balance between (automated) dismantling and mechanical sorting is a key issue.

- **Economic drivers and KPIs capture the performance of Figure 1 best**: Policy goals need to align with the economics of the complete system, including the longer term macro-economic level (i.e. conservation of specific critical metal resources for future applications even if their recovery currently is not economical). Policy plays a key role in creating the economic conditions that incentivise waste to go to registered BAT operations. This demands that policy making should be based on a deep understanding of the entire recycling system from design to metallurgy/slag chemistry.

- **DfRE:** Computer based-modelling and simulation of the recycling technology and system performance of products is available to help guide product design

that improves Resource Efficiency. It is based on the realities of how products and their constituents break-up and separate in likely BAT recycling processes. Design for Recycling has its limits if materials are brought together for functionality reasons (*e.g.* a PC motherboard), however Design for Disassembly can bring some improvement but it cannot override required product functionality. Computer based-models can provide the basis to feed policy with sound and detailed information on recycling systems can indicate key issues to improve resource efficiency.

- **Thermodynamically underpinned recycling policy:** Policy targets should not exceed what is physically, technologically and thermodynamically possible and do not prioritise one or more metals at the inadvertent expense of other metals found in the input stream. Economics and market conditions will also affect this.

- **Incentives for all in stakeholders:** There are incentives for all of the participants in recycling, from product design to purchase of recycled metal, to engage with other participants in the system to improve the overall system's recycling performance. Incentives can be purely legislative or purely economic, but work best as a combination of policy and profit. Economic benefit might not always keep on track with dynamic changing resource scarcity issues.

- **Technology and system innovation considering the complete system:** Process technology development should be incentivised and supported in ways that bring forward new commercial solutions to sort and separate metals in mixed waste streams in novel systems. The recycling metals industry has the depth of talent and wide metallurgical knowledge needed to link up different BAT processes in ways that separate out higher proportions of valuable metals. Metal producers following a more *Product-Centric* approach more frequently look to benefit from production of a wide range of metals, rather than focus on one or two metals (*Material-Centric*) as their production outputs. However for recyclers, it might be difficult to develop recycling technology which can keep up with extremely rapid changes in product development and it should also be realised that critical volumes of products in recycling streams are required (and not always achieved due to rapid changes in product designs *e.g.* LCD to LED screens) to set up new recycling plants for new products. Care should be taken to develop only those aspects which are key and are evident from rigorous system analysis.

- **Recyclate data and its resolution:** A *Product-Centric* view to recycling requires detailed data with sufficient quality and resolution required to parameterise process based system models, which as outcome enable system innovation, which a simplistic MFA does not. Also including product (composition/design) data i.e. the bill of materials/chemical material content declaration *etc*. and special organisation visualised through CAD and 3D tools.

- **Collection, Sampling – Knowing the product "Mineralogy":** Having access to the secondary well defined resources is of crucial importance for recovery. Collecting and pre-sorting of products into similar mineralogies is beneficial for both the physical and metallurgical recycler, especially also knowing the "mineralogy" i.e. the linkages, materials (alloys, compounds, metals, plastics *etc*.) of the secondary resources helps maximising profit for all the stakeholders.

