Chair of Renewable and Sustainable Energy Systems
TUM School of Engineering and Design
Technical University of Munich

Optimization and sustainability assessment of energy systems

Thomas Hamacher

Andrea Cadavid Isaza

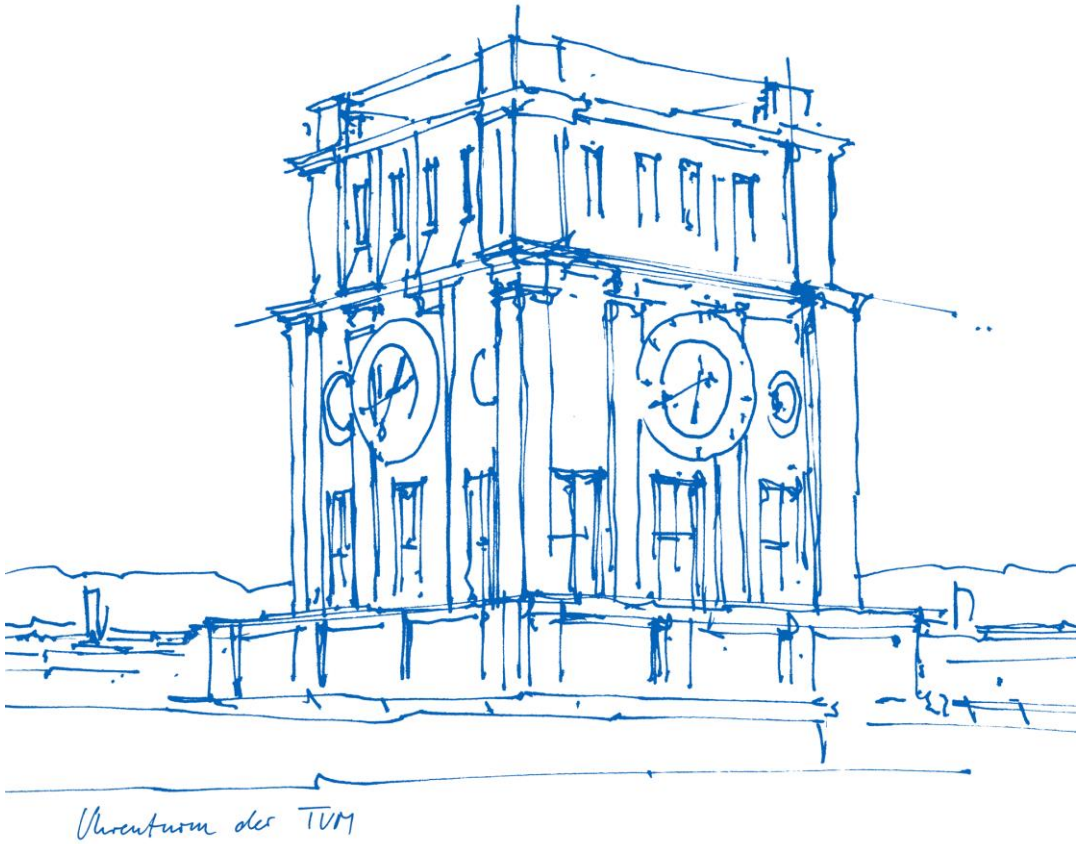
Thushara Addanki

Technical University of Munich

TUM School of Engineering und Design

Chair of Renewable and Sustainable Energy Systems

Montevideo, 15 August 2024



Team

Prof. Dr. Thomas Hamacher
Email: thomas.hamacher@tum.de

Andrea Cadavid Isaza, M.Sc.
Email: andrea.cadavid@tum.de

Thushara Addanki, M.Sc
Email: thushara.addanki@tum.de

Course timeplan

When	Day	Session
15.08	Thursday	Theory LCA
20.08	Tuesday	Examples LCA
22.08	Thursday	Exercise LCA
27.08	Tuesday	Reference energy system, urbs introduction
28.08	Wednesday	Consultation urbs
29.08	Thursday	urbs continuation
03.09	Tuesday	Impuls-urbs
05.09	Thursday	Optimization and dual solutions
09.09	Monday	Consultation Presentations
10.09	Tuesday	Final Presentations

Scan the QR or use link to join

https://forms.office.com/e/1FErTmGjNm

Copy link

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What is your current ocupation?

- Bachelor student
- Master student
- PhD student
- Work in an academic institution
- Work in industry
- Work in the public sector

Agenda

Agenda

A bit of history…

Evolution of Environmental Protection	
Chronology	**Strategy**
1970´s to 1980´s	End-of-Pipe treatment
Mid 1980´s	Waste Minimization/Reduction
Early 1990´s	Cleaner Production
Mid 1990´s	Life Cycle Assessment
2000 and beyond	Sustainable Development/Life Cycle Sustainability Assessment

Sources: [1], [2], [3]

A bit of history…

- First recognized as partial LCA study (unpublished)
- To account the resource requirements, emissions and waste flow of different beverage containers.
- Worst container was not dismissed.
- They adjusted its production to reduce the impacts.

- For aluminium, they included the use of recycled aluminium and reduced so 90% of the energy demand along the life cycle of this container.

A bit of history…

SETAC

1993

"CODE OF PRACTICE FOR LIFE CYCLE ASSESSMENT"

ISO International Organization for Standardization

1997

SETAC: Society of Environmental Toxicology and Chemistry

Why do we conduct LCA ?

- Every product has a life cycle, which we will discuss more in detail later. Environmental impacts happen at each life cycle stage, but many environmental investigations consider only the impacts of the use case. LCA takes a holistic view and considers all stages equally.

- The importance of individual stages of the life cycle become obvious and can lead to countermeasures.

The phase of production will gain weight while the use phase will lose weight as is the case for renewable energies. A bigger emphasis is on material supply.

- Without LCA we run in to the danger to miss important impacts and design wrong policies.

To answer questions…

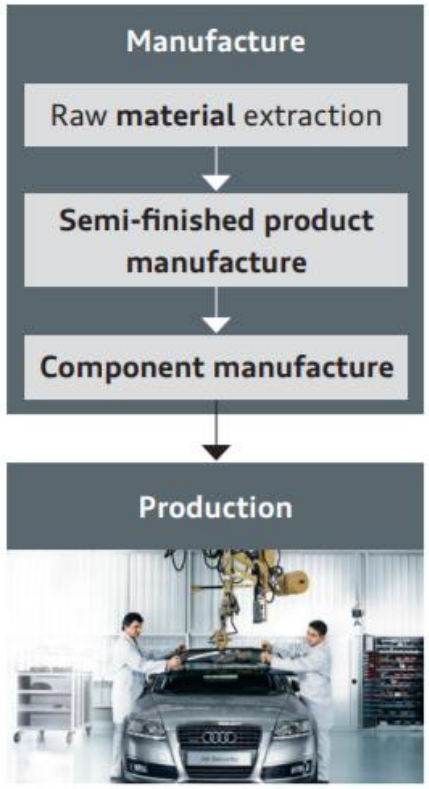
- Which product or process cause the least environmental impact, overall or in each stage of it‘s life cylcle?
- How might changes to the current system affect the environmental impacts across all life cycle stages?
- How can the process be changed to reduce a specific environmental impact of concern?
- ….

Who will use LCA analysis and why?

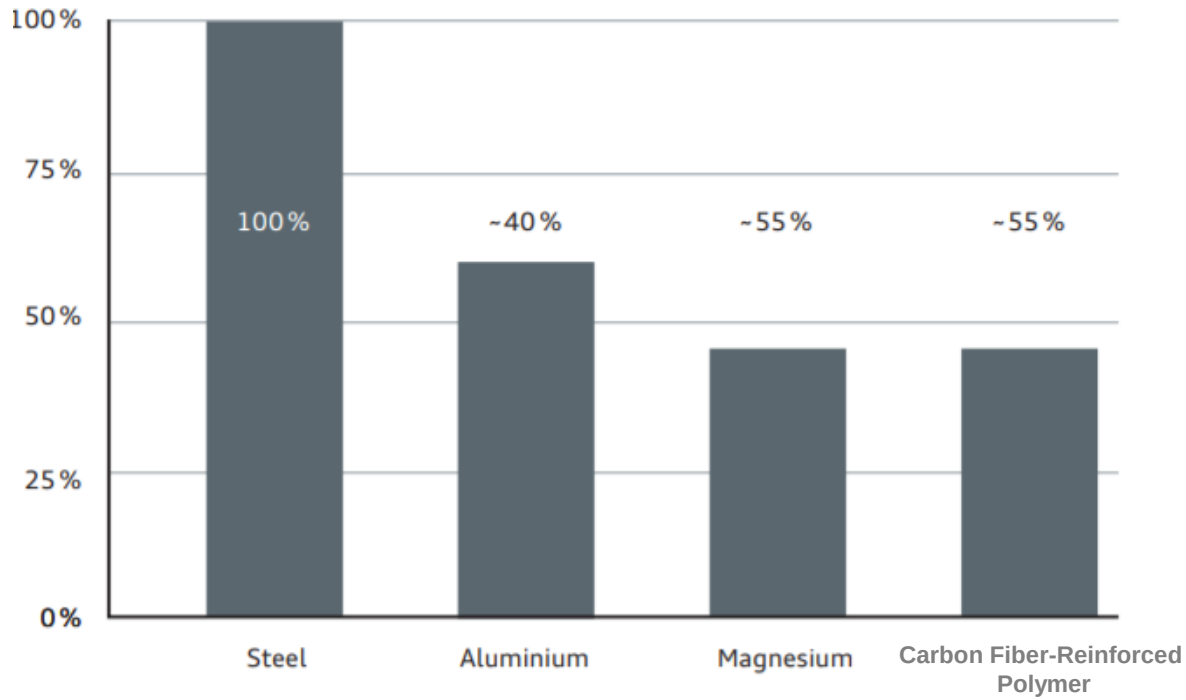
- Product designers
- Policy makers
- NGO‘s and other interest groups
- Marketing departments

Why do we conduct LCA ?

- **Eco-design example:** What effects does the use of different materials have on the production phase of a vehicle?



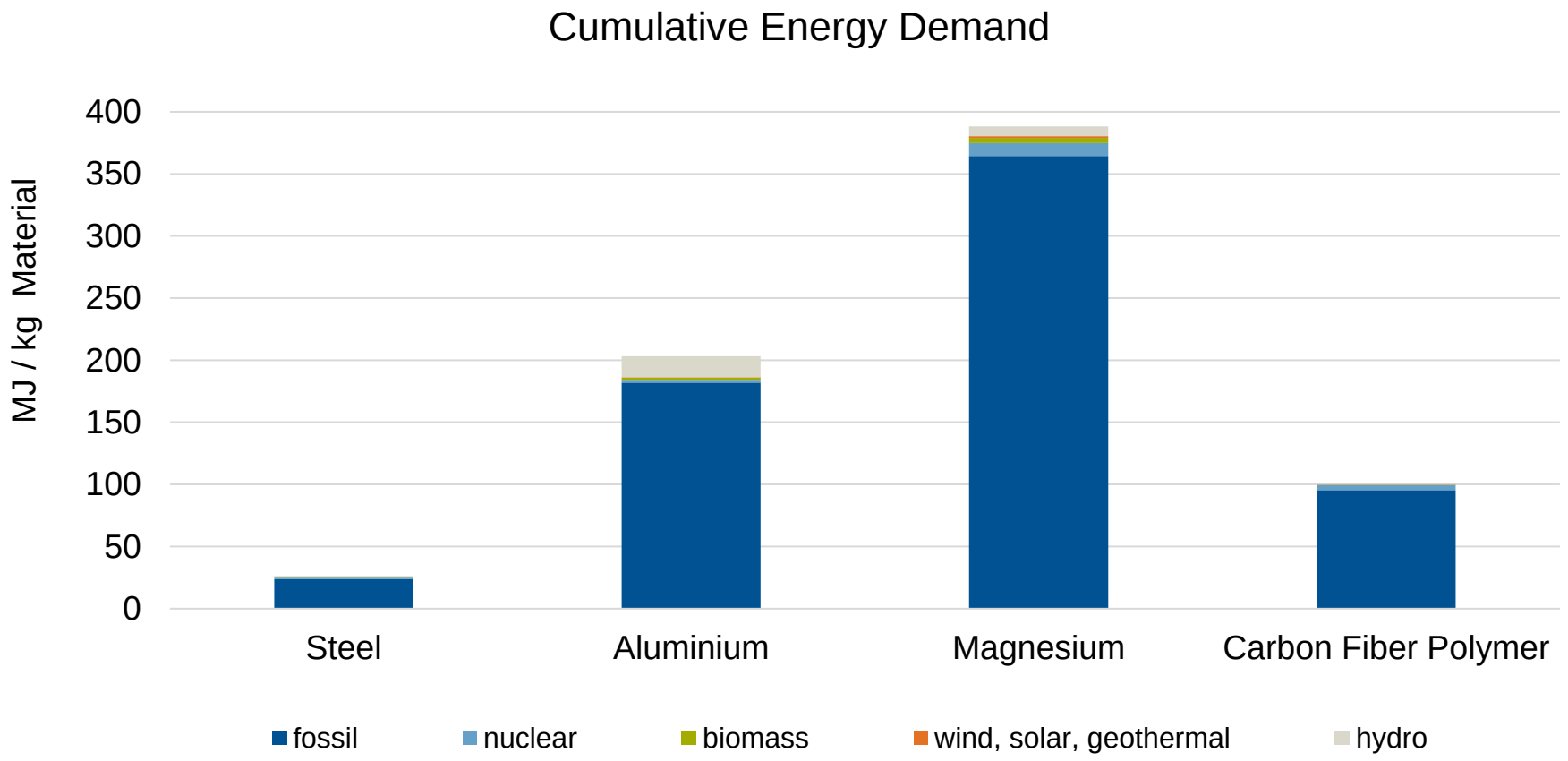
Weight saving potential, depending on material and manufacturing process (compared to steel, same functions)



Source: Audi AG 2011, Life Cycle Assessment: Audi looks one step ahead

Why do we conduct LCA ?

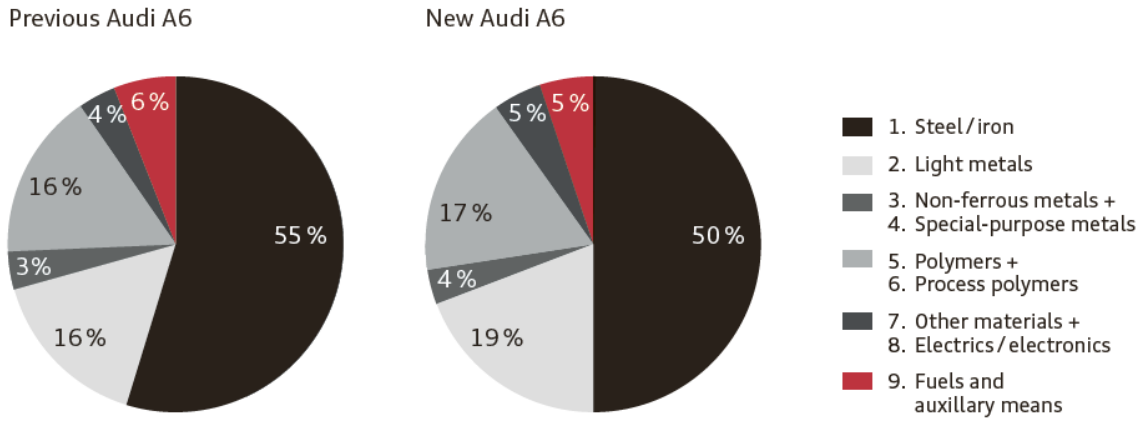
- **Eco-design example:** Which impact does the use of different materials have on the production phase of a vehicle?



Why do we conduct LCA ?

We can use the life cycle assessment:

- for a **single system** or to compare **2 different products**



- for **internal** or **external** use:
  - Identifying ways to reduce environmental impacts
  - inform consumers
  - to provide scientifically sound evidence for policy making
  - as a marketing instrument

Why do we conduct LCA ?

