Evaluating the environmental impacts of circularity scenarios in power electronics using Life Cycle Assessment

Contributions from: Pierre-Yves Pichon, Thomas Guillemet, Nicolas Degrenne

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2025/6/24

MITSUBISHI ELECTRIC R&D CENTRE EUROPE

MFR2025-ARC-0270/ MFR2025-ECD-0216

Focus on **methods (toolbox)**

- 1/ How to consider **repair** and **diagnostic** in **LCA**?
- 2/ How to introduce **circularity loops** in **LCA**? (Example of recycling)
- 3/ **Reality** of recycling => towards a stronger **thermodynamic** basis of LCA?

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Reliability
Modularity
Diagnostic

- 2/ How to introduce **circularity loops** in **LCA**? (Example of recycling)

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Allocation
European standards
Effect on design

- 3/ **Reality** of recycling => towards a stronger **thermodynamic** basis of LCA?

Focus on **methods (toolbox)**

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  - *Reliability*
  - *Modularity*
  - *Diagnostic*
- 2/ How to introduce **circularity loops** in **LCA**? (Example of recycling)
  - *Allocation*
  - *European standards*
  - *Effect on design*
- 3/ **Reality** of recycling => towards a stronger **thermodynamic** basis of LCA?
  - *Irreversible losses*
  - *Metallurgical processes*
  - *Material quality*

1

How to consider repair and diagnostic in LCA?

- **PhD thesis Briac Baudais (2024):**

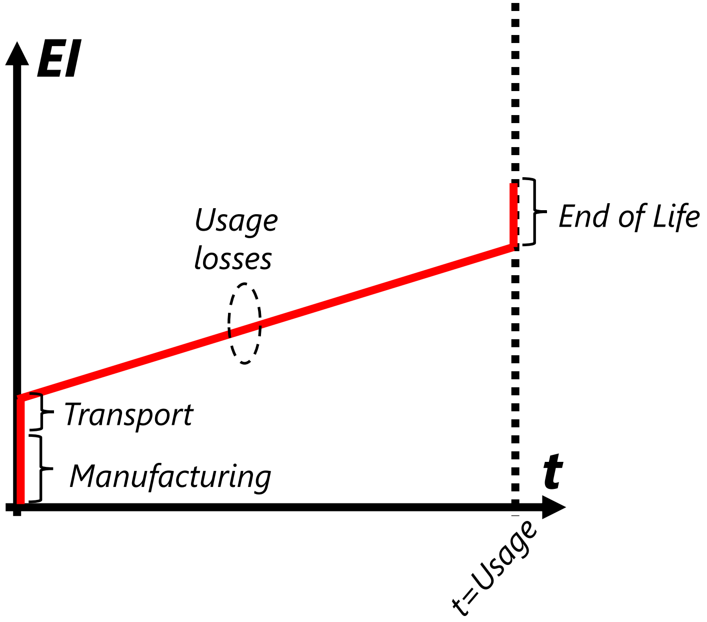
‘Ecoconception en électronique de puissance. Impact du dimensionnement, de la modularité et de la diagnosticabilité

Direction: Stephane Lefebvre, Hamid Ben Ahmed, Gurvan Jodin, Nicolas Degrenne

Step 1 : Linear economy perspective

Baudais, B et al. *Energies 2023*

End of Life = usage time
(incl. Repair operations ⇔ durability)



Method

1. Manufacturing
2. Transport
3. Usage
4. End of Life

Step 1 : Linear economy perspective

Method

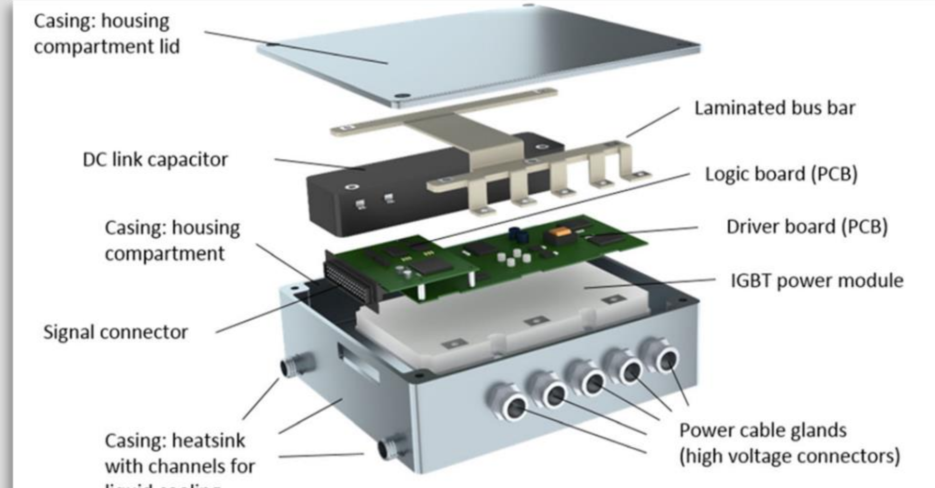
1. Manufacturing ☐
2. Transport ☐
3. Usage ☐
4. End of Life ☐

Hypothesis

Scope

- Component: eV inverter
- Nominal Power 150kW
- Bus Voltage 450V
- Liquid cooling
- Usage => 15 ans
- Impacts: PEF – EF 3.1 (16 impacts)

Component



Source : Chalmers

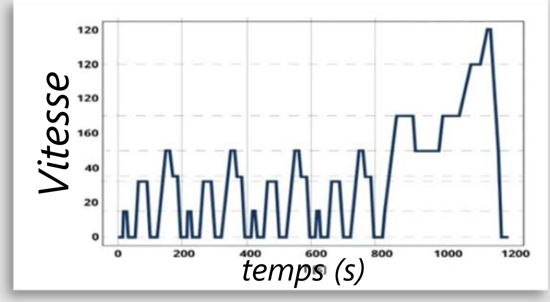
Step 1 : Linear economy perspective

Method
1. Manufacturing ☑
2. Transport ☐
3. Usage ☐
4. End of Life ☐

Scope

Component

Usage profile(WLTP)

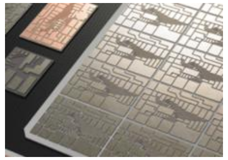


Manufacturing

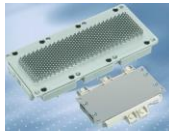
Power electronic subparts → Manufacturing Model-based LCI

Power dice (IGBT, diode, MOSFET)

Ceramic substrate



Baseplate

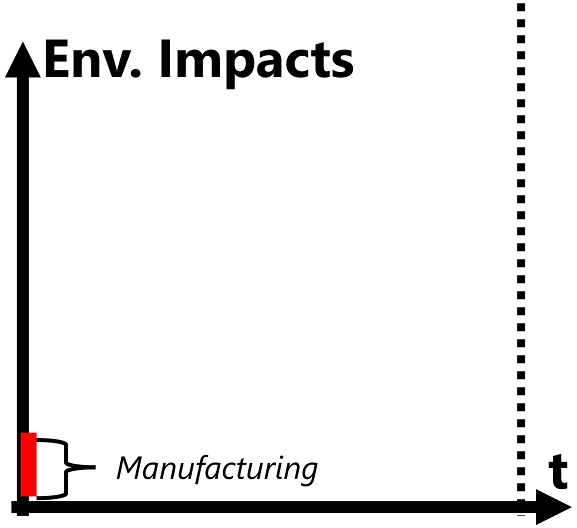


Power modules

Inventory (LCI)

Manufacturing
- Manufacturing models
- Reverse eng.
- Chalmers. Uni

Evaluation
- *Brightway*
- *Ecoinvent*
- *LCIA*



1 Step 1 : Linear economy perspective

Method
1. Manufacturing ☑
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Scope

Component

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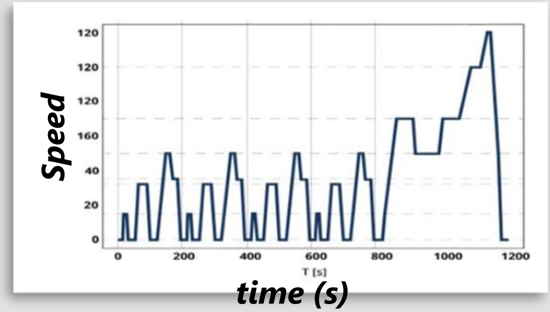


Manufacturing

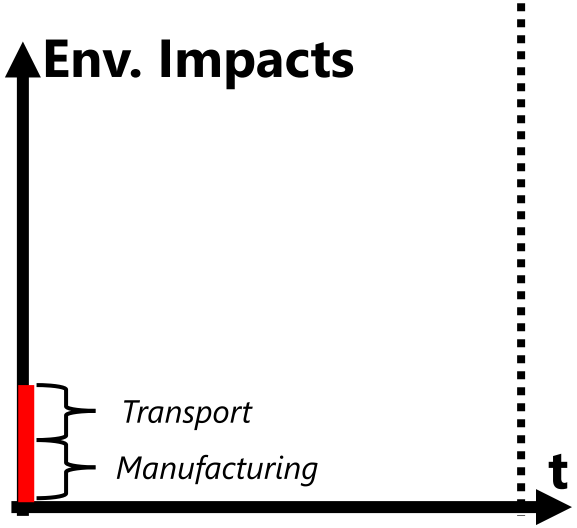
Transport

Inventory (LCI)

Manufacturing
- HybridKit Drive
- Reverse eng.
- Chalmers. Uni

Transport
- PEF

Evaluation
- *Brightway*
- *Ecoinvent*
- *LCIA*



Step 1 : Linear economy perspective

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Changes for the Better

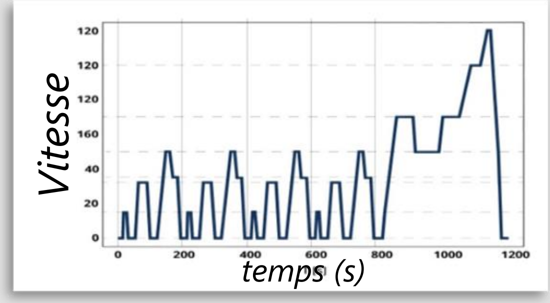
Method
1. Manufacturing ☑
2. Transport ☑
3. Usage ☑
4. End of Life ☐

Scope

Component

Source : Chalmers

Usage profile(WLTP)



Manufacturing

Transport

Usage time

Usage

Losses

Physical model
- Loss model

Energy

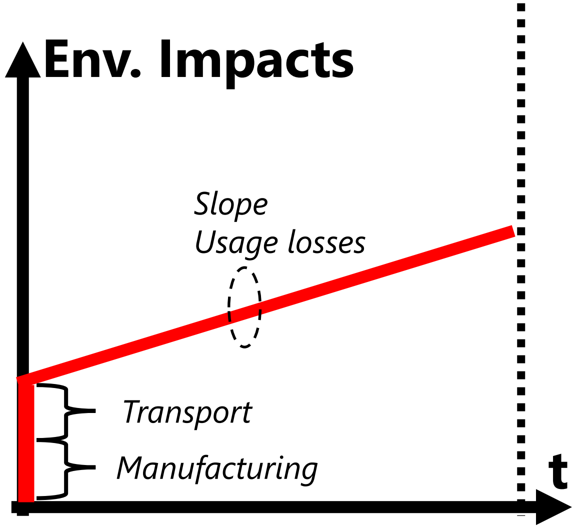
Inventory (LCI)

Manufacturing
- HybridKit Drive
- Reverse eng.
- Chalmers. Uni

Usage
- Losses

Transport
- PEF

Evaluation
- *Brightway*
- *Ecoinvent*
- *LCIA*



Step 1 : Linear economy perspective

Method
1. Manufacturing ☑
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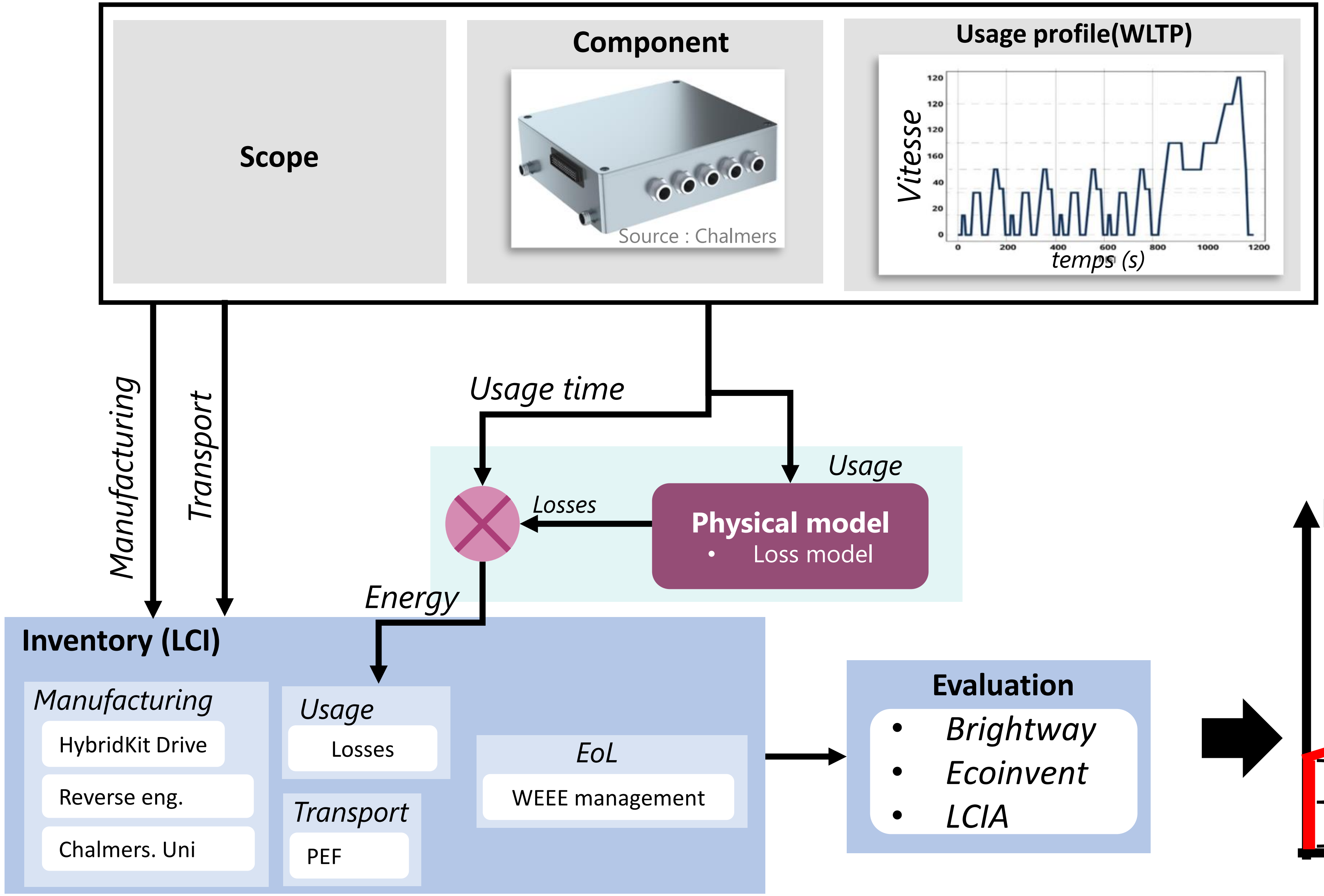
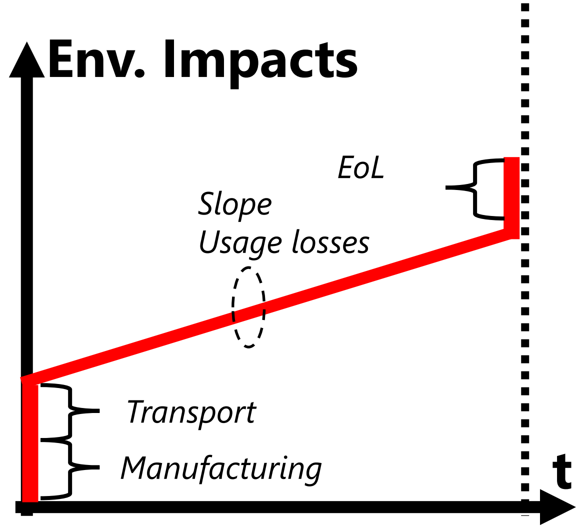


