

# MARAS

Material Recycling and Sustainability

## Design for Recycling

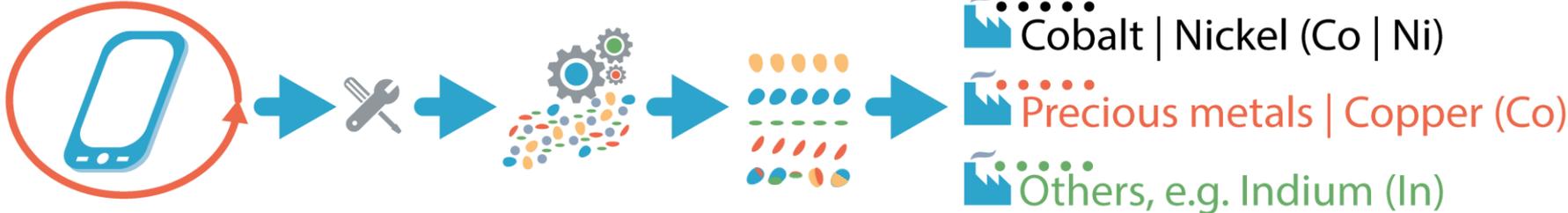
Dr. ir. Antoinette van Schaik

# Design for Recycling and Resource Efficiency

## Product-Centric View

General initial question

How can we use a product as resource?



EoL Product  
Design

Pretreatment  
Dismantling/shredding/sorting

Chemical & Processing  
Metallurgical processing  
Less waste

## How can we define DfR rules to optimise Resource Efficiency?

Design for waste  
stream sorting

Design for  
shredding/  
liberation

Design for recovery in  
final treatment  
processing

Design for  
disassembly

Design for  
sorting

# 10 Design Rules and Simulation Derived Guidelines

## Fundamental 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/available in a format which is compatible with the **detail** required to quantify and optimise recycling performance of products for all metals, materials and compounds present
4. Economically viable **infrastructure and rigorous tools** must be in existence for realizing industrial DfR rules and methodologies
5. **CAD/Design** tools must be **linked** to recycling system process **simulation tools** to realise technology based, realistic and economically viable DfR

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

# 10 Design Rules and Simulation Derived Guidelines

## Possible DfR guidelines – Derived from Fundamental DfR Rules

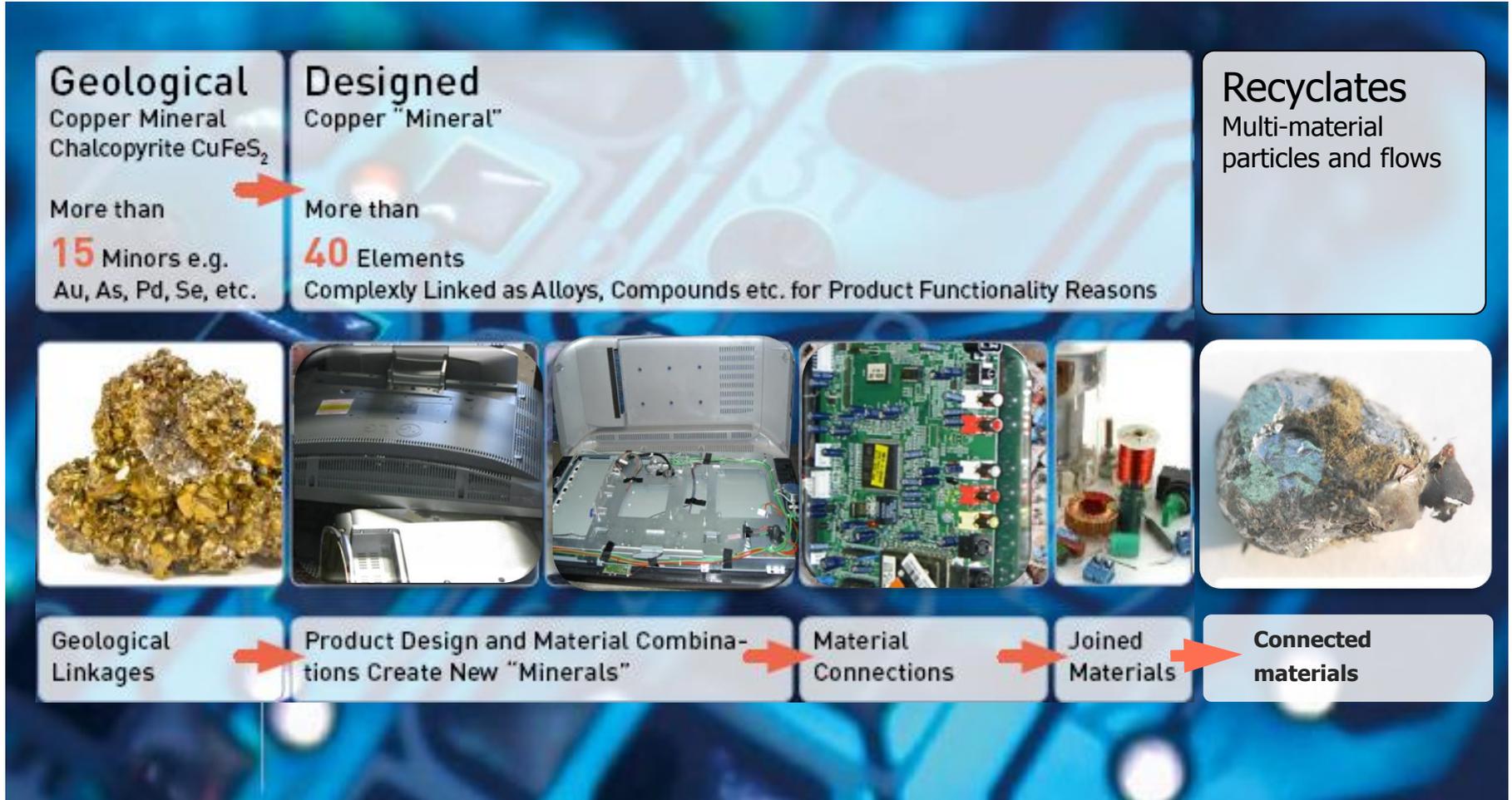
Iteratively checked by simulation and validity

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)
9. **Labelling** (including carefully considered standardisation) of products/components based on recovery and/or **incompatibility** for easy identification (and removal) from recyclates and waste streams
10. Be mindful of **liberation** of materials in design (Design for Liberation)

# DESIGN FOR RECYCLING RULES

# DfR Rule 1 : DfR is product specific

DfR rules are product and recycling system specific - each product has a unique recyclability profile