- Many LCAs lead to unexpected and non-intuitive results

- LCA is a holistic method aiming to get a whole picture of the system

Two examples:

  - Water bottles

  - Diapers

Plastic (PET) vs refillable aluminium bottles

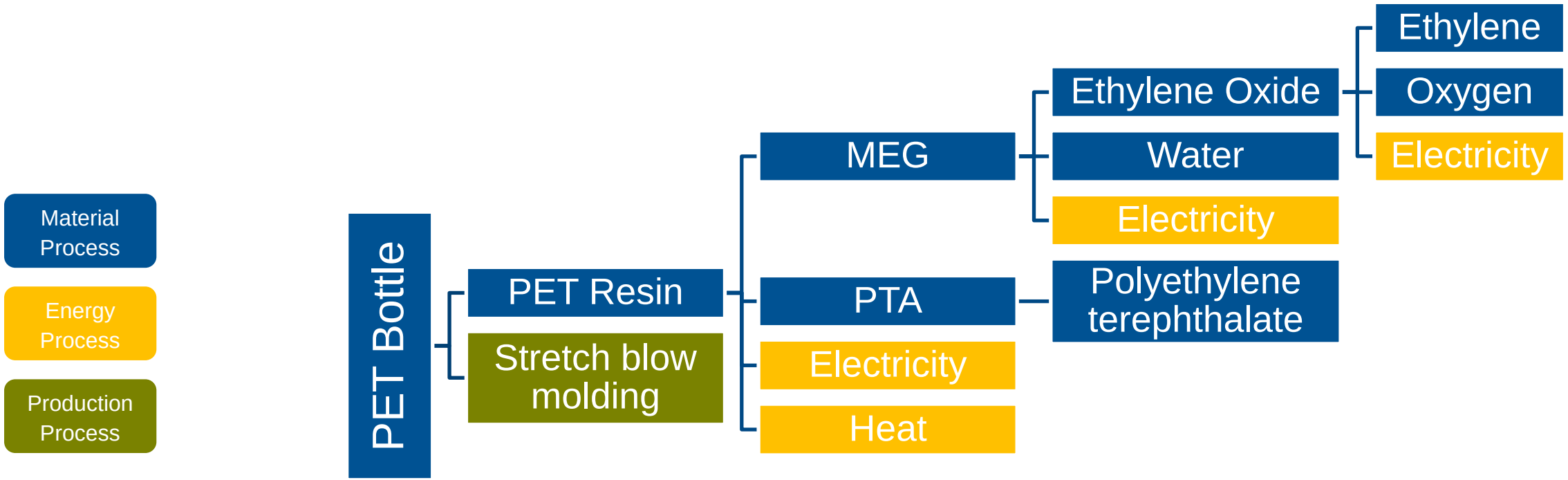
What is the most sustainable choice for drinking water? A life-cycle (LCA) analysis

VS

Further Information:
https://www.youtube.com/watch?v=-_eGOyAiNIQ
https://www.youtube.com/watch?v=jwc-n3W9rNY

Plastic (PET) bottle production

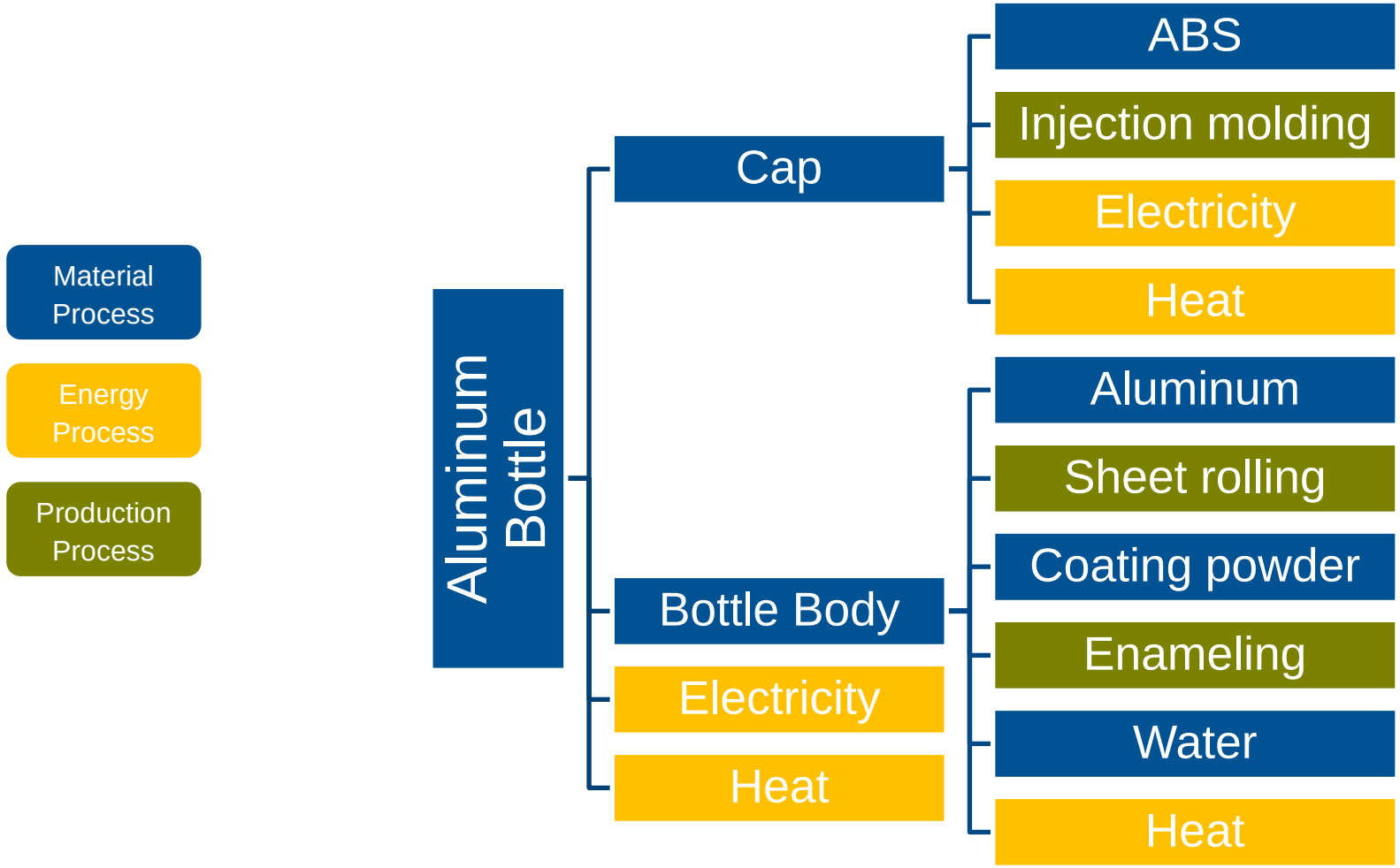
What is the most sustainable choice for drinking water? A life-cycle (LCA) analysis



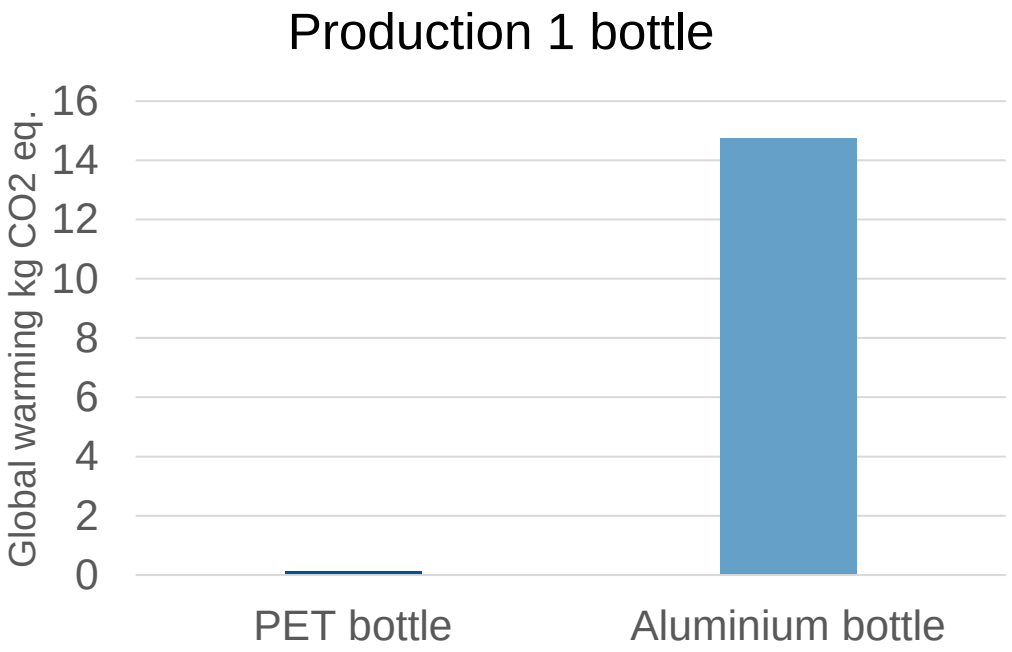
* MEG = monoethylene glycol; ** PTA = purified terephtalic acid. ABS = Acrylonitrile-butadiene-styrene, PET= Polyethylene terephthalate

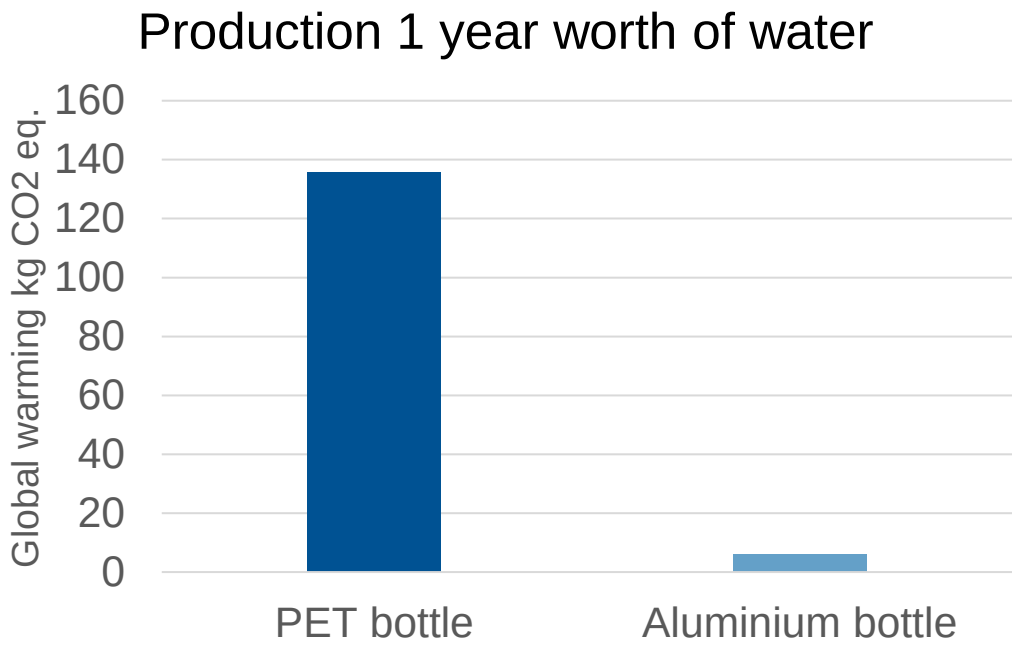
Refillable aluminum bottle production

What is the most sustainable choice for drinking water? A life-cycle (LCA) analysis



Production Phase



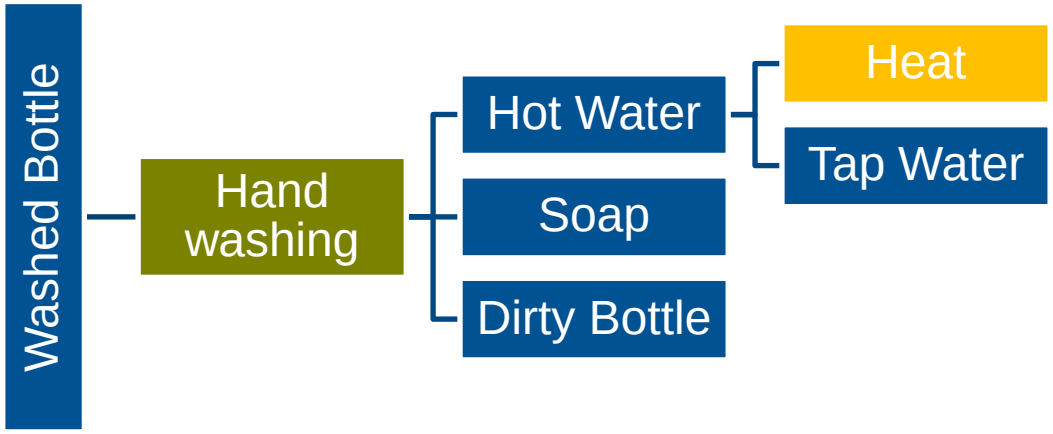


The production required for 1 year of water, assuming:

- Daily water consumption: 1,5 L per day
- 500 ml PET Bottle → 3 required per day
- 750 ml Aluminum bottle, with a lifetime of 2.5 years → 0.4 bottles per year, technical lifetime 25 years