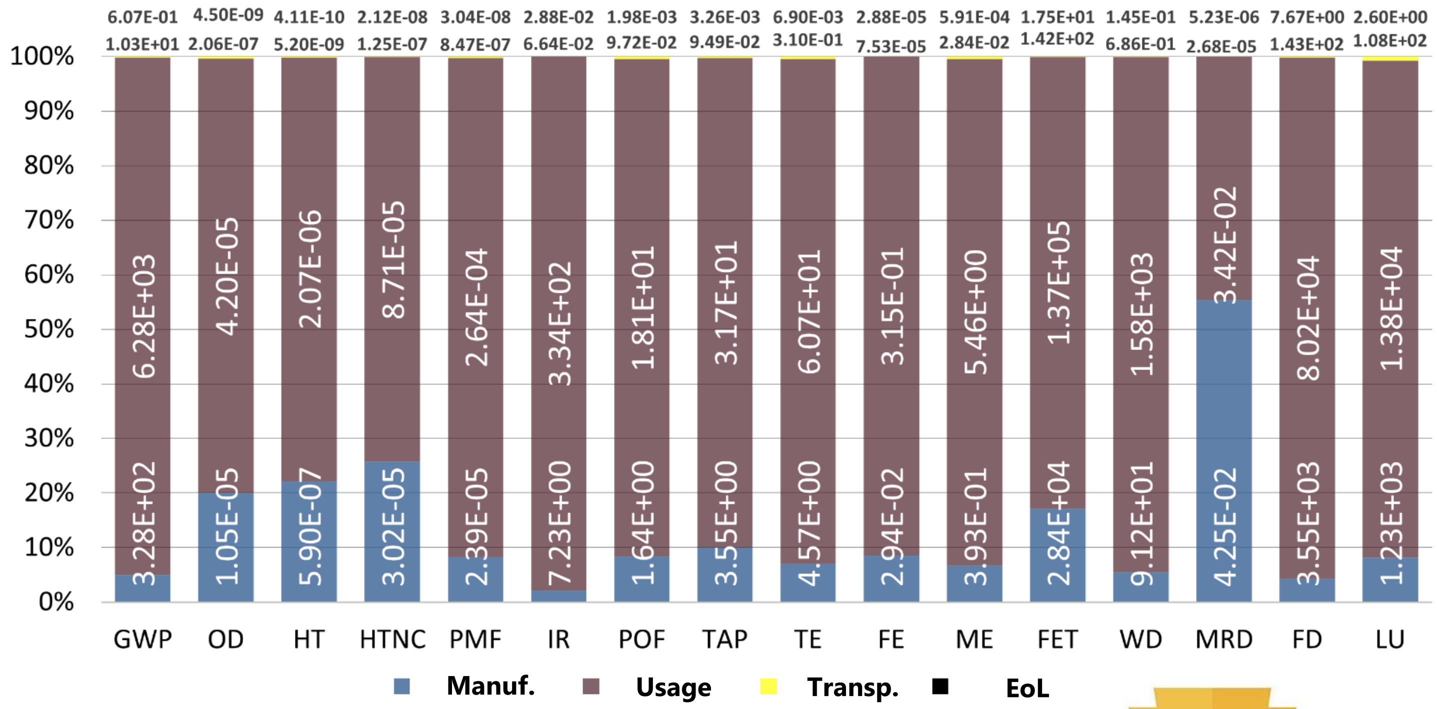


Step 1 : Linear economy perspective: results

Baudais, B et al. *Energies 2023*

Hotspots:

- Manufacturing
- Usage (global mix, efficiency=92%)



Legend:

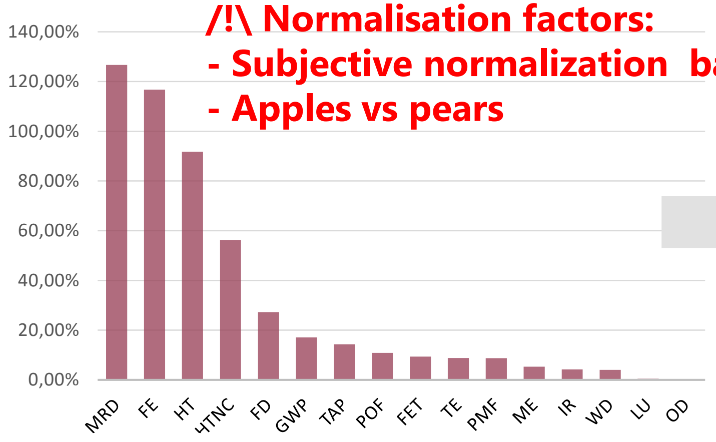
GWP	Global warming potential	**FET**	Ecotoxicity freshwater
OD	Ozone depletion	**WD**	Water use
FD	Resource use, fossil fuels	**FE**	Eutrophication, freshwater
HT	Human toxicity cancer	**ME**	Eutrophication, marine
HTNC	Human toxicity, non-cancer	**TAP**	Acidification
PM	Particulate matter	**TE**	Eutrophication, terrestrial
IR	Ionizing radiation	**MRD**	Mineral Ressource Depletion

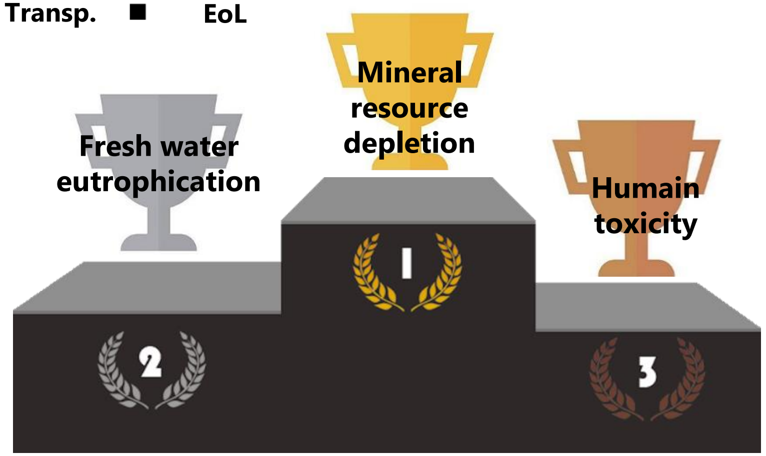
Normalisation **with global impacts/person/year** (PEF, EU commission)

Impact category rating

$$IE^{(e)}_{normalisation} = \frac{IE^{(e)}}{IE^{(e)}_{ref}}$$

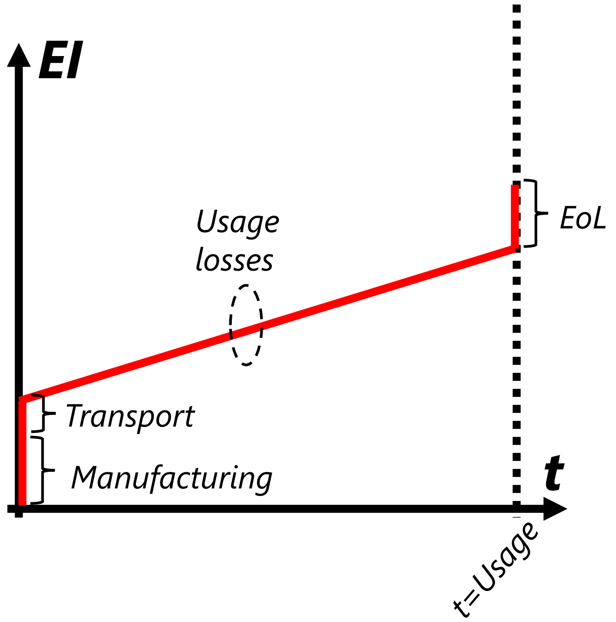
/!\ Normalisation factors:
- Subjective normalization basis
- Apples vs pears





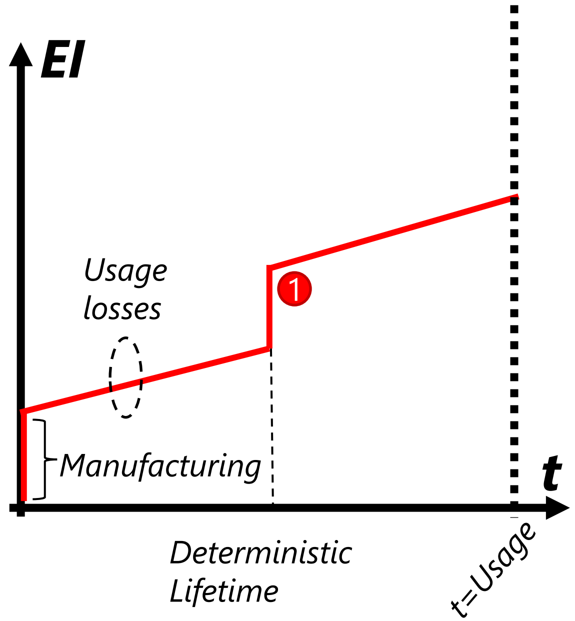
Step 2: introducing replacement

Baudais, B et al. *SGE 2023*



Method

1. Manufacturing
2. ~~Transport~~
3. Usage
4. ~~End of Life~~



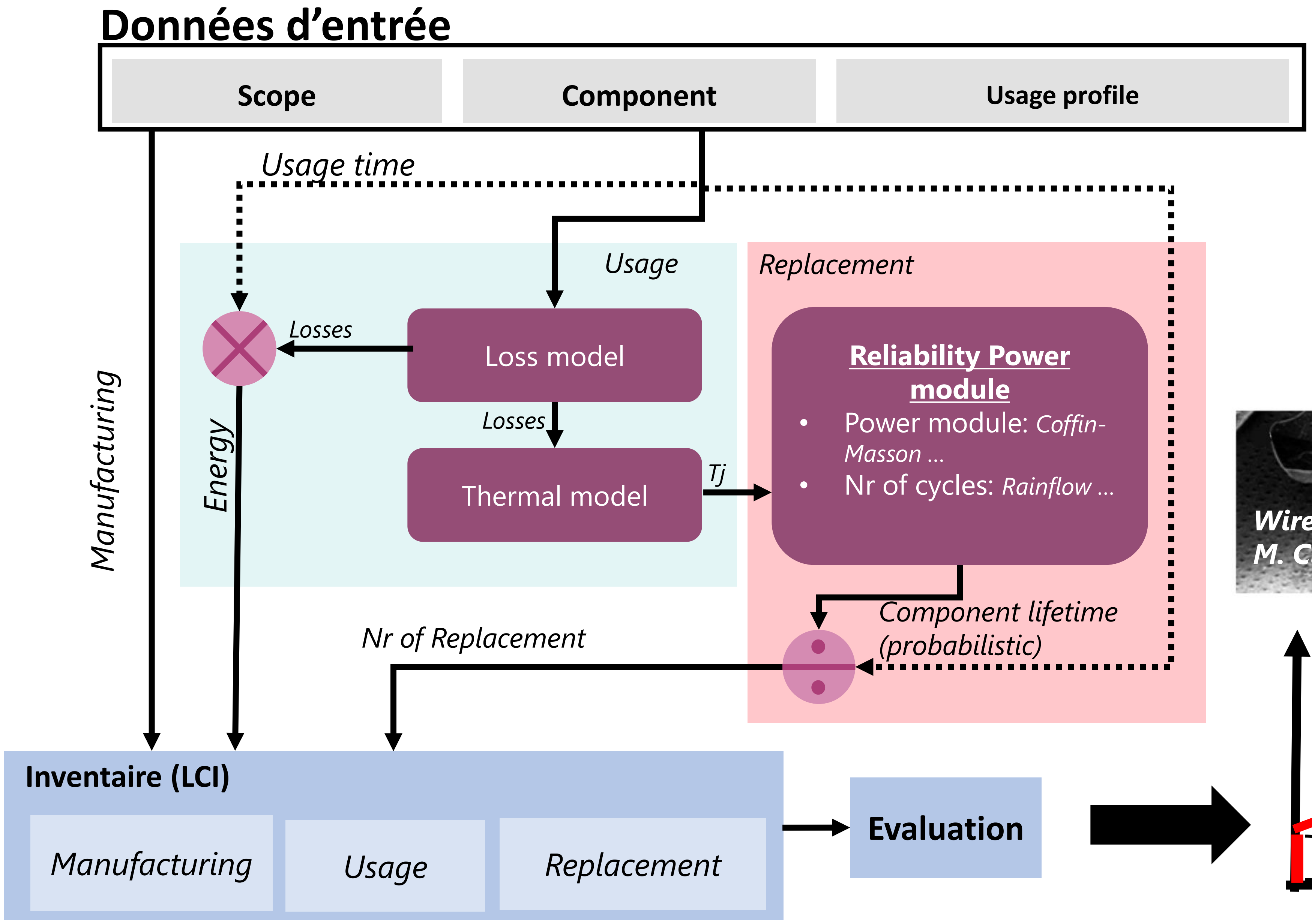
Method

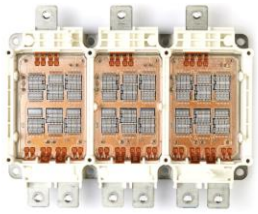
1. Manufacturing
2. Usage
3. Replacement

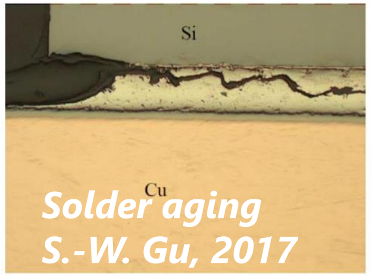
Step 2: introducing reliability

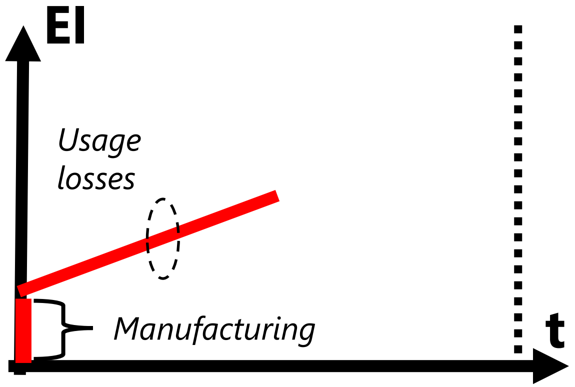
Method

1. Manufacturing ✓
2. Usage ✓
3. Replacement ☐









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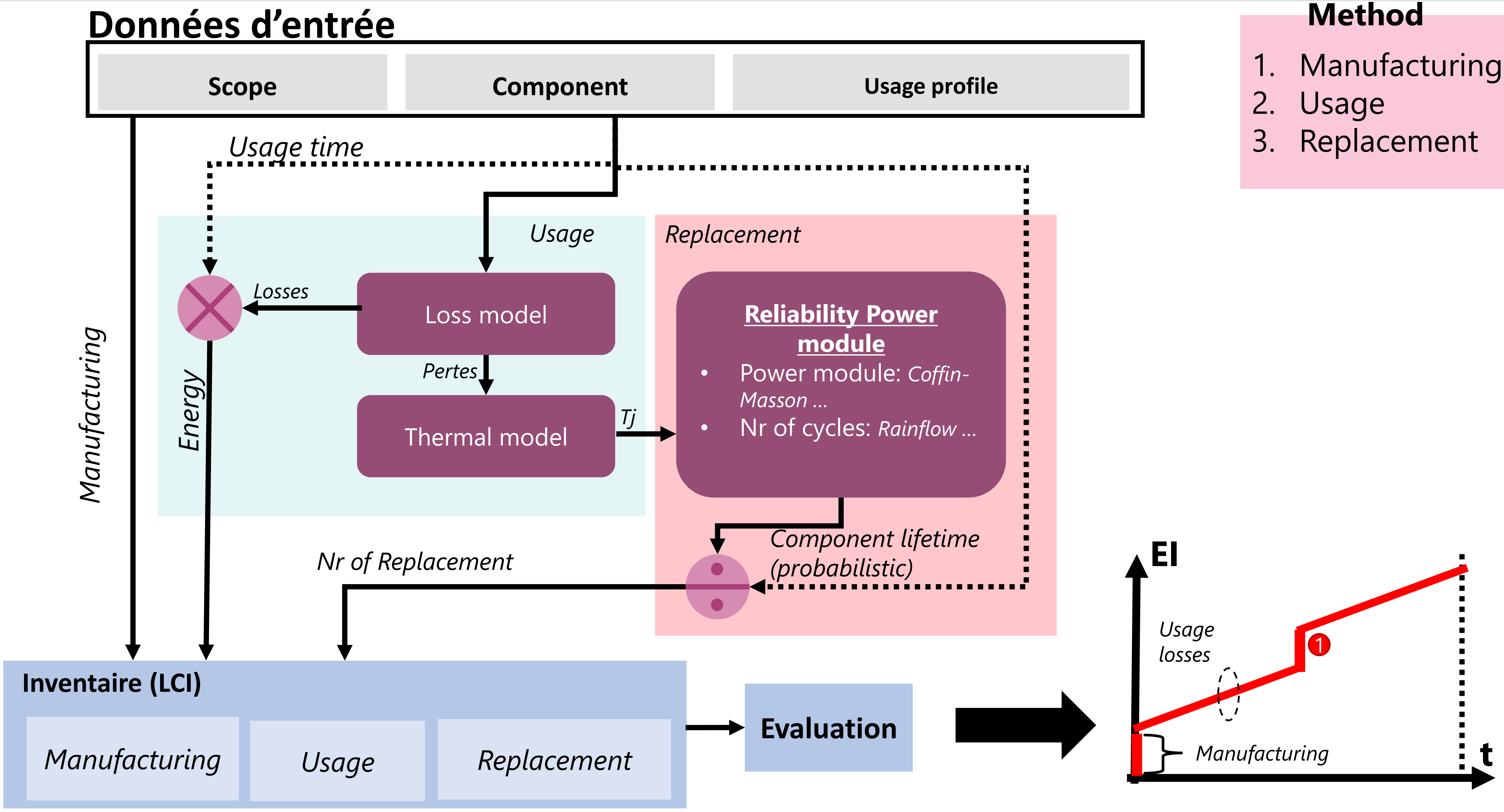
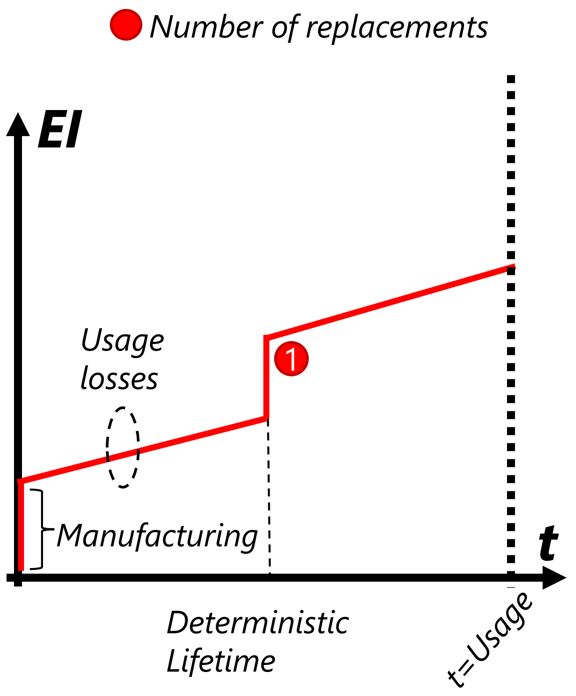


