CIRAIG™

International Reference Centre for the
Life Cycle of Products, Processes and Services

Introduction to Life Cycle Assessment

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POLYTECHNIQUE MONTRÉAL

Course outline

- Context
  - IPAT equation, great acceleration and planetary boundary
- Introduction to LCA
- Reasons to perform a LCA
  - Few LCA examples
- Defining the goal and scope of LCA
  - Function, functional unit, reference flows, system boundary
- Life cycle inventory
  - Scaling intermediary flows, LCI databases, allocation rules
- Life cycle impact assessment
  - Classification, characterization, normalization and weighting
- Interpretation
- Conclusion
  - Key points for an LCA

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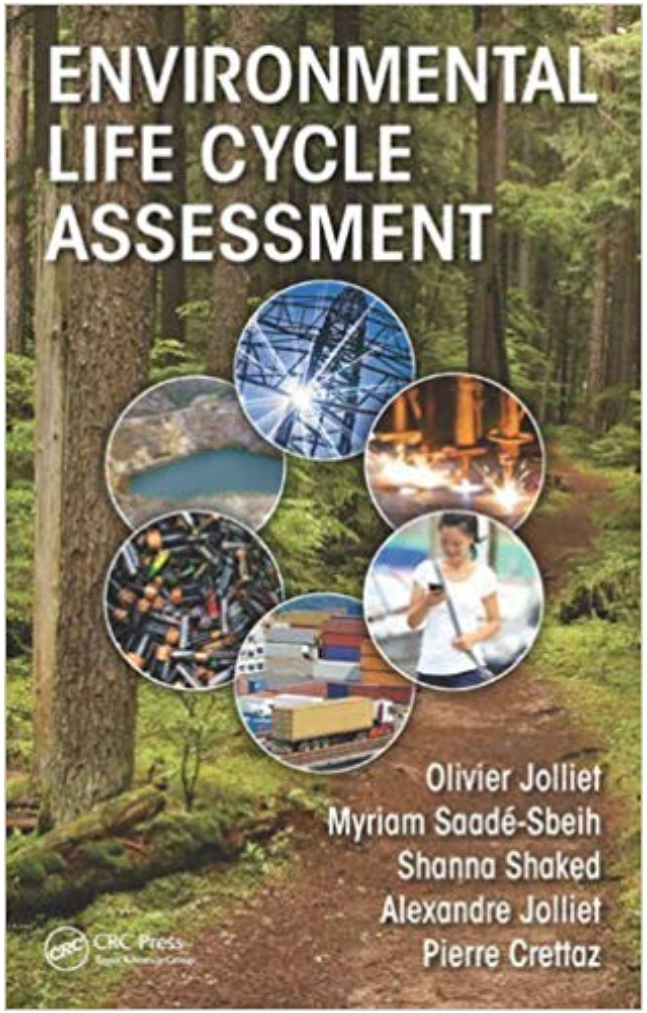
LCA textbooks



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Literature references

ISO 14 040 (2006) *Environmental management — Life cycle assessment — Principles and framework*, **International Organization for Standardization, 28 p.**

ISO 14 044 (2006) *Environmental management — Life cycle assessment — Requirements and guidelines*, **International Organization for Standardization, 54 p.**

THE EUROPEAN PLATFORM ON LIFE CYCLE ASSESSMENT - ILCD Handbook, http://eplca.jrc.ec.europa.eu/?page_id=86

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IPAT equation

$$\text{Impact} = \text{Population} * \text{Affluence} * \text{Technology}$$

$$\text{Environmental Impact} = \text{population} \times \frac{\text{GDP}}{\text{person}} \times \frac{\text{impact}}{\text{GDP}}$$

Concept developed by Ehrlich and Holdren (1971).

read article:
Chertow (2000). The IPAT Equation and Its Variants: Changing Views of Technology and Environmental Impact. Journal of Industrial Ecology, Volume 4, Number 4, pp 13-29.

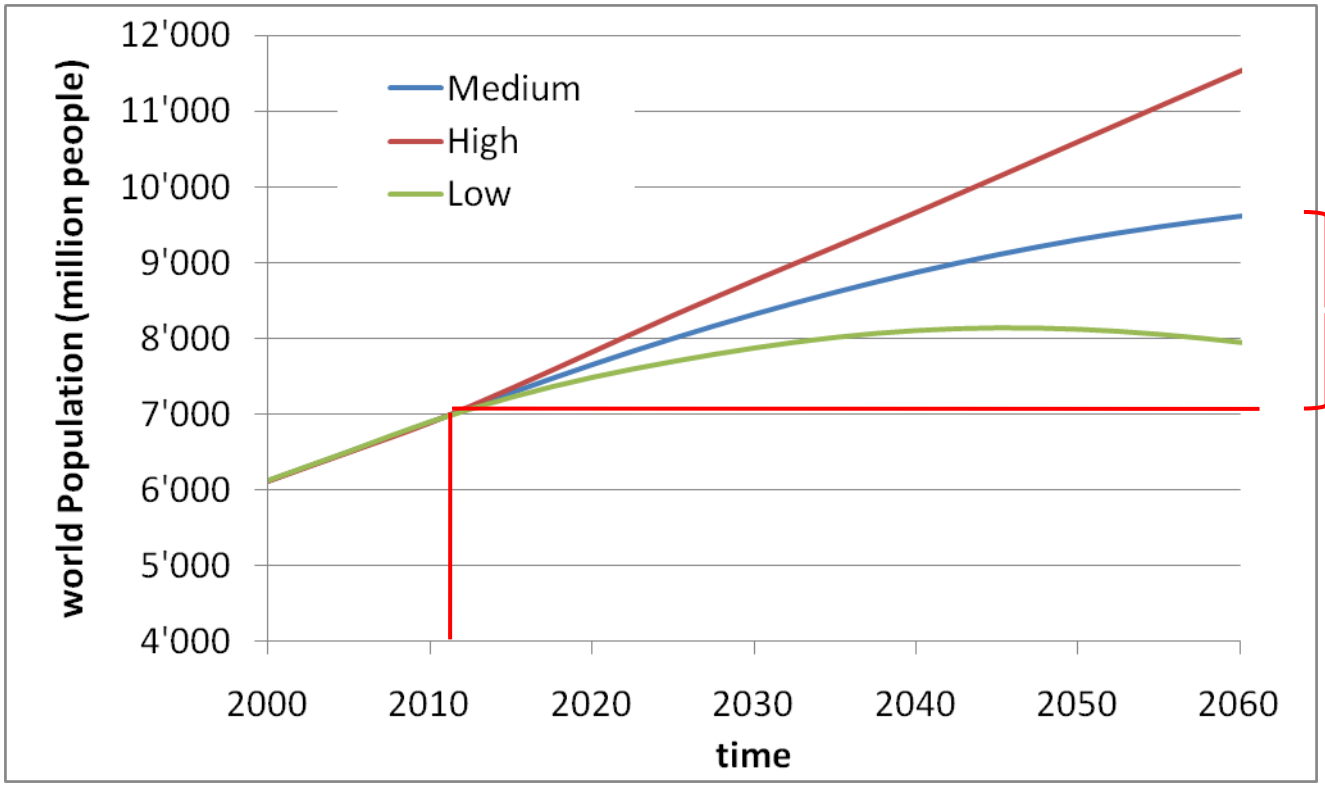
IPAT equation: Population

$$\text{Environmental Impact} = \text{population} \times \frac{\text{GDP}}{\text{personne}} \times \frac{\text{impact}}{\text{GDP}}$$

Should we control population?

Population Evolution Scenarios

As compared to today, by how much will environmental impacts increase by 2060, due to population growth alone?



+ 35% as compared to today, on average

Source: UN World Population Prospects: The 2010 revision

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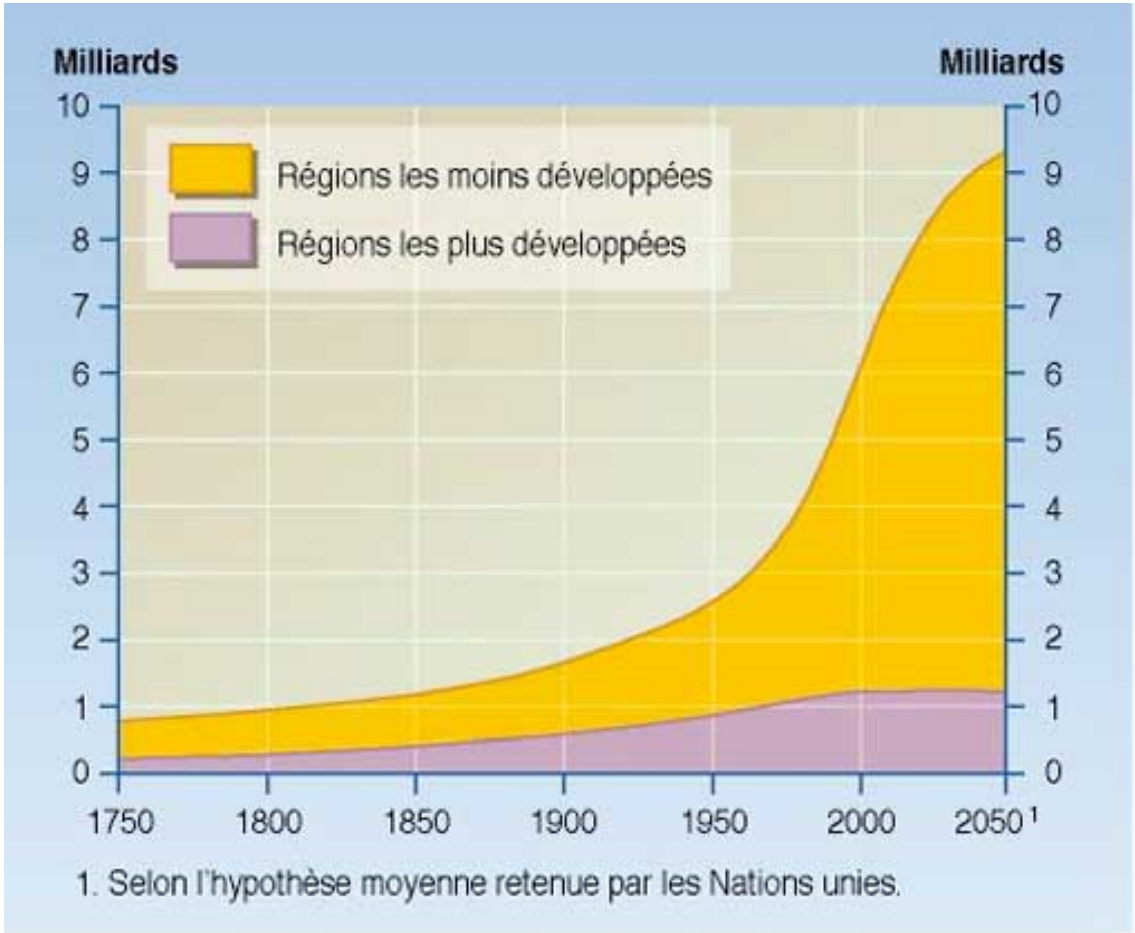
IPAT equation: Population

Is it a problem from developing countries?



Source : *World population 1998, The World at Six Billion* (octobre 1999) et *World Population Prospects: The 2000 Revision*, (février 2001), Nations unies, Département des affaires écono-miques et sociales, Division de la population, New York.

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IPAT equation: Affluence

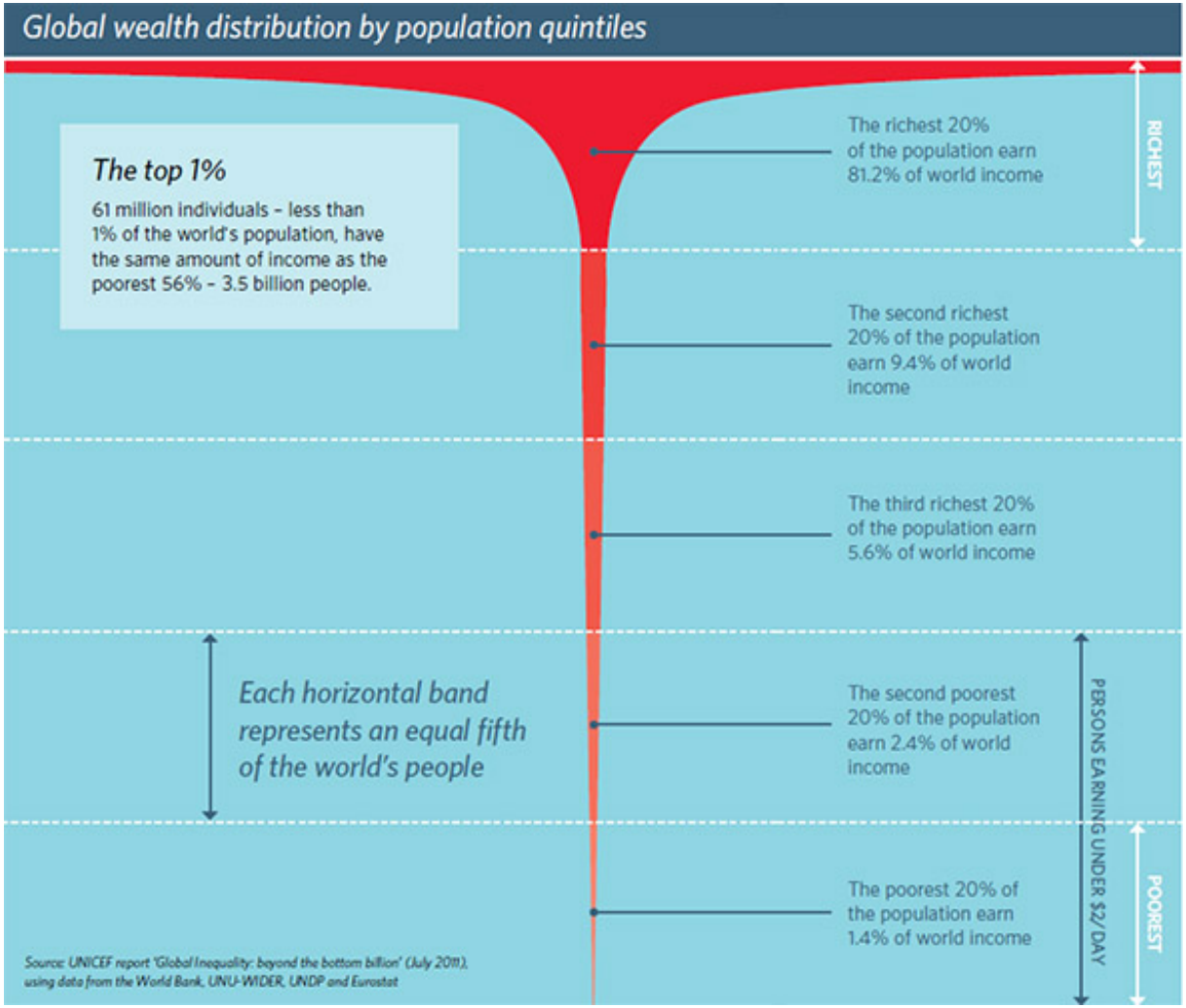
$$\text{Environmental Impact} = \text{population} \times \frac{\text{GDP}}{\text{person}} \times \frac{\text{impact}}{\text{GDP}}$$

Is the social and human wellbeing coupled to GDP? How much?

Is it possible to decouple GDP and human wellbeing?

IPAT equation: Affluence

Problem stamming from reach countries?



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IPAT equation: Affluence

Middle class houlsehold- Californie

Middle class household- Mali

Photographie de Peter Menzel, Material World (1994)

20% of the population is responsible for 90% of the consumption
20% of the population live with less than 1$/day

Commission du développement durable de l'ONU, 2002

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Affluence in the World (2010 to 2060 predictions)

Compared to today, by how much will environmental impacts increase by 2060, due to growth in affluence alone?

	Population total	GDP / capita	GDP / capita growth, avg past 10 years
Low income countries	817 million	1'980 $	2.8%
Middle income countries	4'920 million	3'979 $	4.6%
High income	1'123 million	38'293 $	1.0%

Source: World Bank Statistics

	GDP / capita
Current global affluence	9'358 $
2060 global affluence (prediction)	38'287 $

4-fold increase compared with today's impact

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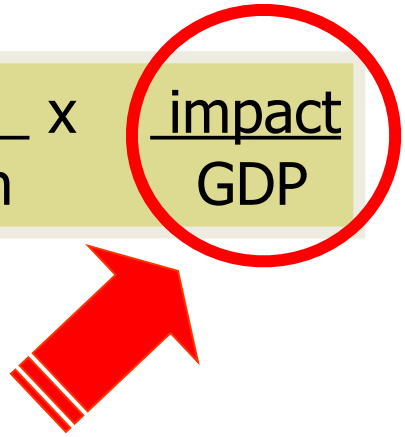
Équation IPAT : Recherche des leviers: T

$$\text{Environmental Impact} = \text{population} \times \frac{\text{GDP}}{\text{person}} \times \frac{\text{impact}}{\text{GDP}}$$



Impact reduction of economic/technological activities?

Field where the engineer is finding solutions

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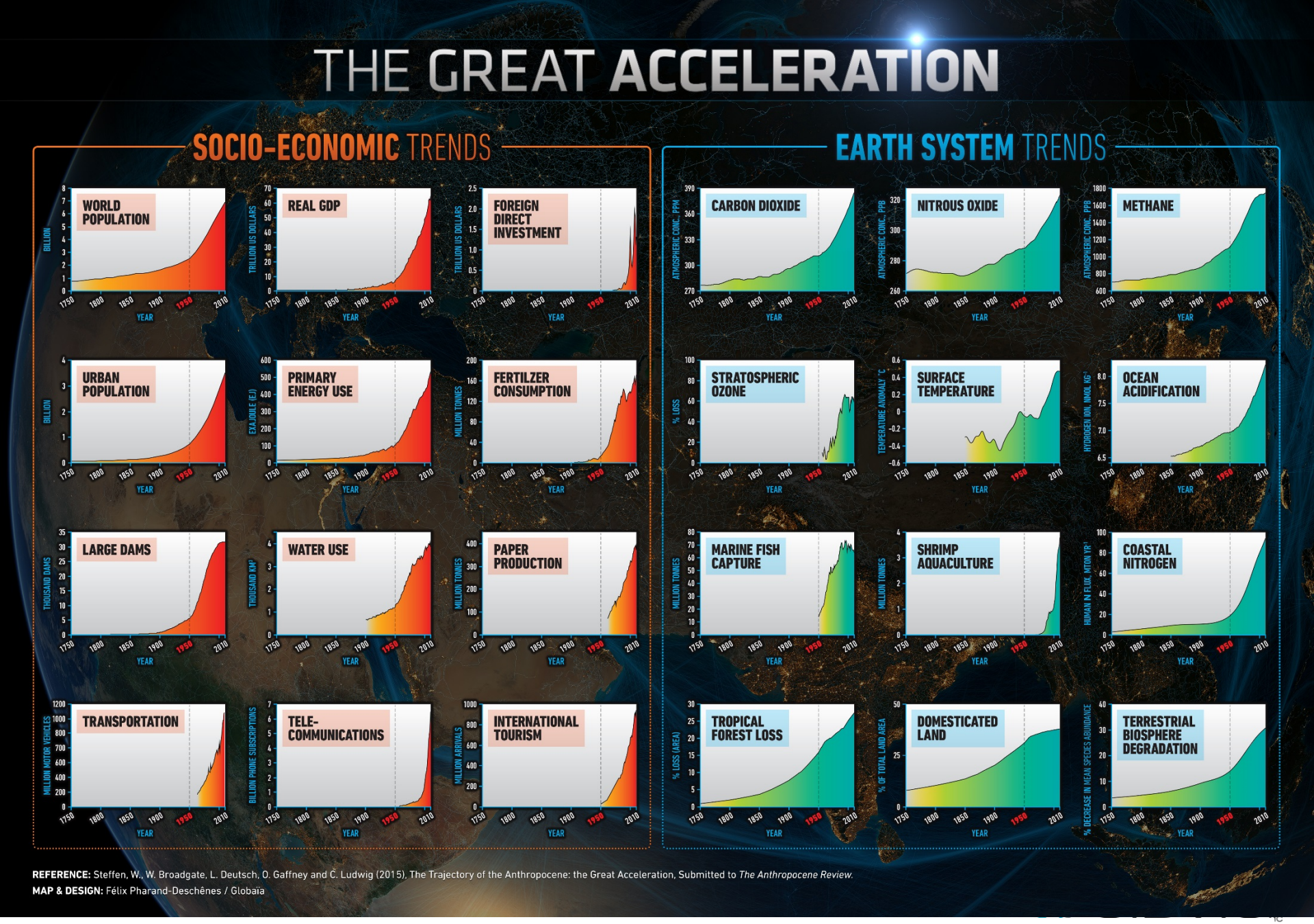


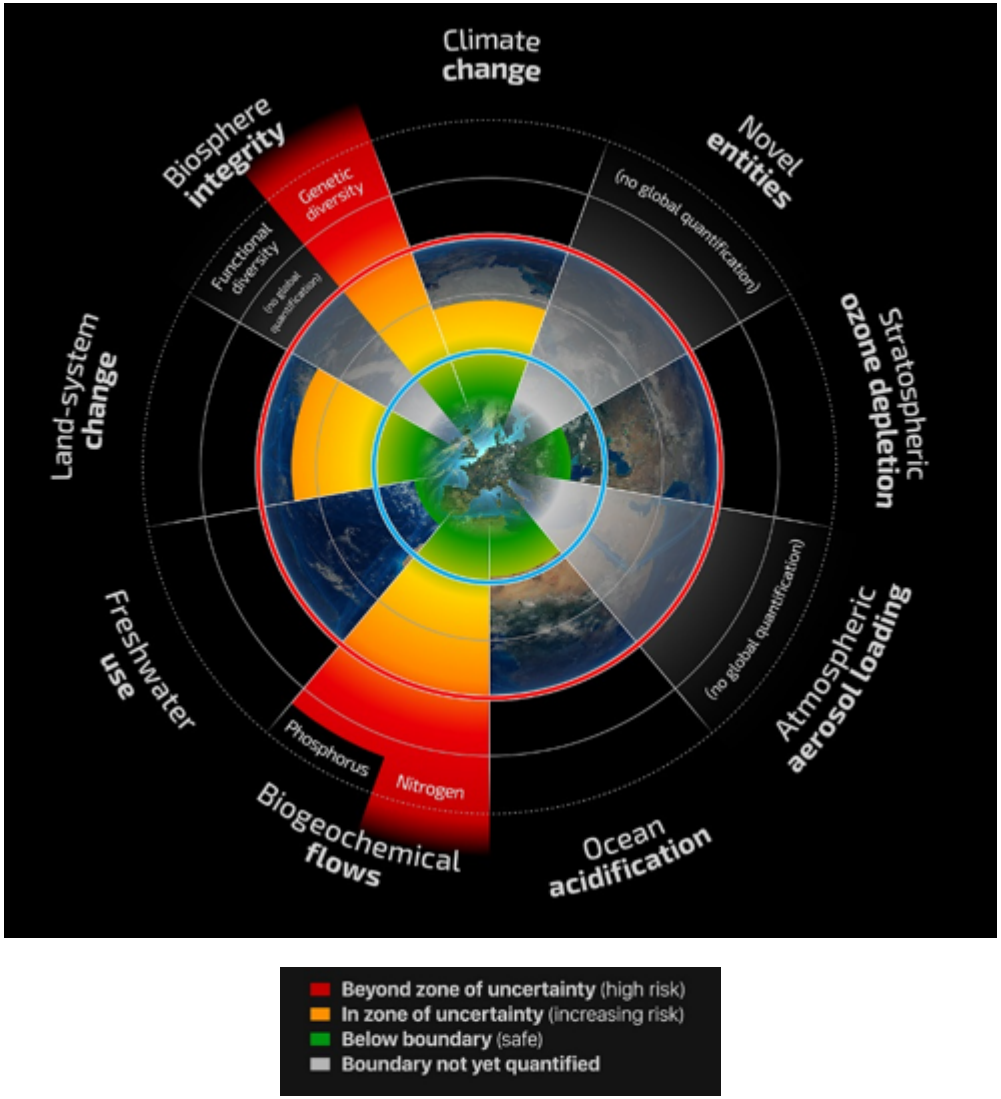
REFERENCE: Steffen, W., W. Broadgate, L. Deutsch, O. Gaffney and C. Ludwig (2015), The Trajectory of the Anthropocene: the Great Acceleration, Submitted to *The Anthropocene Review*.

MAP & DESIGN: Félix Pharand-Deschênes / Globaïa

http://www.igbp.net/globalchange/greatacceleration.4.1b8ae20512db692f2a680001630.html

Planetary Boundaries: A safe operating space for humanity

- **Four of nine planetary boundaries have been crossed**
- **Transgressing a boundary increases the risk that human activities could drive the Earth System into a much less hospitable state, damaging efforts to reduce poverty and leading to a deterioration of human wellbeing in many parts of the world, including wealthy countries**

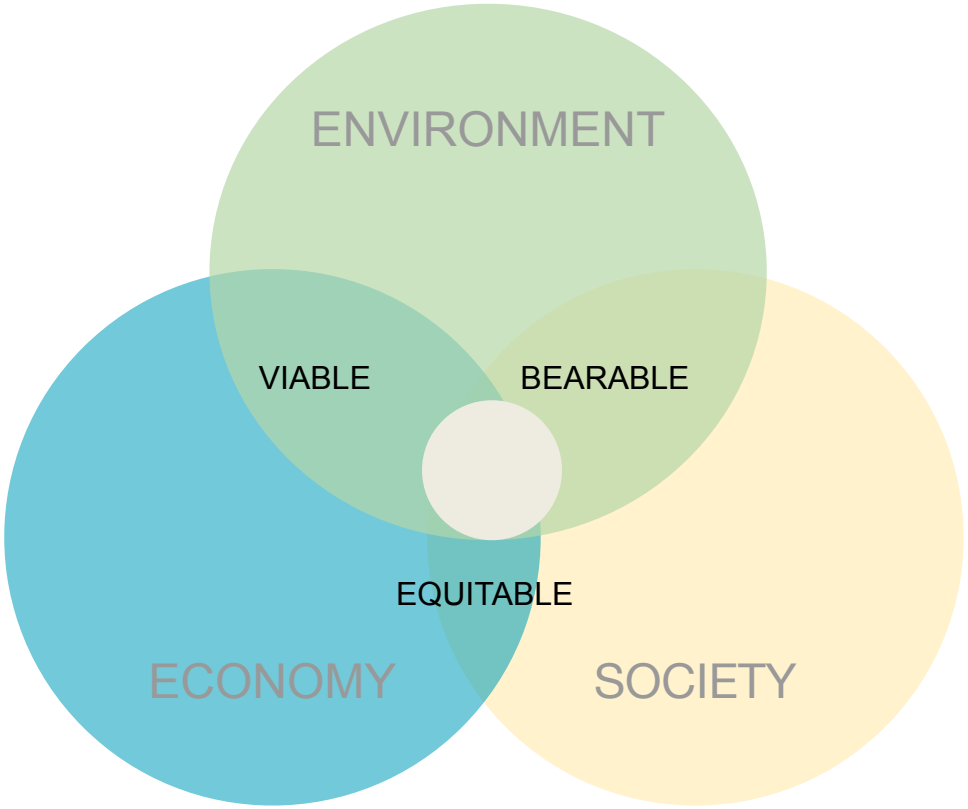


(http://www.stockholmresilience.org/21/research/research-programmes/planetary-boundaries.html)

Sustainable development

Meeting the needs of today without compromising the needs of the future

- **Brundtland Report, 1987**



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Sustainable consumption and production

Johannesburg World Summit (2002)

The concept of sustainable consumption and production(*) is recognized in order to foster economic and social development.

(*) "the use of services and related products, which respond to basic needs and bring a better quality of life while minimizing the use of natural resources and toxic materials as well as the emissions of waste and pollutants over the life cycle of the service or product so as not to jeopardize the needs of further generations" (Oslo symposium, 1994).

(http://sustainabledevelopment.un.org/index.php?menu=204)

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Car comparison: illustrative example

- Diesel
- Biodiesel 5% vol. (canola)
- Gasoline
- Ethanol 5% vol. (sugar cane)
- Natural gas
- Electricity

Which is the best? The worst?

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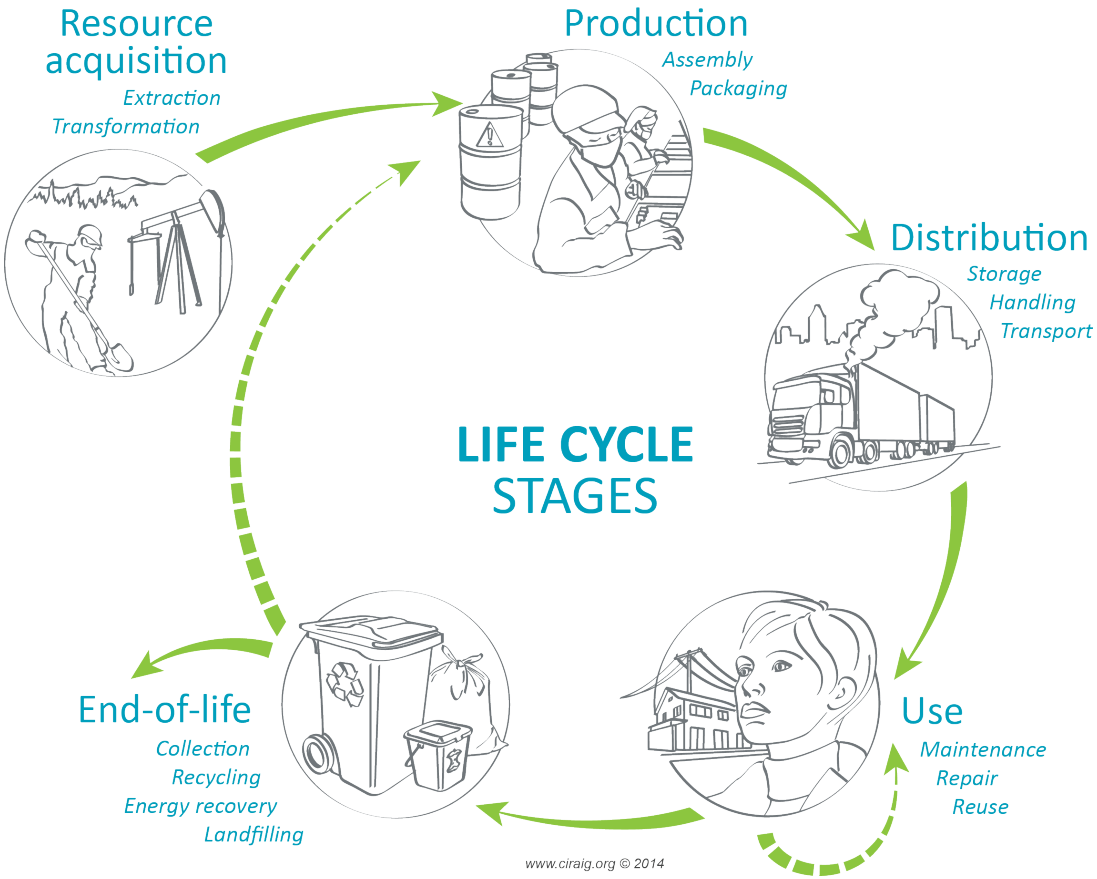
The life cycle of a product

All processes associated with the product, wherever and whenever they might occur



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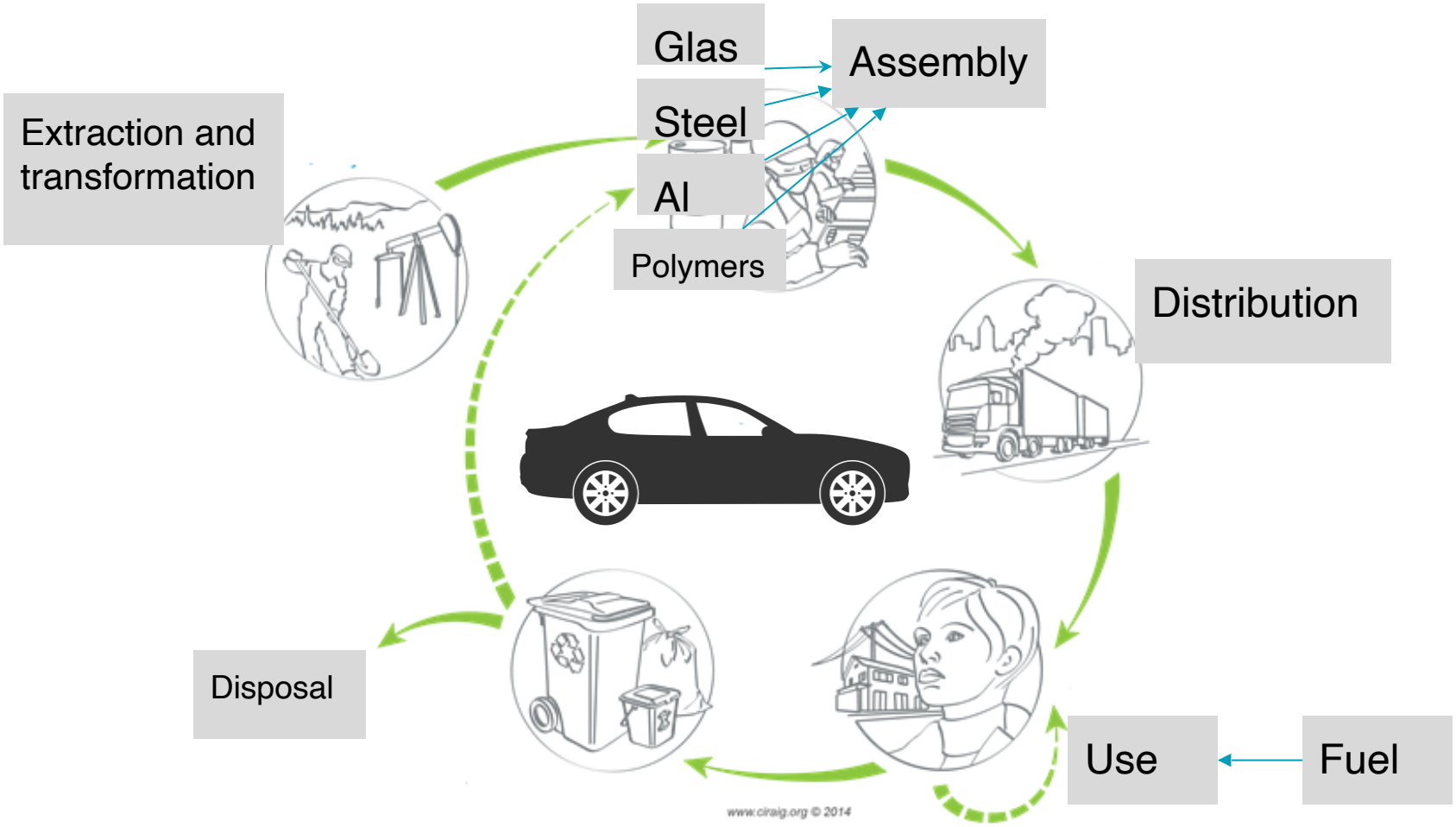
The life cycle of a car



