A Recycling Analysis

Physics based standard for CE recycling assessment and quantification

Workshop
'Recycling Automotive Electronics: Exploring Legislative and Standardisation Gaps in the Context of the TREASURE Experience'
31st May 2023

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Challenges

- Defining a physics and recycling-technology based methodology and standard for assessment, quantification and optimisation of recycling and EoL circularity

- Develop KPI’s for Circular Economy with respect the automotive recycling chain which go beyond currently applied mass driven and average total recycling rates to move towards Circular Economy

- Increase the recycling/recovery of car electronics and contained critical/minor elements

- Providing bench-mark for technology comparison and definition of most optimal recycling processing flowsheets

- Industrial recycling-technology basis for EoL circularity assessment and advice

Approach and tools

TREASURE

- Simulation-based analysis of metallurgical and recycling systems to assess the recycling and circularity of car electronic parts - digital twins for the End-of-Life stage

- Evaluation of recycling circular economy systems and product design in terms of mass, energy and exergy balances in addition to the normal environmental foot-printing for all materials in the product/part

- Definition and calculation of recyclability KPIs/CE indicators and results e.g:
  - recycling rates for total part and all individual materials while maintaining material and energy quality
  - assessment of different recycling routes
  - definition of most optimal recycling system flowsheets
  - disassembly and DfR recommendations

- Physics based assessment, Design for Recycling and Eco Design by linking actors, tools and data in the automotive supply chain

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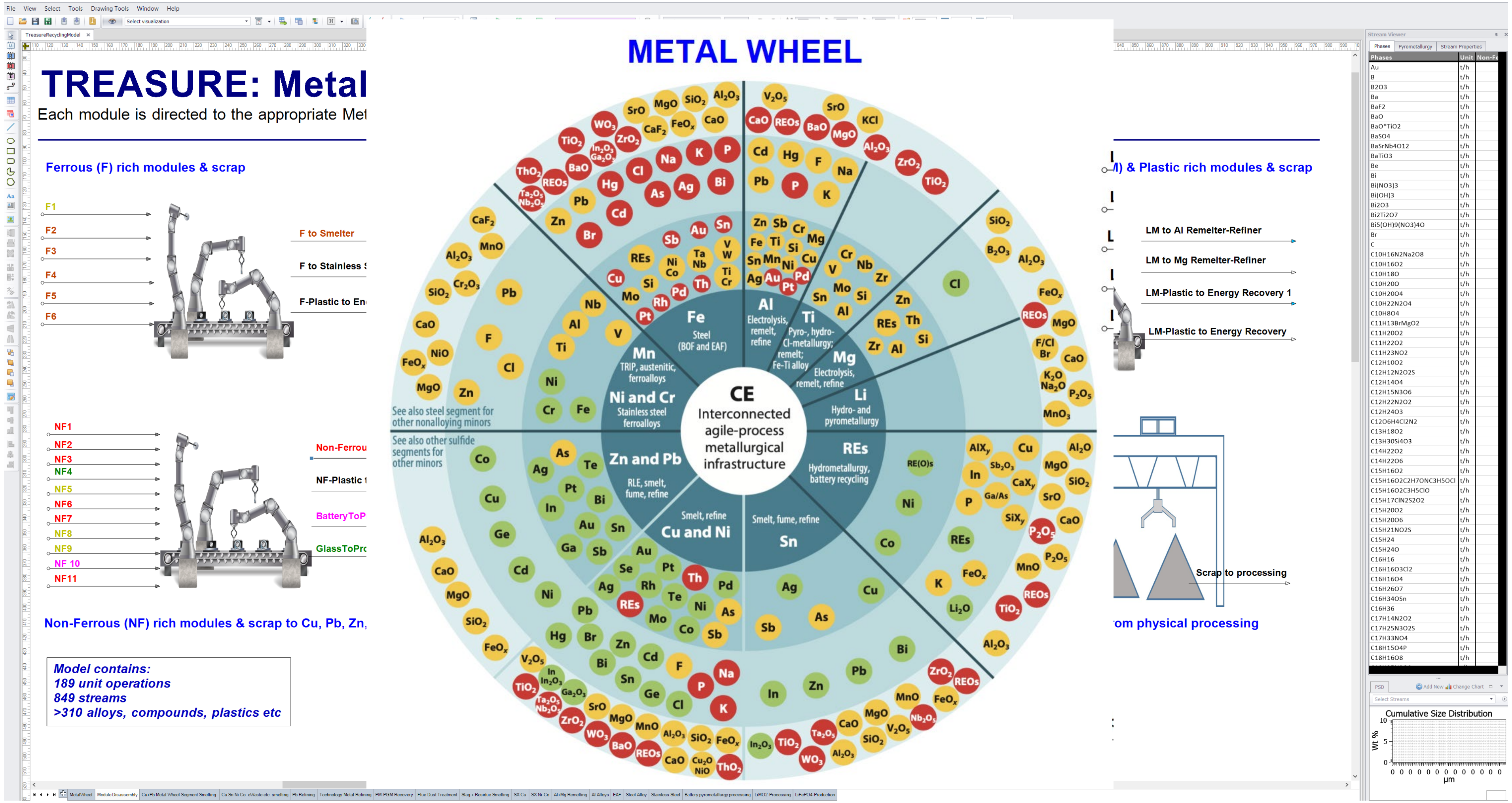
Simulation-based analysis of metallurgical and recycling systems