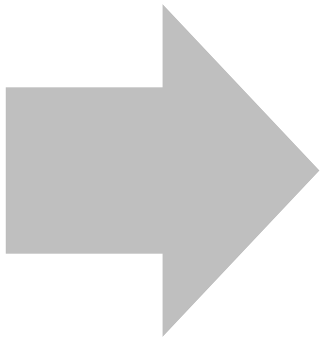
Method

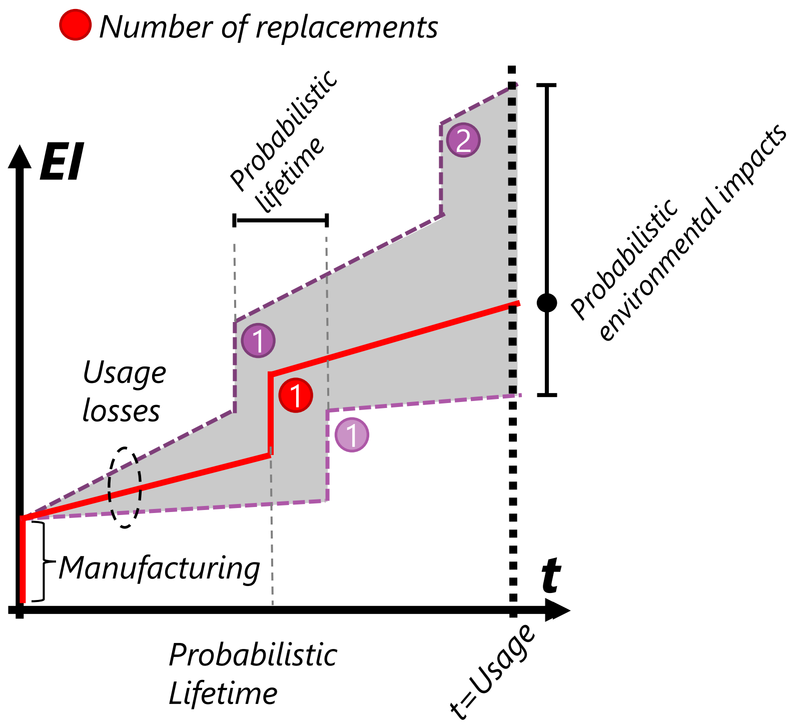
1. Manufacturing ✓
2. Usage ✓
3. Replacement ✓

Step 2: introducing reliability

Baudais, B et al. *SGE 2023*







Method

1. Manufacturing
2. Usage
3. Replacement

MERCE open-source approach: PELCA tool

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Excel Input

Inventory
Manuf. + Use

Fault parameters
(Weibull)

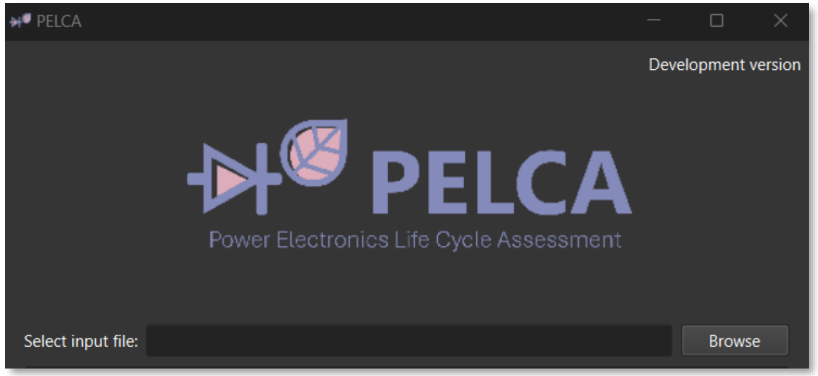
Curative Maint.
(diagnosis)

Preventive Maint.
(schedule)

Economic impact
(cost / price)

PELCA software architecture

Graphical user interface



Python-based

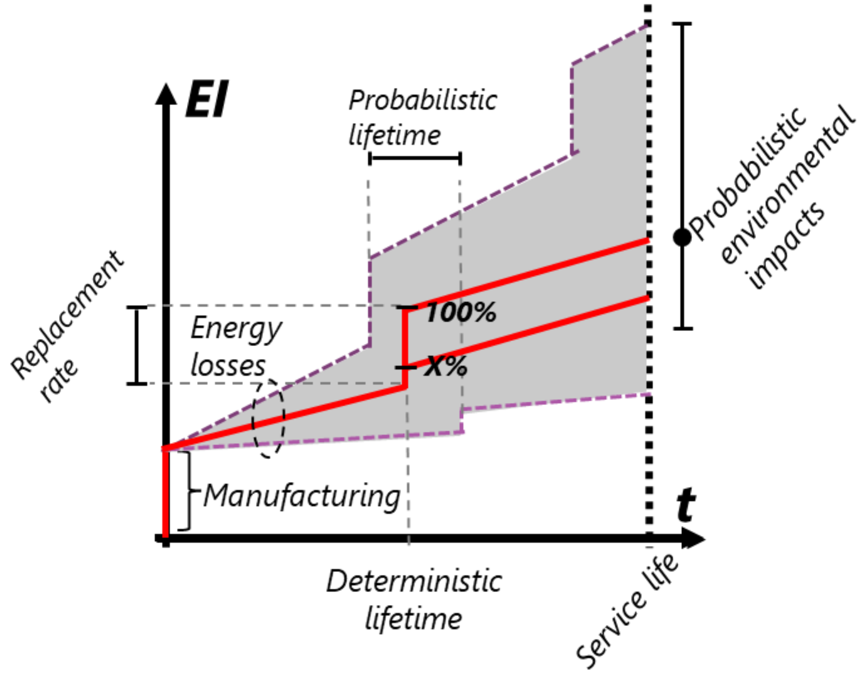
Database

ecoinvent

LCA library

Brightway

Output example (staircase curve)



- **Software installation:**
  - GitHub repository → [***https://github.com/merce-fra/PELCA***](https://github.com/merce-fra/PELCA)
  - < 1h to install and run example

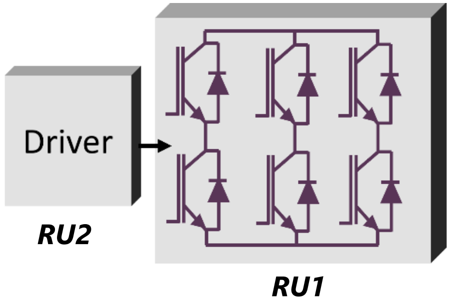
New Release now available !
PELCA v1.3 (v1.4 coming soon)

Modularity and diagnostic

Case study

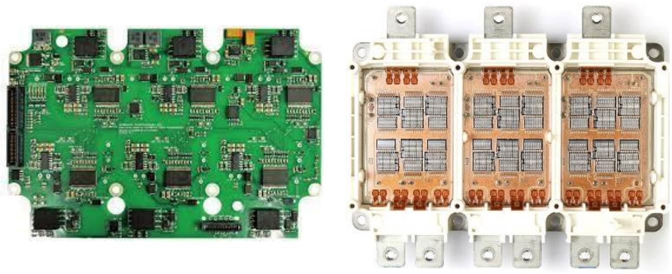
Case study: 3 phase inverter power module + driver

Integrated



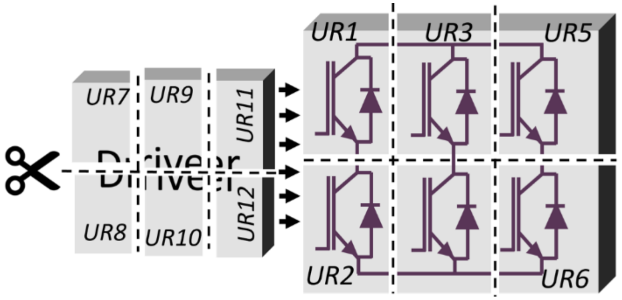
- IGBT power module+ diode (V=750V ; I=820A)

→ ***Reference case, low modularity***



Modularity ⬄ replacement units (RU)

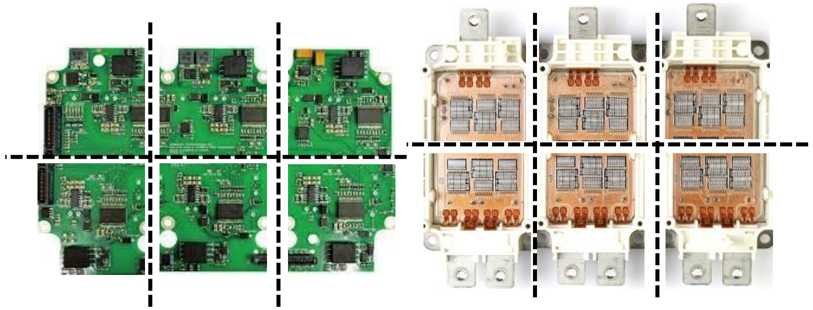
Modular *(1)*



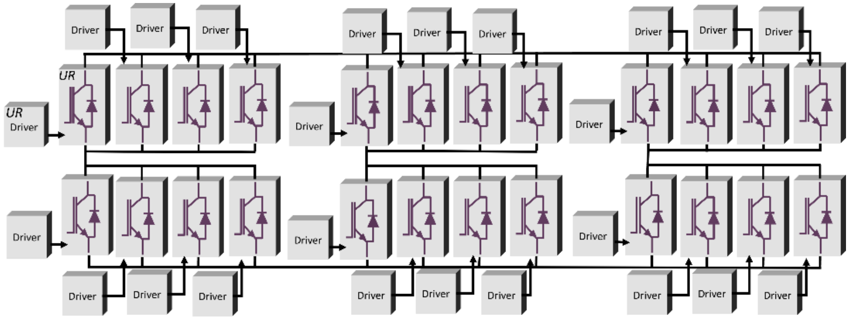
- ⬄ 'virtual' cut integrated case

→ ***Modularity & diagnosticability***

→ ***For result interpretation, not realistic***

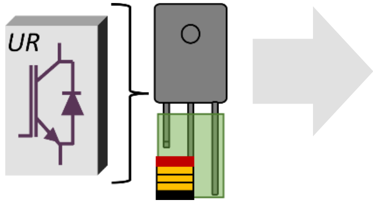


Modular *(2)*



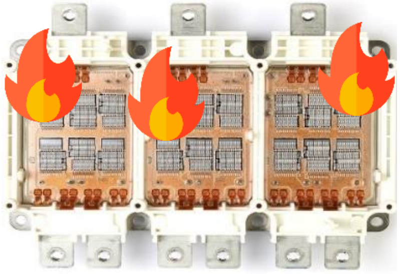
- Discrete devices (TO247) (V=750V ; I=205A)