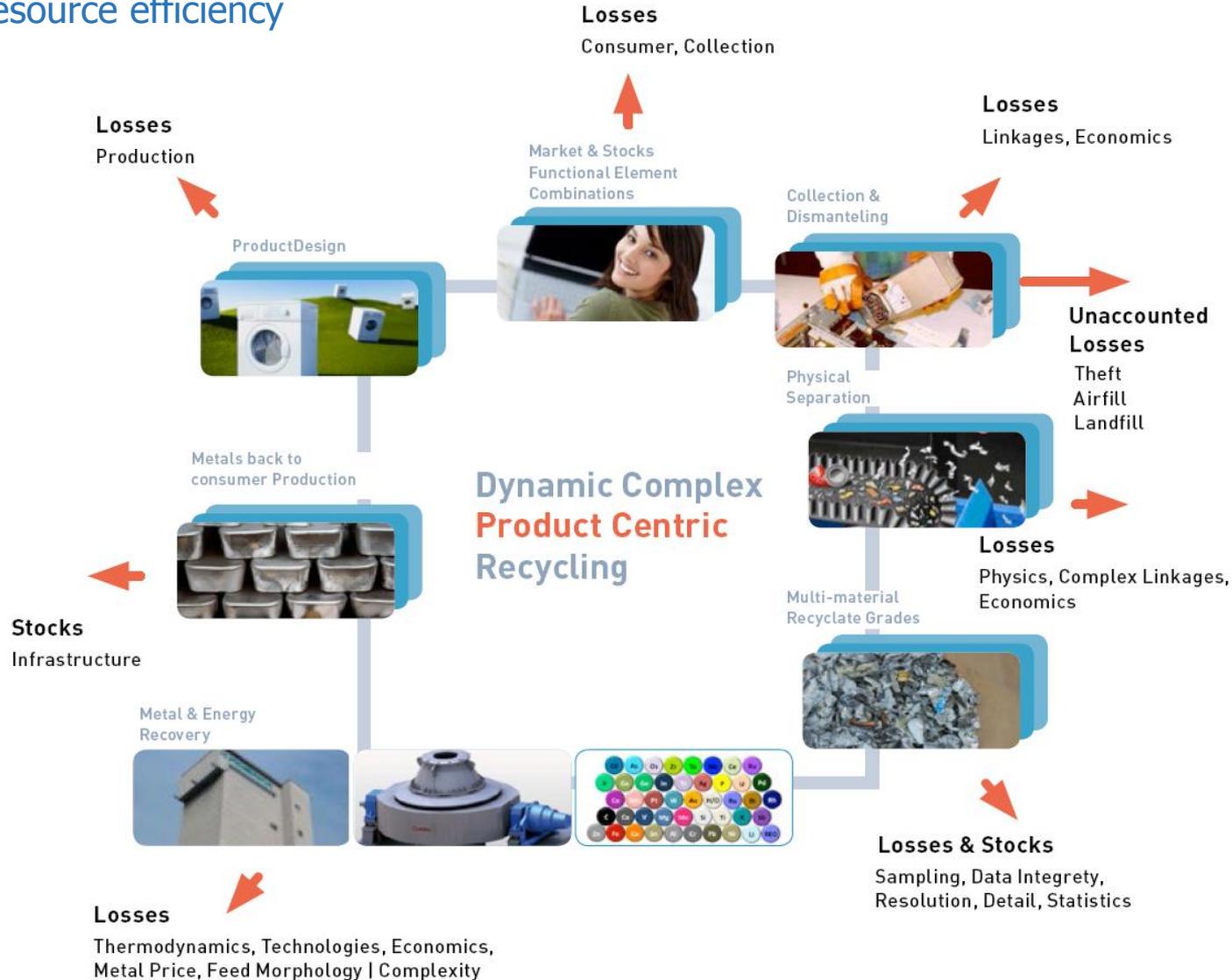
# DfR Rule 1 : DfR is product specific

Each product has a recyclability profile and a set of product and recycling system specific DfR guidelines

Recoverability per application	PMs		PGMs		Rare Earth (Oxides)			Other					
	Ag	Au	Pd	Pt	Y	Eu	Other	Sb	Co	In	Ga	W	Ta
<b>Recovery possible</b> If separately recovered and/or if there is appropriate technology and recovery available.													
Washing machine													
Large Hh Appliance													
Video recorder													
DVD player													
Hifi unit													
Radio set													
CRT TV									●	●		●	●
Mobile telephone	●	●	●	●					●	●		●	
Fluorescent lamps													
LED										●	●	●	
LCD screens										●	●		
Batteries (NIMH)					●	●	●		●				
<b>Limited recovery under certain conditions</b> If separately recovered. Partial or substantial losses during separation and/or processing/metallurgy. Recovery if appropriate systems exist.													
Washing machine	●	●	●	●									
Large Hh Appliance	●	●	●	●									
Video recorder	●	●	●					●					●
DVD player	●	●	●					●					●
Hifi unit	●	●	●										●
Radio set	●	●	●										●
CRT TV	●	●	●	●	●	●	●	●	●				●
Mobile telephone					●	●	●		●	●			●
Fluorescent lamps					●	●	●						●
LED					●	●	●		●	●			●
LCD screens	●	●	●							●	●		
Batteries (NIMH)										●	●		
<b>No separate Recovery</b> Pure recovery not possible. Lost in bulk recyclates during separation and/or during metallurgy into different non-valuable phases.													
Washing machine	●	●	●										
Large Hh Appliance	●	●	●										
Video recorder								●					●
DVD player								●					●
Hifi unit								●					●
Radio set								●					●
CRT TV								●					●
Mobile telephone					●	●	●						●
Fluorescent lamps													●
LED					●	●	●					●	
LCD screens													
Batteries (NIMH)													

# DfR Rule 1 : No oversimplification

Oversimplification of recycling by defining general DfR rules will not produce the intended goal of resource efficiency



# DfR Rule 2 : Quantification

Quality of recyclates : design, shredding and sorting determines recoverability and recycling of product and components (example on Printed Circuit Board)

Ferrous recyclate



PCB recyclate



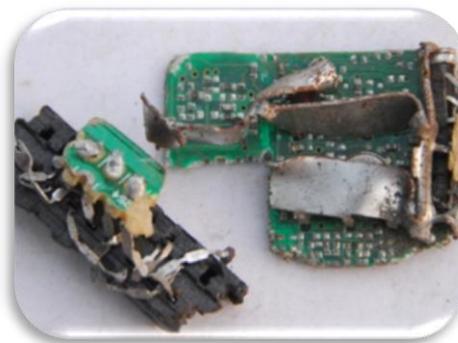
Plastics recyclate



Residue fraction

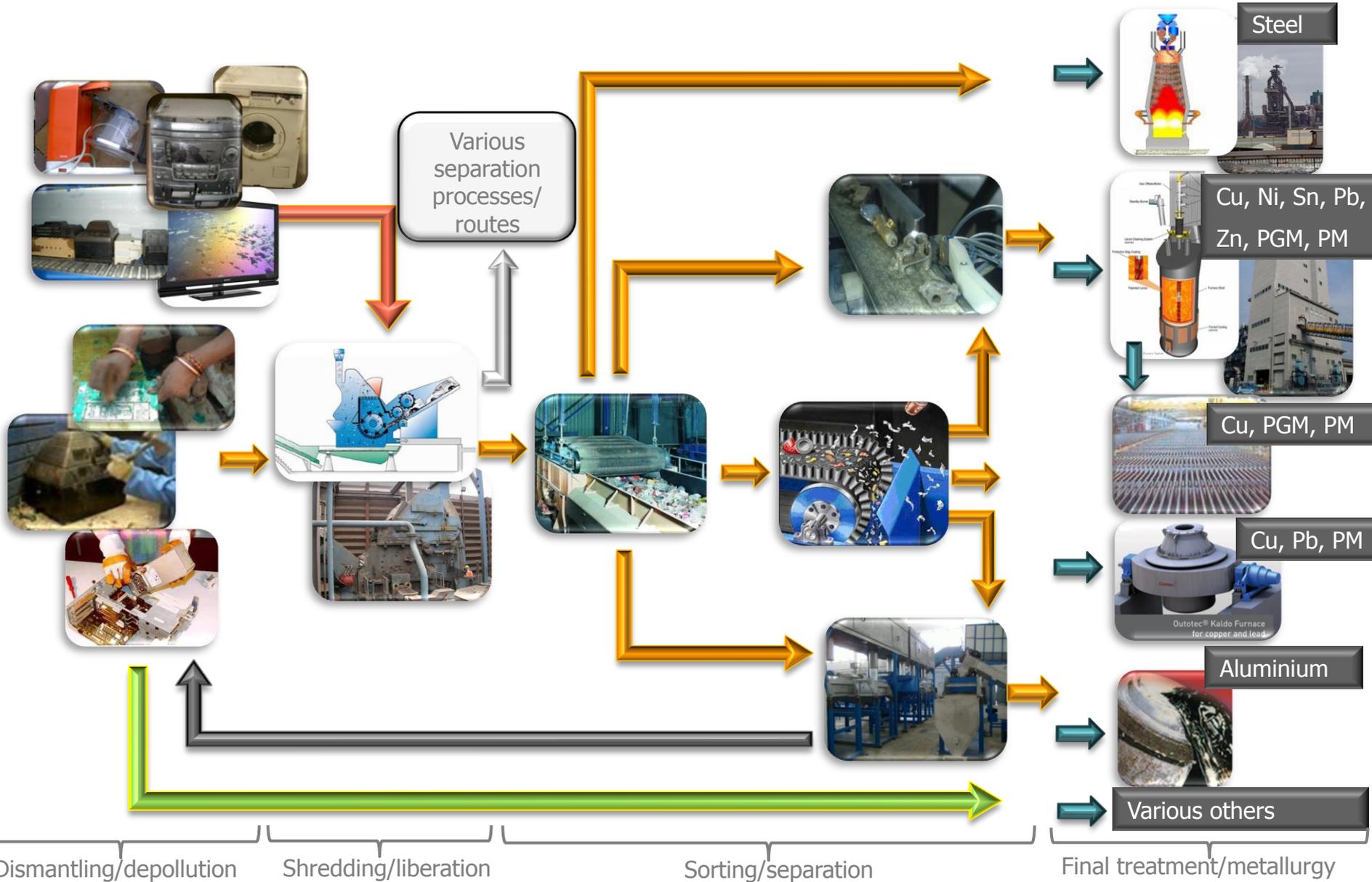


Different appearances of PCB in (PCB) recyclates



# DfR Rule 2 : Quantification

DfR needs model and simulation based quantification of recycling performance



# DfR Rule 3 : Design data

Design data on product composition and construction should be available in a consistent format that matches with the detail required to quantify and optimise recycling