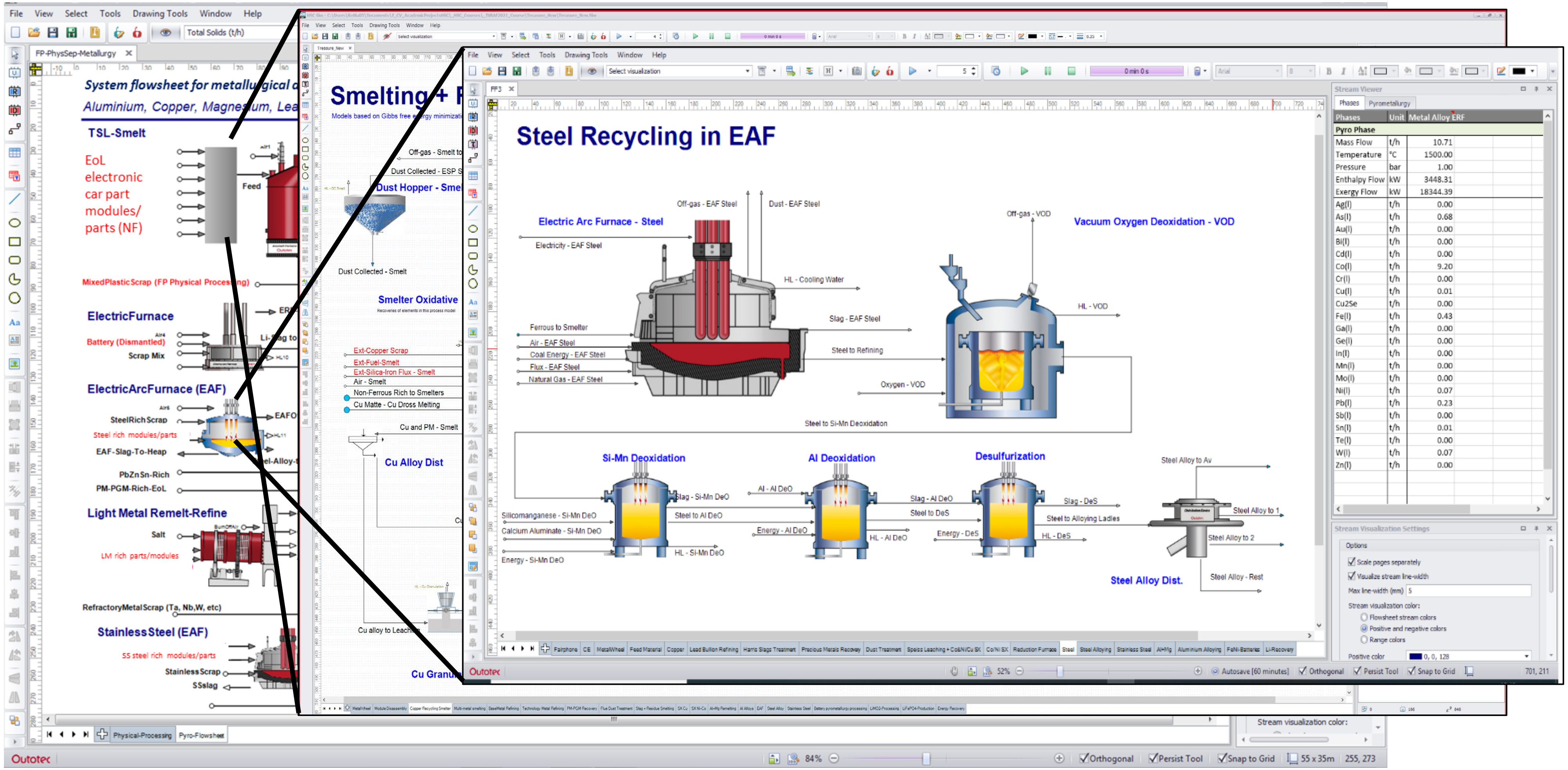
TREASURE



Simulation-based analysis of metallurgical and recycling systems

Metallurgical recycling (and organics processing) infrastructures

TREASURE



Linking product data and recycling

Data linking from MISS/CAD data to thermodynamic recognisable compounds

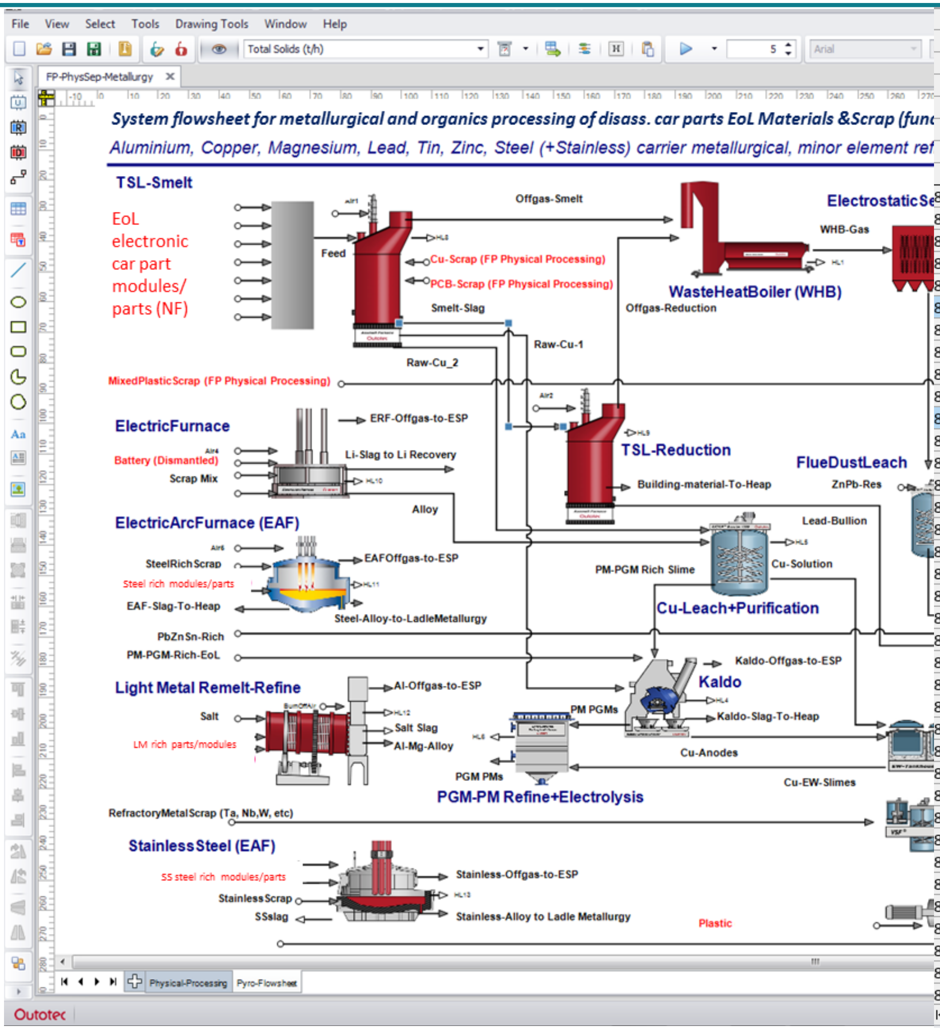
TREASURE

Car part	
	Infotainment
	Combi instrument
	Exterior mirrors
	Additional brake lighting
	Speed sensor
	Rain sensor
	Air quality sensor