Each stage is composed of processes

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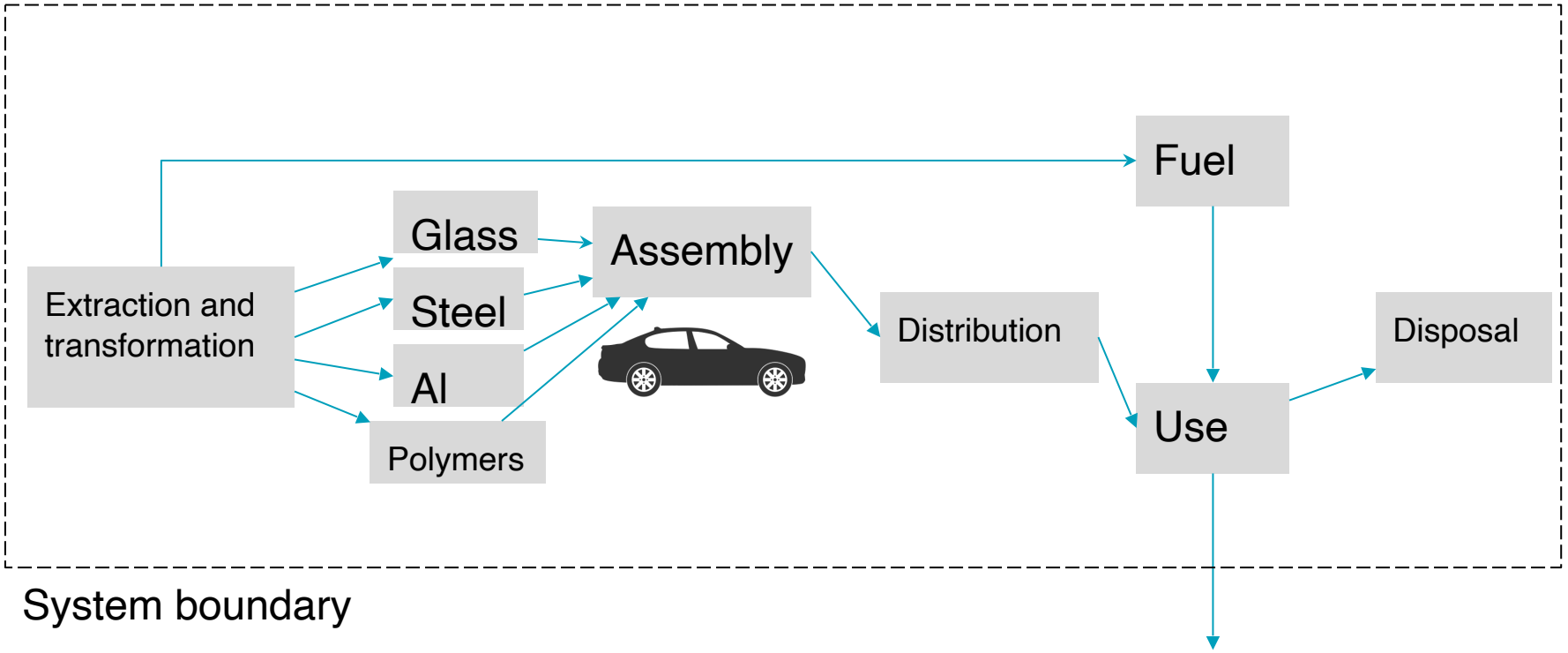
The life cycle of a car



All the processes make up a system

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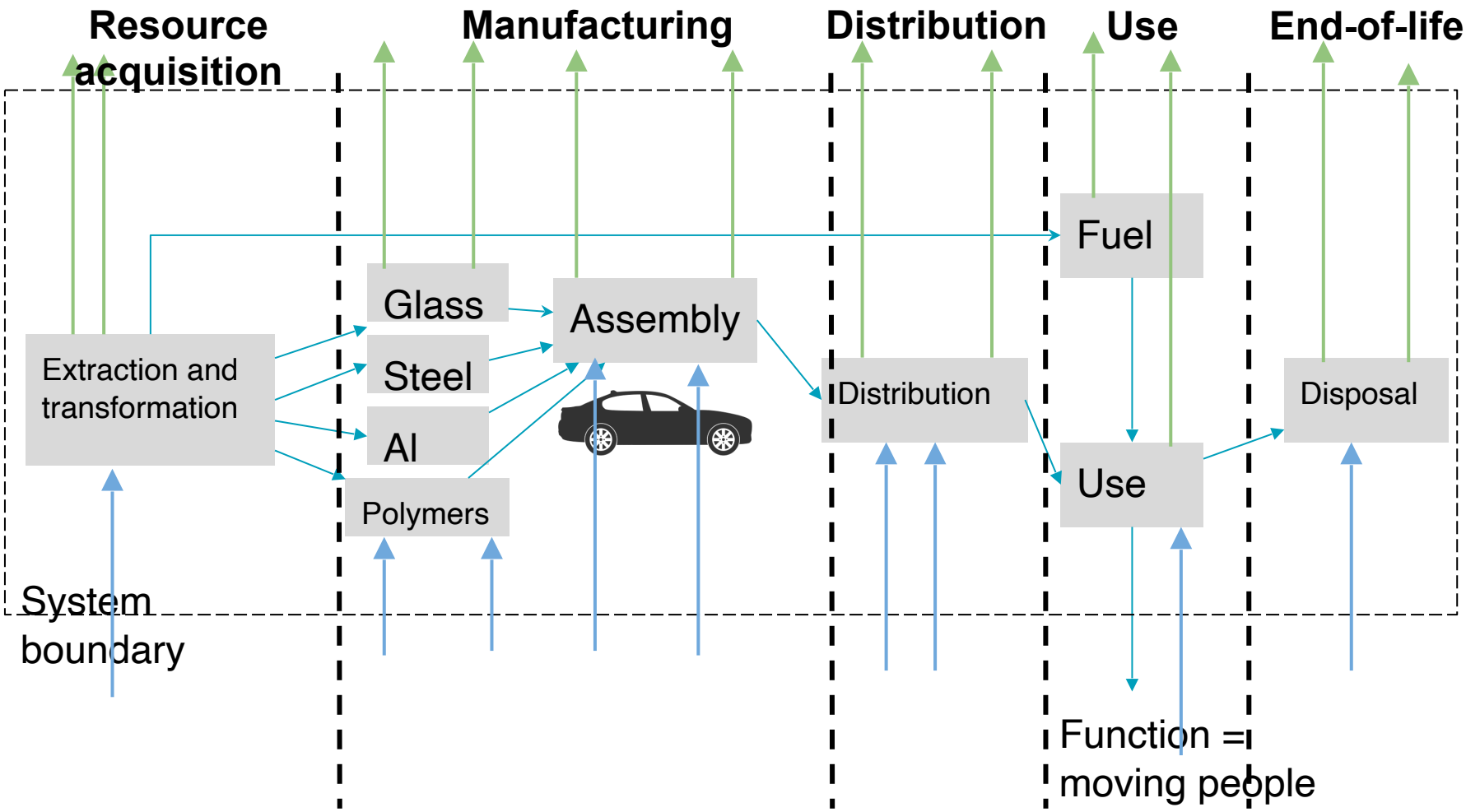
The life cycle of a car



Each process has emissions (outputs) & uses resources (inputs)

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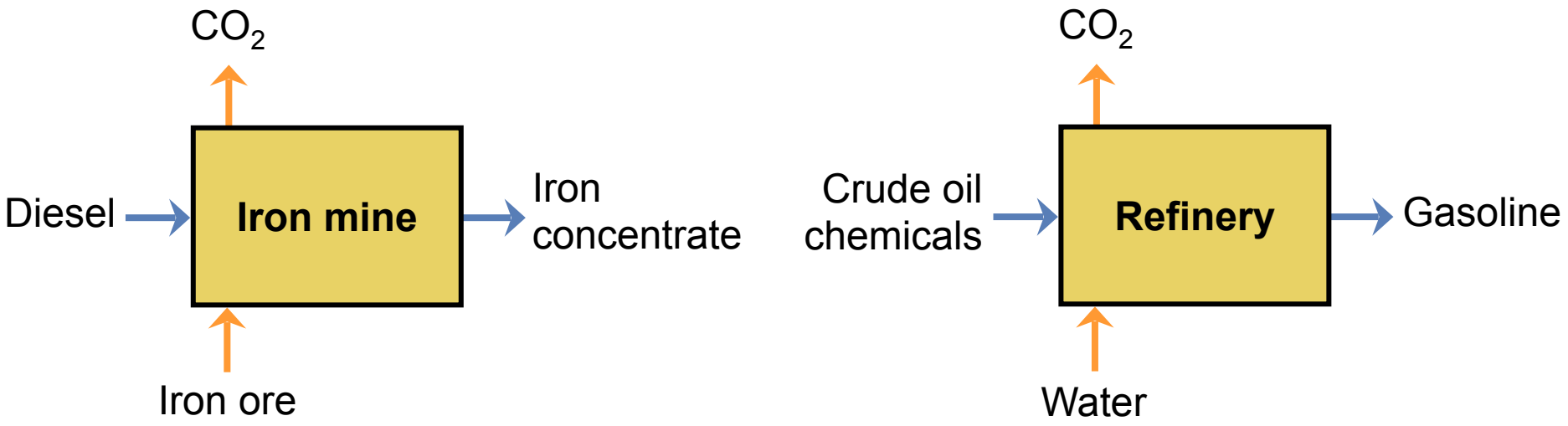
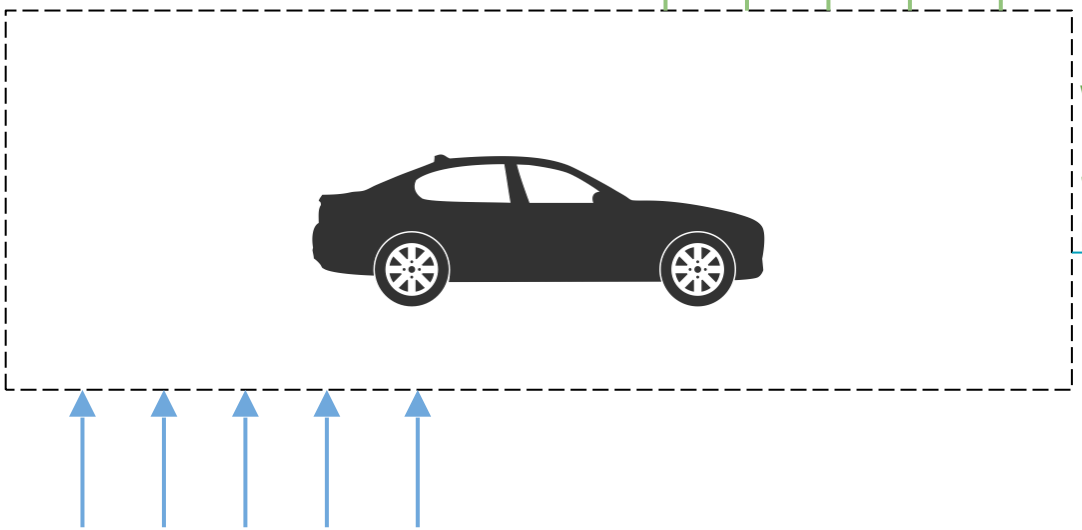
Inputs and outputs of processes



The inputs and outputs of processes, exchanged between processes or with the environment, can be quantified, compared and aggregated

The life cycle inventory of a car



OUTPUTS
Emissions to
Air : CO_2, SO_2,
PM, VOC
Water : PO_4, NO_3
Soil : pesticides,
metals

Functional unit

INPUTS
Natural resources
- Iron ore
- Crude oil
- Water
- Wood
- Land use

These inputs and outputs can be quantified, compared and aggregated for the entire system

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Life cycle impacts

Elementary flows

Inputs:

Iron ore
Crude oil
Water
Wood
Solar energy
Land use
…

Outputs :

CO_2
SO_2
PM
VOC
PO_4
NO_3
Pesticides
Metals
…

Impact categories

Global warming
Ozone layer depletion
Land use
Natural resource depletion
Acidification
Eutrophication
Photochemical ozone generation
Human toxicity
Ecotoxicity

Single score

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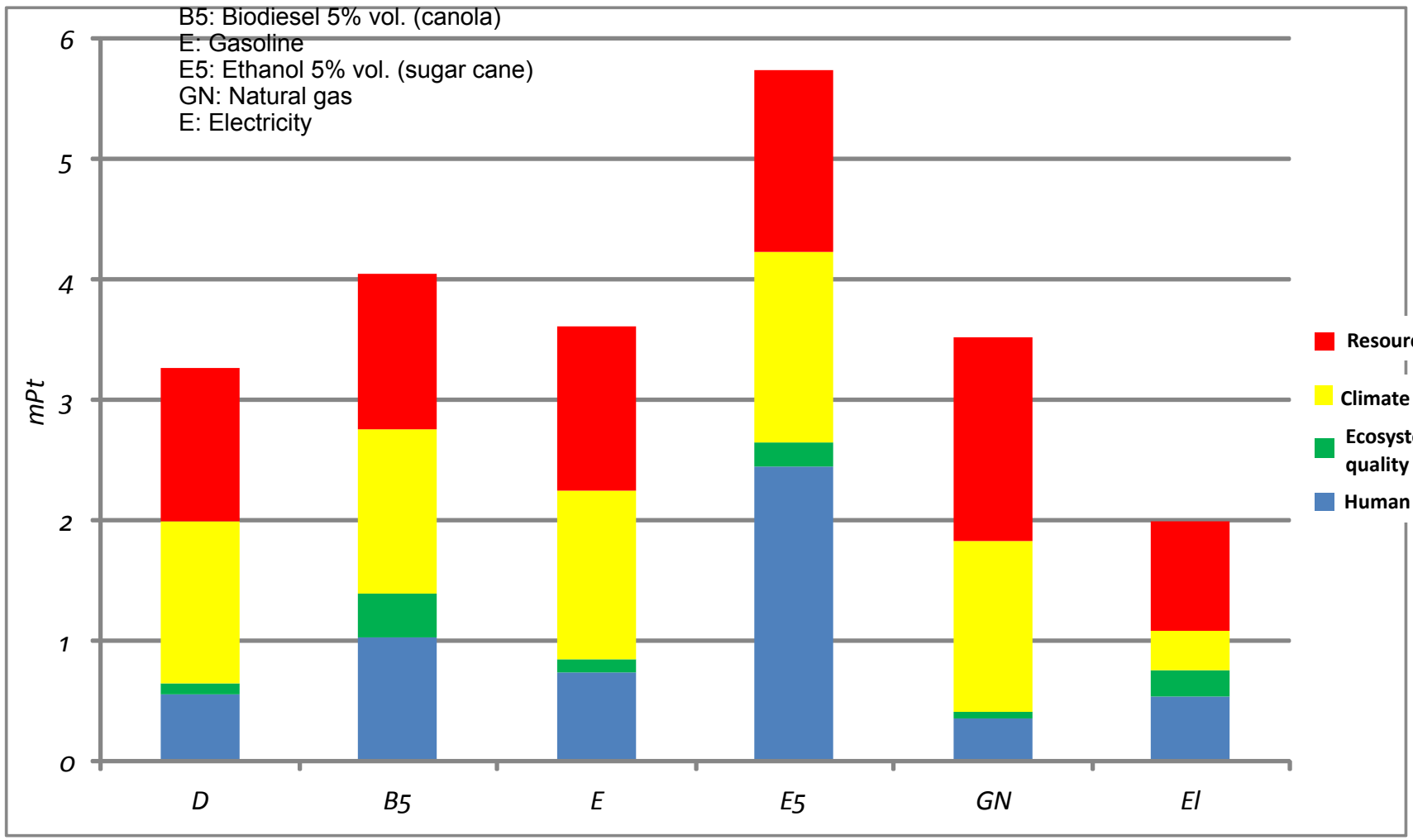
IMPACT 2002+ – Single score for the cars



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What is LCA?

Quantitative and comparative/relative environmental assessment tool

"I am greener than…" BUT NOT "I am green!"

Standardized methodology (ISO 14040/44, ILCD Handbook, GHG Protocol, several PCRs, etc.)

Level of detail and resources needs (time, money, expertise) very variable, depending on objectives of study

Numerous methodological choices
→ transparency

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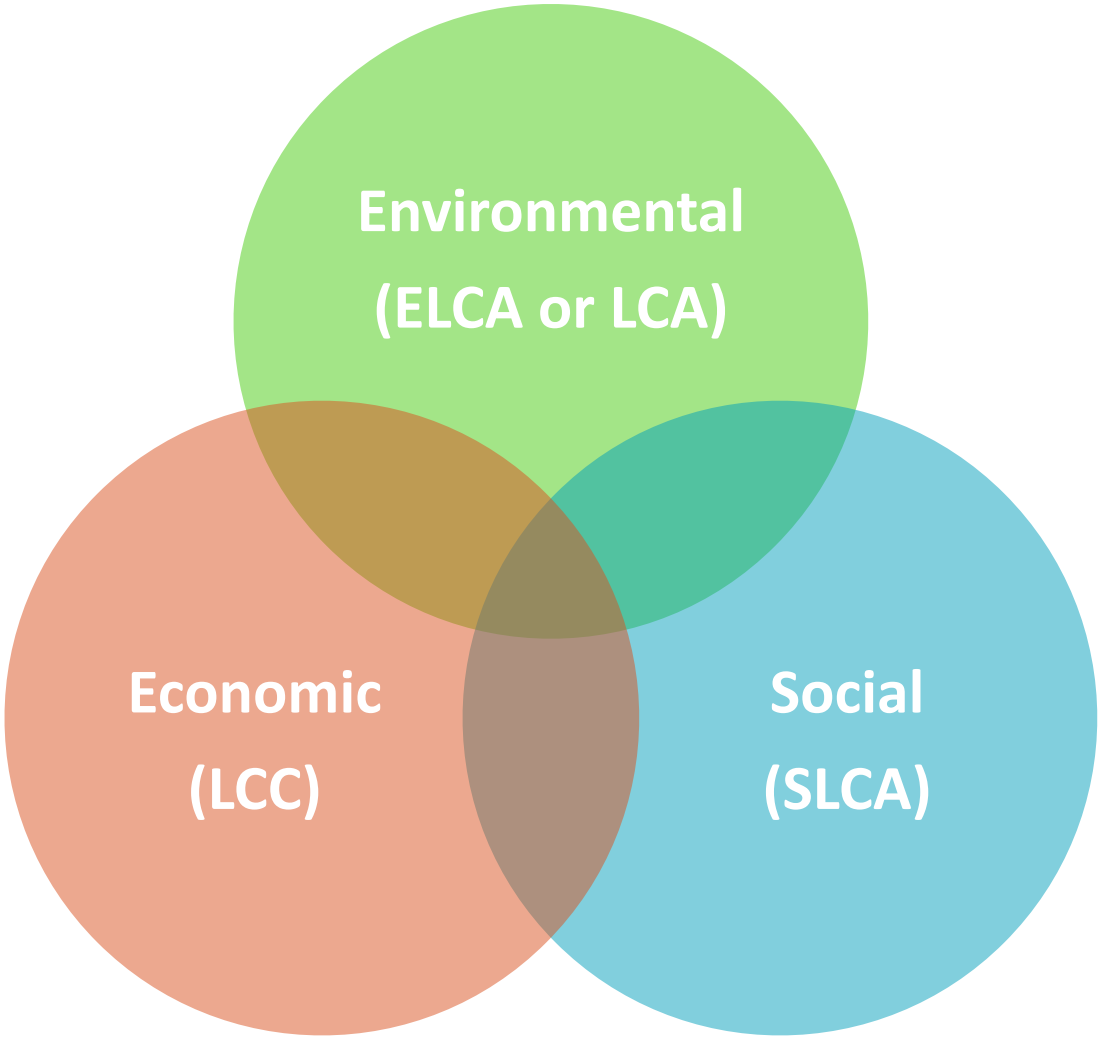
3 ways of looking at life cycle



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Why do an LCA?

1) Compare things (products, services, components, materials, suppliers, life cycle stages)

→ Decision/choice support: product eco-design and improvement, priority/"hot spots" identification, green procurement, investment options, marketing/positioning (branding), identifying risks in supply chain, authorization request

2) Establish environmental profile (product, service, organization)

→ Environmental product declaration, communication, ecolabels,

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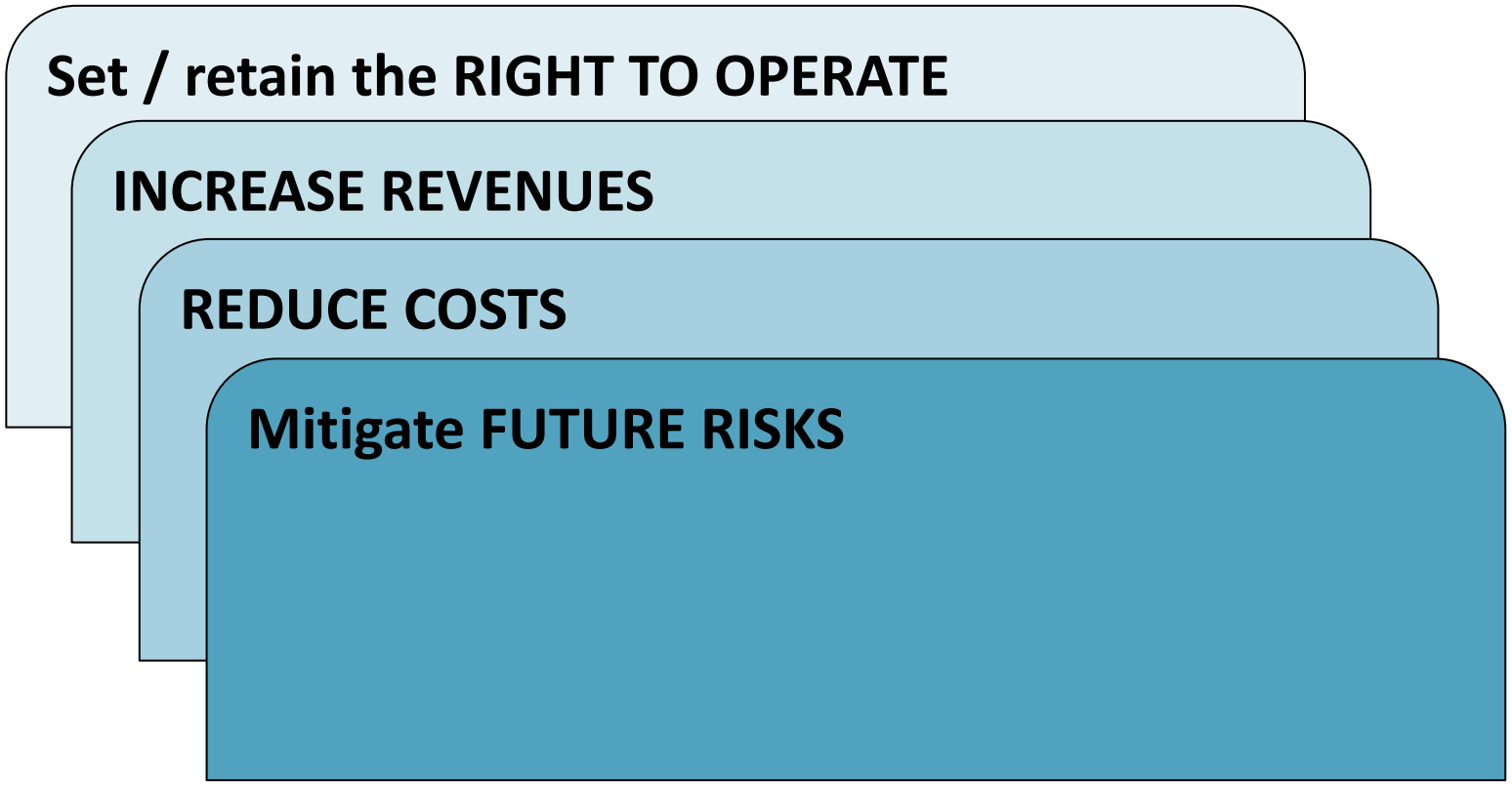
4 ultimate drivers for LCA



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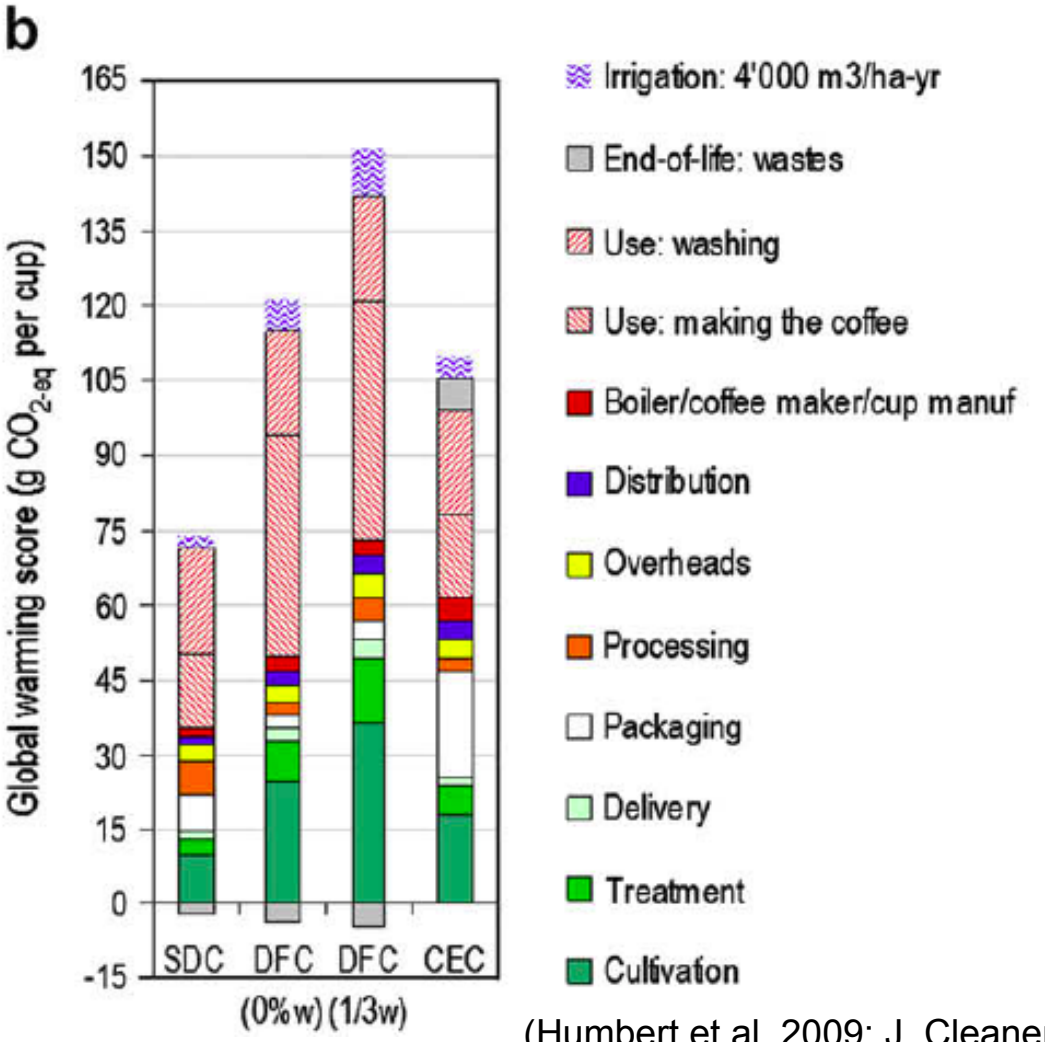
Comparison of alternatives

SDC: Spray dry coffee

DFC: Filtred coffee

CEC: expresso capsules



(Humbert et al. 2009; J. Cleaner Prod.)

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Electric car: better or worst a conventional car?

Zero emission here…

Emissions « elsewhere »!

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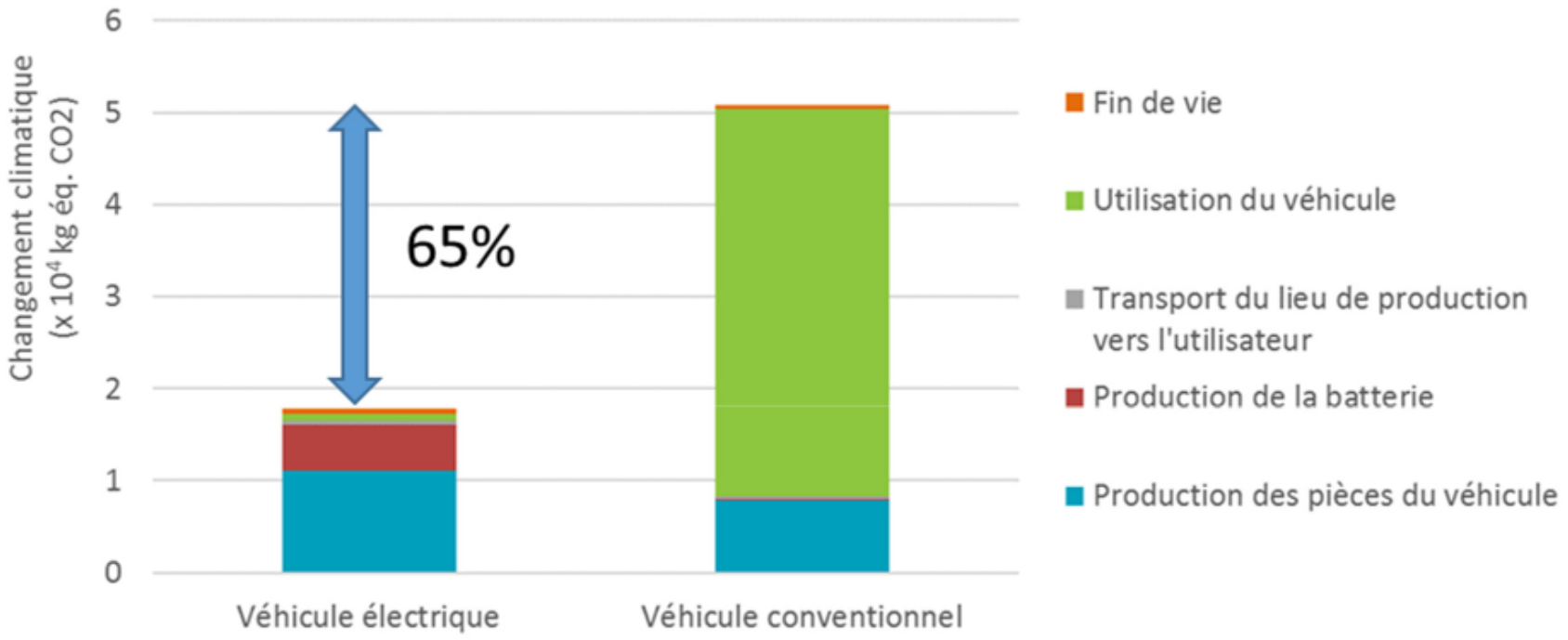
Comparison electric vs. conventional car in Québec over 150000 km (Functional unit)



(CIRAIG, 2016; http://www.hydroquebec.com/developpement-durable/centre-documentation/acv-vehicule-electrique.html2016)

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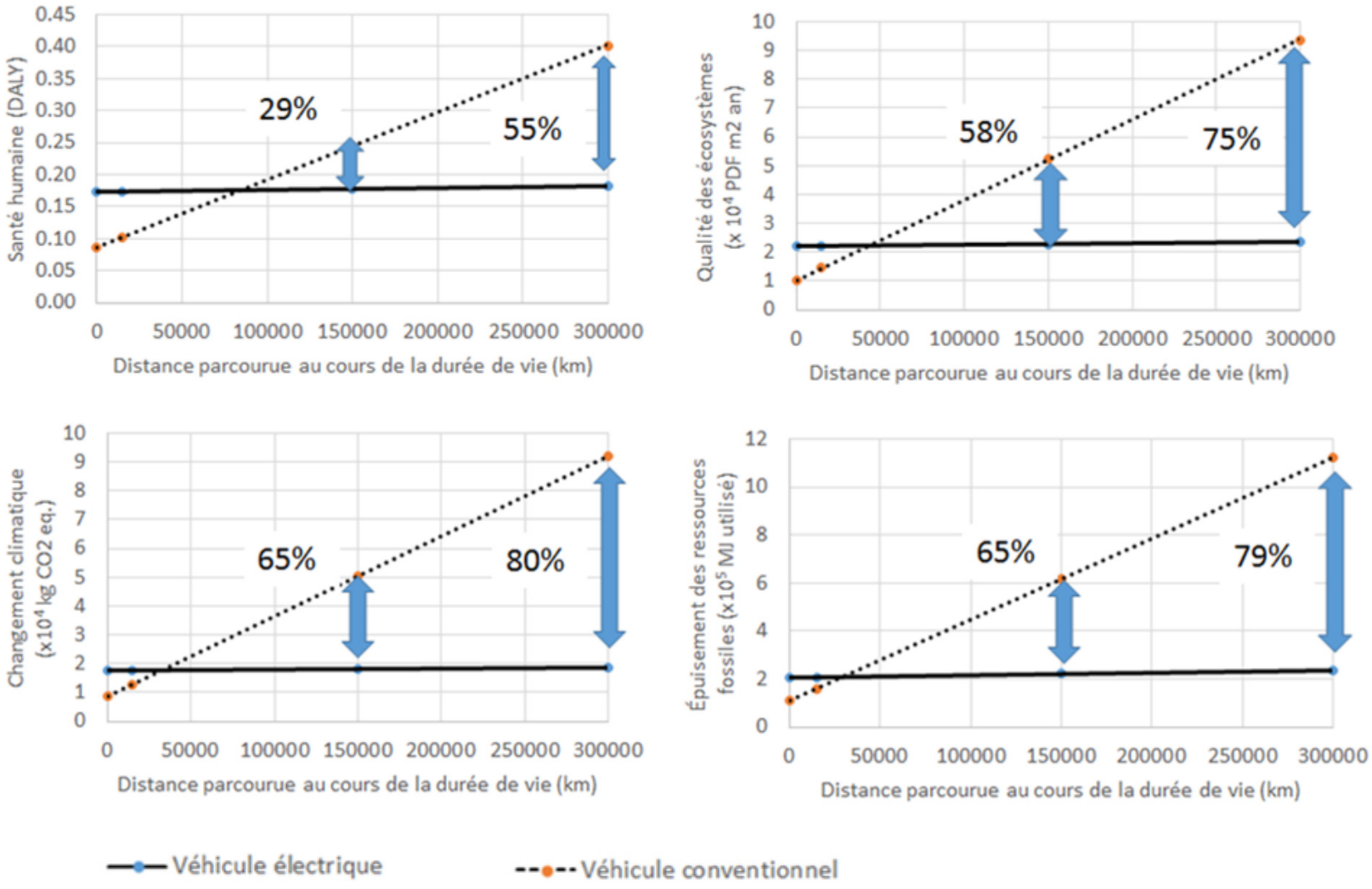
Comparison electric vs. conventional car in Québec as a function of distance



(CIRAIG, 2016; http://www.hydroquebec.com/developpement-durable/centre-documentation/acv-vehicule-electrique.html2016)