Material usage and material combinations in products



Connection of complex components to structural parts/materials



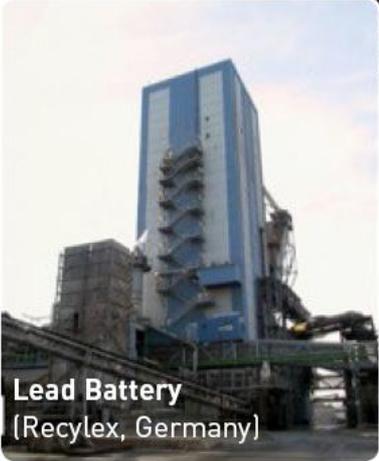
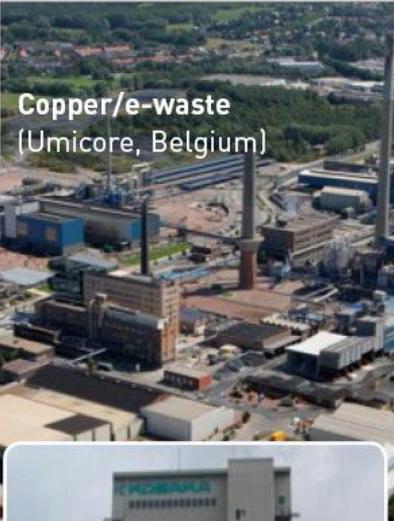
Material usage, chemical compounds and combinations in components and its variations



Chemical composition and compounds in e.g. electrical components and its variations

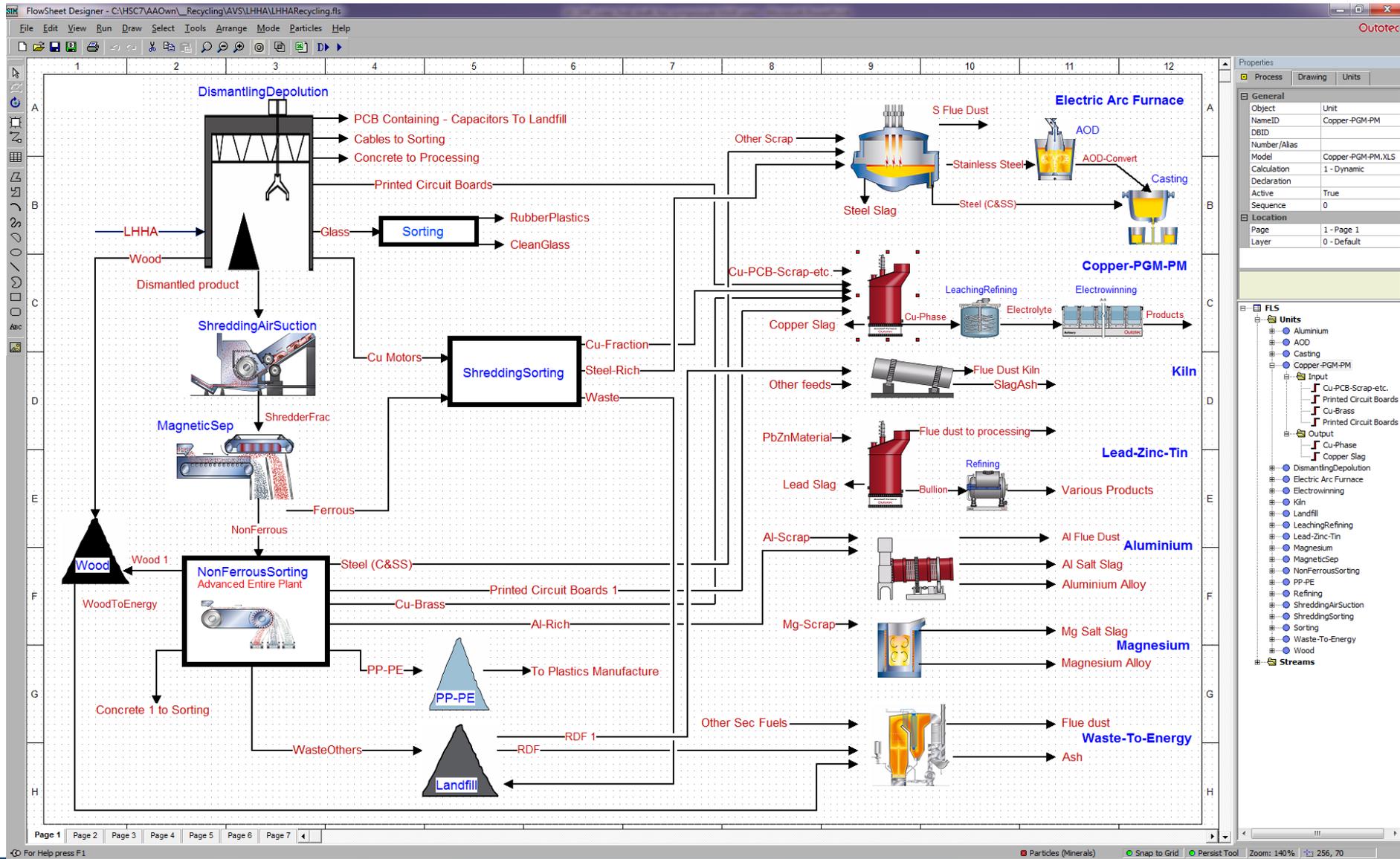
# DfR Rule 4 : Infrastructure and tools

Robust metallurgical infrastructure should be in place to ensure maximum recovery