Infotainment-Combi Instrument - Air conditioning unit			
Leon II			
Compounds (chemical formulas)	Mass % in car part	Compounds (chemical formulas)	Mass % in car part
*2CoO*TiO2		Si	0.038089945
*3MgO*4SiO2*H2O		Si(CH3)2O(g)	0.081145506
Ag	0.050879254	Si(OC2H5)4(l)	8.91422E-05
Al	3.324194317	SiN(g)	
Al(OH)3	0.000221513	SiO	0.017611932
Al2O3	0.010980374	SiO2	6.120841659
Al2O3*2SiO2	0.000735423	Sn	0.330726024
AlO		SnO2	
As	6.25873E-05	SrFe12O19	0.369481684
As(CH3)3	0.000389997	SrO	0.002444903
Au	0.003174198	Ta	0.034698979
B	0.011693839	Tb	
B(OH)3		Te	
B2O3	0.000159093	Ti	0.000190354
Ba	0.026569005	TiO2	0.05595244
BaO	0.004543896	Ti(OC3H7)4(TTIPg)	0.003168093
BaSO4	0.006158511	V	0.000866525
BaTiO3		W	
Be	7.60241E-06	Zn	0.273005216
Bi	0.001581435	Zn(OH)2	7.19722E-06
Bi2O3	7.22426E-06	Zn5(OH)6(CO3)2	
C	0.079298357	ZnC2O4*H2O*CH3OH	
CaCO3		ZnO	0.000238977
CaMg(CO3)2		ZnSO4	
CaHPO4*2H2O	5.2456E-05	ZrO2	
…	…	…	…
…	…	…	…
…	…	…	…
Pb	0.147341834	C6H12O6(ADG)	3.332776712
PbO	0.000165707	C6H18OSi2(HMDI)	0.08860842
PbO*TiO2	0.000809446	C6H4O2(QUIg)	0.307403945
PbO*ZrO2	0.000668399	C6H5F(FBZg)	
PbSiO3		C6H6S(BTHg)	0.158417758
PC6H18N3(g)		C6H6S(BTHl)	
Pd	0.002698819	C7H4F3NO2(3NIBg)	0.014802409
Pt	1.92979E-05	C2H6O12Zn5 - C36H70O4Zn	4.74074E-05
Ru	9.73492E-05	C7H6O2(BAC)	
RuO2	1.07967E-05	C8H18O2S(DBSg)	0.00169436
S	0.01450747	C8H18OSi2	
Sb	0.002978447	C8H24O4Si4	0.000222076
Sb2O3	0.008691691	C8H8(COTl)	0.00615385
Sb2O5	3.36309E-05	C9H16(2NOg)	0.422591563
Se		**SUM**	100.000

Recycling system simulation

Twinning reality (with industrial experience) – on the basis of thermodynamics



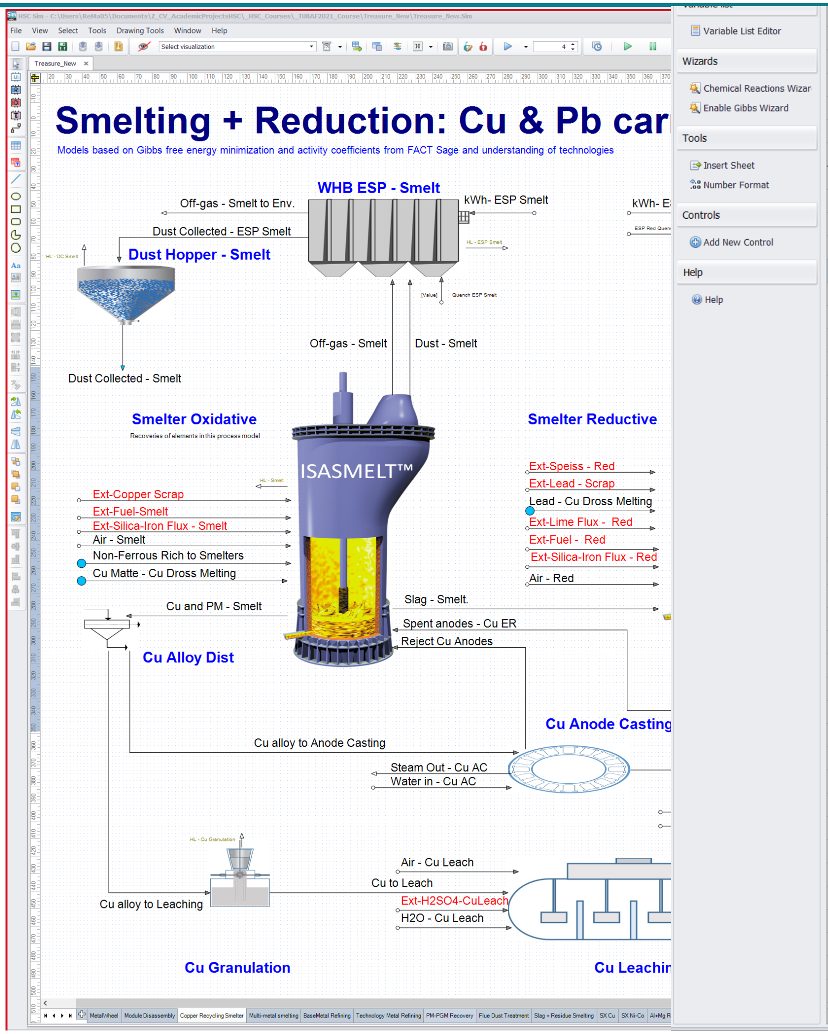
	A	B	C	D	E	F	G	H	I	J	K	L	U	V	W
1			Input												
2															
3															
4	**Flags**		**Input streams**	**Value**	**Units**	**Flow Rates**			**Thermal E Flow**	**Total H Flow**	**Thermal E**	**Tot H**	**Chem Ex Flow**	**Phy Ex Flow**	**Tot Exergy Flow**
5	MIXER					kg/h	Nm³/h	kmol/h	kW	kW	kWh/kmol	kWh/kmol	kW	kW	kW
6			Total Gas Flow	0.00	Nm3/h										
7			Total Condensed Flow	120.14	t/h	120 135.20	#DIV/0!	1 285.75	- 2.42	-243 325.10			235 540.37	- 11.32	235 529.05
837															
838			**Leon III Infotainment NF**	40.00	t/h	Flow Rates			Thermal E Flow	Total H Flow	Thermal E	Tot H	Chem Ex Flow	Phy Ex Flow	Tot Exergy Flow
839			Temperature	25.00	°C	kg/h	Nm³/h	kmol/h	kW	kW	kWh/kmol	kWh/kmol	kW	kW	kW
840			Pressure	1.00	bar										
841	Fix		Total	100.00	wt-%	39 999.97	#DIV/0!	677.99	- 1.36	-27 446.40			96 207.43	- 10.66	96 196.76
842			*2CoO*TiO2	0.00		0.54	#DIV/0!	0.00	0.00	- 0.96	0.00	- 407.00	0.12	0.00	0.12
843			*3MgO*4SiO2*H2O			0.00	0.00	0.00	0.00	0.00	0.00	-1 638.03	0.00	0.00	0.00
844			Ag	0.04		16.79	0.00	0.16	0.00	0.00	0.00	0.00	4.29	0.00	4.29
845			Al	4.00		1 599.13	0.59	59.27	0.00	0.00	0.00	0.00	13 099.81	0.00	13 099.81
846			Al(OH)3	0.11		43.03	0.02	0.55	0.00	- 195.56	0.00	- 354.48	2.08	0.00	2.08
847			Al2O3	0.25		99.34	0.03	0.97	0.00	- 453.51	0.00	- 465.47	4.06	0.00	4.06
848			Al2O3*2SiO2	0.00		0.04	0.00	0.00	0.00	- 0.18	0.00	- 928.10	0.01	0.00	0.01
849			AlO			0.00	0.00	0.00	0.00	0.00	0.00	24.17	0.00	0.00	0.00
850			As	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01
851			As(CH3)3			0.00	0.00	0.00	0.00	0.00	0.00	- 4.72	0.00	0.00	0.00
852			Au	0.01		4.37	0.00	0.02	0.00	0.00	0.00	0.00	0.31	0.00	0.31
853			B	0.00		0.45	0.00	0.04	0.00	0.00	0.00	0.00	7.21	0.00	7.21
854			B(OH)3			0.00	0.00	0.00	0.00	0.00	0.00	- 304.11	0.00	0.00	0.00
855			B2O3	0.00		0.01	0.00	0.00	0.00	- 0.07	0.00	- 353.78	0.00	0.00	0.00
856			Ba	0.05		18.42	0.01	0.13	0.00	0.00	0.00	0.00	28.89	0.00	28.89
857			BaO	0.00		0.26	0.00	0.00	0.00	- 0.26	0.00	- 153.82	0.12	0.00	0.12
858			BaSO4	0.01		4.13	0.00	0.02	0.00	- 7.20	0.00	- 406.82	0.19	0.00	0.19
859			BaTiO3			0.00	0.00	0.00	0.00	0.00	0.00	- 444.65	0.00	0.00	0.00
860			Be			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
861			Bi	0.00		0.54	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.20
862			Bi2O3			0.00	0.00	0.00	0.00	0.00	0.00	- 157.59	0.00	0.00	0.00
863			C	0.16		63.37	0.03	5.28	0.00	0.00	0.00	0.00	601.31	0.00	601.31
864			CaCO3			0.00	0.00	0.00	0.00	0.00	0.00	- 335.17	0.00	0.00	0.00
865			CaMg(CO3)2	0.00		0.07	0.00	0.00	0.00	- 0.23	0.00	- 646.04	0.00	0.00	0.00
866			CaHPO4*2H2O			0.00	0.00	0.00	0.00	0.00	0.00	- 672.55	0.00	0.00	0.00
867			CaO	0.48		193.75	0.06	3.46	0.00	- 609.35	0.00	- 176.37	122.62	0.00	122.62
868			CaSO3	0.00		0.03	#DIV/0!	0.00	0.00	- 0.08	0.00	- 322.05	0.02	0.00	0.02
869			CaZrO3			0.00	0.00	0.00	0.00	0.00	0.00	- 490.34	0.00	0.00	0.00
870			Cd	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
871			Cl(g)			0.00	0.00	0.00	0.00	0.00	0.00	33.70	0.00	0.00	0.00
872			Cl2(g)			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
873			Co	0.00		0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.00	0.32