Use phase

Washing the Aluminum bottle

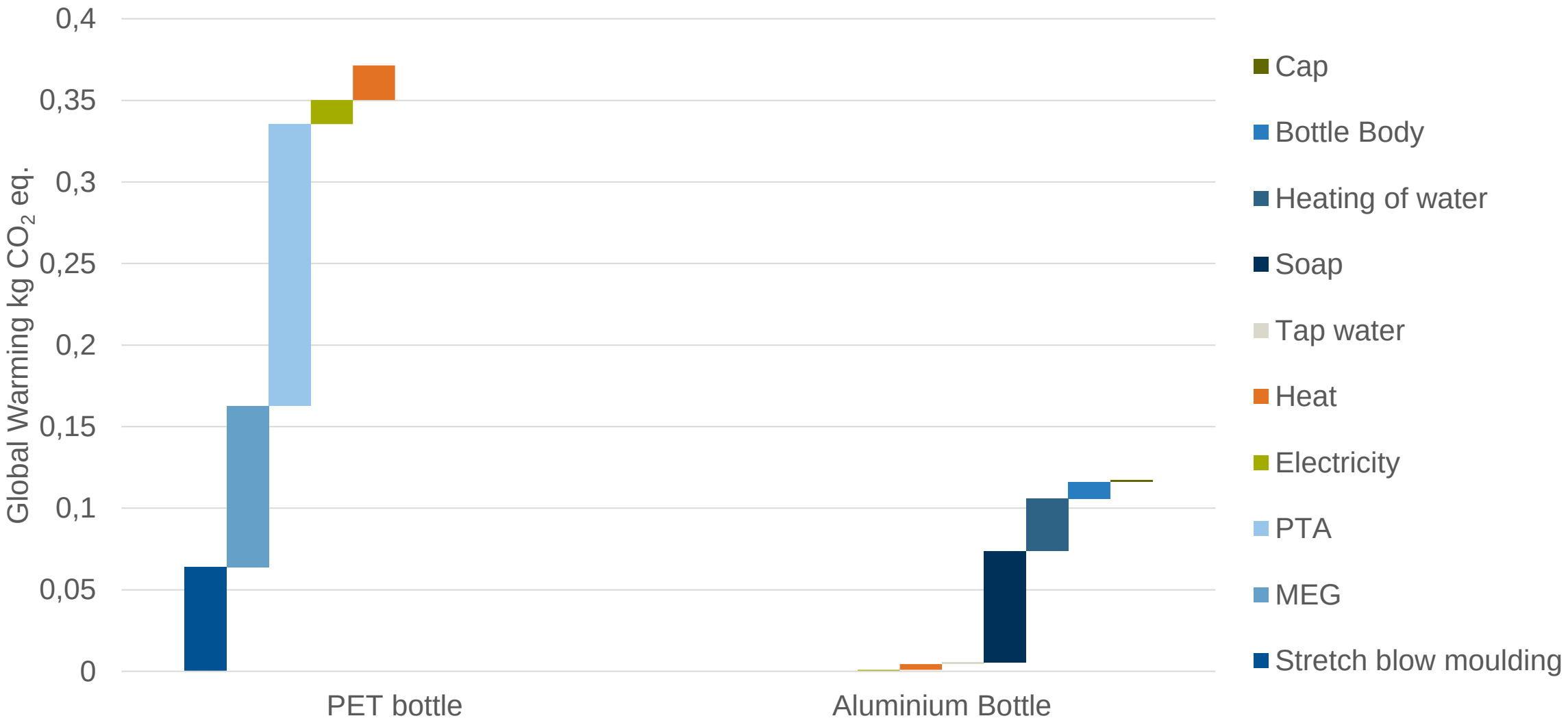


Assuming washing the bottle once a day with warm water and soap

Hot water: Tap water+ heat

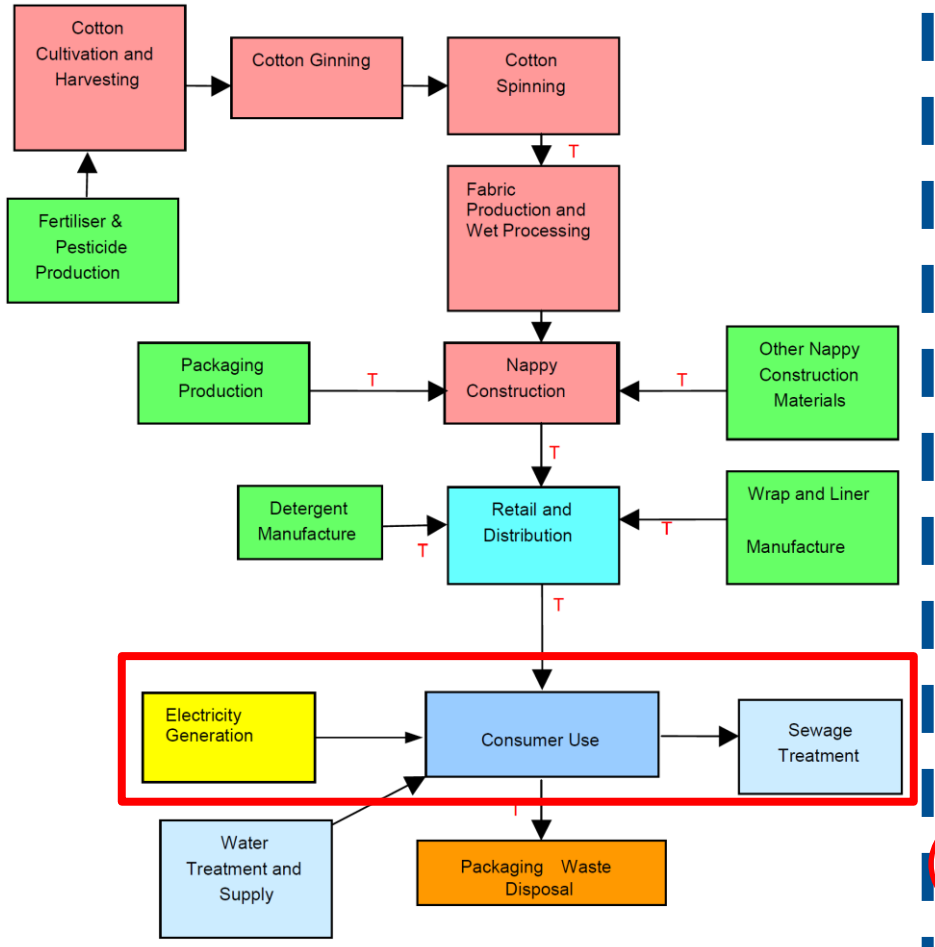
Heat: 119Wh
T_0=15 °C
T_{end}= 49°C

Consumption impacts per person per day

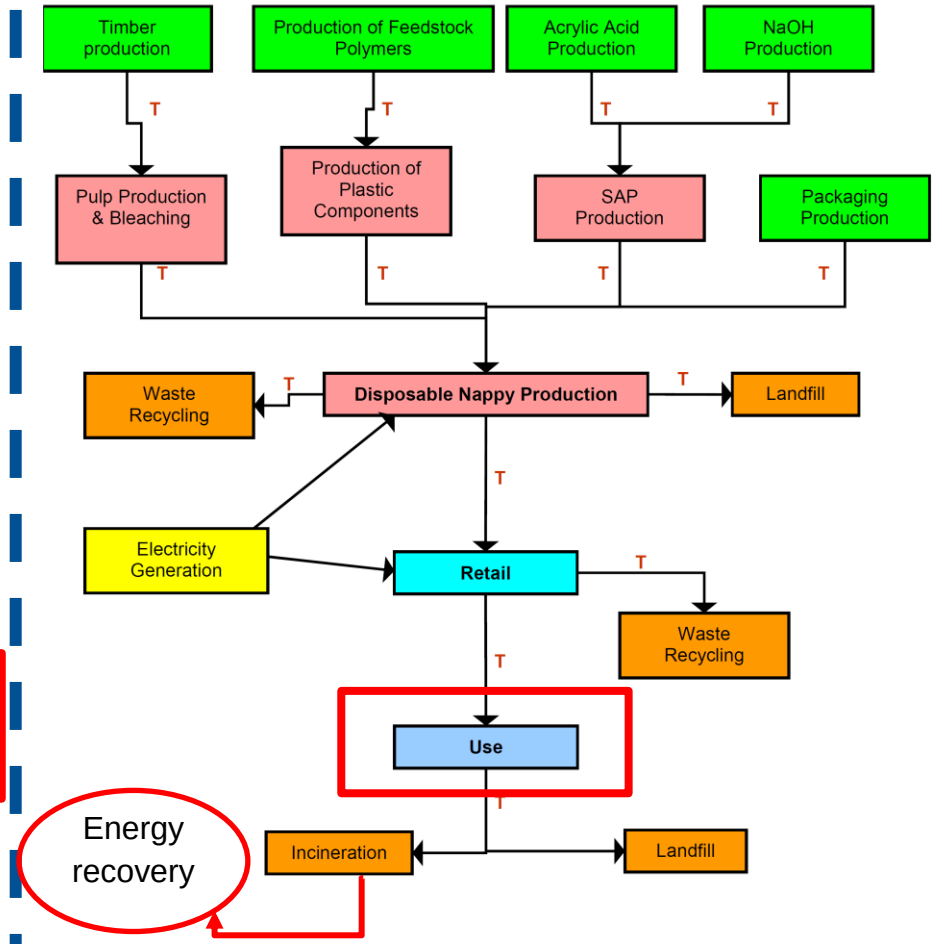


non-intuitive results

Reusable Diaper System Boundaries



Disposable Diaper System Boundaries



Source: LCA of disposable and reusable Nappies in the UK at www.environment-agency.gov.uk

Agenda

Life Cycle Assessment

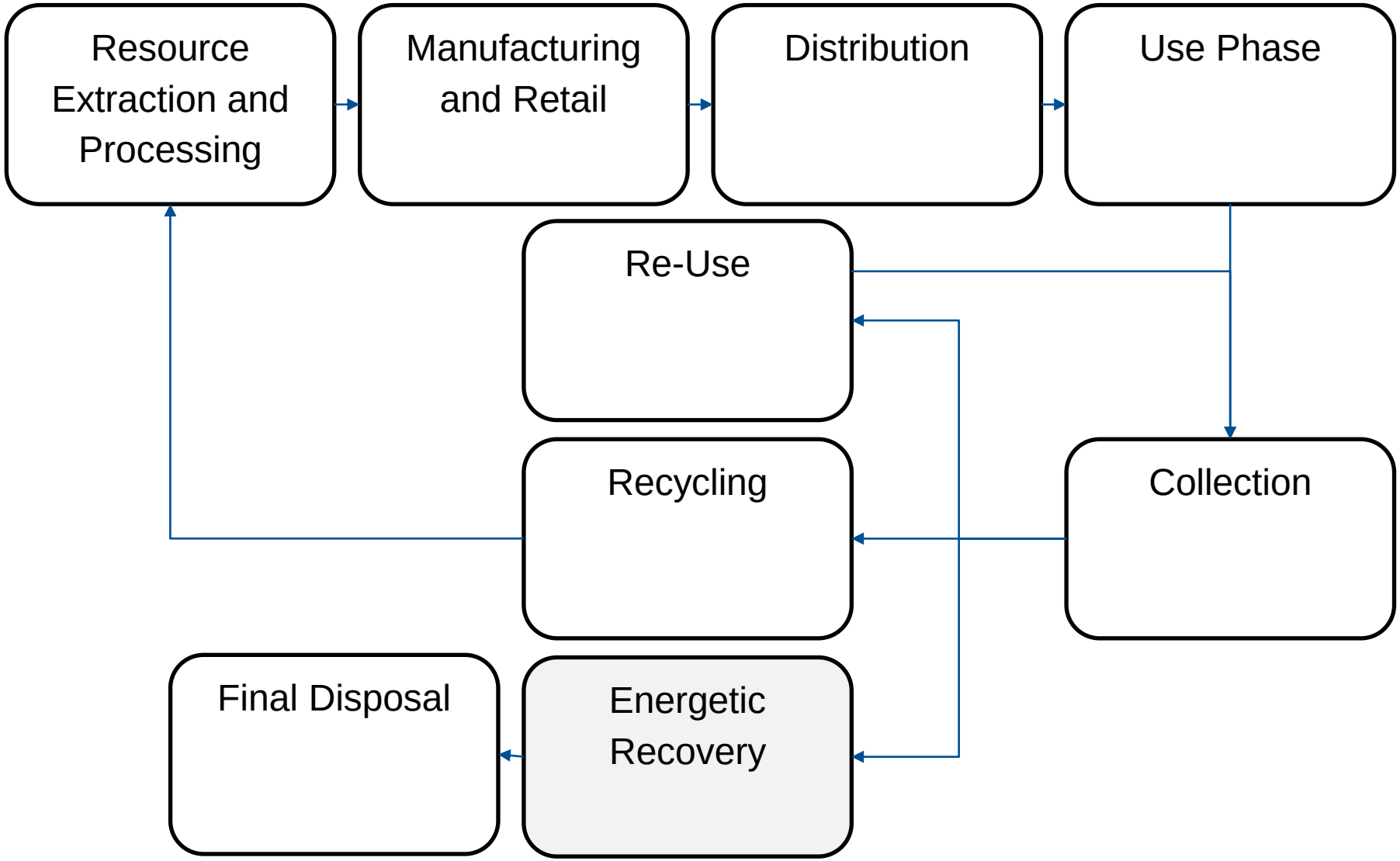
- technique to assess the environmental impacts associated with all stages of a product´s life cycle by:
  - collecting an inventory of all inputs and outputs in terms of energy,
  - raw materials, emissions, co-products, …
  - Evaluating the potential impacts associated to each input and output
  - Interpreting the results to support decision makers.
- LCA is a “cradle to grave” analysis
- ISO 14040:2006; 14044:2006


