Responsible digital technologies (2)

Life Cycle Analysis

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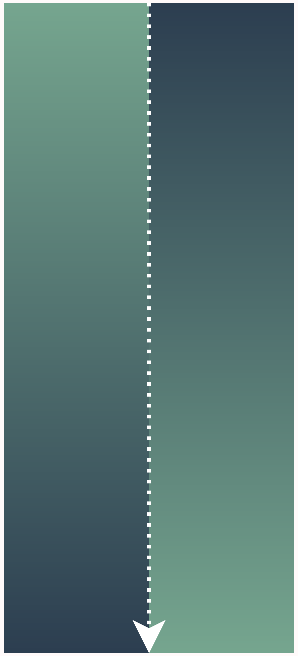
Reminders



Digital sufficiency
Computing within limits
Permacomputing
Circular economy
& product life extension

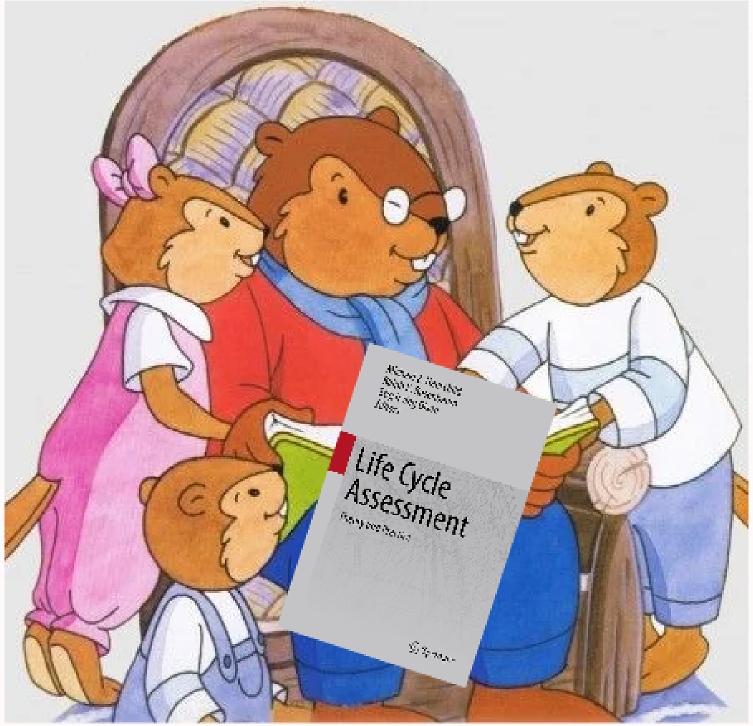
Life Cycle Assessment

Software eco-design
Green software engineering

Carbon-aware computing
Energy measurement

Today's plan

- Provide an overview of what is and isn't an LCA;
- Take a look at a completed LCA for a [surprise].



Science-based targets

> ❞ **:** setting science-based targets to reduce their greenhouse gas emissions in line with the goals of the Paris Agreement.

https://en.wikipedia.org/wiki/Science_Based_Targets_initiative

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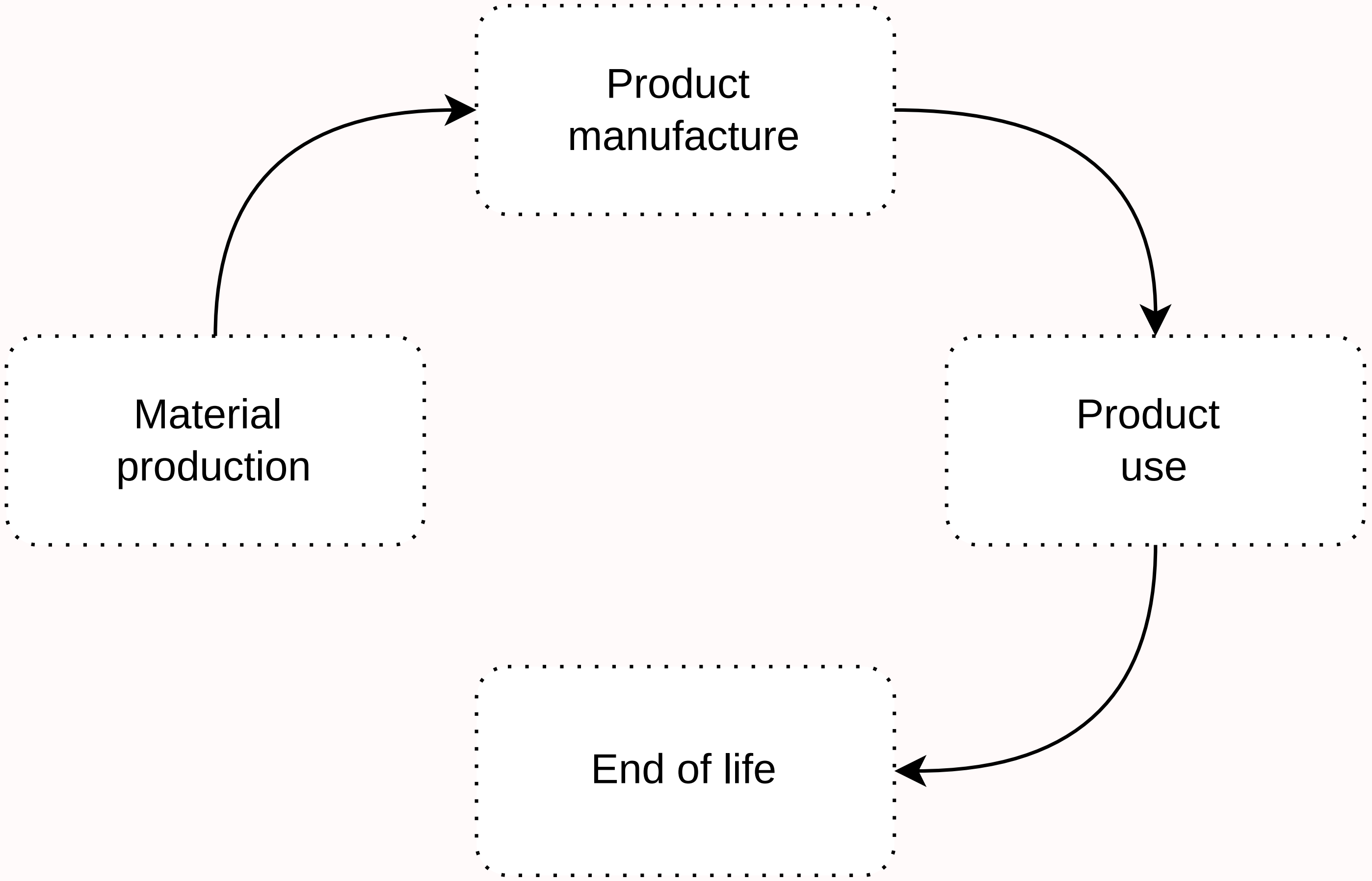
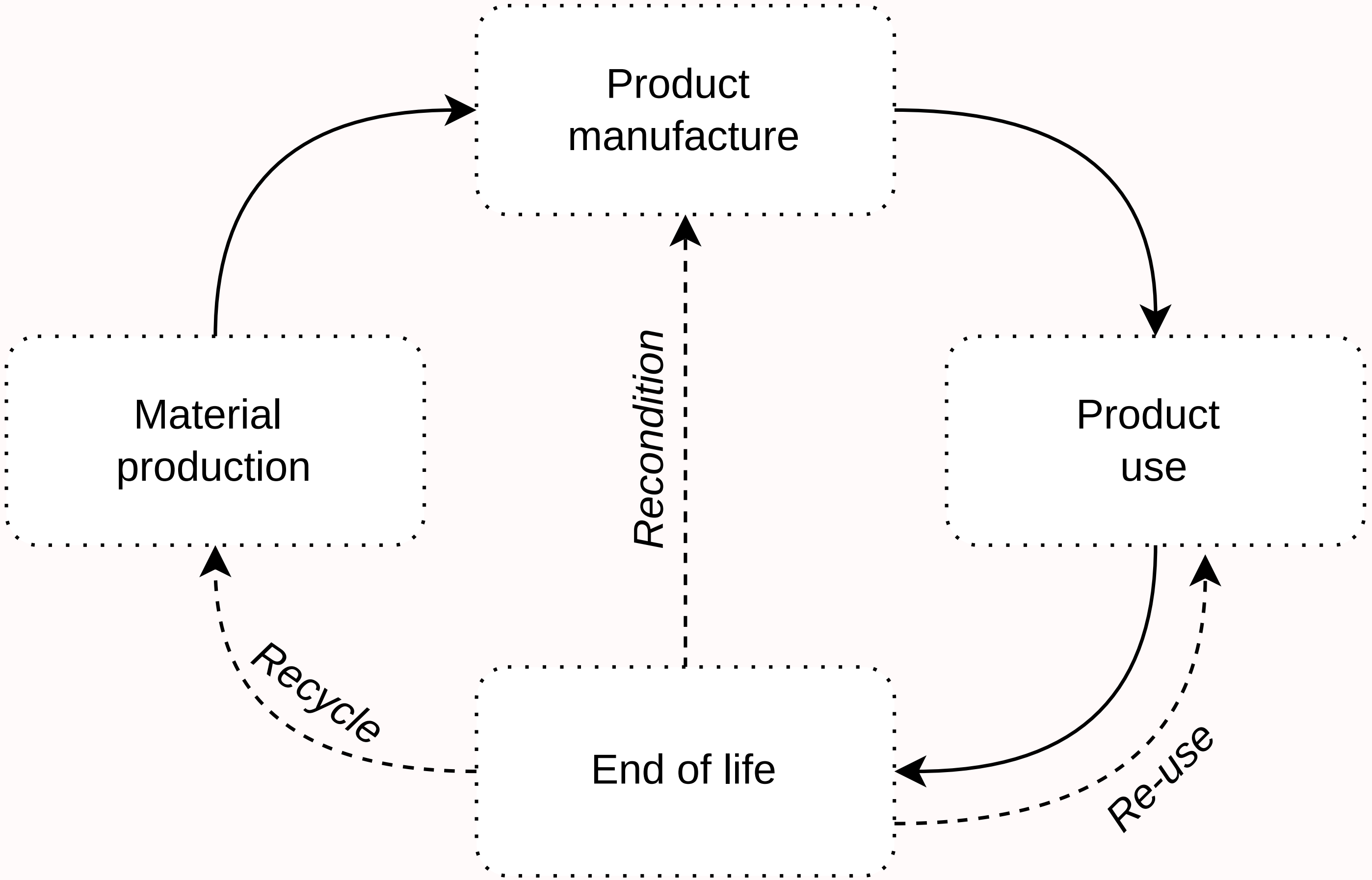
Cool idea.

How do we obtain these science-based targets, though?

Life cycle


Product manufacture
Material production
Product use
End of life

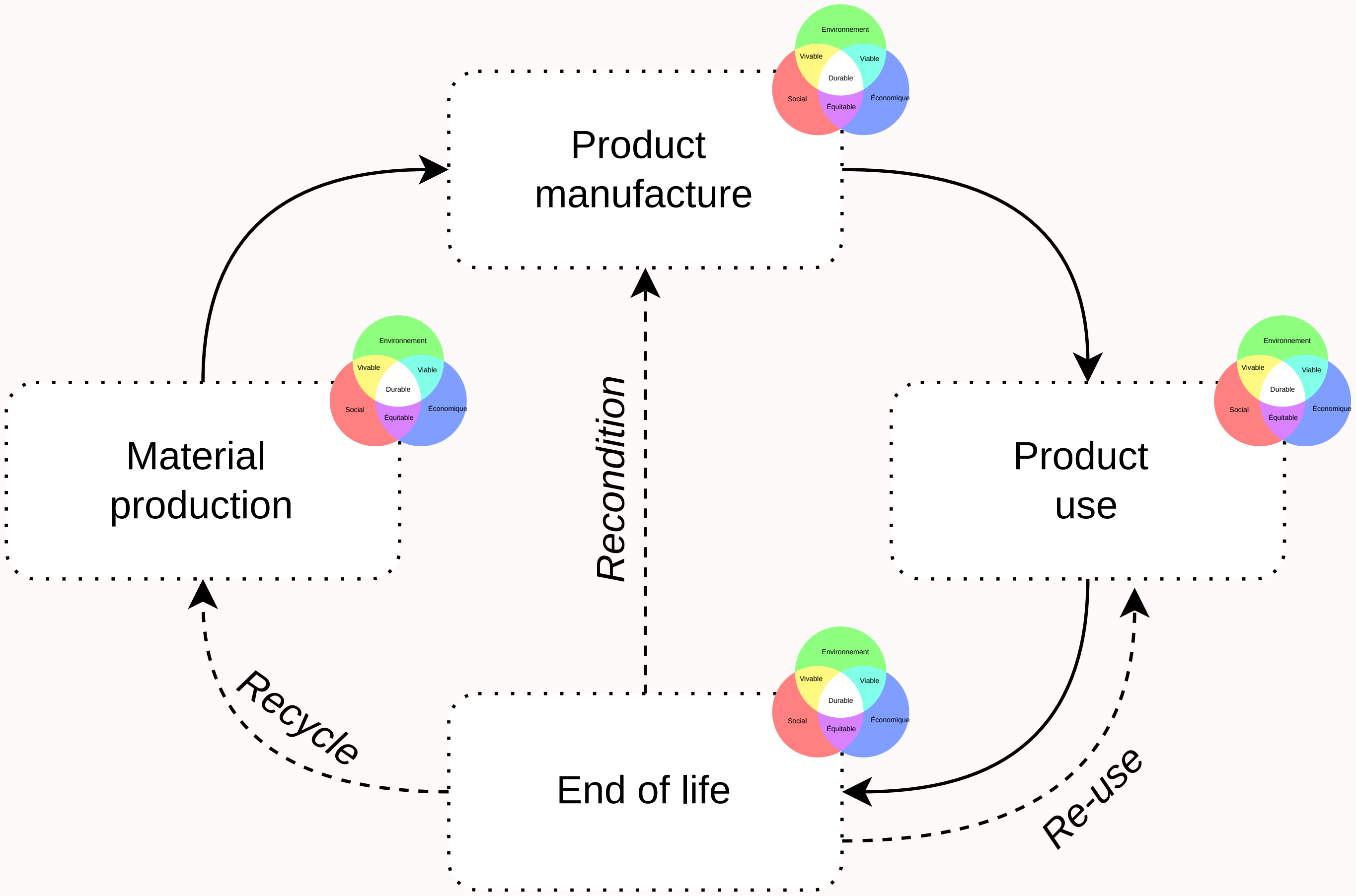
Life cycle



Product manufacture
Material production
Recondition
Product use
Recycle
End of life
Re-use