Input / Output / Dist / Controls / Model / Mixer / Weight per subcomponent

Recycling system simulation

Detail of digital twin of industrial processing

TREASURE



#	A	B	C	D	E	F	G	H	I	J	K	DE	DF	DG	DH	HB	HC	HD	HE
1																			
2																			
3		WIZARD: Chemical Reactions							CHEMICAL REACTIONS										
4																			
5	Type	VARIABLES:	Units	INPUT	OUTPUT	BALANCE		Progress	REACTANTS				PRODUCTS			REACTION ENTHALPY		LogQ	
6		Phases/Species		Total	Total	Total		%								-5.22	kW	Simulated	
7	A	Mass Flow	kg/h	332.13	332.13	0.00		90.00	Cu(s)			=	Cu(+2a)	e-		64.90	kJ/mol	-2.88	
8	T	Temperature	°C	0.00	0.00			Coef.	1.00				1.00	2.00		0.28	kW/kg		
9	Pr	Pressure	bar	0.00	0.00			kmol/h	0.15				0.15	0.30		2.71	kW		
10	V	Volumetric Flow	m3/h	0.11	0.11			t/h	0.01				0.01	0.00					
11	H	Enthalpy Flow	kW	750.91	750.91	0.00		95.56	Cu(+2a)	e-		=	Cu			-64.90	kJ/mol	2.88	
12	Ht	Thermal Energy Flow	kW	2125.27	2130.48	5.22		Coef.	1.00	2.00			1.00			-0.28	kW/kg		
13	Hc	Heat Content Flow	kW	14.34	12.88	-1.46		kmol/h	0.14	0.29			0.14			-2.59	kW		
14	Cp	Heat Capacity	kJ/kgK	3.91	3.69			t/h	0.01	0.00			0.01						
15	Ex	Exergy Flow	kW	2131.58	17.61	-2113.97		90.00	As	H2O		=	AsO2(-a)	H(+a)	e-	142.63	kJ/mol	-10.21	
16	P1g	Gas Phase	Nm3/h	0.00	0.00			Coef.	1.00	2.00			1.00	4.00	3.00	0.53	kW/kg		
17		O2(g)	Nm3/h	0.00	0.00	0.00		kmol/h	0.00	0.00			0.00	0.00	0.00	0.00	kW		
18		N2(g)	Nm3/h	0.00	0.00			t/h	0.00	0.00			0.00	0.00	0.00				
19	P2a	Water Phase	kg/h	321.23	321.70			30.00	AsO2(-a)	O2(g)	H2O	=	AsO4(-3a)	H(+a)		-175.35	kJ/mol	-2.80	
20		H2SO4	kg/h	19.68	0.00	-19.68		Coef.	2.00	1.00	2.00		2.00	4.00		-0.46	kW/kg		
21		H(+a)	kg/h	0.00	0.40	0.40		kmol/h	0.00	0.00	0.00		0.00	0.00		0.00	kW		
22		H2O	kg/h	301.55	301.55	0.00		t/h	0.00	0.00	0.00		0.00	0.00					
23		SO4(-2a)	kg/h	0.00	19.28	19.28		90.00	Sb	H2O		=	SbO2(-a)	H(+a)	e-	111.42	kJ/mol	-7.94	
24		Cu(+2a)	kg/h	0.00	0.42	0.42		Coef.	1.00	2.00			1.00	4.00	3.00	0.25	kW/kg		
25		Cu(+a)	kg/h	0.00	0.00			kmol/h	0.00	0.00			0.00	0.00	0.00	0.00	kW		
26		AsO2(-a)	kg/h	0.00	0.00	0.00		t/h	0.00	0.00			0.00	0.00	0.00				
27		AsO4(-3a)	kg/h	0.00	0.00	0.00		90.00	Bi	H2O		=	BiO2(-a)	H(+a)	e-	272.09	kJ/mol	-10.72	
28		SbO2(-a)	kg/h	0.00	0.01	0.01		Coef.	1.00	2.00			1.00	4.00	3.00	0.36	kW/kg		
29		BiO2(-a)	kg/h	0.00	0.00	0.00		kmol/h	0.00	0.00			0.00	0.00	0.00	0.00	kW		
30		e-	kg/h	0.00	0.00	0.00		t/h	0.00	0.00			0.00	0.00	0.00				
31		Pb(+2a)	kg/h	0.00	0.00	0.00		90.00	Ag(s)			=	Ag			0.00	kJ/mol	0.00	
32		Ni(+2a)	kg/h	0.00	0.04	0.04		Coef.	1.00				1.00			0.00	kW/kg		
33	P3s	Pure Phase	kg/h	10.90	10.43			kmol/h	0.00				0.00			0.00	kW		
34		Cu	kg/h	0.00	9.13	9.13		t/h	0.00				0.00						
35		Cu(s)	kg/h	10.61	1.06	-9.55		90.00	Pb			=	Pb(+2a)	e-		0.92	kJ/mol	#NUM!	
36		Ag	kg/h	0.00	0.06	0.06		Coef.	1.00				1.00	2.00		0.00	kW/kg		
37		Ag(s)	kg/h	0.06	0.01	-0.06		kmol/h	0.00				0.00	0.00		0.00	kW		
38		Bi	kg/h	0.00	0.00	0.00		t/h	0.00				0.00	0.00					
39		Sb	kg/h	0.01	0.00	-0.01		100.00	Pb(+2a)	SO4(-2a)		=	PbSO4			-11.29	kJ/mol	#DIV/0!	
40		Pb	kg/h	0.00	0.00	0.00		Coef.	1.00	1.00			1.00			-0.02	kW/kg		
41		PbSO4	kg/h	0.00	0.00	0.00		kmol/h	0.00	0.00			0.00			0.00	kW		
42		As	kg/h	0.00	0.00	0.00		t/h	0.00	0.00			0.00						