INTERNATIONAL STANDARD

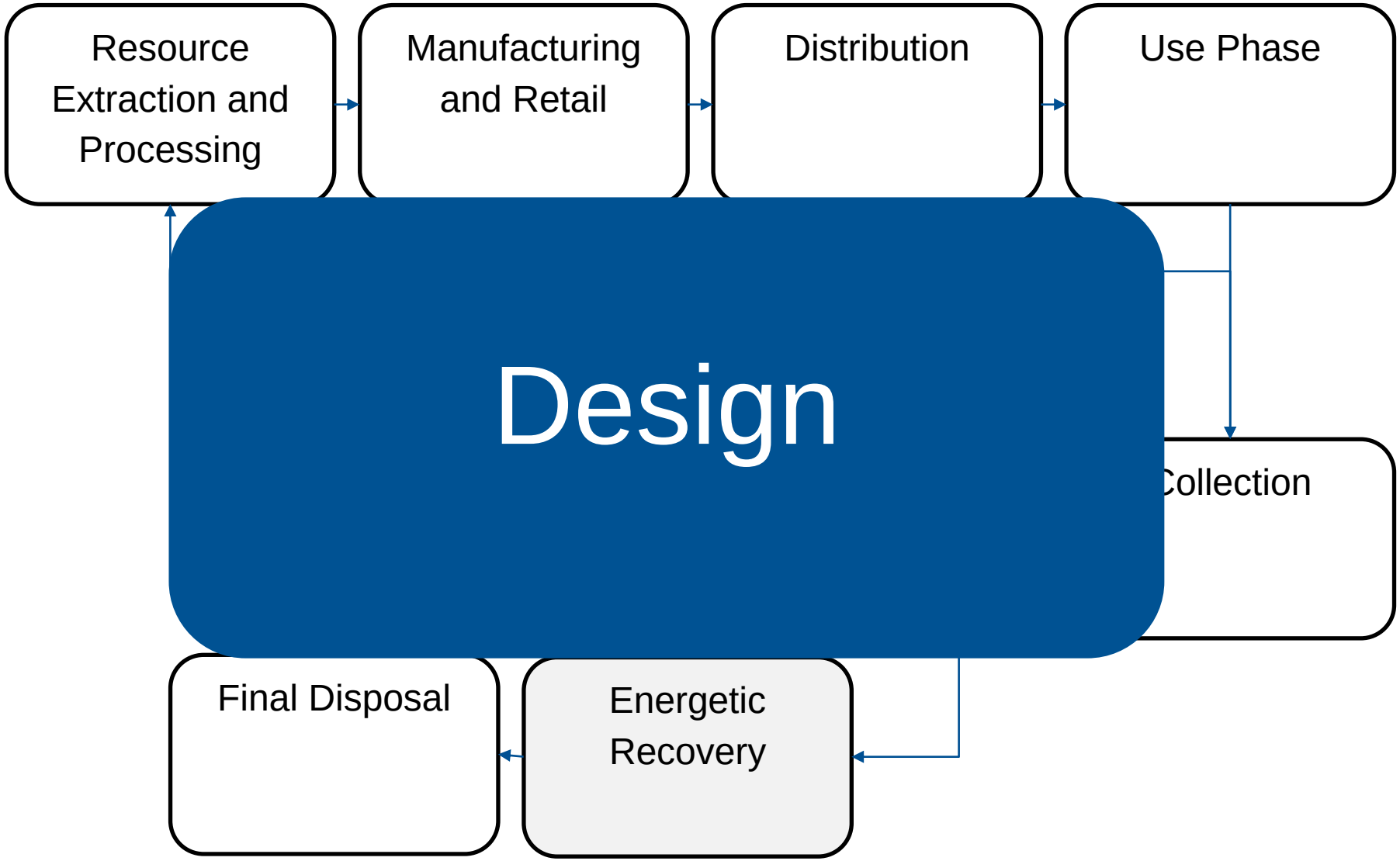
ISO 14040

Environmental management — Life cycle assessment — Principles and framework

The concept of a Life Cycle of a product

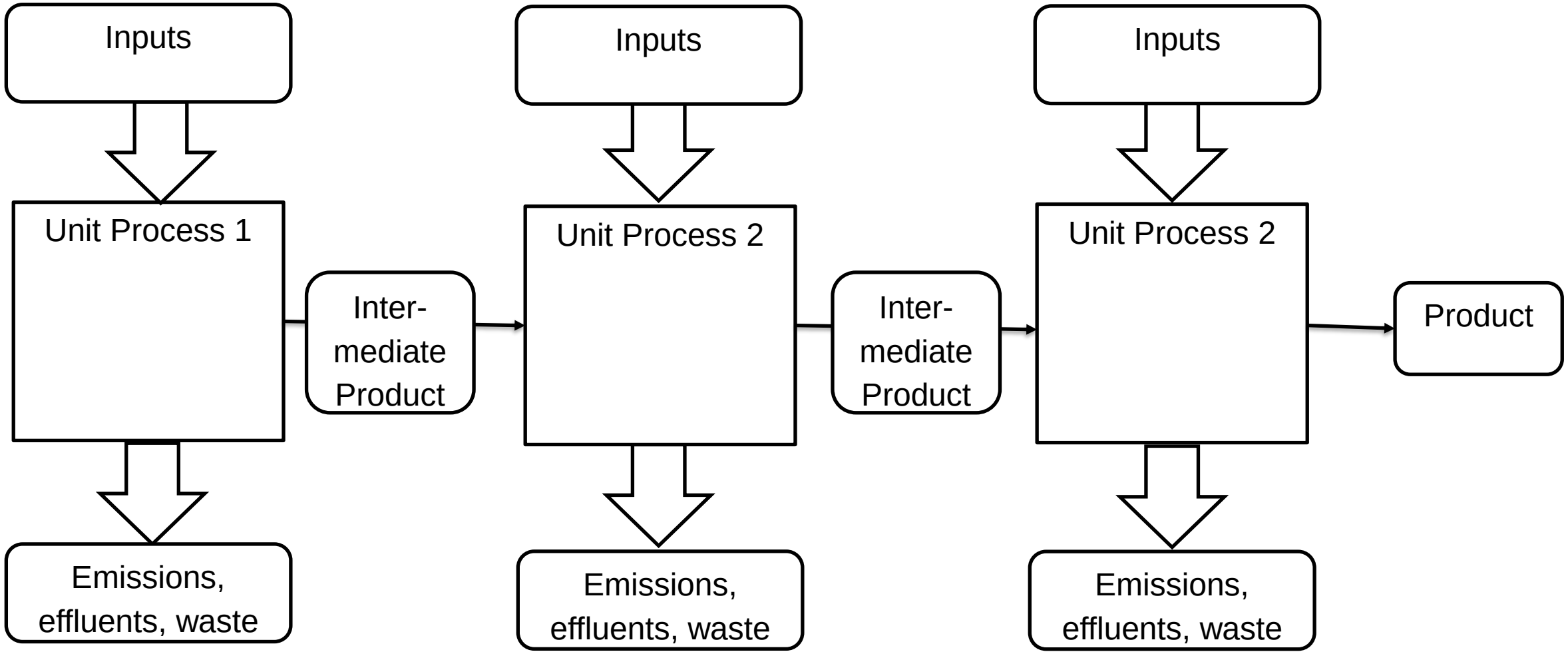


The concept of a Life Cycle of a product

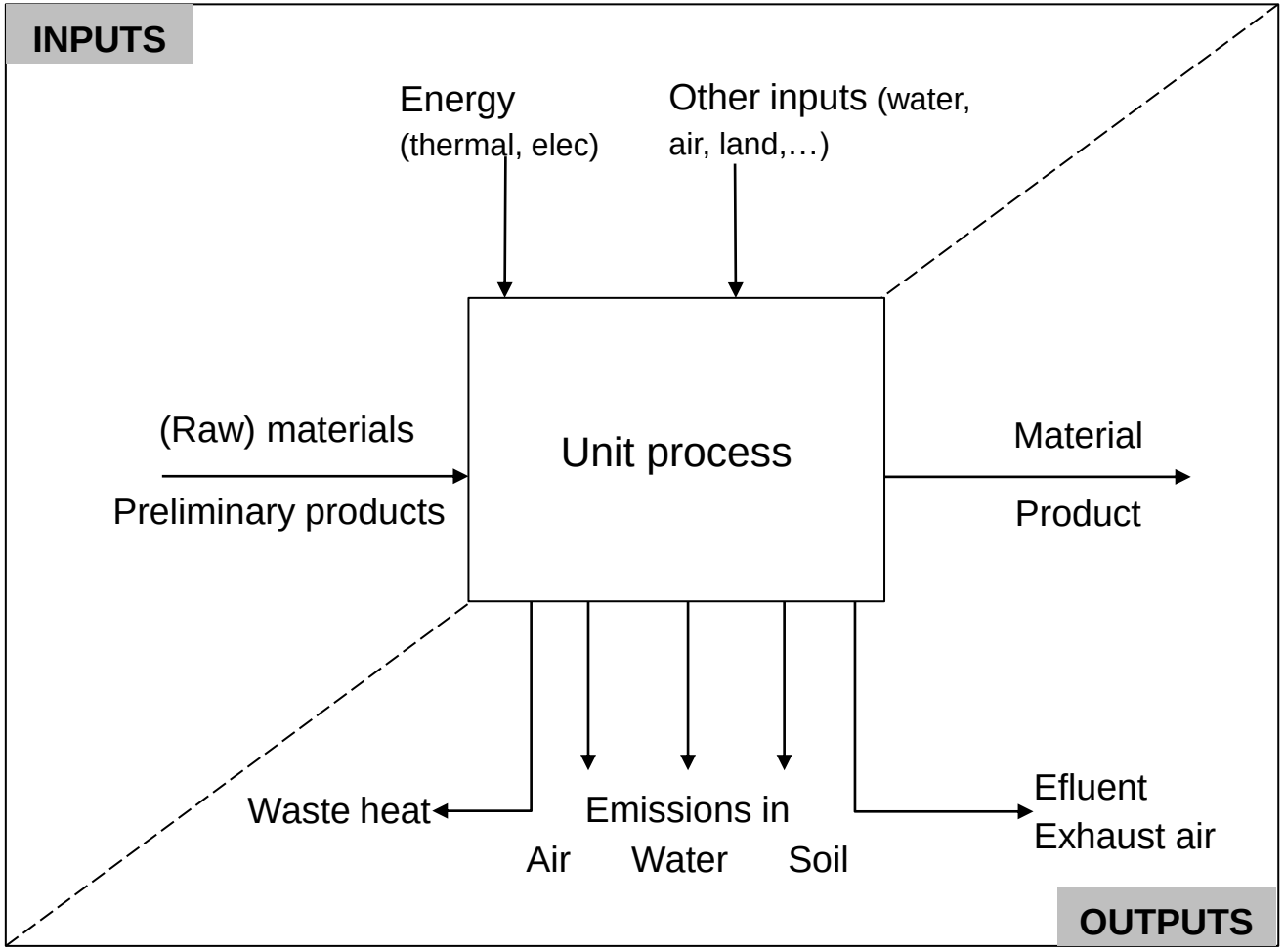


The production system

The System is the connection of many unit processes. I most cases the graph has a tree structure.



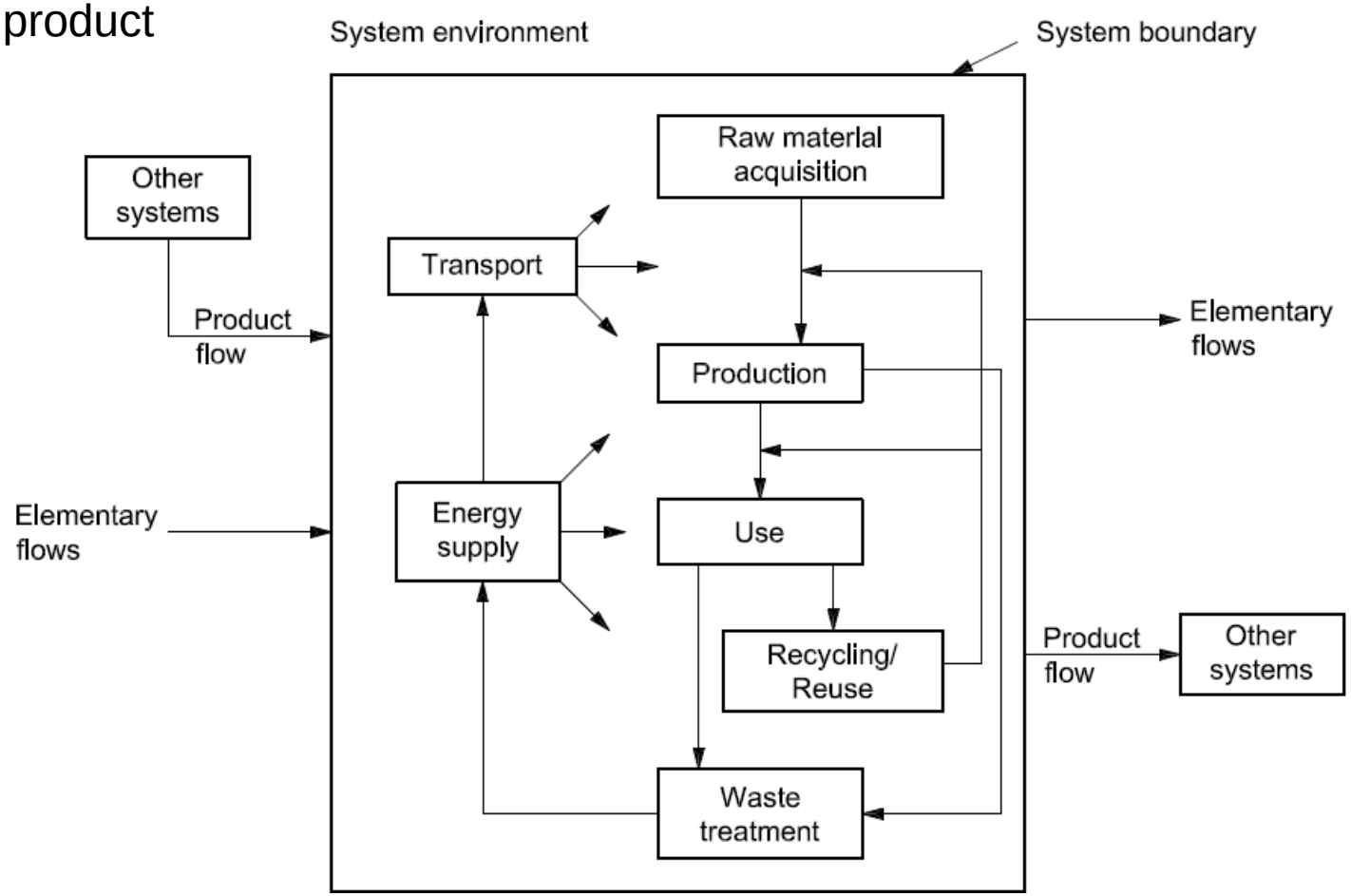
The Unit Process



Source: Klöpffer and Wagner, 2007

Some definitions

- the life cycle of a product

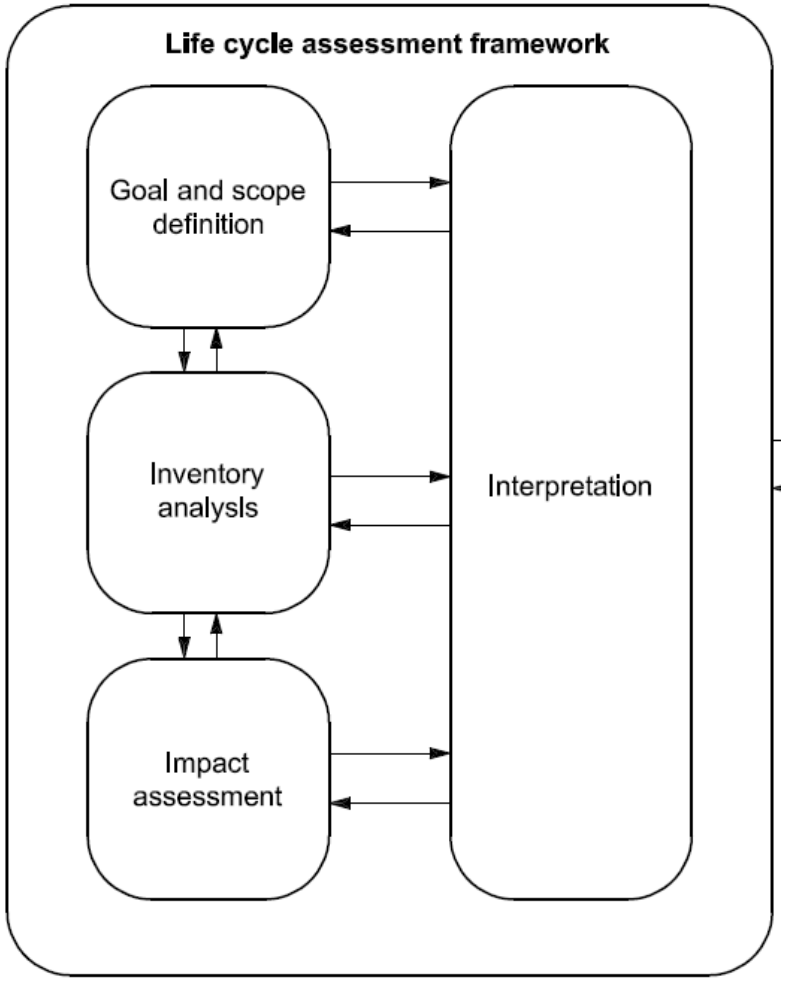


Source: ISO 14040:2006

Agenda

Phases of a LCA

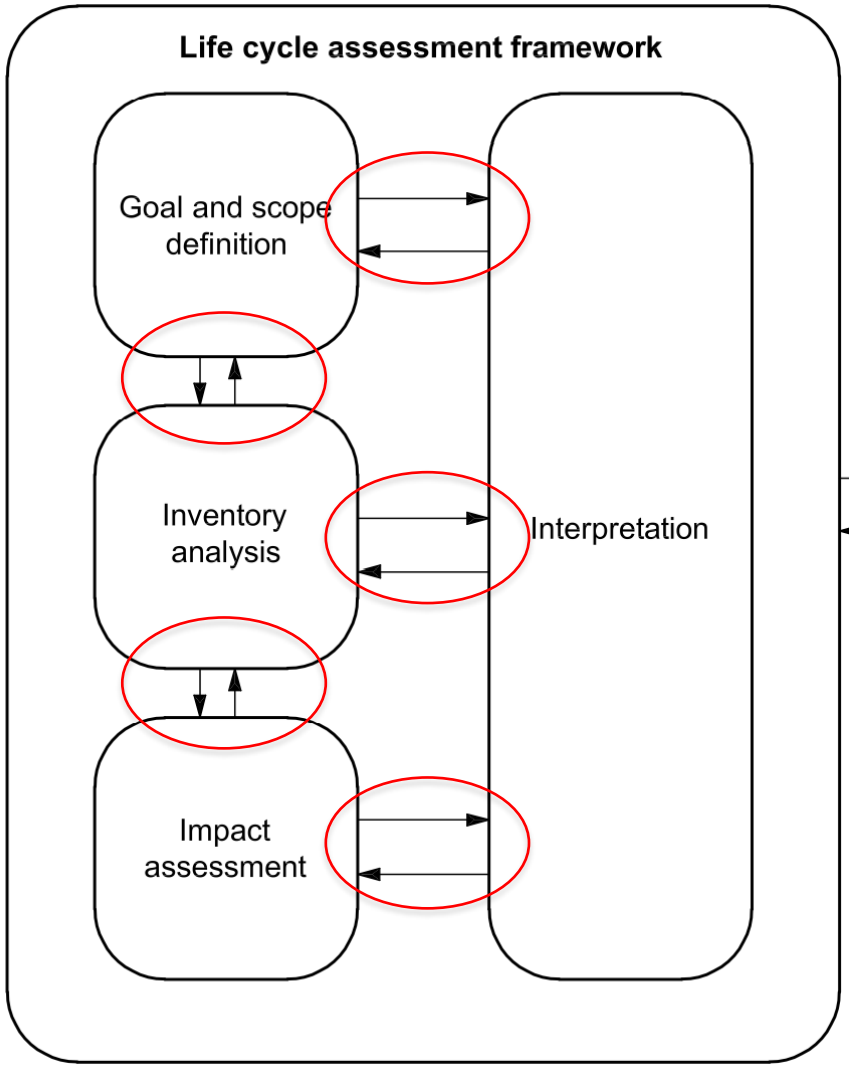
- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation



Source: ISO 14040:2006

Phases of a LCA

- Not at once through process- all phases are iterative!!
- Adjust as you go along
- Changes via iteration happen in almost 100% of the studies.



Source: ISO 14040:2006

Agenda

Goal and scope definition

Definition of goal and scope should answer the following questions:

- Why are we doing the analysis?
- What do we want to analyze?
- Who is the audience for our study?

Goal and scope definition

- Scope defines the following aspects:

  - The functions of the system;
  - The functional unit and the reference flows;
  - The system boundary;
  - Impact categories;
  - Allocation procedures;
  - data requirements;
  - main assumptions;
  - main limitations
  - needs of critical review and the type
  - type and format of the report

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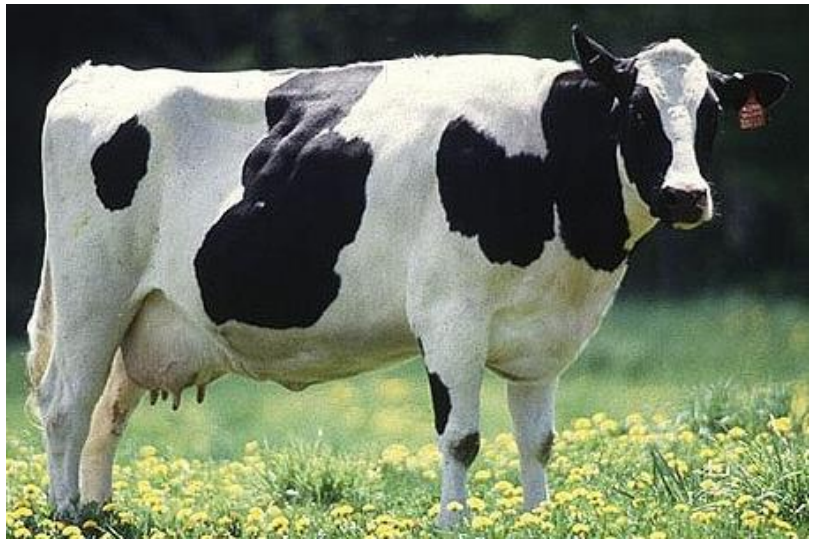
The function of the system

What is the function of the system?

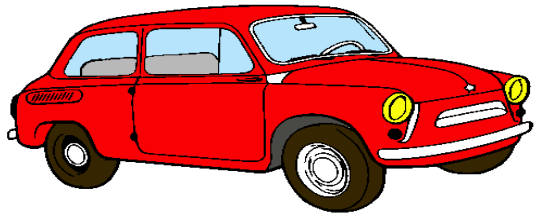
- A system can have a large number of possible functions.
- The function(s) selected for a study depends on the scope of the LCA.
- It describes the operational characteristics of the system.

The function of the system

- It describes the operation characteristics of the system



The function of the system



The functional unit and the reference flow

- **FU** quantifies the performance of a product system for use as a reference unit
- **Reference flow** is a quantified amount of product necessary for a product system to deliver the performance described by the functional unit

System A

System B

- Function of the systems? → Drying hands
- Funtional Unit? → Drying 100 pairs of hands size 7,5
- Reference flow? → System A: x m^3 warm air
  → System B: z kg of recycled paper

The functional unit and the reference flow

- A system can be analyzed from different approaches, depending on the function.