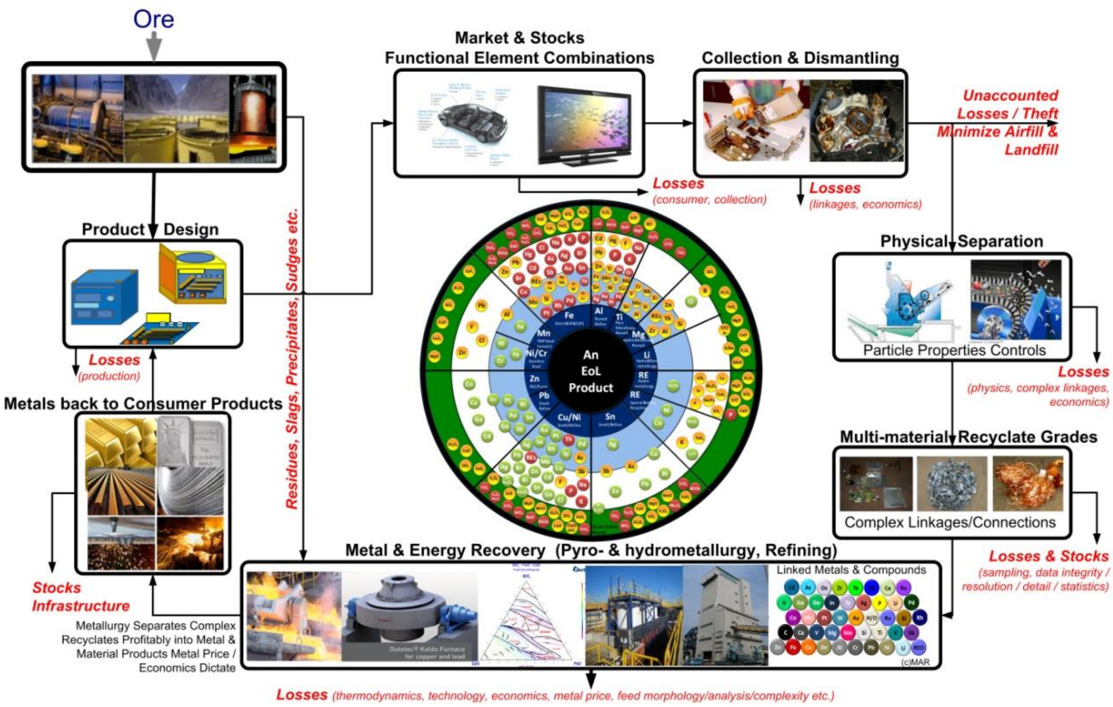


Figure 1: Design for Resource Efficiency – Optimally linking mining, minerals processing, BAT for primary and secondary extractive metallurgy, energy recovery, OEMs & product design, end-of-life products, recyclates, residues, wastes; while minimising resource losses. The Metal-Wheel in centre shows the destination of various elements in various carrier metal production sectors *(Green if recovered, Red if lost, Yellow in intermediate streams for each Carrier Metal)*. Slag chemistry is central, shown by phase diagram in centre of bottom block

The reader is also referred to UNEP[6] for further information, which is partially the basis for this contribution.

Opportunities and Limits of Recycling

The previous points will be briefly discussed under the headings below.

Best Available Technology & Techniques (BAT) and Economics

Metals arriving at recycling operations are almost always mixed with other metals, alloys and compounds inclusive of plastics and other materials. For example, end-of-life products are made of a mixture of materials, and are then typically mixed with other products and metal-containing waste streams as well as plastics among others before entering processing (*e.g.* mixing of small household appliances). These materials all have a monetary value, which is maximised the purer the recyclates are. Table 1 gives an approximate idea of some costs of end-of-life (EoL) products as well as the materials constituting the parts (right hand detail), noting that some parts are complex mixtures of numerous materials, metals, alloys, compounds, joined in a functional useful manner that in turn increases the treatment charges incurred by custom smelters and processors of the recyclates. The London Metal Exchange (LME) for example determines the metal prices, which then in turn also affect recyclate prices and the economics of the complete system. It should be noted that costs/revenues can differ and change rapidly due to changing product design, materials applied and market economics. Table 1 shows also relatively high revenue products contrary to other WEEE products resulting in a completely different picture then presented in this table.

Table 1: Costs of some WEEE goods and a breakdown for a Desktop PC[8]

WEEE Item	Value (€/t)	Cost Breakdown for Desktop PC	Weight (g)	Revenue(€)
Desktop PC	~1100	Steel & Aluminium	5241	1.41
Laptop	~1800	High grade PC-Boards (PWB-hi)	448	4.03
Printer (Consumer)	~120	Low grade PC-Boards (PWB-low)	397	1.39
Printer/Copier (commercial)	~330	Chips and Processors	68	2.55
Flatscreen	~900	Hard-disk drive	598	0.45
		Cables	198	0.28
		Other valuable items	444	0.27
		Plastics w/o flame retardants	122	0.03
		Plastics for energy recovery	226	-0.02
		Other fractions with cost	0	-0.00
		Labour	3 min	-1.50
		Net Revenue for PC	**7742**	**8.61**

In the recycling process, products and components are usually broken/cut/shred into small pieces and sorted into economic concentrates, in an attempt to separate out different mixed materials (see Figure 1). However, this is often only partially

successful. This breaking up of EoL products and sub-units *etc*. often leaves different materials fixed to, or mixed with, each other. For example, materials that are purposefully attached to each other, as they would be in joints in a product, are likely to stay close together (there is no value in Design for Recycling for these). Metals used in small quantities next to each other on a Printed Wire Board (PWB) or combined in electronic components on the PWB are also likely to stay together, even when the PWB is broken into pieces. It is therefore better to speak of Design for Resource Efficiency that covers the whole *Product-Centric* recycling view. However, when *e.g.* shredding circuit boards, parts of the brittle components (*e.g.* ceramic capacitors) mounted on the surface could be broken to dust, which then, unless systematically collected, settles in the plant or on surfaces of other material streams or in the flue dust. Therefore metals enter metallurgical processing as functionally mixed, rather than as single metal streams.

Economy of scale recycling technologies and processes often already exist that can economically separate many metals into high quality products (Figure 2 and Figure 3), but whether the metals entering recycling are separated depends on the choice of processes used and also product functional design. There are different metallurgical processes for the production of the most common commodity metals used in society, *e.g.* iron, aluminium, lead and copper, and these are also used for recycling and waste processing as shown by Figure 2 and Figure 3.