# DfR Rule 4 : Infrastructure and tools

Rigorous tools for recycling simulation and DfR



# **SIMULATION DERIVED GUIDELINES**

# Guideline 6 : Material characteristics

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

**Problematic materials  
in design**

Concrete in washing machines



Glass in fridges



Isolation materials



Colored Printed Wire Boards



**Problems/consequences  
in sorting/separation**

Difficult to dismantle & distributes over recycle fractions



Process waste, decreases recycling performance



Contaminates recycle fractions - material losses



Losses of PCB to other recyclates - contamination of PCB fraction



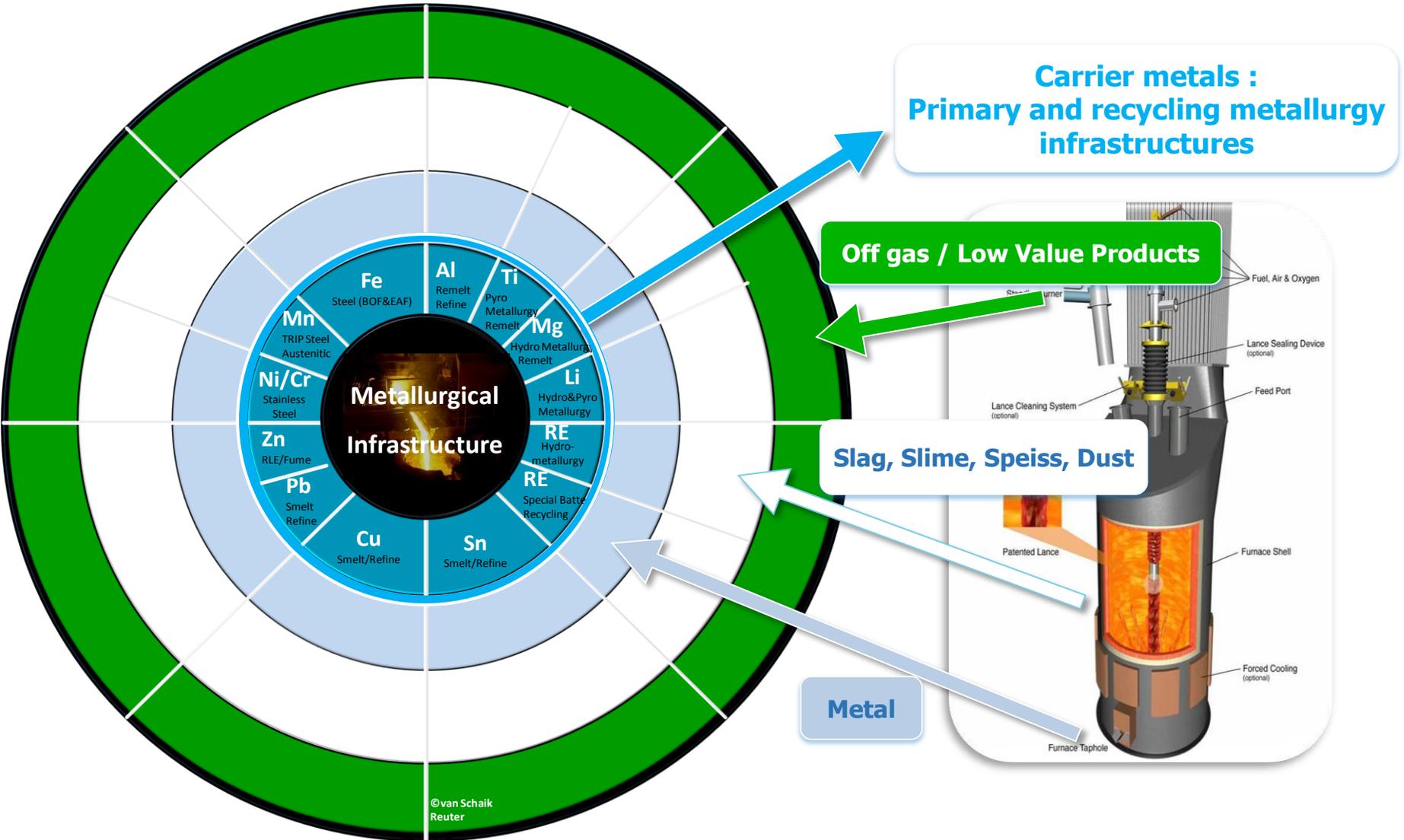
# Guideline 7 : (In) compatibility of combined materials

Identify and minimize the use of materials which will cause losses due to combined & applied materials



# Guideline 7 : (In) compatibility of combined materials

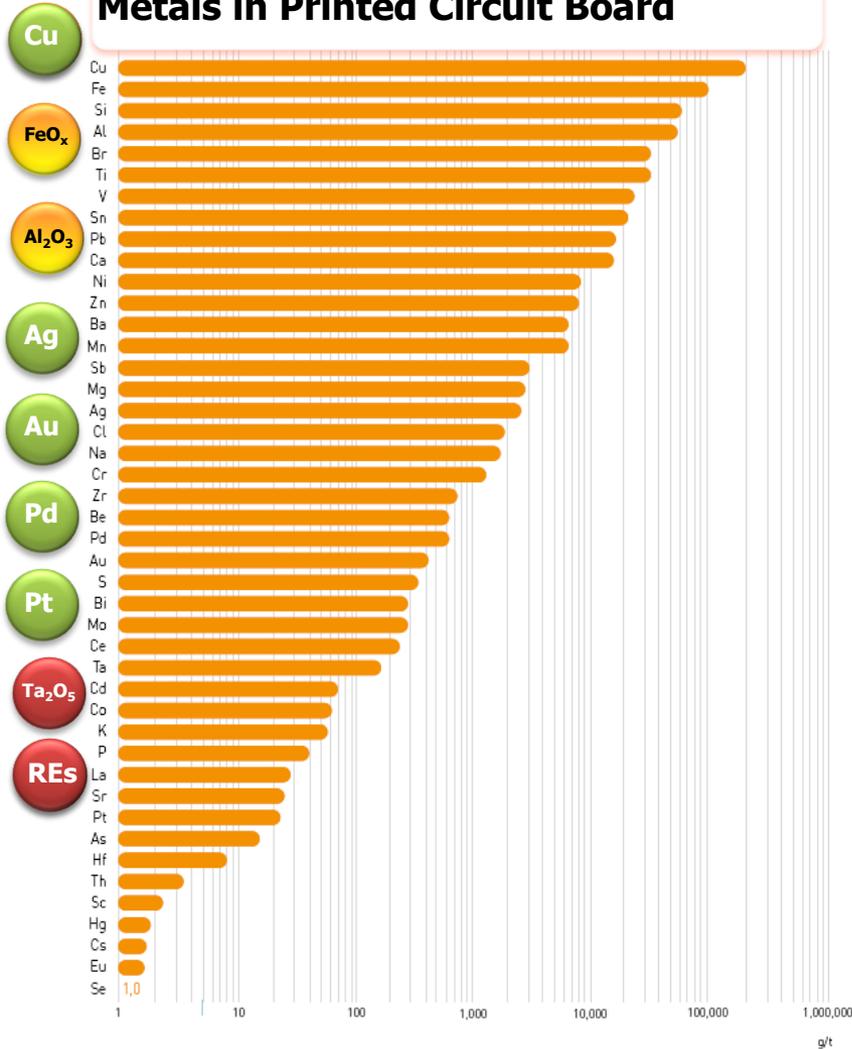
Society's Essential Carrier Metals: Metal recycling products, by products & residues



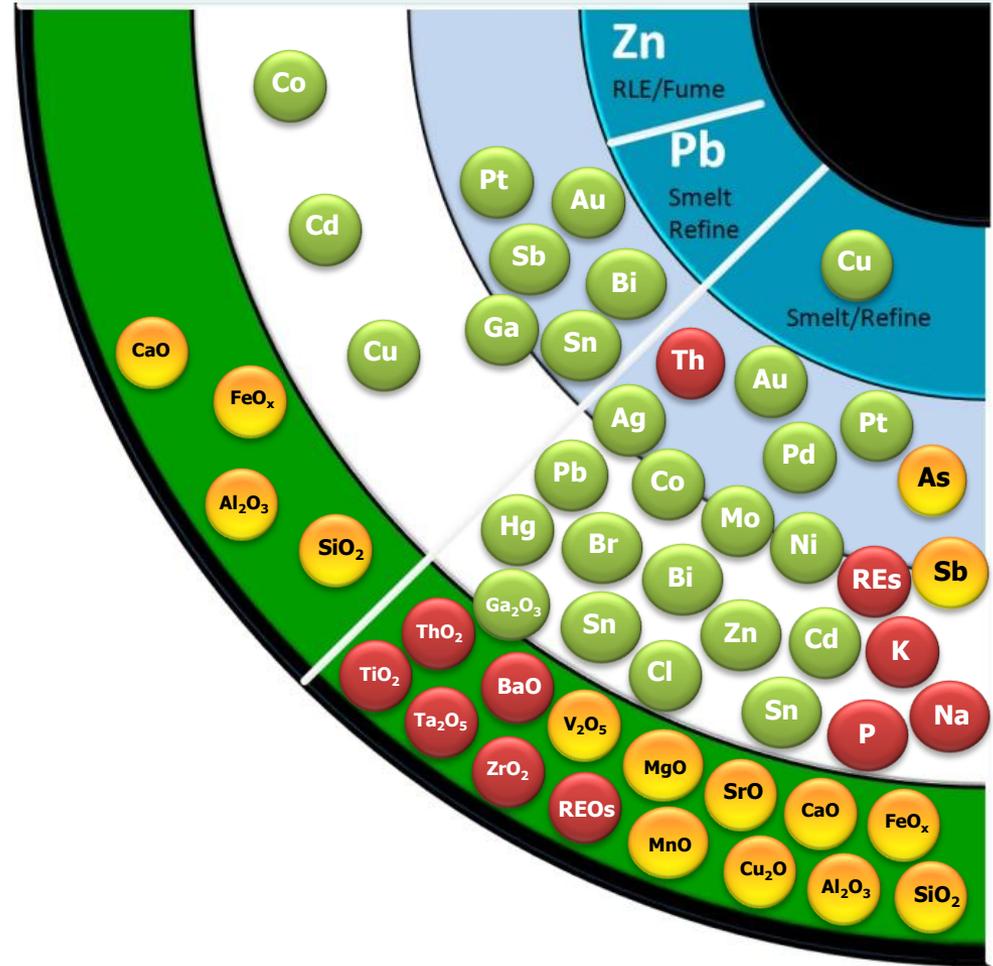
# Guideline 7 : (In) compatibility of combined materials