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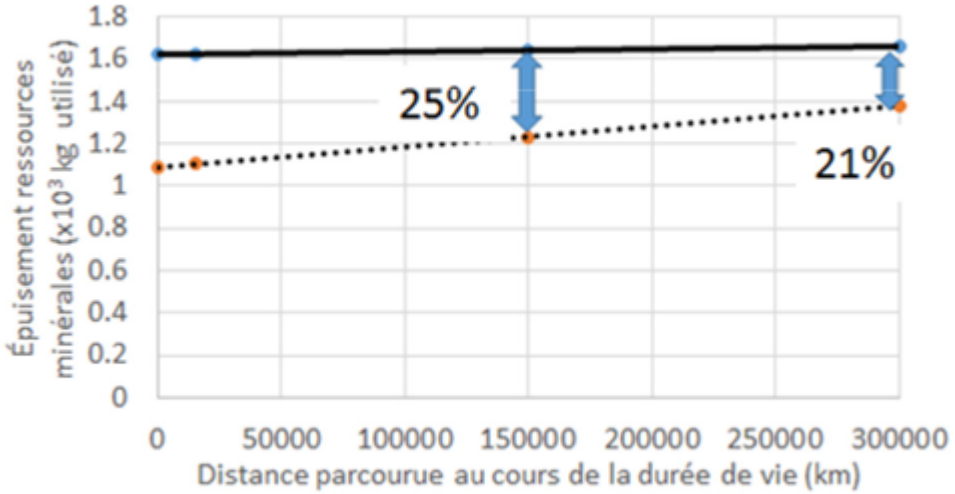
Comparison electric vs. conventional car in Québec as a function of distance

- **Better for :**
  - impacts on climate change, human health, ecosystem quality, fossil ressources consumption,
- **But, trade-off with**
  - resource consumption



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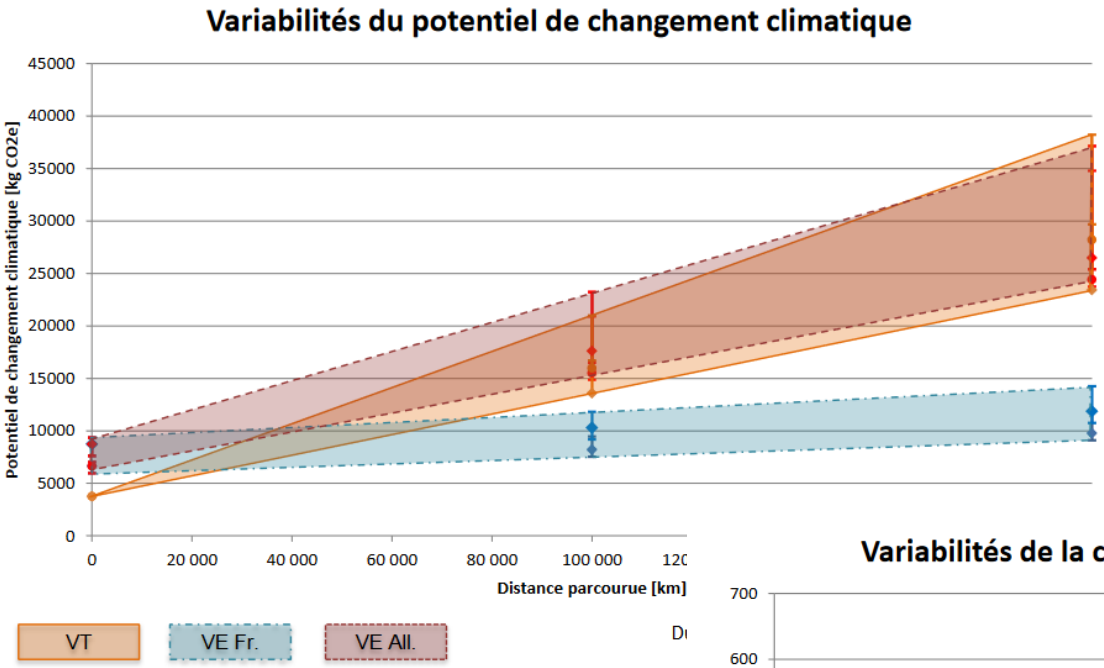
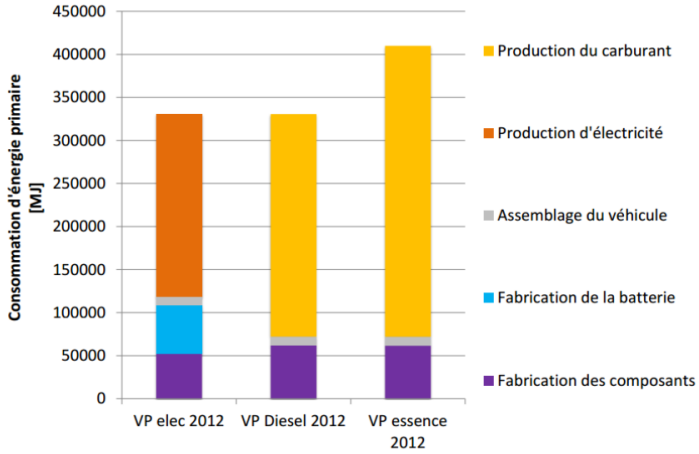
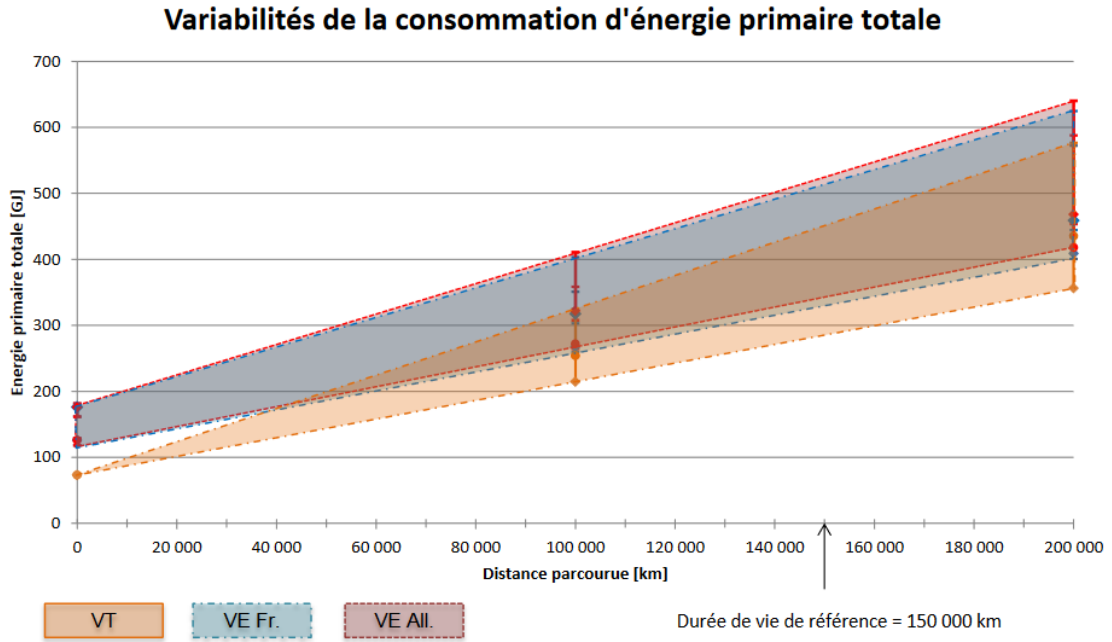
… What about a different geographical context? FR and DE







(ADEME, 2013; http://www.ademe.fr/sites/default/files/assets/documents/90511_acv-comparative-ve-vt-rapport.pdf

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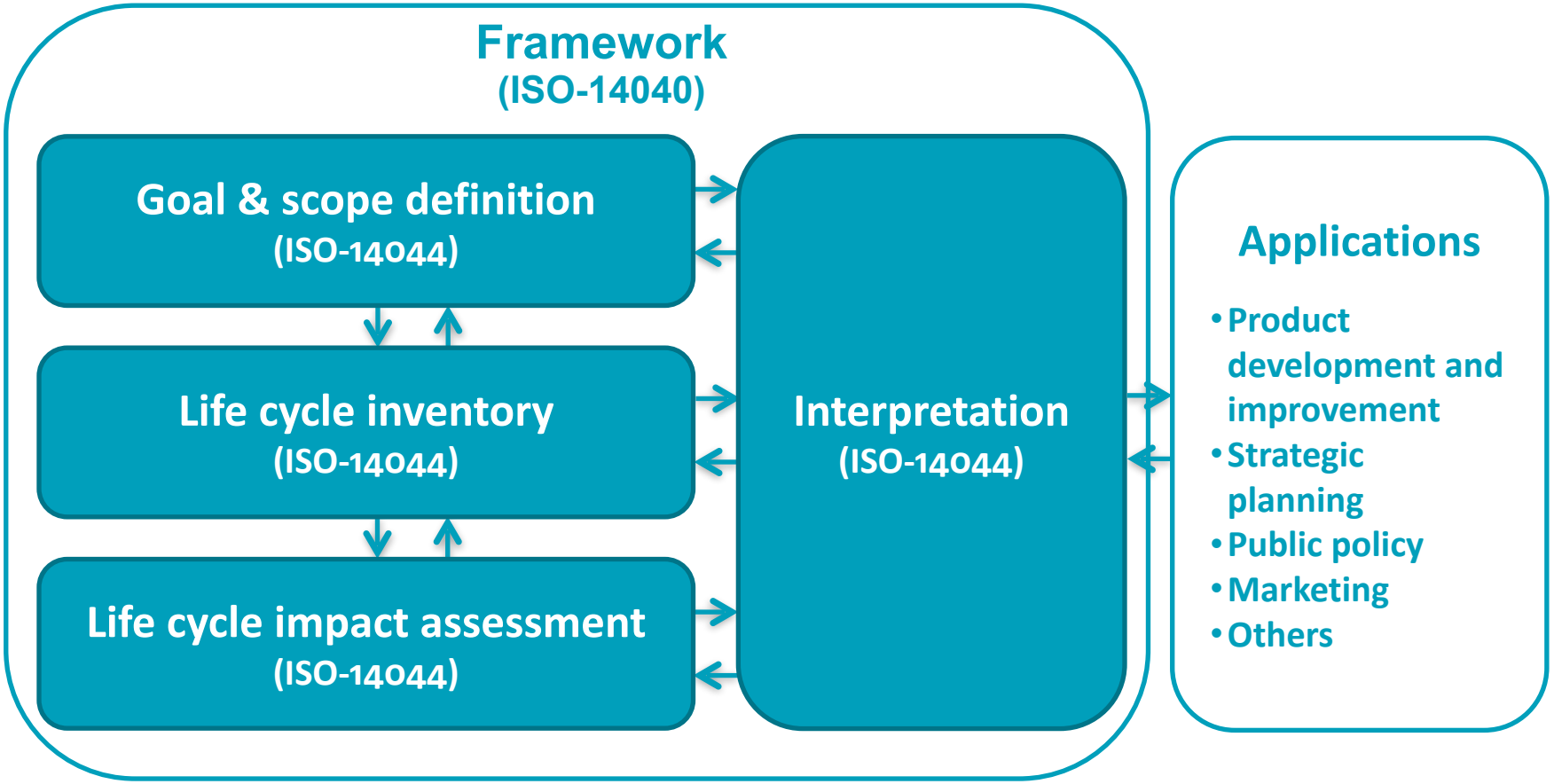
LCA procedure according to ISO 14040



Iterative method

- **The collected data may lead to the modification of the scope of the study**
- **The goal itself can also be revised**

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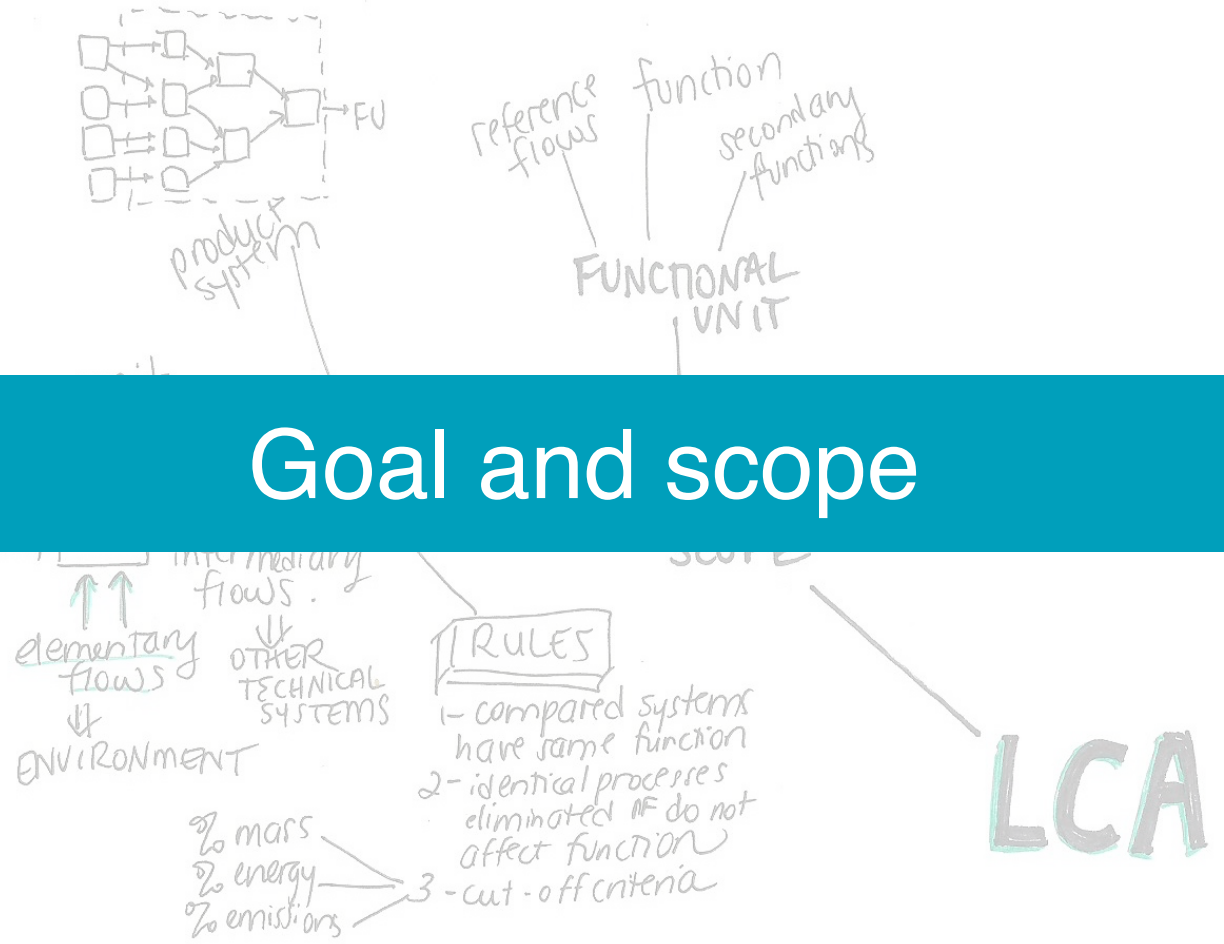

Goal and scope

Goal = The « What? » and the « What for? »

The goal must clearly define:

- **the object**
- **the reason and the intended application of the study**

Examples (from ISO 14040):

Identifying opportunities to improve the environmental performance of products at various points in their life cycle,

Informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign)

Marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).

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Goal = The « For who? »

The goal must clearly define:

- **the object**
- **the reason and the intended application of the study**
- **the intended audience of the study (i.e. for who are the results intended)**

Examples of link between audience and application:

Consumer : **differentiate functionally equivalent products to make more « ecological » choices**

Manufacturer: **looking for way to reduce the impacts associated with its products, to communicate their environmental merits**

Government : **refine environmental legislation, elaborate incentive measures**

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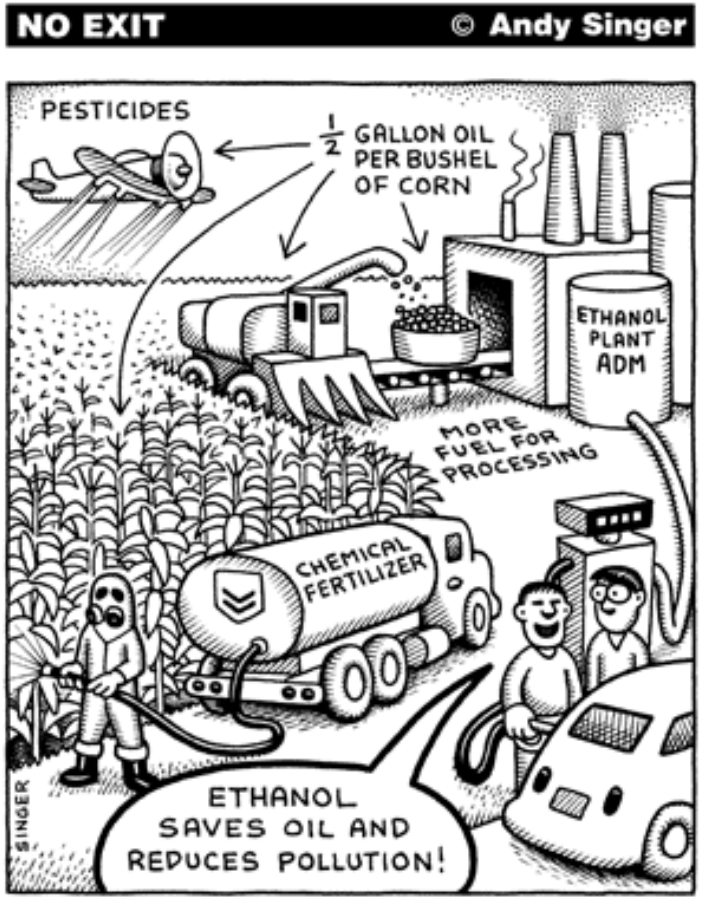
Biofuels

- Solution or ecological illusion?



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LCA as a basis for policy making

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Bundesamt für Energie BFE
Bundesamt für Umwelt BAFU
Bundesamt für Landwirtschaft BLW

LIFE CYCLE ASSESSMENT OF ENERGY PRODUCTS:

ENVIRONMENTAL IMPACT ASSESSMENT OF BIOFUELS

- Executive Summary -

Rainer Zah
Heinz Böni
Marcel Gauch
Roland Hischier
Martin Lehmann
Patrick Wäger

Empa
Technology and Society Lab
Lerchenfeldstrasse 5
CH-9014 St. Gallen, Switzerland
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(Zah et al., 2007)

Objectives:

- **analysis of the possible environmental impacts of biofuels suitable**
- **used as a basis for granting an exemption from the excise duty on fossil fuels.**

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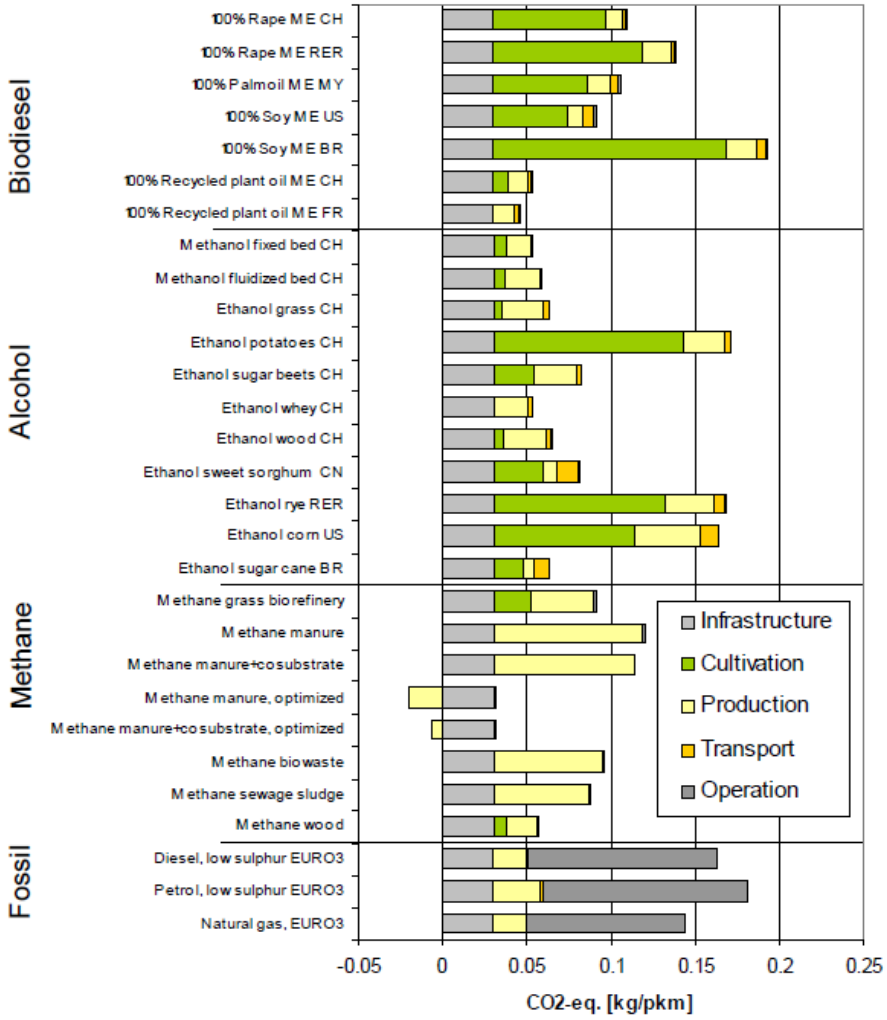
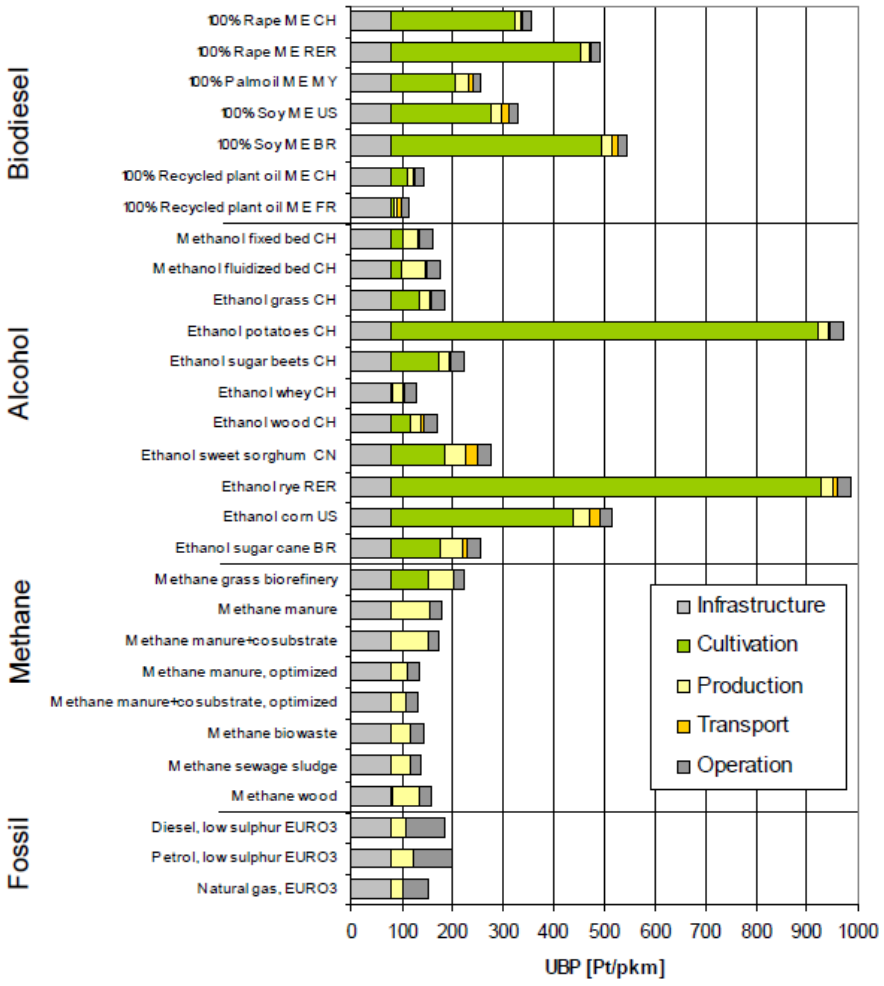
GHG emissions and overall environmental impact of biofuels vs. fossil fuels





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Tax Exemption for biofuels in Switzerland (2016)

…provided that they fulfil environmental and social requirements

Environmental requirements:

- at least 40% less greenhouse gas emissions (from cultivation of raw materials till end use) compared to the life cycle emissions of fossil petrol
- biofuels must not be significantly more harmful to the environment (from cultivation of raw materials till end use) compared to fossil petrol
- raw materials must not be obtained from converted land (after 1 January 2008) or high biodiversity value

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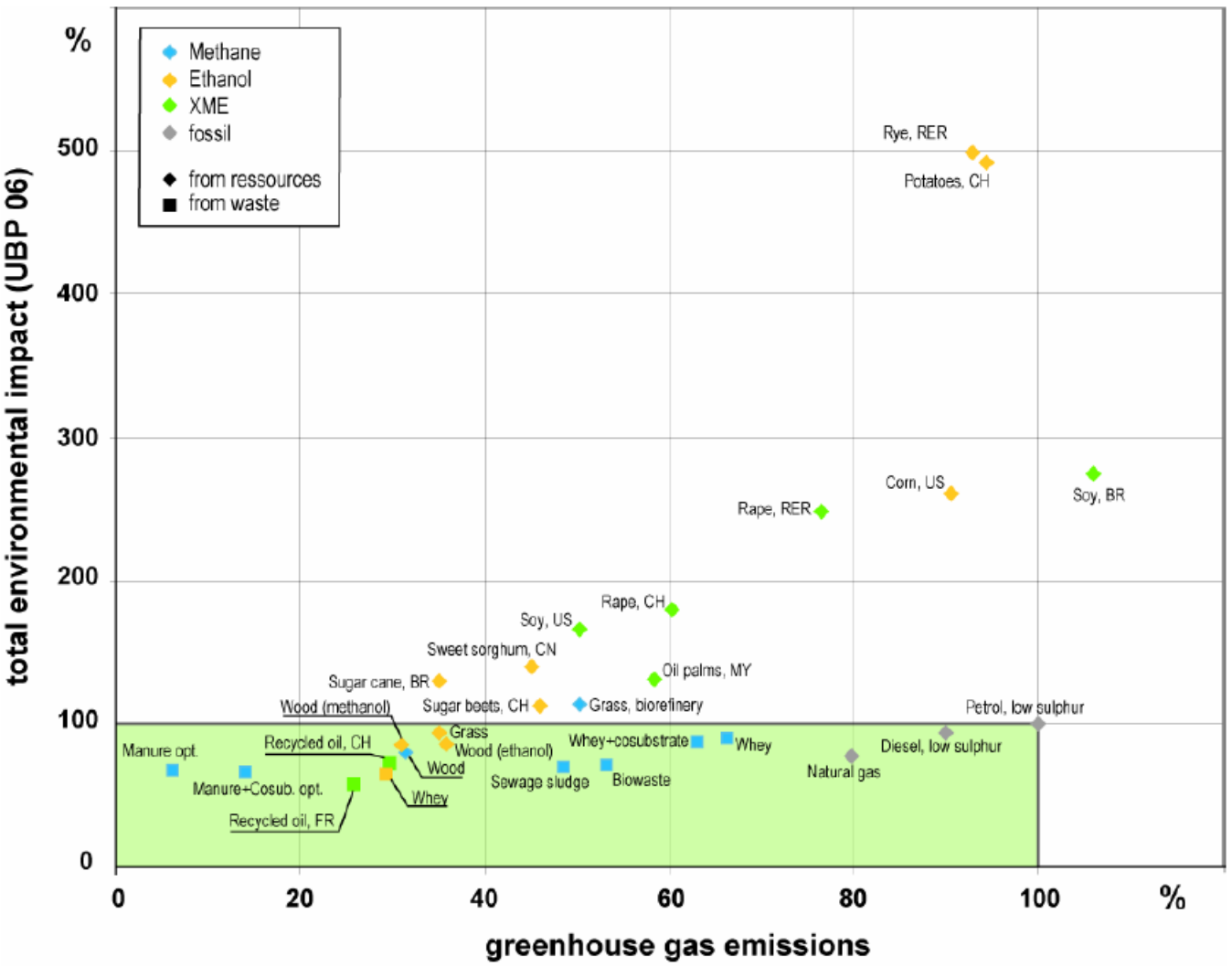
GHG emissions and overall environmental impact of biofuels vs. fossil fuels



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Scope = Guide for the study

The goal will guide the depth and scope of the study:

- **Systems studied**
- **Functional unit and reference flows**
- **System boundaries**
- **Initial unit processes inclusion criteria**
- **Allocation rules**
- **Inventory data quality requirements**
- **LCIA method**
- **Need for a critical review?**

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Function = Starting point

In defining:

- **The functional unit = the calculation reference**
- **The system boundaries = the included unit processes**

Some systems may be multifunctional

Need to differentiate between primary and the secondary functions

In comparison, the systems must have the same functional performance (= the same functional unit)

Reference flows

Amounts of products necessary to fulfill the amount of function specified by the functional unit

➔ « What must be purchased in order to fulfill the function »

Different for each compared system

Often related to the functional unit by key parameters for the optimization of the system:

- **Product life**
- **Number of uses**
- **Amount of matter/energy used (efficiency)**

Defining the functional unit and reference flows of a car

Product	Primary function	Secondary functions
Diesel	Moving people	Moving goods Social status
Biodiesel 5%		
Gasoline		
Ethanol 5%		
Natural gas		
Electricity		

Product	Functional unit = « service provided »	Reference flow = « what is needed »	Key parameters
Diesel	Moving 1 person over 100 km (= 100 pkm)	X_1 car+ Y_1 L fuel	Lifetime Energy use
Biodiesel 5%		X_2 car+ Y_2 L fuel	
Gasoline		X_3 car+ Y_3 L fuel	
Ethanol 5%		X_4 car + Y_4 L fuel	
Natural gas		X_5 car+ Y_5 L fuel	
Electricity		X_6 car+ Y_6 L fuel	

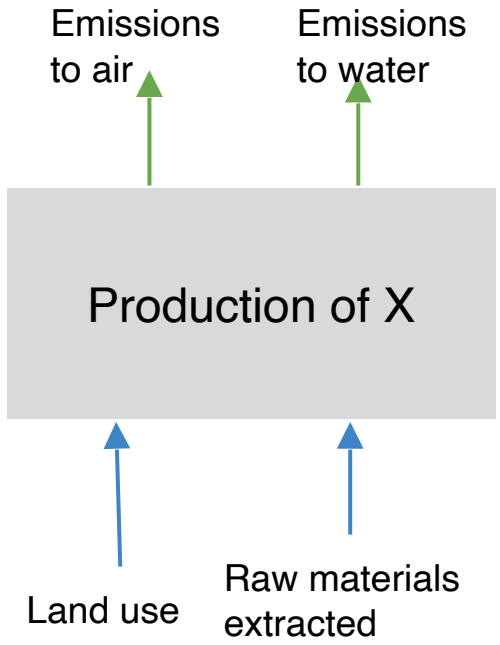
Unit process

A subdivision of the product system assuring a unique or a group of activity/operations

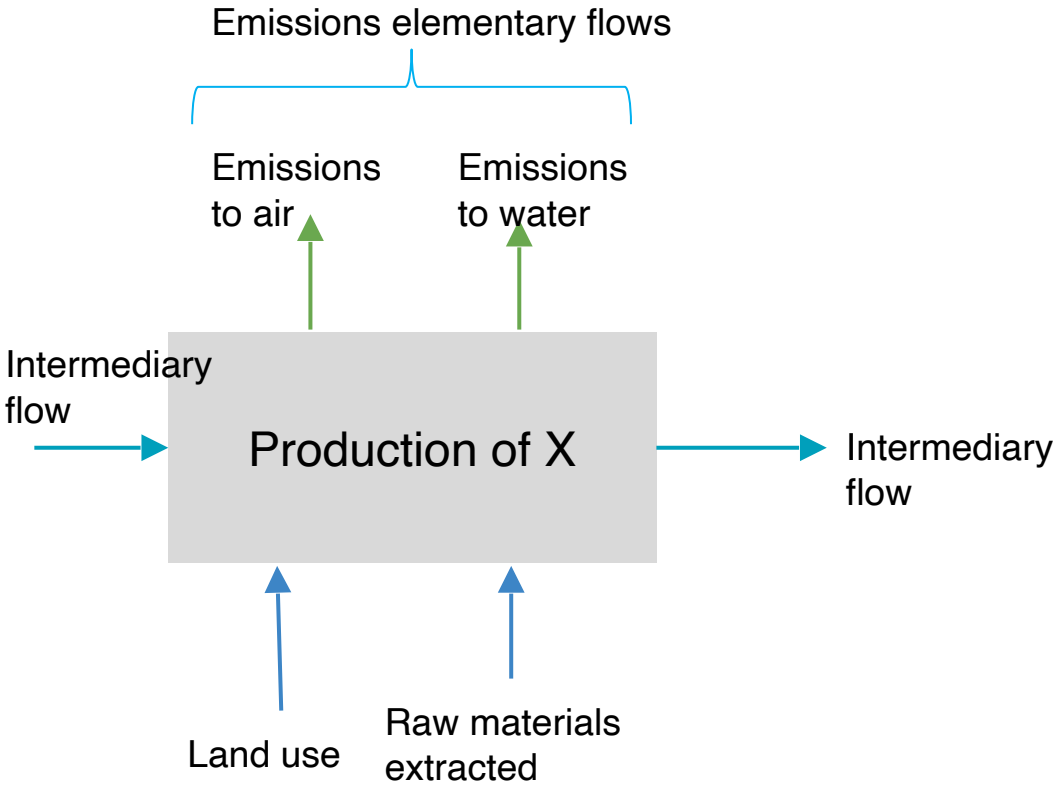
2 types of flows (inputs/outputs):

- **Intermediary (= economic) flow: linking 2 unit processes. One (or more) represents the function of the unit process**
- **Elementary flows: linking the unit process with the environment (= environmental intervention)**