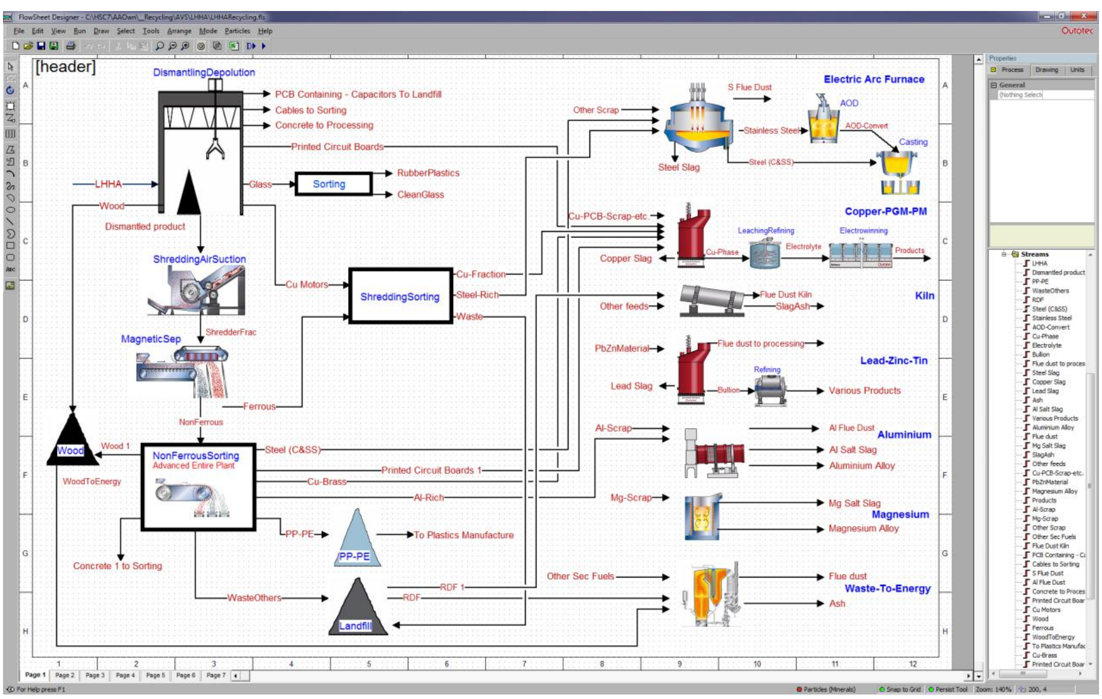


Figure 2: A complete recycling flowsheet for end-of-life products showing the link of physical separation with metallurgical processing represented by the HSC Sim process simulator (www.outotec.com)

Figure 3: A selection of existing metal containing residues, sludges, e-waste among others processing plants using state-of-the-art Ausmelt TSL and Kaldo technologies (www.outotec.com)

Due to rapidly changing material compositions and EoL products it will be rather wise to invest much more time and effort in innovating, optimising and maintaining the metallurgical processing infrastructure rather than (re)inventing new processes as the basic structure in for example the EU can take care and recover many elements already. Also the CAPEX of metallurgical infrastructure is high hence detailed understanding of this system is crucially important rather than simply (re-)inventing “new” process and wasting tax-payer R&D money on projects that are doomed to fail due to economy of scale, technological issues as well as lack of know-how. E-waste (which may contain some of each of these metals, alongside many other minor and/or critical) can enter any of these processes, however, in some cases materials are recovered maximally and in other cases lost maximally. It must be noted that *e.g.* GaAs may be present as a minute fraction of a percent in e-waste printed circuit boards (and cannot be economically recovered) and may well be locked up in slag due to thermodynamics, or end in flue dust and be environmentally benign as it is well ponded. Therefore recycling these elements in this case makes no (economic) sense. Therefore, important is the existence of a system that can take care of all these mixes of elements while maximising metal recovery and obviously profit and minimising ecological damage as reflected by for example the complex metallurgical flow sheet depicted by Figure 4 for Korea Zinc.[9]

Each process in this flowsheet has different abilities to deal with mixes of sludges, materials and compounds. This example also excellently shows how in a smart system, residues and slags can be treated to maximally recover- metals while producing benign residues that can be used for building materials for example. This

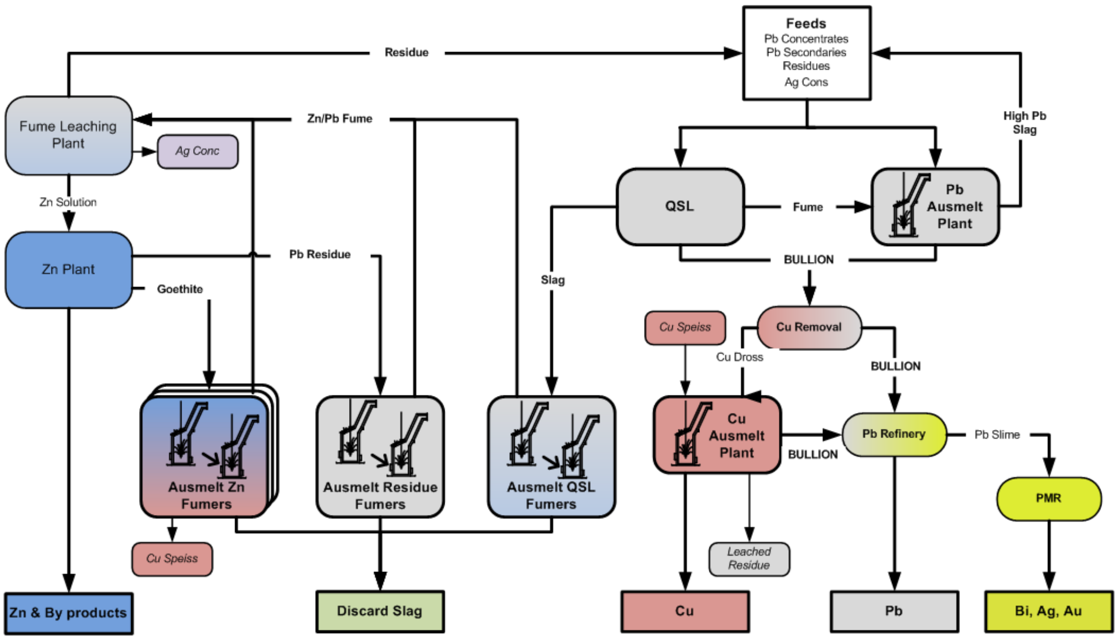


Figure 4: An example (Korea Zinc) of a Zn-Pb-Cu-Ni Segment in the Metal Wheel (Figure 1) that economically and optimally recovers the carrier metals Zn, Cu and Pb while treating electrolytes, sludges, Goethite, slags from own and other production facilities while economically recovering various minor elements of which a few are shown Outotec Ausmelt TSL furnaces are used, highlighting the versatility of this type of technology[9]