Recovery&losses determined by quality and destination/processing route of recycle/component

## Metals in Printed Circuit Board



## Destination (recovery/losses) of elements PCB



# Guideline 7 (In) compatibility of combined materials

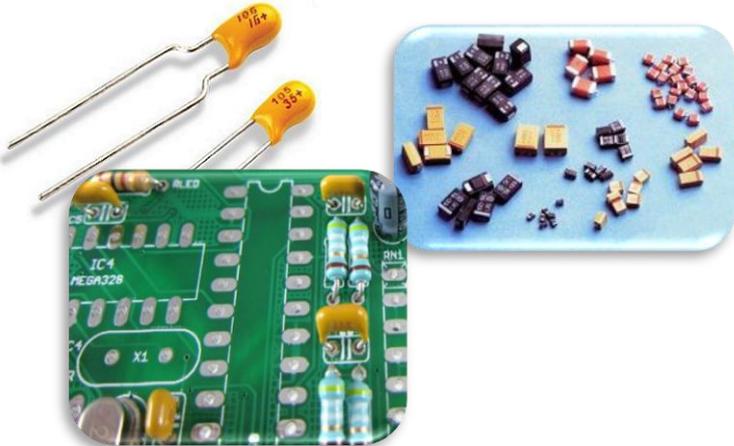
Compatibility tables for a first quick screening – based on Metal Wheel

Materials in input streams (from WEEE materials)	Society's Essential Carrier Metals: Primary Product Extractive Metallurgy's Backbone (primary and recycling metallurgy)						
	To Remelting, Smelting, Hydrometallurgy, Refining	Fe Steel (BOF&EAF)	Al Remelt/Refine	Cu Smelt/Refine	Zn RLE/Fume Pb Smelt/Refine	Ni/Cr Stainless Steel	Rare Earths Hydrometallurgy
PCBA (washing machine/LHHA)							
Ag	Red	Red	Green				
Al	Yellow	Green	Yellow				
Al <sub>2</sub> O <sub>3</sub>	Yellow	Red	Yellow				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 <sub>2</sub> O			Yellow				
Fe	Green	Yellow			Green		
FeO <sub>x</sub>			Yellow		Yellow	Yellow	Yellow
Ni		Yellow	Green		Green		Green
Pb		Yellow	Green	Green	Yellow		
Pd	Red	Red	Green	Yellow	Red		
Sb	Red	Red	Yellow	Green			
Sb <sub>2</sub> O <sub>3</sub>						Yellow	
Si	Yellow	Yellow					
SiO <sub>2</sub>			Yellow		Yellow	Yellow	
Sn	Red	Yellow	Green	Green			
Zn			Green	Green			
Elastomers						Yellow	Red
Thermosets						Yellow	Red
Thermoplastics (flame retardants etc.)						Yellow	Red
Epoxy						Yellow	Red



# Guideline 9 : Labelling/Sorting

Labelling and marking for Waste stream Sorting and (Automated) Disassembly & Sorting



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



CFL versus LED lamps



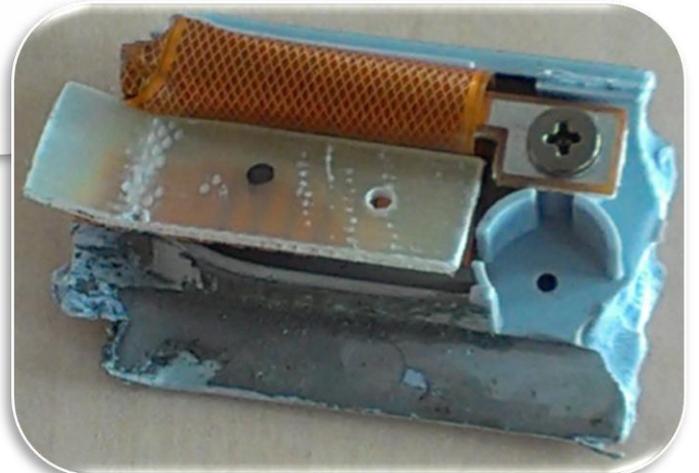
Compressors - Marking of tapping point



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

## Guideline 10 : Design for Liberation

Avoid bolts/rivets of dissimilar materials (e.g. Fe bolts) as these produce generally a liberation problem therefore creates cross-contamination of the different recyclate fractions



# Guideline 10 : Design for Liberation

Minimize the use of non reversible adhesives for incompatible/undesired material combinations



Glass glued to steel mask



Shrink films



Sealed batteries



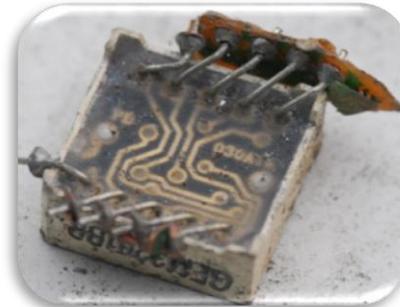
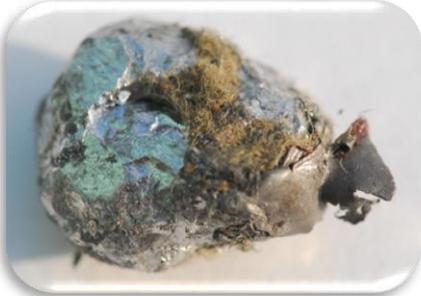
PUR glued to steel, Al, plastics



Glued wood/plastic

# Guideline 10 : Design for Liberation

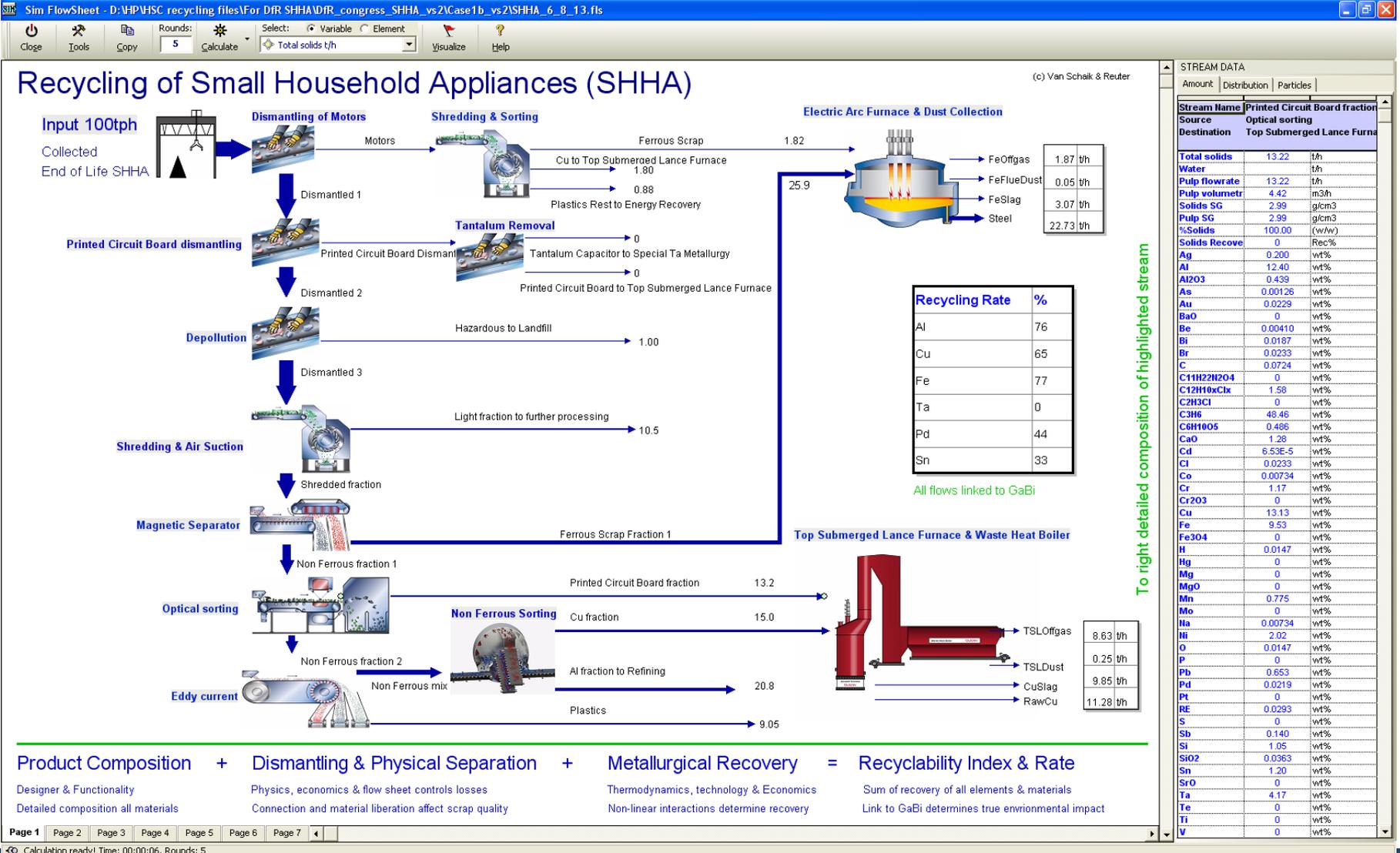
Particulate quality – an impression of un-liberated & multi-material particles