→ ***Realistic case, high modularity***

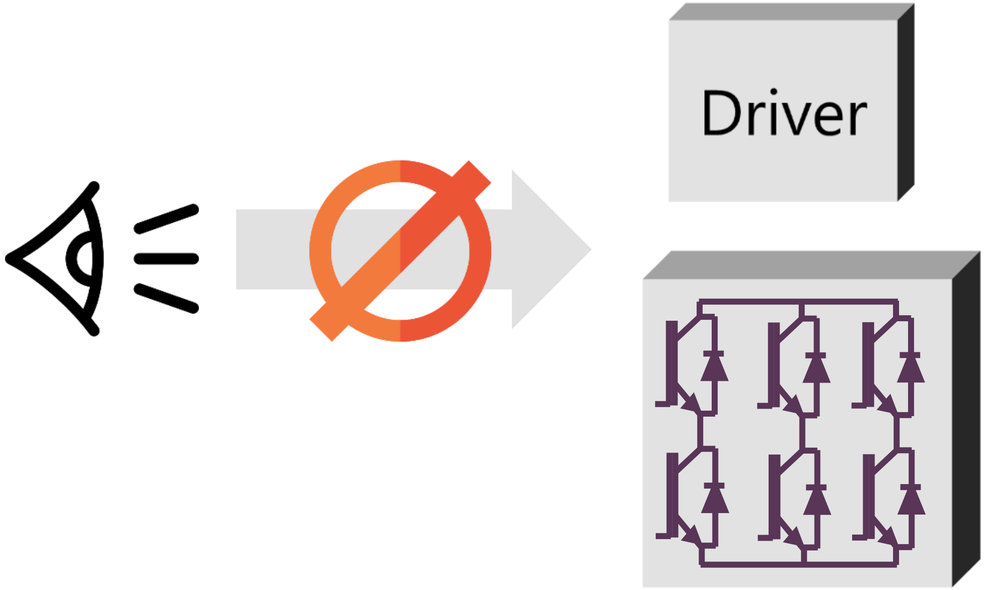


LCA discrete

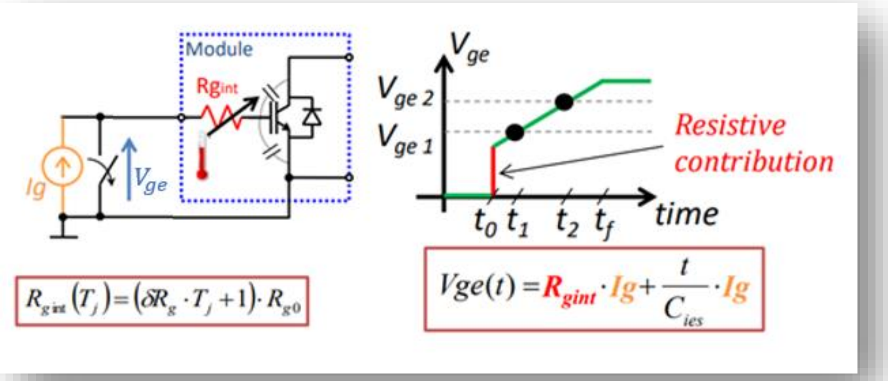
3 imposed failures
⇒ Comparability

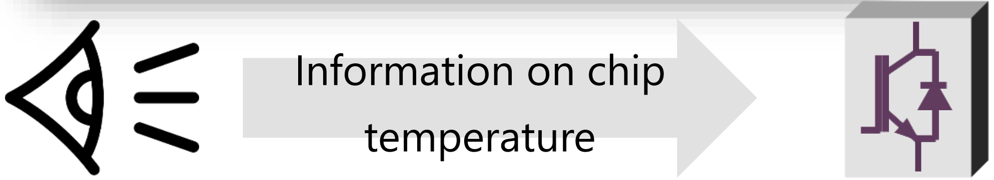


No diagnostic A	*With diagnostic* B



Tjbalancing : TSEP Rgin

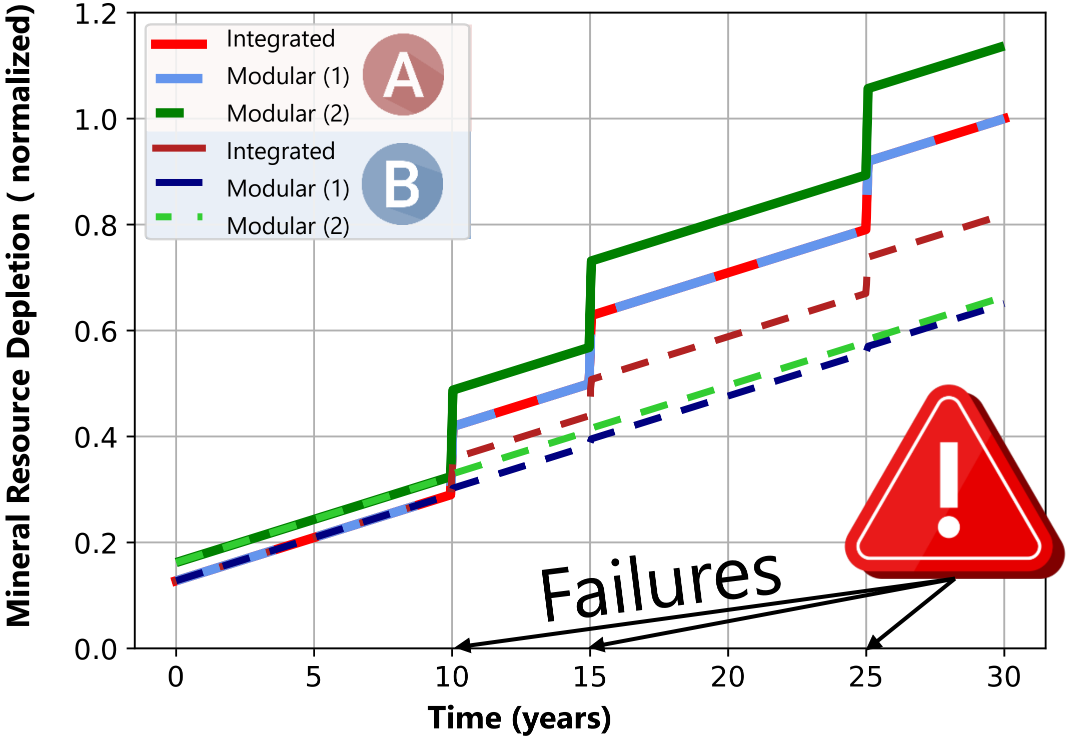


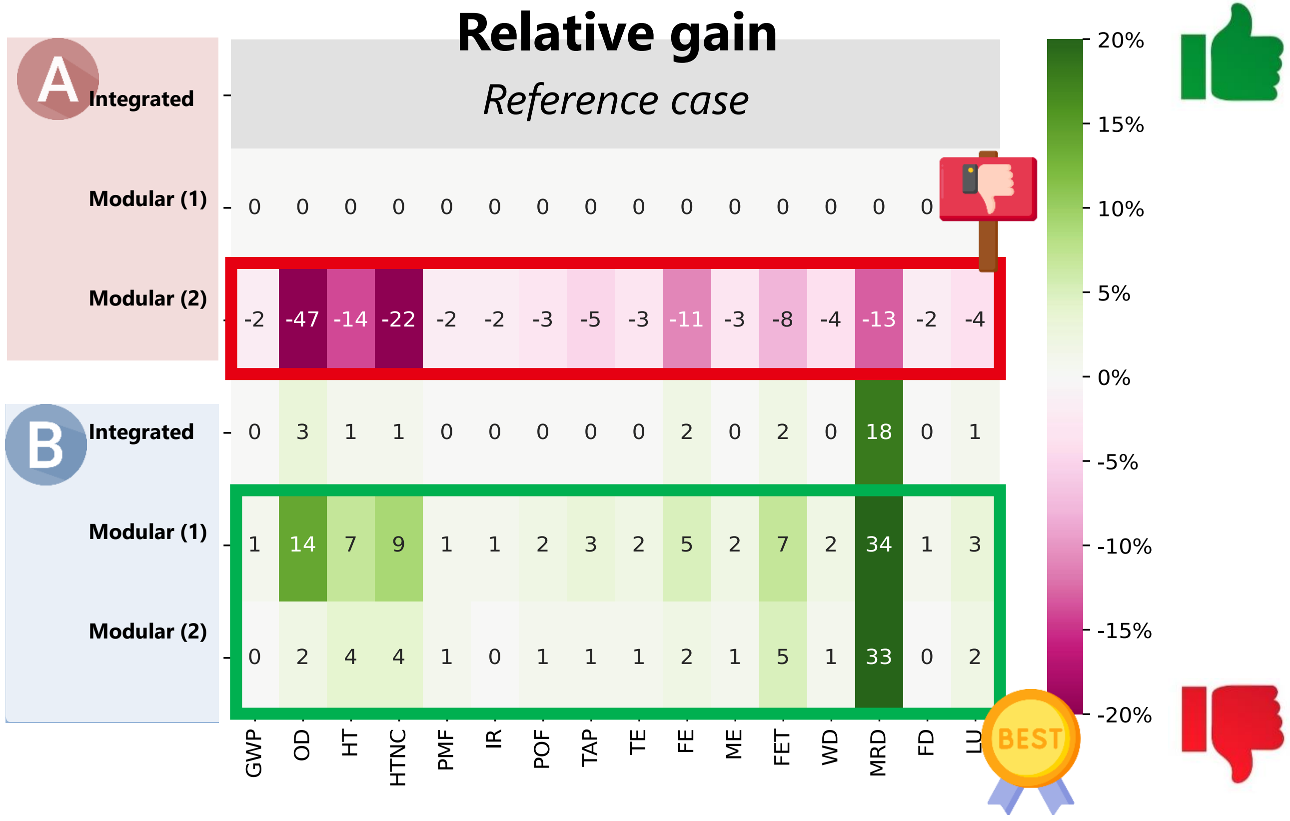


x1 RU

Failure and diagnostic – Life-cycle impacts

Baudais, B et al. *PCIM 2024*





Conclusions

Worst solution :
Modular without diagnostic

Best solution :
Modular with diagnostic

Modularity is relevant only if it is combined with diagnostic
(otherwise it can ↗ EI)

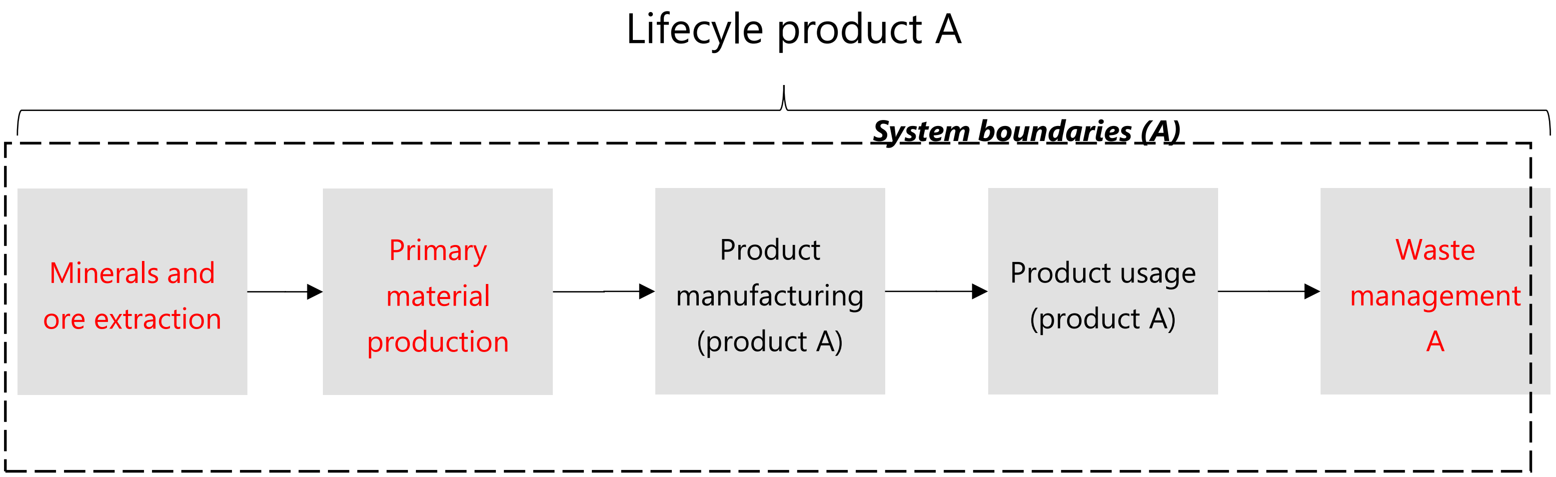
2 How to introduce circularity in LCA?

- **Impact on designer choices ?**

- Focus on recycling (but can be extended to repair)

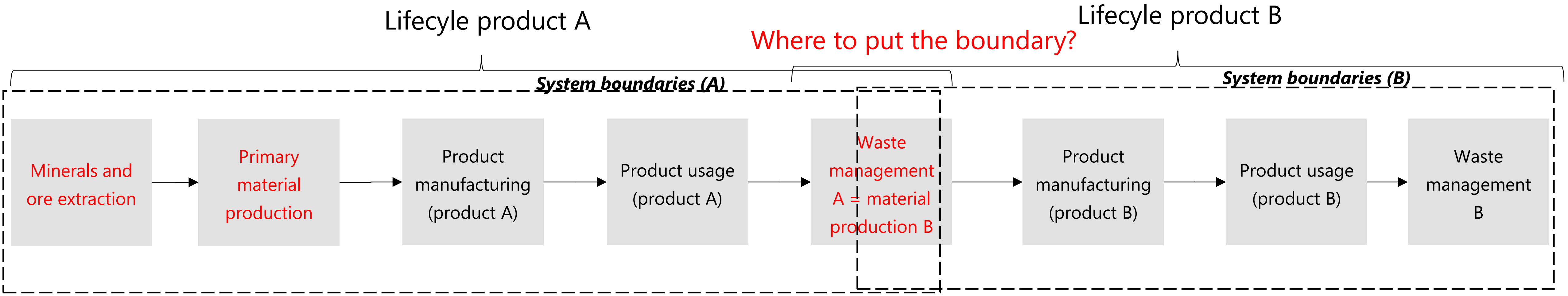
How to consider circularity loops in LCA ?

- Impact on **designer choices** ?
- Focus on recycling (but can be extended to repair)



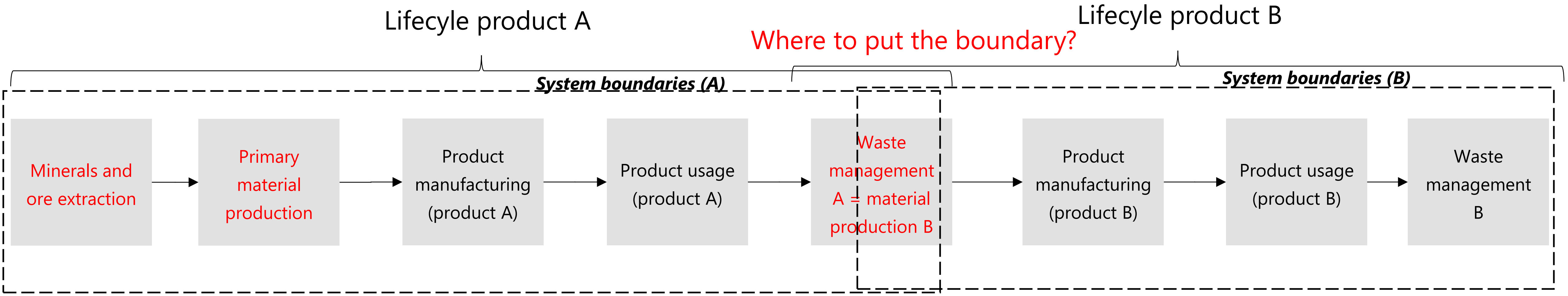
How to consider recycling in LCA ?

- Some waste of Product A becomes resource from product B



How to consider recycling in LCA ?

- Some waste of Product A becomes resource from product B
- **Questions: How to share the environmental burdens/benefits between product A and product B?**
  - Mineral extraction and primary materials production
  - Waste treatment / recycling



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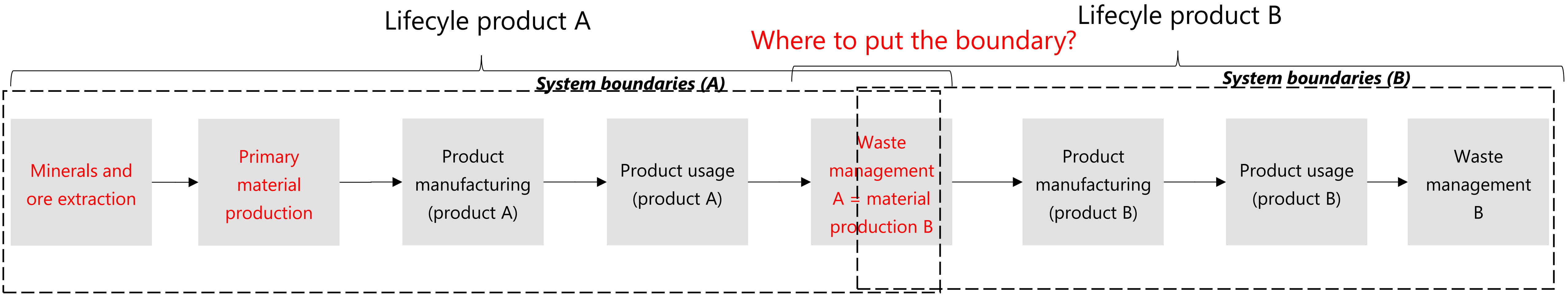
- Hints (ISO 14044):
  - Extend **system boundaries**
  - Inputs/outputs **allocation based on Physical relationships**



 Export Control: NLR Non-Confidential

How to consider recycling in LCA ?

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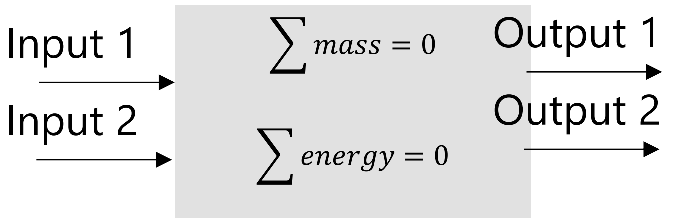
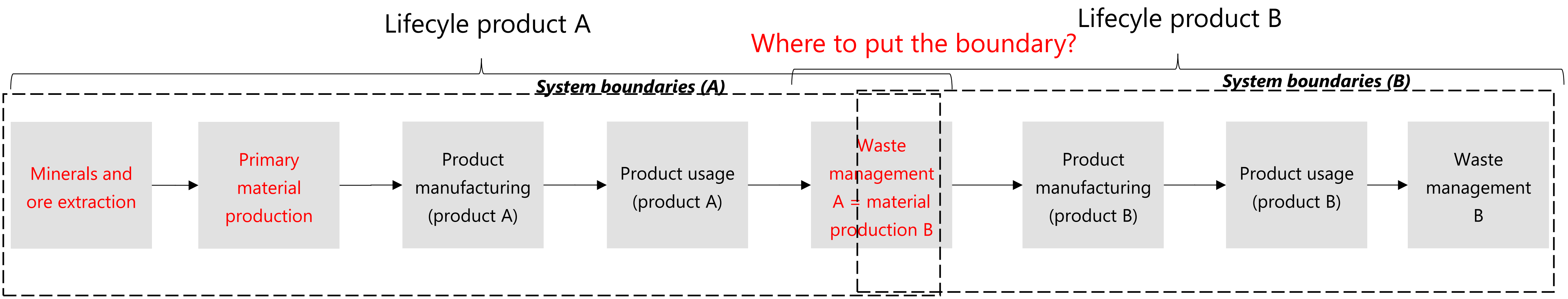
1st law principles (energy/mass conservation)



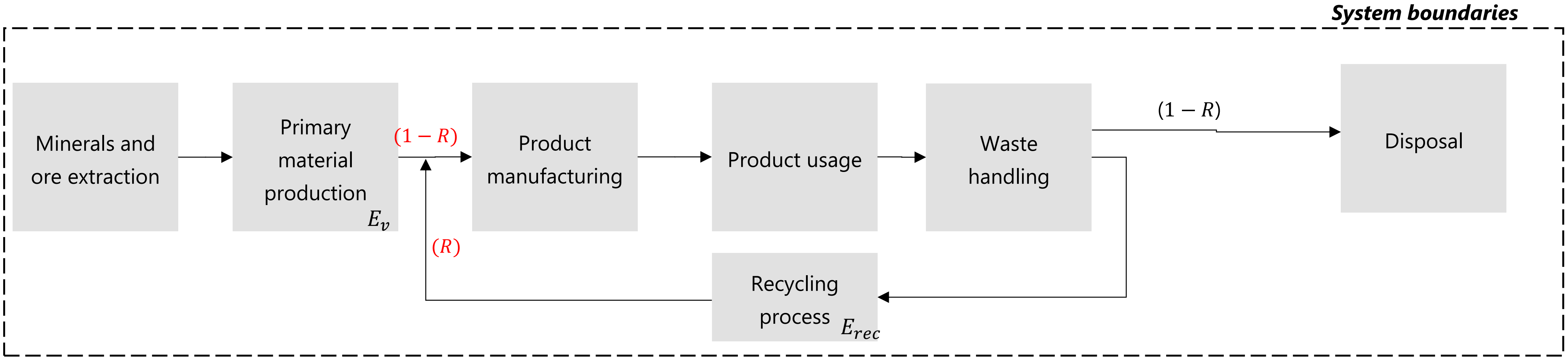


How to consider recycling in LCA ?