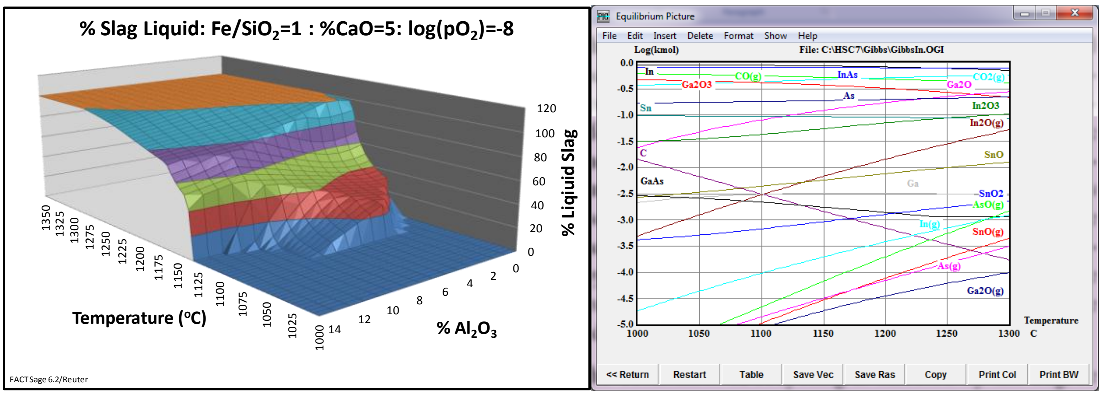
figure also suggests that establishing dedicated recycling facilities for single elements only (*e.g.* In, Ga, *etc.*) as is seemingly often championed even on EU level by academics and DfR people through studies, is economically and technologically challenging. It must happen in systems that can deal with the complexity and economic realities as suggested by Figure 4 i.e. the system must take care of all elements of end of life products at the same time.

The Metal-Wheel in Figure 1 illustrates generally what happens to different metals in an end-of-life product entering either the Iron (Fe), Aluminium (Al), Copper (Cu), Zinc (Zn) and Lead (Pb) processes. Each circle indicates the destination of a metal found in mixed, end-of-life electronic product (waste), be it metal, slag, intermediate, flue dust *etc*. The ideal situation would be a system that connects scrap and residues to all Carrier (Base) Metals processes – a system that could be conceptualised as the centre of the Metal-Wheel – so that scrap and residues then flow, as determined by thermodynamics and economics, into the appropriate Carrier Metal technologies (or Metal-Wheel slices – an example is Figure 4), with further links between each technology (or slice) for processing the residues from each technology. This is obviously Utopian and can not be totally achieved with existing technology.

Nevertheless, the conceptualisation can help understanding the intricate system and knowledge required for recycling and waste/residue processing, what is truly meant by a systemic view to recycling and what deep thermodynamic and process knowledge is required to “close” the loop. This suggests clearly that Cradle-to-Cradle thinking fails for even simple products due to the (limits imposed by the) laws of Nature (thermodynamically) and illustrates that Product Resource Efficiency has its limits.

The thermodynamic properties of each metal and their various compounds/alloys are particularly important. When metals and their compounds in end-of-life goods and recyclates have thermodynamic and physical properties that are compatible with a particular base metal metallurgical infrastructure, the metallurgical processing technologies used by metals producers and refiners can usually separate and recover them economically from the various streams that are created such metal, matte, speiss, sludges, precipitates, slimes, flue dusts, fumes, slags *etc*. minimising the losses to streams that have a dumping/ponding cost attached to them. This is also the basis for Design for Recycling within the constraints of product functionality and performance demands.

The economics of recycling is affected by the degree to which metals can be separated, recovered and transformed into high quality materials that can be applied for example in sustainability enabling products. Where metals do not separate, they can either reduce the quality of the primary recycled metal product; they can not be recovered for use as separate metals themselves; and/or they tend to increase the energy needed during the recycling process. Elements within complex products, recyclate, sludges, are not recycled individually. Instead, they pass through one of a wide range of combinations of processes as shown by for example Figure 4. The choice of process is an economic and physics based technological optimisation puzzle for the recycling operation, one that is driven by the changing values of the metal and high end alloy products. Secondary materials can be fed into the flowsheet as shown by Figure 5, but this can only be done by experts that know the processes and suitable simulation software. The usual material flow analysis tools used by researchers active in recycling do not have the basis to do this and therefore cannot be used to advance and innovate in the recycling and waste processing system. This leads to the conclusion that a metal production infrastructure as shown in for example Figure 1 to Figure 4 must exist that allows flows of metals between Carrier Metal processes. This needs to be developed and nurtured over a long time, not least due to investment lead times, significant capital costs, the need for cross-Carrier Metal expertise and because for each product type a different Metal-Wheel exists.