Input / Output / Dist / Controls / Model / Operation Parameters

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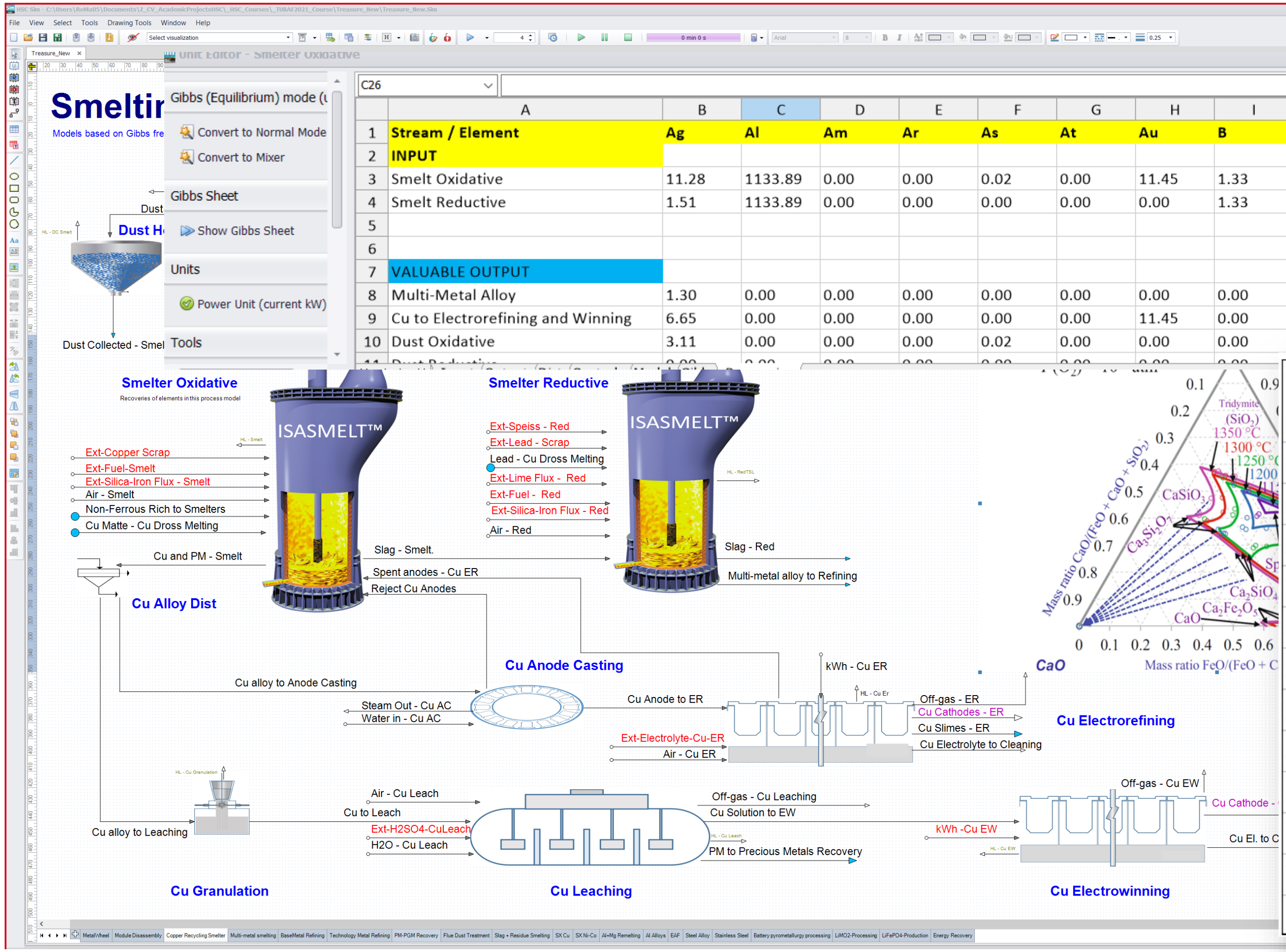
Results of simulation models