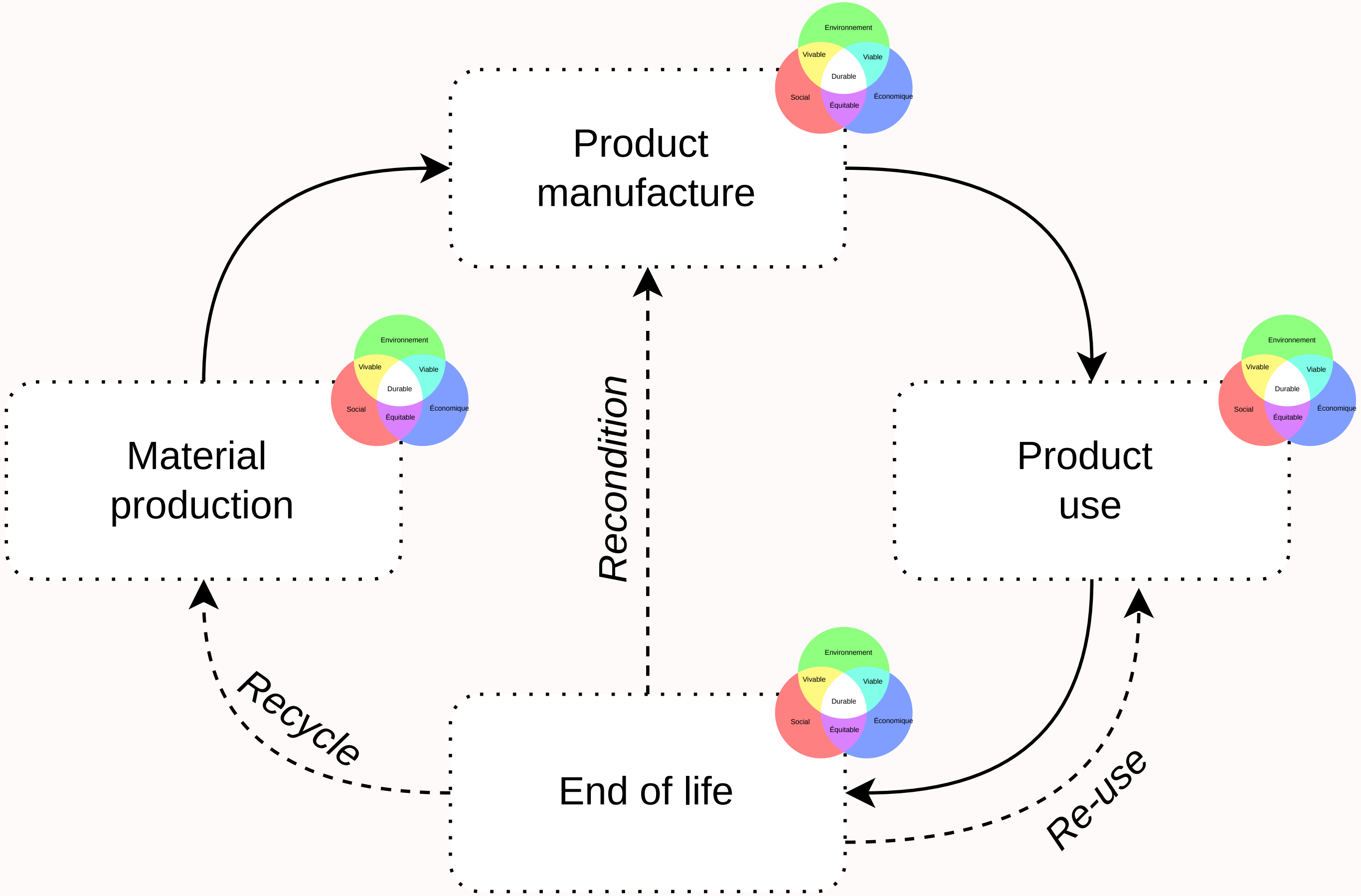
Life cycle Assessment

Life cycle Assessment



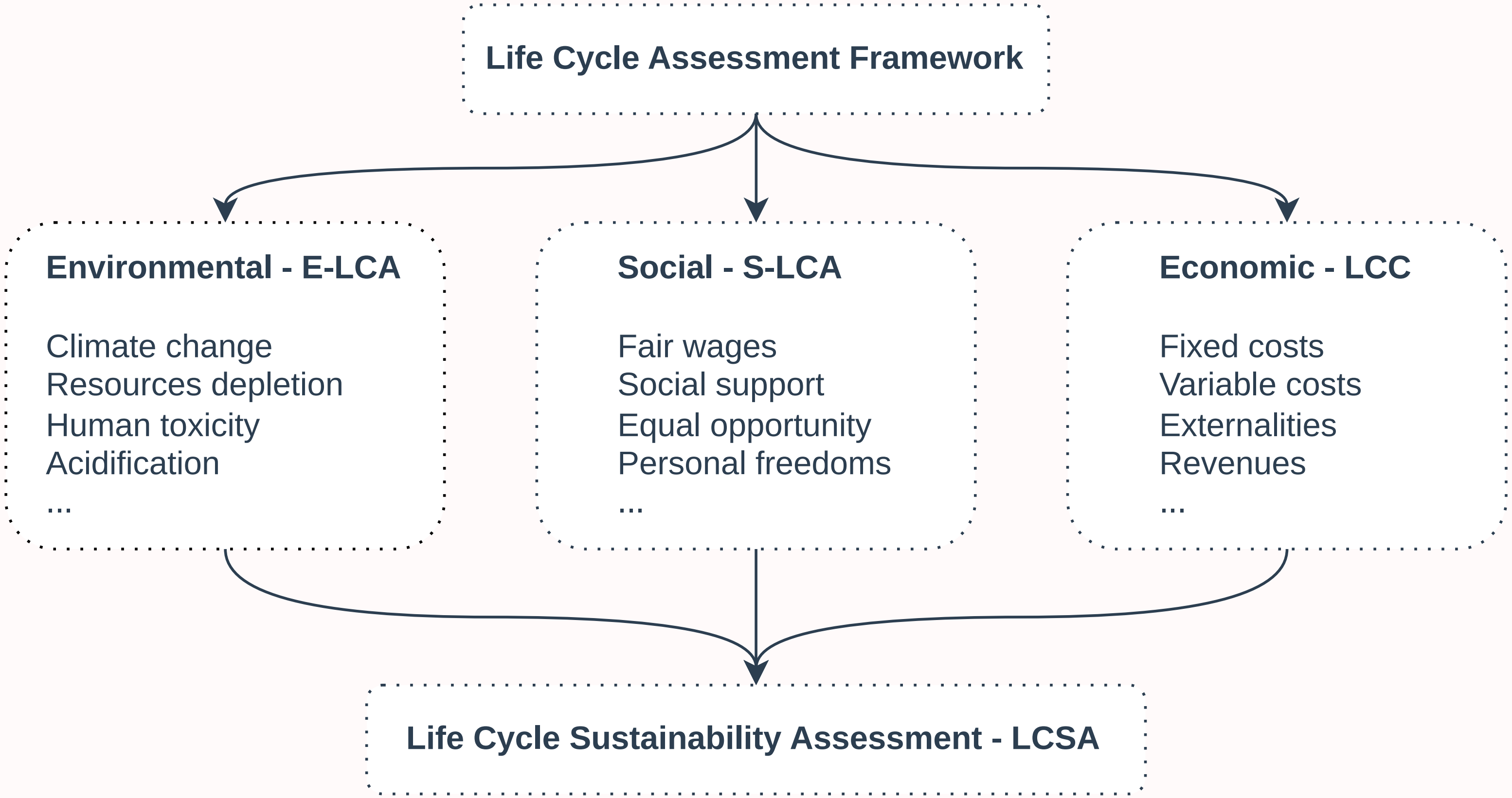
> **ISO 14040:2006:** [...] compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle.

Life cycle Assessment



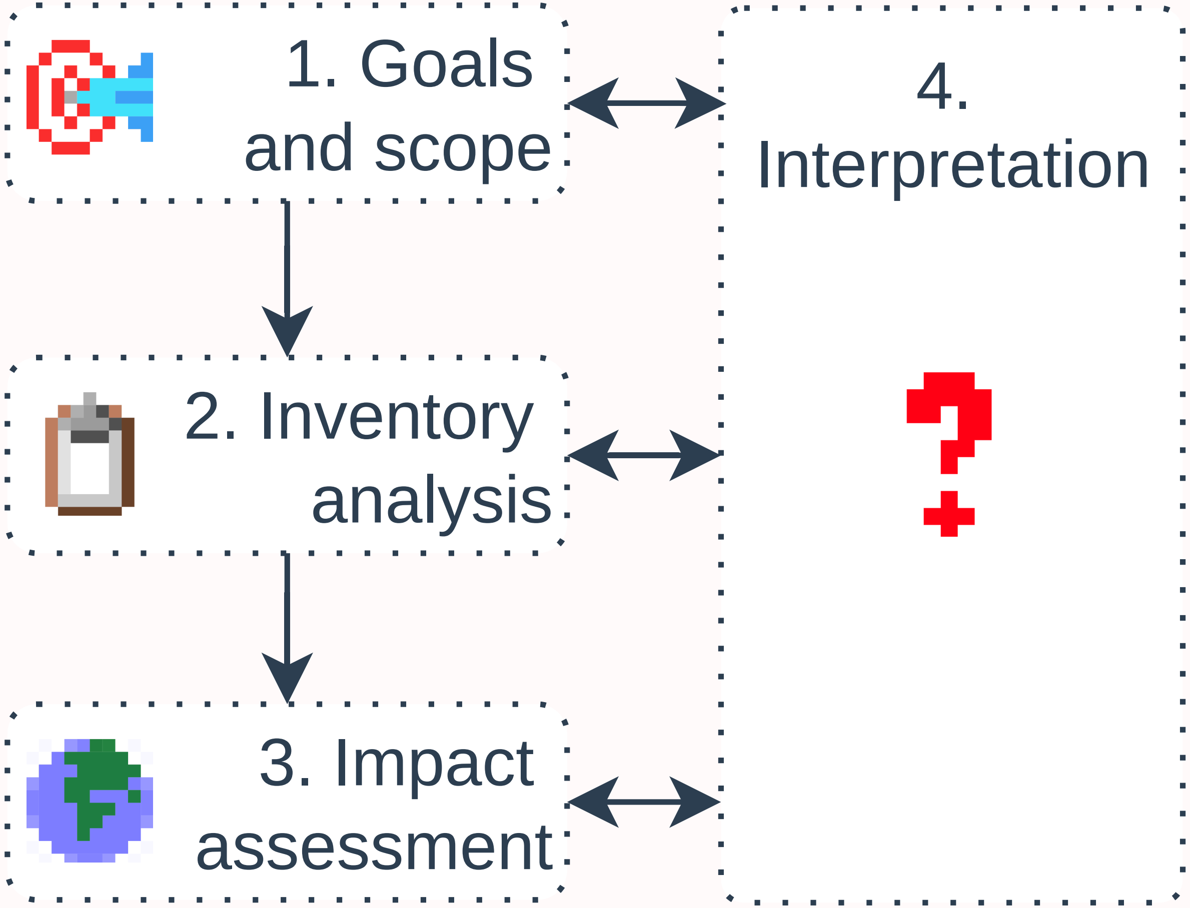
aka: an accounting process to assess a solution w.r.t. each sustainability pillar.

LCA framework

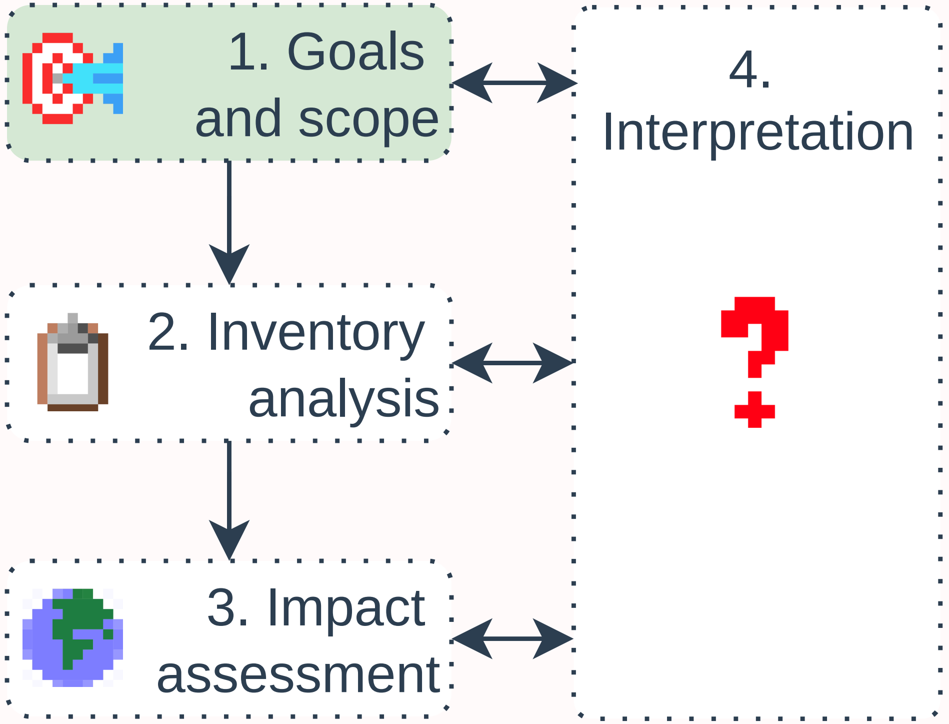


ISO 14040/14044. “Environmental management — Life cycle assessment.” ISO (2006).

LCA 101


1. Goals and scope
2. Inventory analysis
3. Impact assessment
4. Interpretation

Goals and scope



- Identify the purpose of the assessment;
- Define the system boundaries;
- Define the function & functional unit;
- Identify the stakeholders;
- Identify the inventory categories.

Goals

- **Product development & improvement**: which phase is most damaging
- **Supply-chain management**: suppliers/subcontractors provide E-LCAs
- **Sales & marketing**: consumers/governments want environmental (re)assurance
- **Research & development**
- **Public policy making**
- …

- The level of detail required depends (i.e., quick study vs full ISO 14040 analysis).
- Generally:
  - "Which phase/product part is/would be the most damaging?"
  - "Is this solution better than this other?"

Attributional or consequential?

Attributional

- "What share of impacts belongs to this product?"
- An *accounting* question
- Uses average data
- Finding hotspots

Consequential

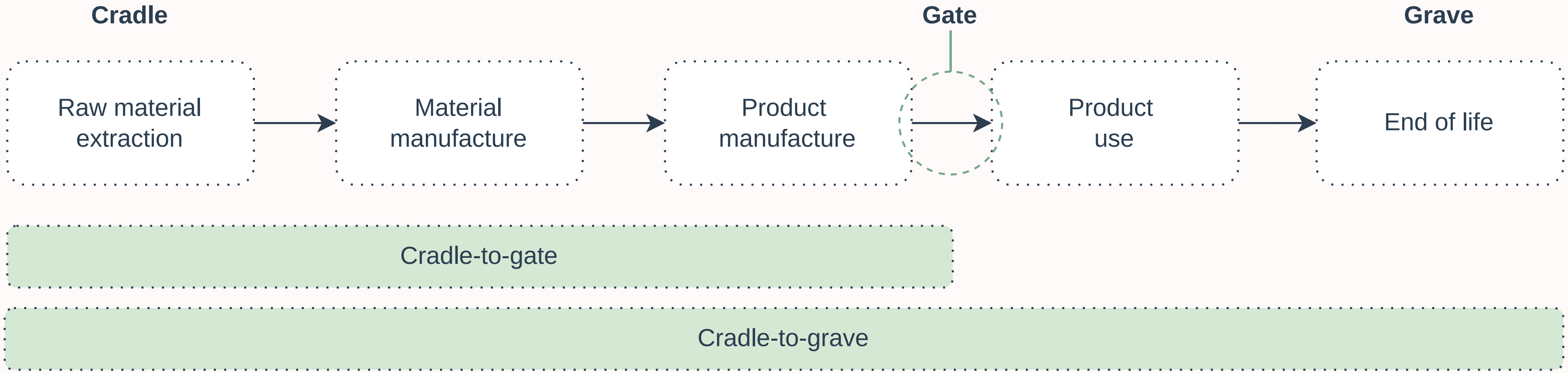
- "What changes if we make one more, or one less?"
- A *decision* question
- Uses marginal data
- Policy, investment

This impacts later choices: how shared processes are handled, which data is kept or excluded, what are the boundaries…[1]

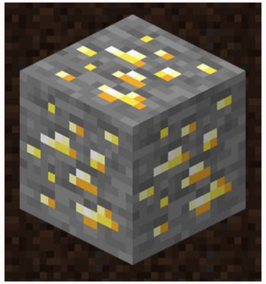
[1] Hauschild, et al. "Life Cycle Assessment: Theory and Practice." Springer (2018).

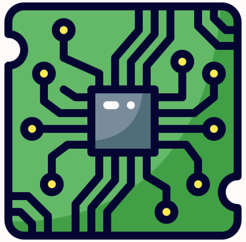
Scope

- Where the LCA starts and ends
- Sometimes, the complete life cycle is not needed



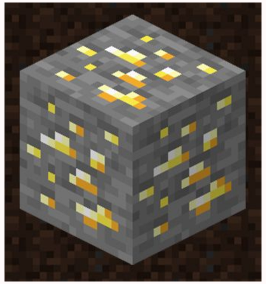
Scope example

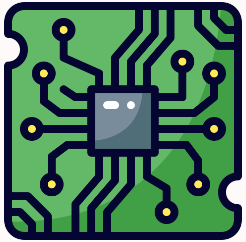




Ore to Chip → Chip to Server → Server to Data centre → Data center to E-waste

Scope example





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Chip to Data centre

System boundaries

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- Some parts of the system are not specific to our product.

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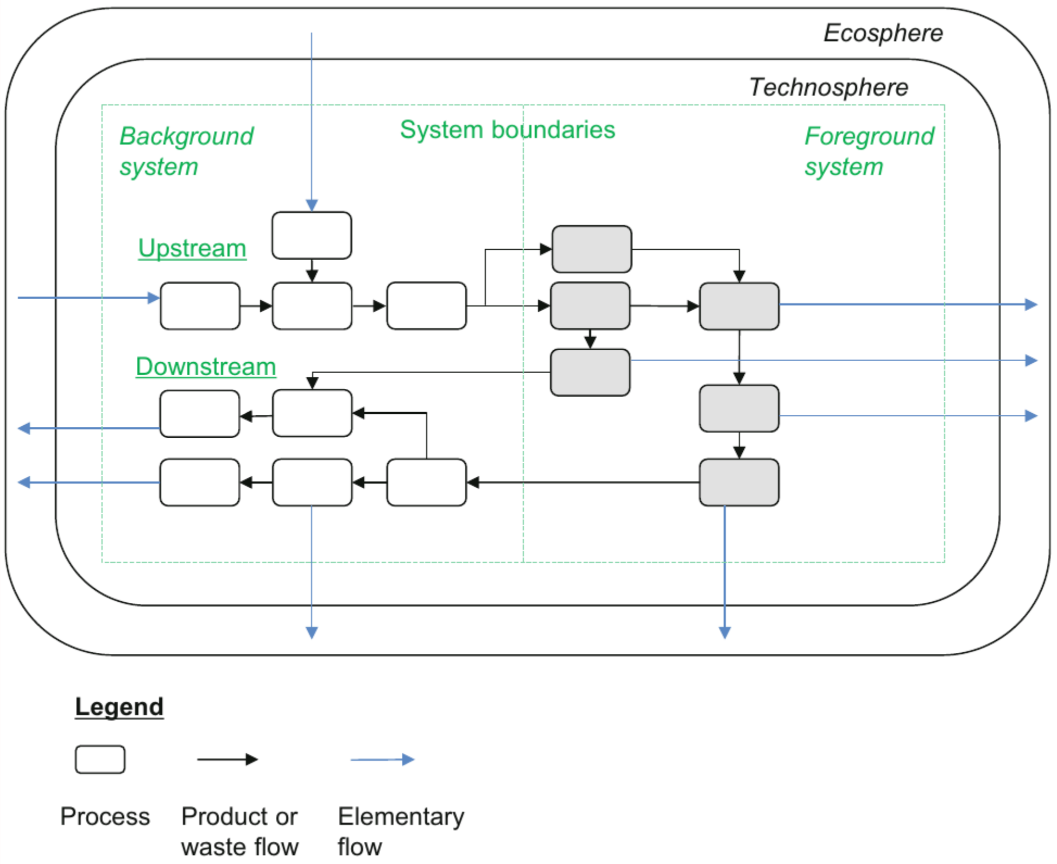
- We do not control *every* part of the production.
- Some parts of the system are not specific to our product.
- **Foreground** system:
  - Processes specific to the target product, usually under our influence;
  - Modeled with primary/measured data.
- **Background** system:
  - Processes not specific to our product (e.g., the electricity grid, copper mining, waste treatment…).
  - Still fully counted in the results. Modeled with generic average data from a database (see later).