(a) *(b)*

Figure 5: (a) The effect alumina on the slag chemistry i.e. amount of solids in slag, melting temperature *etc*. for different processing conditions as simulated by FACT Sage (www.factsage.com) and (b) A selection of metals and compounds for GaAs and ITO *(90% In_2O_3+10%SnO_2)* mixture that are created in the temperature range and pO_2 shown with all the compounds arising as simulated by HSC Chemistry (www.outotec.com/HSC)

Some process and thermodynamic detail

Economically it has been shown that it is wise first to treat e-waste, after suitable sorting and concentration, pyrometallurgically (a first rough separation at higher temperature that also permits energy recovery from plastics), followed by hydrometallurgy, producing the refined metals and materials of sufficient high purity to return the EEE product. For residues, sludges *etc*. treatment at high temperature is often preferred to capture elements such as iron in benign slags as hydrometallurgy would then create further residues such as jarosite and Goethite. In some cases hydrometallurgy is preferred if materials are well sorted, especially for some high value materials and for example rare earths, but then contamination must be limited. At the heart of Product-Centric recycling is deep knowledge; a brief explanation what is meant by this is given below:

- If aluminium (Al), for example, is not separated physically from the WEEE it usually ends in the slag of pyrometallurgical processing as alumina (Al2O3) or various other compounds such as Al2SiO5, CaAl2SiO6, CaAl2O4, FeAl2O4, Fe3Al2Si3O12, *etc*., which can precipitate in the molten slag and create sometimes very disruptive operational issues due to viscosity, flow, foaming and separation problems. Slag chemistry also affects the distribution of elements into various phases and has to therefore be carefully managed. Figure 5 (a) shows the effect of different conditions on the precipitation of some phases for the typical non-ferrous smelting system as well as the final melting point when all possible phases are in the molten state. This would

clearly indicate that care should be taken during physical separation to remove the aluminium before it is lost in the slag and in addition disrupts and/or limits operation and the recovery of elements from for example WEEE sourced recyclates.

- Metals arise in numerous species due to among others their possible valancy states, which depends on what the conditions are within the process technology. This implies that metals can either, be recovered in the metal phase, can be volatilised into a flue dust and collected for further processing or into the slag or speiss phase, where it may go lost from the material cycle if the slag cannot be processed economically. To illustrate this consider a GaAs based semiconductor and indium-tin-oxide (ITO) containing recyclate, processed under the temperature range as shown Figure 5 (b). This figure shows a selection of the possible metal, oxide and gaseous species that could arise at the prevailing partial oxygen pressure created by the addition of carbon, either through waste plastics or coal or similar reductant types. Following a hydrometallurgical route also brings its own complexity as many As-Sn-In-Ga cation and anion species appear in solution. All dissolved species have to be recovered from solution to produce high value metal products by *e.g.* energy intensive electrowinning or precipitation and subsequent processing.

Process and Recycling System Optimisation

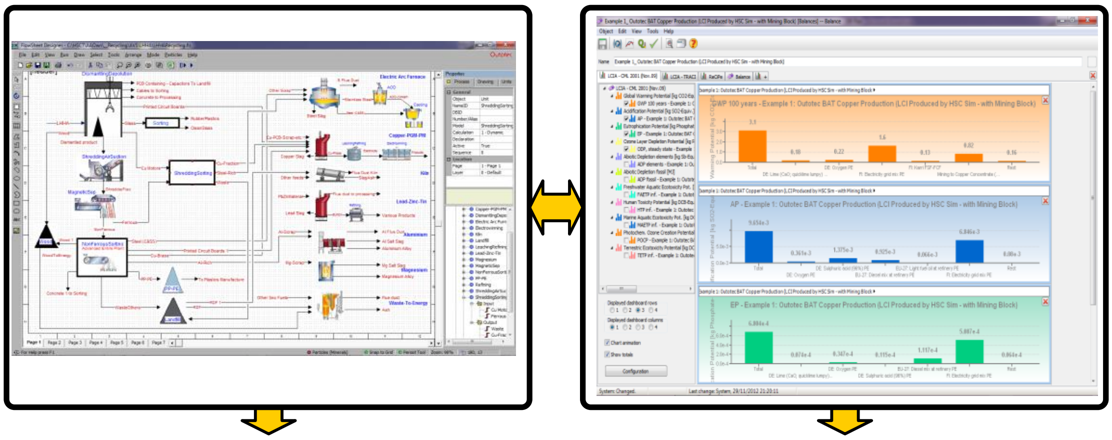
Rigorous economic and physics based understanding of technology and systems for recycling make it possible to make informed decisions over the complete system boundary. Sophisticated tools exist that enable the evaluation of resource recovery in metal and material processing systems as shown by Figure 6.

These produce consistent mass and energy balance for all compounds and materials in a processing system, be it for a complete copper plant from rock to refined metal (Figure 6) or a complete recycling system that is shown by Figure 7 for LCD Screen recycling using the same HSC Sim tool as shown in Figure 2 and Figure 6. These simulations are typically based on deep process knowledge, thermodynamic simulation and slag chemistry as shown in Figure 5, and economic and technological feasibility.