# SIMULATION EXAMPLE

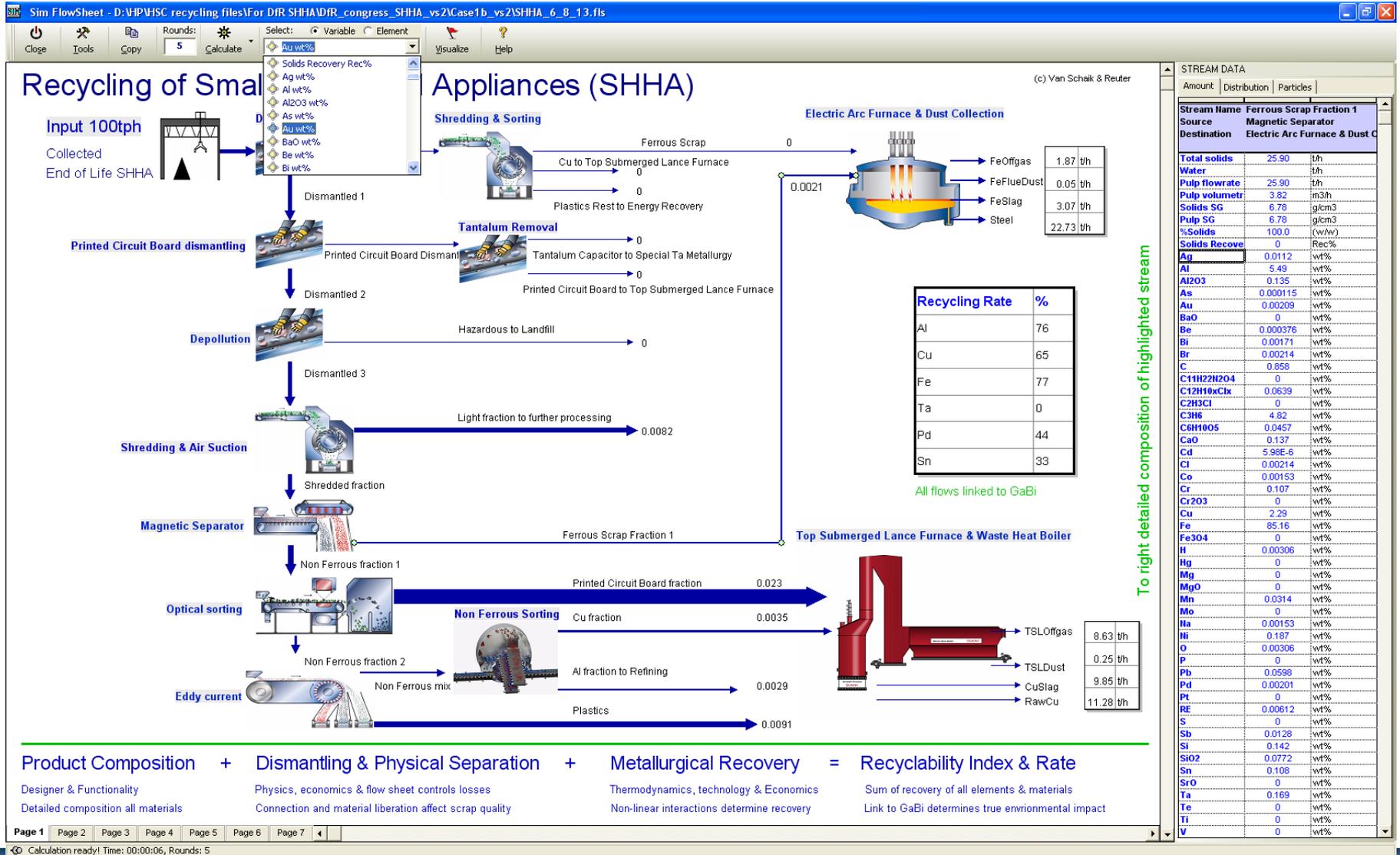
# A Simulation Example : Quantification

Quantification of Recycling Rate, Mass flows and quality/composition of flows



# A Simulation Example : Quantification

Distribution/dispersion of elements/compounds can be traced – example on Gold

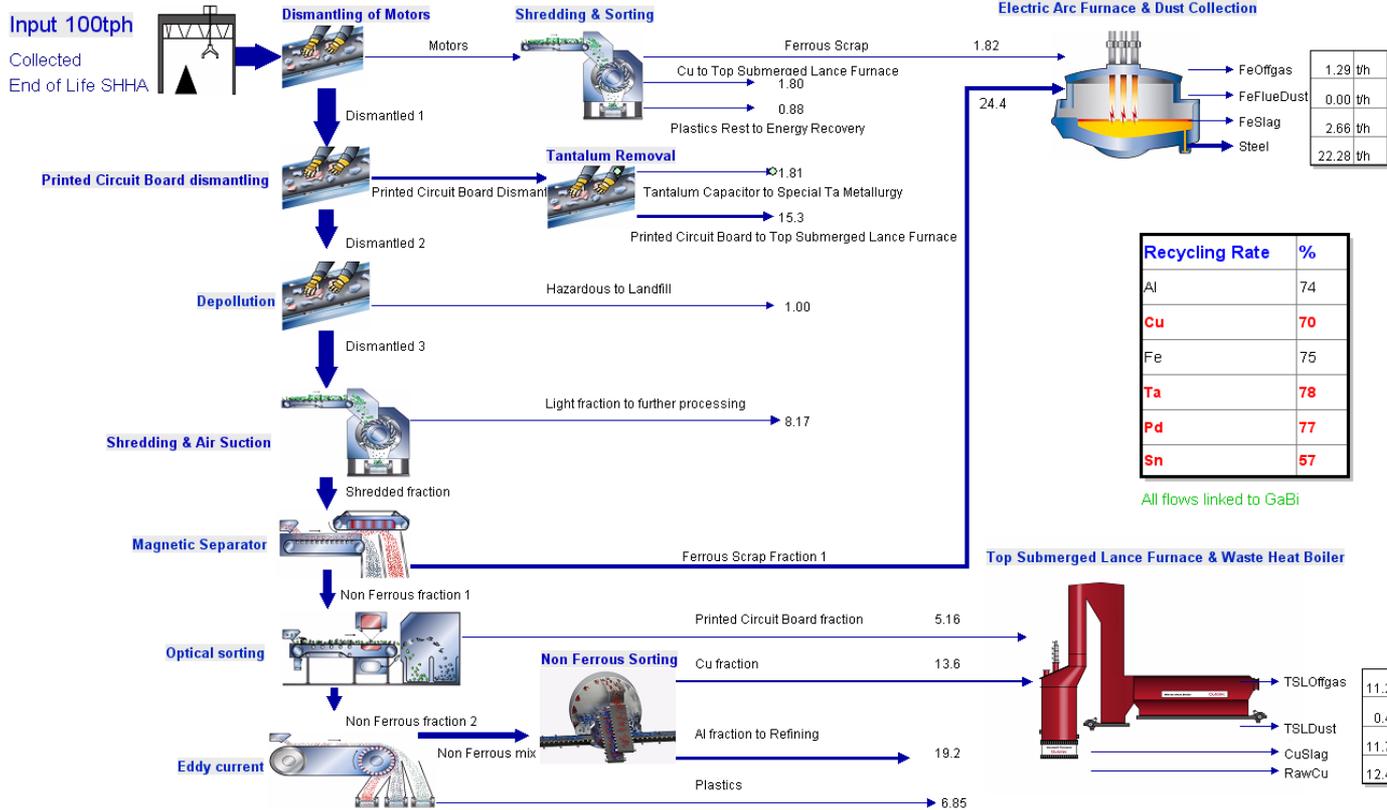


# A Simulation Example : Redesign and recycling route

Removal/sorting of PCBs & Ta capacitors through design changes by e.g. labelling and identification options for sorting