System boundaries



System boundaries and goal

We want to provide the public with daily access to information about evolving events. If we study a news website (to compare with TV, radio, print…):

- Articles are hosted on data centre servers (materials, energy, cooling, emissions);
- Content is delivered over the network to each reader (energy, emissions);
- Readers access it on their own device (embodied impact, electricity).

But wait:

- The data centre and network also serve thousands of unrelated services;
- Readers' devices were bought for many other uses too.

System boundaries and goal

→ The further back we go, the less precise the data are.

→ The goal must be clear (Who’s the LCA for? Why do they want it?)

Functional unit

Let’s do an LCA to compare 2 laptops.

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> These two laptops aren’t used the same way (2h/day of email vs. 8h/day of video editing).

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> Oh wait, couldn’t a tablet do some of that too?

Functional unit: “What does this product *do*?”

Answer with: **action verb** + **performance level** + **condition and duration of use**

Everything put in the functional unit is a constant for a given LCA, anything else can change/vary.

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Functional unit example:
provide computing for 1 user, 4 hours a day, in an office setting, over 4 years.

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Even shorter: per user-hour of office computing

Functional unit examples

Function	Functional unit
Personal transport	per passenger km
Communicating news on daily basis	
Paint	
Refrigerator	
Video streaming	
Cloud storage	

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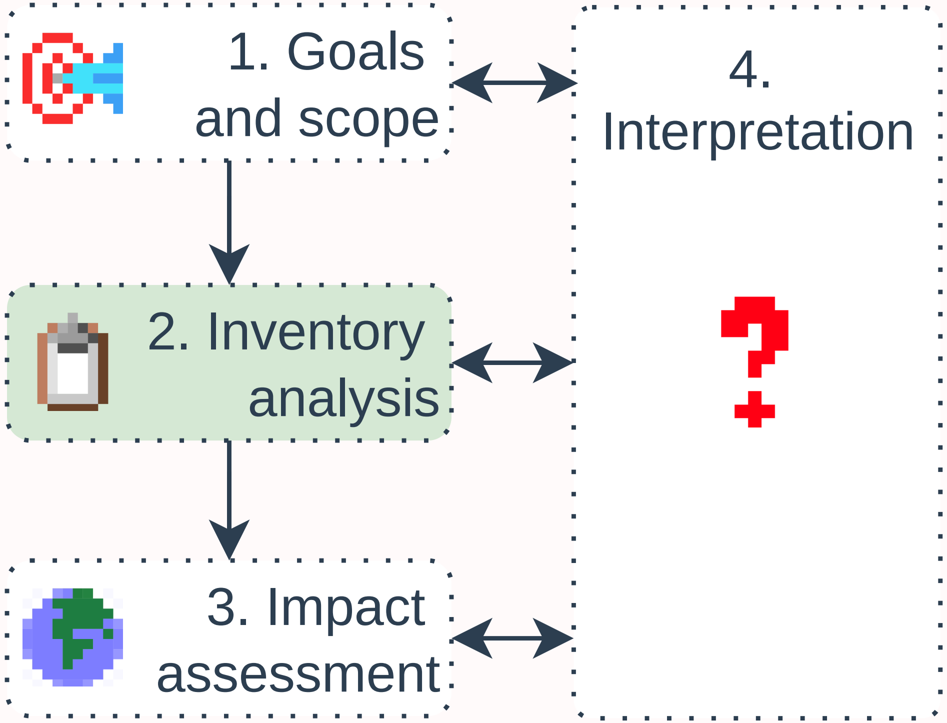
Video streaming	per hour of video watched, at a given resolution
Cloud storage	per GB stored per year

Your turn 🤸

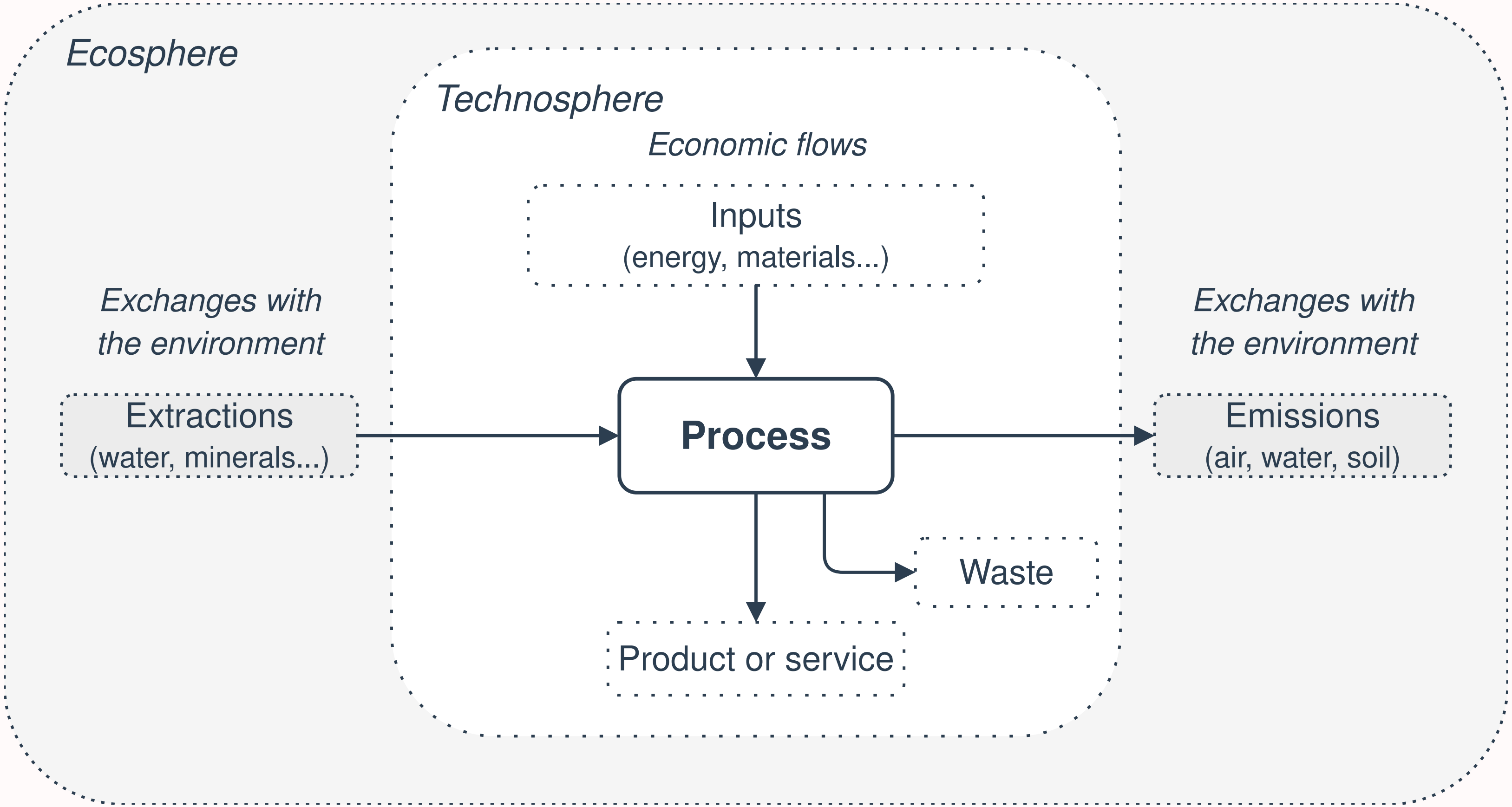
Write down a goal, scope, and functional unit related to choosing between keeping your current laptop or replacing it with a new one.

Inventory analysis

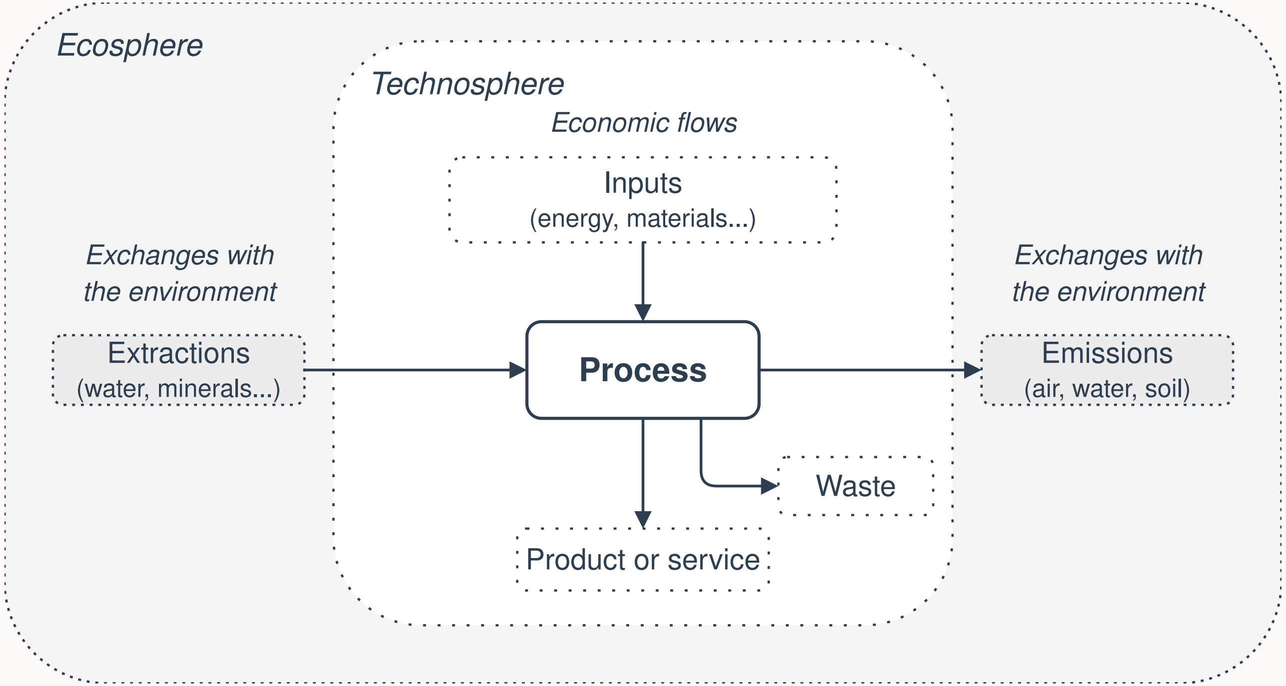


List processes with their inputs and outputs flows.

Inventory analysis

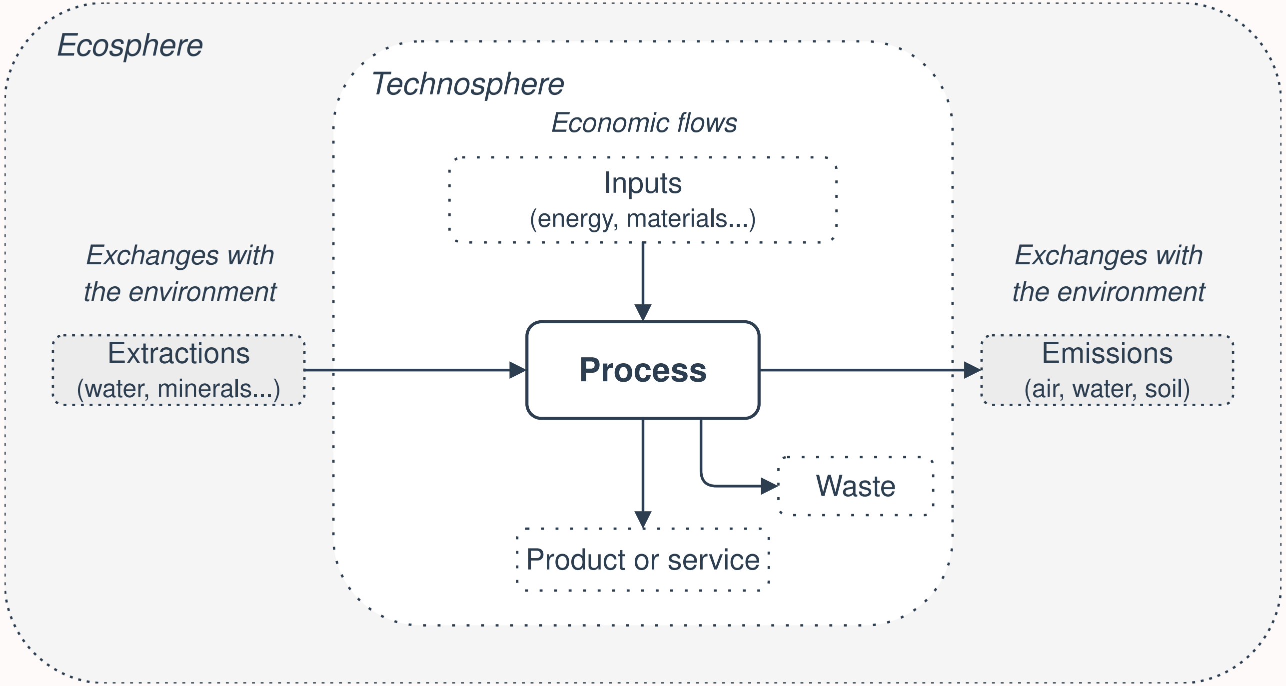


Inventory analysis



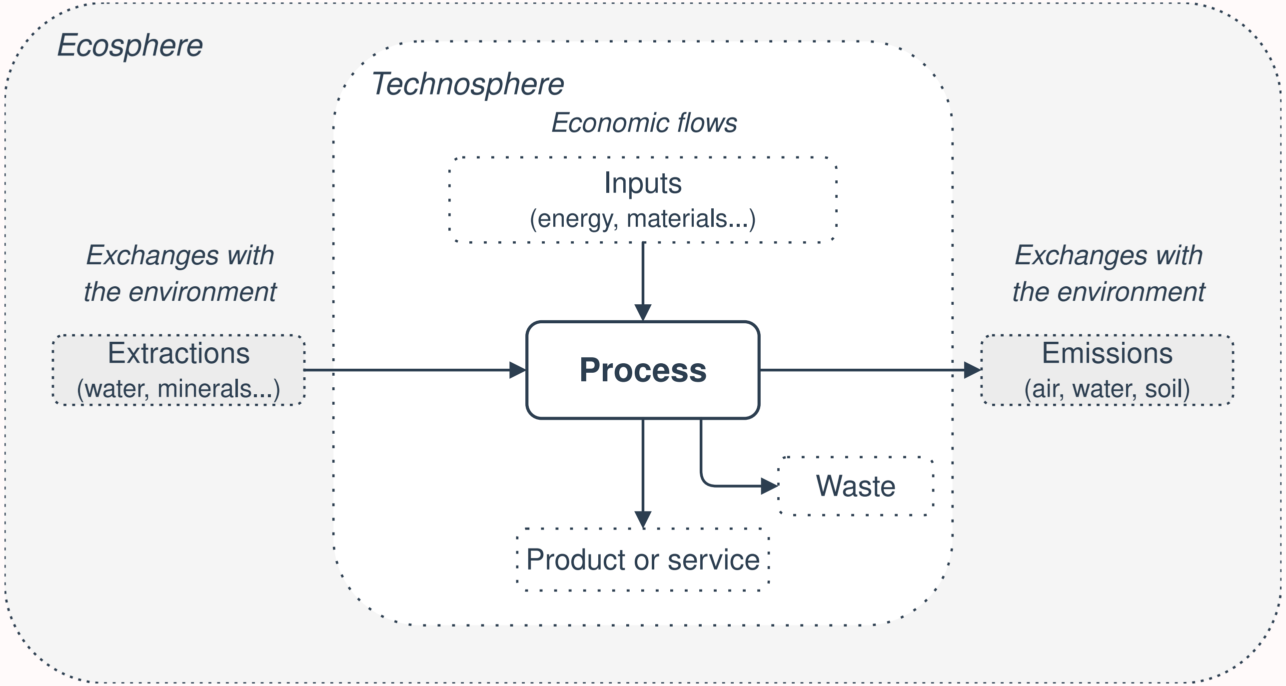
Flow: Anything crossing the boundary of a unit process (materials, energy, ...).