- Extend system boundaries => **let us try to 'close the loop' !**

⇒ **System boundaries are clearly defined, and the system is closed**

- Only one recycling rate R need to be defined



How to consider recycling in LCA ?

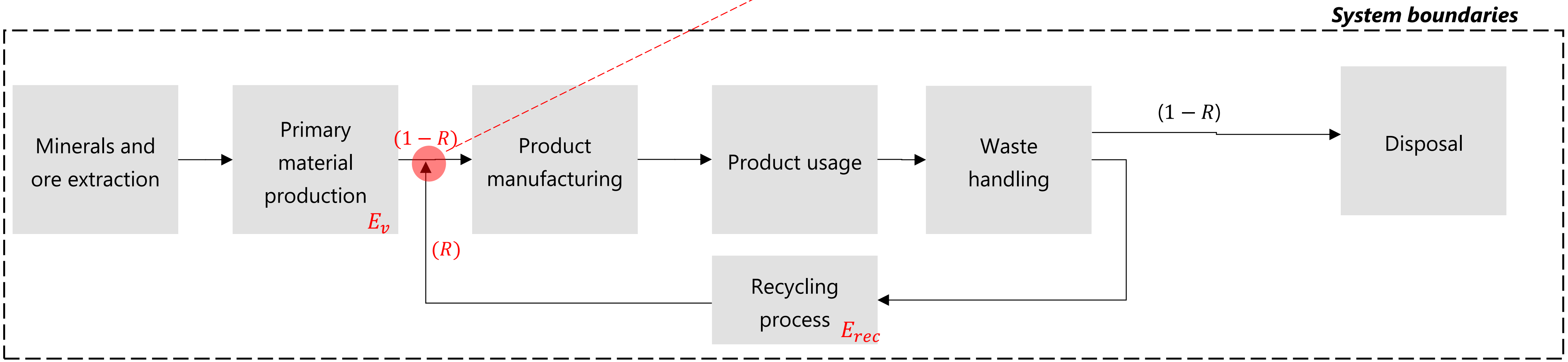
- Extend system boundaries => **let us try to 'close the loop' !**

$\Rightarrow$ **System boundaries are clearly defined, and the system is closed**

- Only one recycling rate R need to be defined: $0 < R < 1$
- Mass/energy/impact balance equation at **'point of substitution'**

$$E_{mat} = (1-R)E_v + RE_{rec}$$

$$E = \begin{bmatrix} GWP\ (CO2e) \\ MRD\ (Sbe) \\ \ldots + other\ impact\ indicators \\ electricity\ (energy) \\ materials\ (mass) \\ chemicals\ (mass) \\ \ldots + other\ input.output\ mat \end{bmatrix}$$



How to consider recycling in LCA ?

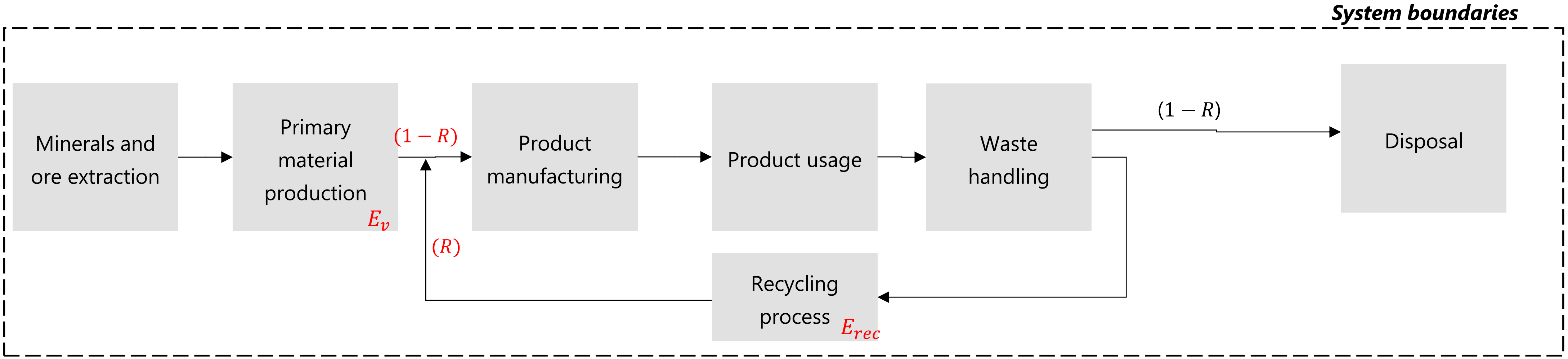
- Extend system boundaries => **let us try to 'close the loop' !**

$\Rightarrow$ **System boundaries are clearly defined, and the system is closed**

- Only one recycling rate R need to be defined: $0 < R < 1$
- Mass/energy/impact balance equation at point of substitution
- Example: Global Warming Potential of Copper Ecoinvent 3.9.1 cut-off (Cathode; 99,99%)
  - Primary Cu (Electrorefining of copper, GLO): GWP_v = 8.24 kgCO2e/kgCu
  - Recycled: (Treatment of copper scrap by electrolytic refining, RoW): GWP_{rec} = 2.41 kgCO2e/kgCu

$\Rightarrow$ **Often beneficial to the designer to increase recyclability / recycled material mass share**

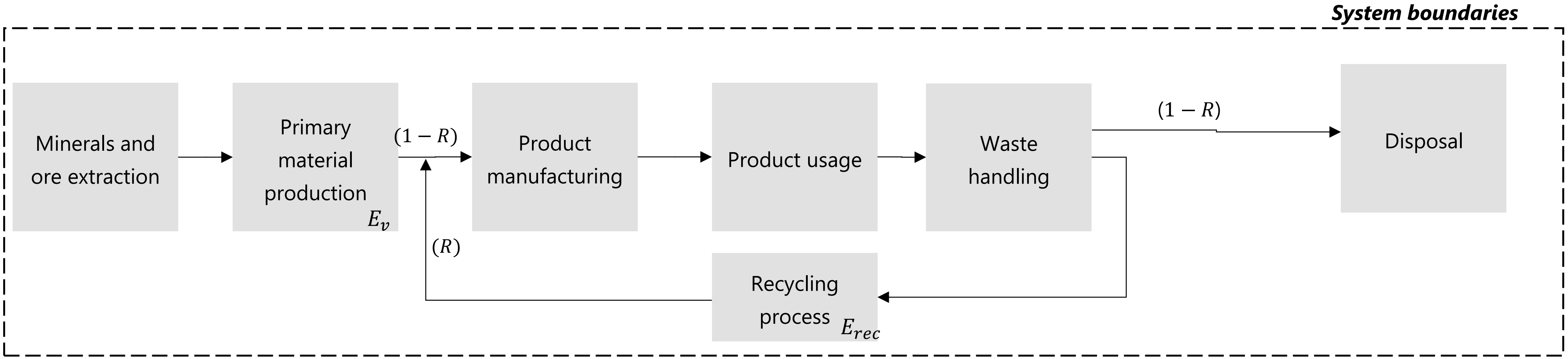
$$m_{Cu}(kg) = (1-R)m_{Cu,v} + R.m_{Cu,rec}$$
$$GWP(CO2e) = (1-R)GWP_v + R.GWP_{rec}$$



How to consider recycling in LCA ?

- At which step to allocate the recycling impacts?
    - End of Life
    - Material production step

$$E_{mat} = \underbrace{(1-R)E_v}_{\text{Materials/energy and Impact share of primary metal}} + \underbrace{RE_{rec}}_{\text{Materials/energy and Impact share of secondary metal}}$$



How to consider recycling in LCA ?

- At which step to allocate the recycling impacts?
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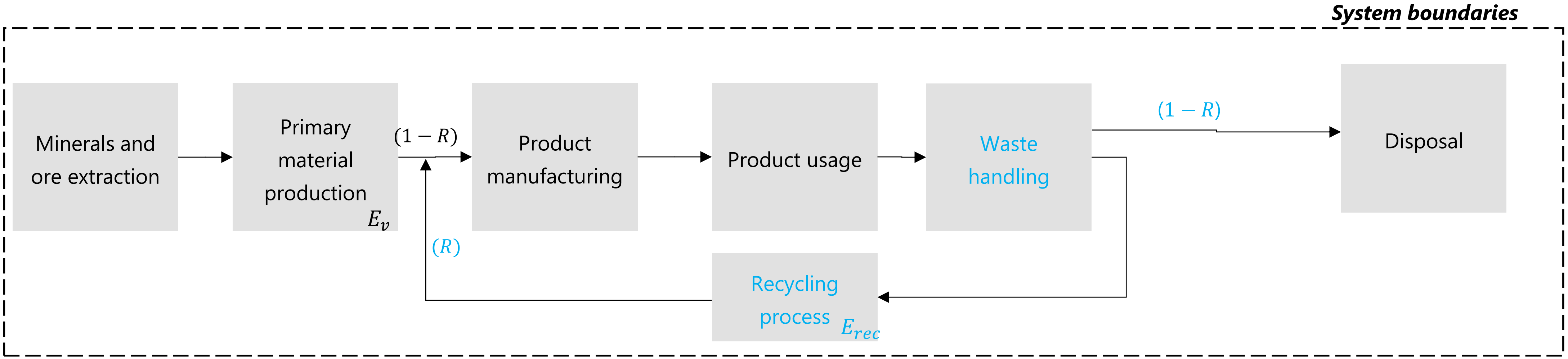
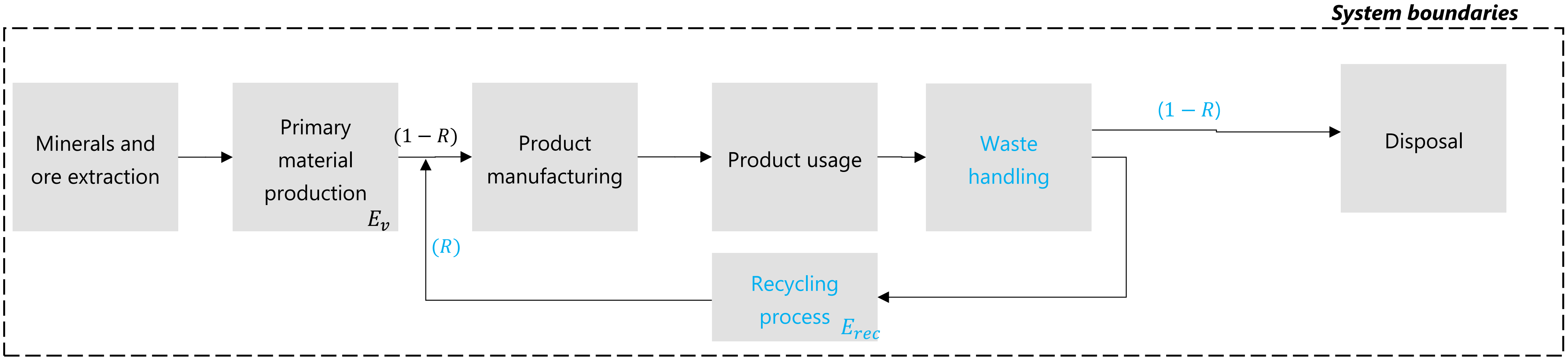


How to consider recycling in LCA ?

- At which step to allocate the recycling impacts?
    - End of Life
    - ⇒ Benefit will be given to the EoL
    - ⇒ Actual impact reduction will occur **in the future (15…25 year?)**
    - Material production step

Question: effect on design?

$$E_{mat} = \underbrace{(1-R)E_v}_{\text{Materials/energy and Impact share of primary metal}} + \underbrace{RE_{rec}}_{\text{Materials/energy and Impact share of secondary metal}}$$



How to consider recycling in LCA ?

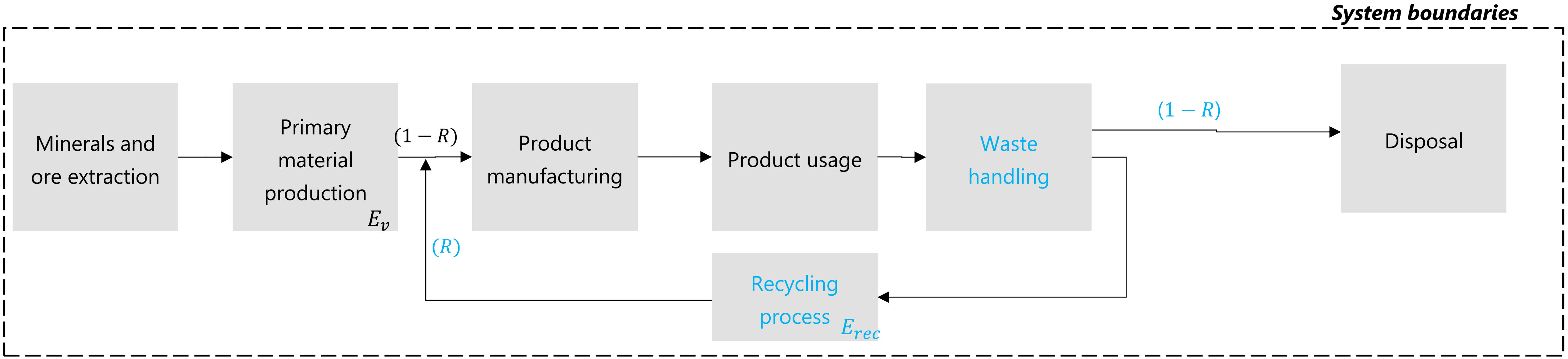
- At which step to allocate the recycling impacts?
  - End of Life

  ⇒ Benefit will be given to the EoL

  ⇒ Actual impact reduction will occur **in the future (15…25 year?)**

  ⇒ **Product designer will make easily recyclable product**
  - Material production step

$$E_{mat} = \underbrace{(1-R)E_v}_{\text{Materials/energy and Impact share of primary metal}} + \underbrace{RE_{rec}}_{\text{Materials/energy and Impact share of secondary metal}}$$



How to consider recycling in LCA ?

- At which step to allocate the recycling impacts?
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  ⇒ Benefit will be given to the material manufacturing

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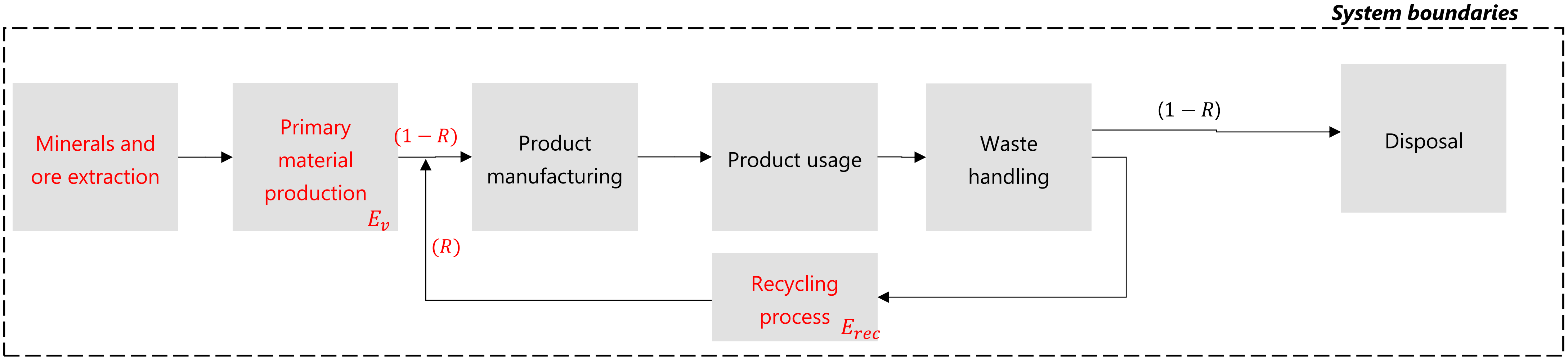


How to consider recycling in LCA ?