Recycling assessment : recycling KPIs and quality of recycling & other flows

TREASURE



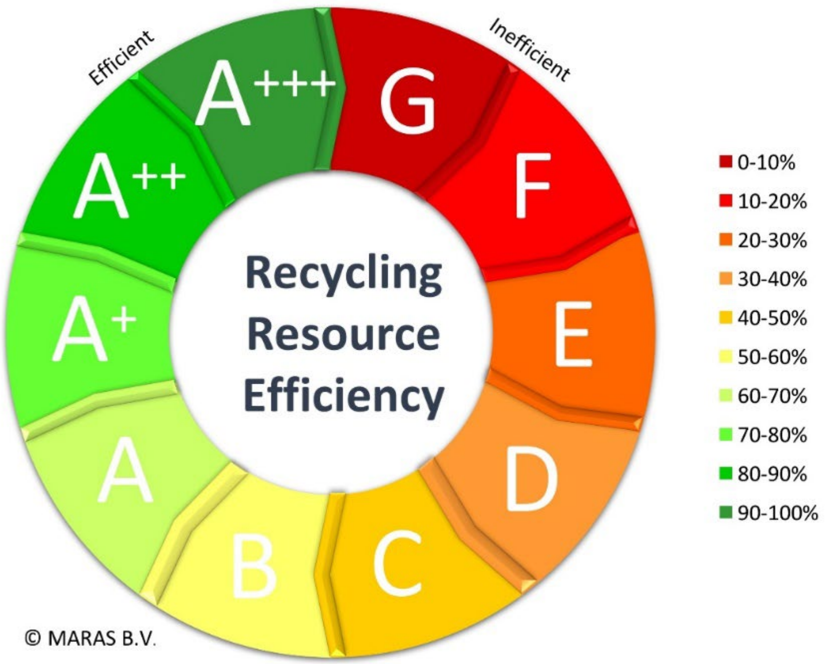
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	Stream / Element	Ag	Al	Am	Ar	As	At	Au	B	Ba	Be	Bi	Bk	Br	C	Ca	Cd	Ce	Cf	Cl	Cm	Co
2	INPUT																					
3	Smelt Oxidative	11.28	1133.89	0.00	0.00	0.02	0.00	11.45	1.33	5.60	0.00	0.24	0.00	47.83	10743.81	35.87	0.00	0.00	0.00	82.39	0.00	0.11
4	Smelt Reductive	1.51	1133.89	0.00	0.00	0.00	0.00	0.00	1.33	5.60	0.00	0.00	0.00	0.00	930.00	71.55	0.00	0.00	0.00	0.00	0.00	0.11
5																						
6																						
7	VALUABLE OUTPUT																					
8	Multi-Metal Alloy	1.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	Cu to Electrorefining and Winning	6.65	0.00	0.00	0.00	0.00	0.00	11.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	Dust Oxidative	3.11	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.22	0.00	15.02	0.00	0.00	0.00	0.00	0.00	0.37	0.00	0.00

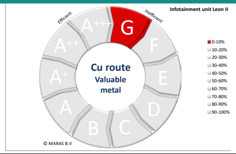
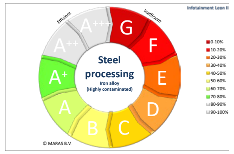
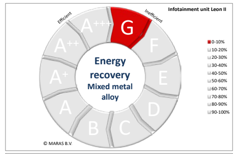
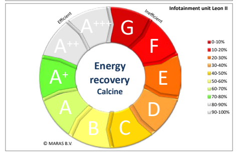
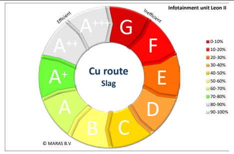
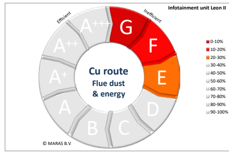
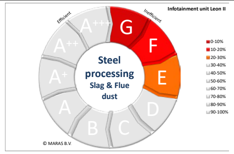
To high quality product or intermediates for further processing in this model

Selection of elements in product compounds	% Recovery
Ag (99.999% purity) electrolytic	74.24
Al, Ba, Ca, Fe, Mg, Si (as Al2O3, BaO, CaO, FeOx, SiO2 in slag)	99.00
Au (99.999% purity) electrolytic (see PM-PGM Recovery tab)	99.64
Bi (as oxide in flue dust)	99.19
Cu (99.999% purity) electrolytic	97.41
In (to alloy for further processing)	99.99
Sn (to various intermediates for further processing to recover rest)	28.68
Zn (to flue dust for further processing)	99.59
Pb (to flue dust for further processing)	99.53
Plastics recovered as energy and reductant	
Ni (rest to be recovered from slag)	90.15

Recycling KPI's

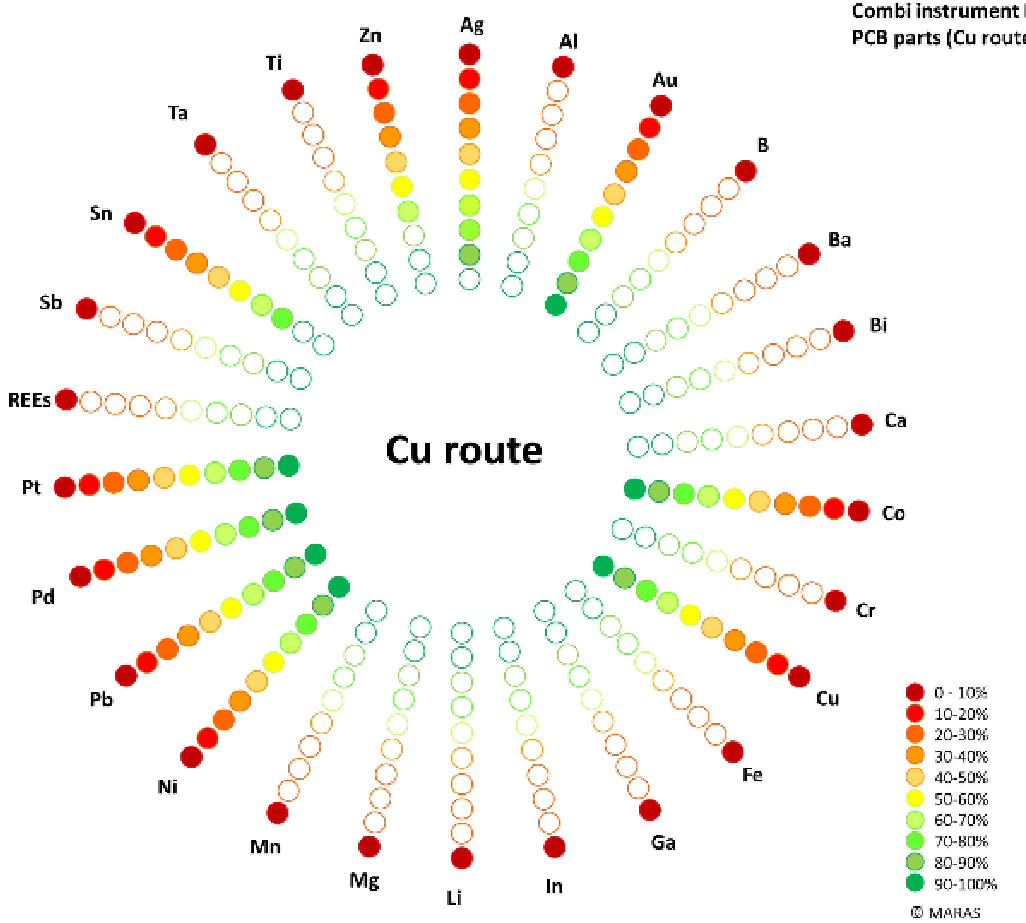
Recycling Index (total RR) for different CE levels