Inventory analysis



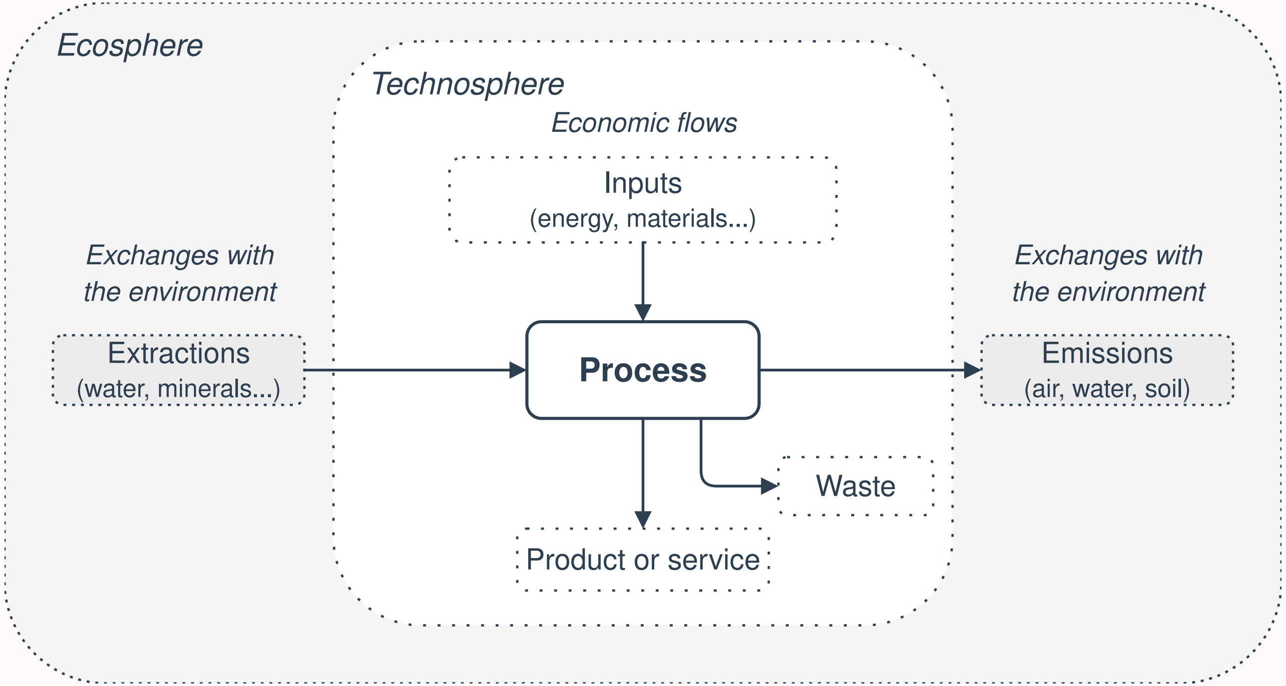
- **Intermediate flows**: exchanged with *another process* of the technosphere.

Inventory analysis



Elementary flows: exchanged directly with *the environment*

Inventory analysis



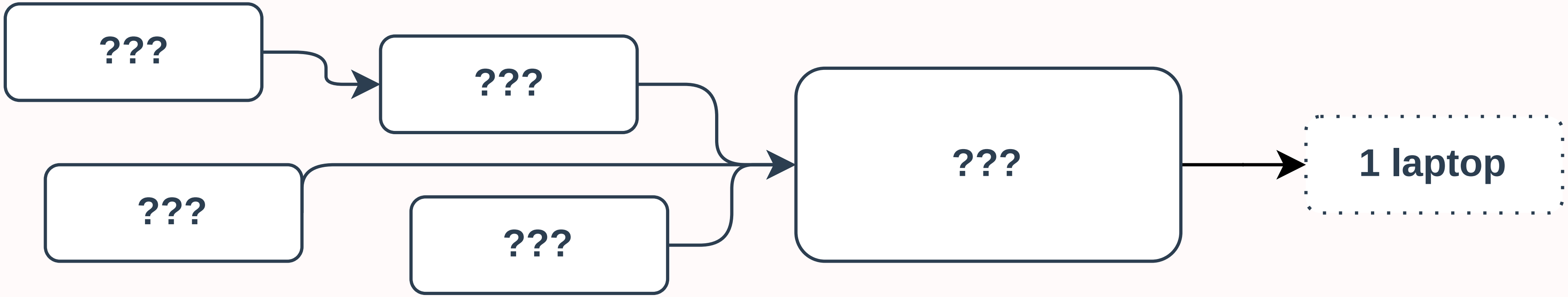
Reference flow: the intermediate flow that delivers the functional unit.

Inventory analysis example

What if we want to analyse the process of building a laptop?

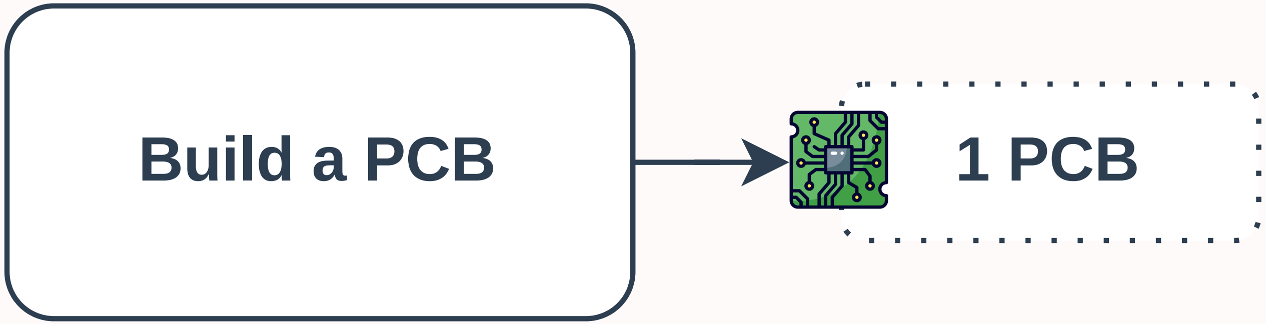
Inventory analysis example

Might be a tad bit complex:



Inventory analysis example

Let's simplify:[2]



[2] PCB example & following slides source: Beuve. "Allocation in Life Cycle Assessment." ESOS seminar (2026).

Inventory analysis example

Let's simplify:[3]

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Inventory analysis example

Recursively iterate for each input:

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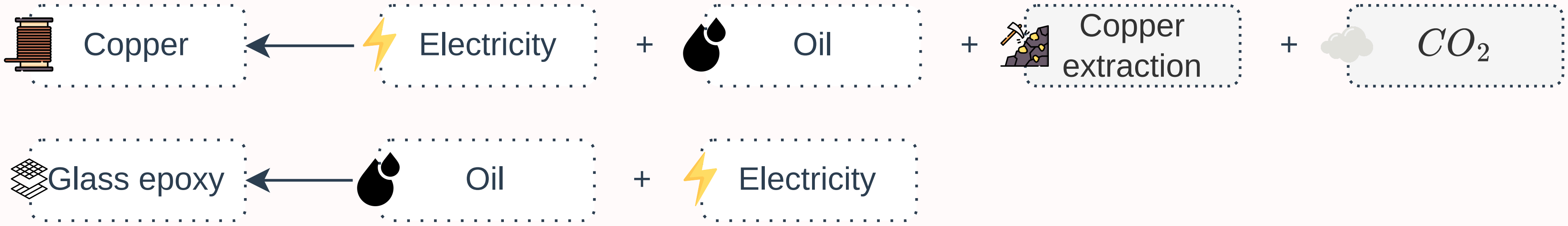

Inventory analysis example

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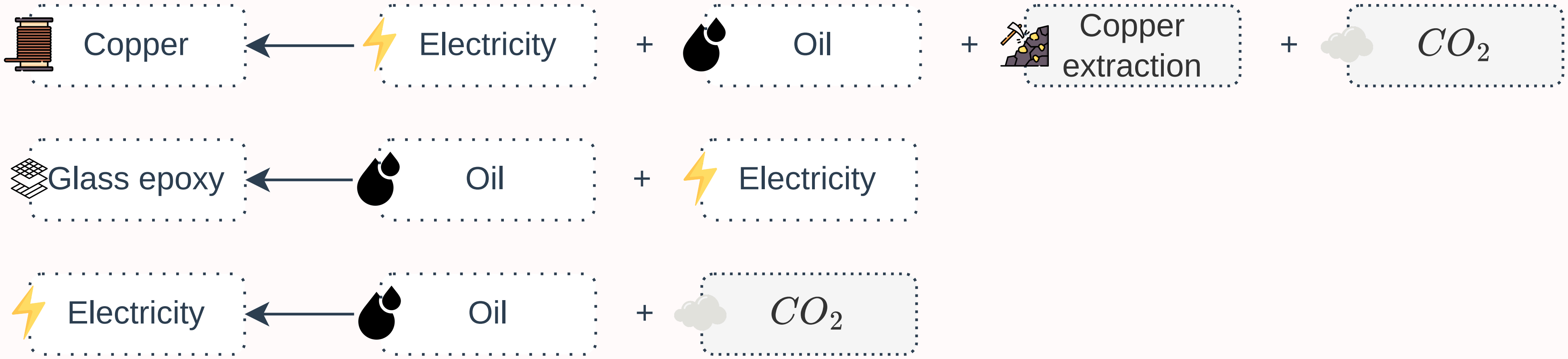

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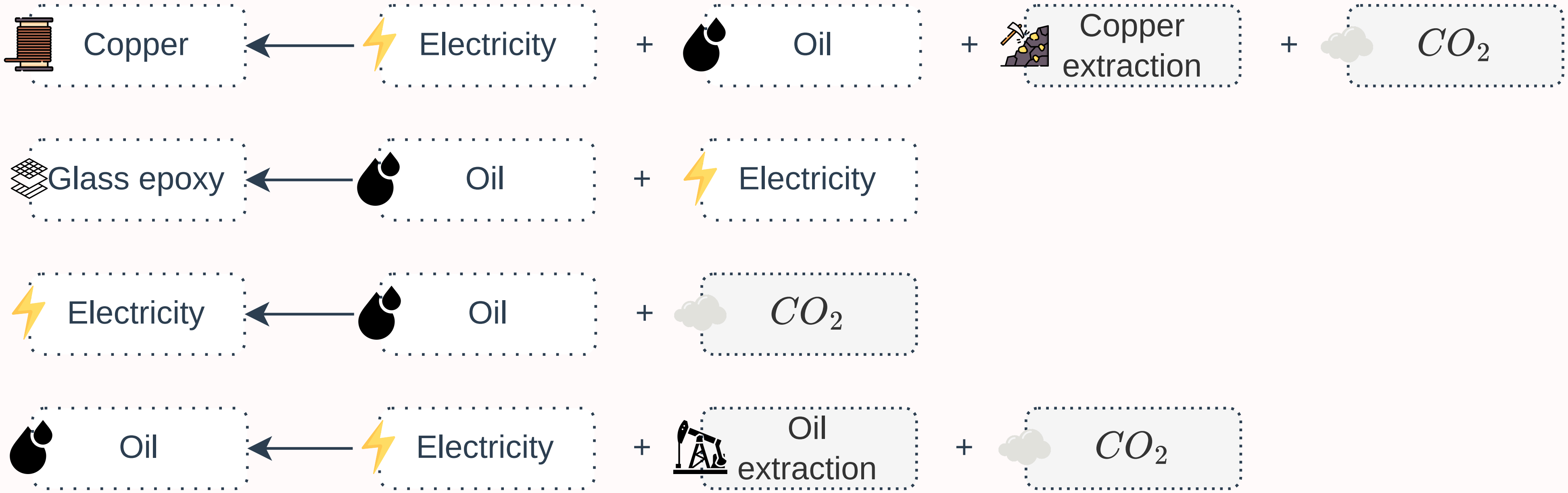
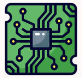
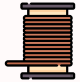
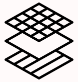
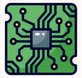
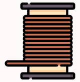
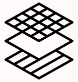


Inventory analysis example

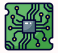
We can never follow every branch to its end:

- The tree is cut at some depth;
- A process-based LCA always misses some upstream flows;
- *Systematically underestimates* impacts.

Inventory: technology matrix

					
	1	0	0	0	0
	-0.02	1	0	0	0
	-0.2	0	1	0	0
	-0.1	-1	-1	1	-0.1
	0	-10	-2	-1	1

UNITS

 → cm²

 → kg

 → L

 → kWh

 → L

Inventory: technology matrix

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

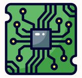
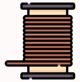
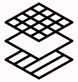
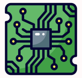
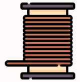
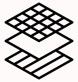
	x50				
	1	0	0	0	0
	-0.02	1	0	0	0
	-0.2	0	1	0	0
	-0.1	-1	-1	1	-0.1
	0	-10	-2	-1	1

UNITS

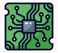
→ cm^2
→ kg
→ L
→ kWh
→ L

Inventory: technology matrix

$$\begin{bmatrix} 50 \\ -1 \\ -10 \\ -5 \\ 0 \end{bmatrix}$$

	x50 				
	1	0	0	0	0
	-0.02	1	0	0	0
	-0.2	0	1	0	0
	-0.1	-1	-1	1	-0.1
	0	-10	-2	-1	1

UNITS

 → cm²

 → kg

 → L

 → kWh

 → L

Inventory: technology matrix

$$
\begin{bmatrix} 50 \\ -1 \\ -10 \\ -5 \\ 0 \end{bmatrix}
\qquad
\begin{array}{ccccc}
\text{x50} & \text{x1} & & & \\
\left[\begin{array}{ccccc}
1 & 0 & 0 & 0 & 0 \\
-0.02 & 1 & 0 & 0 & 0 \\
-0.2 & 0 & 1 & 0 & 0 \\
-0.1 & -1 & -1 & 1 & -0.1 \\
0 & -10 & -2 & -1 & 1
\end{array}\right] & & & &
\end{array}
$$

UNITS

→ cm²
→ kg
→ L
→ kWh
→ L

Inventory: technology matrix

$$\begin{bmatrix}50\\0\\-10\\-6\\-10\end{bmatrix}$$

	x50	x1			
	1	0	0	0	0
	-0.02	1	0	0	0
	-0.2	0	1	0	0
	-0.1	-1	-1	1	-0.1
	0	-10	-2	-1	1

UNITS

→ cm^2
→ kg
→ L
→ kWh
→ L

Inventory: technology matrix

		x50	x1	x10		
50		1	0	0	0	0
0		-0.02	1	0	0	0
−10		-0.2	0	1	0	0
-6		-0.1	-1	-1	1	-0.1
−10		0	-10	-2	-1	1

UNITS

→ cm^2
→ kg
→ L
→ kWh
→ L

Inventory: technology matrix

		x50	x1	x10		
50		1	0	0	0	0
0		-0.02	1	0	0	0
0		-0.2	0	1	0	0
−16		-0.1	-1	-1	1	-0.1
−30		0	-10	-2	-1	1

UNITS

→ cm^2
→ kg
→ L
→ kWh
→ L

Inventory: technology matrix

$$\begin{bmatrix} 50 \\ 0 \\ 0 \\ -16 \\ -30 \end{bmatrix}$$

	x50	x1	x10	x16	
	1	0	0	0	0
	-0.02	1	0	0	0
	-0.2	0	1	0	0
	-0.1	-1	-1	1	-0.1
	0	-10	-2	-1	1

UNITS

→ cm^2
→ kg
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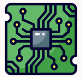
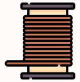
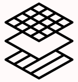
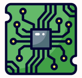
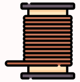
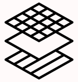
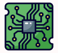
Inventory: technology matrix

$$\begin{bmatrix} 50 \\ 0 \\ 0 \\ 0 \\ -46 \end{bmatrix}$$

	x50	x1	x10	x16	
					
	1	0	0	0	0
	-0.02	1	0	0	0
	-0.2	0	1	0	0
	-0.1	-1	-1	1	-0.1
	0	-10	-2	-1	1

UNITS

 → cm²

 → kg

 → L

 → kWh

 → L

Inventory: technology matrix

$$\begin{bmatrix} 50 \\ 0 \\ 0 \\ 0 \\ -46 \end{bmatrix}$$

x50	x1	x10	x16	x46
1	0	0	0	0
-0.02	1	0	0	0
-0.2	0	1	0	0
-0.1	-1	-1	1	-0.1
0	-10	-2	-1	1

UNITS

→ cm²
→ kg
→ L
→ kWh
→ L

Inventory: technology matrix

$$\begin{bmatrix} 50 \\ 0 \\ 0 \\ -4.6 \\ 0 \end{bmatrix}$$

	x50	x1	x10	x16	x46
	1	0	0	0	0
	-0.02	1	0	0	0
	-0.2	0	1	0	0
	-0.1	-1	-1	1	-0.1
	0	-10	-2	-1	1

UNITS

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	0	-10	-2	-1	1

UNITS

- → cm²
- → kg
- → L
- → kWh
- → L

Inventory: technology matrix

$$\begin{bmatrix} 50 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

	x50	x1	x10	x21.1	x51.1
	1	0	0	0	0
	-0.02	1	0	0	0
	-0.2	0	1	0	0
	-0.1	-1	-1	1	-0.1
	0	-10	-2	-1	1

UNITS

→ cm²
→ kg
→ L
→ kWh
→ L

Inventory: technology matrix

$$
\begin{bmatrix} 50 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}
\qquad
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
-0.02 & 1 & 0 & 0 & 0 \\
-0.2 & 0 & 1 & 0 & 0 \\
-0.1 & -1 & -1 & 1 & -0.1 \\
0 & -10 & -2 & -1 & 1
\end{bmatrix}
\qquad
\begin{bmatrix} 50 \\ 1 \\ 10 \\ 21.1 \\ 51.1 \end{bmatrix}
$$

Inventory: technology matrix

$$
\boldsymbol{f} = \begin{bmatrix} 50 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}
\qquad
\boldsymbol{A} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ -0.02 & 1 & 0 & 0 & 0 \\ -0.2 & 0 & 1 & 0 & 0 \\ -0.1 & -1 & -1 & 1 & -0.1 \\ 0 & -10 & -2 & -1 & 1 \end{bmatrix}
\qquad
\boldsymbol{s} = \begin{bmatrix} 50 \\ 1 \\ 10 \\ 21.1 \\ 51.1 \end{bmatrix}
$$