Recycling is clearly a complex thermodynamic and resulting economic puzzle to solve, obviously with no one answer, one set of Design for Recycling rules, nor solvable with beautiful credos such as Cradle-to-Cradle, *etc*. It would also be self-

OT's HSC Sim 7.1x
(>19,000 licences www.outotec.com)

PE-International's GaBi
(www.PE-International.com)



BAT, Flow Sheets & Recycling System Maximizing Resource Efficiency – Benchmarks

\$US / t Product (CAPEX & OPEX)
Recyclability Index (based on system simulation of whole cycle)
GJ & MWh / t Product (source specific) and Exergy
kg CO_2 / t Product
kg SO_x / t Product
g NO_x / t Product
m^3 Water / t Product *(including ions in solution)*
kg Residue / t Product *(including composition)*
kg Fugitive Emissions / t Product
kg Particulate Emissions / t Product
Etc.

Environmental Indicators based on BAT Driving Benchmarks of Industry

Global Warming Potential (GWP)
Acidification Potential (AP)
Eutrification Potential (EP)
Human Toxicity Potential (HTP)
Ozone Layer Depletion Potential (ODP)
Photochemical Ozone Creation Potential (POCP)
Aquatic Ecotoxicity Potential (AETP)
Abiotic Depletion (ADP)
Etc...

Figure 6: Linking rigorous process simulation tools with environmental impact assessment tools to optimise plants and complete systems – linking particle based simulation with molten metal and slags as well as aqueous solutions to capture the full complexity of recycling systems

evident that "mining" the urban mine, which has hype sound to it, will be rather a complex and even (economically) impossible task as reflected by the non-linear effects in Figure 5 and the complexity of the urban "ore body" and its "mineralogy". It would also be clear that for each mixture and each condition this separation will be different, implying that general (MFA/LCA/DfR) methodologies which do not address this depth of mineralogy (i.e. compounds, alloys, transformations *etc.*) will obviously and inevitably lead to false conclusions and uneconomic and unrealistic technological recommendations. It is hence worrying to see that these methods are still well adopted and do not match the recycling industry and the sophistication of product design and its CAD and other tools. It also suggests clearly that all the figures in the document are snap-shots and will be different for each new situation. This demands very rigorous modelling to reveal the opportunities and limits of recycling. Design for Resource Efficiency captures this detail.

Design for Resource Efficiency (DfRE) and Recyclability Index

The interactions in the recycling system are two directional along the chain from design, disposal, collection, sorting and recycling. Each of the stages from design downwards impacts on final recycling through the changes it creates in the physical properties of the material going for recycling. In the other direction, the realisation of economic value from final recycled metals is the natural driver for collection activities, incentives for disposal and, potentially, DfRE. If products were all produced out of one metal, the system would be relatively simple, and the interactions linear, up and down the recycling ‘chain’.

In practice, as each product contains many metals as well as other substances imparting functionality, there are many ‘recycling chains’ (from product to recycled metal) for each metal. These chains interact during design, collection and recycling. This creates a complex system, with a level of complexity that needs to be understood in a workable way by actors in the chain, and policy makers as reflected by Figure 7.

Figure 2 and Figure 7 give a general overview of various technologies applied during recycling and the processing of waste materials. If this is concretised more specifically for a product such as a LCD screen, various specific technologies come into play as reflected by the HSC (www.outotec.com) simulation (Figure 2 and Figure 7) of the interlinked system of technologies and activities. Rigorous simulation will provide a thermodynamic basis also for the environmental impact analysis that is linked to GaBi (www.pe-international.com). Through this link, it is possible to evaluate the environmental impact of different designs and scenarios based on actual environmental impact linked to the mass and material flows, the detailed compositions of each stream, including design and recycling routes dependent recoveries, losses and the environmental footprint of created residues. This is not possible with currently applied LCA/environmental performance calculations based on general data bases, which are therefore incapable of capturing the essential detail of recycling technology in view of recycling optimisation and design for recycling.

A result of this is also a rigorously based estimation of the recyclability of products to determine an Eco-Label for a product as these tools can be directly linked to design tools and their produced bill of materials, full material declaration and/or chemical content analysis. Figure 7 shows such a basis for the creation of a rigorous Recyclability Index based on BAT technology, moving away from the simplistic indexes as still being developed and applied thoughtlessly by non recycling experts (*e.g.* OEM’s and component designers) which do not represent the complexities and depth of recycling technology, its physics, chemistry and economics.