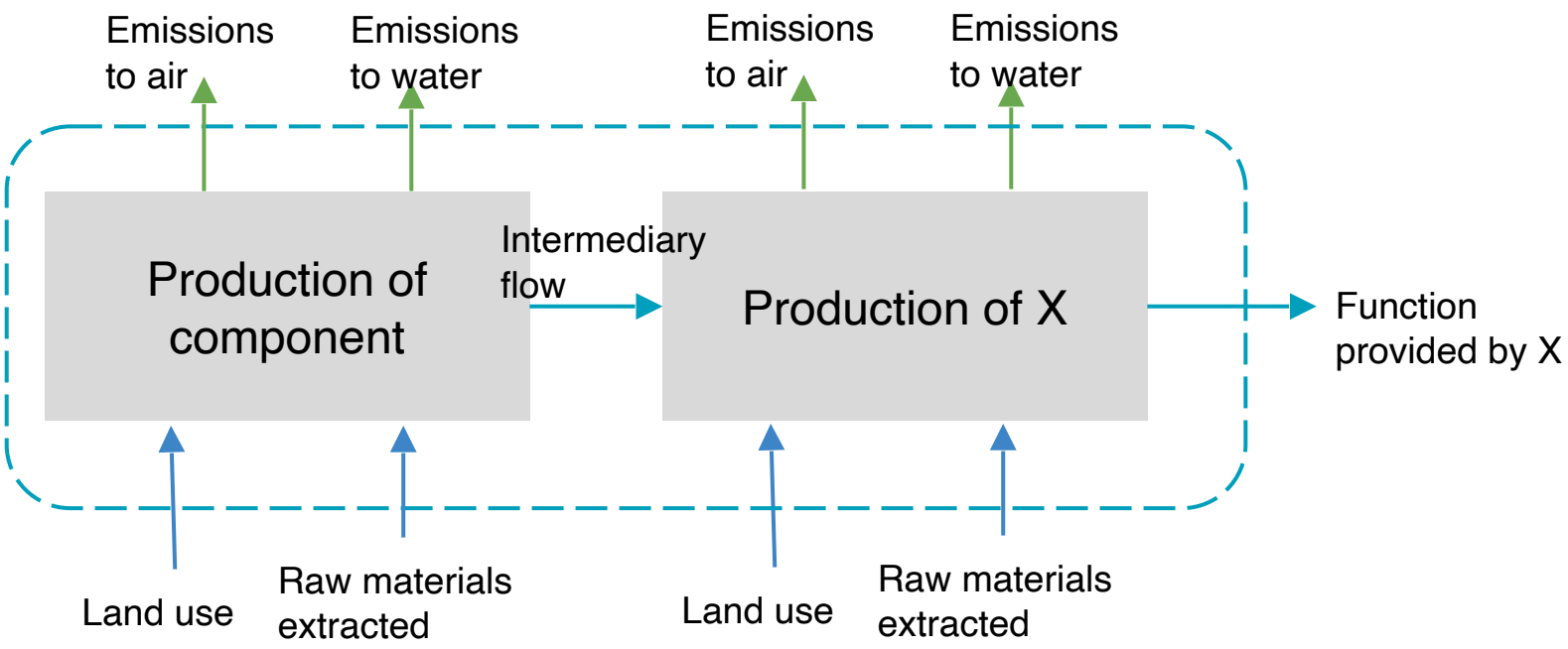
Unit process



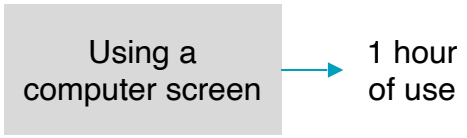
Unit process



System boundary



System boundary of a screen



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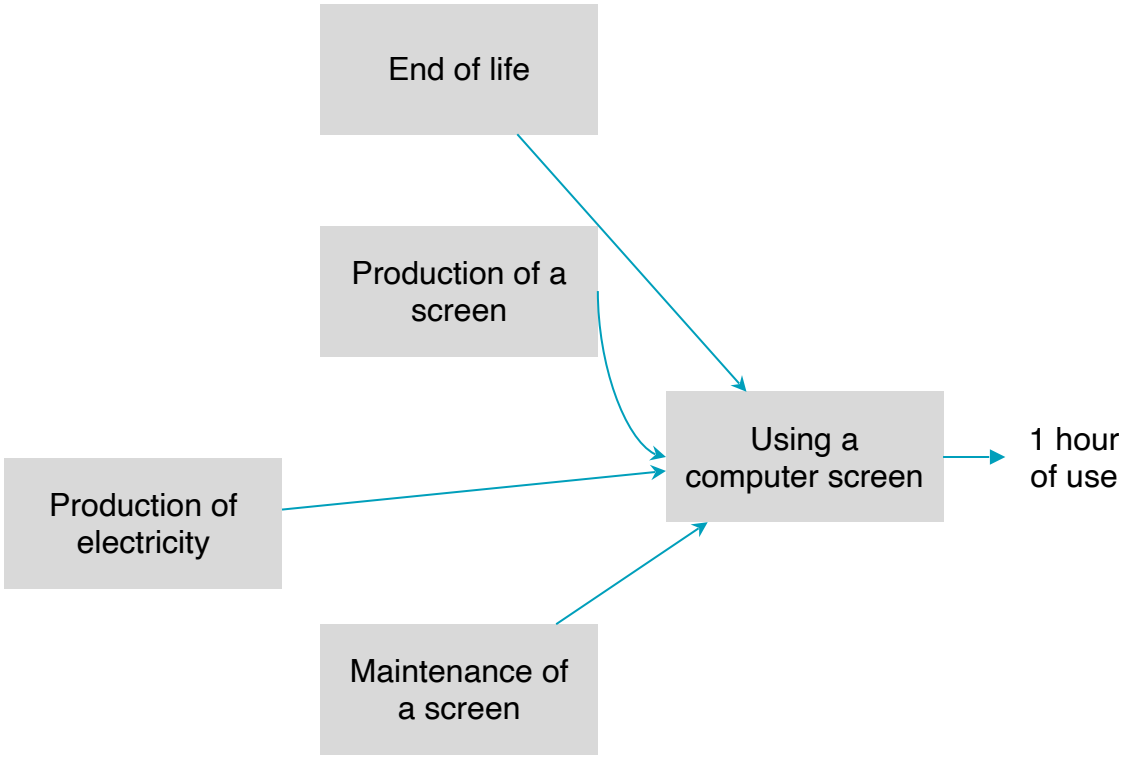
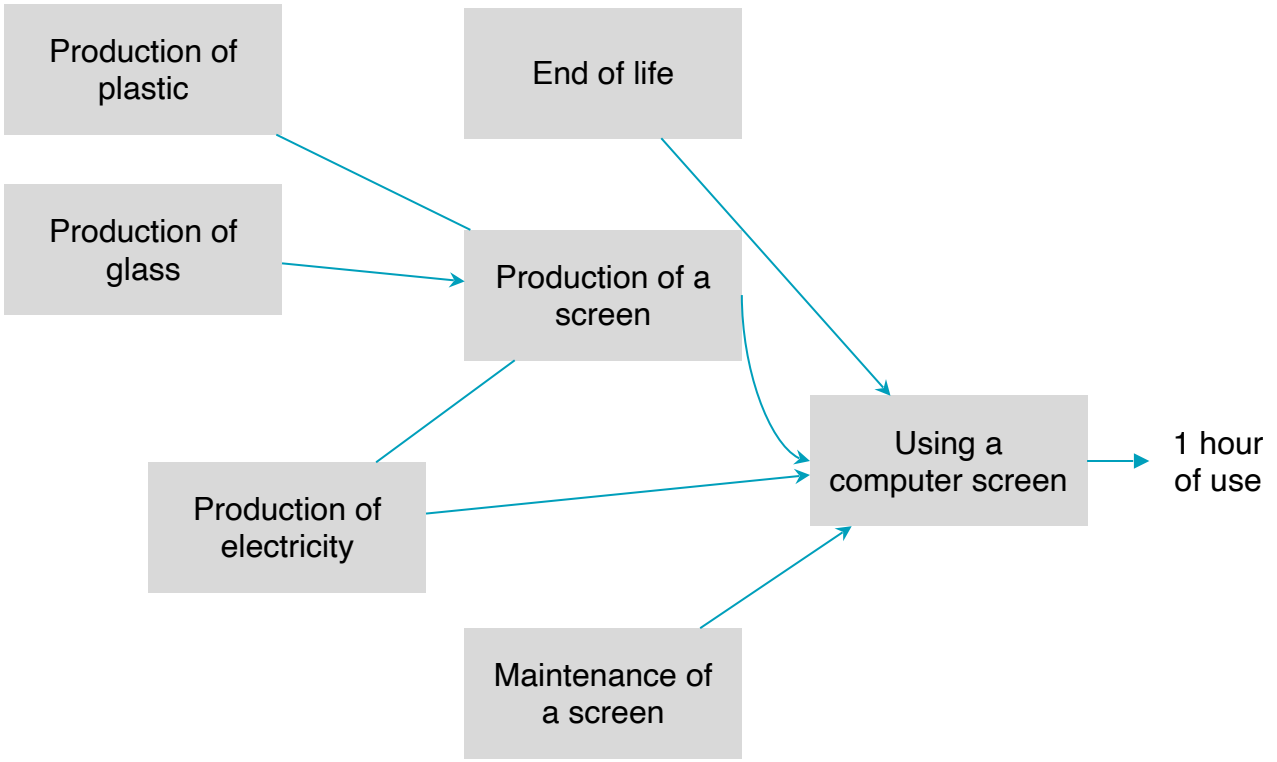
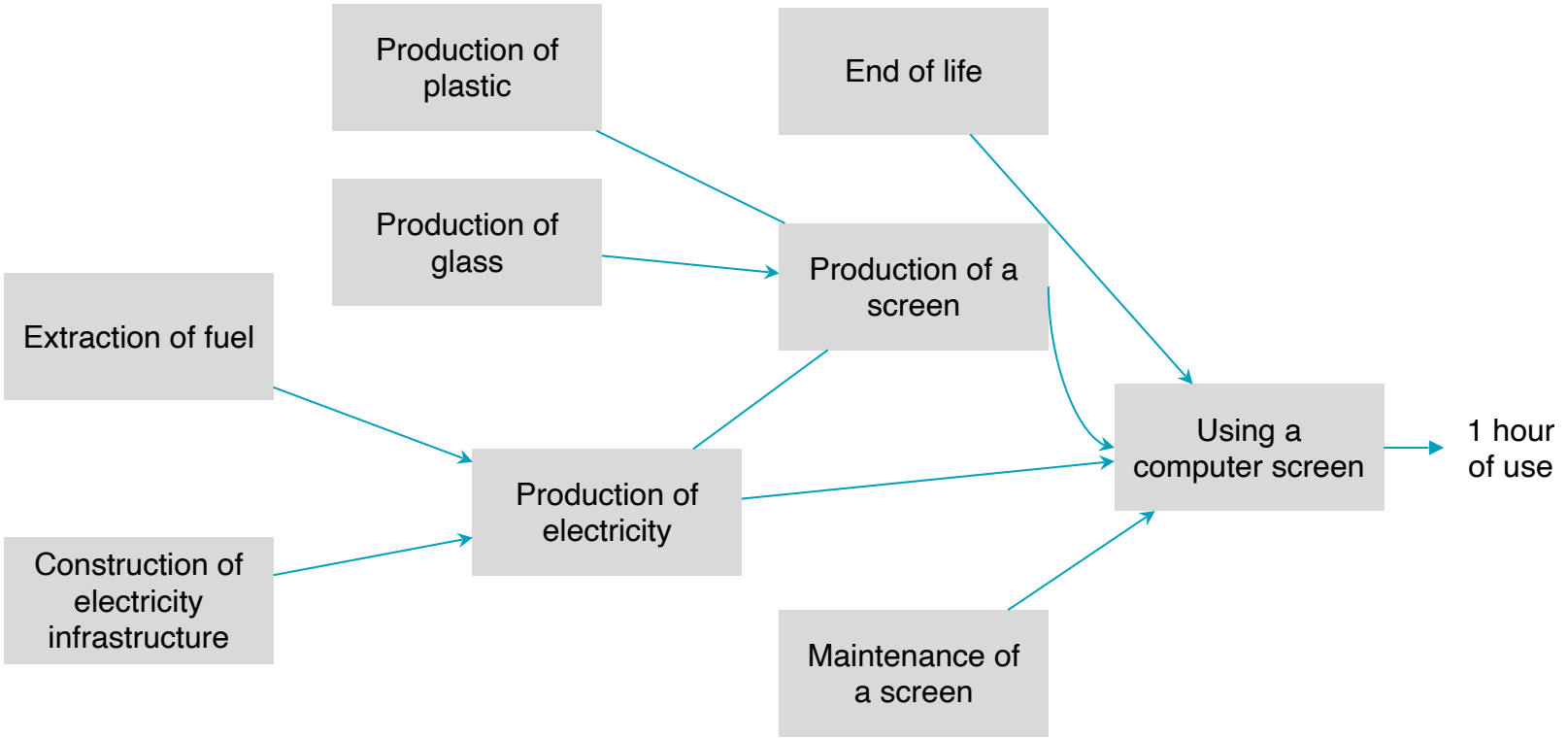
System boundary of a screen



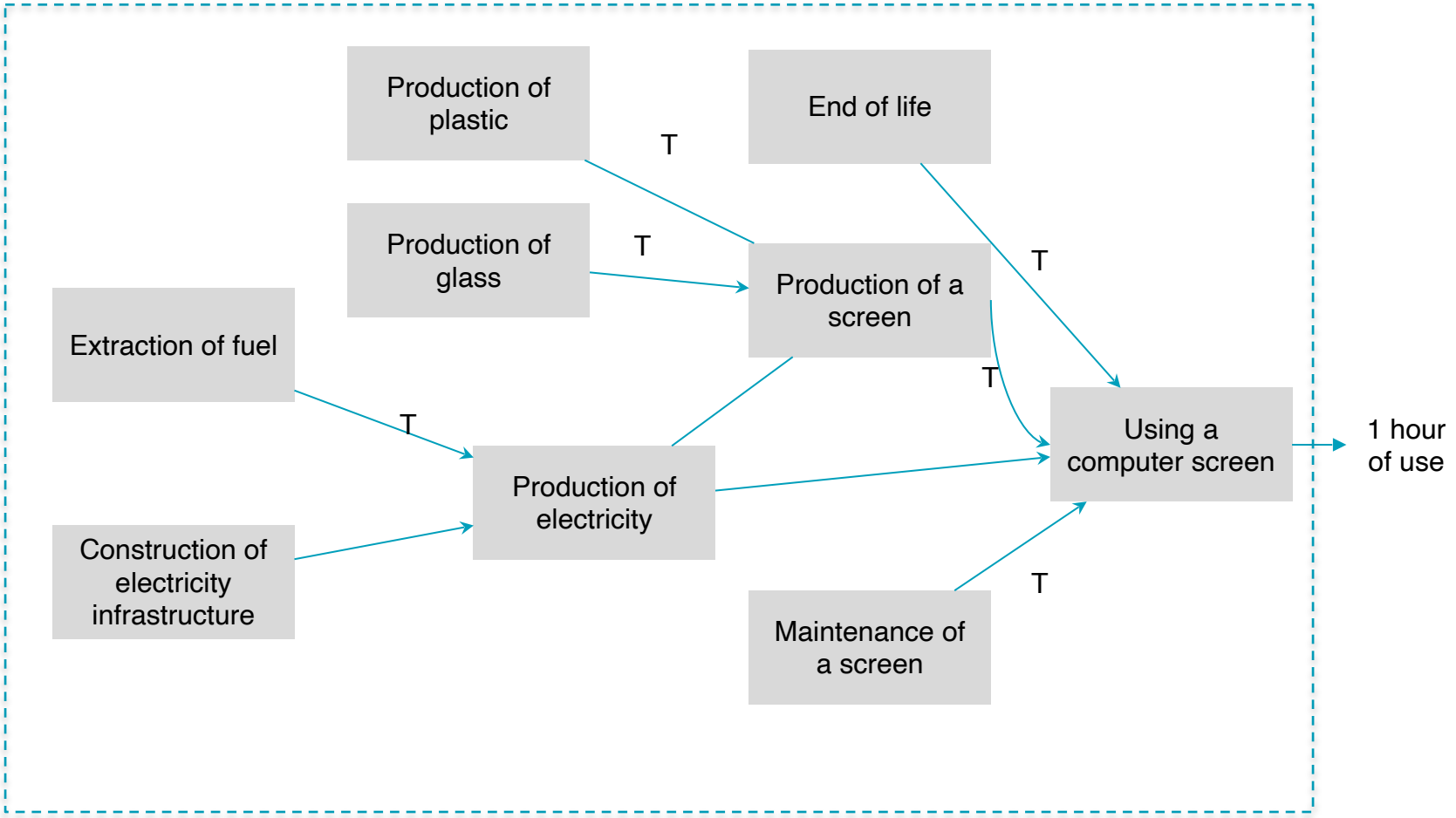
System boundary of a screen



System boundary of a screen

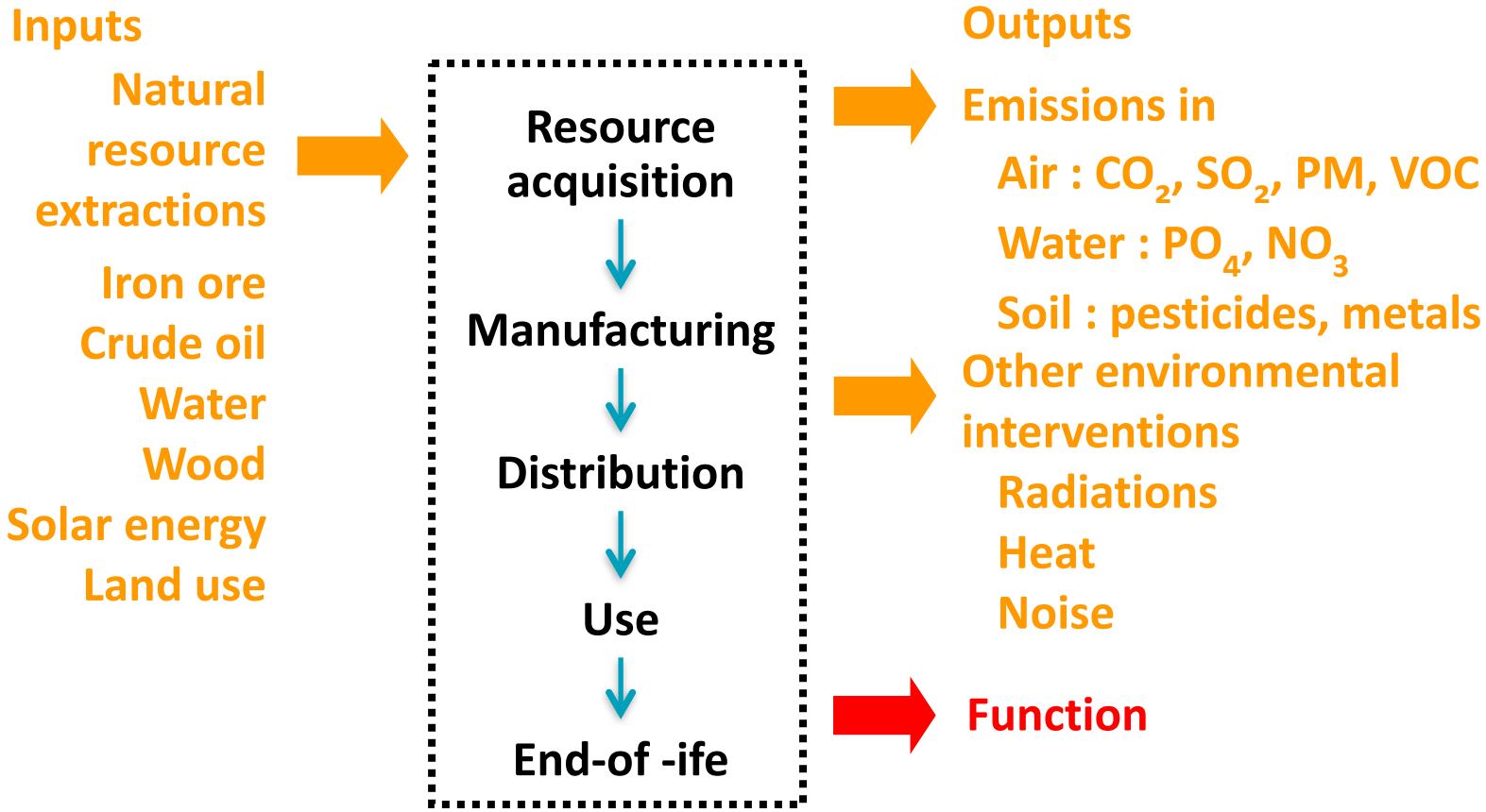


System boundary of a screen



In theory

All processes required to fulfill the function should be included

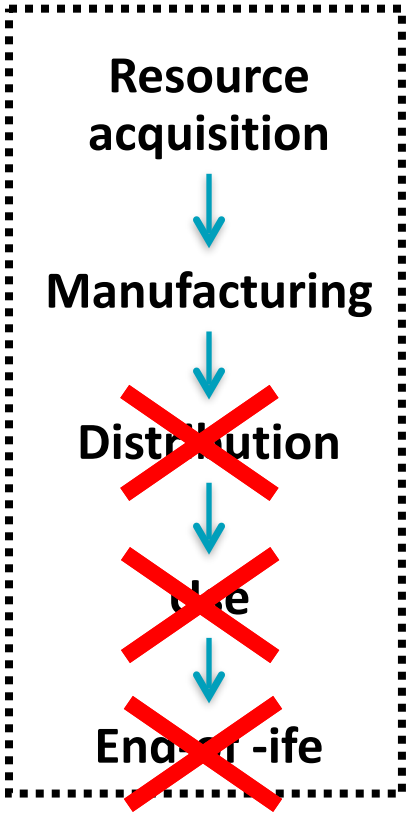


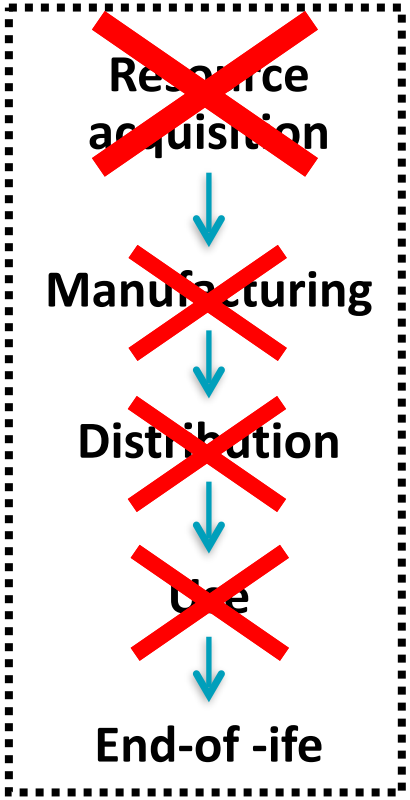
Complete life cycle?

LCA comparing different manufacturing processes for the same product

The product being unchanged, the use and end-of-life stages are the same and can be excluded

→ « *Craddle to gate* » study





LCA on municipal waste management

The stages before the end of life are the same and can be excluded

→ « *Gate to grave* » study

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The 3 rules to define the system boundaries

1. The compared systems must provide the same function
2. The identical stages/processes between compared systems can be excluded ONLY IF this does not affect their functional equivalence
3. The included processes are those which contribute more than a fixed percentage (cut-off criteria)
    a. of the total mass of the reference flows
    b. of the total energy demand of the system
    c. of the total emissions of an environmentally relevant substance

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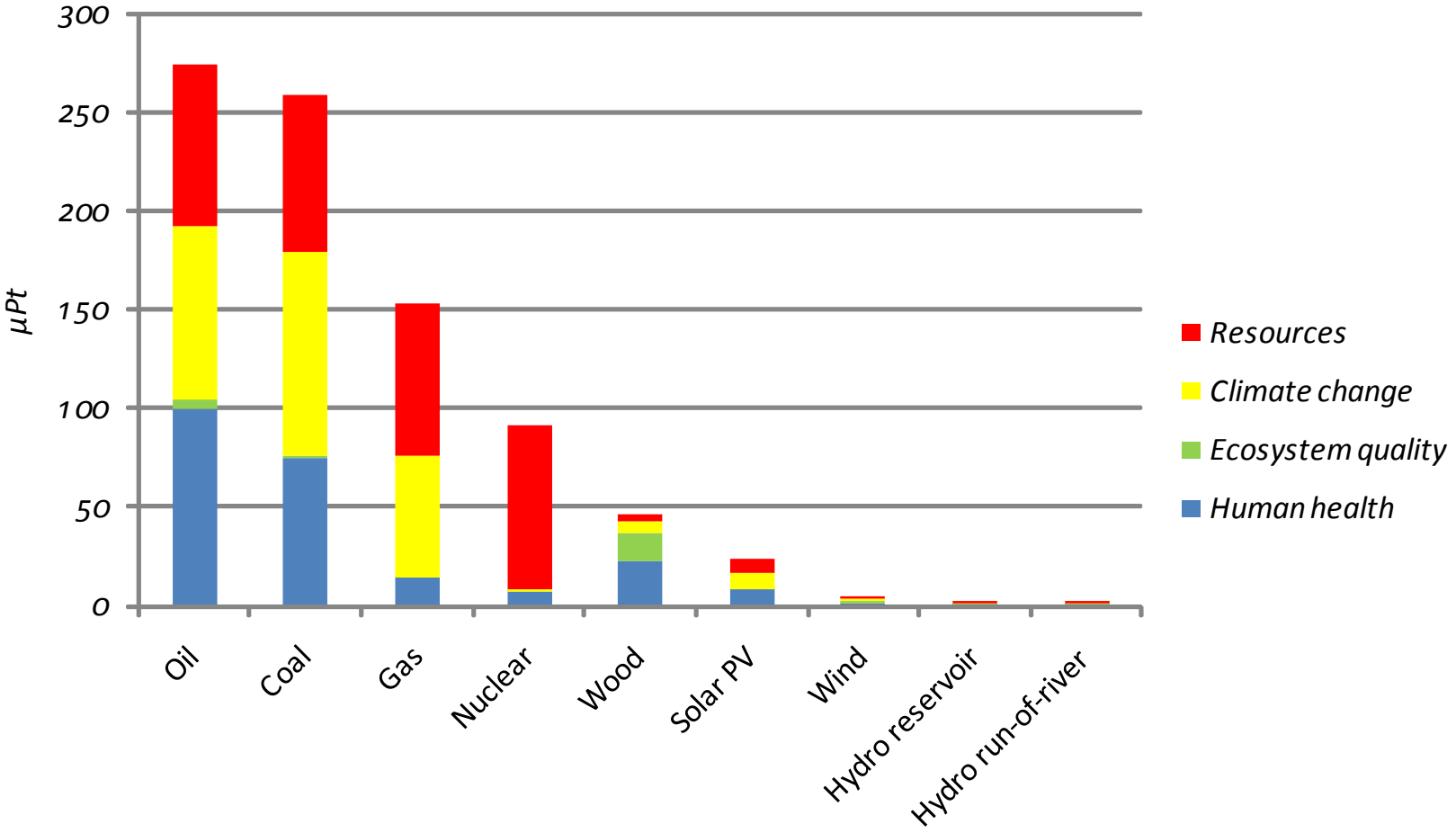
Electricity generation

It is important to account for the composition of the grid mixes feeding the different unit processes included in the system boundaries

SINCE

- **The environmental impacts associated with the different generation modes vary greatly**
- **The proportions of the different modes vary from one region to another**

The potential impacts of electricity generation



Inventory : ecoinvent 2.2 (European averages)
LCIA method : IMPACT 2002+ (single score)

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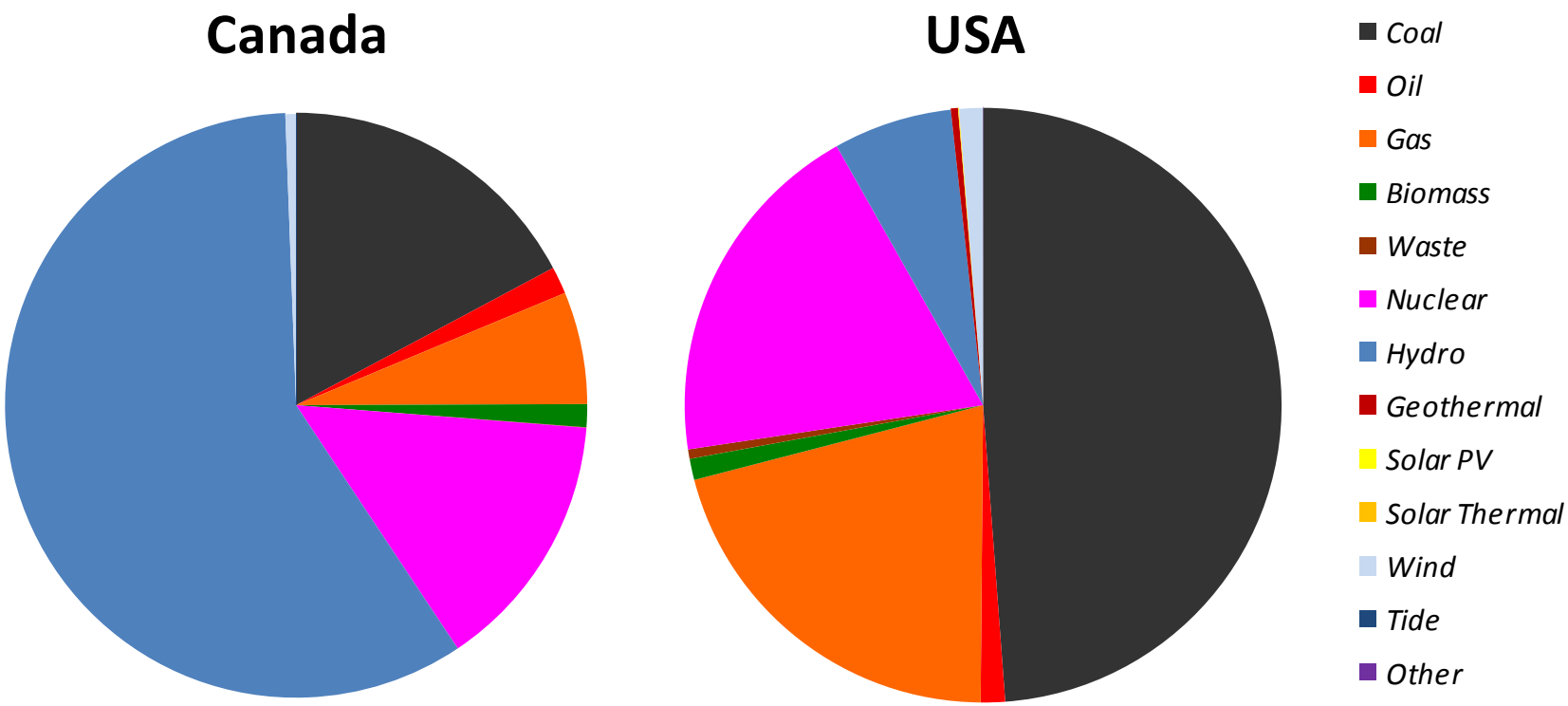
Electricity generation in Canada and the USA



From International Energy Agency – 2008 data

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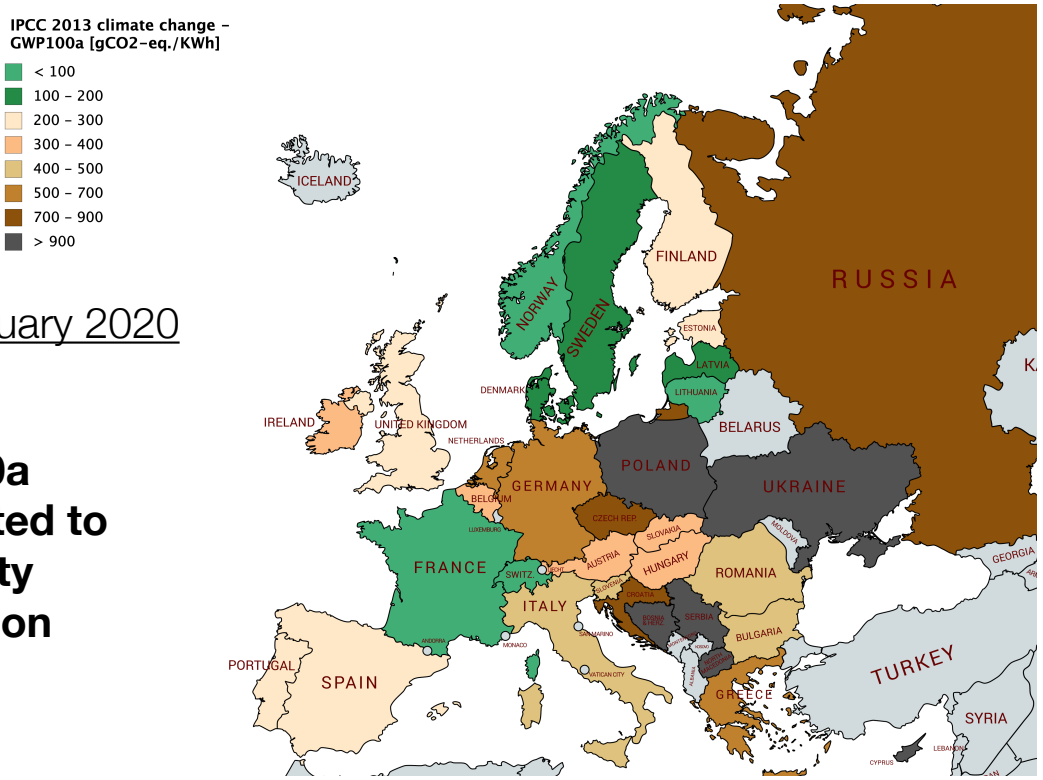
Dynamic LCA - real time emissions



26th January 2020
12:00

GWP100a associated to electricity generation

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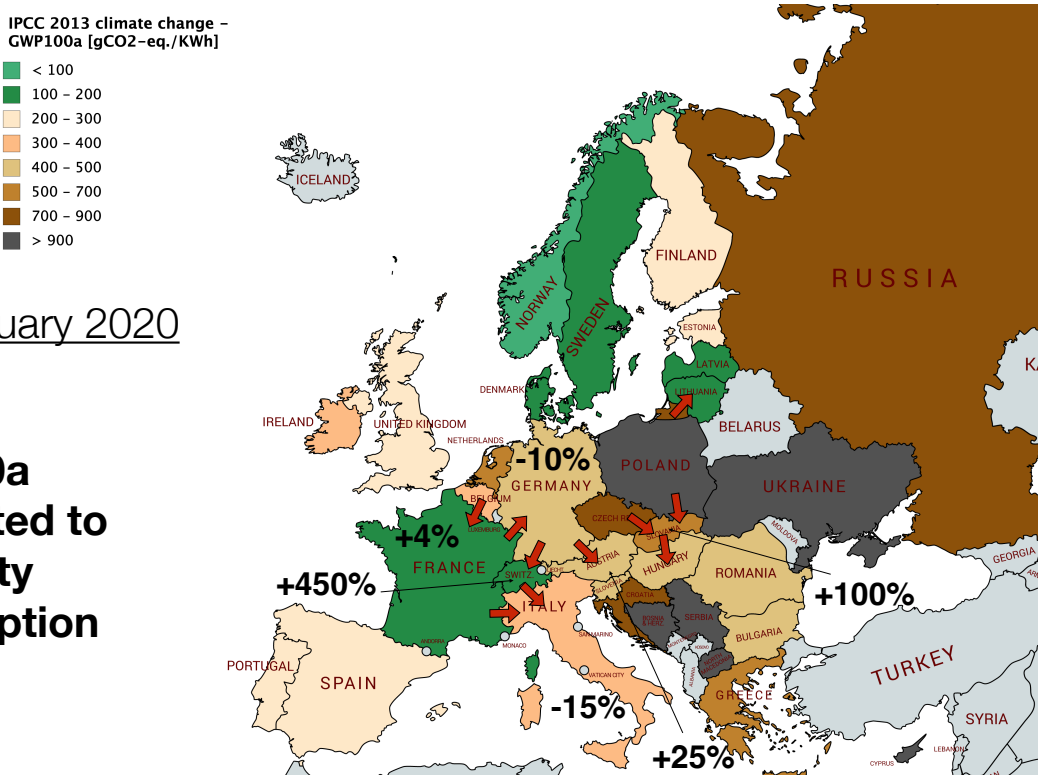
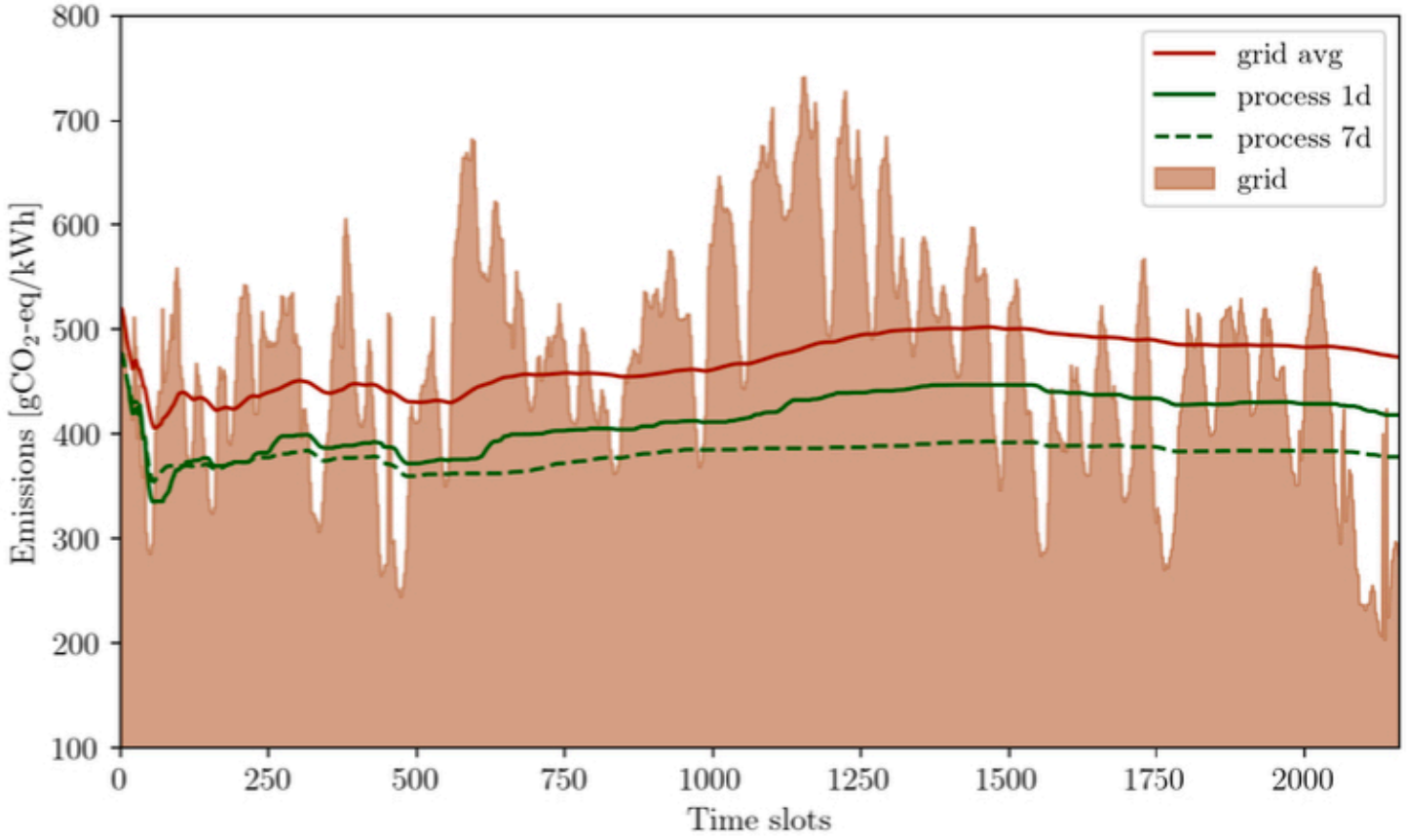
Dynamic LCA - effect of exchanges



26th January 2020
12:00

GWP100a associated to electricity consumption

Electricity mix and CO2 emissions ?