Inventory: technology matrix

$$\boldsymbol{f} = \boldsymbol{A}\boldsymbol{s}$$

Inventory: intervention matrix

	x50	x1	x10	x21.1	x51.1
	0	10	0	0.5	0
	0	1.5	0	0	0
	0	0	0	0	1.2

$$\begin{bmatrix} 20.6 \\ 1.5 \\ 61.3 \end{bmatrix}$$

UNITS

→ kg

→ kg

→ L

Inventory: intervention matrix

$$
\begin{bmatrix} 20.6 \\ 1.5 \\ 61.3 \end{bmatrix}
\quad
\begin{bmatrix} 0 & 10 & 0 & 0.5 & 0 \\ 0 & 1.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.2 \end{bmatrix}
\quad
\begin{bmatrix} 50 \\ 1 \\ 10 \\ 21.1 \\ 51.1 \end{bmatrix}
$$

Inventory: intervention matrix

$$\boldsymbol{g} = \begin{bmatrix} 20.6 \\ 1.5 \\ 61.3 \end{bmatrix} \qquad \boldsymbol{B} = \begin{bmatrix} 0 & 10 & 0 & 0.5 & 0 \\ 0 & 1.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.2 \end{bmatrix} \qquad \boldsymbol{s} = \begin{bmatrix} 50 \\ 1 \\ 10 \\ 21.1 \\ 51.1 \end{bmatrix}$$

Inventory: intervention matrix

$$\boldsymbol{g} = \boldsymbol{B}\boldsymbol{s}$$

Inventory phase

$$\begin{cases} \boldsymbol{f} = \boldsymbol{A}\boldsymbol{s} \\ \boldsymbol{g} = \boldsymbol{B}\boldsymbol{s} \end{cases}$$

Inventory phase

$$\begin{cases} \boldsymbol{s} = \boldsymbol{A}^{-1}\boldsymbol{f} \\ \boldsymbol{g} = \boldsymbol{B}\boldsymbol{s} \end{cases}$$

Inventory phase

$$\begin{cases} \boldsymbol{s} = \boldsymbol{A}^{-1}\boldsymbol{f} \\ \boldsymbol{g} = \boldsymbol{B}\boldsymbol{A}^{-1}\boldsymbol{f} \end{cases}$$

Inventory phase

$$\begin{cases} s = A^{-1} f \\ g = B A^{-1} f \end{cases}$$

s	PCB	50	cm^2
	Copper	1	kg
	Glass Epoxy	10	L
	Electricity	21.1	kWh
	Oil	51.1	L
g	CO_2 emissions	20.6	kg
	Copper extraction	1.5	kg
	Oil extraction	61.3	L

Your turn 🤸

The same factory line makes both laptops and tablets, and its electricity meter isn’t split by product.

How would you share that electricity’s impact between a laptop and a tablet? What would you need to know to decide?

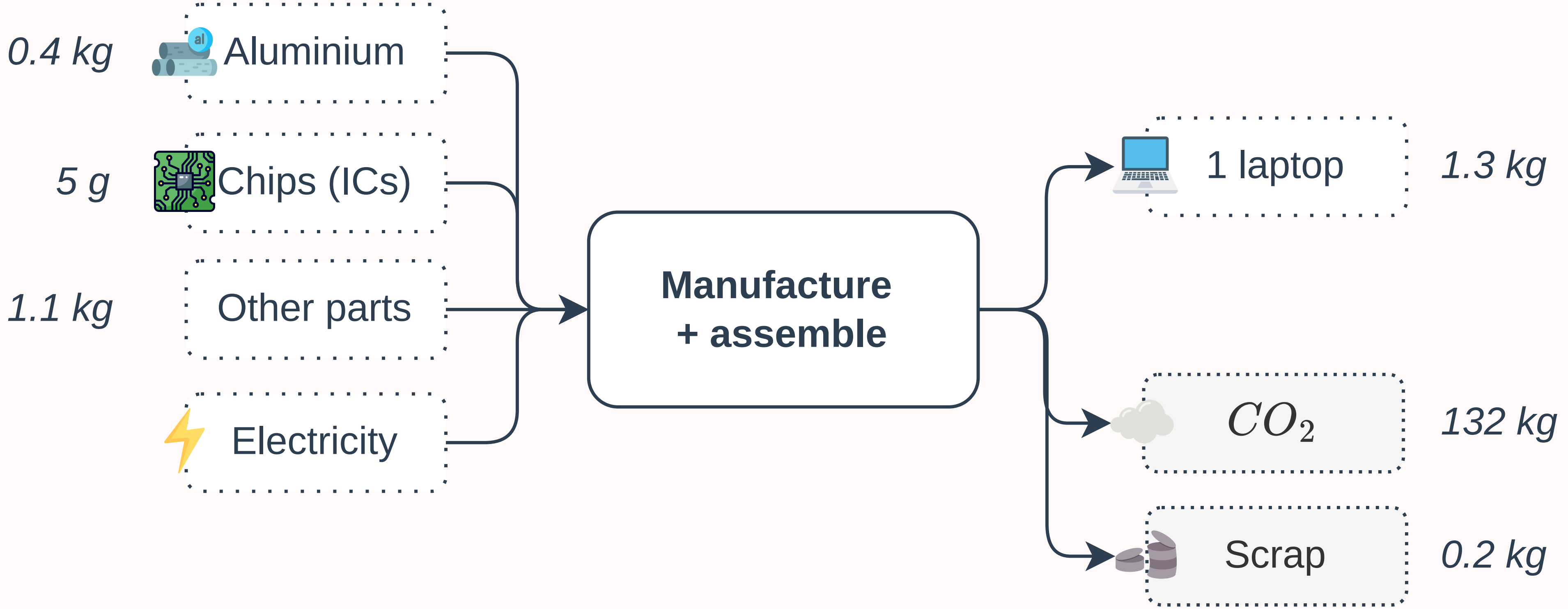
Methodological choices

Consider building the inventory as an accounting process:

- **Amortisation**: spread a one-off impact over the units it serves;
- **Allocation**: split one process between its several outputs;
- **Allocation factors**: *how* we split (mass? energy? money?);
- **Cut-off**: what we deliberately leave out;
- **Avoided burden**: credit for displacing another production;
- **Recycling & modelling choice**: which life cycle carries the burden.

Methodological choices

(All following values are illustrative.)



Amortisation

Amortisation:

- A durable good is produced once but serves many functional units;
- Its impact is spread over its whole service life.

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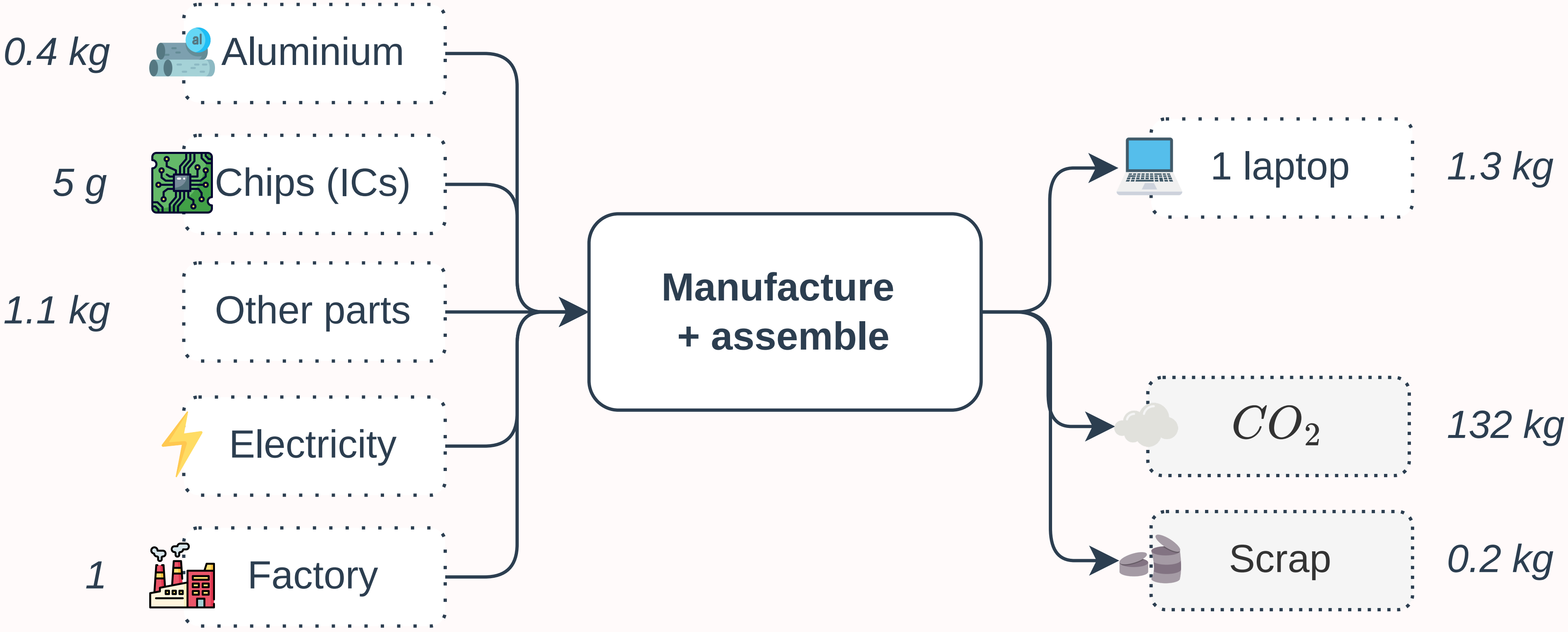
Framework Laptop 13 (2022): production ≈ 132 $kgCO_2e$ (about two thirds of its ≈ 200 $kgCO_2e$ over the 5-year functional unit) → ≈ 26 $kgCO_2e$ per year of embodied impact.[4]

[4] Baur, et al. "Life Cycle Assessment of the Framework Laptop 2022." Fraunhofer IZM (2023).

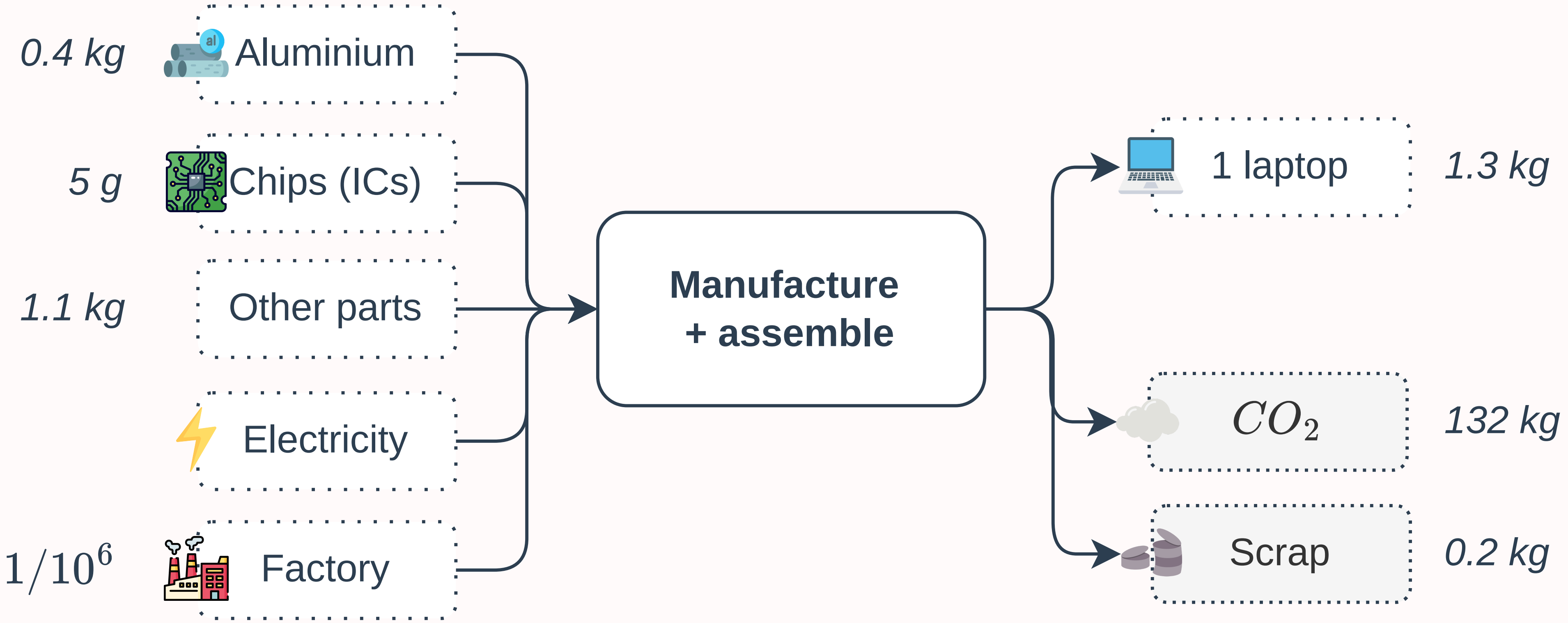
Amortisation

Wait, we need a factory.



Amortisation

Maybe not the whole factory, though:

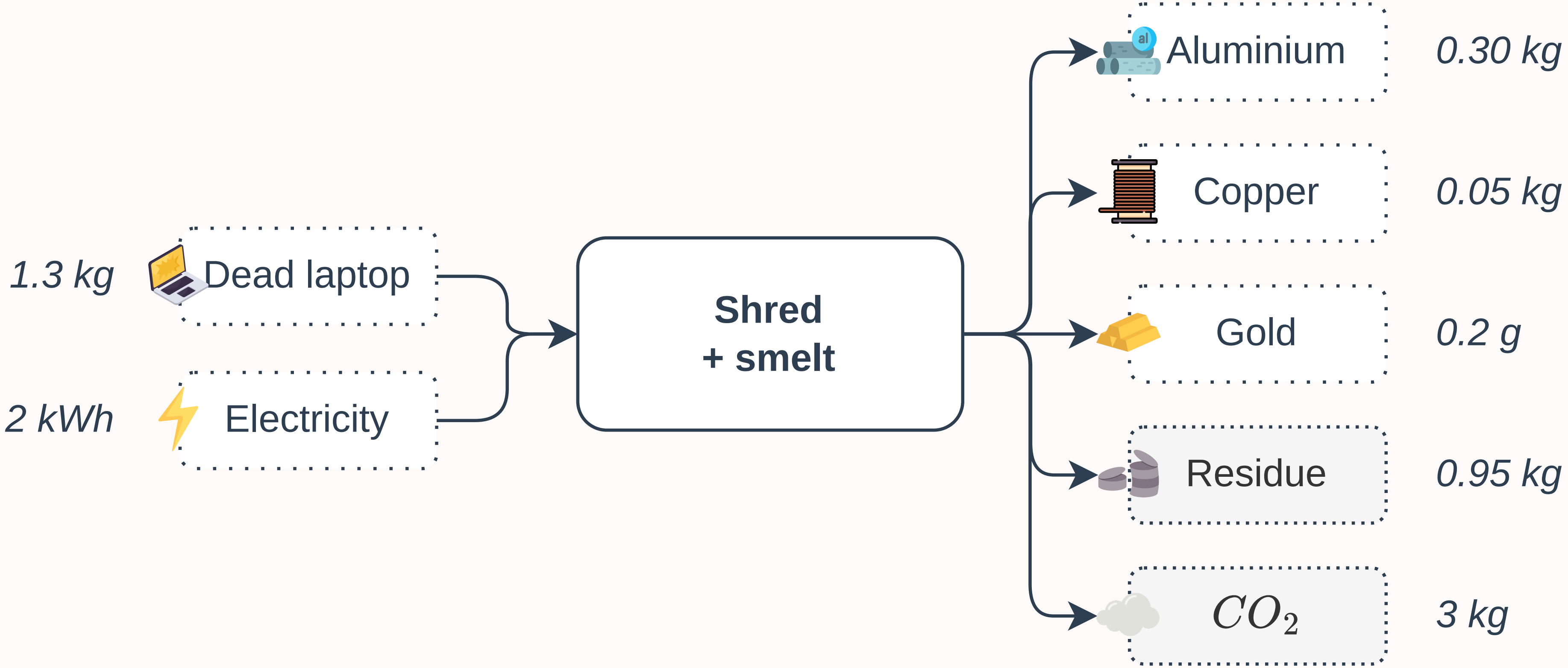


Allocation

Allocation: When one process yields several useful outputs (co-products), its inputs and emissions must be divided among them.