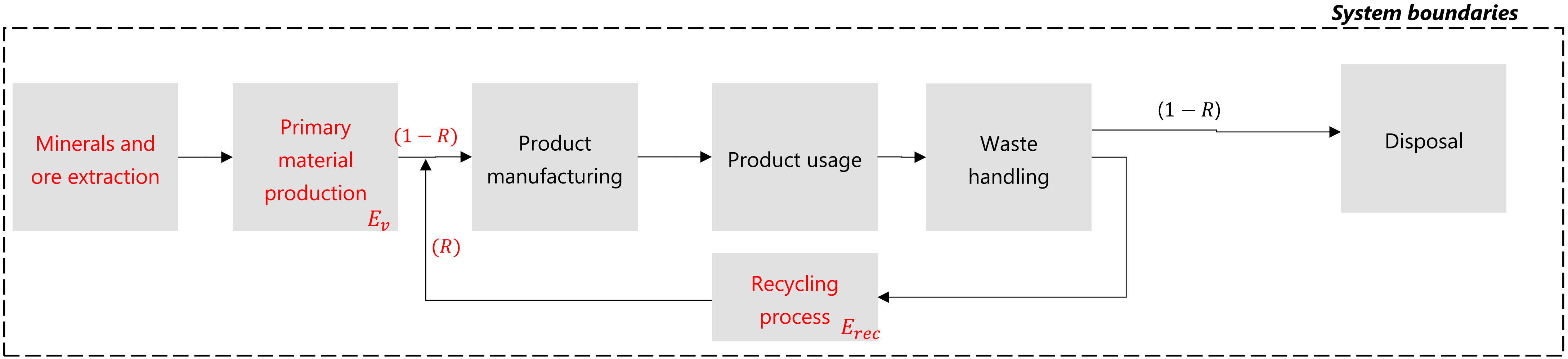
- At which step to allocate the recycling impacts?
  - End of Life
  - Material production step:

⇒ Benefit will be given to the material manufacturing

⇒ Impact reduction will occur **in a short timeframe**

⇒ Designer with **include materials with high recycled share**

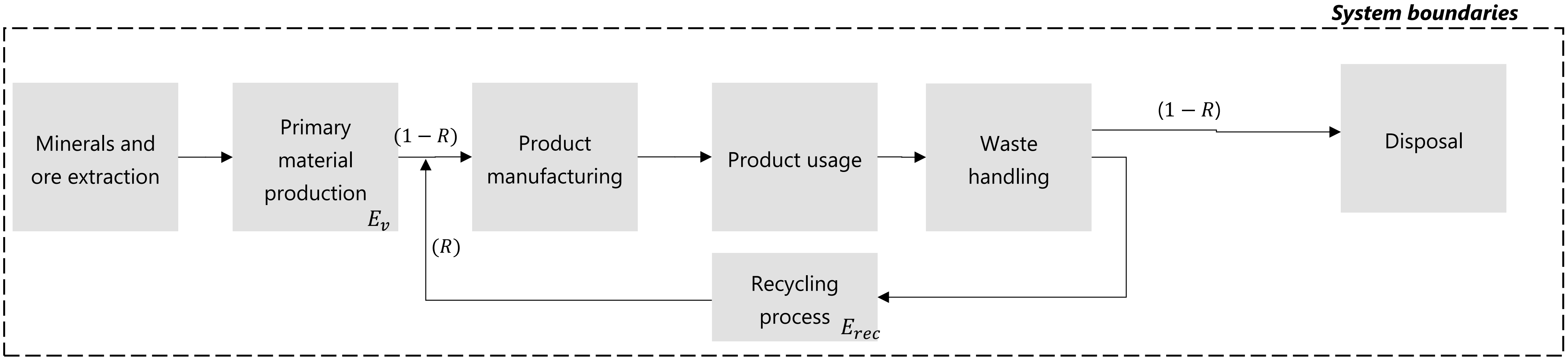
$$E_{mat} = \underbrace{(1-R)E_v}_{\text{Materials/energy and Impact share of primary metal}} + \underbrace{RE_{rec}}_{\text{Materials/energy and Impact share of secondary metal}}$$



How to consider recycling in LCA ?

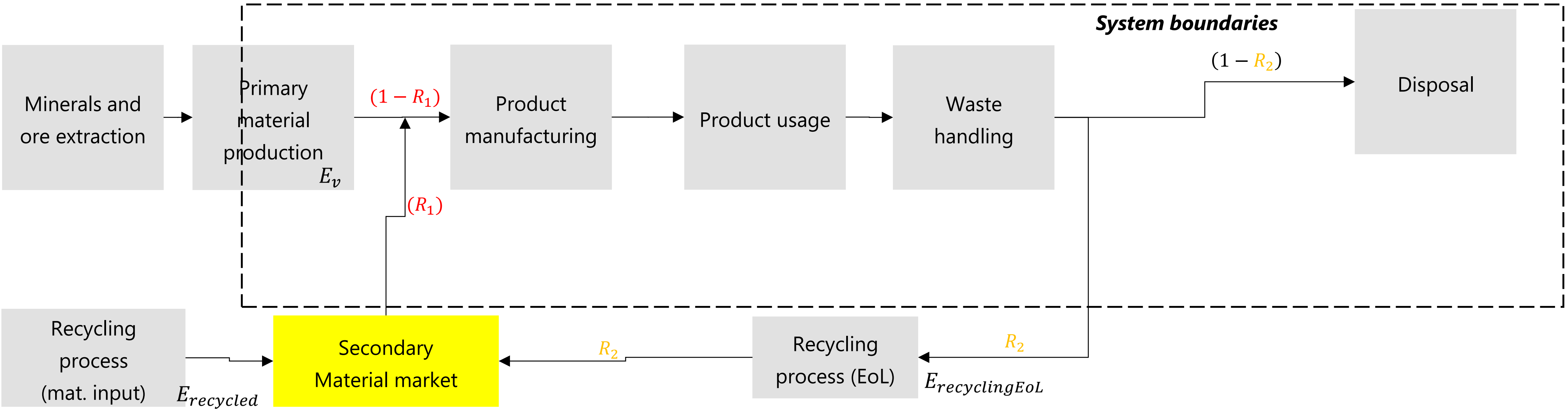
- At which step to allocate the recycling impacts?
  - End of Life
  - Material production step
- **Important:**
  - **do not count recycling twice**
  - **check databases processes assumptions**

$$E_{mat} = \underbrace{(1-R)E_v}_{\text{Materials/energy and Impact share of primary metal}} + \underbrace{RE_{rec}}_{\text{Materials/energy and Impact share of secondary metal}}$$



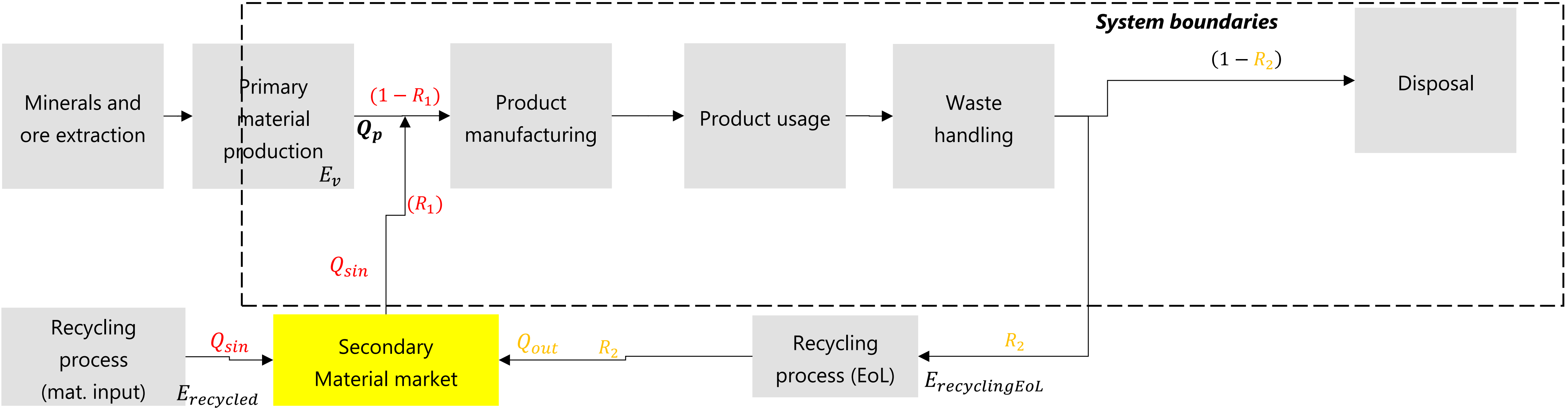
How to consider recycling in LCA ?

- Reality of recycling:
  - Complex material streams, difficult to track materials => modelled by secondary material market, outside system boundaries



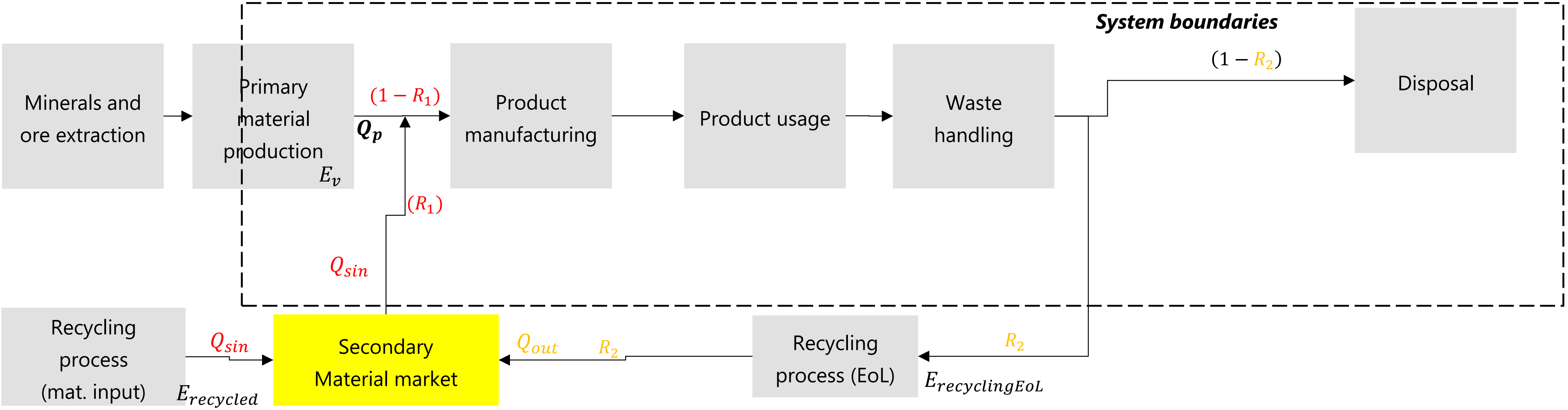
How to consider recycling in LCA ?

- Reality of recycling:
  - Complex material streams, difficult to track materials => modelled by secondary material market, outside system boundaries
  - Quality differences: Q_p (primary); Q_{sin} (input recycled stream) ; Q_{out} (output material stream EoL)



How to consider recycling in LCA ?

- Reality of recycling:
  - Complex material streams, difficult to track materials => modelled by secondary material market, outside system boundaries
  - Quality differences: Q_p (primary); Q_{sin} (input recycled stream) ; Q_{out} (output material stream EoL)
  - **Allocations problems are back ! How to solve this?**



MITSUBISHI ELECTRIC Changes for the Better

CFF :Circular Footprint Formula (JRC/EU commission) used in Product Environmental Footprint method (PEF; EN15804)

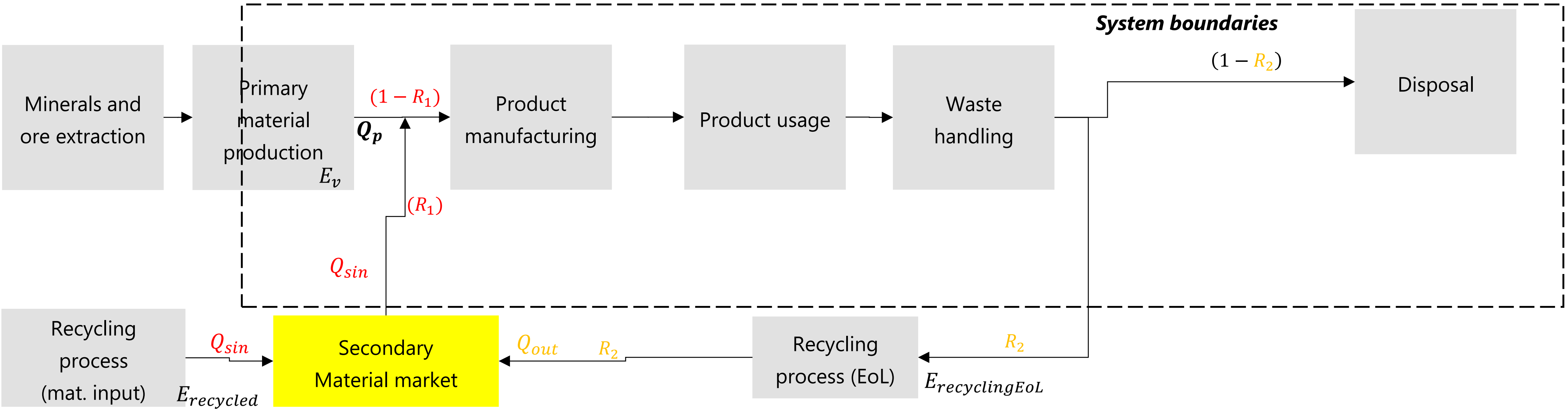
- Option 1: **burden/credit given to the user of material**
  - For the manufacturing phase => to the product
  - For the EoL phase => to the recycler

$\Rightarrow$ Purchasing department will choose materials suppliers with high recycled share

$\Rightarrow$ Impact reduction will occur in a short time (during product manufacturing)

- Also called **'cut-off'** approach

$$E_{mat} = (1 - R_1)E_v + R_1 E_{recycled}$$



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CFF :Circular Footprint Formula (JRC/EU commission) used in Product Environmental Footprint method (PEF; EN15804)

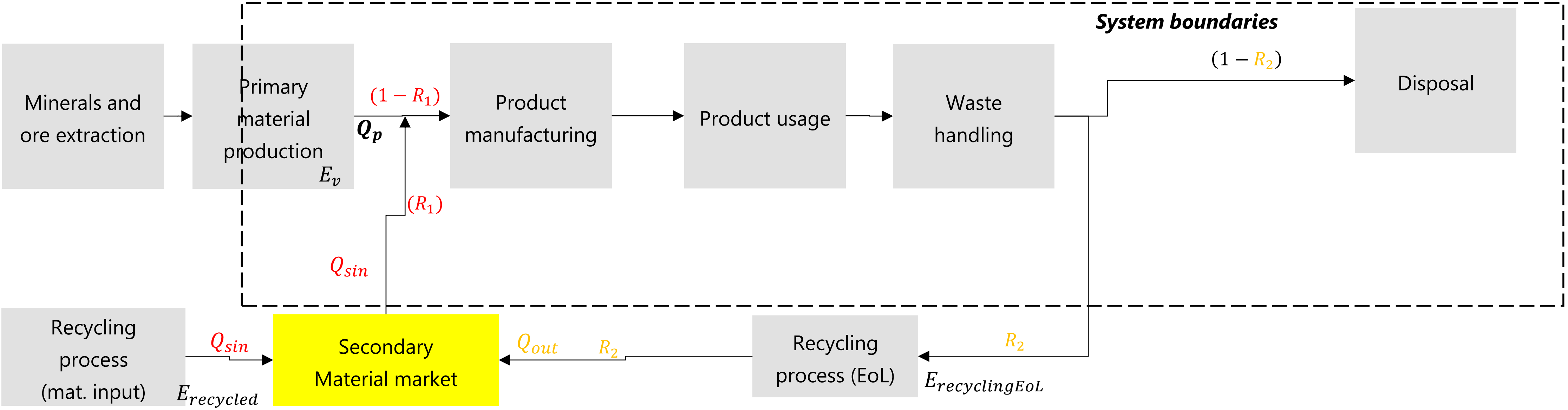
- Option 2: **burden/credit given to the producer of material**
  - For the manufacturing phase => to the recycler
  - For the EoL phase => to the product

⇒ product designer will make easily recyclable product

⇒ Impact reduction will occur in the future (15…25 year?)