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Infrastructure

= Capital goods investments

For a chemical production unit process:

- the construction, maintenance and disposal of the reactor and whole facility

For a truck transport unit process:

- the construction, maintenance and disposal of the vehicle and road

Infrastructure

Infrastructures participate in the production of a very large number of product units during their lifetime

➔ **Only a very small share of the infrastructure is allocated to each**

1 kg of boric acid requires 1/2 500 000 000 of a plant

1 tkm of transport requires 1/5 400 000 of a truck

➔ **Was previously assumed that the infrastructures (and their life cycle) had a negligible contribution**

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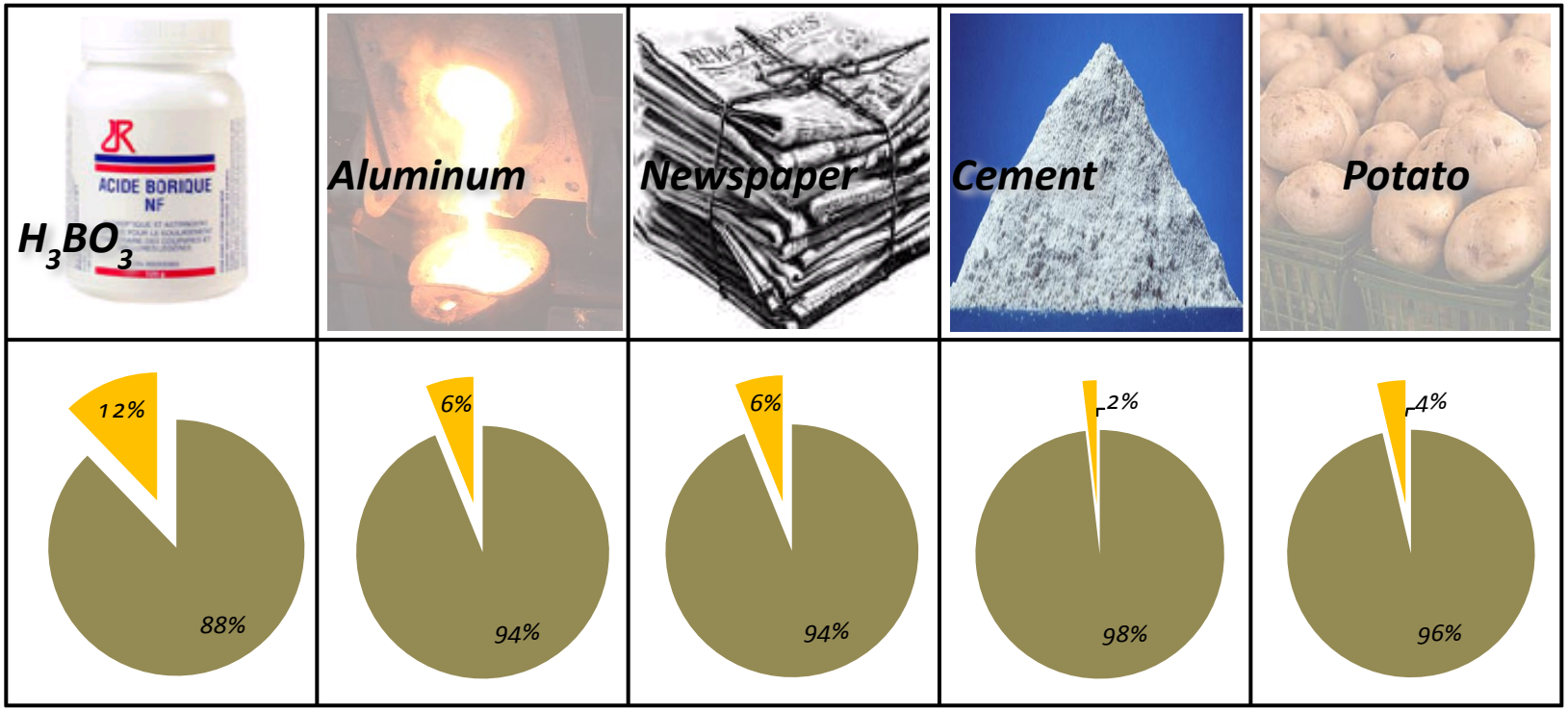
Infrastructure



Infrastructure

Process

Inventory : ecoinvent 2.2 (European averages)
LCIA method : IMPACT 2002+ (single score)

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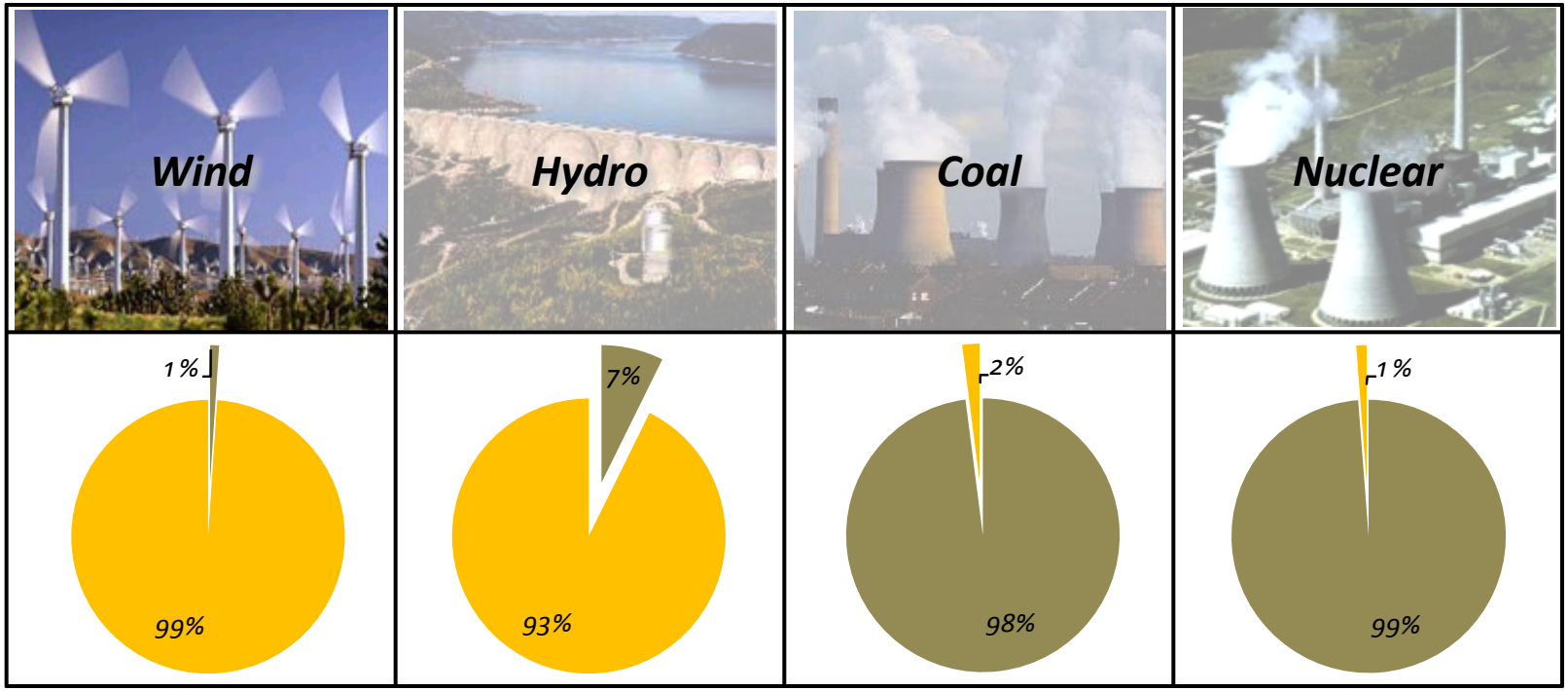
Infrastructure



Infrastructure

Process

Inventory : ecoinvent 2.2 (European averages)
LCIA method : IMPACT 2002+ (single score)

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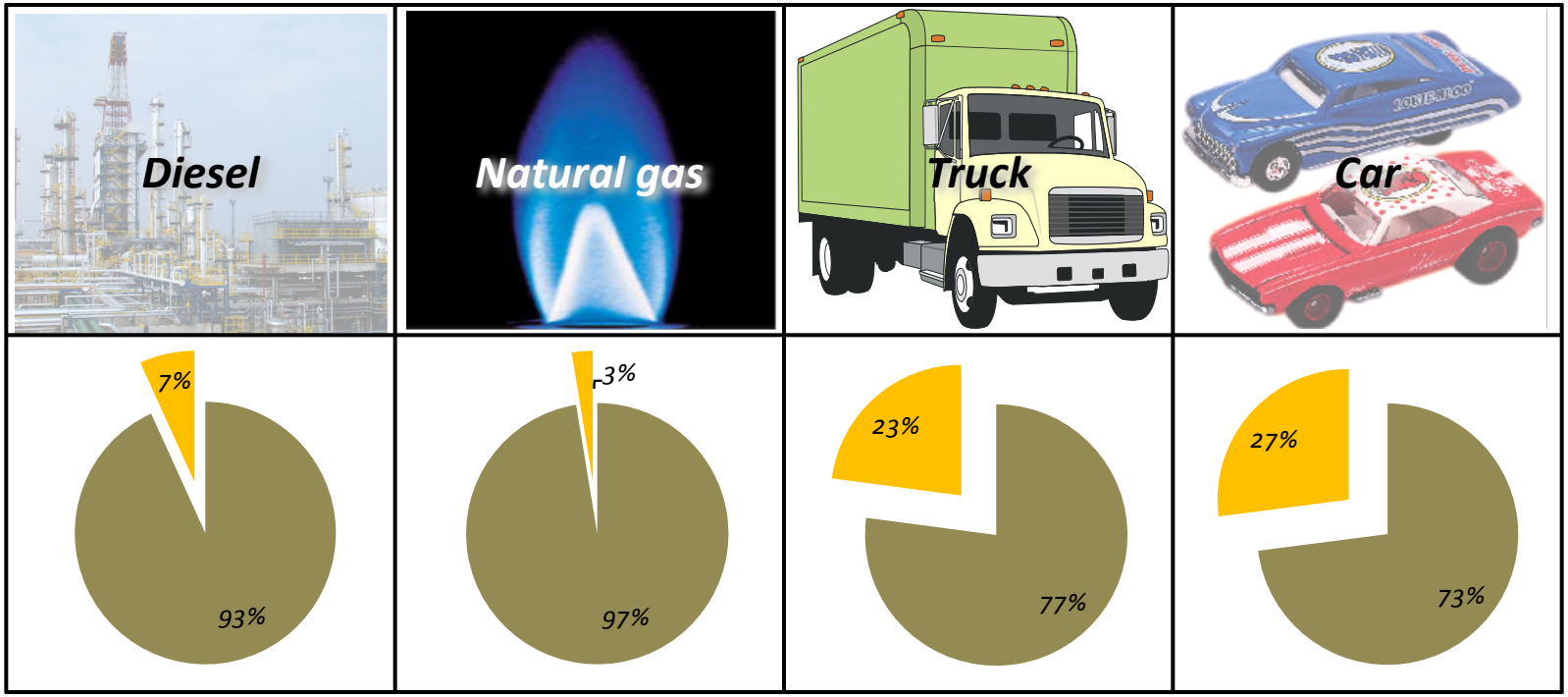
Infrastructure



Inventory : ecoinvent 2.2 (European averages)
LCIA method : IMPACT 2002+ (single score)

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Data source

Primary data

Specifically collected to do the LCA and which directly concern the studied product

- **at the manufacturer (inputs and outputs of a required process)**
- **on the use profile of the product**
- **on key parameters**
- **…**

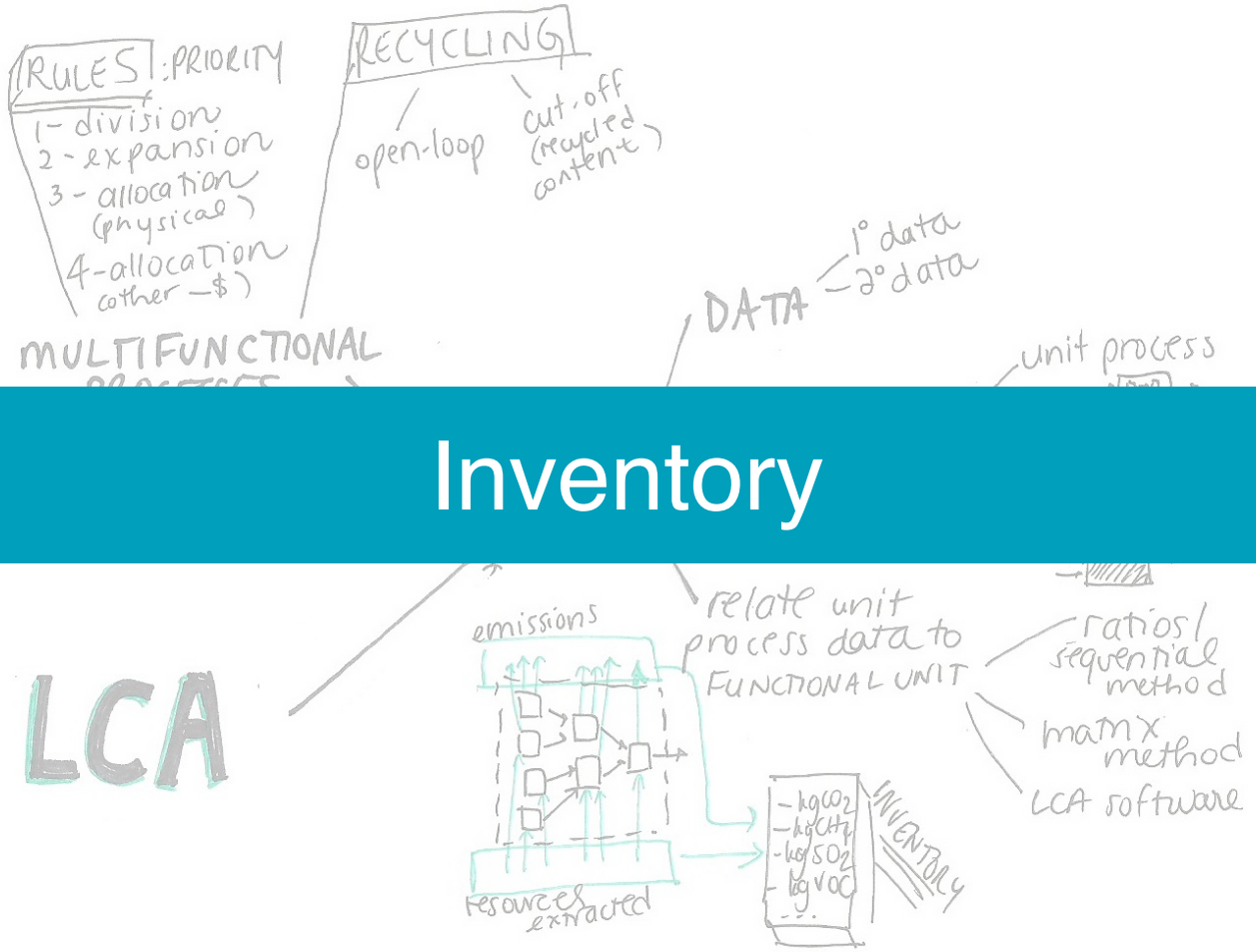
Data source

Secondary data

NOT specifically collected to do the LCA

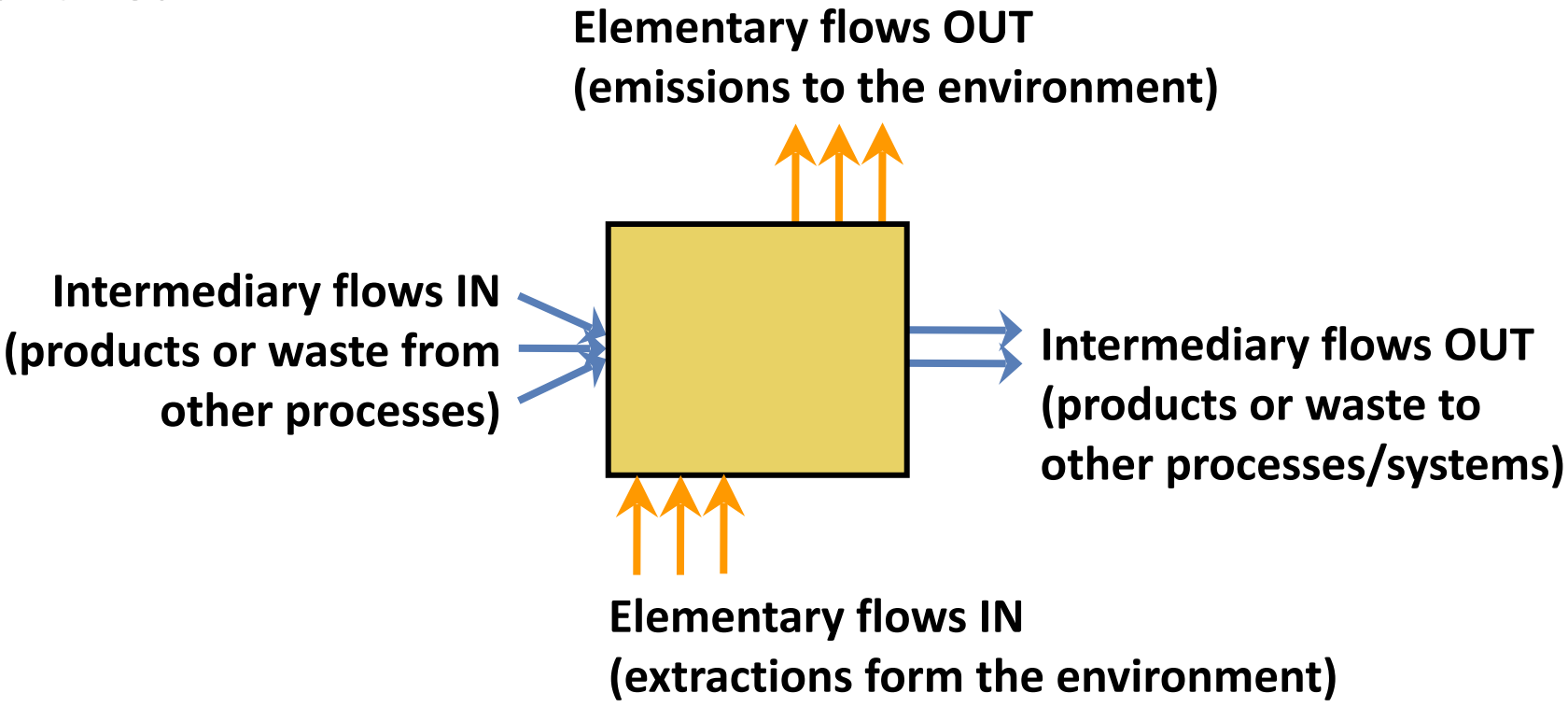
- **Data from literature on a process (e.g. theoritic or empiric model, standard design criteria)**
- **Average data on inputs and outputs of a unit process found in LCI databases**

Inventory


RULES: PRIORITY
1- division
2- expansion
3- allocation (physical)
4- allocation (other - $)
RECYCLING
open-loop
cut-off (recycled content)
MULTIFUNCTIONAL
DATA
1° data
2° data
unit process
LCA
emissions
relate unit process data to FUNCTIONAL UNIT
ratios / sequential method
matrix method
LCA software
resources extracted
INVENTORY

LCI in short

For each unit process*, the inputs and outputs (2 types of flows) are quantified



* : smallest element of a product system for which data are collected, can represent a unit operation, a production line, a production site, a cradle-to-gate system

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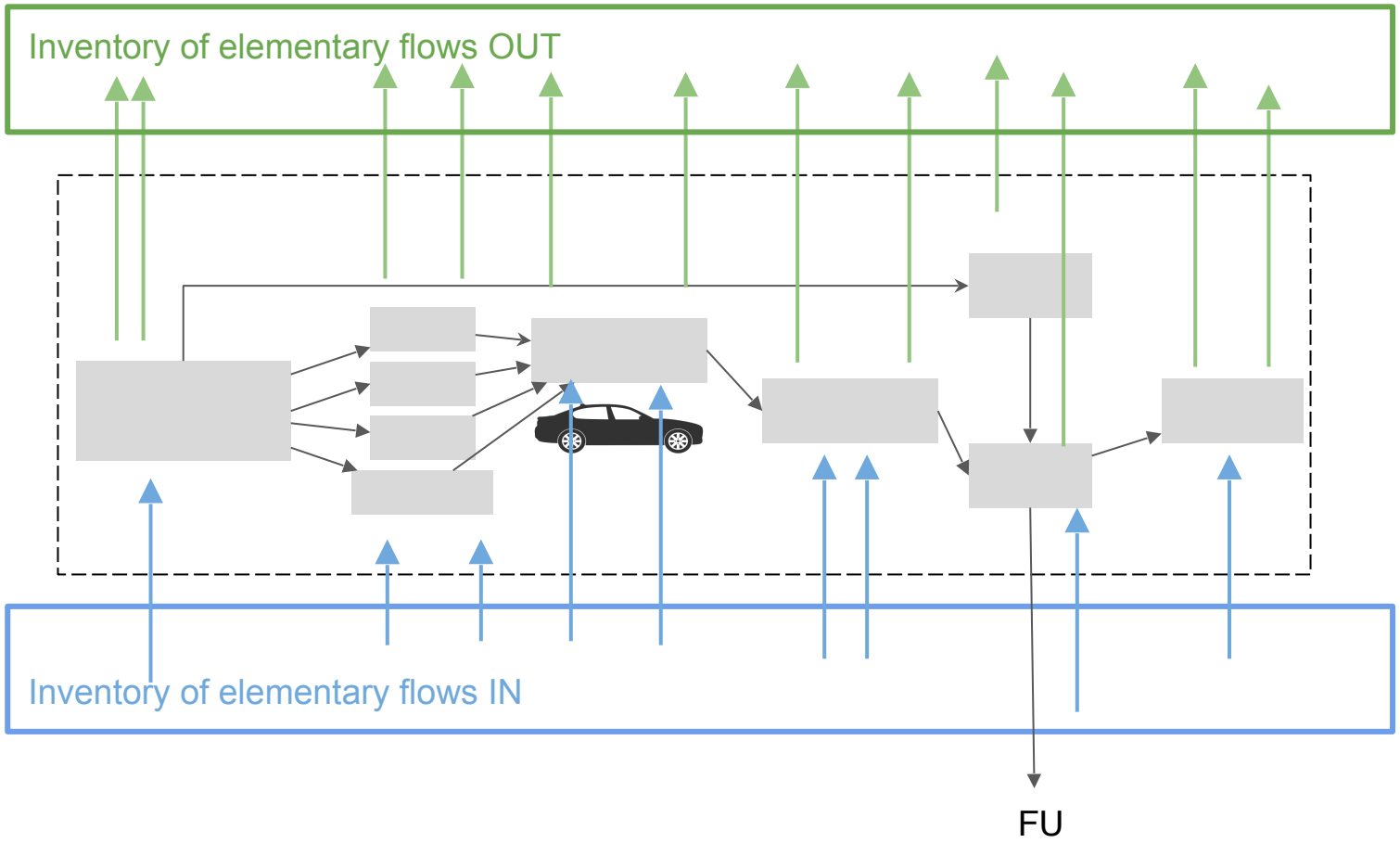
Life Cycle Inventory (LCI) ***relates all inputs and outputs*** *of all processes to the functional unit and aggregates them*



LCA databases

Practically impossible to quantify all the flows of all processes

- **The length of supply chains is in theory infinite**
- **Each economic activity is linked to (almost) all the others**

Even if only limited to the most important processes, redoing the data collection all over again for key sectors (base materials, energy production) for each LCA would incredibly inefficient

→ Use of LCI databases

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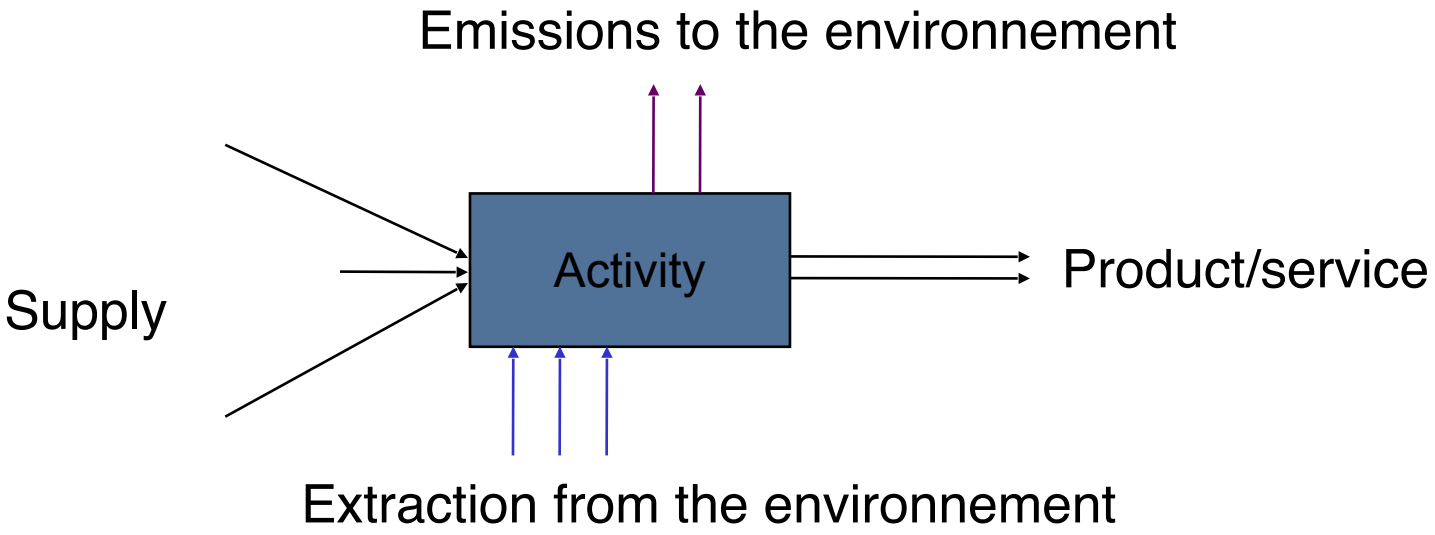
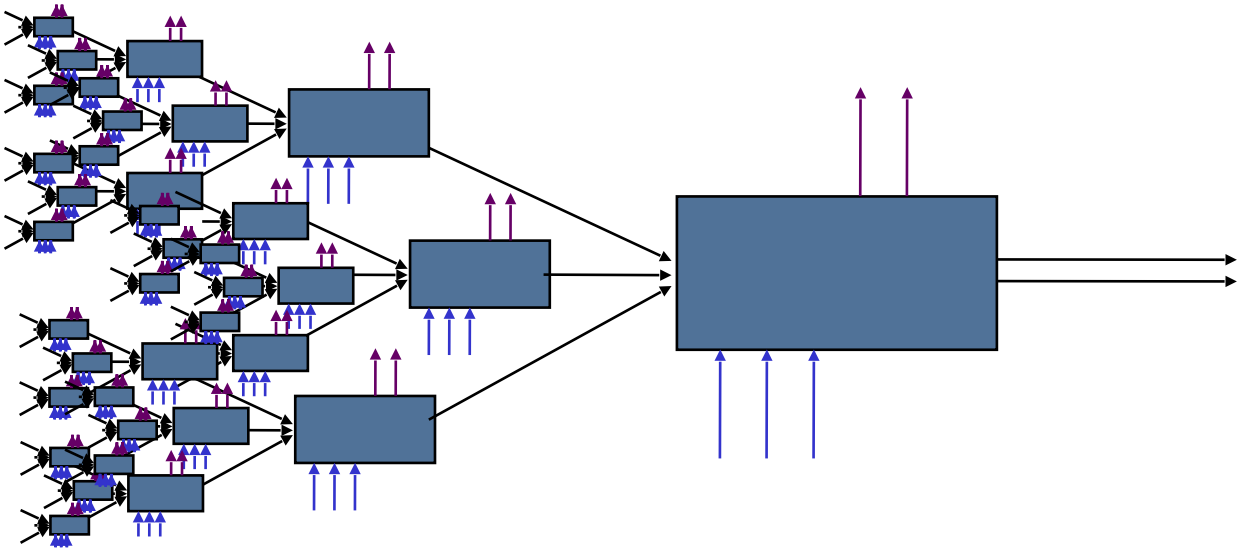
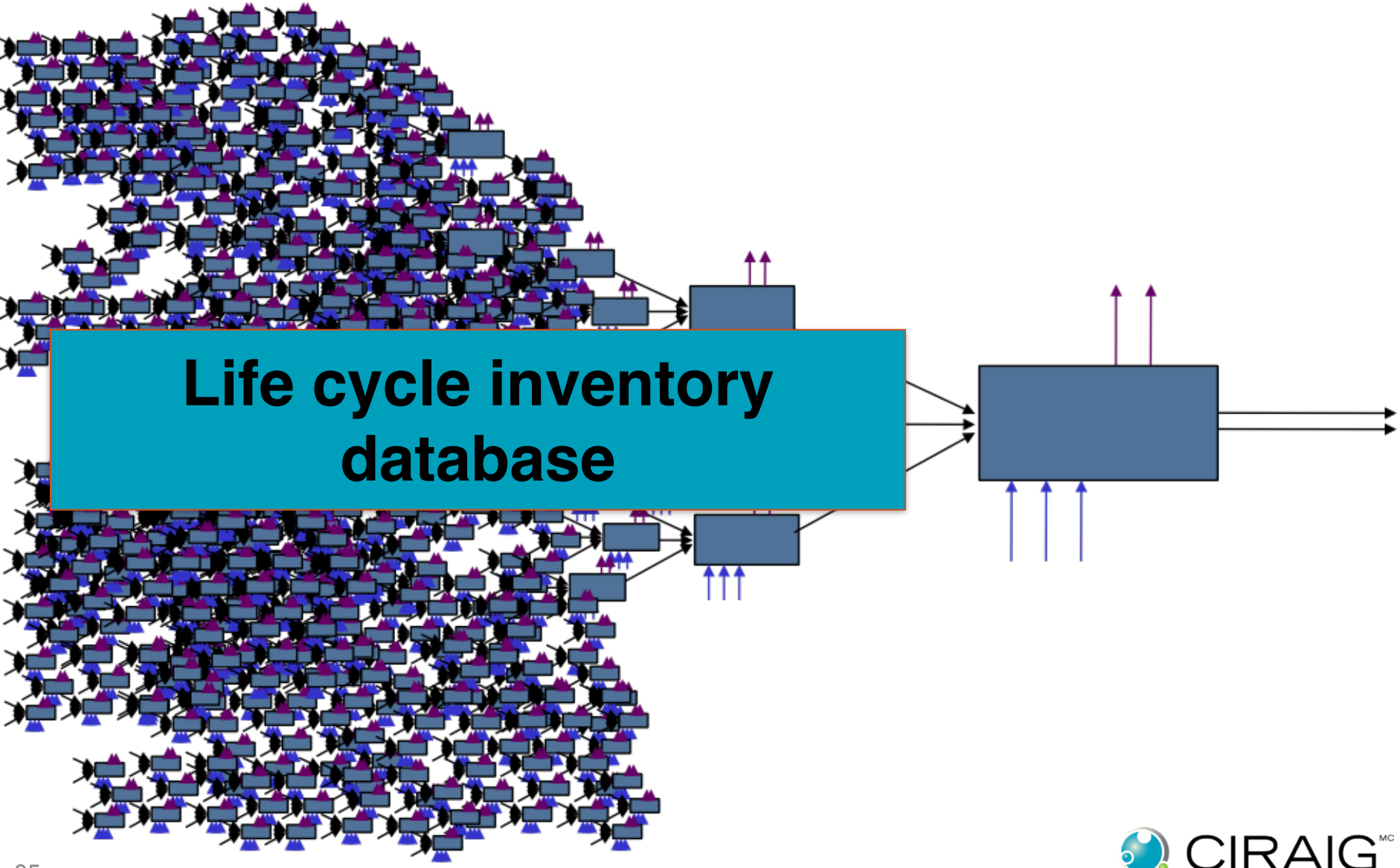
Linkage with a life cycle inventory database