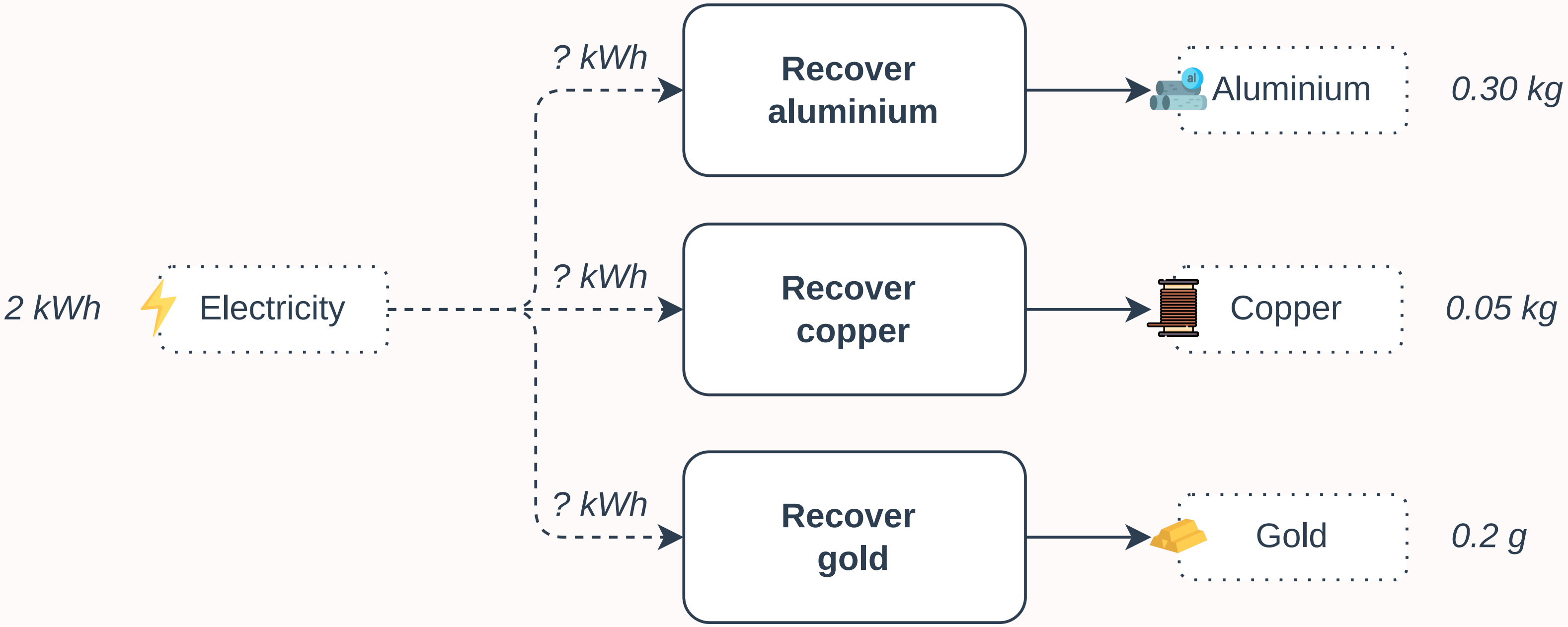
Allocation factors

For example, let's shred a laptop.



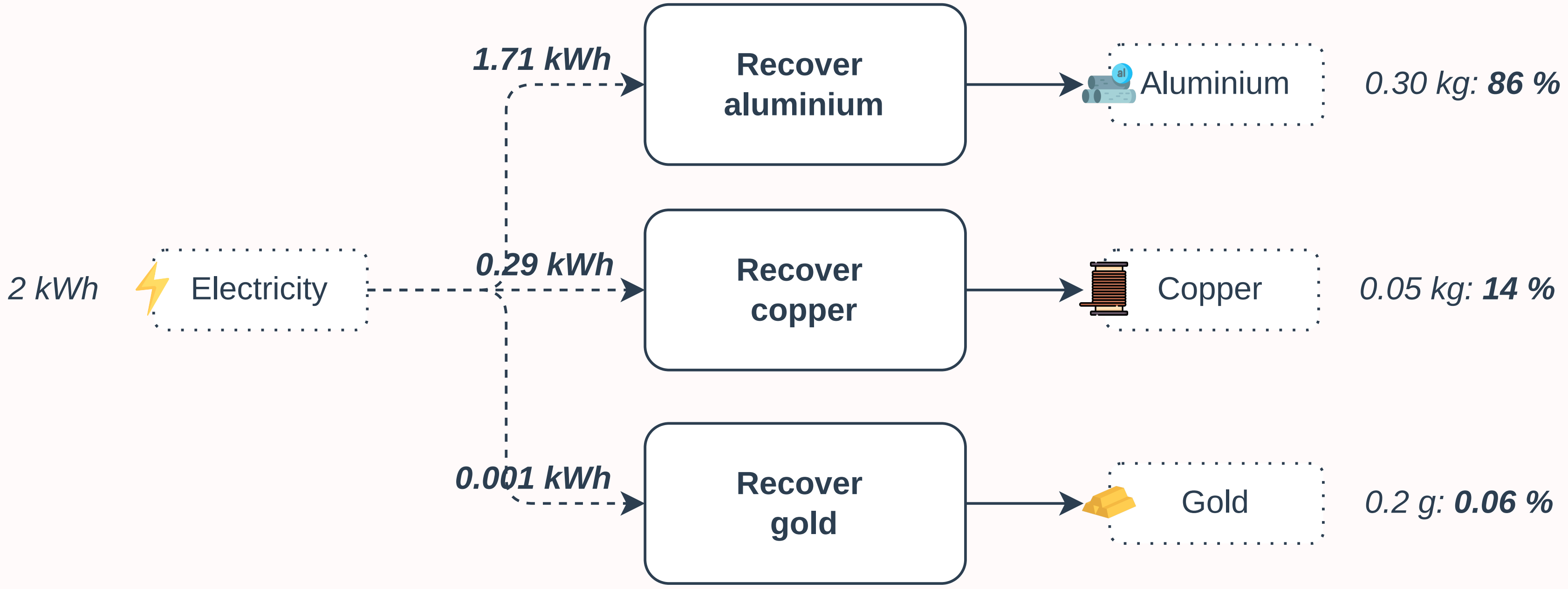
Allocation factors

How can we distribute the consumed electricity to each recovered component?



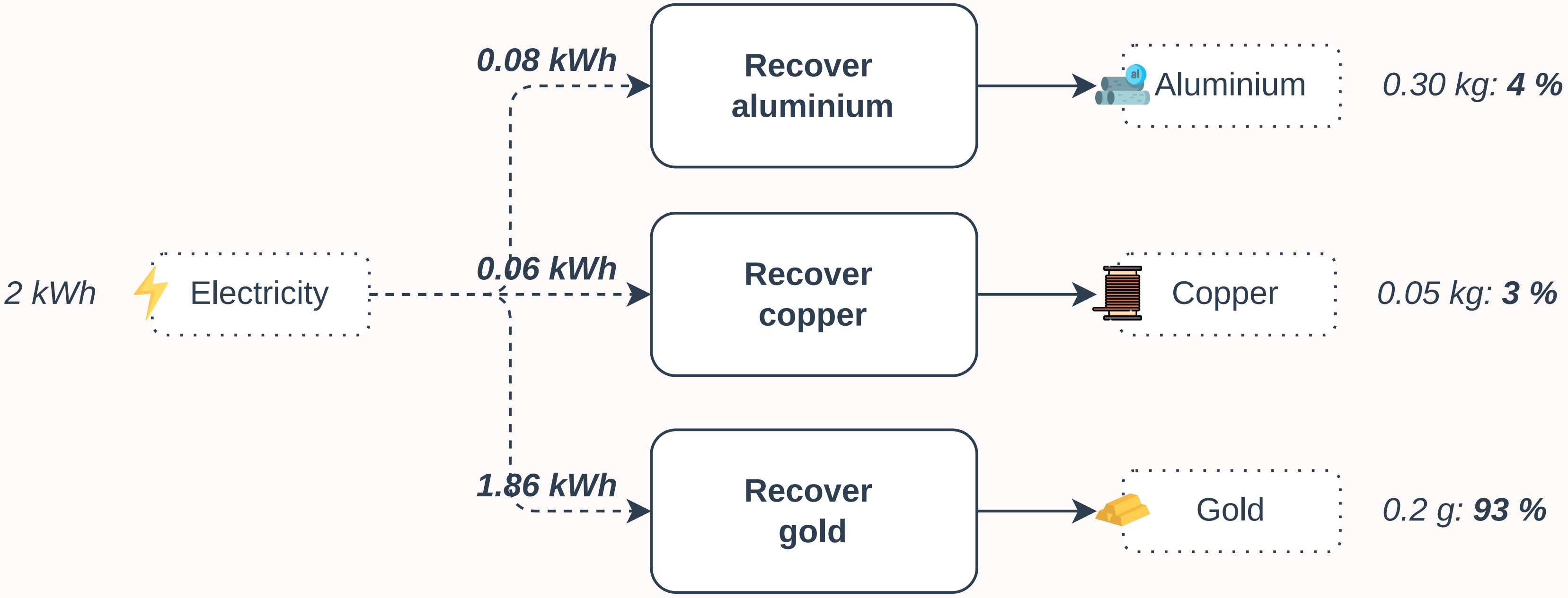
Allocation factors

We could use their respective mass:



Allocation factors

Or their economic value:



Allocation factors

Allocation factors should be chosen in that order:

1. a *physical* relationship (mass, energy, ...), if one exists and is meaningful;
2. *economic value*, only as a fallback when no meaningful physical relationship applies.

Allocation: avoid it if you can

ISO 14044 asks you to *avoid* allocation before splitting anything.[5]

[5] ISO 14044:2006, §4.3.4.2 (allocation procedure) and §4.3.4.3 (reuse and recycling).

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ISO 14044 asks you to *avoid* allocation before splitting anything.[6]

1. Subdivision:

- Split the process into finer sub-processes, each tied to a single product.
- E.g., split a shared data centre cooling system into one dedicated sub-process per tenant rack, instead of allocating a single cooling total across all of them.

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- Enlarge the system so the options compared deliver the **same** functions (or credit the surplus one: avoided burden).
- E.g., compare "your cloud service + 19 others" against "the 19 others alone".

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If both fail → **partition** the burden with an allocation factor.

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Cut-off

An LCA is a complex, time-consuming process with sometimes limited sources of data.

> **Cut-off:** Inputs and outputs below a chosen threshold are excluded and the omission is *justified*. E.g., by mass, energy or environmental significance.[9]

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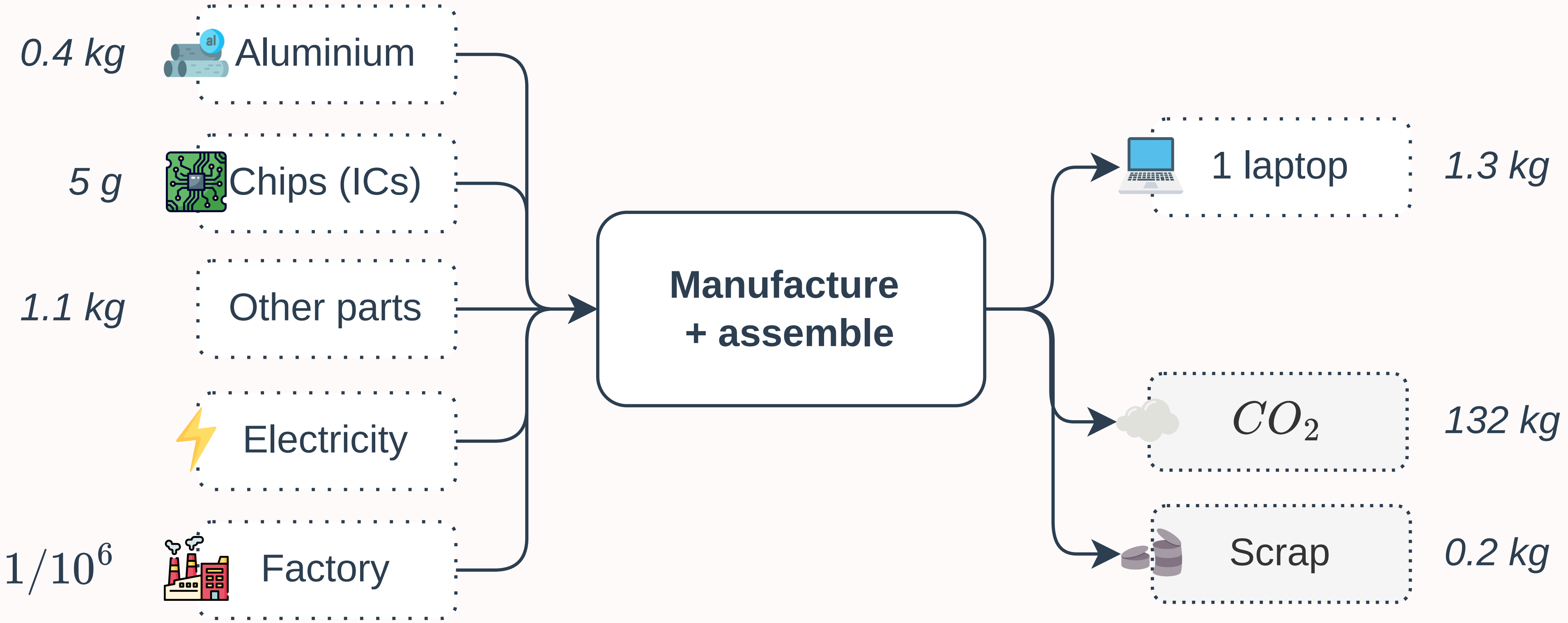
What does this mean for reported values and associated interpretations?

[10] ISO 14044:2006, §4.2.3.3.3 (cut-off criteria).

Cut-off

Remove inputs / outputs considered insignificant, and report why.



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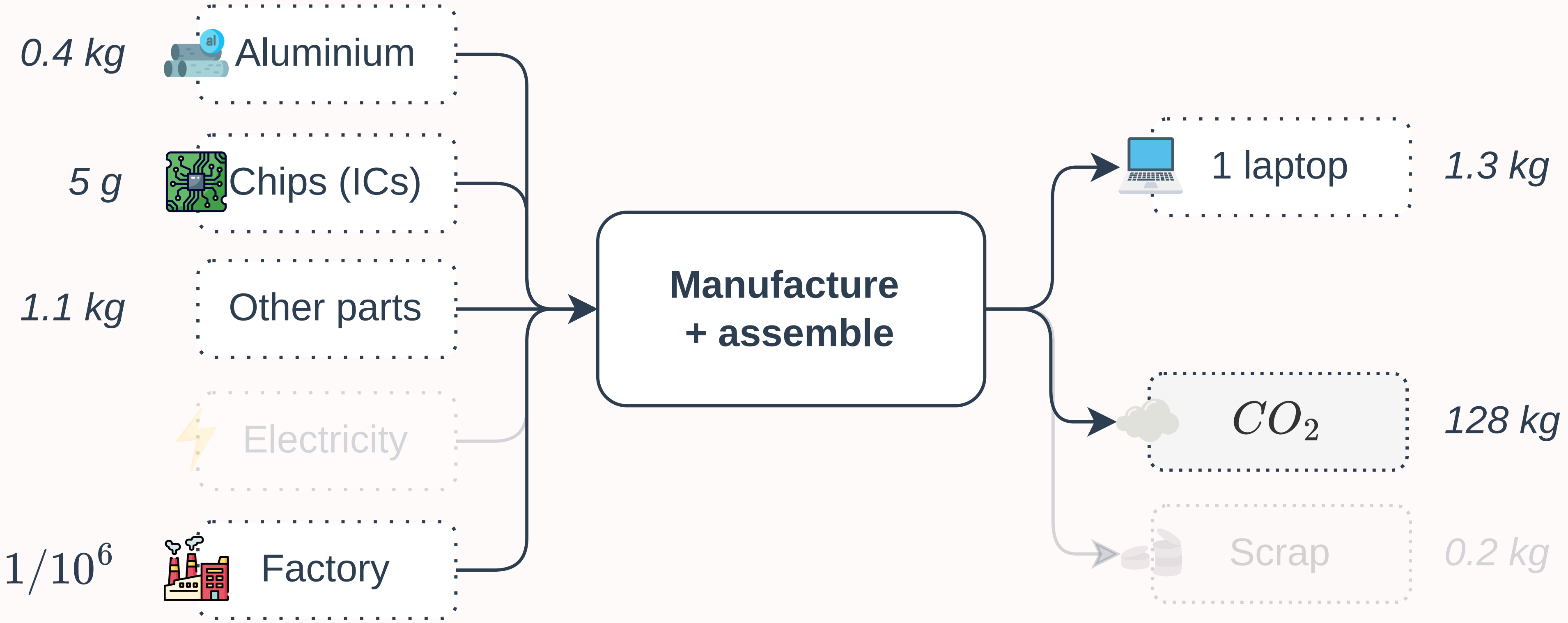
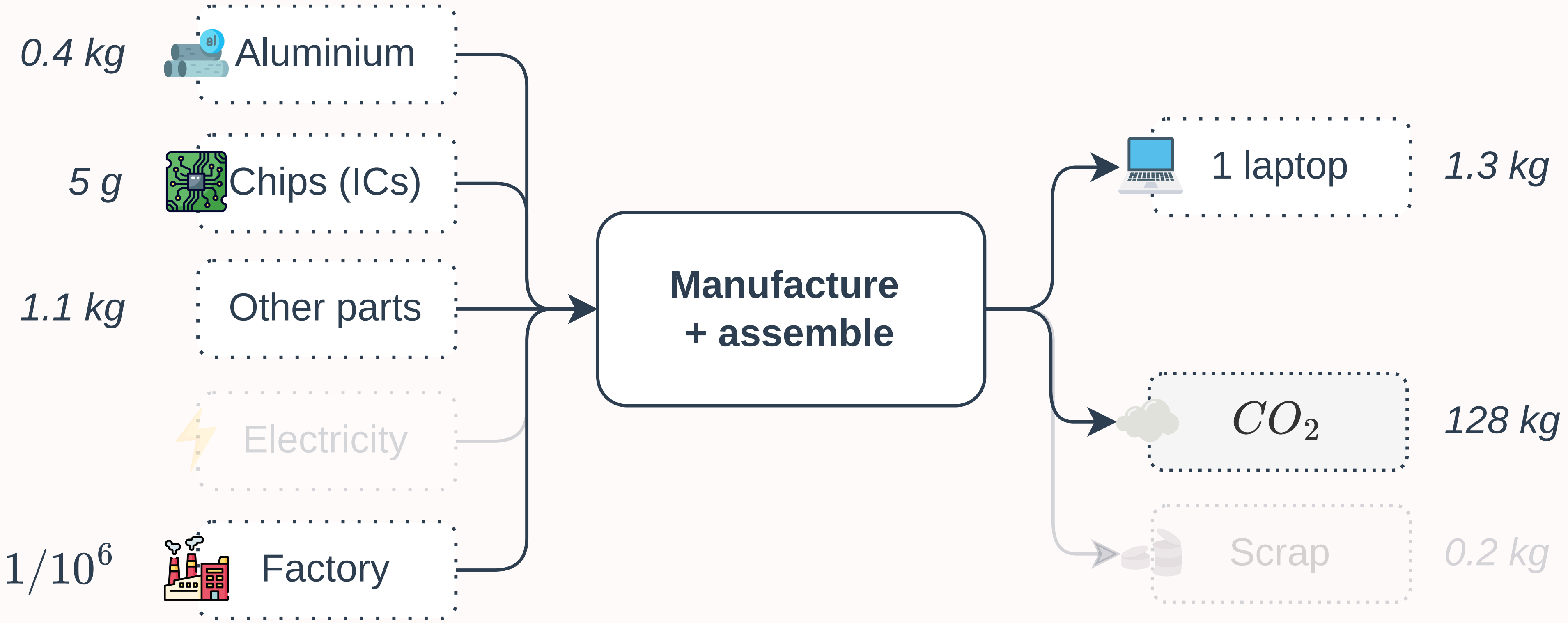


Cut-off

For electronics the cut-off should be **impact-based**, not mass-based.