- Agriculture residues

→ From a <u>waste management</u> approach:

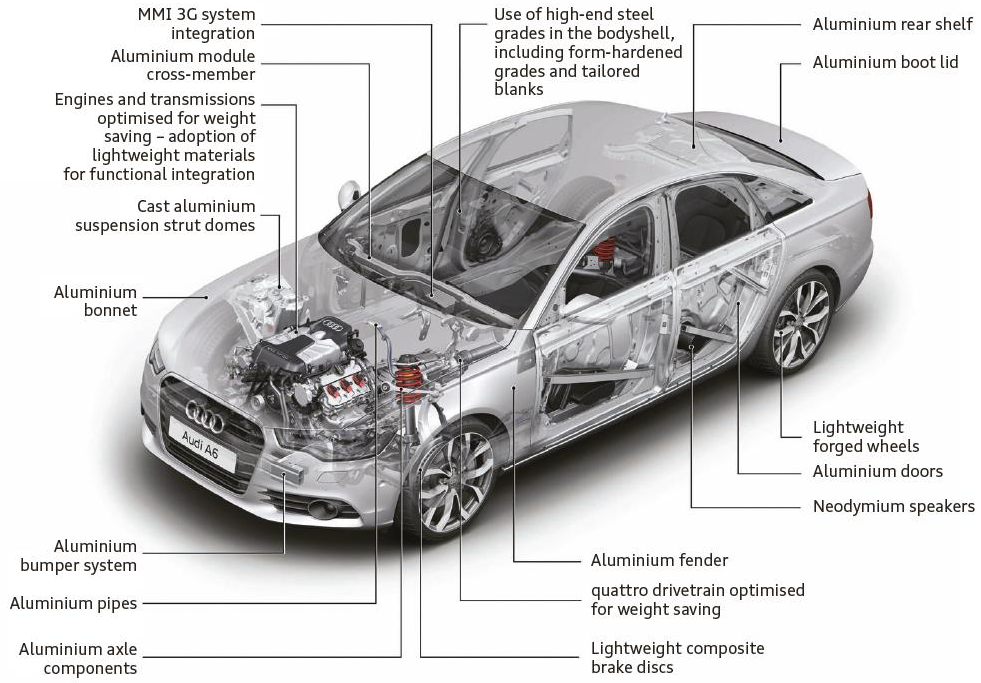
  - treating 1 ton of agriculture residues by 2 technologic options
  - FU: 1 ton of agriculture residues

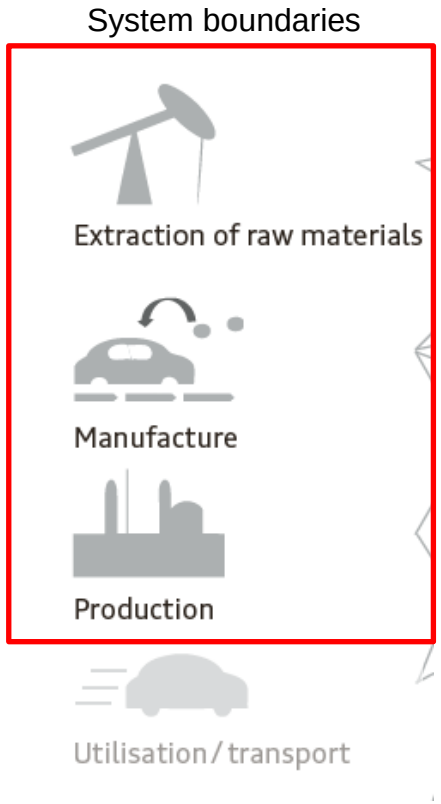
→ From an <u>energy approach</u>:

  - Delivering energy
  - FU: 1000 MWh of electricity produced from agriculture residues

The function of the system

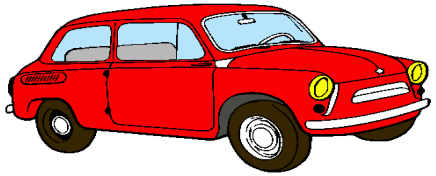
- Example: Analysis of the environmental performance in the production of a car
- Function of the system: producing cars.





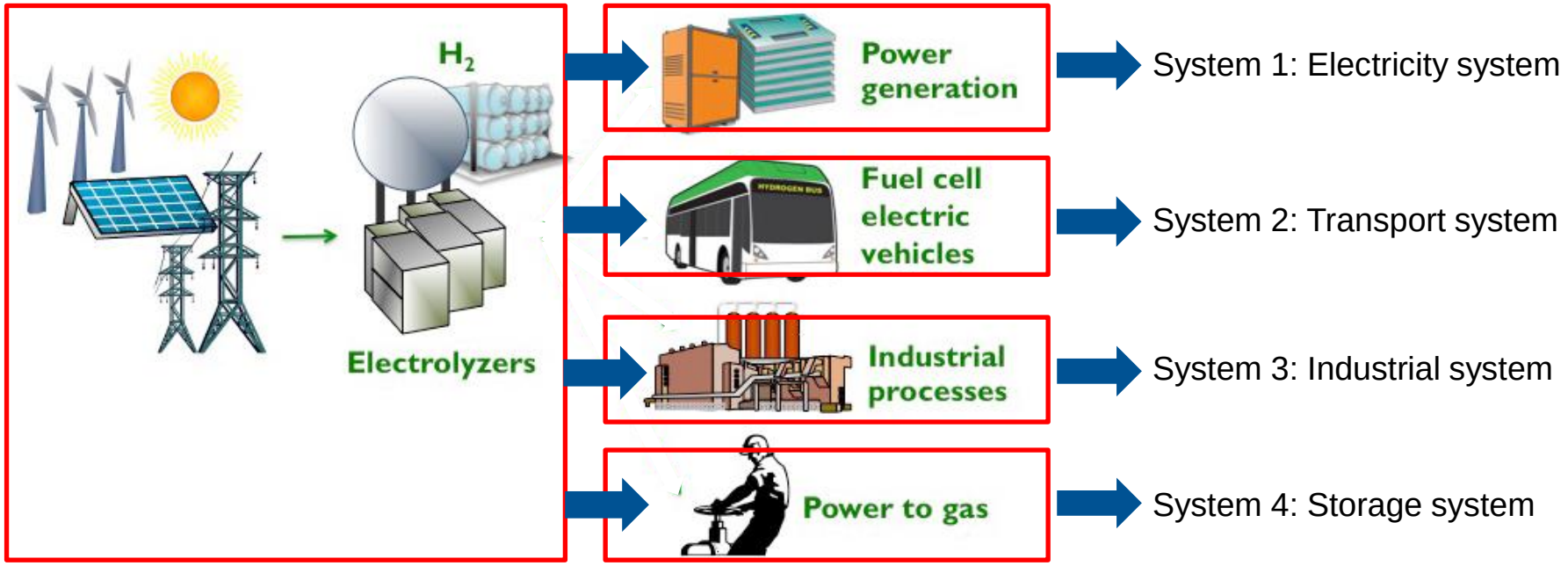
The function of the system

- Example: Analysis of the environmental performance of transport
- Function of the system: to transport people or goods from one place to another.



The function of the system

- One product could belong to several product systems
- Example: Hydrogen
- Function of the system: several functions. We should define which is under our interest.

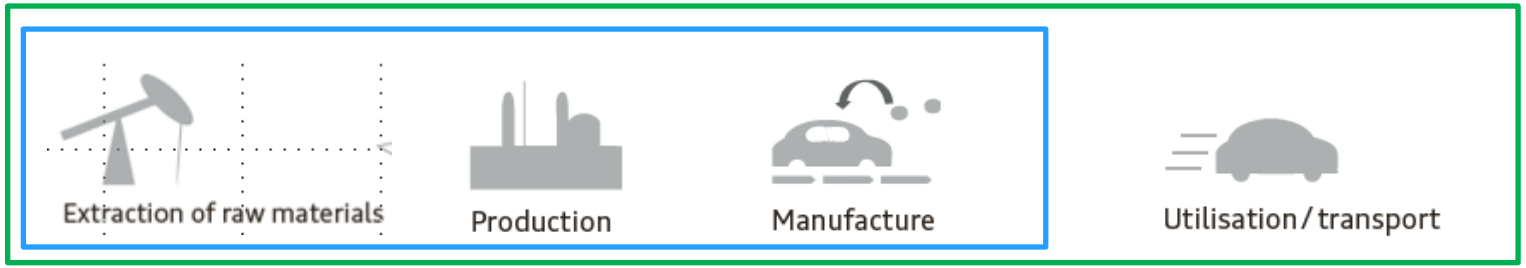


The functional unit

- The functional unit **quantifies the performance of a product** system for use as a reference unit.
- The main purpose of a functional unit is to create a reference to which the input and output flows are related.

- Example: Analysis of the environmental performance in the **production** of a car
- **Function of the system:** Autos **herstellen**
- **Functional unit**: 1 vehicle, model Z,

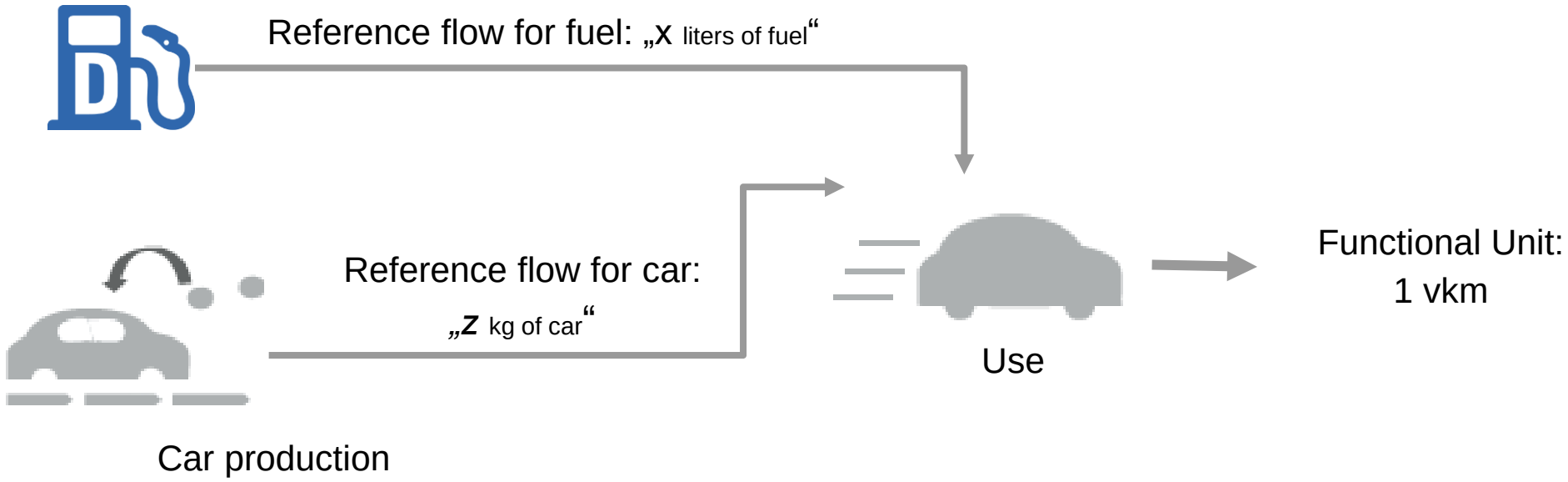
- Example: Analysis of the environmental performance of **transport**
- **Function of the system**: to transport people or goods from one place to another.
- **Functional unit**: 1pkm



The reference flows

- It is very important to correctly define a functional unit when comparing two systems.

- The reference flow measures the outputs from a process required to fulfil the function, expressed by the functional unit.



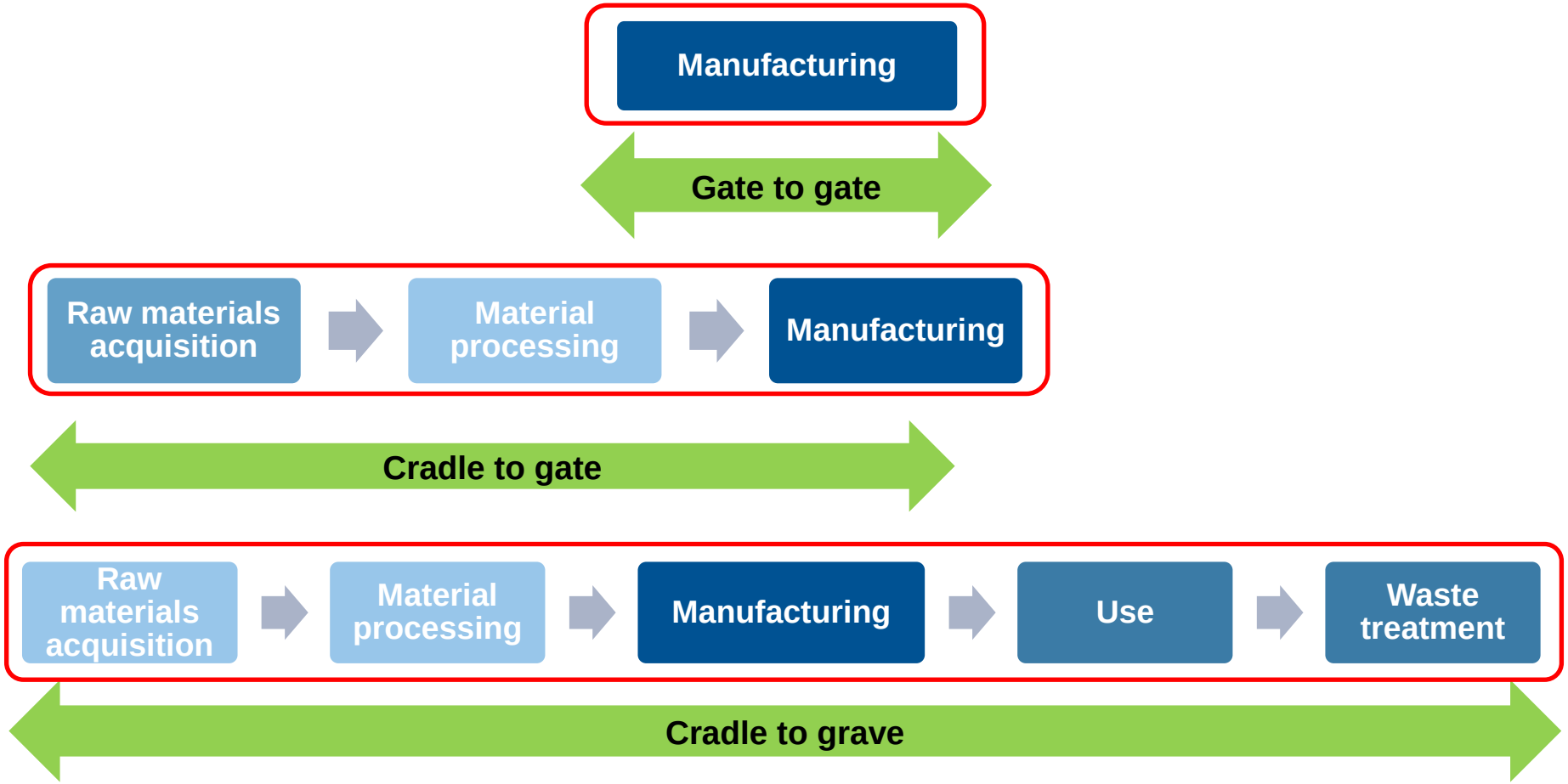
The functional unit and the reference flows

- Other examples

Product system	**Function**	**Functional Unit**	**Results in reference to the functional unit**
Automobile factory	Production of car	1 Million vehicles	CED MJ / *Million vehicles*
Freight transport	Transport of goods	1 tkm	Kg $PM_{2.5}$ / *tkm*
Biofuels	Deliver energy	1 MJ	Kg CO_2 eq / *MJ*

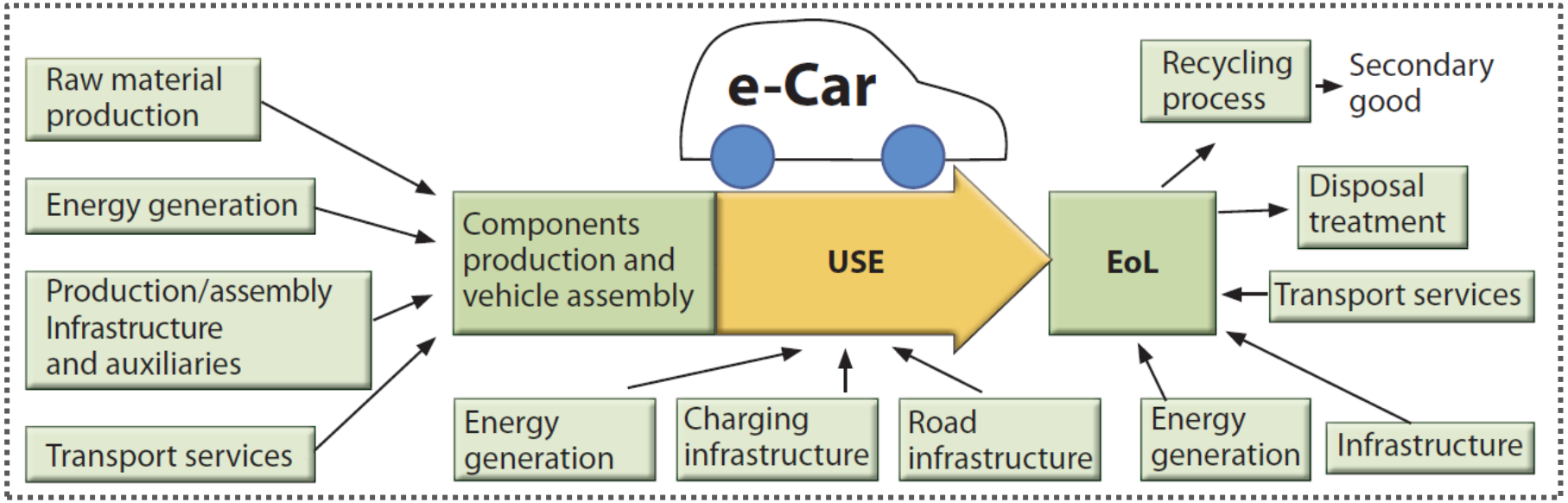
Some definitions

System boundaries



The system boundaries

System boundaries for the LCA of an electric vehicle



Source: Del Duce et al 2013 Guidebook for LCA studies in the context of e-mobility

Impact categories

a) **Impact category:** category that represents important environmental issues

i.e.: Climate change.

b) **Impact indicator:** how we measure this environmental impact.

i.e.: CO_2 equivalent for climate change

c) **Characterization factor**: Factor derived from a characterization model.