Linkage with a life cycle inventory database



Linkage with a life cycle inventory database



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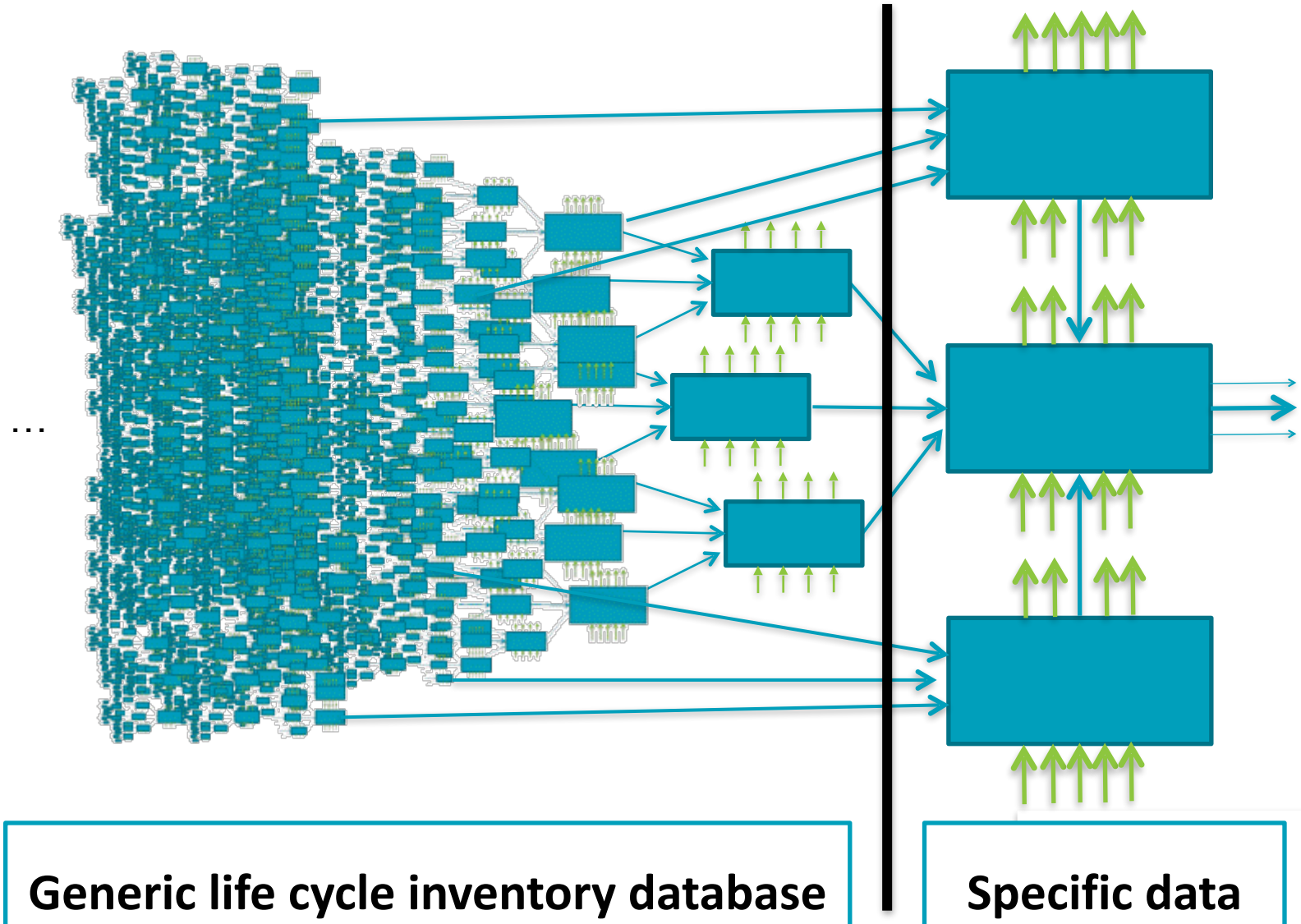
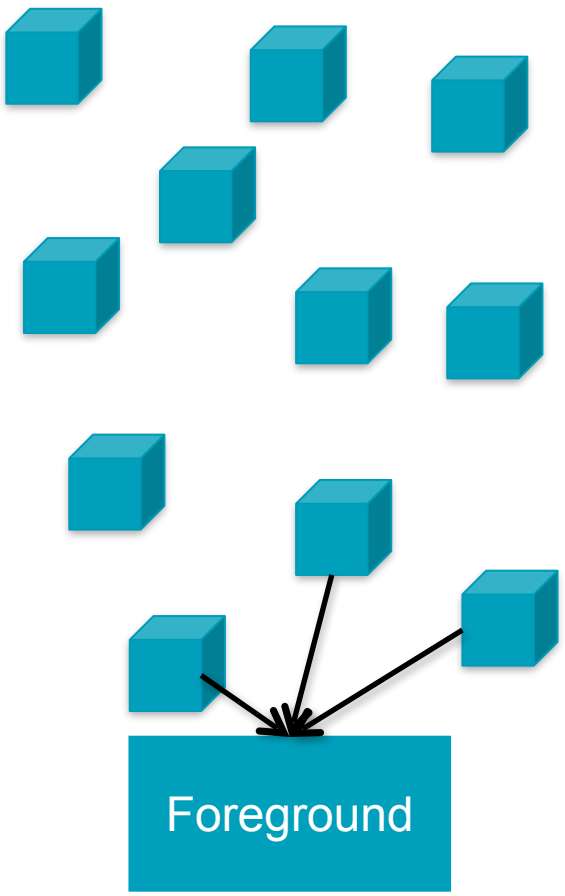
Linkage with a life cycle inventory database



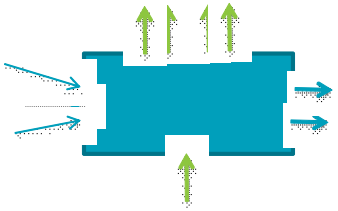
LCI-DB archetypes



“Collection” of elementary processes

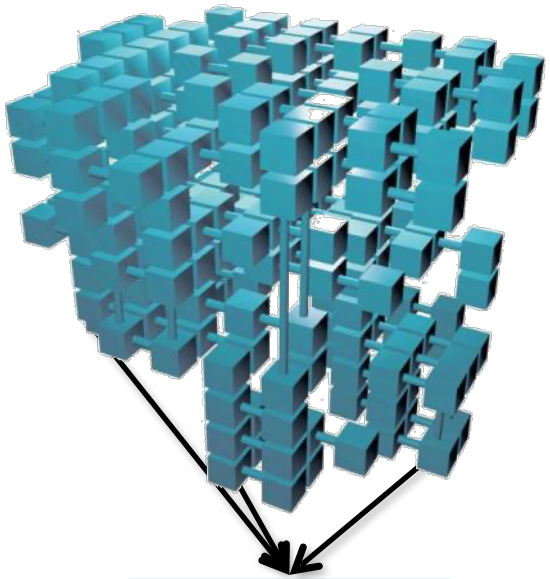
(p.ex. U.S. LCI)

« gate-to-gate » LCI data, allowing to see the detail of modeled activities and modify them if needed



Linking unit processes (theoretically up to the infinite supply chain) is let to the LCA practitioners

LCI-DB archetypes



Desaggregated LCI-DB
(e.g. ecoinvent version « Unit process »)

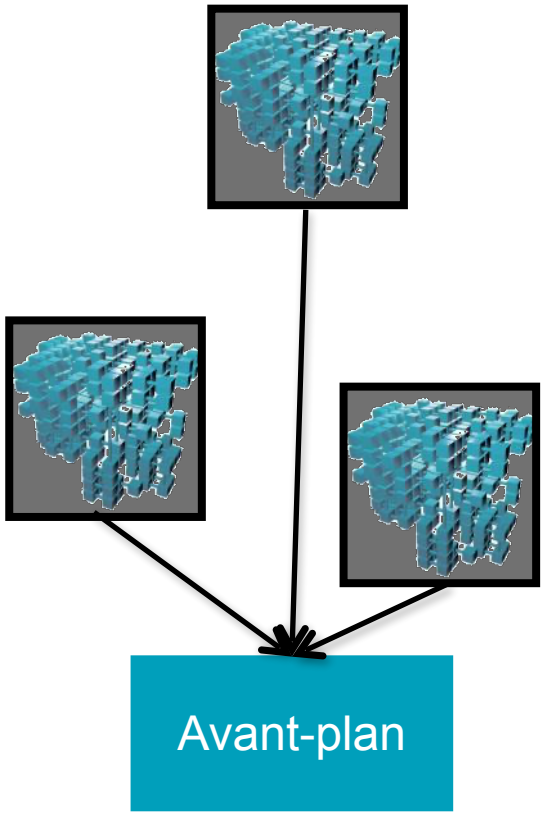
« gate-to-gate » LCI data transparently provided that can be modified accordingly

Links between unit processes are given according to a modeling principle (e.g. attributional, consequential, etc.)

Such links allow to calculate the LCI in software without the intervention of the LCA practitionners

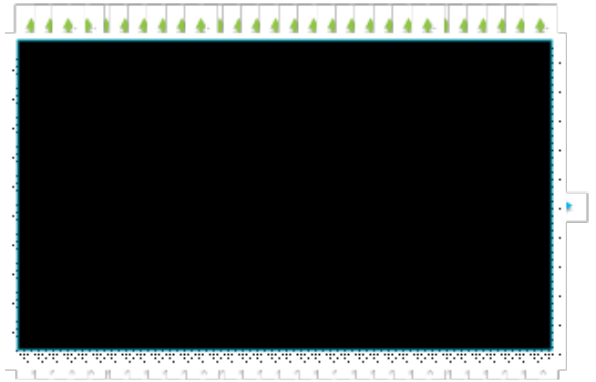
Links can be modified accordingly

LCI-DB archetypes



Aggregated LCI-DB
(e.g. GaBi « agg », ecoinvent version « system »)

Precalculated « cradle-to-gate » life cycle invetory for hundreds of unit processes



→gate-to-gate unit processes
Links between unit processes are no more visible

Allow to hide confidential information
Calculation is simpler

Types of databases

	Disaggregated	Aggregated
User friendliness	X Need software for calculations	√ Calculations already done per systems
Possibility to adapt datasets	√ Possible to adapt individual datasets	X No adaptation possible, black box model
Validity	√ Depends on database but can be checked	X Depends on database, but cannot be checked
Contribution analysis	√ Yes, high resolution (process level)	X Yes, low resolution (material level)
Possibility to create « distributed » datasets	√ Yes	X No

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Available process databases

Free:

World Steel (Europe) http://www.worldsteel.org/publications/position-papers/lca.html
PlasticsEurope (Europe) http://www.plasticseurope.org/plasticssustainability/eco-profiles.aspx
FEFCO (Europe) http://www.fefco.org/technical-documents/lca-database
ELCD Database (Europe) http://eplca.jrc.ec.europa.eu/?page_id=126
CPM LCA Database (Sweden) http://cpmdatabase.cpm.chalmers.se/
US LCI Database (United-States) http://www.nrel.gov/lci/
Life Cycle Assessment Commons (United-States) http://www.lcacommons.gov/
https://nexus.openlca.org – several databases (free or not) for openLCA
Athena Institute (Canada) http://www.athenasmi.org/our-software-data/overview/
ADEME AgriBalyse (France) http://www.ademe.fr/expertises/produire-autrement/production-agricole/passer-a-laction/dossier/levaluation-environnementale-agriculture/loutil-agribalyse-agribalyse-program

Commercial:

ecoinvent http://www.ecoinvent.org
Australian Industrial Ecology Laboratory (Australia) http://ielab-aus.info:8080/IndustrialEcology/
SimaPro et ECO-it – Pré Consultants http://www.pre-sustainability.com
GaBi – ThinkStep https://www.thinkstep.com/software/gabi-lca/gabi-databases
Umberto NXT http://www.umberto.de/en/versions/umberto-nxt-lca/
Team – Ecobilan http://ecobilan.pwc.fr/boite-a-outils/deam.html

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Economic Input-Output databases

Economic Input-Output databases

- **« *Environmental Input-Output LCA* »**
- **Data collected at the economic sector level on commercial exchanges between sectors**
- **Complete (covers the whole economy) but low resolution**
- **Monetary intermediary flows instead of physical ones (material or energy)**

Ex. :

CEDA®

openIO BETA 1.4

eiolca.net

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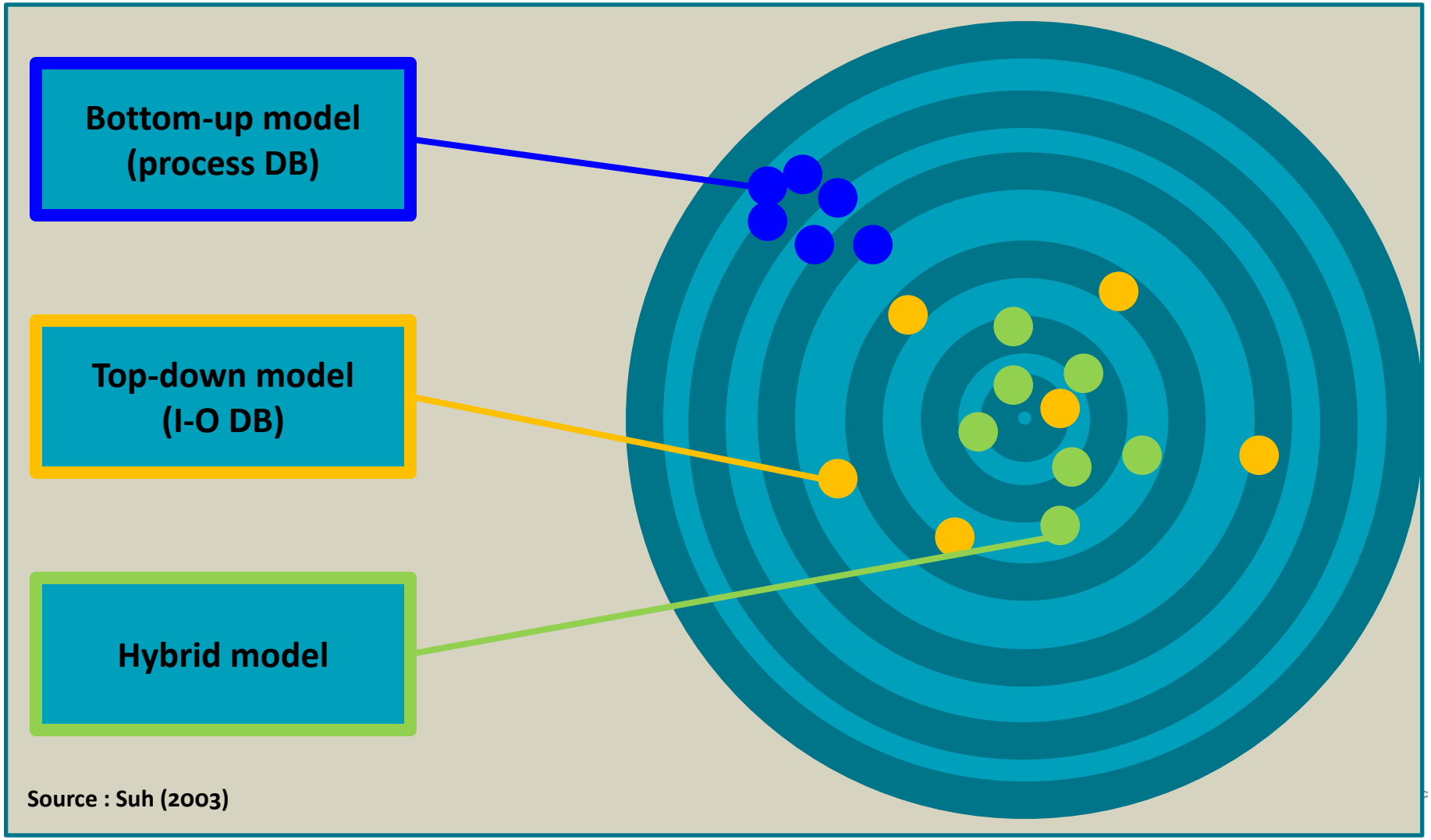
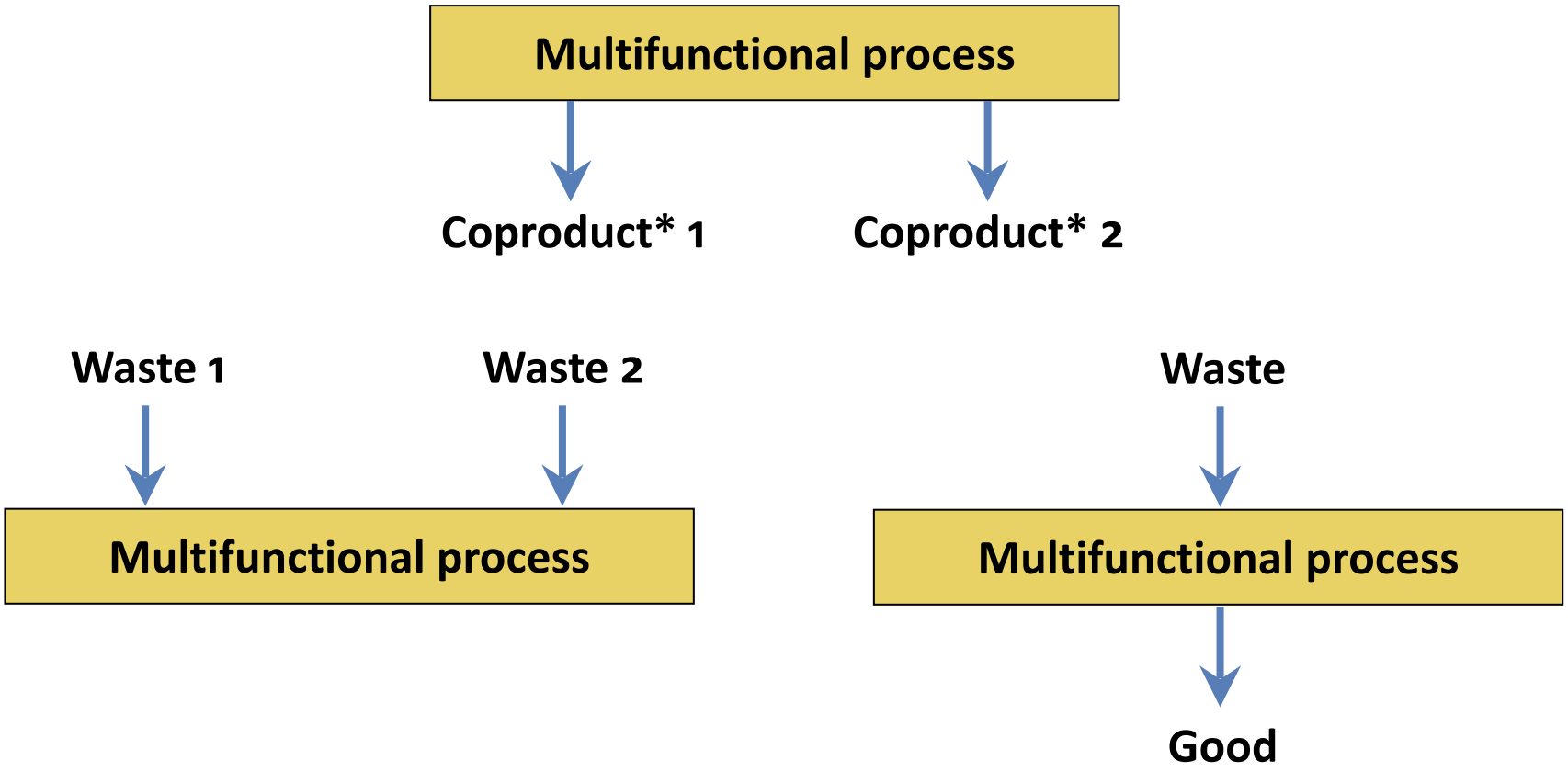
Types of databases

Hybrid databases



Source : Suh (2003)

Multifunctionality and allocation



* : The distinction between coproduct and byproduct (product of less economic value) is irrelevant to the multifunctional character of the unit process

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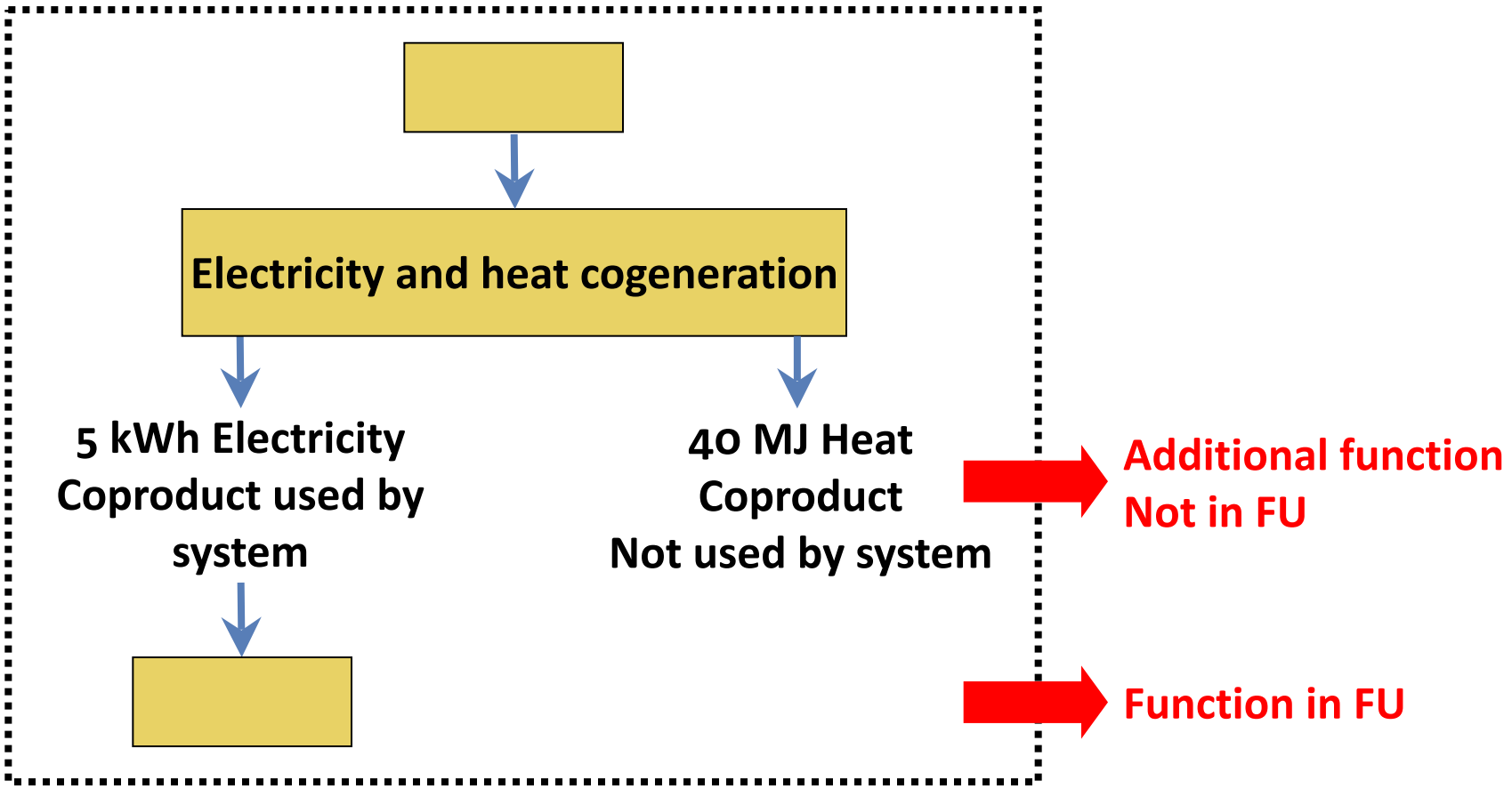
The problem



Multifunctional process

→ The system has more then one function!

The ISO recommendations

a) Wherever possible, *allocation should be avoided* by

1) **dividing the multifunctional process into sub-processes and collecting the input and output data related to each sub-process**

   ➔ « division » approach

2) **expanding the product system boundaries to include the additional functions related to the coproducts**

   ➔ « expansion » approach

b) *Where allocation cannot be avoided*, the inputs and outputs of the system should be partitioned between its coproducts or functions in a way that reflects the underlying physical relationships between them

➔ « allocation » approach

c) Where physical relationship cannot be established or used as the basis for allocation, other relationships should be used to allocate the inputs and outputs between the coproducts and functions

➔ « allocation » approach

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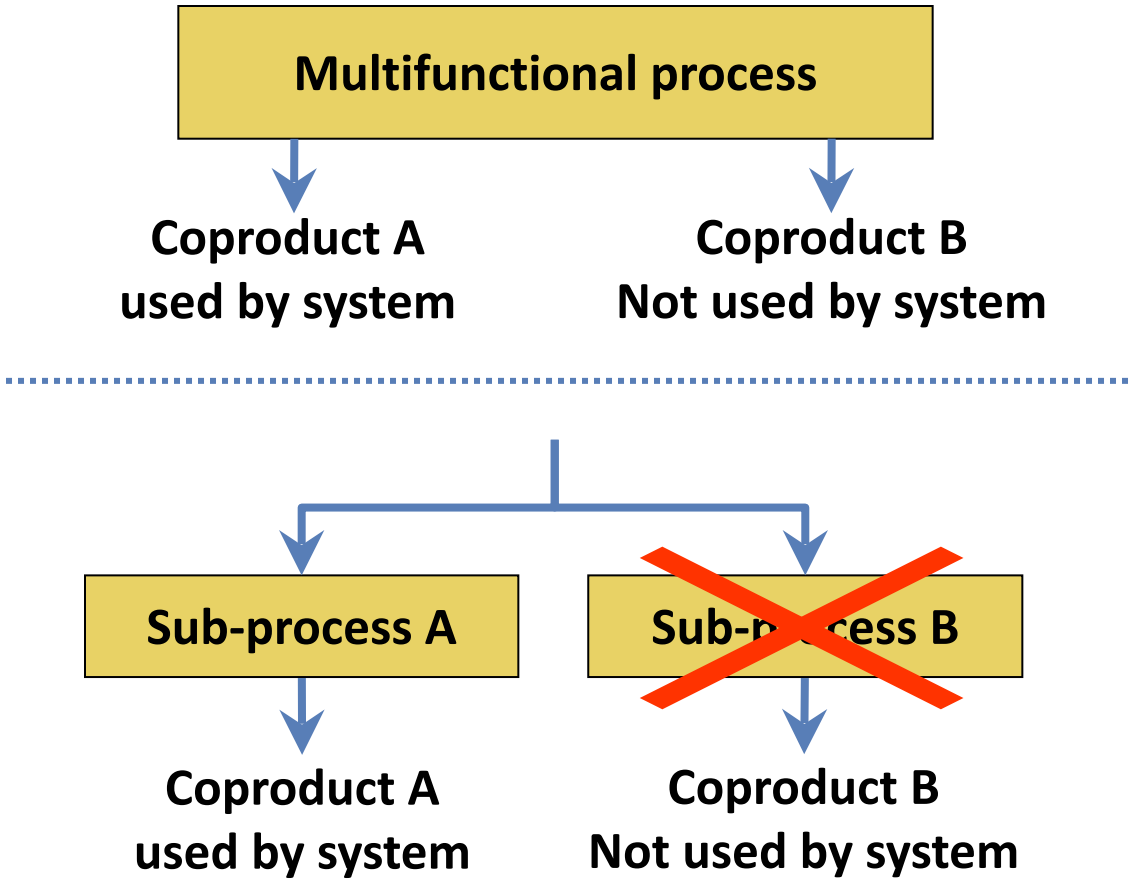
Division approach

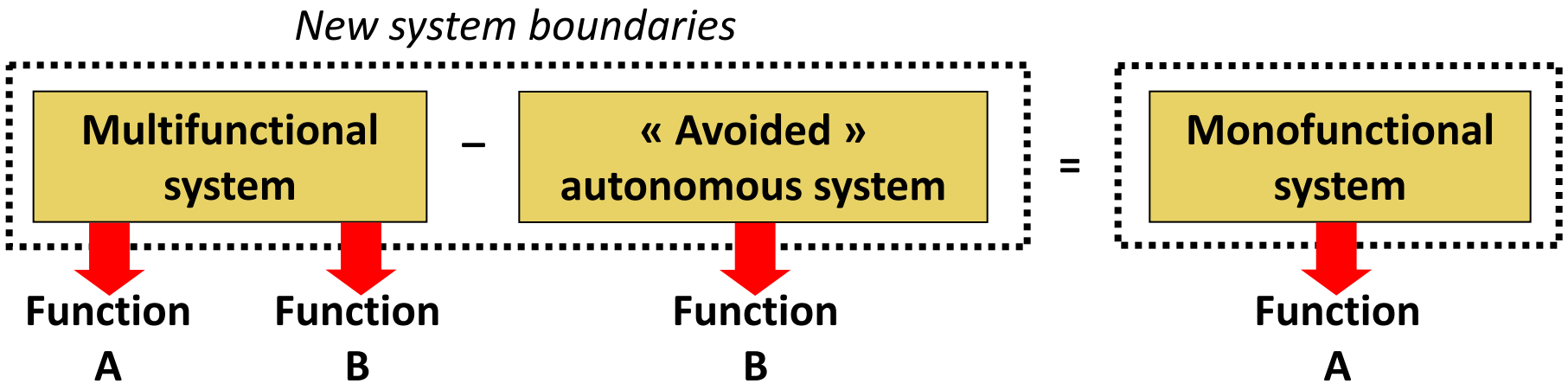


Expansion approach

LCA on function (product) A, system provides A and B

Boundaries are expanded to include unit processes providing function equivalent to B → these processes make up an « avoided » autonomous system

The resulting constructed system is considered equivalent to a system providing only A



Expansion approach

Treatment of 1 kg of plastic waste

- Collection
- Transport
- Sort
- Recycling

↓

0.8 kg of plastic film

Treatment of 1 kg of plastic waste

- Collection
- Transport
- Sort
- Valorisation

↓

26 MJ of heat

Treatment pathways cannot be compared since outputs are not the same!