Sim FlowSheet - D:\HP\HSC\_recycling\_files\For DIR SHHA\dir\_congress\_SHHA\_vs2\Case1a\_vs2\SHHA\_23\_6\_13.fls

## Recycling of Small Household Appliances (SHHA)



(c) Van Schaik & Reuter

FeOffgas	1.29 t/h
FeFlueDust	0.00 t/h
FeSlag	2.66 t/h
Steel	22.28 t/h

Recycling Rate	%
Al	74
Cu	70
Fe	75
Ta	78
Pd	77
Sn	57

All flows linked to GaBi

To right detailed composition of highlighted stream

STREAM DATA	
Amount	Distribution   Particles
<b>Stream Name</b> Tantalum Capacitor to Special	
<b>Source</b>	Tantalum Removal
<b>Destination</b>	?
<b>Total solids</b>	1.81 t/h
<b>Water</b>	0 t/h
<b>Pulp flowrate</b>	1.81 t/h
<b>Pulp volumetr</b>	0.669 m <sup>3</sup> /h
<b>Solids SG</b>	2.70 g/cm <sup>3</sup>
<b>Pulp SG</b>	2.70 g/cm <sup>3</sup>
<b>%Solids</b>	100.0 (w/w)
<b>Solids Recover</b>	0 Rec%
<b>Ag</b>	1.60 wt%
<b>Al</b>	0 wt%
<b>Al2O3</b>	0 wt%
<b>As</b>	0 wt%
<b>Au</b>	0 wt%
<b>BaO</b>	0 wt%
<b>Be</b>	0 wt%
<b>Bi</b>	0 wt%
<b>Br</b>	0 wt%
<b>C</b>	0.200 wt%
<b>C11H22N2O4</b>	0 wt%
<b>C12H10xClx</b>	18.10 wt%
<b>C2H3Cl</b>	0 wt%
<b>C3H6</b>	0 wt%
<b>C6H10O5</b>	4.20 wt%
<b>CaO</b>	0 wt%
<b>Cd</b>	0 wt%
<b>Cl</b>	0 wt%
<b>Co</b>	0 wt%
<b>Cr</b>	0 wt%
<b>Cr2O3</b>	0 wt%
<b>Cu</b>	1.60 wt%
<b>Fe</b>	0 wt%
<b>Fe3O4</b>	0 wt%
<b>H</b>	0 wt%
<b>Hg</b>	0 wt%
<b>Mg</b>	0 wt%
<b>MgO</b>	0 wt%
<b>Mn</b>	8.90 wt%
<b>Mo</b>	0 wt%
<b>Na</b>	0 wt%
<b>Ni</b>	3.00 wt%
<b>O</b>	0 wt%
<b>P</b>	0 wt%
<b>Pb</b>	0 wt%
<b>Pd</b>	0 wt%
<b>Pt</b>	0 wt%
<b>RE</b>	0 wt%
<b>S</b>	0 wt%
<b>Sb</b>	0 wt%
<b>Si</b>	9.90 wt%
<b>SiO2</b>	0 wt%
<b>Sn</b>	0.400 wt%
<b>SO</b>	0 wt%
<b>Ta</b>	47.90 wt%
<b>Te</b>	0 wt%
<b>Ti</b>	0 wt%
<b>V</b>	0 wt%

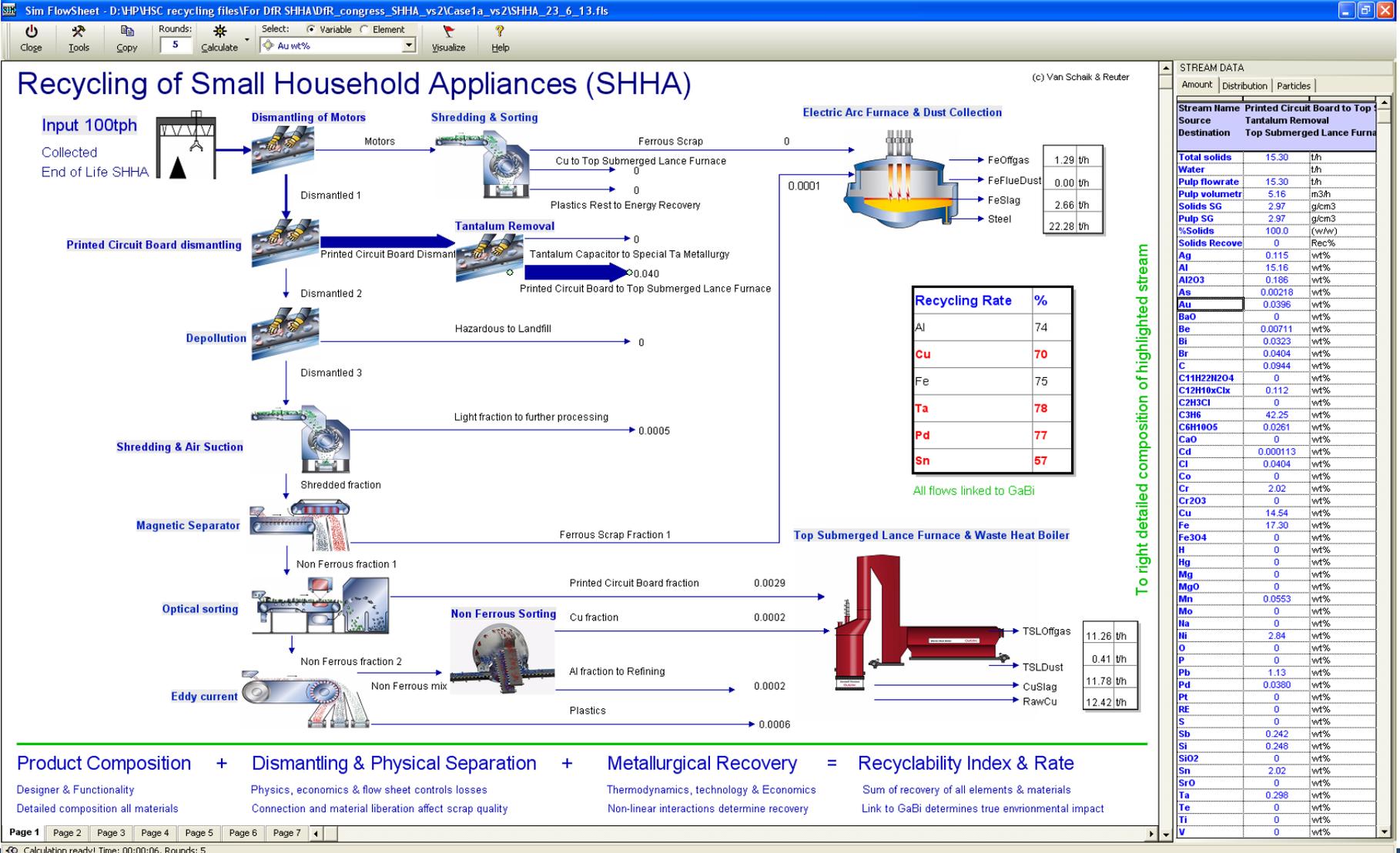
Product Composition + Dismantling & Physical Separation + Metallurgical Recovery = Recyclability Index & Rate

Designer & Functionality      Physics, economics & flow sheet controls losses      Thermodynamics, technology & Economics      Sum of recovery of all elements & materials

Detailed composition all materials      Connection and material liberation affect scrap quality      Non-linear interactions determine recovery      Link to GaBi determines true environmental impact