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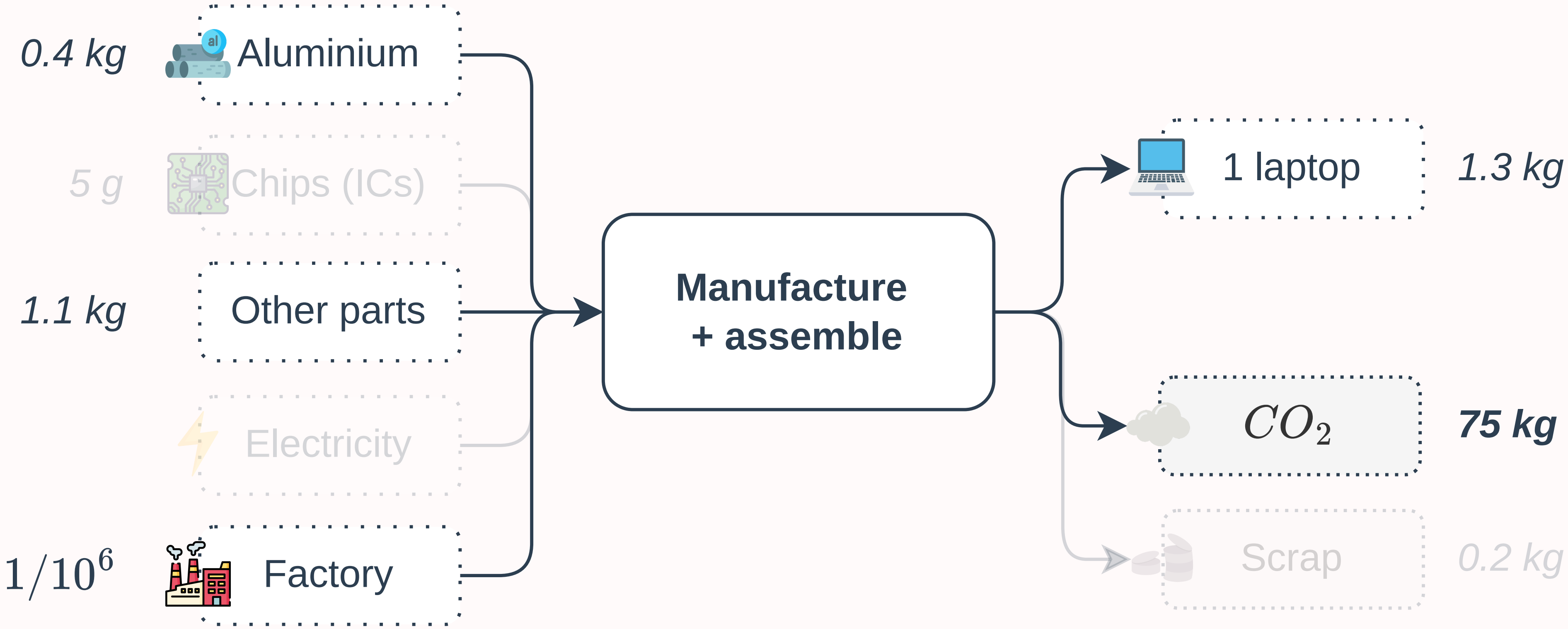


Avoided burden

Avoided burden: Yielding something that displaces another production earns a **credit** (a negative impact). Also: **system expansion** / **substitution**.

Avoided burden

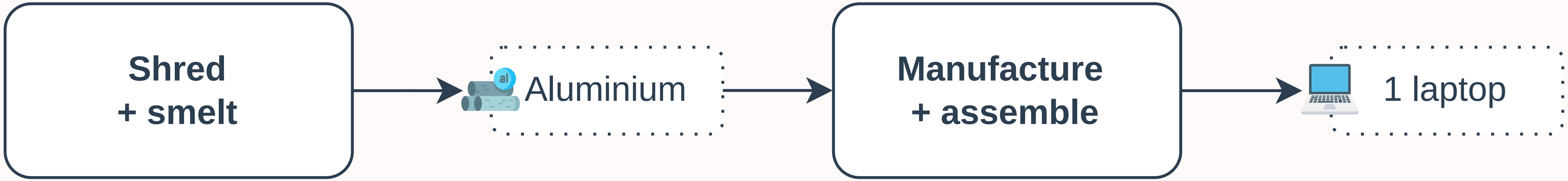
Net: +3 - 9.4 ≈ - 6.4 kg CO_2

Avoided burden

This also works for:

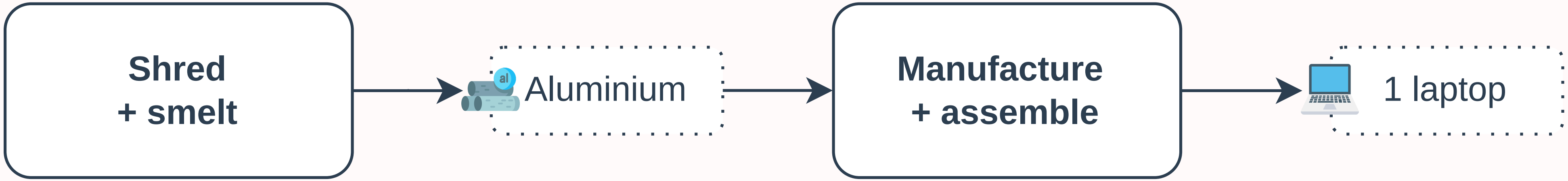
- Refurbishing a machine (avoids producing a new one);
- Redirecting waste heat towards buildings around a data centre.

Recycling: who counts what?



- Who carries the burden?
- Who gets the credit for avoided primary material?

Recycling: who counts what?



- Who carries the burden?
- Who gets the credit for avoided primary material?

Approach	Rule
Cut-off (100:0)	Each life cycle bears its own processing; recyclate enters burden-free, no credit for scrap
Substitution (0:100)	The discarding system is credited for the primary production it displaces (= avoided burden)
50:50	Burden and credit shared evenly between both life cycles
…	

Recycling: who counts what?

FYI: other methods exist, including the Circular Footprint Formula:[11]

Life Cycle Inventory (LCI) of primary material

LCI associated to secondary material input

LCI of the material recycling (or part/product reuse) process minus the credit for avoided primary material

Material

$$\boxed{= (1-R_1)E_V} + \boxed{R_1 \times \left(AE_{recycled} + (1-A)E_V \times \frac{Q_{Sin}}{Q_p}\right)} + \boxed{(1-A)R_2 \times \left(E_{recyclingEoL} - E_V^{*} \times \frac{Q_{Sout}}{Q_P}\right)}$$

Energy

$$+ \boxed{(1-B)R_3 \times (E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec})}$$

Disposal

$$+ \boxed{(1-R_2-R_3) \times E_D}$$

LCI of the disposal of remaining waste

LCI of the energy recovery process minus the credit for avoided primary energy

11 European Commission. “Environmental Footprint methods.” green-forum.ec.europa.eu (2020).

Closed loop vs open loop

Closed loop

- Material returns to the **same** product system, no loss of quality;
- Allocation can often be avoided;
-

Open loop

- Material is recycled into a **different** product and/or degrades;
- Burden must be shared between the two product systems;
-

Closed loop vs open loop

Closed loop

- Material returns to the **same** product system, no loss of quality;
- Allocation can often be avoided;
- **Aluminium frame → aluminium frame**.

Open loop

- Material is recycled into a **different** product and/or degrades;
- Burden must be shared between the two product systems;
- **Laptop's copper → plumbing**.

Most electronics: open-loop and "downcycling".

Recap: allocation decision

1. Can you **subdivide** the process into single-product steps? → do it
2. Can you **expand the system** / substitute a co-product? → do it (avoided burden)
3. Is there a **physical** relationship (mass, energy, ...)? → partition by it
4. Otherwise → partition by **economic value**

For end-of-life recycling the same logic gives the named approaches: **cut-off**, **substitution**, or a **50:50** compromise.

Uncertainty

Every number in an LCA comes with varying degrees of uncertainty, depending on:

- **Parameter**: imprecise or unrepresentative input data (e.g. a generic background dataset standing in for your actual supplier);
- **Model**: simplifications baked into the process or characterization models themselves;
- **Choices & scenarios**: functional unit, system boundaries, allocation method, cut-off criteria…

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- **Choices & scenarios**: functional unit, system boundaries, allocation method, cut-off criteria...

→ justify everything so reader can actually interpret the results.

Data quality

- *Foreground* (measured, specific) data
- *Background* (generic, database) data

Question: “how much do we trust background data?”

Pedigree matrix: Score each data point: *reliability*, *completeness*, *temporal correlation*, *geographical correlation*, *further technological correlation*. Lower score = higher quality.[12]

[12] Weidema & Wesnæs. “Data quality management for life cycle inventories.” Journal of Cleaner Production (1996). As presented in Hauschild, et al. “Life Cycle Assessment: Theory and Practice.” Springer (2018).

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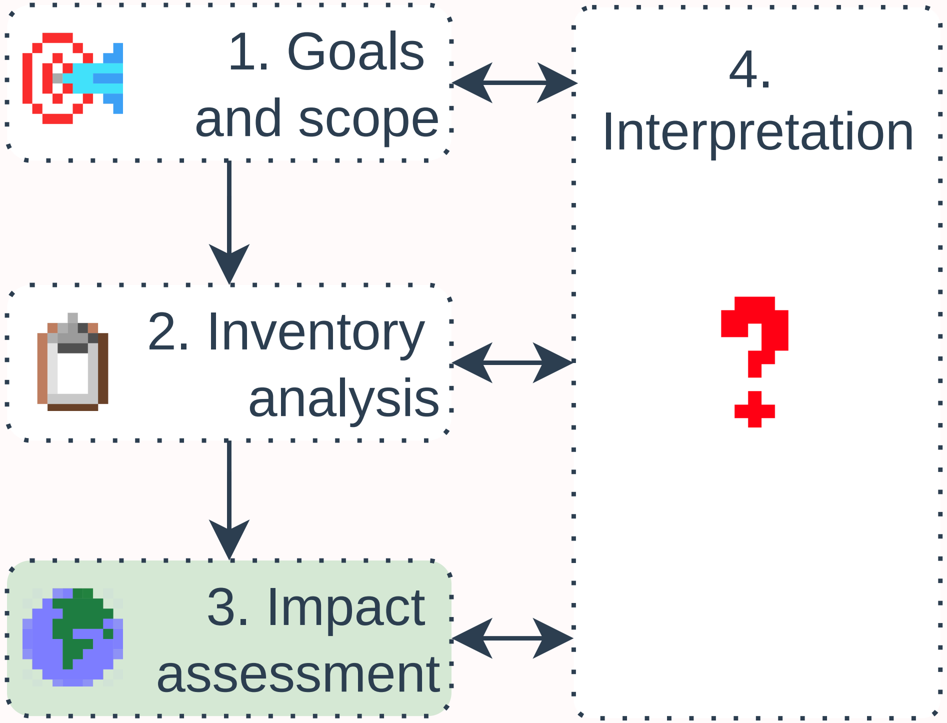
E.g., a Danish electricity-grid dataset reused as-is for a factory in Vietnam would score poorly on *geographical correlation* (even though the number itself is perfectly correct for Denmark).

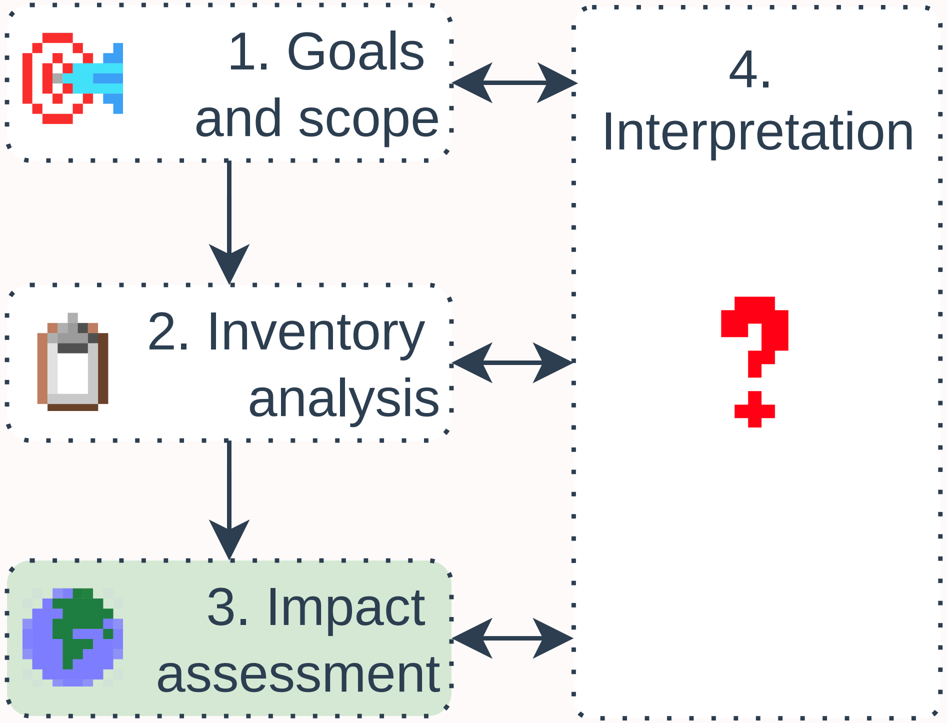
[13] Weidema & Wesnæs. "Data quality management for life cycle inventories." Journal of Cleaner Production (1996). As presented in Hauschild, et al. "Life Cycle Assessment: Theory and Practice." Springer (2018).

Impact assessment



- Take each elementary flow (extractions/ emissions from the inventory analysis)
- Check how (much) they impact a series of indicators (e.g., climate change, acidification, ecotoxicity...)

Impact assessment



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- Check how (much) they impact a series of indicators (e.g., climate change, acidification, ecotoxicity…)

- “Option A emits less than option B” ✅
- “Option A is sustainable” 🫠

From inventory to impacts

> ⓘ How do we compare 1 kg of lead emitted to water with 1 kg of CO_2 emitted to air?

- LCIA models the *environmental mechanism* behind each flow;
- It groups and converts flows into a handful of *impact scores*
- Results are *potential* impacts.