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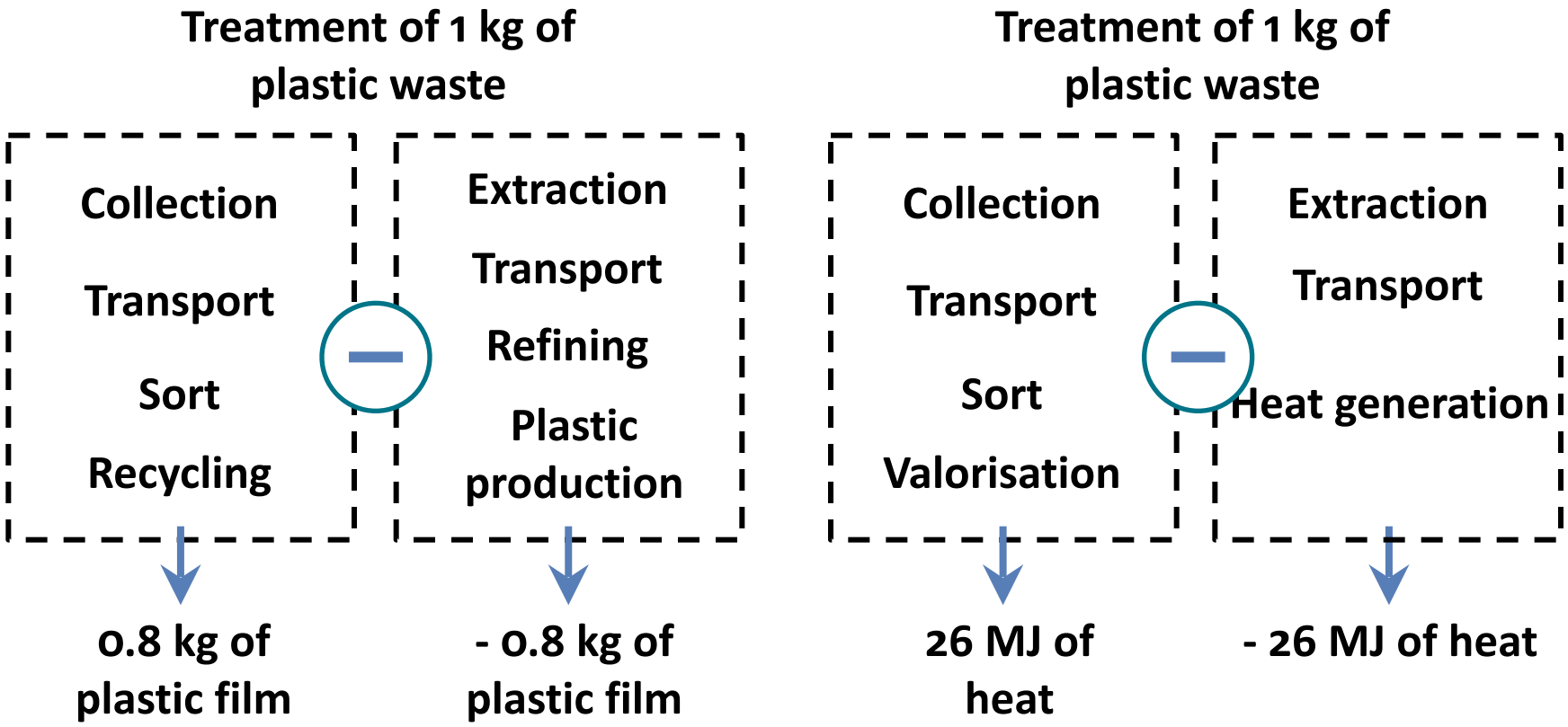
Expansion approach



Outputs cancel out themselves

→ FU is monofunctional

Expansion approach

The equivalence between the coproduct of the multifunctional process and the product of the avoided system is not always exact

The identification of the unit processes making up the avoided autonomous system is not always easy

These processes themselves can be multifunctional → the system can quickly become very large and not resemble the original life cycle considered

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Allocation approach

Allocate the inputs and outputs of the multifunctional process to its coproducts in a way that reflects:

a) Wherever possible, allocation should be avoided

b) the underlying physical relationships between them

Useful if the amounts of each coproduct can be varied independently

c) other types of relationships between them
   a) a physical property: mass, volume, surface, energy content, elemental composition, product units
   b) the economic value (See : J B Guinée, R Heijungs, G Huppes (2004) *Economic Allocation: Examples and Derived Decision Tree*, Int J LCA, 9(1), p. 23-33)
   c) another valid relationship

Causality principle: the parameter used to allocate a flow to a coproduct must reflect the responsibility of the coproduct in the generation of that flow

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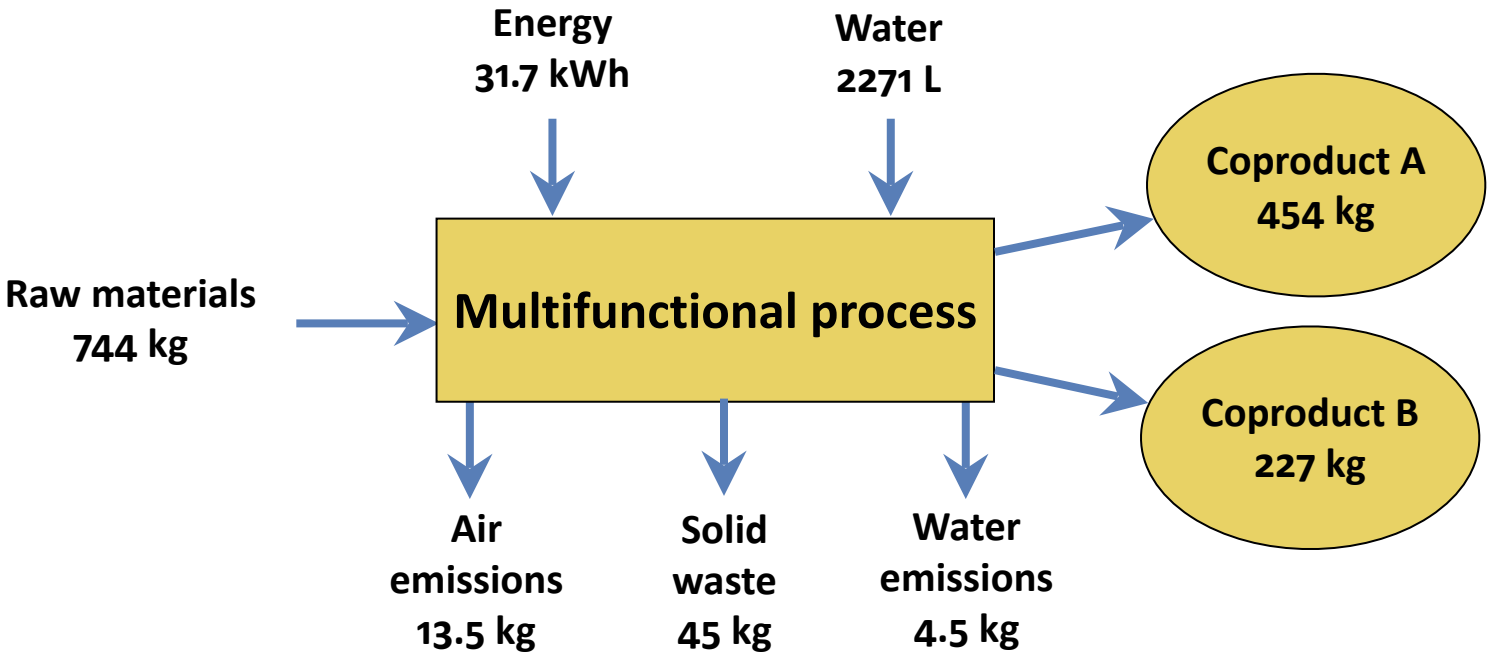
Allocation – Other types of relationships

Production process with 2 coproducts (A and B)
Total mass of coproducts = 681 kg/day



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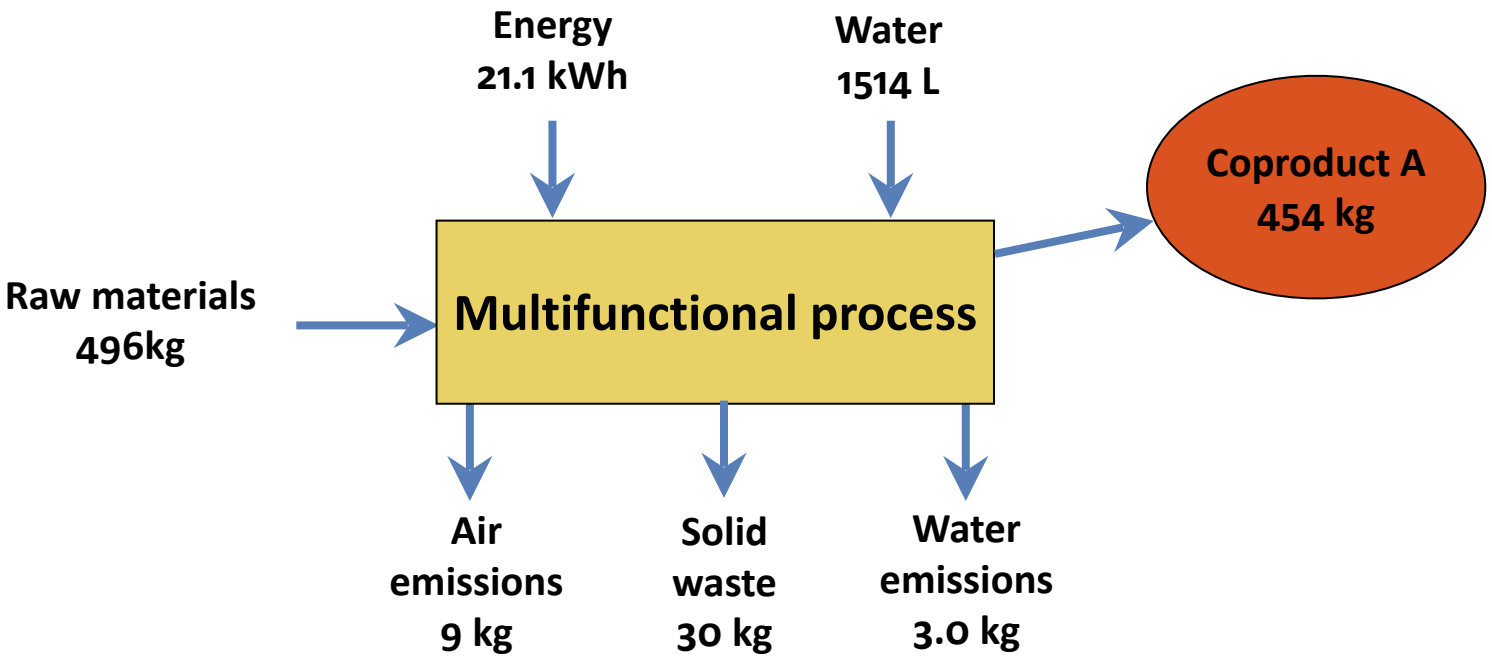
Allocation – Other types of relationships

Mass allocation factor for coproduct A
= 454 kg A/681 kg A&B = 2/3



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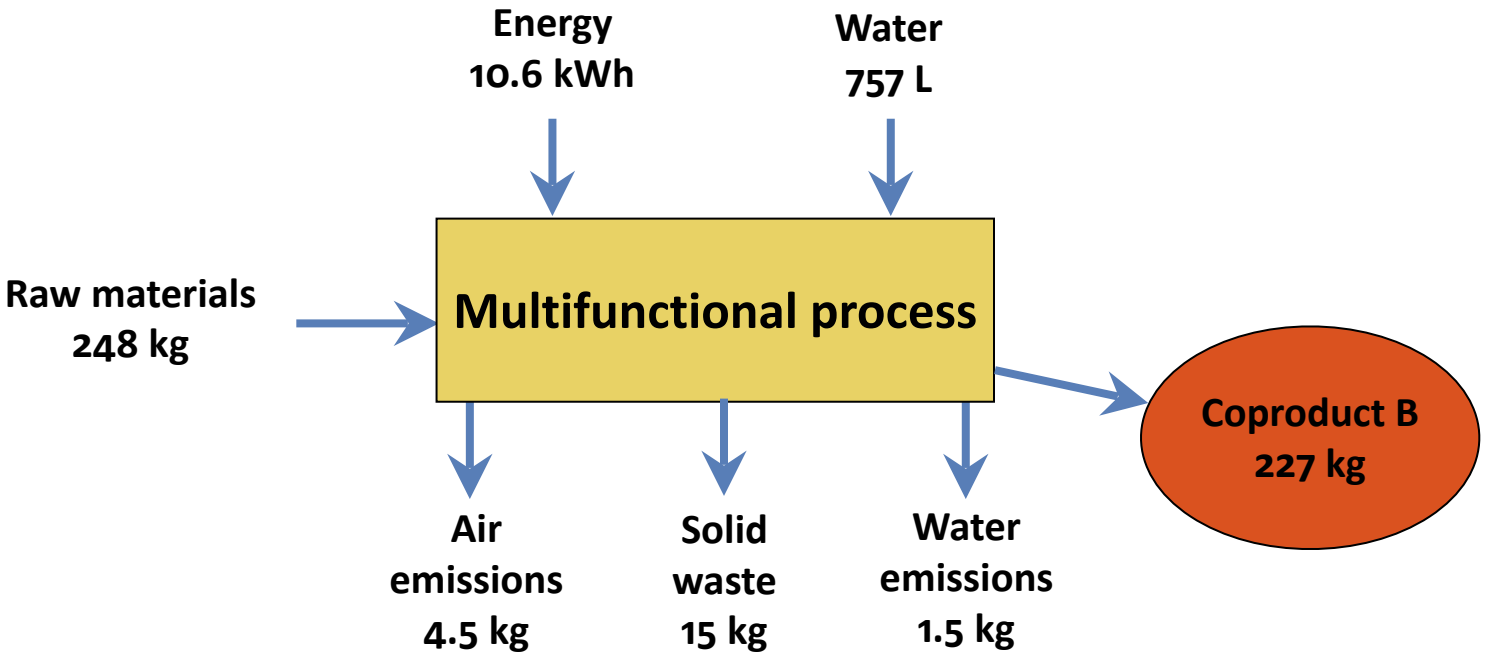
Allocation – Other types of relationships

Mass allocation factor for coproduct B
= 227 kg B/681 kg A&B = 1/3



The sum of the allocated inputs and outputs must equal the amounts before the allocation

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Conclusion

There are several approaches to treat multifunctional unit processes/systems

The most appropriate is not always clear-cut

As possible, follow ISO recommendation

- ➔ **Do sensitivity analyses to illustrate the consequences of the chosen approach**

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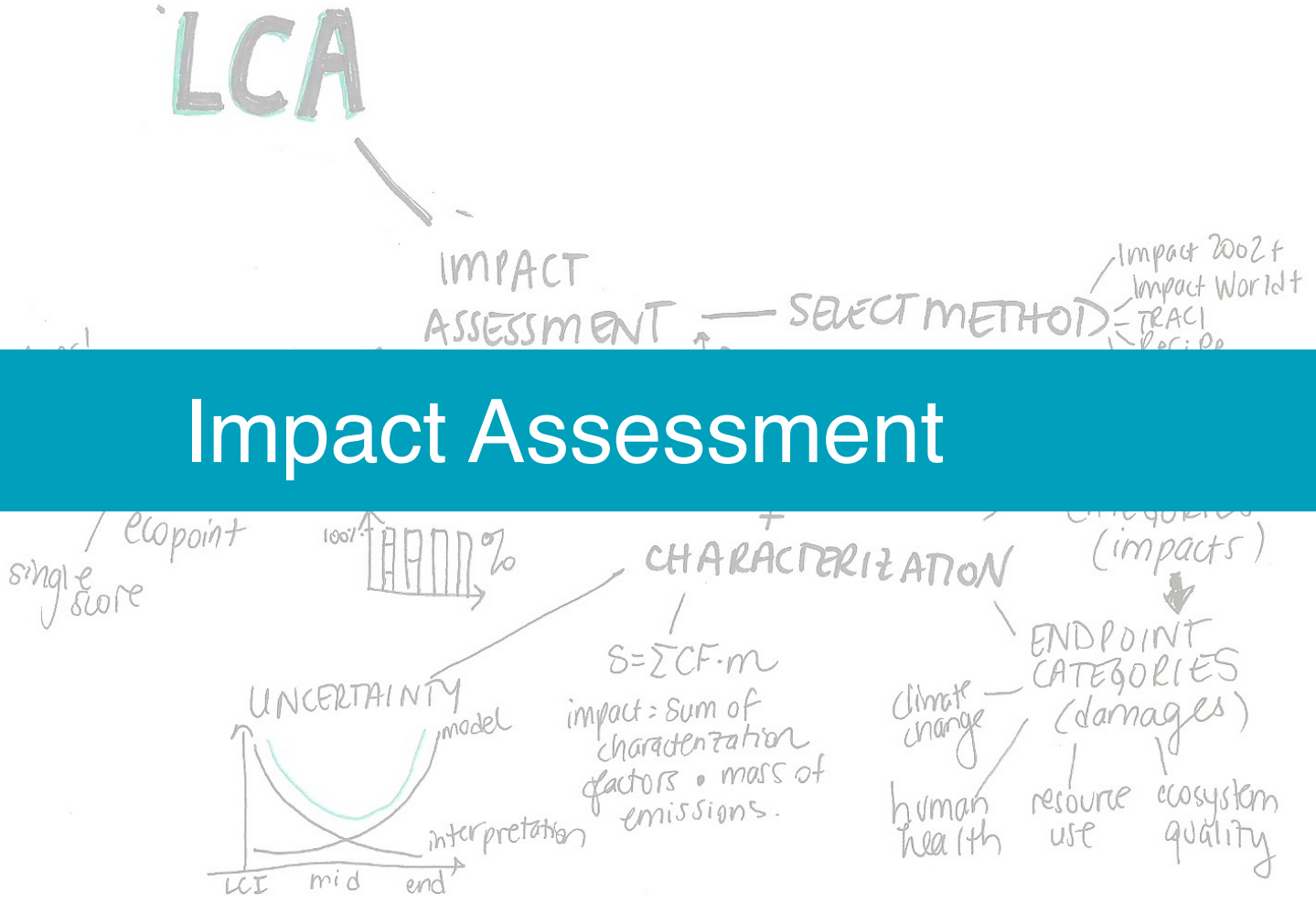
Impact Assessment



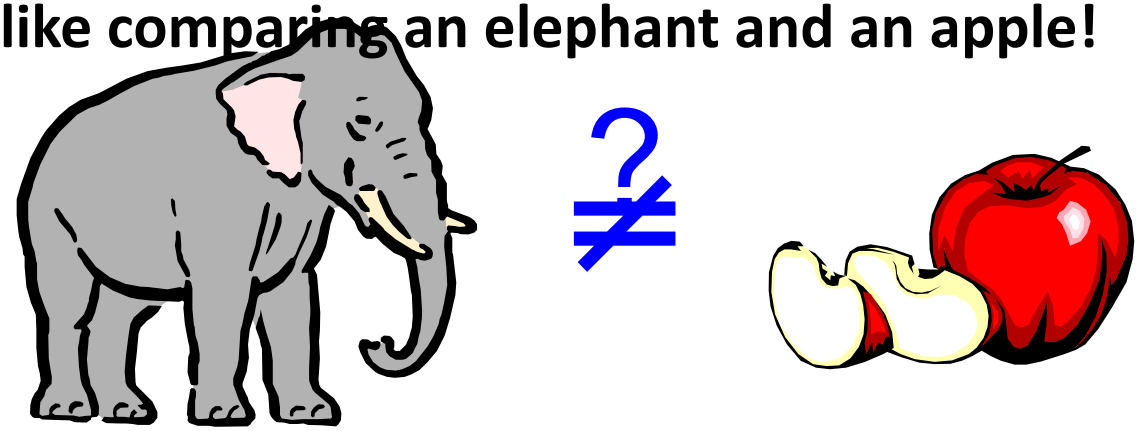
Problem = weigthing pollutants

Weighting is not straightforward

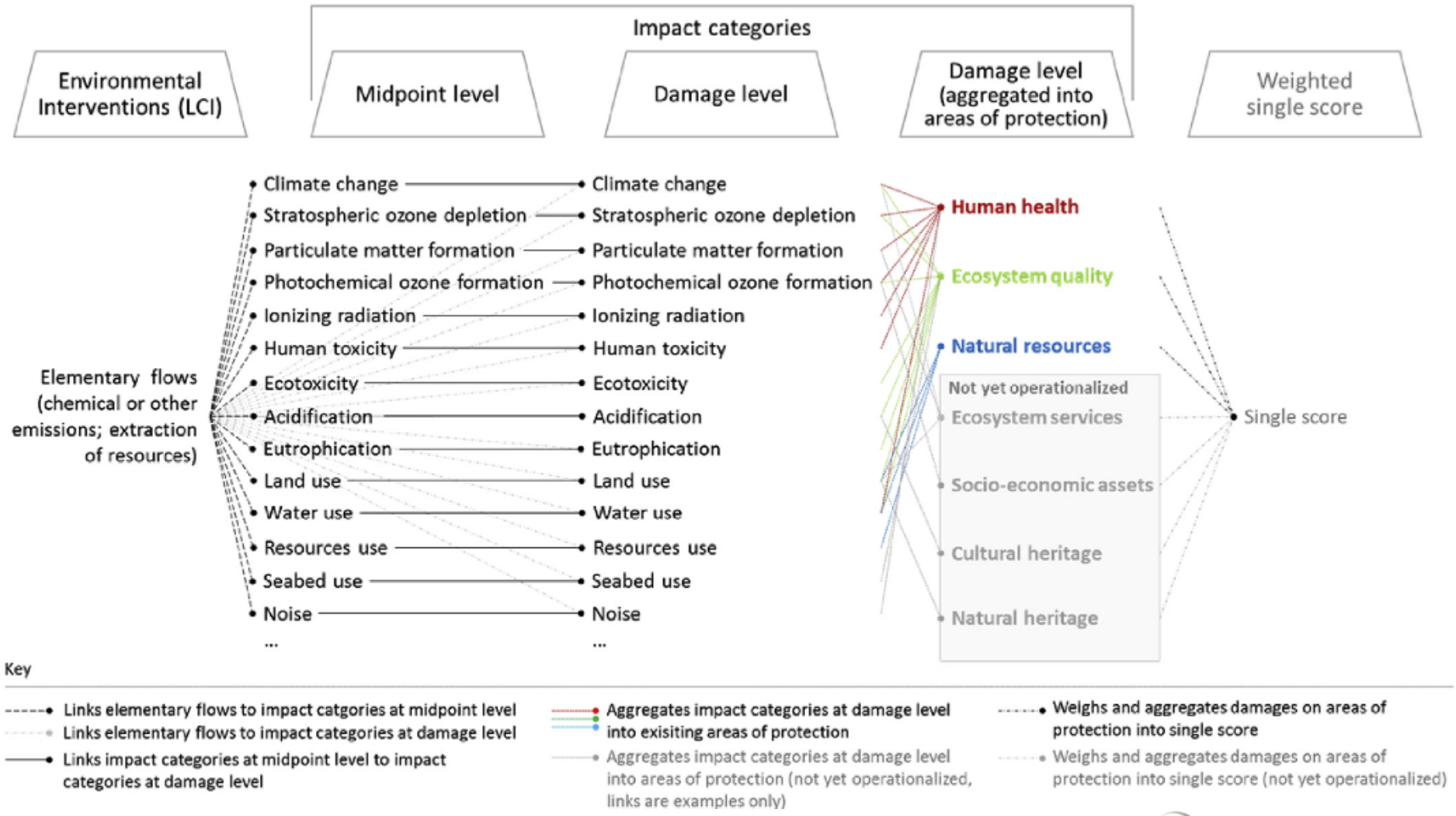
➔ like comparing apples and oranges

When considering the amounts emitted and the very different nature of the extractions and emissions included in inventory

➔ more like comparing an elephant and an apple!



Midpoint-Damage Life Cycle Impact Assessment framework



(Verones, et al. (2017). LCIA framework and cross-cutting issues guidance within the UNEP-SETAC Life Cycle Initiative. *Journal of Cleaner Production, 161* 957-967)

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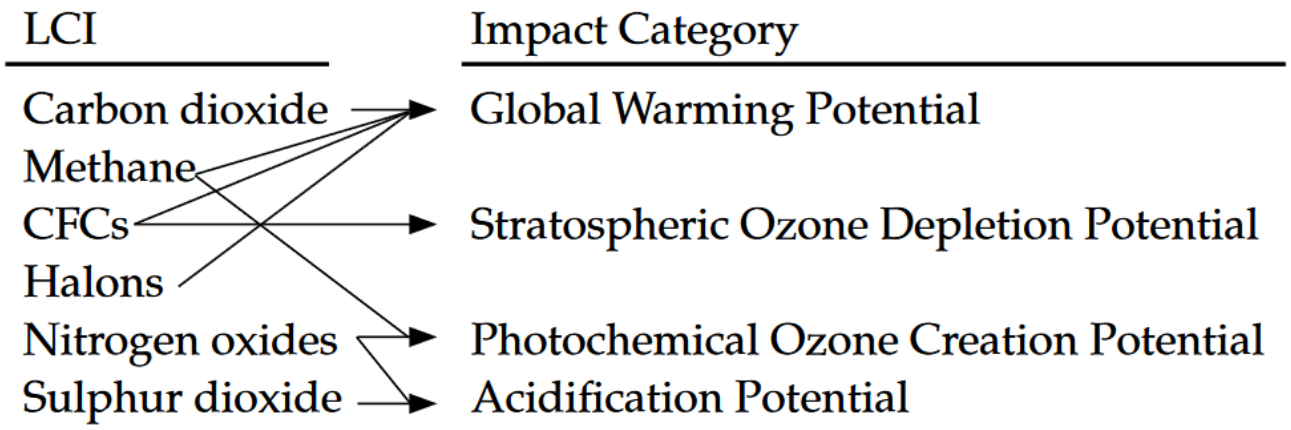
2. Classification - Definition

The classification steps allows to allocate the pollutants (results of the LCI) to the different impact categories

Example:



Environmental mechanism and indicator

Global warming *Infrared radiative forcing generated by a greenhouse gas emitted in the atmosphere on different time horizons*

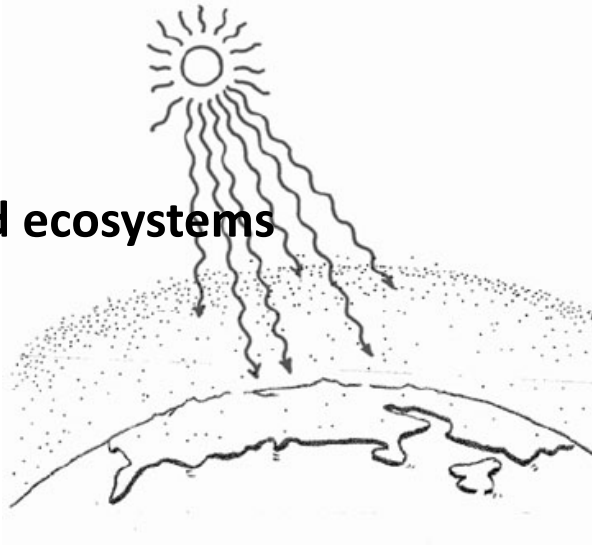
Category indicator

Environmental mechanism = cause and effect chain

1. **GHG emission (elementary flow)**
2. **Infrared radiative forcing (1st order effect)**
3. **Increase in global temperatures (2nd order effect)**
4. **Sea level rise due to water expansion and glsteels melting (3rd order effect)**

…

n. Damage to human health and ecosystems (nth order effect)



Characterisation model

Global warming characterization model

- **Developed by the IPCC**
- **Used to calculate the characterisation factors**
- **Considers the infrared radiative forcing generated by a greenhouse gas emitted in the atmosphere over different time horizons (20, 100 ot 500 years)**
- **Two parameters: atmospheric lifetime and heat absorption**

Characterisation factor

Global warming

Characterisation factor = Global warming potential (GWP)

Unit = kg CO_2 eq./kg gas

$$GWP_i = \frac{\int_0^T a_i . C_i(t).dt}{\int_0^T a_{CO_2} . C_{CO_2}(t).dt}$$

where:

a_i radiative efficiency per unit of concentration of gas i

$C_i(t)$ concentration of gas i at time t

T time horizon

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Global warming potential (GWP)

Characterization factor = Global warming potential for each GHG (kg CO_2eq/kg_i)

Greenhouse gas	GWP à 100 ans [$kgCO_2eq/kg_i$]
CO_2	1
CH_4	28
N2O	265
SF_6	26 100
HCFCs	59 - 1 980
CFCs	4 660 - 13 900

(from the 5th IPCC report, 2018)

https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf (p. 731-737)

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Why does GWP vary depending on the selected time horizon?

Acronym, Common Name or Chemical Name	Chemical Formula	Lifetime (Years)	Radiative Efficiency (W m^{-2} ppb^{-1})	AGWP 20-year (W m^{-2} yr kg^{-1})	**GWP 20-year**	AGWP 100-year (W m^{-2} yr kg^{-1})	**GWP 100-year**
Carbon dioxide	CO_2	see*	1.37e-5	2.49e-14	**1**	9.17e-14	**1**
Methane	CH_4	12.4†	3.63e-4	2.09e-12	**84**	2.61e-12	**28**
Fossil methane‡	CH_4	12.4†	3.63e-4	2.11e-12	**85**	2.73e-12	**30**
Nitrous Oxide	N_2O	121†	3.00e-3	6.58e-12	**264**	2.43e-11	**265**
Chlorofluorocarbons							
CFC-11	CCl_3F	45.0	0.26	1.72e-10	**6900**	4.28e-10	**4660**
CFC-12	CCl_2F_2	100.0	0.32	2.69e-10	**10,800**	9.39e-10	**10,200**
CFC-13	$CClF_3$	640.0	0.25	2.71e-10	**10,900**	1.27e-09	**13,900**
CFC-113	CCl_2FCClF_2	85.0	0.30	1.62e-10	**6490**	5.34e-10	**5820**
CFC-114	$CClF_2CClF_2$	190.0	0.31	1.92e-10	**7710**	7.88e-10	**8590**
CFC-115	$CClF_2CF_3$	1,020.0	0.20	1.46e-10	**5860**	7.03e-10	**7670**
Hydrochlorofluorocarbons							
HCFC-21	$CHCl_2F$	1.7	0.15	1.35e-11	**543**	1.35e-11	**148**
HCFC-22	$CHClF_2$	11.9	0.21	1.32e-10	**5280**	1.62e-10	**1760**
HCFC-122	$CHCl_2CF_2Cl$	1.0	0.17	5.43e-12	**218**	5.43e-12	**59**
HCFC-122a	$CHFClCFCl_2$	3.4	0.21	2.36e-11	**945**	2.37e-11	**258**
HCFC-123	$CHCl_2CF_3$	1.3	0.15	7.28e-12	**292**	7.28e-12	**79**

▪ ▪ ▪

(From 5th IPCC report)

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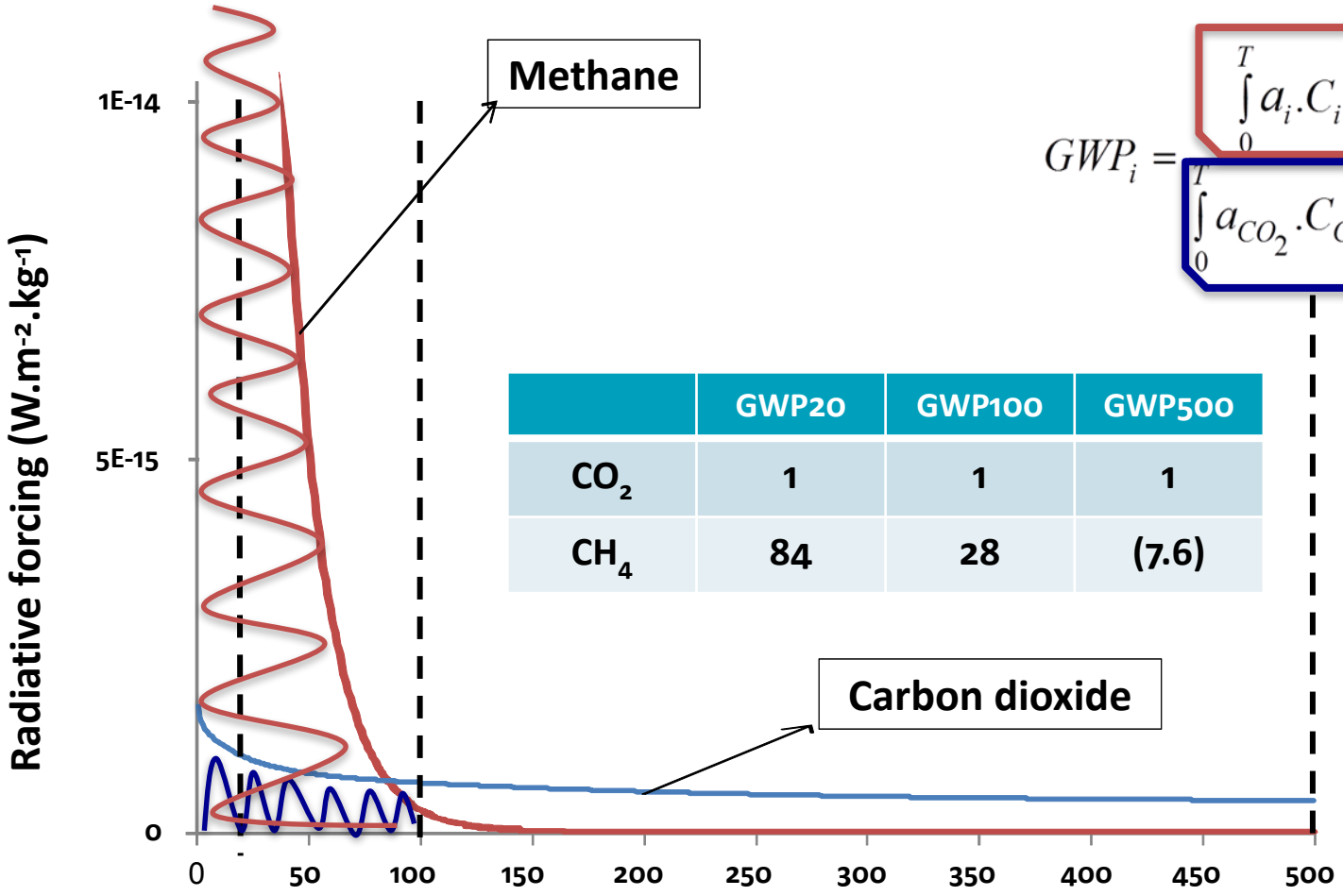
Why does GWP vary depending on the selected time horizon?



$$GWP_i = \frac{\int_0^T a_i.C_i(t).dt}{\int_0^T a_{CO_2}.C_{CO_2}(t).dt}$$

	GWP20	GWP100	GWP500
CO_2	1	1	1
CH_4	84	28	(7.6)

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Characterization – GWP for cars

Substance	Diesel		Biodiesel 5%		Gasoline		Ethanol 5%		Natural gas		Electricity	
	Flow (kg)	GWP (kg CO_2 eq.)	Flow (kg)	GWP (kg CO_2 eq.)	Flow (kg)	GWP (kg CO_2 eq.)	Flow (kg)	GWP (kg CO_2 eq.)	Flow (kg)	GWP (kg CO_2 eq.)	Flow (kg)	GWP (kg CO_2 eq.)
CO_2 bio.	1,42E-02	0,00E+00	9,84E-01	0,00E+00	1,72E-02	0,00E+00	1,35E+00	0,00E+00	1,60E-02	0,00E+00	1,51E-01	0,00E+00
CO_2 fos.	1,27E+01	1,27E+01	1,28E+01	1,28E+01	1,35E+01	1,35E+01	1,50E+01	1,50E+01	1,28E+01	1,28E+01	3,00E+00	3,00E+00
CO bio.	9,45E-06	0,00E+00	1,80E-03	0,00E+00	1,02E-05	0,00E+00	9,24E-02	0,00E+00	9,80E-06	0,00E+00	4,38E-05	0,00E+00
CO fos.	4,13E-02	7,84E-02	4,79E-02	9,10E-02	5,71E-02	1,09E-01	6,51E-02	1,24E-01	3,75E-02	7,13E-02	1,15E-02	2,19E-02
CH_4 bio.	2,23E-05	5,58E-04	3,44E-05	8,61E-04	2,68E-05	6,69E-04	9,05E-04	2,26E-02	3,18E-05	7,94E-04	3,06E-04	7,64E-03
CH_4 fos.	1,41E-02	3,91E-01	1,44E-02	4,00E-01	1,35E-02	3,74E-01	1,49E-02	4,13E-01	3,70E-02	1,03E+00	7,06E-03	1,96E-01
N_2O	3,89E-04	1,16E-01	1,09E-03	3,24E-01	1,29E-04	3,83E-02	2,72E-04	8,10E-02	9,30E-05	2,77E-02	1,52E-04	4,53E-02
SF_6	4,75E-08	1,08E-03	5,25E-08	1,20E-03	5,77E-08	1,31E-03	6,47E-08	1,47E-03	5,82E-08	1,33E-03	6,72E-07	1,53E-02
Others		2,17E-02		2,21E-02		2,18E-02		2,24E-02		2,30E-02		5,58E-02
TOTAL		1,33E+01		1,36E+01		1,40E+01		1,57E+01		1,40E+01		3,34E+00

Characterization factors

(IMPACT 2002+ (2011) → IPCC 2007, 100 year time horizon)

CO_2 (biogenic / fossil) → (0 / 1) kg CO_2 eq. / kg CO_2

CO (biogenic/ fossil) → (0 / 1,9) kg CO_2 eq. / kg CO

CH_4 (biogenic / fossil) → (25 / 27,75) kg CO_2 eq. / kg CH_4

N_2O → 298 kg CO_2 eq. / kg N_2O

SF_6 → 22 800 kg CO_2 eq. / kg SF_6

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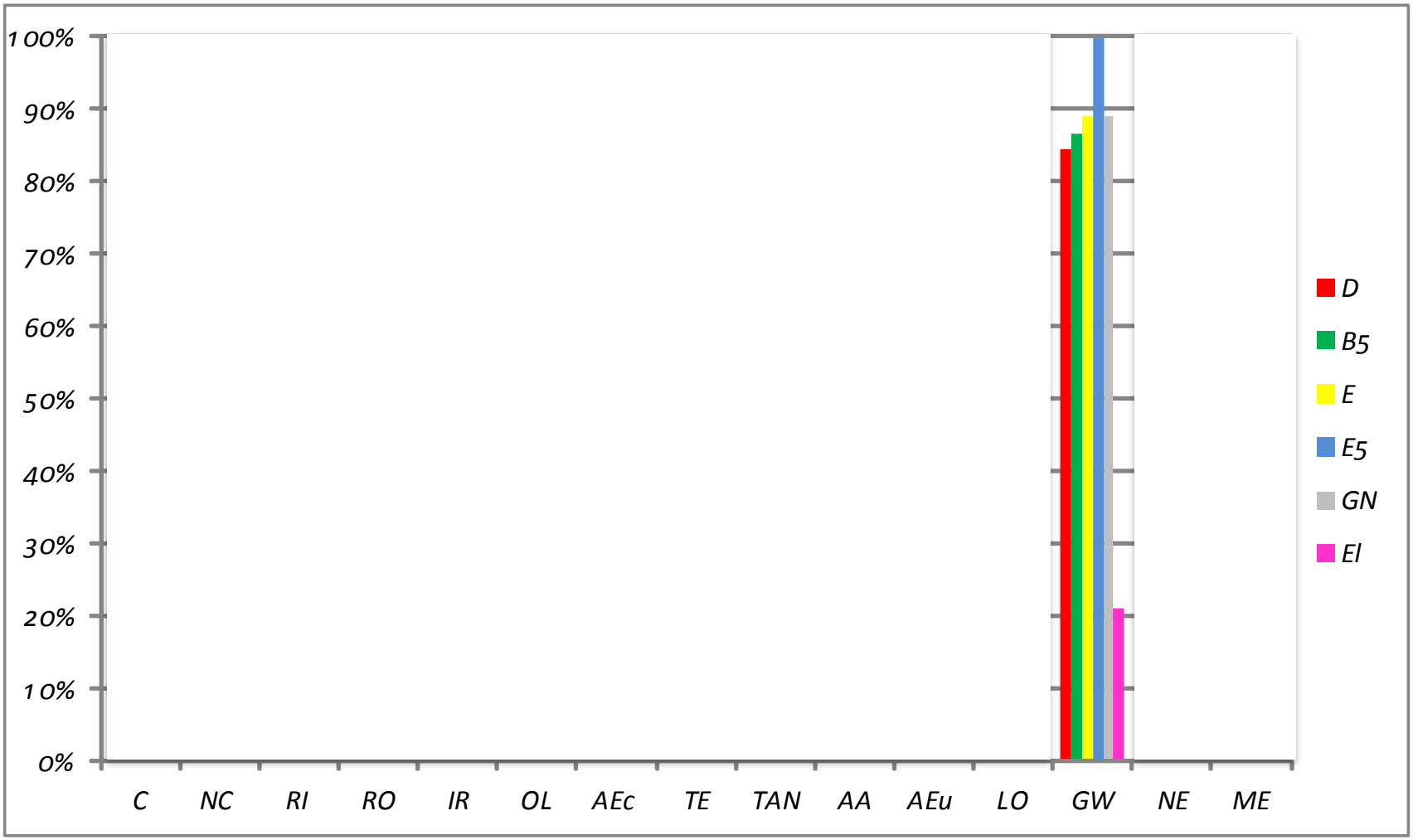
IMPACT 2002+ – Global warming impact scores