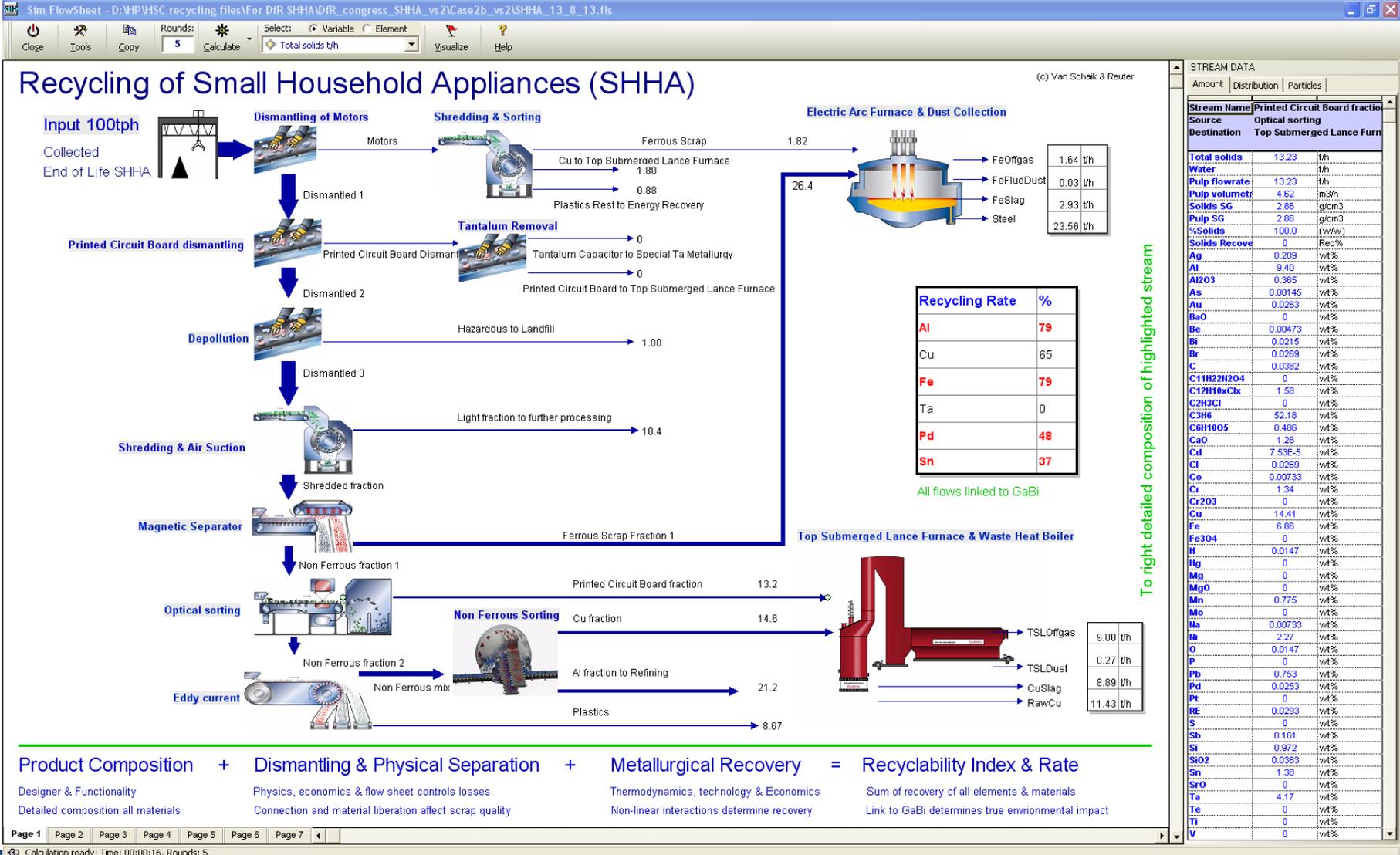
# A Simulation Example : Redesign and recycling route

Removal/sorting of PCBs & Ta capacitors through design changes by e.g. labelling and identification options for sorting – distribution of Gold



# A Simulation Example : Design for Liberation

Effect of construction/connections of Printed Wire Board in product – improved liberation of Al heat sinks and Fe containing components/bolts

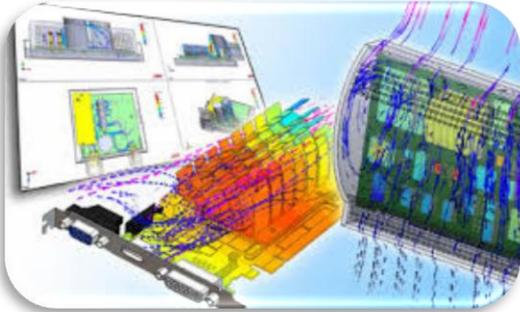


# CONCLUDING REMARKS & RECOMMENDATIONS

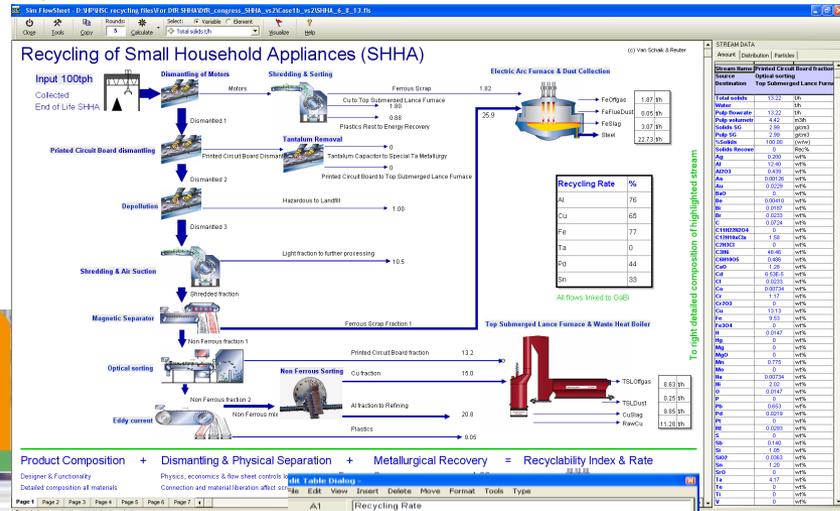
# DfR Rule 4 & 5 : Recycling Simulation linked to Design

Recycling process simulation tools, including environmental footprint to be linked to CAD/Design tools to realise technology based, realistic and economically viable DfR & Ecodesign

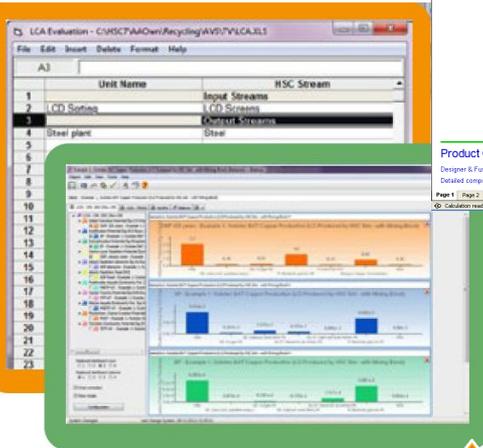
CAD/Design (BOM/FMD/etc)



Recycling system process simulation tools



To right detailed composition of highlighted stream



Environmental Impact Analyses (Product /system specific)

Product Composition + Dismantling & Physical Separation + Metallurgical Recovery = Recyclability Index & Rate

Material	Recycling Rate (%)
Al	76
Cu	65
Fe	77
Ta	0
Pd	44
Sn	33

Recycling & recovery rates + losses/emissions (Product and recycling system specific)

# Recommendations

## (Policy) targets for Recycling and Eco-design

- should remain within what is technologically (physically and thermodynamically) and economically possible and 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 interest and expertise of all stakeholders in the product and recycling system and stimulate interaction;
- should respect the dynamic (time-varying) product characteristics and recycling profile over time.

# Acknowledgements

- Coolrec bv
- Remondis Electrorecycling GmbH
- Alba Service GmbH
- Indaver nv
- Sims Recycling Solutions
- Van Dalen / De Ruiter Schroot bv
- Markus Reuter (Outotec Oyj and Aalto University)

# Contact

Dr. ir. Antoinette van Schaik

MARAS - Material Recycling and Sustainability -

Rijsbes 46

2498 AS Den Haag

The Netherlands

Tel.: +31 6 53836042

[A.vanSchaik@marasustainability.nl](mailto:A.vanSchaik@marasustainability.nl)

[www.marasustainability.nl](http://www.marasustainability.nl)