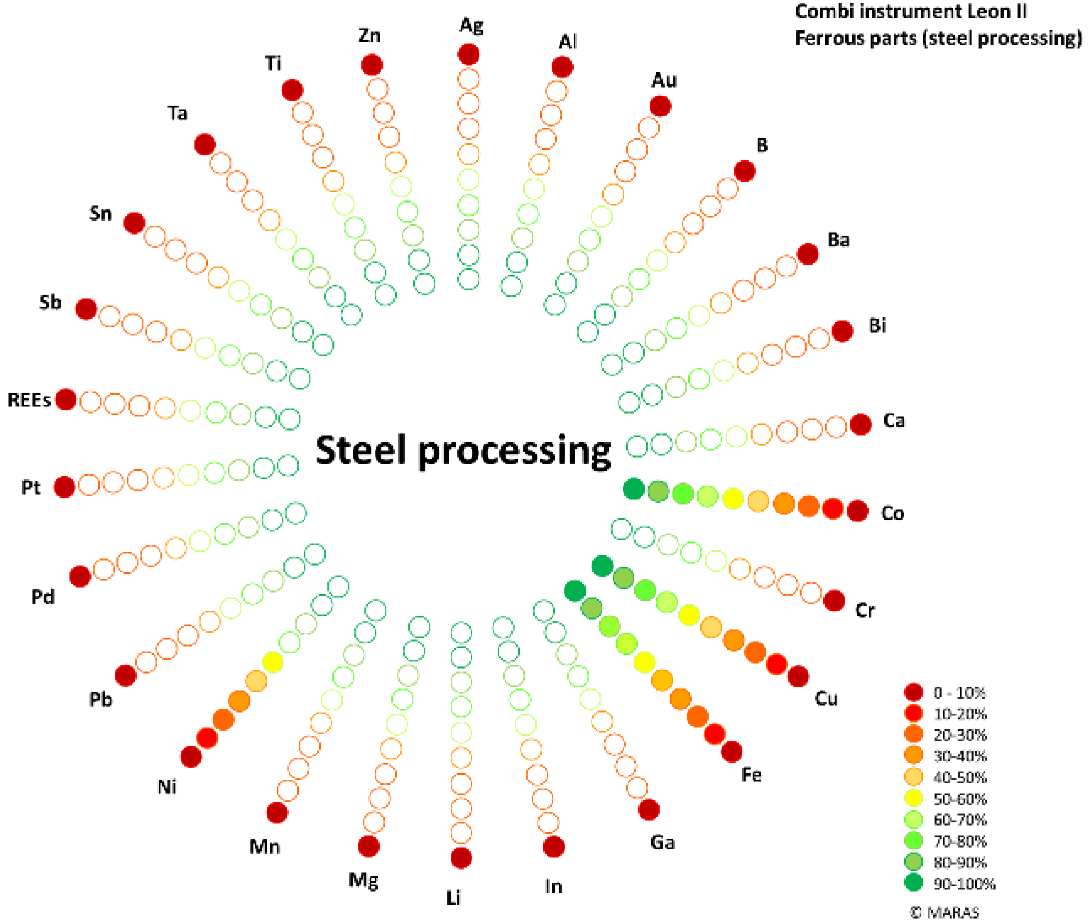


Recycling in terms of CE recycling products	Cu processing route	Steel processing	Energy recovery
1. Closed loop CE – high quality products which can go straight back into part or product		No high quality CE products	No high quality CE products
2. Open loop CE to be processed into closed loop CE – intermediate products			 
3. Open loop CE – (intermediate) products for repurposing e.g. as building / construction material etc.	 		
4.Energy recovery from feed	0.15 MWh/t feed	No energy recovery (energy input required in the process)	1.77 MWh/t feed

Recycling KPIs

Individual material recycling rates (%) (selection)

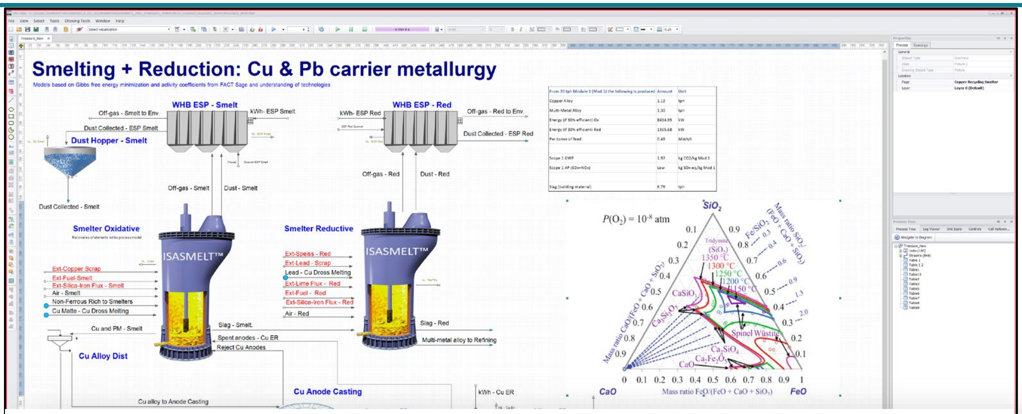


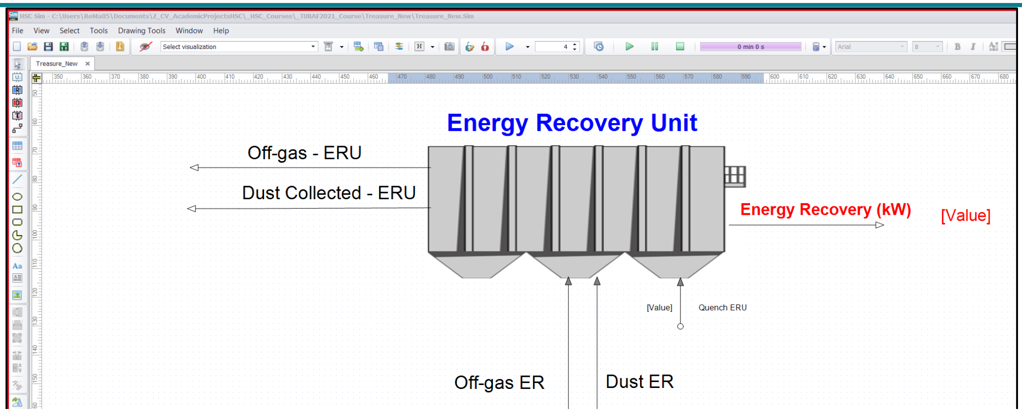


Flowsheet and processing options assessment

On basis of CE KPI's and full process in- and output quantifications

TREASURE





20 tph Module 1 (Mod 1) products	Amount	Unit
Copper Alloy	1.16	tph
Multi-Metal Alloy	1.28	tph
Energy (if 30% efficient) Ox	6892.1	kW
Energy (if 30% efficient) Red	1760.6	kW
Per tonne of feed	0.43	MWh/t
Scope 1 GWP	1.55	kg CO2/kg Mod 1
Scope 1 AP (SOx+NOx)	Low	kg SOx-eq/kg Mod 1
Slag (building material)	9.39	tph