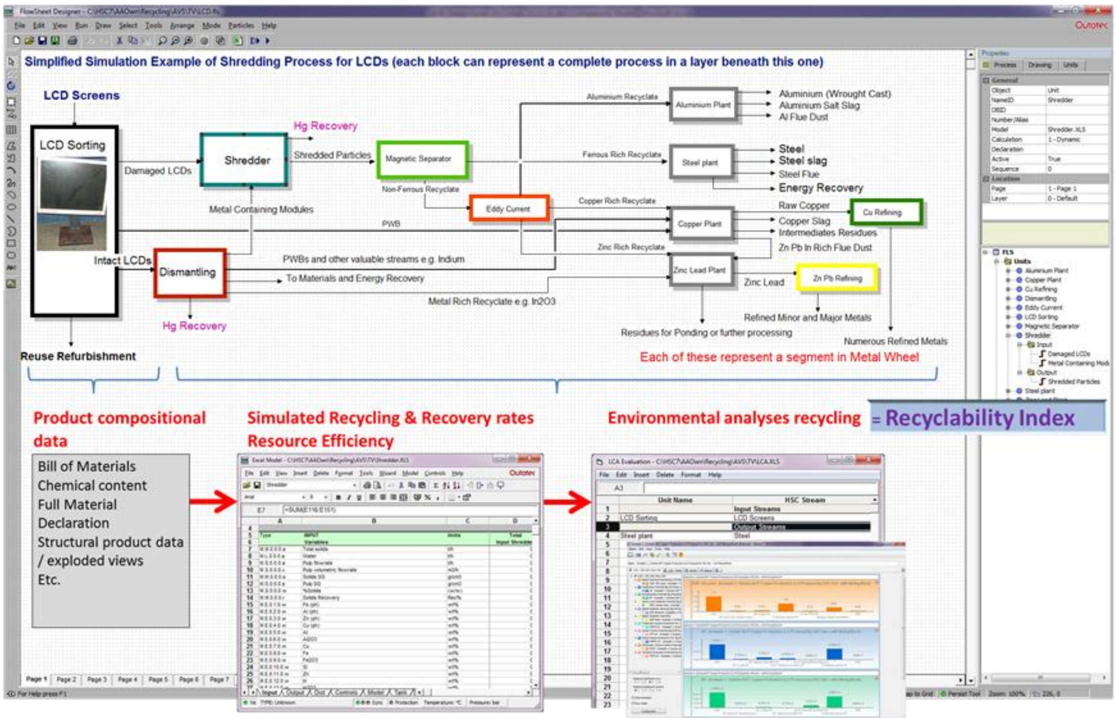


Figure 7: Rigorous estimation of a Recyclability Index or Eco-Label of a product based on the bill of materials/chemical material content through linking design tools with simulation and environmental impact tools as shown

Care should hence be taken by policy makers and OEM's when applying these simple linear calculations for recycling indexes, since these will be leading to false conclusions with respect to resource efficiency improvement and might lead to harmful decisions for the industry. Furthermore, using this basis can provide a rigorously based estimation of design rules as shown by Figure 8[10]. However, it must be noted that these are only loose estimations (much favoured by the product designers that have no thermodynamic basis); best would be to estimate recyclability of products with tools such as shown below run by true experts in the recycling field which have knowledge of metallurgy and process technological experience.

Much can be gained by representing data, particles, liberation *etc*. in ways that are common to metals, minerals and materials processing. Standardisation of data structures for design will help much to facilitate this. Such recycling knowledge based Eco label has the depth to really distinguish differences in product designs and to distinguish the more Resource Efficient design from the other. This might provide a driver for OEM's to design for resource efficiency. This approach differs fundamentally from many general DfR studies and applications as performed nowadays relying on simplified one-dimensional DfR rules. These rules do not represent and reflect the realities of recycling, recyclate quality as a function of

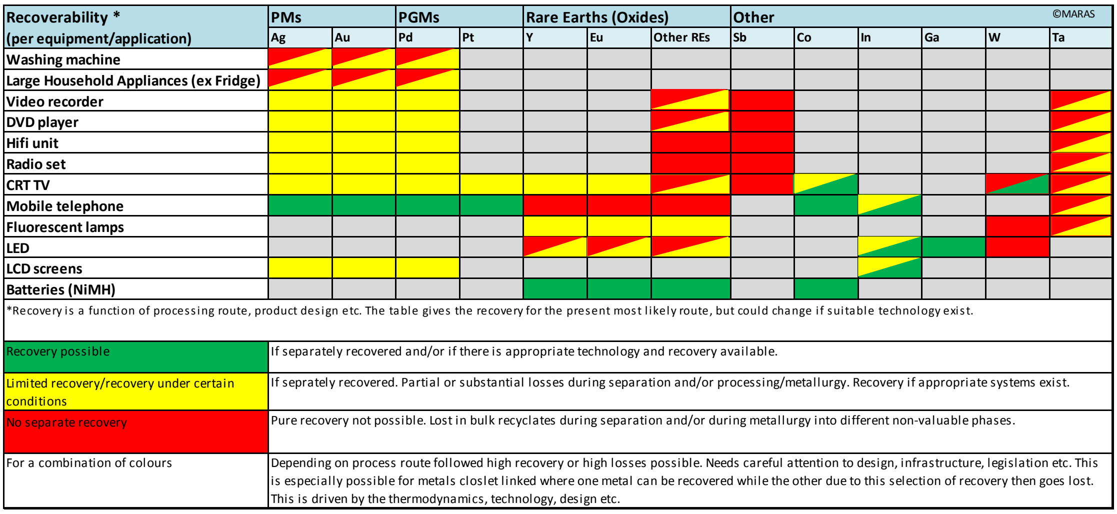


Figure 8: Metal compatibility recyclability matrix[10] developed from experience and estimations from tools such as shown by Figure 6 and Figure 7. The compatibility can be linked fundamentally back to slag chemistry

design, liberation and sorting efficiency and metallurgical process recoveries of different metals/materials as a function of recyclate quality and concentrations of materials in it as captured by the models in Figure 6. The general approaches are not based on a proper process simulation basis which can include this required depth of non-linear design to recycling (including slag chemistry and metallurgical processing efficiencies) to capture the real issues of Resource Efficiency. The discussed approach of Figure 6 based on a Product Centric physics based understanding of recycling allows by its depth for the evaluation of changes in design (for recycling) by including all effects, which one particular change or substitution of materials might have on the entire recycling system.

