

GRONDSTOFFENTERUGWINNING KRITISCH BEKEKEN

Product Centric Simulation Based
Design for Recycling (DfR)

NVMP

By Dr. Antoinette van Schaik (MARAS), Prof. Markus Reuter (Outotec) en NVMP/Wecycle © 2013



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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. MARAS has performed a study on DfR for NVMP to develop DfR rules taking into consideration the possibilities and limits of Recycling. This includes 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. MARAS has investigated numerous recyclates to this end as well to understand the relationship between design and recyclate quality. Based on the information gathered in this study combined with the expertise of MARAS, comprehensive simulation based DfR rules and guidelines have been developed. These

rank from simple guidelines and material (in) compatibility tables to detailed recycling system based DfR rules. 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.

Recycling process simulation tools are crucial to pinpoint and quantify the critical DfR rules for a particular product. Simulation models based on the commercial HSC Sim software as developed by MARAS provide the basis for DfR. Linking of Process Simulation to Design tools is a necessary step forward to realize realistic and economically viable DfR. This is a rigorous basis for industrial useful DfR rules and methodology.

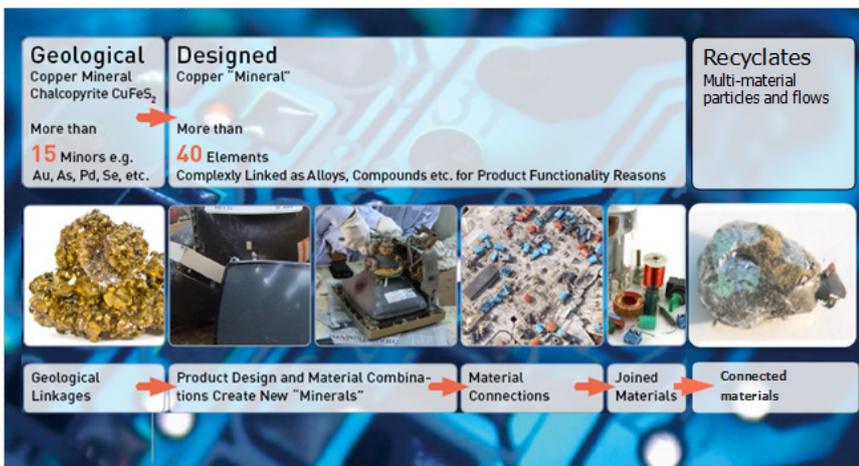


Figure 1 Product Centric Recycling: Application of economically viable technology and methods throughout the recovery chain to extract metals/materials from the complex interlinkages within designed "minerals" i. e. products, gleaning from the deep know-how of recovering metals from complex geological minerals (Reuter and Van Schaik, 2012¹)



1 M.A. Reuter and A. van Schaik (2012). Opportunities and limits of recycling: A dynamicmodel-based analysis, MRS BULLETIN, Vol. 37(4), pp. 339 - 347 (special edition on Sustainability)

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

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 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.
- ▶ 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.

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.)



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).



Figure 2 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 3 illustrates the role of the metallurgical processing infrastructure which takes up the different recyclates from dismantling and sorting. The Metal Wheel (see attached presentation and UNEP 2013) shows the destination (recovery/losses) of the different elements contained in an EoL product and different recyclates of physical recycling (where the quality of is design and 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.

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



- **Mainly Element Lost, not always compatible with Carrier Metal or Product** Detrimental to properties and cannot be economically recovered from e.g. slag unless e.g. iron is a collector and goes to further processing.
- **Dissolves mainly in Carrier Metal if Metallic (Mainly to Pyrometallurgy)** Valuable elements recovered from these or lost (metallic, speiss, compounds or alloy in EoL also determines destination as also the metallurgical conditions in reactor).
- **Compounds Mainly to Dust, Slime, Speiss, Slag (Mainly to Hydrometallurgy)** Collector of valuable minor elements as oxides/sulphates etc. and mainly recovered in appropriate metallurgical infrastructure if economic (EoL material and reactor conditions also affect this).
- **Mainly to Benign Low Value Products** Low value but inevitable part of society and materials processing. A sink for metals and loss from system as oxides and other compounds. Comply with strict environmental legislation.

- **El Mainly Recovered Element** Compatible with Carrier Metal as alloying Element or that can be recovered in subsequent Processing.
- **Mainly Element in Alloy or Compound in Oxidic Product, probably Lost** With possible functionality, not detrimental to Carrier Metal or product (if refractory metals as oxidic in EoL product then to slag / slag also intermediate product for cement etc.).
- **Mainly Element Lost, not always compatible with Carrier Metal or Product** Detrimental to properties and cannot be economically recovered from e.g. slag unless e.g. iron is a collector and goes to further processing.