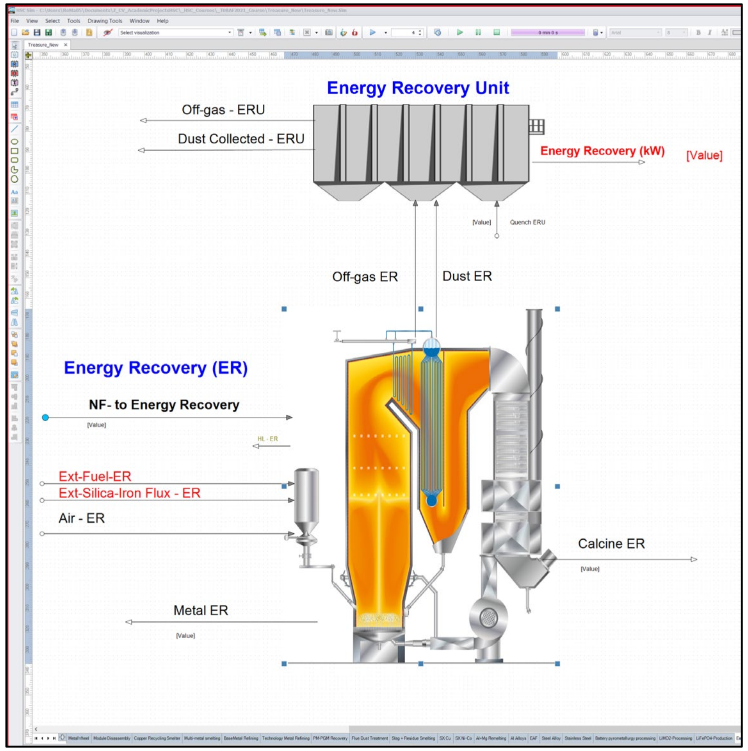
From 20 tph Module 1 (Mod 1) the following is produced	Amount	Unit
Metal phase (recycled to other units in flowsheet)	1.30	tph
Energy (if 30% efficient of boiler)	29824.29	kW
Per tonne of feed	1.49	MWh/t
Scope 1 GWP	1.97	kg CO2/kg Mod 1
Scope 1 AP (SOx+NOx)	Low	kg SOx-eq/kg Mod 1
Calcine (low grade oxidic material - costly to recycle)	6.62	tph

Recycling assessment IMSE

Recycling in existing (metallurgical) recycling infrastructures into high grade materials (LME grade - market green)

TREASURE

Energy recovery processsing of IMSE



Energy

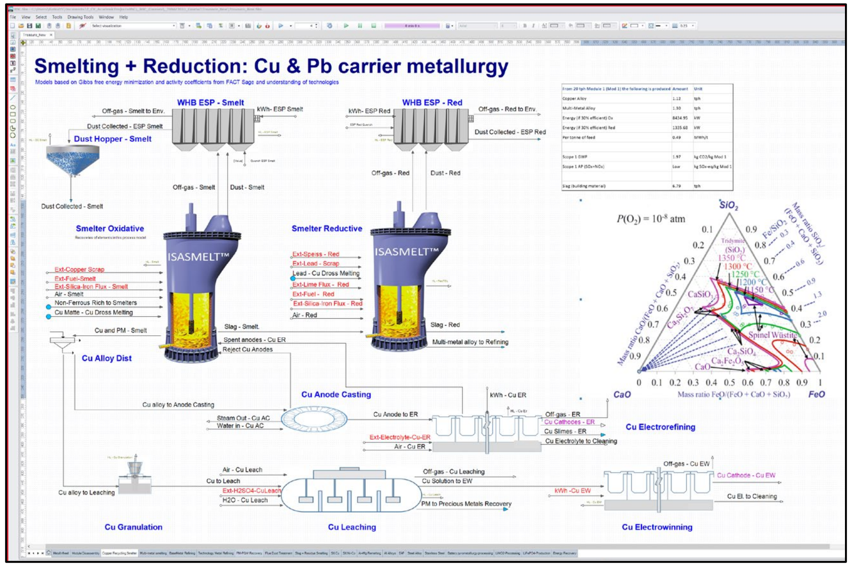
Metal alloy (98.18 % Cu and 1.82% Ag)

+

Flue dust (Ag_2O)

Calcine (98.82% TiO_2 and rest P_2O_5)

Cu metallurgy (on the back of other recycling flows to create economy of scale)



Recovery of Cu > 99% (99.999% purity electrolytic))

Recovery of Ag > 98% (99.999% purity electrolytic)

Recovery of TiO_2 and P (both 100%)

Concluding remarks

TREASURE

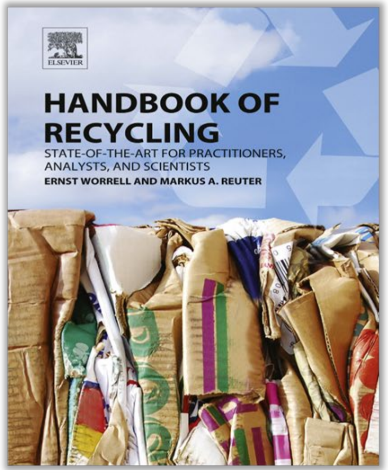
- Innovative physics and industry-based recycling simulation digital twin provides standard to quantify, assess and improve recycling - engineering-based recycling KPIs and CE indicators

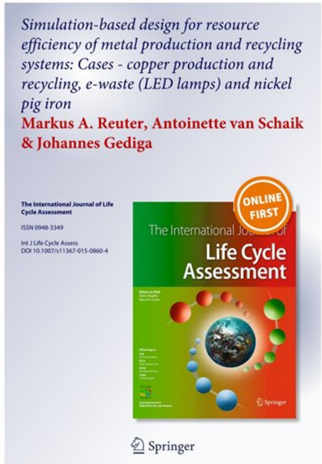
- Engineering industrial reactor & system design for optimal circularity performance
    - Defining best suited recycling flowsheet architectures (linked to disassembly) & benchmark developments in recycling processing
    - Including true circularity in recycling – maintaining the material and energy quality for use in the same quality

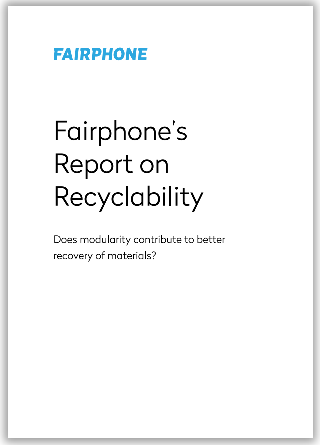
- Setting standards for defining product data availability and transfer to link design to recycling as this is key to evaluate the true recovery of materials and energy and assess recycling system performance

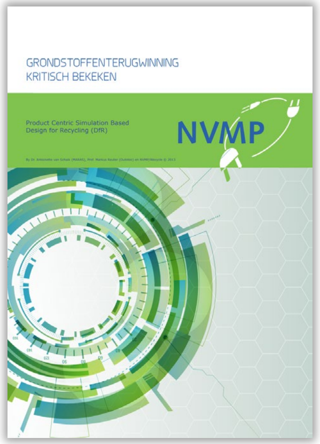
Some references

TREASURE









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