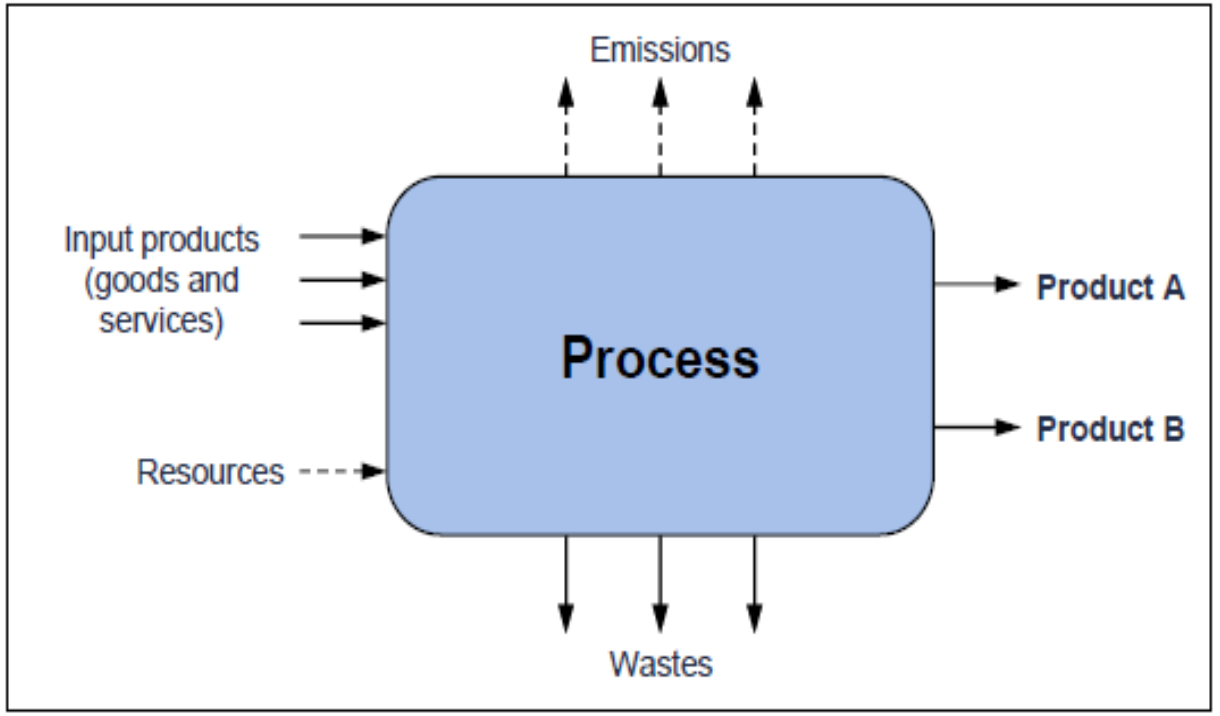
In goal and scope, we define which categories will be covered in the LCA.

Performed in Impact Assessment phase

Allocation procedures

- Many systems produce more than one product → multifunctional system
- How do we share the „environmental responsibility“ among the co-products? → solving this multifunction

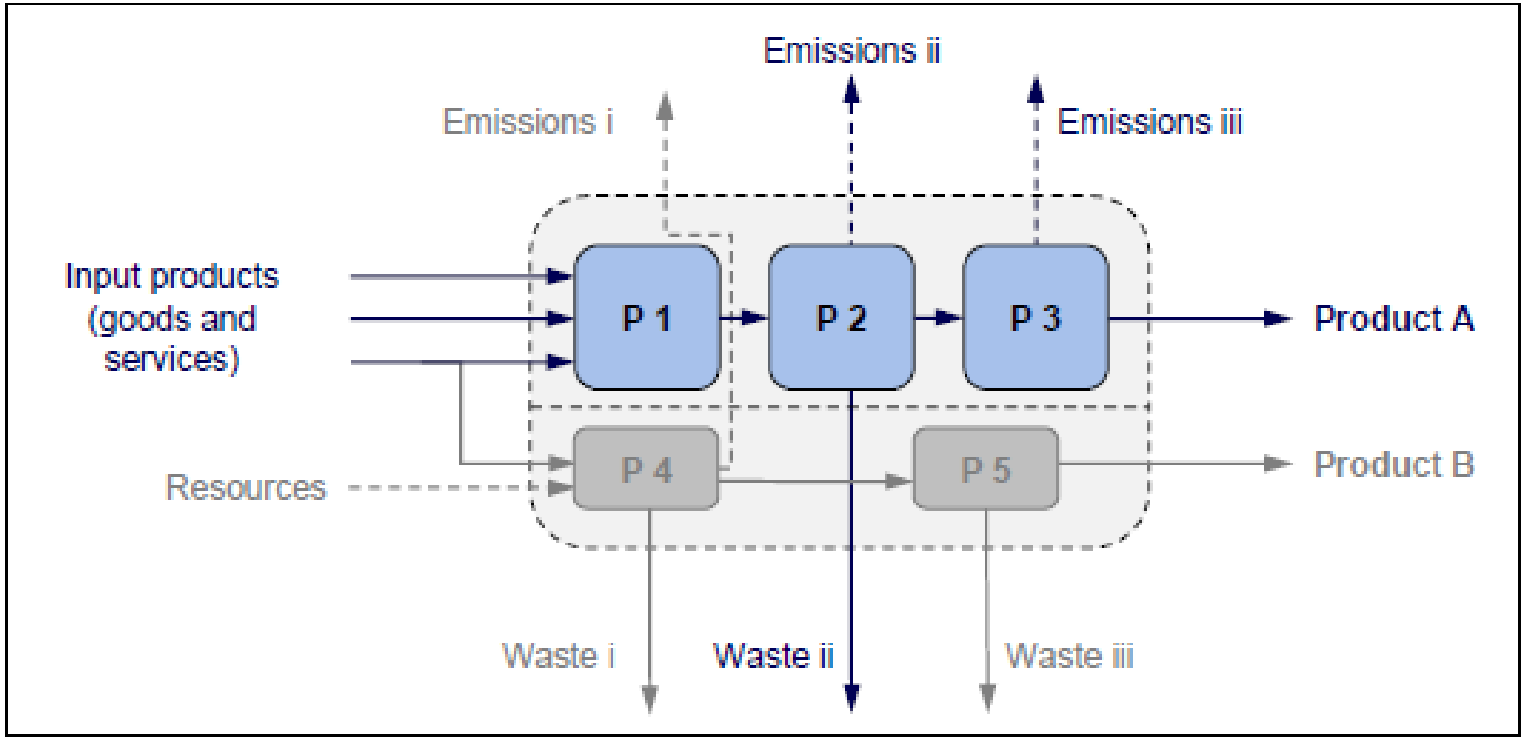
- Which procedure will be used, has to be defined also in the goal and scope
- The type of procedure will influence results



Source: ILCD Handbook, 2012

How to solve multifunctional systems? Subdivision of the systems

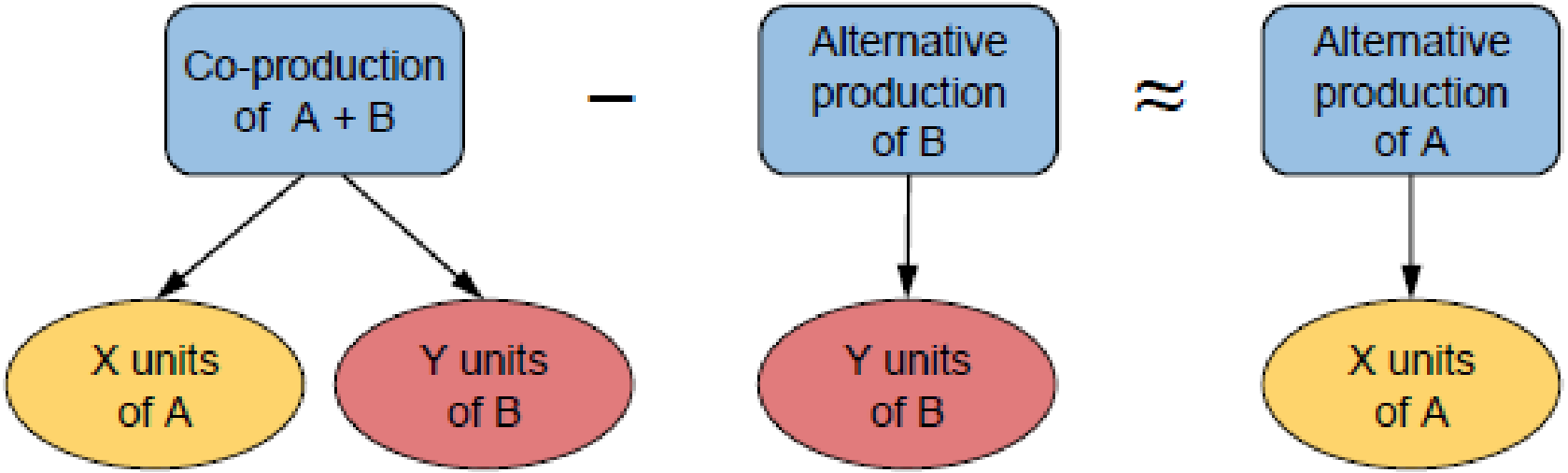
- Whenever it is possible → Subdivision of the systems



Source: ILCD Handbook, 2012

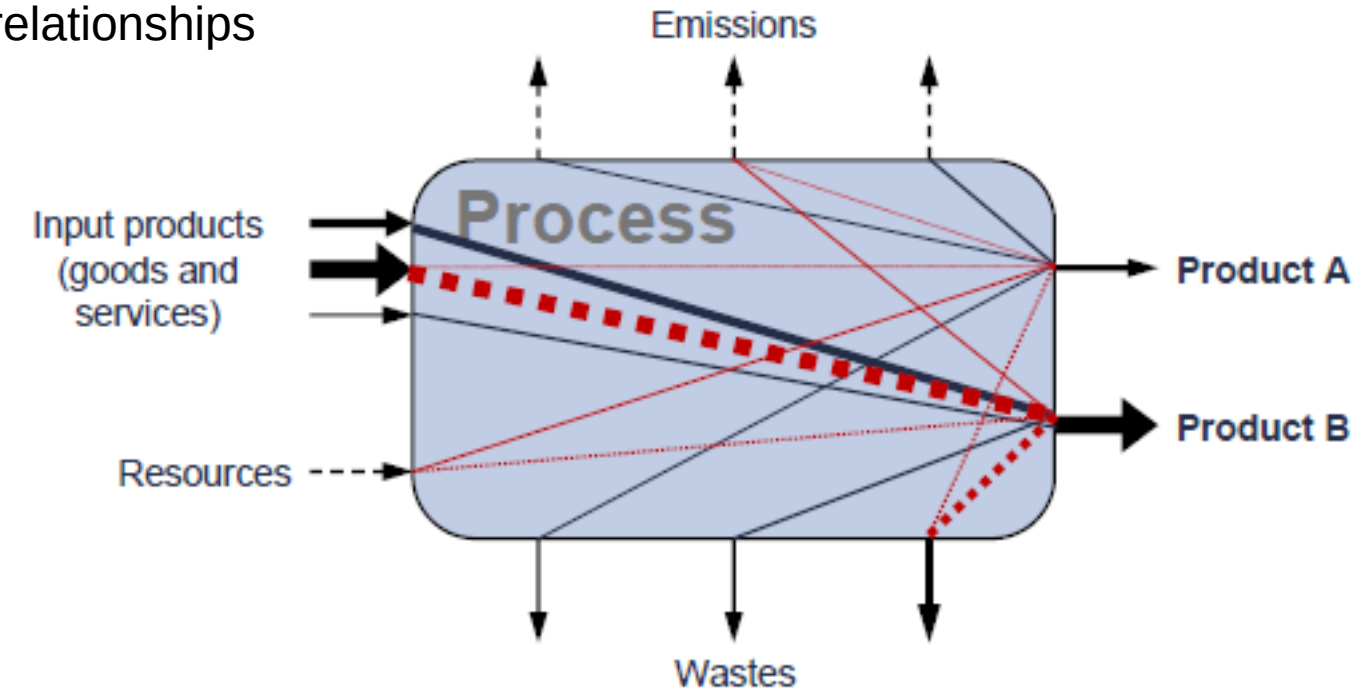
How to solve multifunctional systems? System expansion

- First rule: Expanding the system



How to solve multifunctional systems? Allocation by relationships

- Allocation through relationships



Source: ILCD Handbook, 2012

Solving multifunctional systems following ISO rules

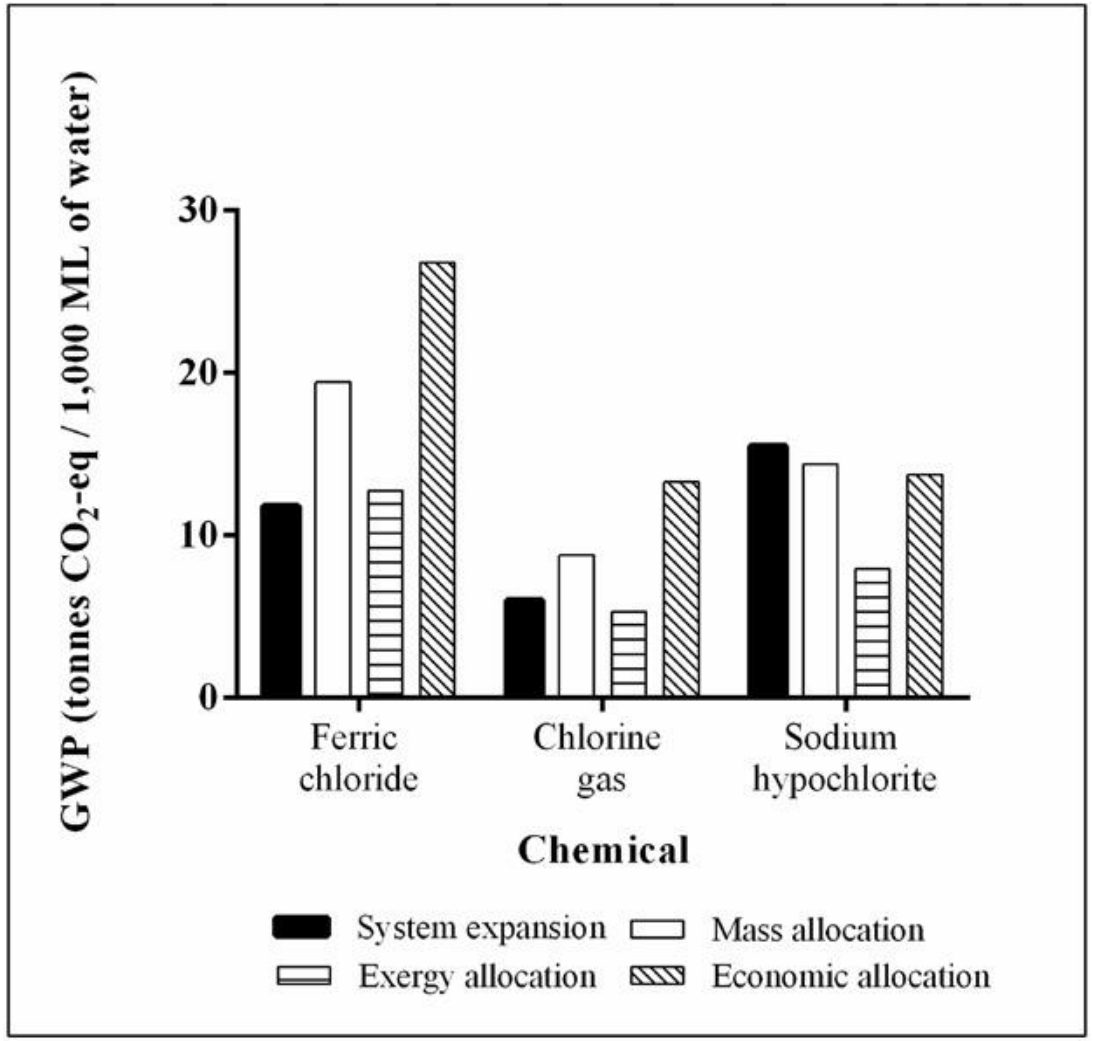
- ISO establishes some rules:

    1. Whenever is possible, allocation will be avoided
    2. If not, then allocation rules will be applied:
        a. The inputs and outputs of the system → allocated based on physical relationships.
        b. The inputs and outputs of the system → allocated based on other relationships

- Allocation: partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems

Effects of allocation in LCA

- Example: LCA of water treatment with different chemicals
- Different procedures lead to different results



Source: Alvarez-Gaitan, J. P., Peters, G. M., Short, M. D., Schulz, M. and Moore, S. (2014), Understanding the impacts of allocation approaches during process-based life cycle assessment of water treatment chemicals. Integr Environ Assess Manag

Data requirements and limitations

- Requirements for main data

Highest score → Lowest score

Indicator		1	2	3	4	5 (default)
Flow reliability		Verified[1] data based on measurements	Verified data based on a calculation **or** non-verified data based on measurements	Non-verified data based on a calculation	Documented estimate	Undocumented estimate
Flow Representativeness	**Temporal correlation**	Less than 3 years of difference[2]	Less than 6 years of difference	Less than 10 years of difference	Less than 15 years of difference	Age of data unknown or more than 15 years
	Geographical correlation	Data from same resolution **and** same area of study	Within one level of resolution **and** a related area of study[3]	Within two levels of resolution **and** a related area of study	Outside of two levels of resolution **but** a related area of study	From a different or unknown area of study
	Technological correlation	All technology categories[4] are equivalent	**Three** of the technology categories are equivalent	**Two** of the technology categories are equivalent	**One** of the technology categories is equivalent	**None** of the technology categories are equivalent
	Data collection methods	Representative data from >80% of the relevant market[5], over an adequate period[6]	Representative data from 60-79% of the relevant market , over an adequate period **or** representative data from >80% of the relevant market, over a shorter period of time	Representative data from 40-59% of the relevant market, over an adequate period **or** representative data from 60-79% of the relevant market, over a shorter period of time	Representative data from <40% of the relevant market, over an adequate period of time **or** representative data from 40-59% of the relevant market, over a shorter period of time	Unknown **or** data from a small number of sites **and** from shorter periods

Critical Review

- **Critical Review**: Process intended to ensure consistency between an LCA and the requirements of ISO 14040 series standards.
- ISO requires critical reviews if a comparative assertion is disclosed to the public.
  - **Comparative assertion**: An environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function
- Review should ensure:
  1. LCA methods are consistent with the ISO standards;
  2. Data are appropriate and reasonable in relation to the goal of the study;
  3. Limitations are set and explained;
  4. Assumptions are explained; and
  5. Report is transparent and consistent and the type and style are oriented to the intended audience.

Performed in Interpretation phase

Critical Review

Types of review: expert should be familiar with LCA and have the appropriate scientific and technical expertise.

- By an expert
  - Independent external reviewer: not involved in the definition or development of the case nor in the organisation that performed or commissioned the case study. Totally independent.
  - Independent internal reviewer: not involved in the definion or development of the case but can be part of the organization.
- By a panel of interested parties: at least three players. It may include government agencies, non-governmental groups, competitors and affected industries.

Performed in Interpretation phase

Agenda

Life cycle inventory analysis

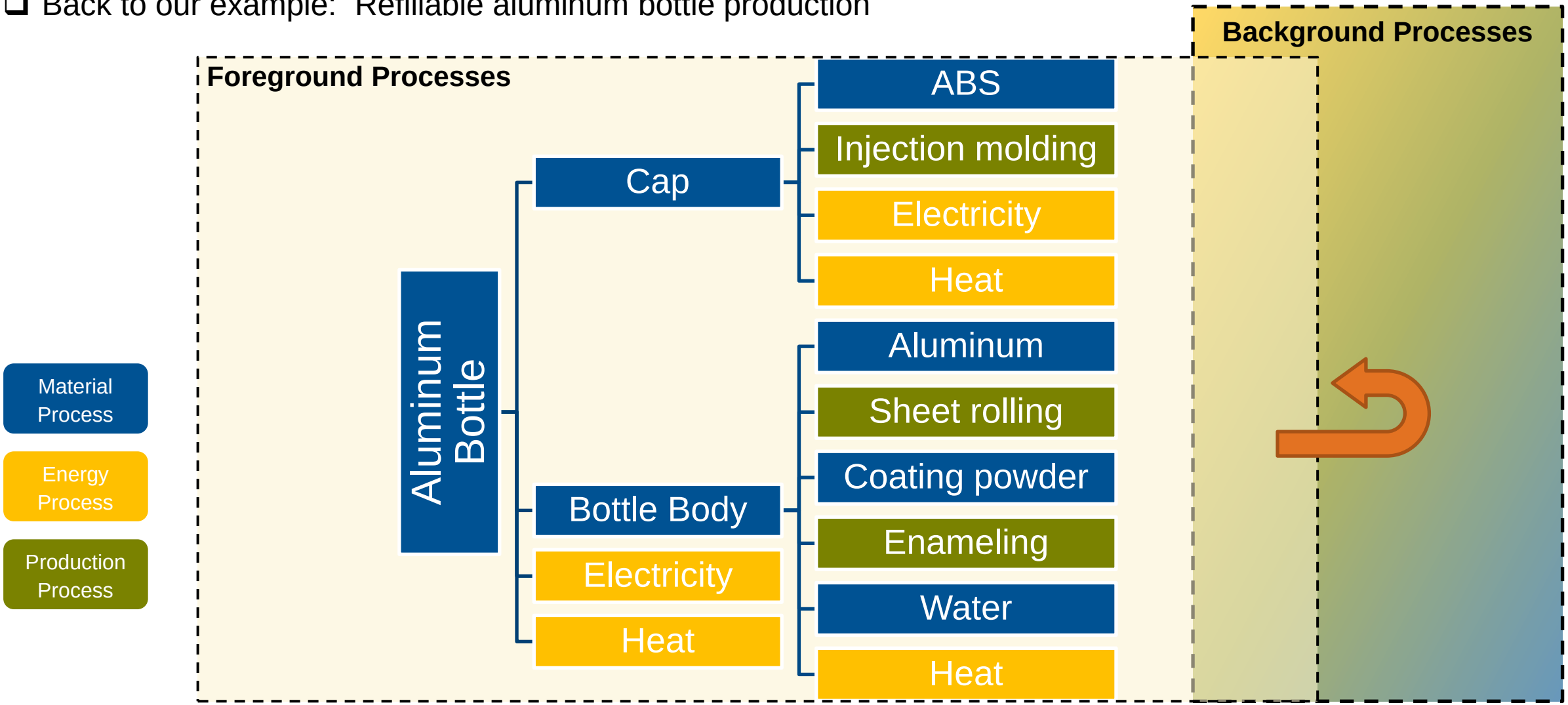
- Data collection for process within the systems boundary
  - energy inputs, raw materials inputs, ancillary inputs, other physical inputs,
  - products, co-products and waste,
  - emissions to air, discharges to water and soil and other environmental aspects.
- Data calculation
  - Validation of data collected
  - Relation of data with processes, functional unit and references flows.
- Allocation of flows and releases

Life cycle inventory analysis

- Foreground system: Primary data
  - Collect specific data from specific companies for your processes.
  - Some data are relatively easy to obtain from a company:
    - Material input, energy, co-products, production waste…
  - Some data are relatively complex to obtain from a company:
    - Emissions into air and water, material input not from direct processes....
- Background system: Generic data
  - General data
  - Mean values or representative single values

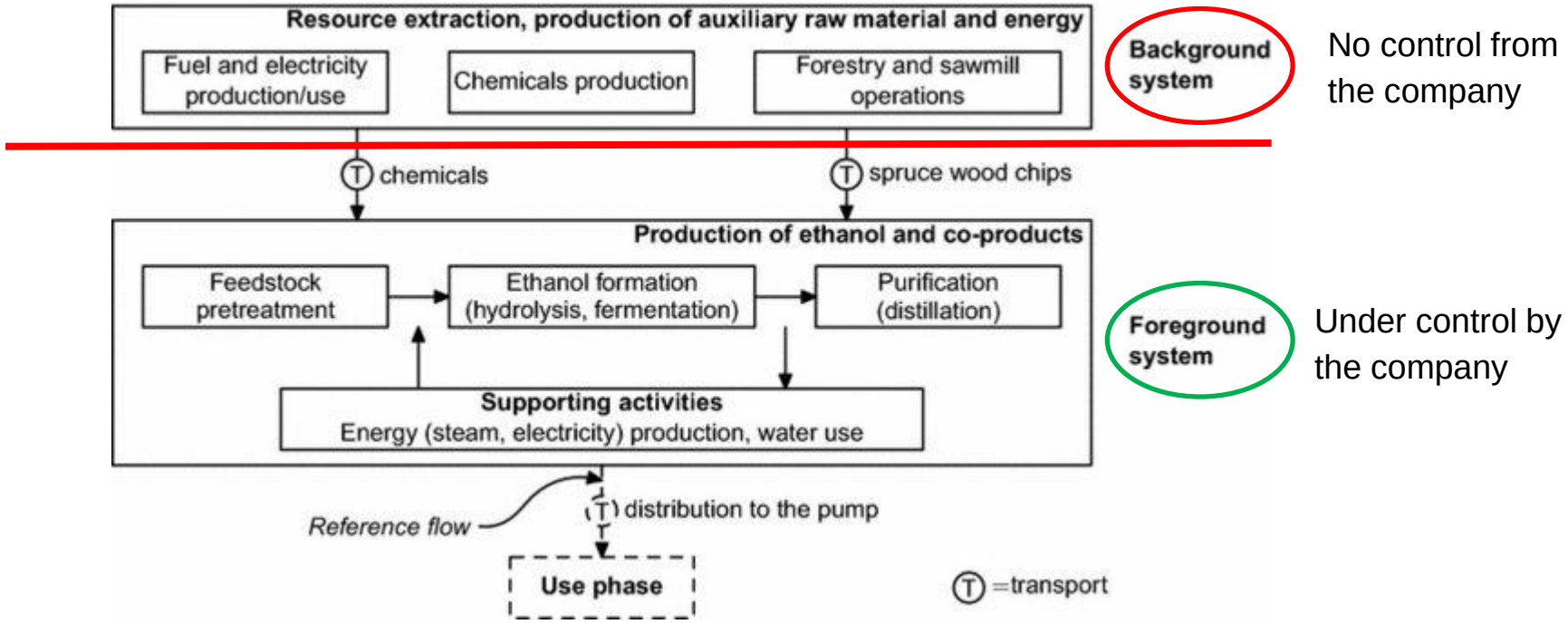
Foreground and background data

❑ Back to our example: Refillable aluminum bottle production



Life cycle inventory analysis

- Analysis of producing ethanol for a company



Source: Janssen et al. 2016 Life cycle impacts of ethanol production from spruce wood chips under high-gravity conditions. Biotechnology for Biofuels. https://doi.org/10.1186/s13068-016-0468-3

Life cycle inventory analysis: Generic data

- The most important areas where generic data/ background data are needed are:

1. Energy:
   - energy sources of fossil origin (natural gas, diesel/light oil, heavy oil, petrol, hard coal, lignite)
   - Uranium ore ex deposit, enrichment
2. Transport
   - Specific consumption of trucks, trains, aircraft, pipelines
   - Specific load capacity, ...
3. Common materials
   - production processes of various metals and plastics: iron, steel, aluminium, PVC,.
   - manufacturing operations

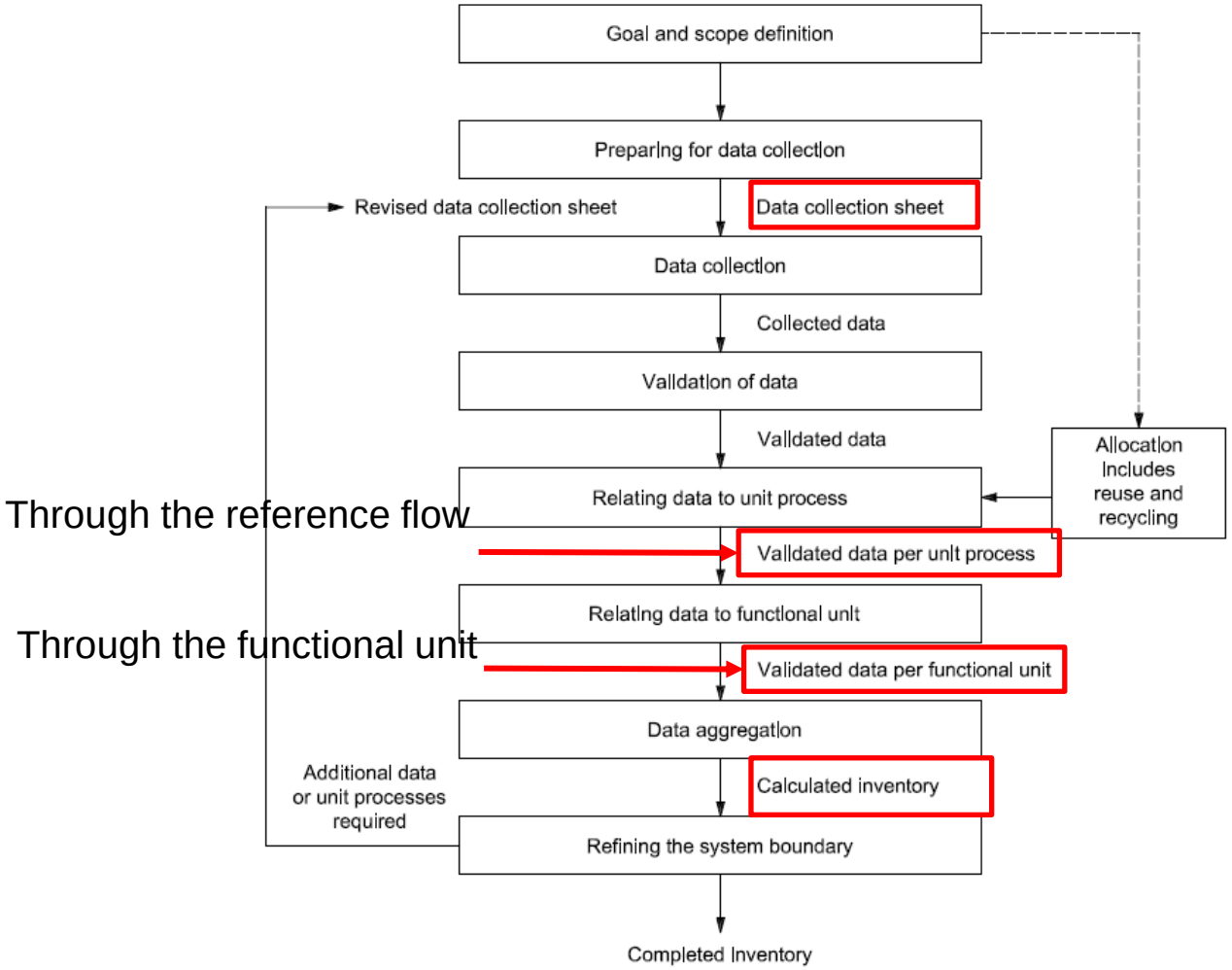
Life cycle inventory analysis: Generic data

- Databases are a good source of generic data.