Also called **'avoided burden'** or **'substitutional'** approach

$$E_{mat} = (1 - R_1)E_v \quad + R_2\left(E_{recyclingEoL}\right)$$



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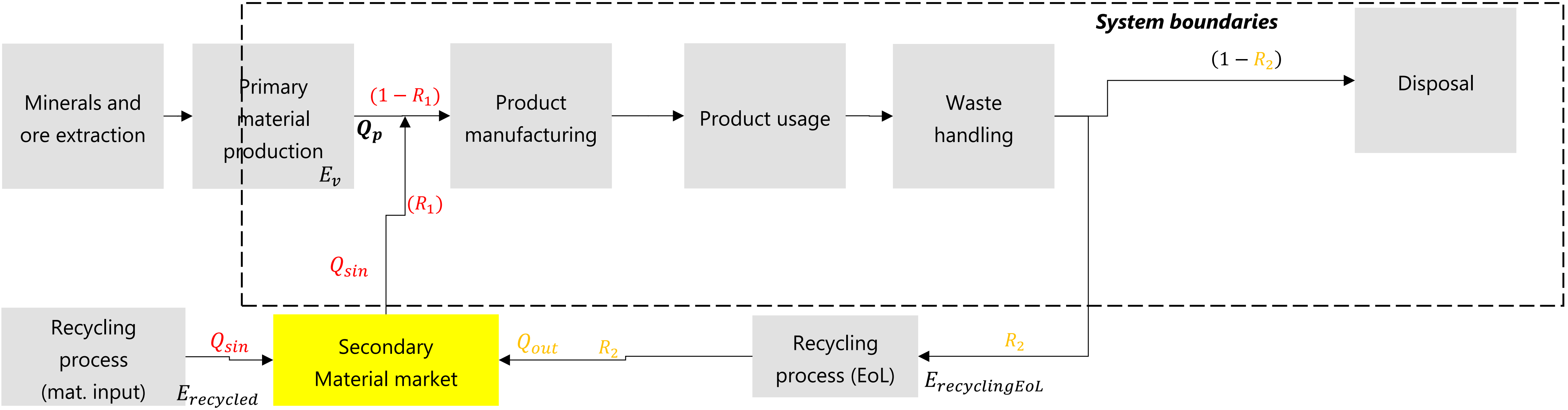
CFF :Circular Footprint Formula (JRC/EU commission) used in Product Environmental Footprint method (PEF; EN15804)

- Option 2: **burden/credit given to the producer of material**
  - For the manufacturing phase => to the recycler
  - For the EoL phase => to the product
  - For loss of primary material entering the secondary material market => to the product (modulo a quality derating factor)

$$E_{mat} = (1 - R_1)E_v + \underbrace{R_1 E_v \frac{Q_{Sin}}{Q_P}} + R_2\left(E_{recyclingEoL} - \underbrace{E_v \frac{Q_{Sout}}{Q_P}}\right)$$

$R_1 E_v \frac{Q_{Sin}}{Q_P} - R_2 E_v \frac{Q_{Sout}}{Q_P}$: quality and material losses of primary material



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CFF :Circular Footprint Formula (JRC/EU commission) used in Product Environmental Footprint method (PEF; EN15804)

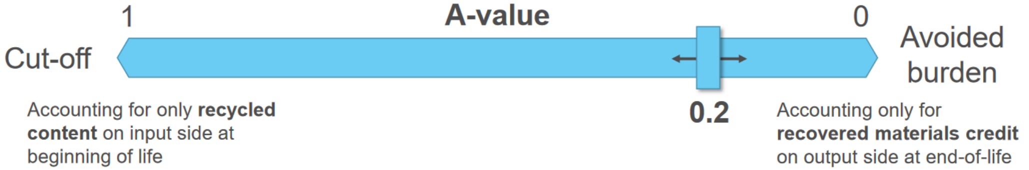
- **Mixed approach: allocation factor A (0<A<1):**
  - **Low offer and high demand** of recyclable materials => A will be low (0.2) to **push designer to design recyclable** products
  - **High offer and low demand** of recycled materials => A will be high (0.8) to **push designer to source recycled materials**

$E =$

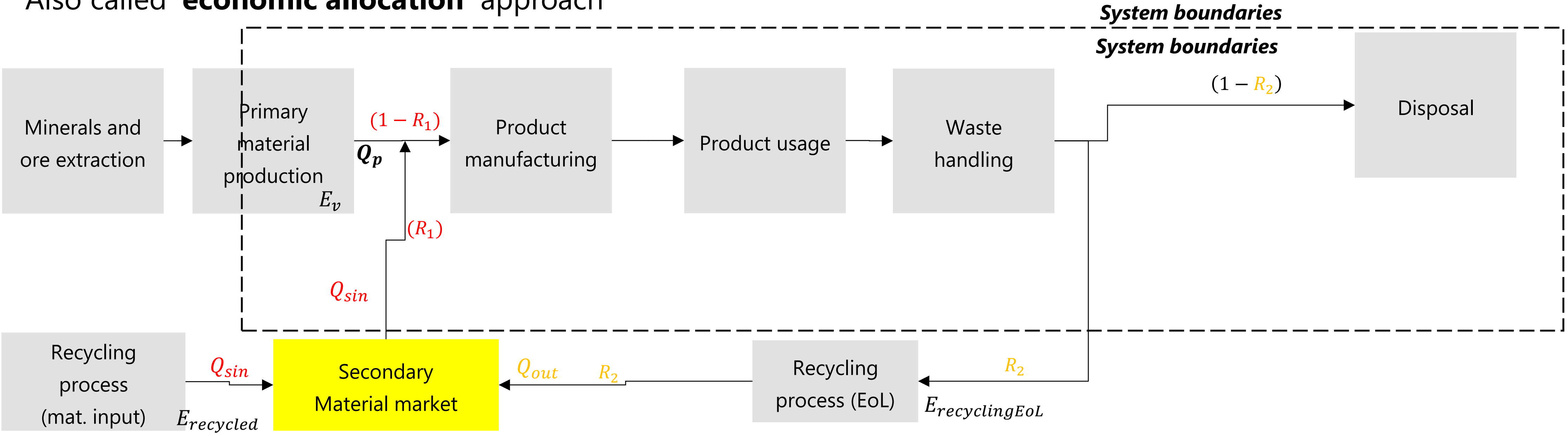
$(1-R_1)E_v + R_1.E_{recycled}$ material production burdens

$-(1-A)R_1\left(E_{recycled} - E_v\frac{Q_{Sin}}{Q_P}\right)$ burden and benefits related to secondary material input

$+(1-A)R_2\left(E_{recyclingEoL} - E_v\frac{Q_{Sout}}{Q_P}\right)$ burden and benefits related to secondary material output



Also called **'economic allocation'** approach



Limitations of the CFF method 1/2

- **Allocation factor A** provided by EU commission:
  - Automotive, PV panels, metals: **A=0.2**
  - ⇒ **designers are pushed to design easily recyclable products**

Examples of some R1, R2 and A factors provided by JRC for PE-related products and materials

https://eplca.jrc.ec.europa.eu/permalink/Annex_C_V2.1_May2020.xlsx

Category	Material	Application	Parameters A	R1	Recycling rate (≈ R2). EU* : Europe (post consumer)	BE
Metals	Steel	MATERIAL	0.2	0	0.85	
		appliances - sheet	0.2	0.18	0.90	
		photovoltaic panel - not specified	0.2	0.37	0	
		photovoltaic panel - mounting structure; electric installation	0.2	0.37	0.95	
		uninterruptible power supply (UPS)	0.2	0	0.93	
	Aluminum	MATERIAL	0.2	0	0.85	
		automotive	0.2	0	0.90	
		appliances - sheet	0.2	0	0.90	
		photovoltaic panel - not specified	0.2	0.32	0	
		photovoltaic panel - mounting structure; electric installation	0.2	0.32	0.95	
		sheet - uninterruptible power supply (UPS)	0.2	0	0.90	
	Aluminum alloys	AlMg3 - photovoltaic panel	0.2	0.77	0	
	Copper	MATERIAL	0.2	0	0	
		electronic applications	0.2	0.72	0.80	
		electrical applications (cables)	0.2	0.30	0.95	
		mechanical applications	0.2	0.79	0.80	
		photovoltaic panel - PV modules or not specified	0.2	0.44	0	
		photovoltaic panel - mounting structure; electric installation	0.2	0.44	0.95	
		tube/sheet in uninterruptible power supply (UPS)	0.2	0	0.93	
	Copper alloys	building - water supply pipes	0.2	0.80	0.95	
		CuZn38 cast - uninterruptible power supply (UPS)	0.2	0	0.93	
	Copper telluride	photovoltaic panel	0.2	0	0	
	Lead	MATERIAL	0.2	0	0	
		lead-acid batteries	0.2	0.80	0.99	

Limitations of the CFF method 2/2

- CFF formula principles:
  - Give a solution to allocation problems for EoL material treatment and sourcing ✓
  - Based on underlying mass / energy balance (1st thermodynamic law) ✓
  - Can potentially handle reuse, repair and refurbish (different point of substitution) ✓
  - **Quality factors not well-defined** X
  - **A-factor** <=> economic allocation (**not physical**) X
  - Linear –economy centric, based on 2 'manufacture-use-dispose', and 'material/scrap market' spaces X

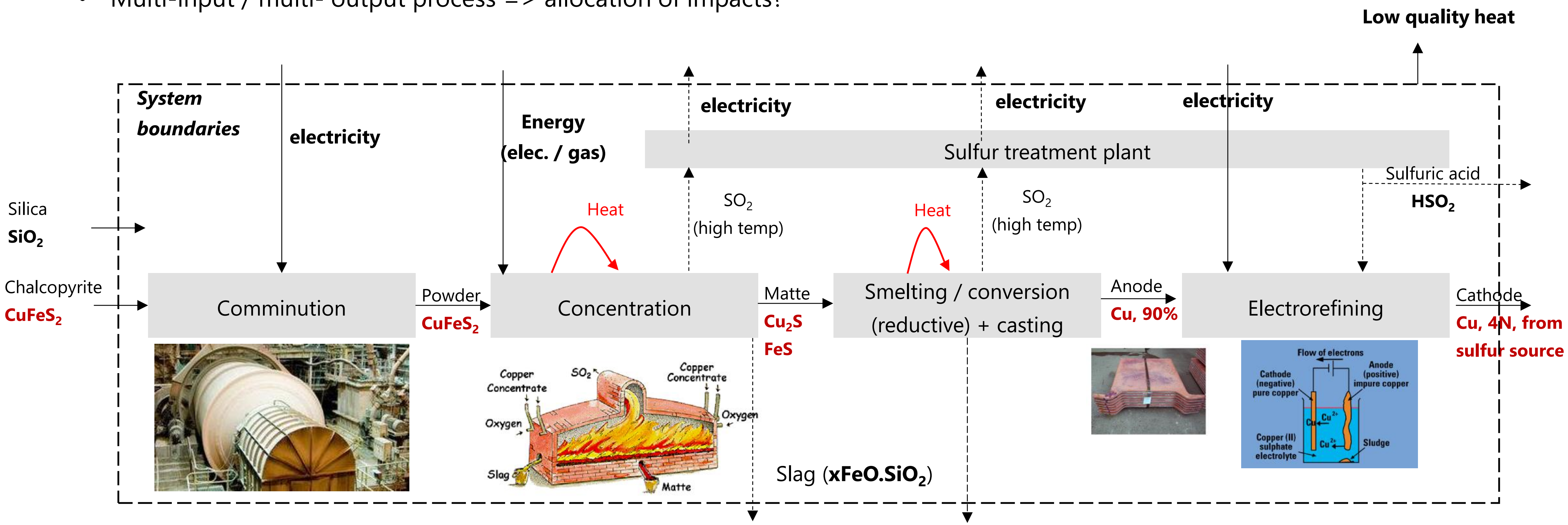
Reality and the physical underlying principles of materials extraction and recycling?

3

Reality of recycling

Towards a stronger thermodynamic basis of LCA?

- **Primary copper** extraction:
  - Thermodynamically favorable reduction of sulfur copper source (exothermic) => Process heavily relying on sulfur fueling
  - Internal recycling / reuse loops already implemented (sulfuric acid for electrorefining)
  - Multi-input / multi- output process => allocation of impacts?



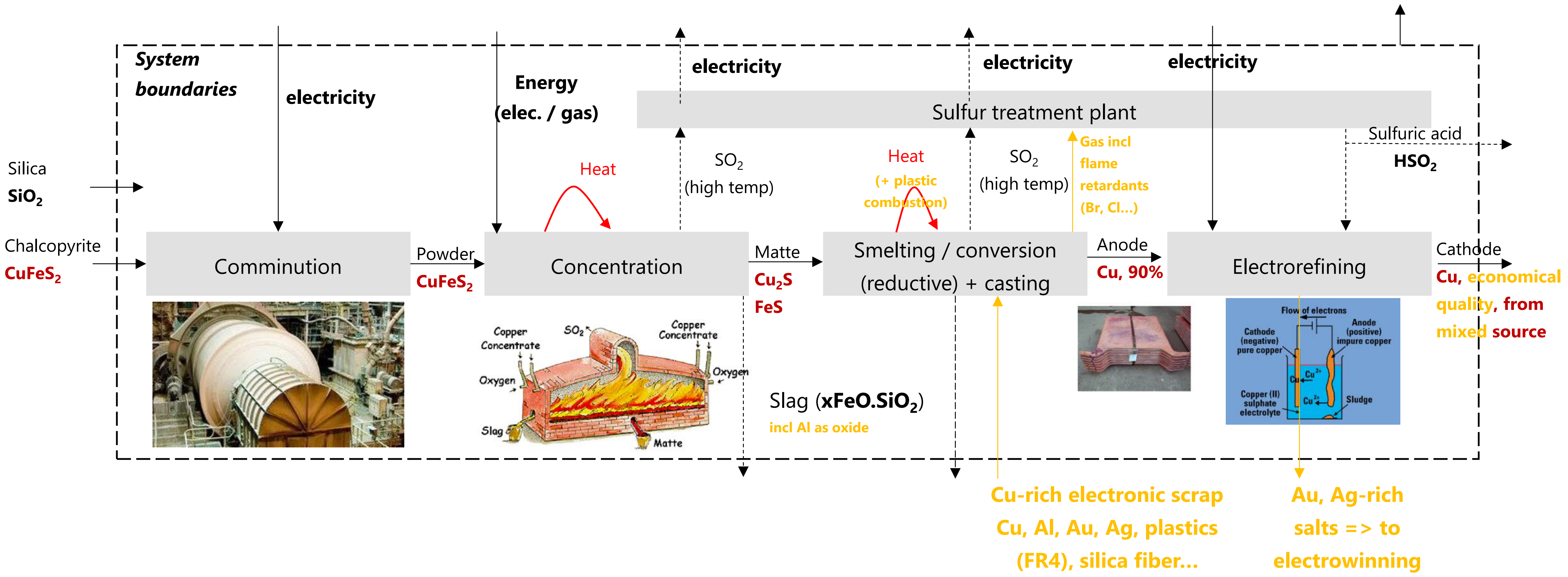
$CuFeS_2 + O_2(g) + SiO_2(s) =>$
$FeS + Cu_2S + 2FeO.SiO_2(slag) + SO_2(g)$

$Cu_2S + O_2(g) => 2Cu + SO_2$
$FeS + 1.5\ O_2(g) + SiO_2(s) => FeO.SiO_2\ (slag) + SO_2$

ΔG (1300°C) < 0 ⇔ heat produced ⇔ Sulfur is fuel

Best Available Technology – example of copper

- **Secondary copper** heavily relies on existing (**primary copper**) infrastructure:
  - Share of Copper-rich electronic scrap is added in the smelter => **Allocation of impacts** between copper sources ? **$CuFeS_2$**; **Cu-rich EEE**
  - Cu is good metal carrier to recover noble metals (Ag, Au) => **Allocation of impacts** for secondary output materials?
  - Less noble metals (Mg, Li, Al, Si ...) are oxidized and lost in the slag
  - Compromise between output copper quality (unwanted alloying, e.g. **Ni**) and input proportion **Cu-rich EEE**



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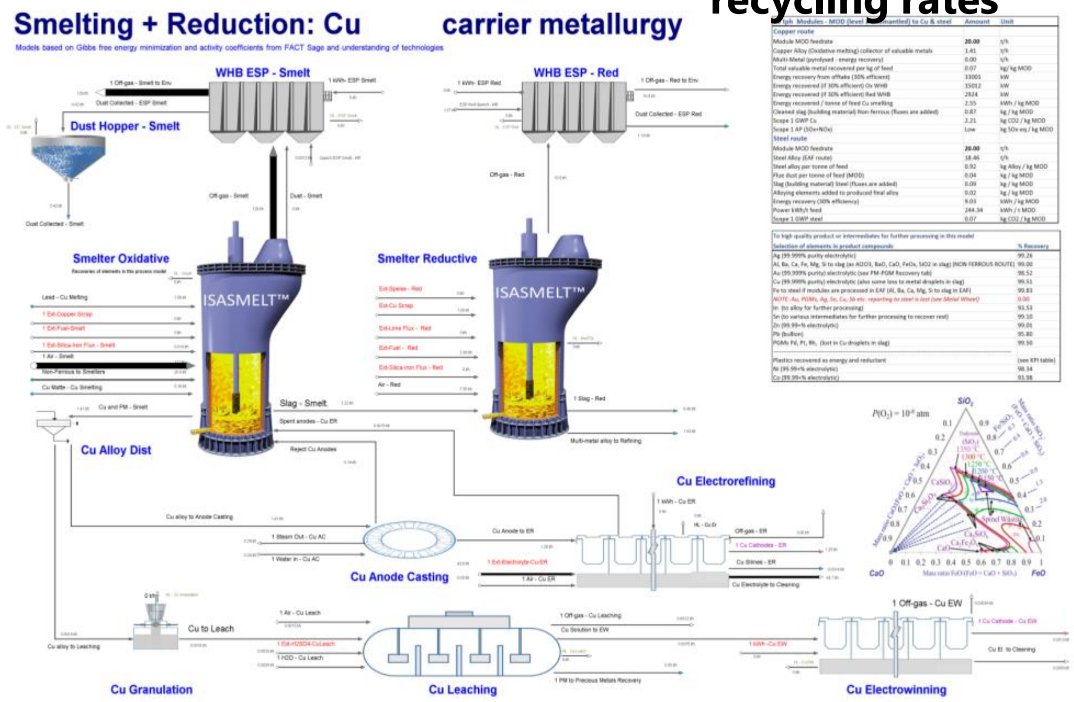
Physics-based process modelling => quantitative recycling rates