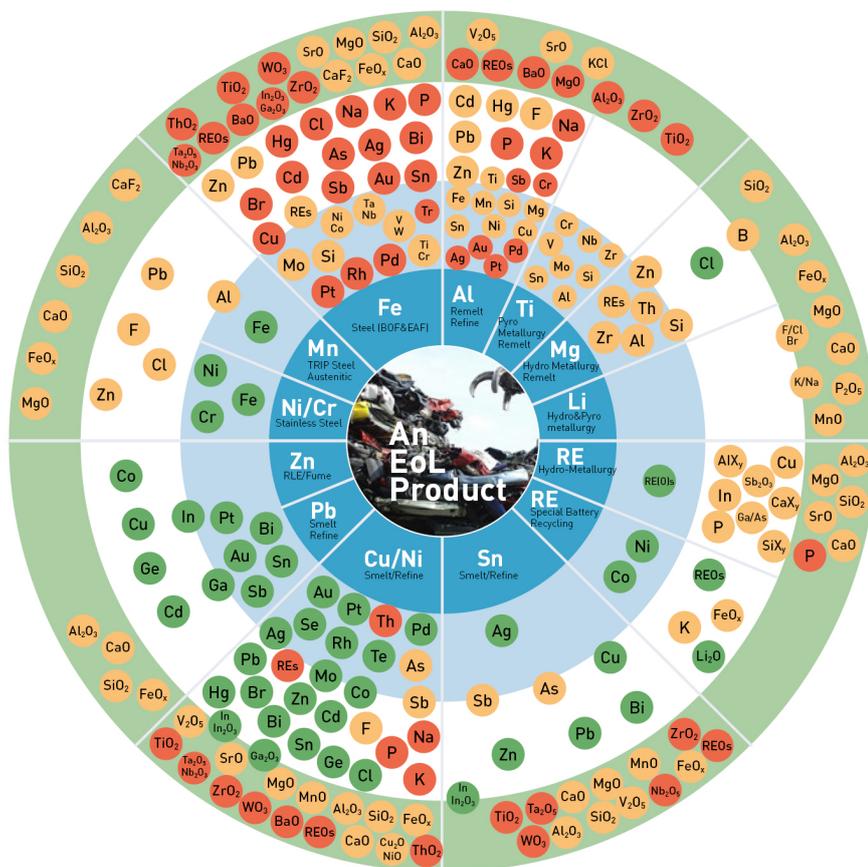


Figure 3 The Metal Wheel based on primary metallurgy reflects the destination of different elements in commodity/ base metal minerals (base or carrier) processed in hydro- and pyrometallurgy and electrorefining/winning infrastructure as a function of interlinked metallurgical process technology and different 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. As there are so many different combinations of materials in products and recyclates only physics based process simulation modelling (see Figure 4) can be used to provide the basis for good predictions in Design for Recycling and Resource Efficiency models. (Reuter and Van Schaik, UNEP 2013²⁾)

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. This is a rigorous basis for industrial useful DfR rules and methodology. The example in Figure 4 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. Eco labels 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. into the evaluation for DfR.

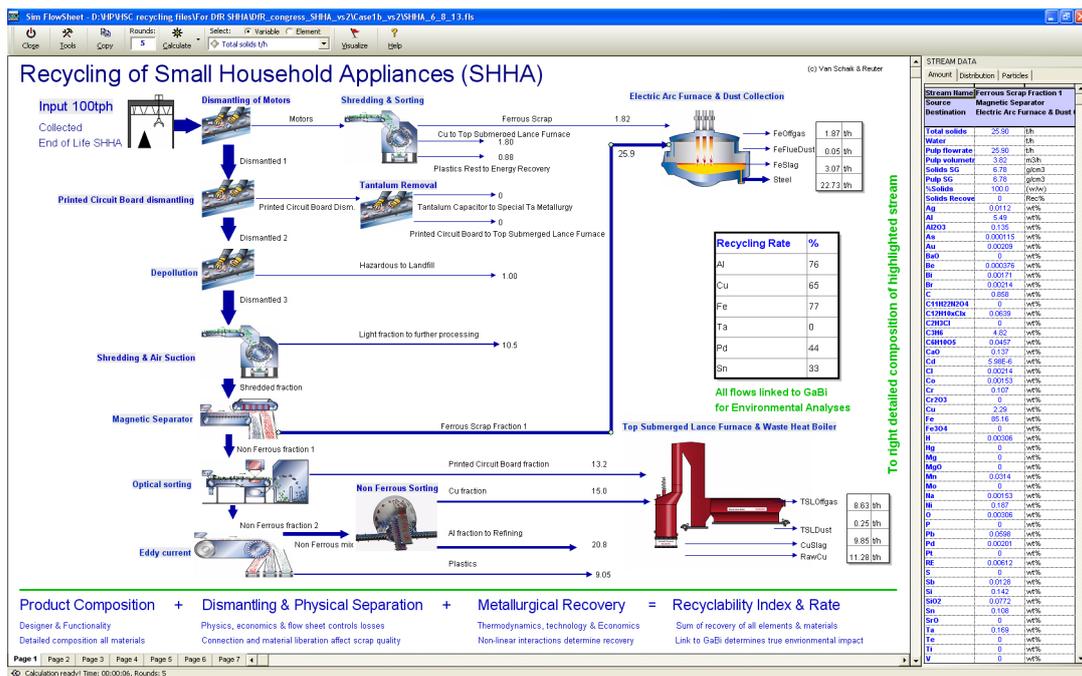


Figure 4 Example of linking existing Process simulation software (including process flow sheet design), with compositional data for a product derived from CAD/Design tools (BOM/FMD/etc) (here example on LCD screens), which lead to simulated resource efficiency data that, in turn, lead to a recyclability index based on environmental analysis as the basis for DfR (a physical and metallurgical processing infrastructure is prerequisite (Reuter and Van Schaik, UNEP 2013)