1. Free databases:
   - European Life Cycle Database,
   - US Life Cycle Inventory Database. NREL,
   - Worldsteel Life Cycle Inventory Database

2. Commercial databases:
   - Ecoinvent Database, Switzerland
   - Sphera Database, Germany

Life cycle inventory analysis



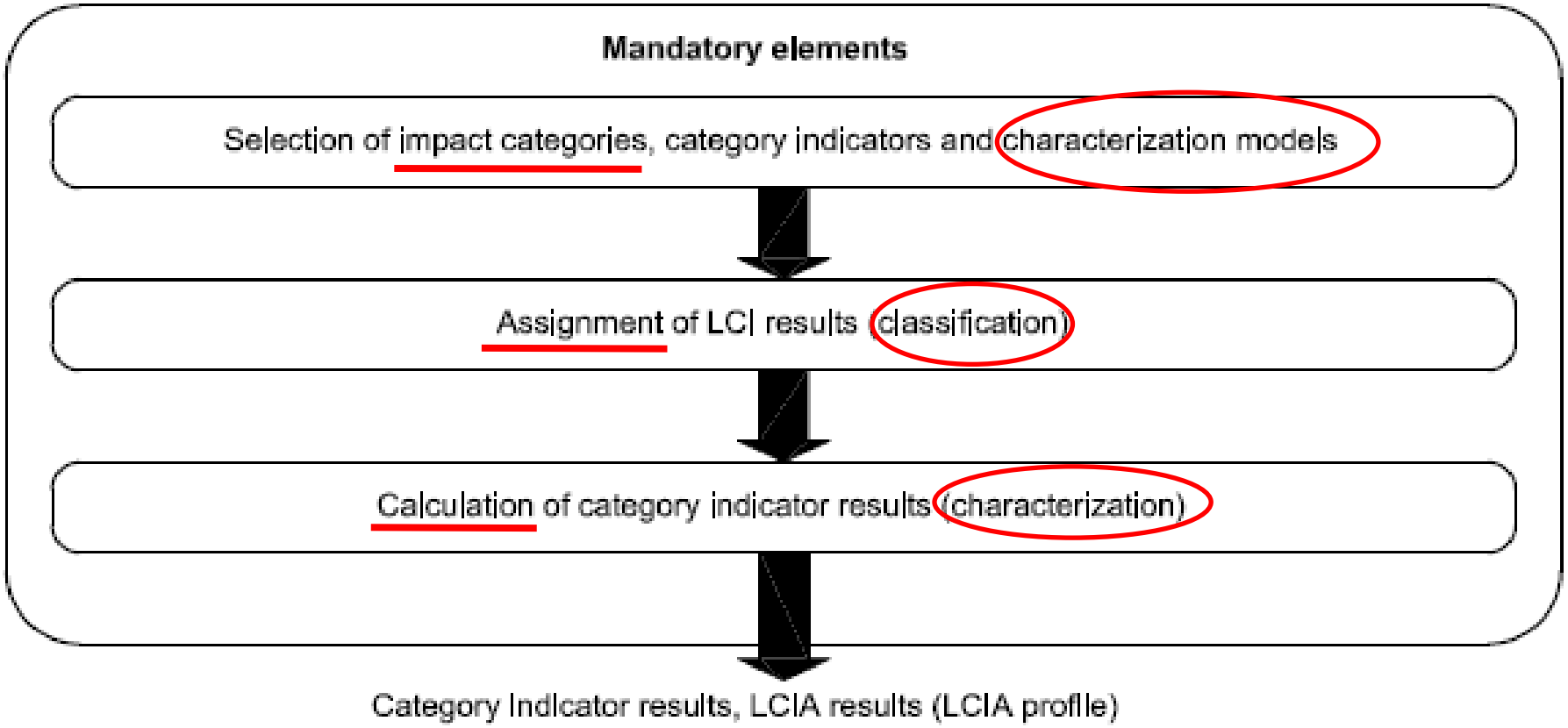
Agenda

Life cycle impact assessment

- It aims to assess the actual effects of environmental burdens on humans, ecosystems, and resources.
- It is based on indicators of impacts or impacts categories.
- Indicators are evaluated under the impact methods previously defined in the goal and scope phases.
- It is the least mature phase of LCA

Life cycle impact assessment

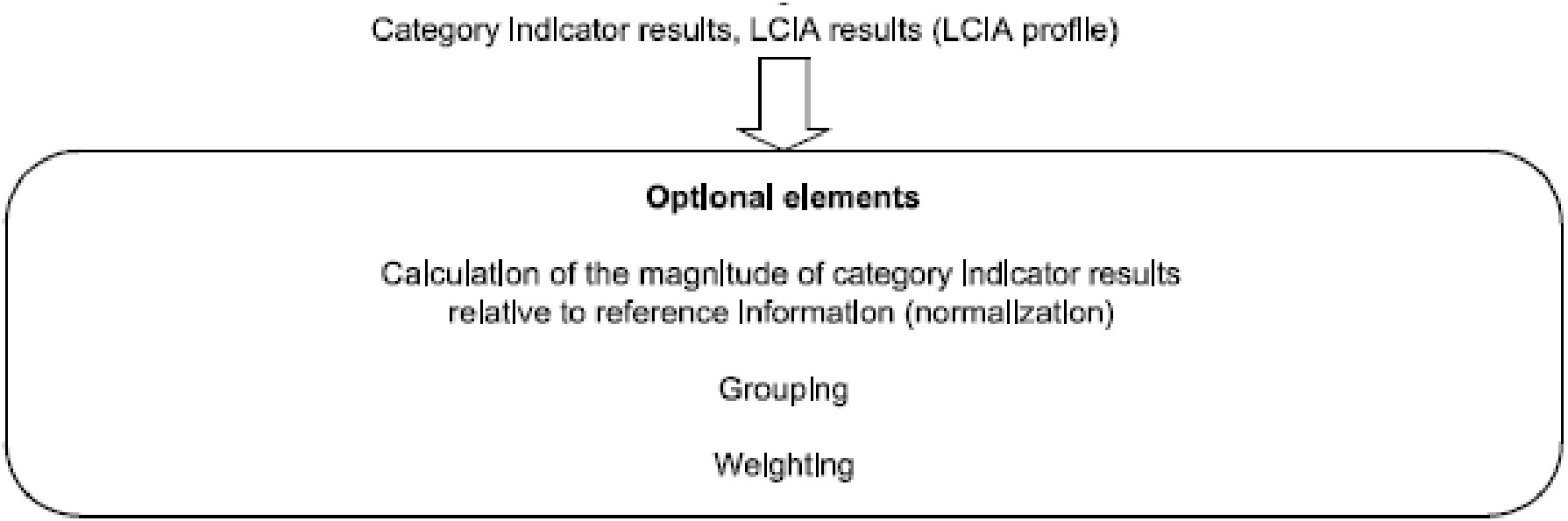
- Mandatory



Source: ISO 14040:2006

Life cycle impact assessment

- Optional elements



Source: ISO 14040:2006

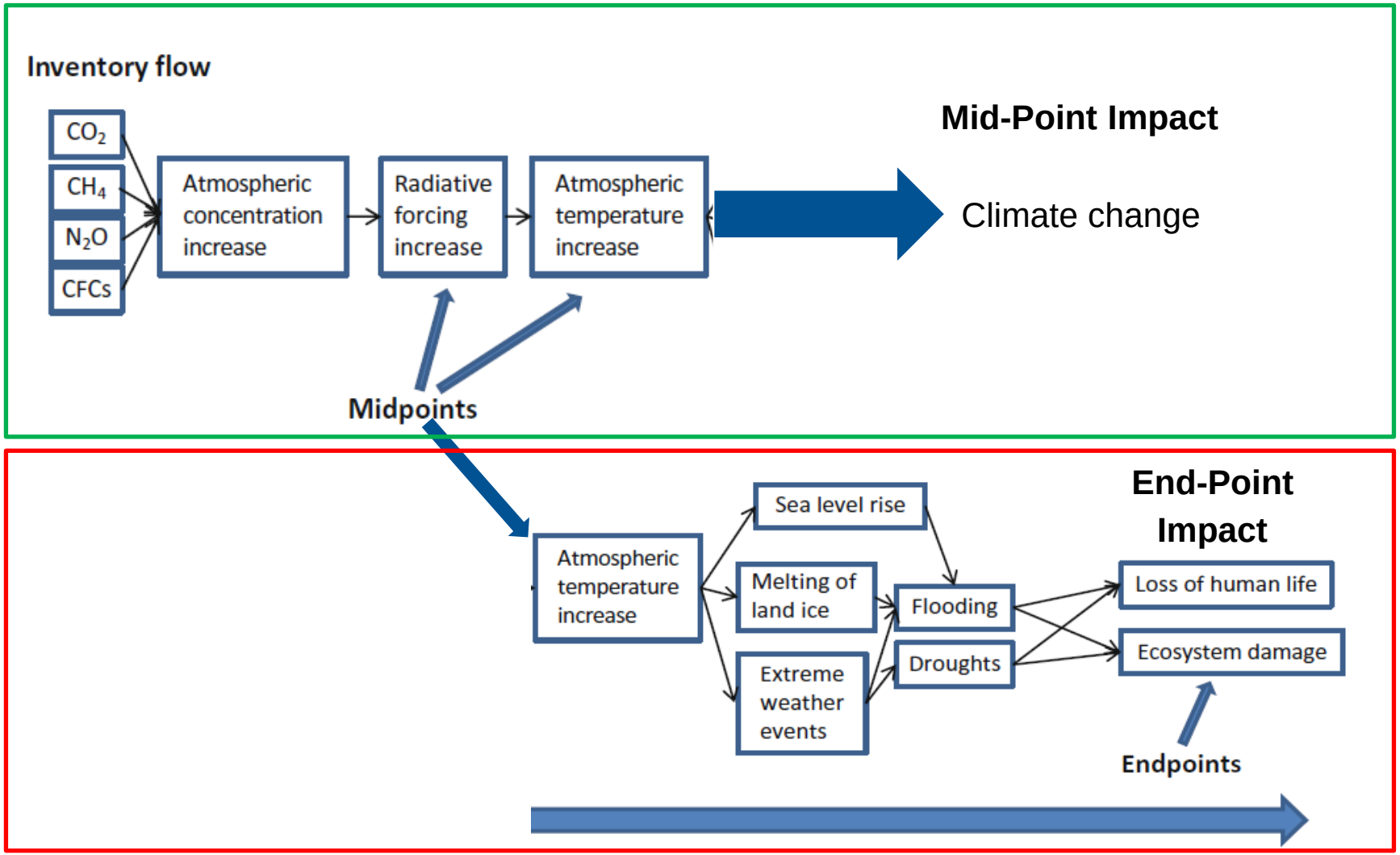
Life cycle impact assessment

- two impact indicators: mid-point and end-point indicators.
- End-point indicators have relatively high uncertainty; not recommended

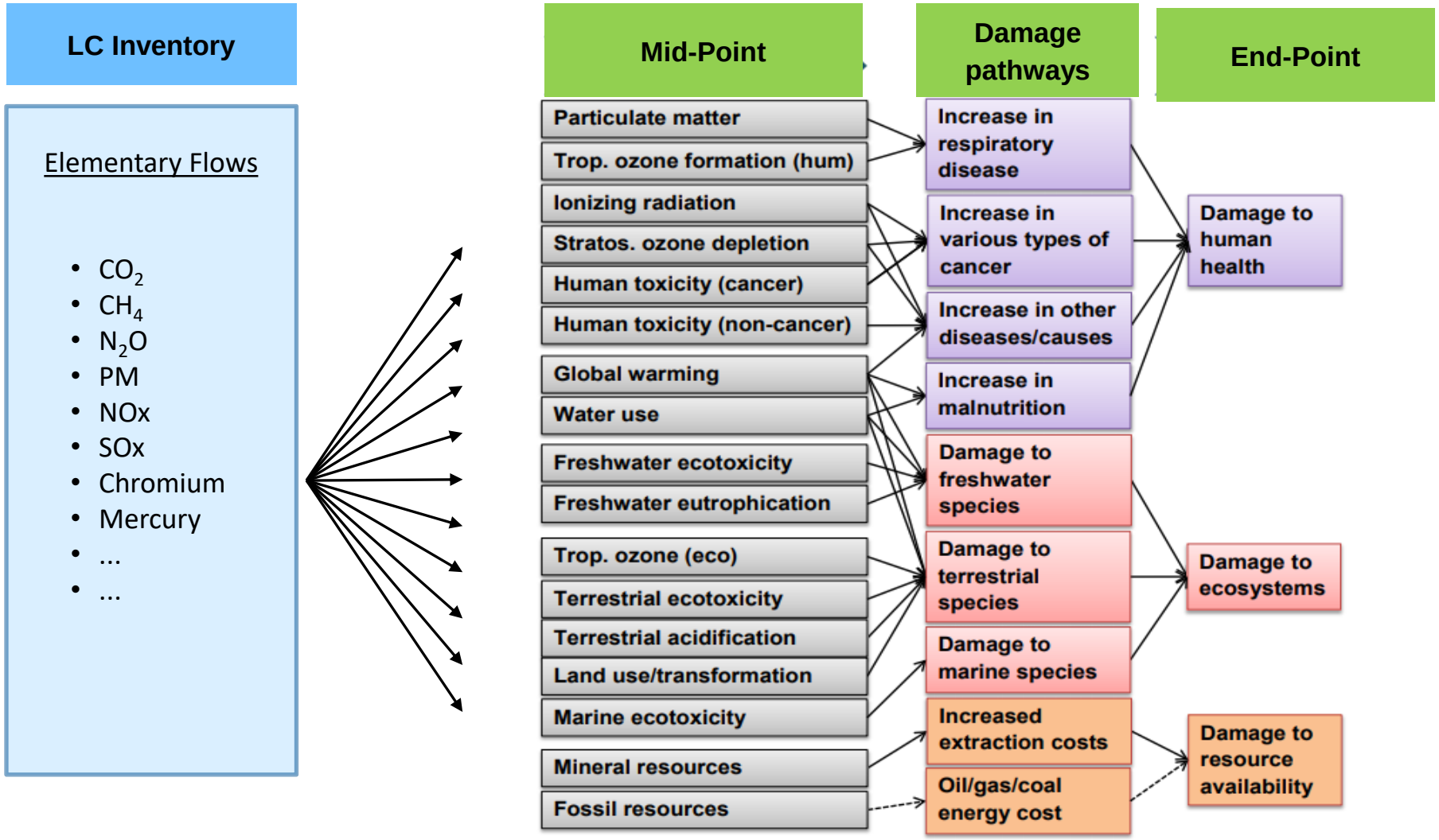
1. A **mid-point indicator** is a measure of a scientifically describable effect that is related to the endpoint of the effect.
   - climate change
   - Stratospheric ozone depletion
   - Photochemical oxidant formation
   - acidification
   - eutrophication
   - Toxic damage by fine dust
   - resource depletion

2. An **end-point indicator**, on the other hand, is a direct measure of the endpoint itself. The use of end-point indicators requires complex models, which in turn are based on various assumptions.
   - Human Health
   - Ecosystem
   - Resources

Life cycle impact assessment



Life cycle impact assessment



Life cycle impact assessment

- Classification: which pollutants cause which impacts.

Elementary flow	Climate change	Ozone layer depletion	Eutrophication
1 kg CO_2 (Carbon dioxide)	X		
100 gram CH_4 (methane)	X		
1 gram CFC142b	X	X	
5 gram NO_2 (nitrogen dioxide)			X

- The result of classification→ substances are assigned to the impact category they contribute to.

Life cycle impact assessment

- Characterization: All substances are multiplied by a factor which reflects their relative contribution to the environmental impact, quantifying how much impact a product or service has in each impact category.

Elementary flow	Climate change		Ozone layer depletion		Eutrophication	
	CF	Result	CF	Result	CF	Result
1 kg CO_2 (carbon dioxide)	1	1				
10 gram CH_4 (methane)	25	0.25				
1 gram CFC142b	2310	2.31	0.07	0.00007		
5 gram NO_2					0.56	0.0028
Impact Category Indicator Result		**3.56**		**0.00007**		**0.0028**
Unit of the result	kg CO_2 equivalent		kg CFC11 equivalent		kg P equivalent	

- As result from characterization, a unique result for each category is obtained in a common unit: CO2 equivalent for climate change, Chlorofluorocarbon 11 for Ozone layer depletion…

Optional steps - Normalization

How important is a global warming impact of 50 tons CO_2 eq?

- Normalization. The quantified impact is compared to a certain reference value, for example the average environmental impact of a European citizen in one year.
- “Normalizes” against some baseline
  - Normalisation based on the total emissions in a county/region, total per-capita, etc.
  - Normalisation against one of the other options being studied (A vs B)
- Normalizing based on total effects generally yields negligible values

Optional steps - Weighting

Is global warming more important than human toxicity?

- Weighting. Comparative weighting of the impacts against each other
- Impact categories are assigned an importance value, and the resulting figures are used to generate a single score
- It is based on value judgement
  - Different people in different contexts, regions, time horizon will give different importance to each impact
- Rarely applied in LCA studies.

Agenda

Interpretation

- Evaluation:
  - Do the results match the objective and the scope of the study?
  - Are there important assumptions that could have a strong influence on the results?
    - ✓ Sensitivity analysis: usually done for allocation procedures. Also in other assumptions such as efficiencies, lifespan, energy mixes…
  - Main conclusions
  - Recommendations and decision-making aids discussed
- Reporting: Pay attention to your audience → scientific (whole LCA), non professional audience (partial, or normalized), …
- Critical review: mandatory when there is an assertive comparison

Limitations of Life Cycle Analysis

General limitations:

- It requires a lot of data.
- Some industries do not share the data for confidential reasons.
- Data uncertainty.
- No direct dynamic perspective: all flows over the entire life cycle are bundled into timeless indicators.
- Despite the simple method, knowledge of the life cycle assessment is very complex. This complexity is hidden in standard LCA tools.
- The software seems to give simple answers, but not always RIGHT!! Life cycle analysis does not always (normally) declare a "winner".