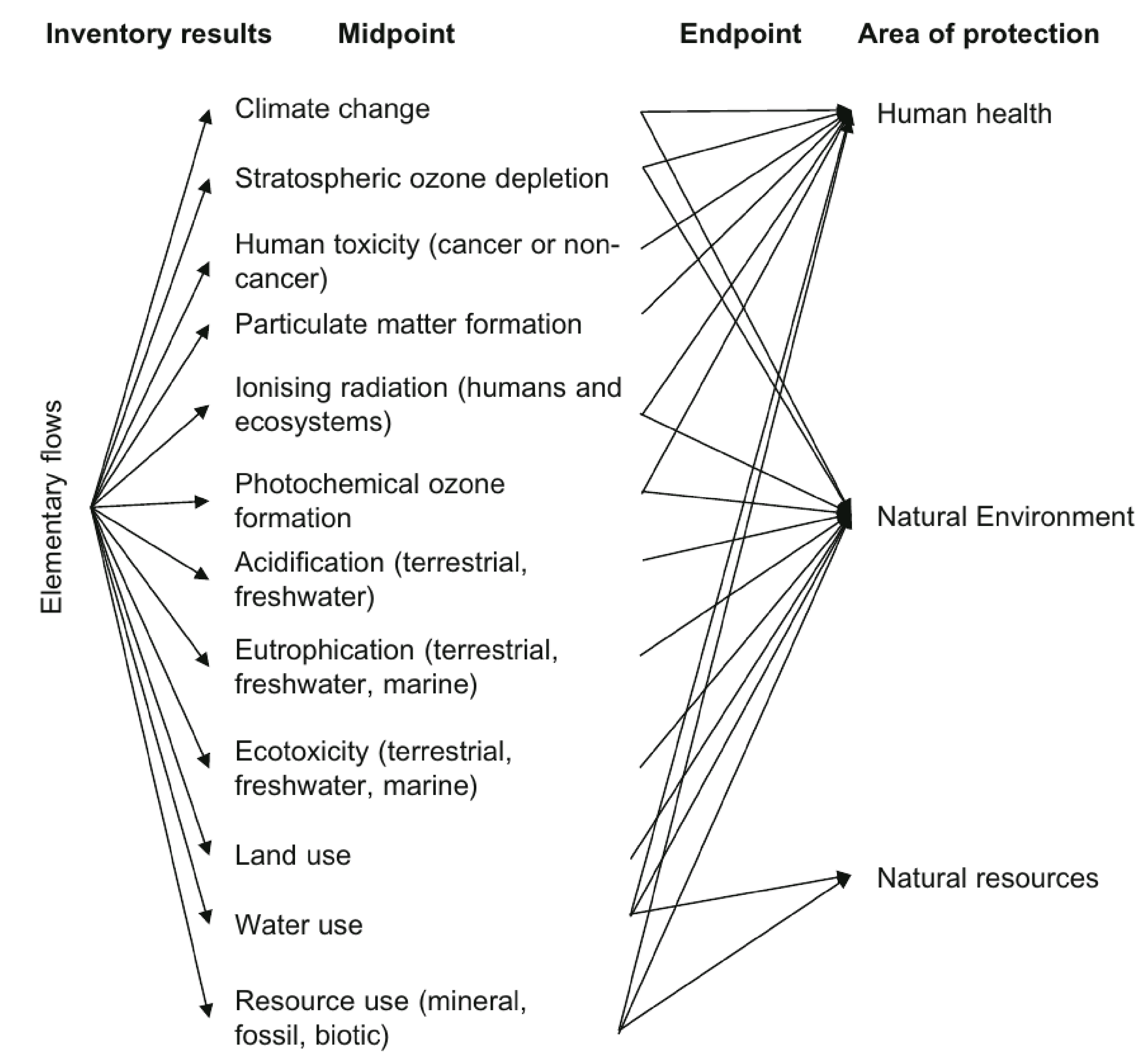
LCIA steps (mandatory)

1. **Selection**: impact categories, indicators and characterisation models;
2. **Classification**: assign each flow to the categories it feeds;
3. **Characterisation**: quantify each category's score.

Selection (→ Classification → Characterisation)

Select indicators in accordance with the goal + justify them. E.g.:

- Which impact categories (or environmental problems) do I need to cover and can I justify those that I am excluding?
- In which region does my life cycle (or its most contributing processes) take place?
- Which elementary flows do I need to characterise?



Hauschild, et al. "Life Cycle Assessment: Theory and Practice." Springer (2018).

Midpoint vs endpoint

Midpoint

- Early in the chain;
- 15 categories (climate change in kg CO_2-eq, acidification…);
- Measurable, less relevant (?).

Endpoint (damage)

- End of the chain;
- 3 areas of protection: human health (DALY), ecosystem quality (PDF), natural resources;
- Relevant (?), more uncertain.

Midpoint impact categories

- Climate change
- Stratospheric ozone depletion
- Acidification
- Eutrophication (terrestrial, freshwater, marine)
- Photochemical ozone formation
- Particulate matter formation
- Human toxicity (cancer, non-cancer)
- Ecotoxicity (terrestrial, freshwater, marine)
- Ionising radiation
- Land use
- Water use
- Abiotic & biotic resource use

(emerging categories: noise, pathogens...)

(Selection →) Classification (→ Characterisation)

Assign every elementary flow to the impact category (or categories) it contributes to:

- CO_2 to air → climate change;
- Water consumed → water use.

(Selection →) Classification (→ Characterisation)

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- CO_2 to air → climate change;
- Water consumed → water use.

A flow can act:

- *in parallel*: SO_2 → acidification *and* human toxicity (when inhaled);
- *in series*: SO_2 → acidification → mobilises soil metals → toxicity.

(Selection → Classification →) Characterisation

Multiply each flow by a *characterisation factor* (CF), then sum, per category c:

$$\mathrm{IS}_c = \sum_i \mathrm{CF}_i \cdot E_i$$

- CF = contribution per unit of flow (same unit for every flow in a category);
- Output: one value per category.
- Often expressed relative to a reference substance, e.g. *global warming potential*: 1 kg CH_4 ≈ 27 kg CO_2-eq over 100 years.

Why “CO_2-eq”?

Global Warming Potential (GWP): Heat trapped by 1 kg of a gas over a chosen time horizon, relative to 1 kg of CO_2. Usually 100 years: GWP100.

- “CO_2-eq” bundles lots of gases into one climate indicator. For a laptop, beyond CO_2: $CH_4 \approx 27$ · $N_2O \approx 273$ · chip-fab gases $CF_4 \approx 7380$, $SF_6 \approx 24300$, $NF_3 \approx 17400$.[14]
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[14] GHG Protocol. “Global Warming Potential Values.” (2024). Compiled from IPCC AR6 (2021).

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- The *time horizon* is a modelling choice: short-lived CH_4 is ≈ 27 over 100 yr, but ≈ 81 over 20 yr.[16]

[15] GHG Protocol. "Global Warming Potential Values." (2024). Compiled from IPCC AR6 (2021).

[16] IPCC. "Climate Change 2021: The Physical Science Basis (AR6, WGI)." (2021). Table 7.15.

Example for a laptop

1. Select multiple impact categories (including: climate change).
2.
3.

Example for a laptop

1. Select multiple impact categories (including: climate change).
2. Zoom in on climate change: compute it as CO_2-eq.
3.

Example for a laptop

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3. Take all the corresponding emission flows and sum their respective GWP.

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$$\mathrm{IS}_{\mathbf{climate}} = m_{CO_2} \cdot 1 + m_{CH_4} \cdot 27 + m_{N_2O} \cdot 273 + m_{CF_4} \cdot 7380 + \ldots$$

voilà.

Example for a laptop

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voilà.

Same inventory, other CFs → acidification (kg SO_2-eq), toxicity (CTUh / CTUe), water use… → one score per category.

Characterisation: the Q matrix

UNITS

Climate change	→	kg CO_2-eq
Acidification	→	kg SO_2-eq
Mineral res.	→	kg Cu-eq

	CO_2	CH_4	N_2O	SO_2	NO_x	Cu
Climate change	1	27	273	0	0	0
Acidification	0	0	0	1	0.7	0
Mineral res.	0	0	0	0	0	1

$$\begin{bmatrix} 180 \\ 0.3 \\ 0.02 \\ 0.5 \\ 0.8 \\ 2 \end{bmatrix}$$

Characterisation: the Q matrix

$$
\begin{bmatrix} 194 \\ 1.1 \\ 2 \end{bmatrix}
\quad
\begin{array}{r}
\\
\text{Climate change} \\
\text{Acidification} \\
\text{Mineral res.}
\end{array}
\begin{array}{cccccc}
CO_2 & CH_4 & N_2O & SO_2 & NO_x & Cu \\
\hline
1 & 27 & 273 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0.7 & 0 \\
0 & 0 & 0 & 0 & 0 & 1
\end{array}
\quad
\begin{bmatrix} 180 \\ 0.3 \\ 0.02 \\ 0.5 \\ 0.8 \\ 2 \end{bmatrix}
$$

Characterisation: the Q matrix

$$\boldsymbol{r} = \begin{bmatrix} 194 \\ 1.1 \\ 2 \end{bmatrix}$$

	CO_2	CH_4	N_2O	SO_2	NO_x	Cu
Climate change	1	27	273	0	0	0
Acidification	0	0	0	1	0.7	0
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$\boldsymbol{Q}$

$$\boldsymbol{g} = \begin{bmatrix} 180 \\ 0.3 \\ 0.02 \\ 0.5 \\ 0.8 \\ 2 \end{bmatrix}$$

LCA in one line

$$\begin{cases} \boldsymbol{g} = \boldsymbol{B}\boldsymbol{A}^{-1}\boldsymbol{f} \\ \boldsymbol{r} = \boldsymbol{Q}\boldsymbol{g} \end{cases}$$

LCA in one line

$$\boldsymbol{r} = \boldsymbol{QBA}^{-1}\boldsymbol{f}$$

Adapted from Di Bari, et al. “Systematising the LCA approaches’ soup: a framework based on text mining.” International Journal of Life Cycle Assessment (2024).

LCIA steps (optional)

4. Normalisation
5. Weighting and grouping

(opt.) Normalisation

Midpoint scores are in incompatible units → hard to tell which ones are large

> **Normalisation:** Divide each impact score by a reference value. E.g.,
> - The impact of an average person over one year in a given region ("person equivalents");
> - A reference scenario.

- Changes the results/interpretation → the choice of reference must be discussed.

(opt.) Weighting and grouping

- **Weighting**: which impacts are most important and how important they are.
  - No scientific basis: always a value choice (prevention cost, distance-to-target, expert panel, cultural perspectives…);
  - Weighted and non-weighted results must be reported together.
- **Grouping**: sort (e.g. global vs regional) or rank (high / medium / low priority) the categories.

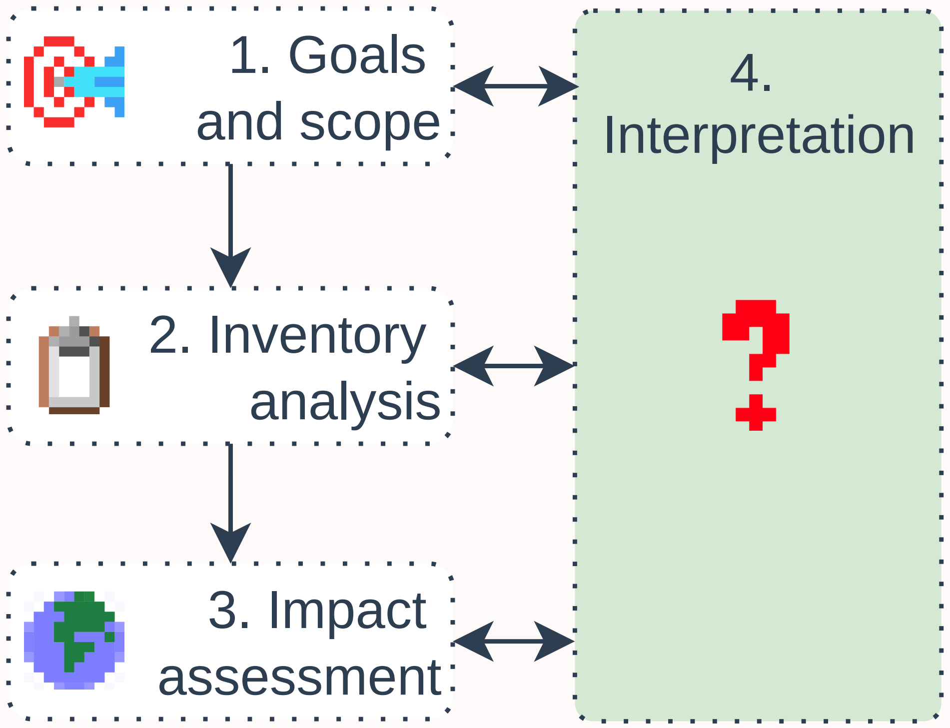
“Potential” impacts

> LCIA scores are *not* predictions.

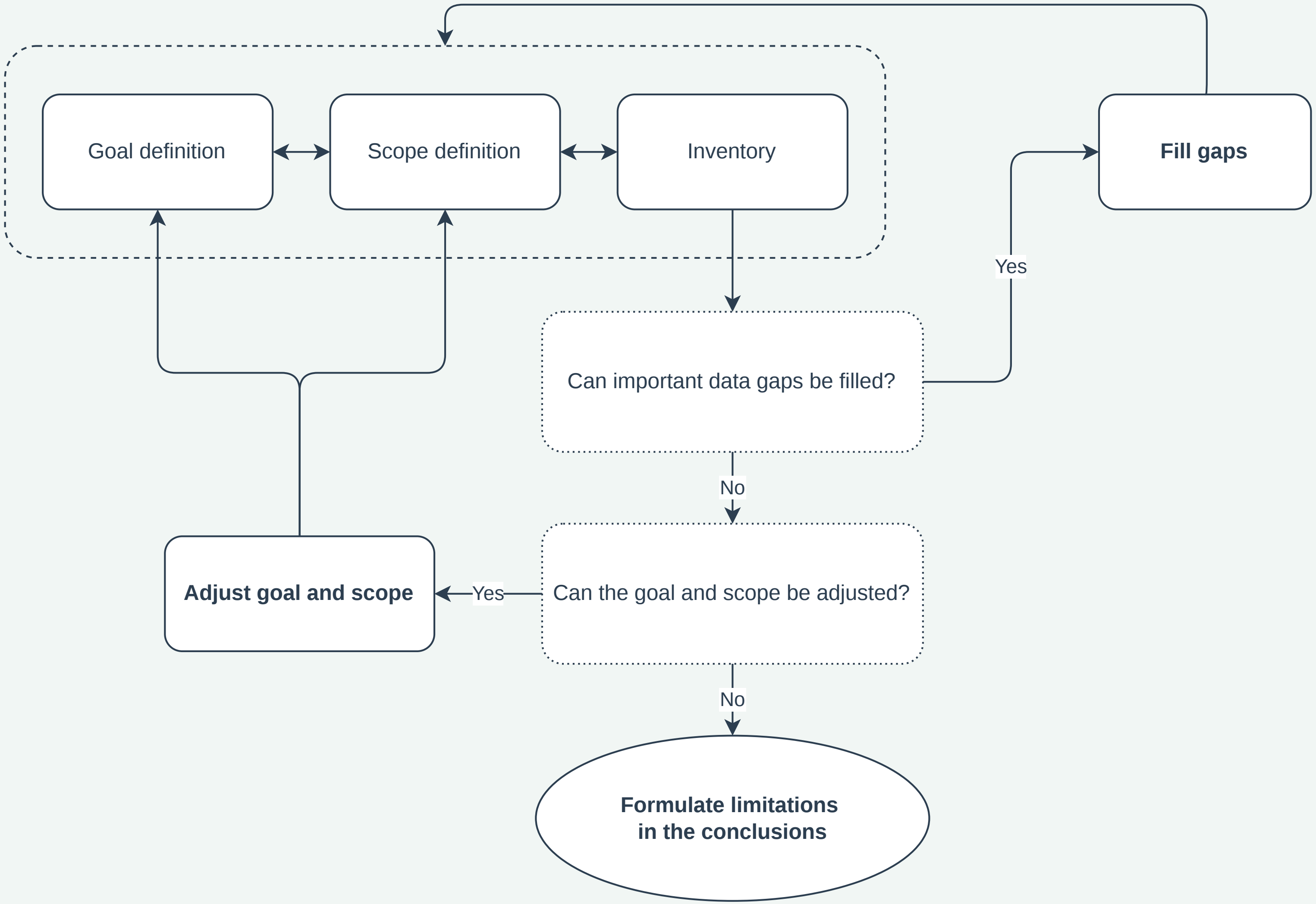
They assume:

- **Linearity** & **steady state**: doubling a flow doubles its impact;
- Integration over **space and time**: no specific site, season or population;
- A **functional unit** reference: results are relative & built for comparison.

Interpretation



- What does the assessment tell us?
- How reliable is it?
- What are we going to do about it?



Adapted from Hauschild, et al. “Life Cycle Assessment: Theory and Practice.” Springer (2018). Fig. 12.2.

What an LCA report must contain

Goal & scope

- Application, audience, commissioner;
- Function, *functional unit*, reference flow
- System boundary & cut-off criteria
- Attributional or consequential; allocation choices

Inventory

- Data sources, collection & calculation procedures
- How allocation was handled; data quality reached

Impact assessment

- Categories, indicators, characterisation models
- Characterised results (+ normalisation / weighting if used)
- Statement: *relative*, *potential* impacts

Interpretation

- Conclusions, limitations, recommendations
- Sensitivity & uncertainty analysis

Critical review

- Mandatory for public comparative assertions: reviewer, statement, responses

A reader must be able to tell *what* was assessed and *why*, and reproduce it.

What LCA does *not* capture

- **Absolute sustainability**: it compares options, it does not certify one as “sustainable”;
- **Rebound effects** (re: 1st lecture);
- **Actual impacts**: scores are *potential* and space/time-integrated;
- **Perfect view of the supply chain**: process LCA truncates deep upstream branches → underestimation.

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- **Absolute sustainability**: it compares options, it does not certify one as "sustainable";
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- **Actual impacts**: scores are *potential* and space/time-integrated;
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… and it is only as trustworthy as its goal, scope, functional unit and data.

Sources and references

- 📖 Hauschild, et al. "Life Cycle Assessment: Theory and Practice." Springer (2018).
- 📖 Ashby. "Materials and Sustainable Development." Butterworth-Heinemann (2022).
- 🇫🇷 Beuve. "Allocation in Life Cycle Assessment." ESOS seminar (2026). https://www.youtube.com/watch?v=KzcKPMFJPQc
- 📄 ISO 14040 & 14044. "Environmental management — Life cycle assessment." ISO (2006).

Document analysis

We have spent the lecture discussing what a LCA is, is not, or should be. Now let’s read a real LCA report:

Sánchez, Baur & Eguren. “**Life Cycle Assessment of the Fairphone 5**.” Fraunhofer IZM (2024). https://www.fairphone.com/wp-content/uploads/2024/09/Fairphone5_LCA_Report_2024.pdf

Associated questions on Edunao, under “Lab 2.1 - LCA document analysis”

LCA report link. ↑