Conclusion

This paper shows that it is not only BAT but also the whole system and its structure that has to be optimised to maximise resource efficiency. Rigorous simulation of the whole chain on the basis of first principles including particle behaviour linked to product design and process metallurgy MUST be the basis for DfR and DfRE. This is essential to provide recyclability indexes or eco-labels with a physics basis, if they are to be keys in innovating new solutions. Slag chemistry is crucial in this and therefore we as extractive metallurgical process engineers have a key role to play in the sometimes rather vague and less fundamentally based policy discussions that lack the necessary depth required to truly maximise resource efficiency.

Furthermore, it is crucial to adopt *Product-Centric* recycling perspectives in recycling and policy to ensure maximum recovery of elements, metals and compounds from

various secondary resources. As indicated, this demands deep process, technological, system and economic simulation models to be combined to optimise resource efficiency and suggest physics based opportunities while highlighting systemic and technological limitations through Design for Resource Efficiency. This deep understanding drives technological and policy innovation while levelling the playing field to physics and economics in recycling and provides the basis for the development of Eco-labelling as briefly alluded on in this paper.

The simpler the products and applications of a metal, the better a *Material (& Metal)-Centric* view, which currently is often still used as the basis to express and improve resource efficiency on the basis of rather simplistic material flow analysis, can explain recyclability only in a simplistic mono-metal way. It is ever clearer that this simplistic view fails for more complex products, many of which have to accommodate complex mixtures and linkages of metal, alloys, compounds linked due to functionality reasons. For these, only sophisticated recycling perspectives, which take into account the compositions of the recyclable streams and the processing routes (i.e. recycling infrastructure) applied, are needed i.e. the *Product-Centric* view. For most purposes, the *Material (& Metal)-Centric and Product-Centric* views on recycling can usefully be considered together, with the aforementioned being a simplistic and limiting sub-set of the latter. Setting up recycling systems from a *Product-Centric* viewpoint needs a keen understanding of the physics of separation, thermodynamics and metallurgy, process technology of all elements at the same time to be able to innovate and optimise product design and policy.

Various design and simulation tools exist to help with this as briefly discussed in the paper. These express what the thermodynamic linkages mean for processing of different metals during recycling and also show the inevitable losses which represent the limitations of the system. Design compatibility tables have been developed on this basis and can be consulted in Reuter and Van Schaik[10]. It is important to realise that these compatibility tables can only be used in conjunction with recycling simulation tools for Design for Recycling due to the complexity of material interactions during the end-of-life phase in shredding, sorting and metallurgy. These are first steps in establishing rigorous recyclability indexes.

References

1. B.D. Santer *et al.*, "A search for human influences on the thermal structure of the atmosphere", *Nature*, **382**, 4th July 1996, 39-46 (1996).
2. IPCC, "Climate Change 2007: Synthesis Report Synthesis Report, An Assessment of the Intergovernmental Panel on Climate Change", This underlying report, adopted section by section at IPCC Plenary XXVII (Valencia, Spain, 12-17 November 2007), represents the formally agreed statement of the IPCC concerning key findings and uncertainties contained in the Working Group contributions to the 4th Assessment Report (2007).
3. EU (2011): EUROPEAN COMMISSION, Brussels, 20.9.2011, SEC(2011) 1067 final, Roadmap to a Resource Efficient Europe, {COM(2011) 571 final} {SEC(2011) 1068 final}
4. A. van Schaik and M.A. Reuter, "Shredding, sorting and recovery of metals from WEEE: linking design to resource efficiency." In *Waste electrical and electronic equipment (WEEE) handbook*, Edited by V. Goodship, University of Warwick, UK and A. Stevels, Delft University of Technology, The Netherlands, 163-211 (2012).
5. M.A. Reuter and A. van Schaik, "Opportunities and Limits of recycling – A Dynamic-Model-Based Analysis", *MRS Bulletin*, **37** (4) 339-347 (2012).
6. M.A. Reuter *et al.*, "UNEP Metal Recycling: Opportunities, Limits, Infrastructure", *United Nations Environmental Programme* (Lead author M.A. Reuter with principal contributors: C. Hudson, C. Hagelüken, K. Heiskanen, C. Meskers, A. van Schaik www.unep.org) 2012 **(In press**).
7. B.K. Reck and T.E. Graedel, "Challenges in metal recycling", *Science*, **337** (6095) 690-695 (2012).
8. K. Hieronymi, "Is enough focus being given to designing-in recyclability in consumer electronics?" *Metal Bulletin Copper Recycling Conference*, Brussels, Belgium, 11-13 June, 2012.
9. N. Huda, J. Naser, G. Brooks, M.A. Reuter and R.W. Matusewicz, "Computational Fluid Dynamic Modeling of Zinc Slag Fuming Process in Top-Submerged Lance Smelting Furnace", *Metallurgical Transactions B*, **43B** (1), 39-55 (2012).
10. M.A. Reuter and A. van Schaik, "Resource efficient metal and material recycling", in *Proceedings of REWAS Symposium 2013*. The Minerals, Metals & Materials Society (TMS), San Antonio, Texas, USA, 2-7 March, 2013.