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 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:

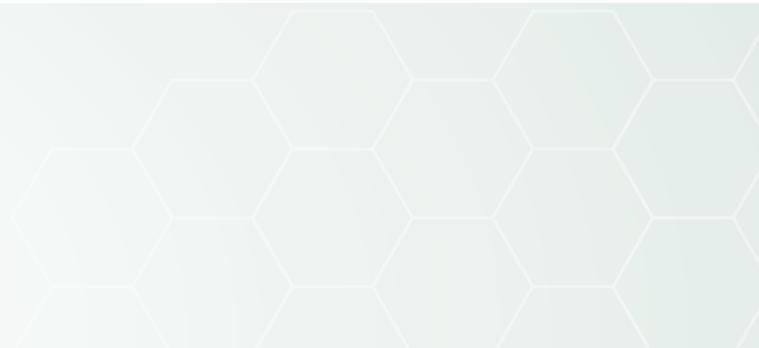
- ▶ Use and construction of concrete in washing machines, which is difficult to dismantle and distributes over different recycle streams;
- ▶ Use of glass plates in fridges, which is considered as process waste and hence decreases recyclability;
- ▶ Application of isolation materials which are difficult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

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 (see attached presentation and UNEP, 2013) 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 indication of resource efficiency, material recovery, losses and fugitive emissions. Figure 5 gives an example of a derived compatibility matrix.

Materials in input streams (from WEEE materials)	Society's Essential Carrier Metals: Primary Product Extractive Metallurgy's Backbone (primary and recycling metallurgy)							
	Fe Steel (BDF&AE)	Al Remelt/Refine	Cu Smelt/Refine	Zn RLE/Fume Pb Smelt/Refine	Ni/Cr Stainless Steel	Rare Earths Hydrometallurgy	Rare Earths Special Battery Recycling	
PCBA (washing machine/LHHA)								
Ag	Red	Red	Green					
Al	Yellow	Green	Yellow			Yellow		Yellow
Al ₂ O ₃		Red						Yellow
Au	Red	Red	Green	Green				
Bi	Red		Green	Green				
Br	Red		Green					
Cl	Red		Green					
Cr	Yellow	Red	Red	Red	Green		Red	
Cu	Red	Yellow	Green	Green				
Cu ₂ O			Yellow					
Fe	Green	Yellow			Green			
FeO _x	Yellow		Yellow	Yellow	Yellow		Yellow	Yellow
Ni	Yellow	Yellow	Green		Green		Green	
Pb	Yellow	Yellow	Green	Green	Yellow			
Pd	Red	Red	Green	Yellow	Red			
Sb	Red	Red	Yellow	Green				
Sb ₂ O ₃							Yellow	
Si	Yellow	Yellow						
SiO ₂	Yellow		Yellow	Yellow	Yellow		Yellow	
Sn	Red	Yellow	Green	Green				
Zn	Yellow	Yellow	Green	Green	Yellow			
Elastomers							Red	Red
Thermosets							Red	Red
Thermoplastics (flame retardants etc.)							Red	Red
Epoxy							Red	Red

Figure 5 Example of a material (in) compatibility matrix for a PCBA (printed circuit board assembly or printed wire board) 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) e.g.:

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

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:

- ▶ 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.

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

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

- ▶ Avoid bolts/rivets of dissimilar materials (e.g. Fe bolts to Al, PWB, plastics, etc.) as these produce generally a liberation problem therefore creates cross-contamination of the different recycle fractions;
- ▶ Minimize the use of non-reversible adhesives for incompatible & undesired material combinations;
- ▶ 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.; and

The Metal Wheel 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.



Recommendations

Policy targets for Recycling and Eco-design

- ▶ should remain within what is technologically (physically and thermodynamically) and economically possible and hence be based on recycling process simulation tools and knowledge;
- ▶ must be set in ways that account for the inevitable losses of materials due to mixing in products for product functional specifications
- ▶ should stimulate Best Available Technology/Techniques (recycling and metallurgical infrastructures);
- ▶ should reflect the interests 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 time³.

- ▶ Also consult: UNEP (2013) 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.

UNEP: <http://www.unep.org/resourcepanel/Publications/MetalRecycling/tabid/106143/Default.aspx>

EC: http://ec.europa.eu/environment/resource_efficiency/news/up-to-date_news/02052013_en.htm

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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.



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