1st law principles

Input 1

Input 2

$$\sum mass = 0$$

$$\sum energy = 0$$

Output 1

Output 2

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Physics-based modelling of recycling metallurgy

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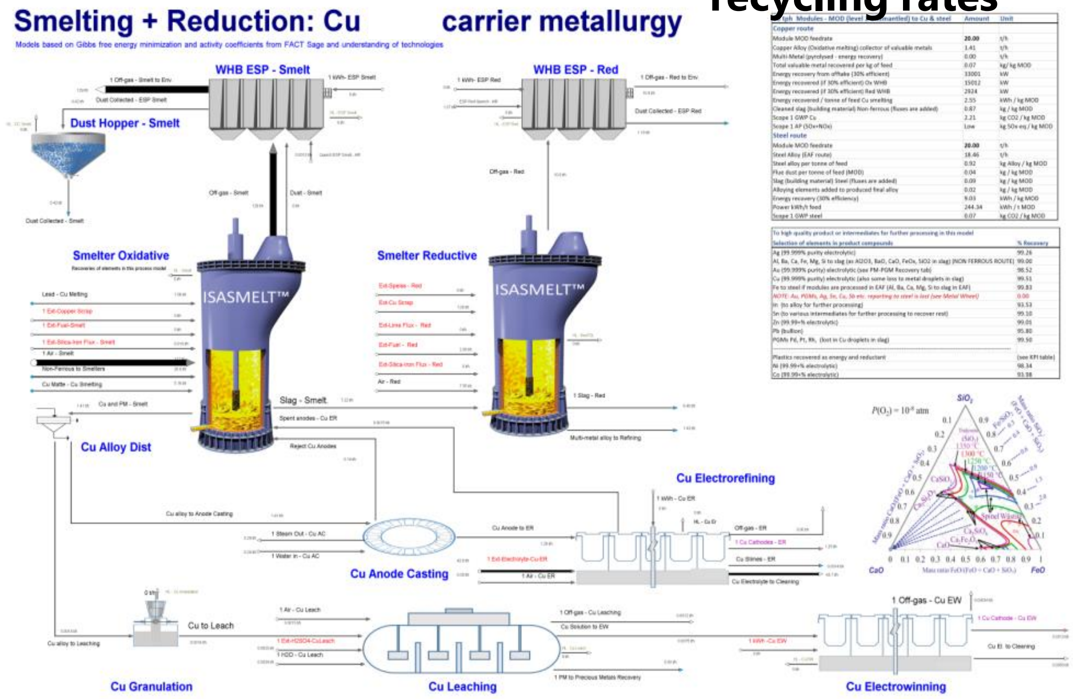
Physics-based process modelling => quantitative recycling rates



1st law principles

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2st law principles

$\Delta S > 0$

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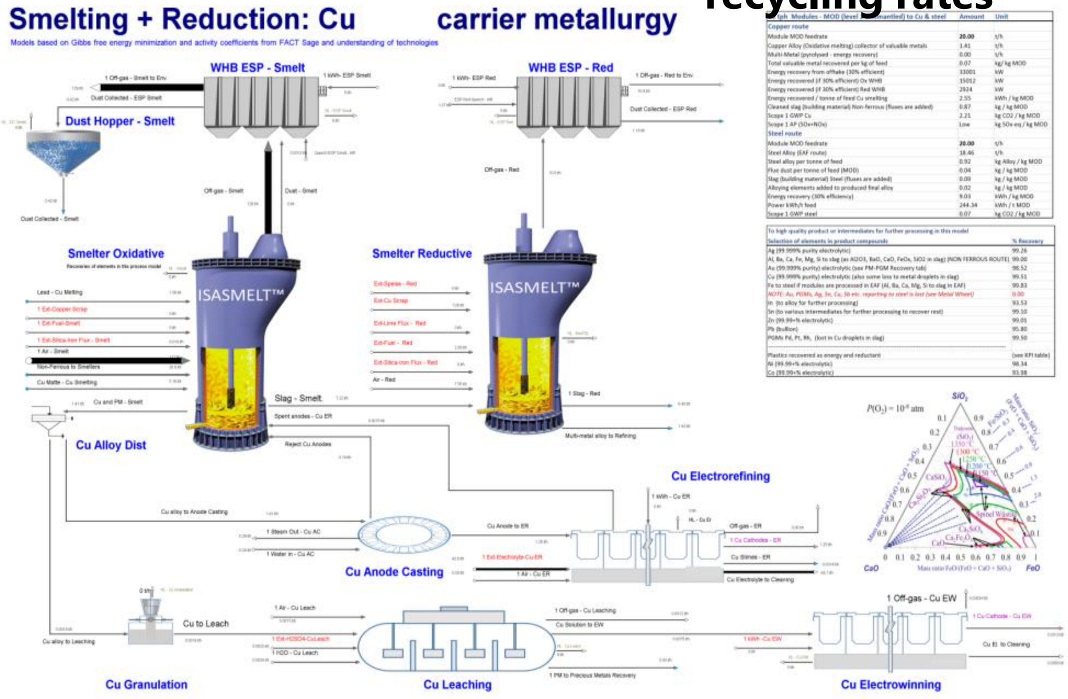
Physics-based modelling of recycling metallurgy

Physics-based process modelling => quantitative recycling rates



1st law principles

2st law principles

Input 1

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Output 2

$$\Delta S > 0$$

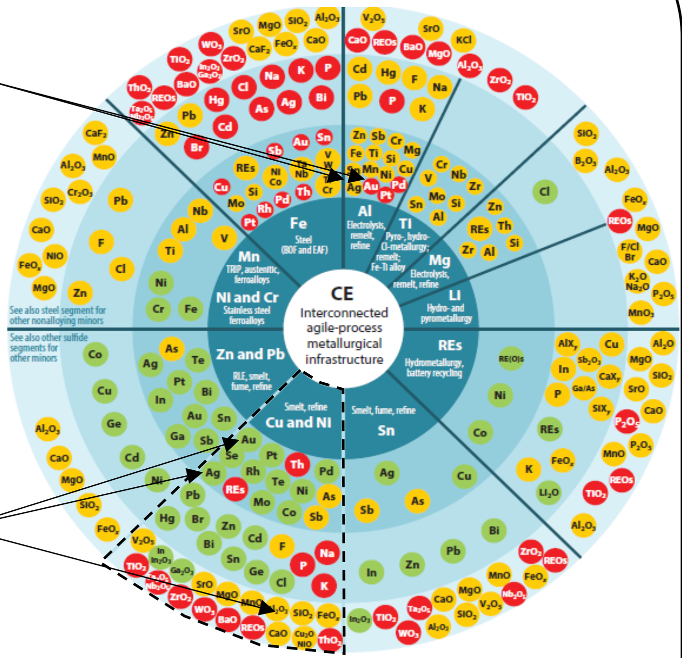
Metal Wheel => qualitative

Au, **Ag**, **Cu** cannot be recovered or is recovered with quantity and quality loss in **Al** **recycling infrastructure**

R **Mainly recovered element**
Compatible with the base metal as an alloying element or can be recovered in subsequent processing.

R/L **Recovered in alloy/compound or lost if in the incorrect stream/scrap/module**
Governed by functionality, if not detrimental to base metal or product (e.g., if refractory metals in EoL product report to slag, and slag is also intermediate product for cement).

L **Mainly lost element: not always compatible with base metal or product**
Detrimental to properties and cannot be economically recovered; e.g., Au dissolved in steel or aluminum will be lost.



Au, **Ag** can be recovered in **Cu** **infrastructure** with good efficiency and quality, **Al** ends up as oxide in slag can cannot be recovered as a metal

Physics-based modelling of recycling metallurgy

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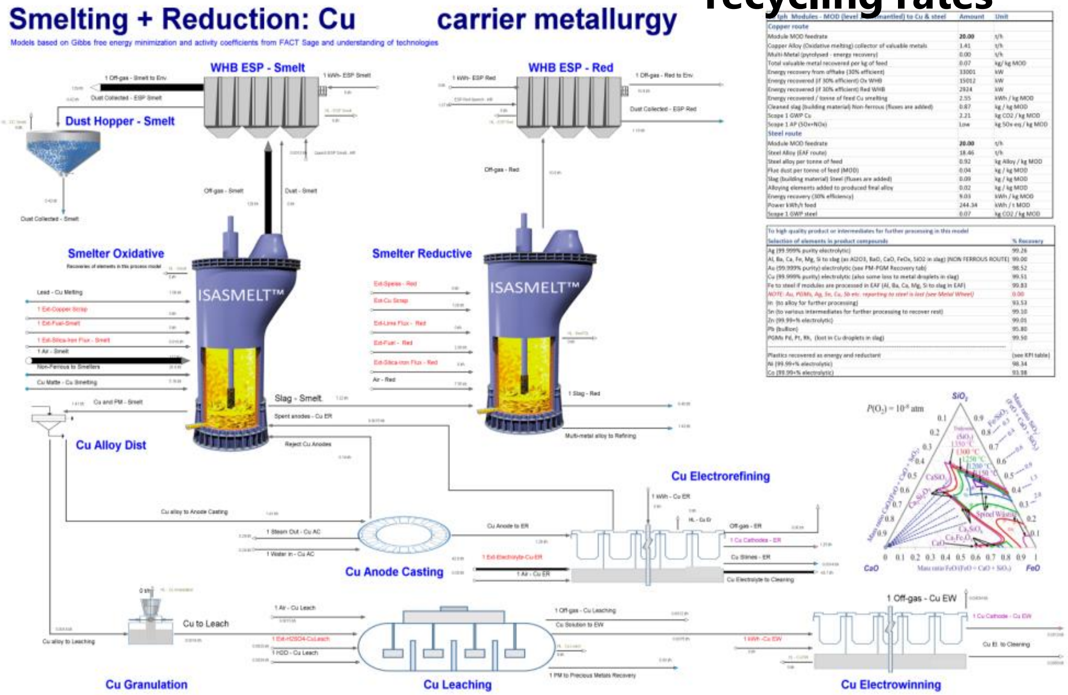
Physics-based process modelling => quantitative recycling rates



1st law principles

2st law principles

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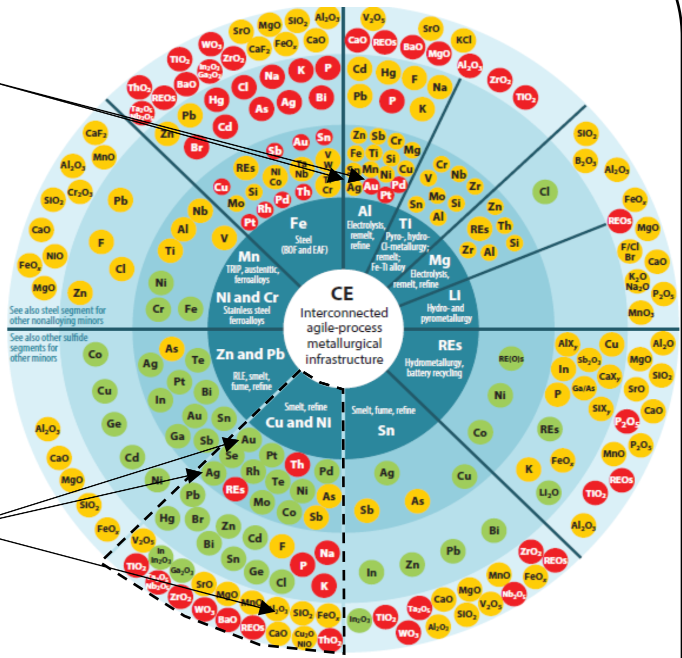

Use of the 'metal wheel':

- **Recycler:** Scrap composition **information** => recycling stream
- **For the (electronic) designer:**
  - Choice of **materials combinations** => recycling rate & quality, precious metals.
  - Choice of **system modularity** based on subsystem material combinations, to send modules to separate infrastructures

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4 Conclusions

Conclusions

- **How to consider repair and diagnostic in LCA?**
  - Modularity without diagnostic can increases impacts
  - Design trade-offs require case-by-case analysis
  - PELCA tool
- **How to introduce circularity in LCA?**
  - Importance of allocation to avoid double (or no counting)
  - Impact of allocation on design strategy
  - Limitations of allocation methods based on default factors and recycling rates
- **Reality of recycling => towards a stronger thermodynamic basis of LCA?**
  - Process modelling based on 1st AND **2nd law**
  - Irreversible losses (material, energy, quality) considered
  - 2nd law principles rarely considered in LCA

5 References

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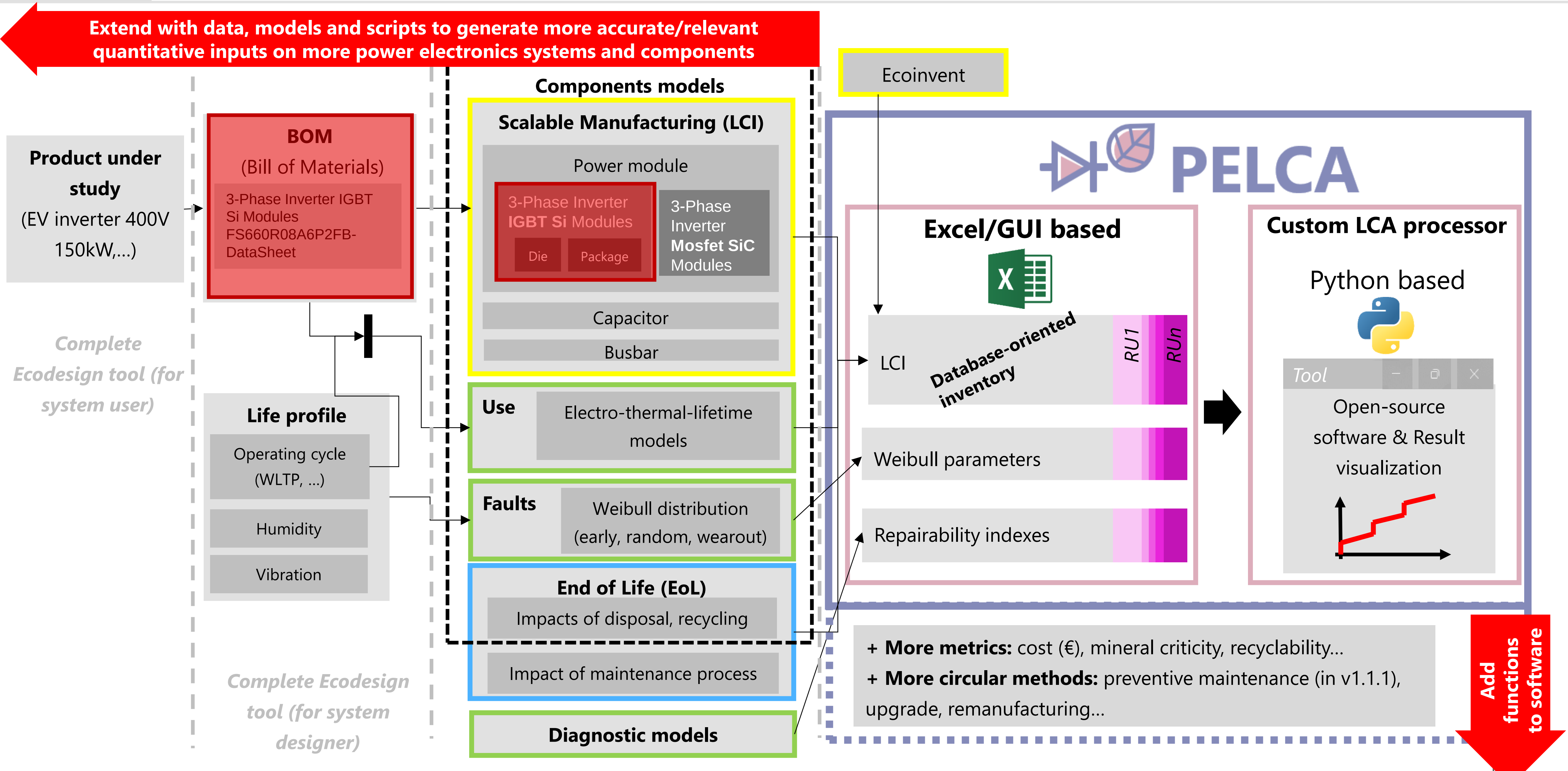
6 Additional slides

MERCE open-source approach – future?



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