D: diesel, B5: Biodiesel 5%, E: gasoline, E5: ethanol 5%, GN: natural gas, El: electricity

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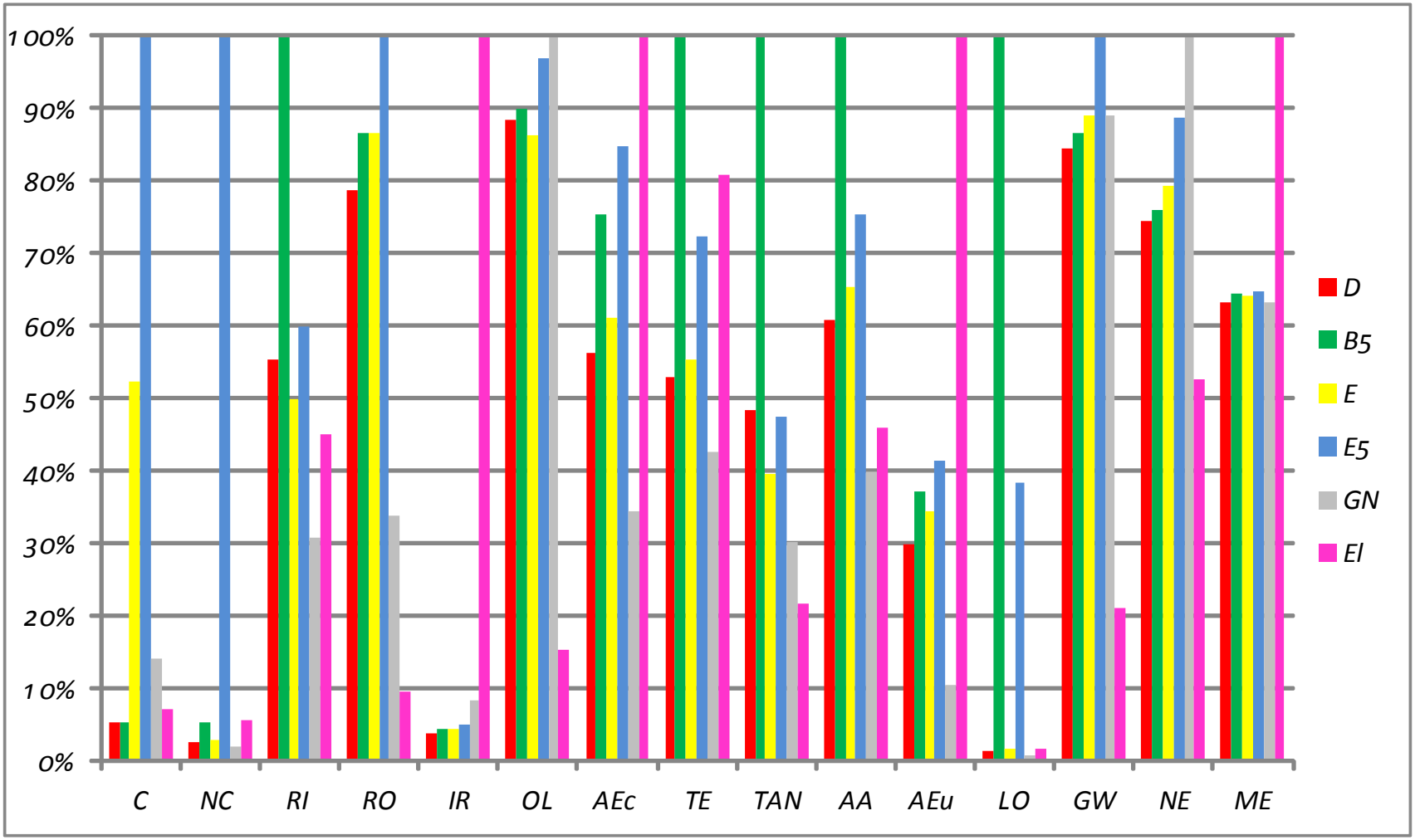
IMPACT 2002+ – Midpoints

Midpoint category		Indicator unit
Carcinogens	C	kg C_2H_5Cl eq. (air)
Non-carcinogens	NC	kg C_2H_5Cl eq. (air)
Respiratory – inorganics	RI	kg $PM_{2.5}$ eq. (air)
Respiratory – organics	RO	kg C_2H_6 eq. (air)
Ionizing radiation	IR	Bq C^{14} eq. (air)
Ozone layer depletion	OL	kg CFC-11 eq. (air)
Aquatic ecotoxicity	AEc	kg Triethylene glycol eq. (water)
Terrestrial ecotoxicity	TE	kg Triethylene glycol eq. (water)
Terrestrial acidification/nutrification	TAN	kg SO_2 eq. (air)
Aquatic acidification	AA	kg SO_2 eq. (air)
Aquatic eutrophication	AEu	kg PO_4^{3-} eq. (water)
Land occupation	LO	m^2.yr organic arable land eq.
Global warming	GW	kg CO_2 eq. (air)
Non-renewable primary energy	NE	MJ primary
Mineral extraction	ME	MJ surplus

IMPACT 2002+ – Midpoints for cars



D: diesel, B5: Biodiesel 5%, E: gasoline, E5: ethanol 5%, GN: natural gas, El: electricity

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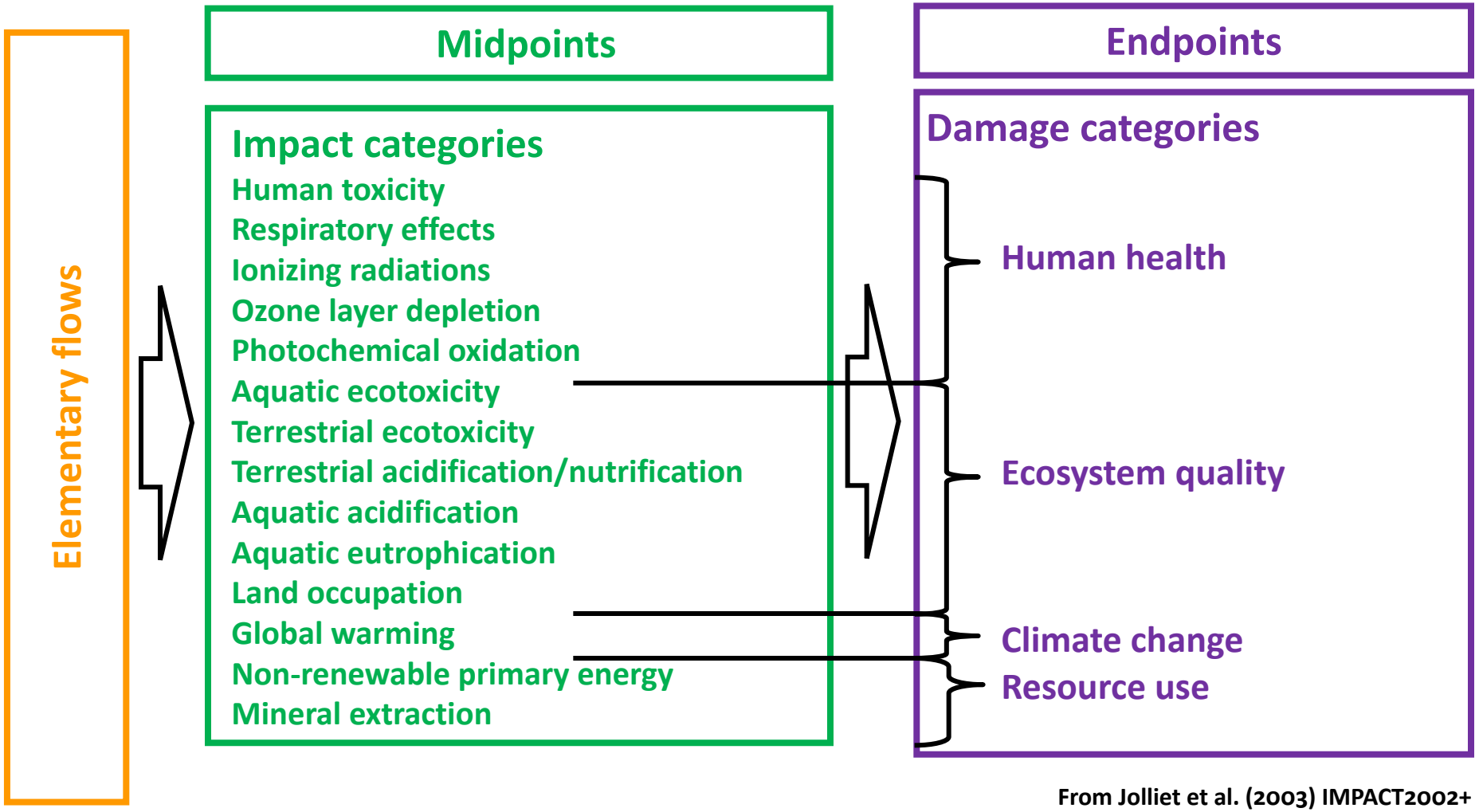
IMPACT 2002+ = A combined approach



From Jolliet et al. (2003) IMPACT2002+

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IMPACT 2002+ – Endpoints

Endpoint category		Indicator unit
Human health	HH	DALY
Ecosystem quality	EQ	PDF.m^2.yr
Climate change	CC	kg CO_2 eq.
Resources	R	MJ primary

DALY (« Disability Adjusted Life Years ») : (Healthy) years of life lost due to premature mortality or morbidity

PDF.m2.an (« Potentially Disappeared Fraction of species ») : fraction of species extinct on a certain territory over a certain period of time

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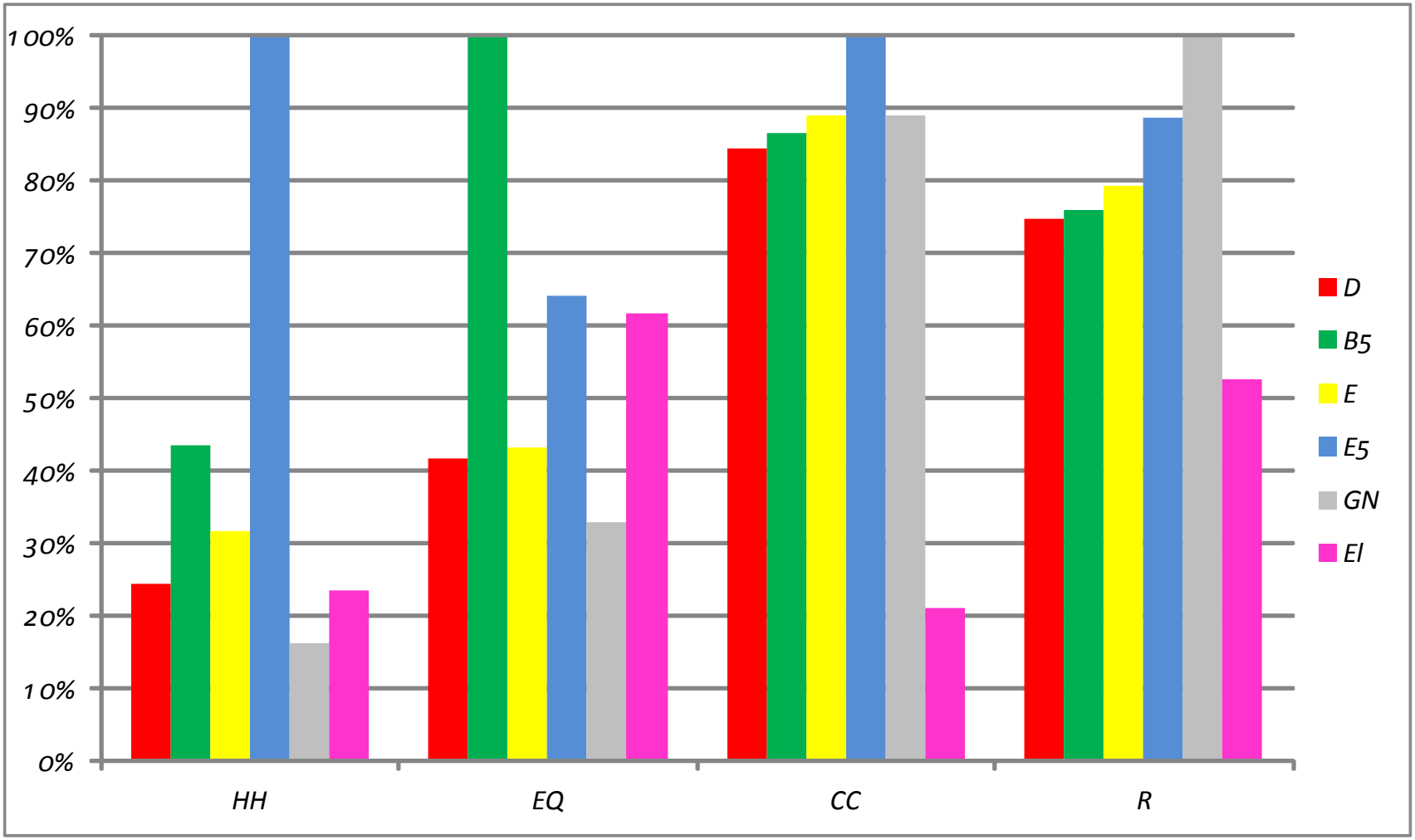
IMPACT 2002+ – Endpoints for cars



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Optional elements: Weighting

« Weighting is the process of converting indicator results of different impact categories by using numerical factors based on value-choices. It may include aggregation of the weighted indicator results.»

(ISO 14044)

How to express the results according to the relative importance that one gives to the impacts?

#

- There is no scientific basis to aggregate results into single score ⇨ weighting requires social value choices (ISO 14'040)
- Factors based on social values attributed to the different damages considered.

Weighting and aggregation are not permitted for LCA used to support public comparative assertion

(ISO 14044)

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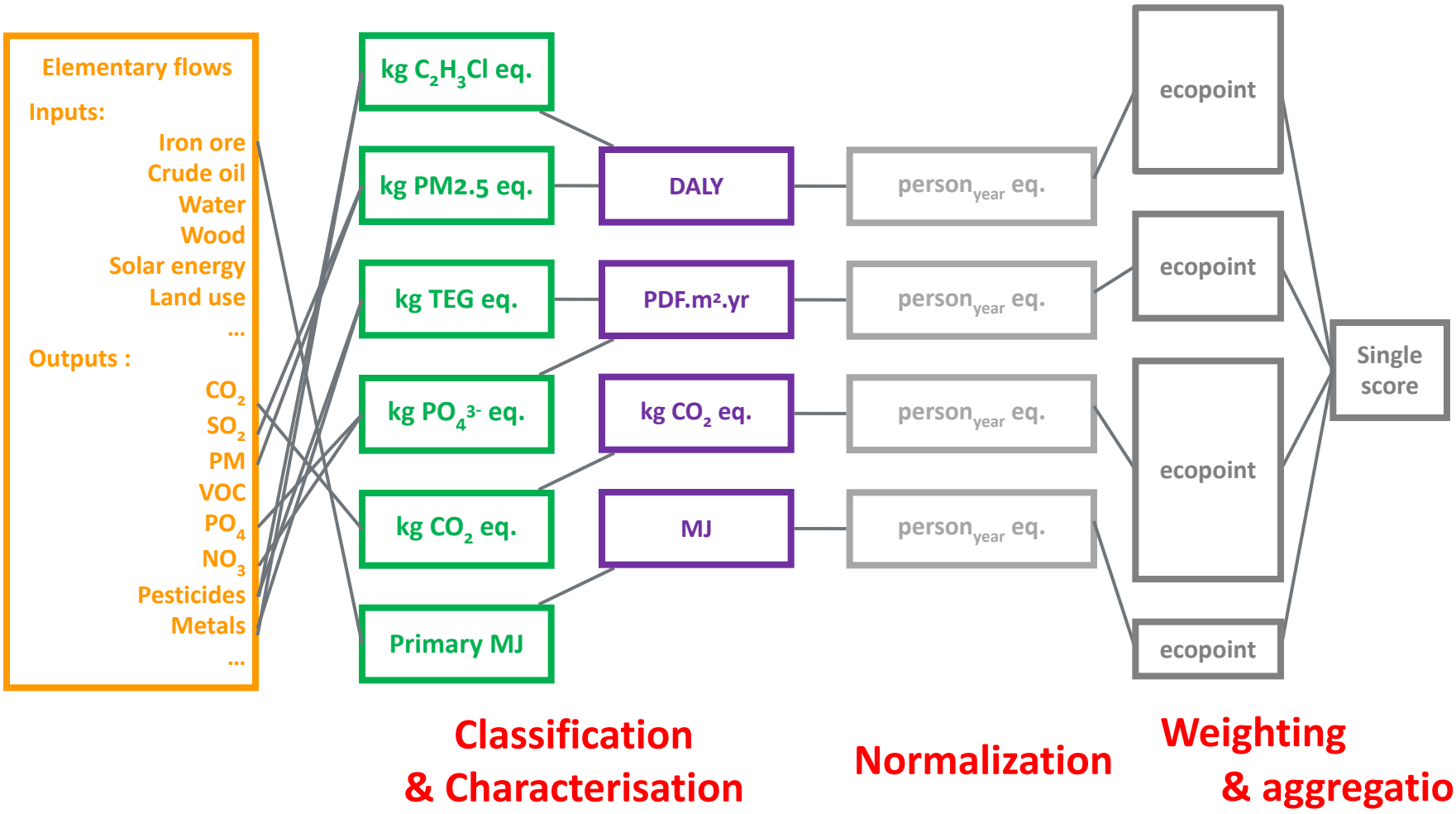
Weighting & aggregation



Three main principles of weighting

Monetization

(willingness to pay, prevention cost)

Expert panel

Distance to target

(Scientific or political)

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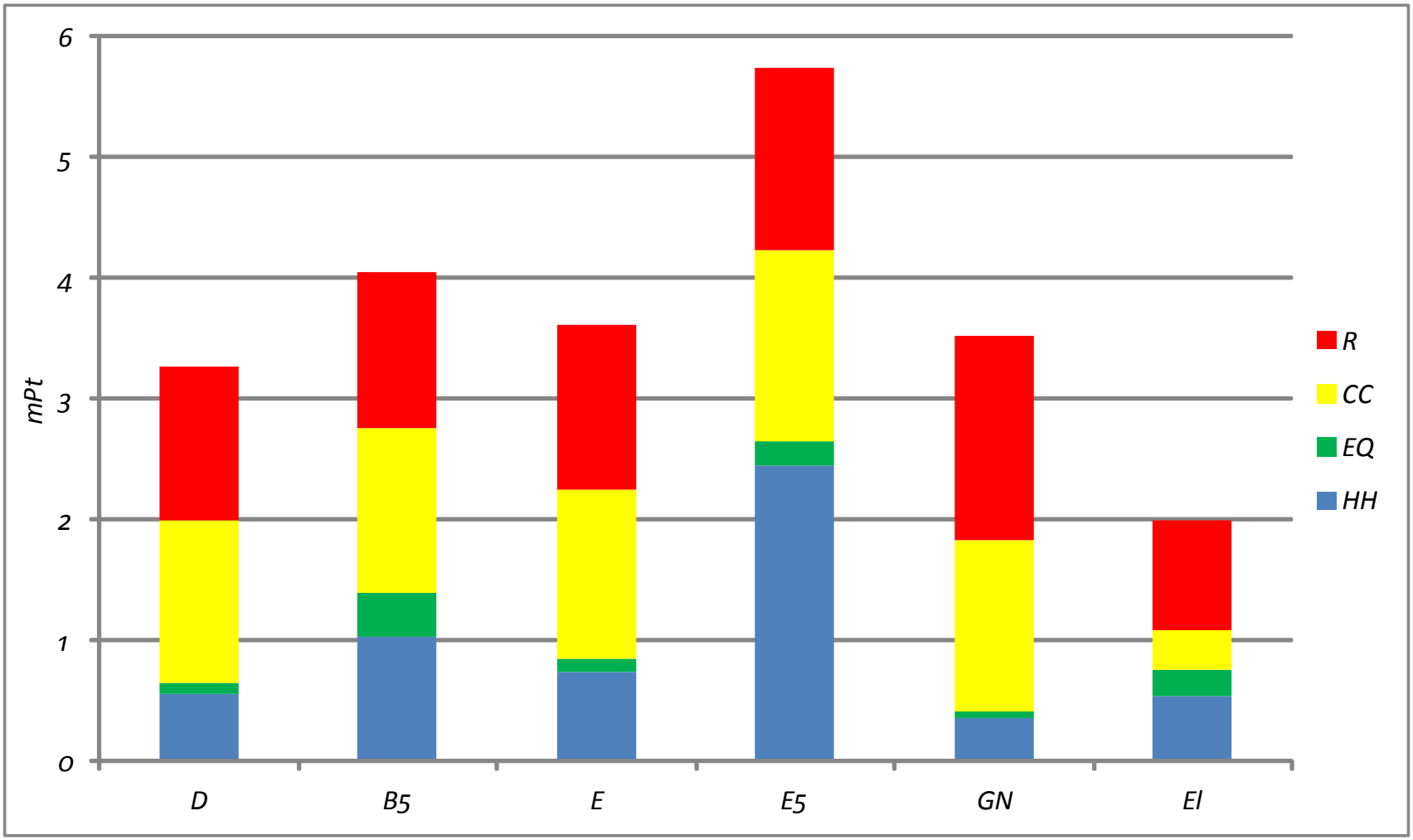
IMPACT 2002+ – Single score for the cars



Available LCIA methods

- Eco-indicator 99: http://www.pre.nl/eco-indicator99/
- EDIP2003: http://ipt.dtu.dk/~mic/EDIP2003
- EPS 2000: http://eps.esa.chalmers.se/
- CML 2001, (Dutch) Handbook on LCA: http://www.leidenuniv.nl/cml/ssp/projects/lca2/lca2.html
- IMPACT 2002+: http://www.impactmodeling.org
- JEPIX: www.jepix.org
- LIME: http://www.jemai.or.jp/lcaforum/index.cfm
- Swiss Ecoscarcity: http://www.e2mc.com/BUWAL297%20english.pdf
- TRACI: http://epa.gov/ORD/NRMRL/std/sab/iam_traci.htm
- ReCiPe: http://www.lcia-recipe.net/
- IMPACT World+: http://www.impactworldplus.org

Methods comparison: http://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-LCIA-Background-analysis-online-12March2010.pdf

Indicators recommendations: http://eplca.jrc.ec.europa.eu/uploads/ILCD-Recommendation-of-methods-for-LCIA-def.pdf

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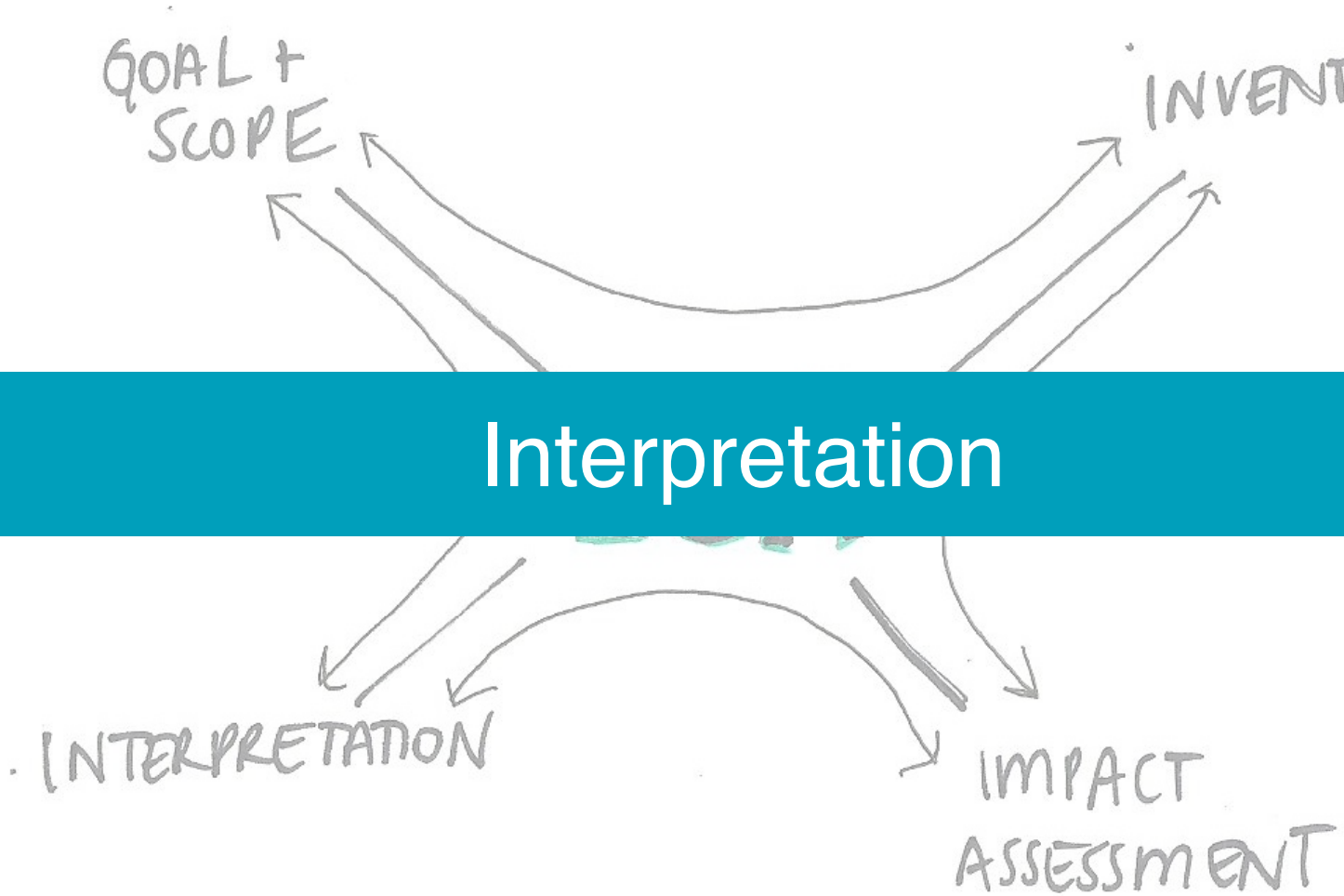


Interpretation

Key features of interpretation phase

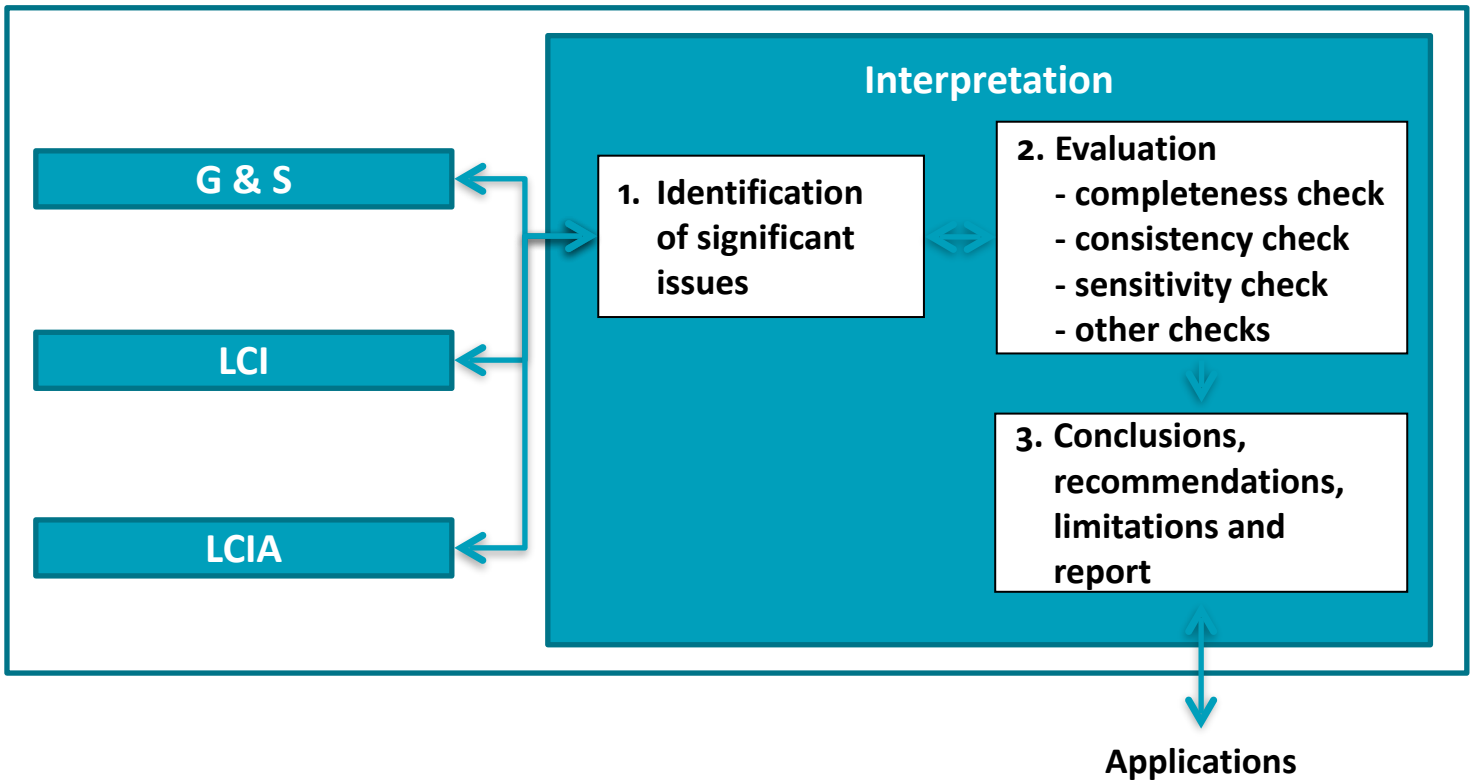
Systematic method to identify, qualify, control, evaluate and present conclusions based on the results of the LCI and/or LCIA phases, in order to fulfill the goal of the study

Iterative method

3 elements:

- **Identification of significant issues**
- **Evaluation considering completeness, consistency and sensitivity checks**
- **Conclusions, limitations and recommendations**

The interpretation procedure



From ISO 14044 (2006)

Identification of significant issues

Structuring results of LCI and LCIA in order to identify significant issues, according to G&S

Must account for the different methodological choices

- **Hypotheses**
- **Multifunctional processes**
- **Excluded processes**
- **Impact assessment method**
- **etc.**

The ISO standard does not indicate what are the significant issues for a specific case

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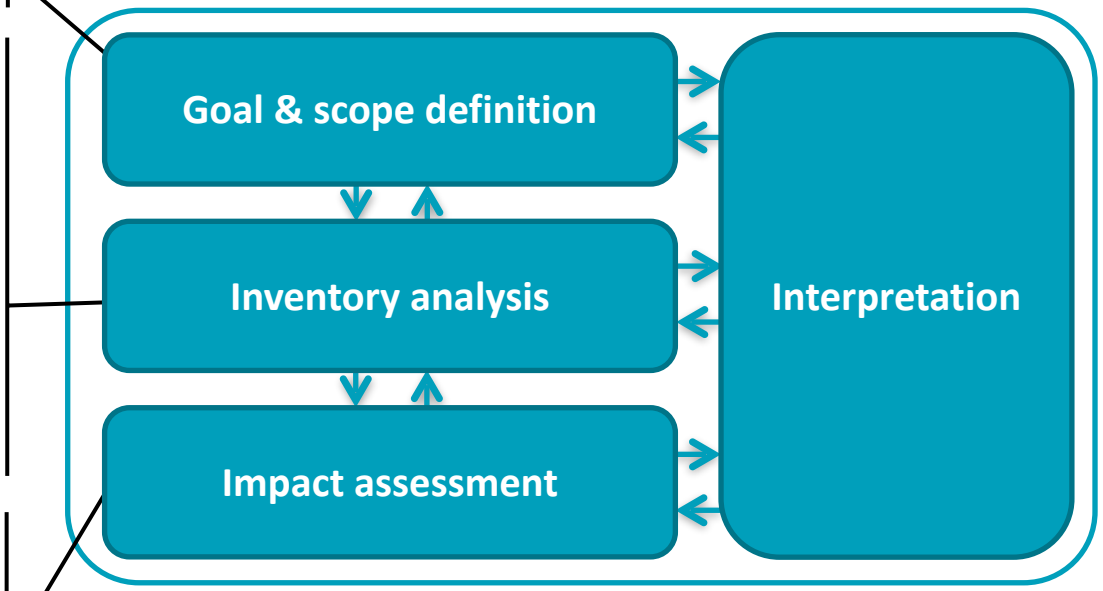
Sources of uncertainty

- **Uncertainties link to choices**
  - functional unit, boundaries
- **Imprecision in measures during data collection**
  - random or systematic error
- **Data gaps**
- **Un-representativeness of data**
  - temporal, geographical and technical coverage
- **Uncertainties link to choices**
  - allocation
- **Model uncertainties**
  - simplifications (linear model for un-linear phenomenon)
- **Uncertainties link to choices**
  - LCIA method



- **Natural variability of measured parameters**
  - spatial, temporal
- **Lack of scientific knowledge**
- **Calculation and other errors**

From A E Björklund (2001) *Survey of Approaches to Improve Reliability in LCA*, **Int. J. of LCA, 7 (2), p. 64-72**

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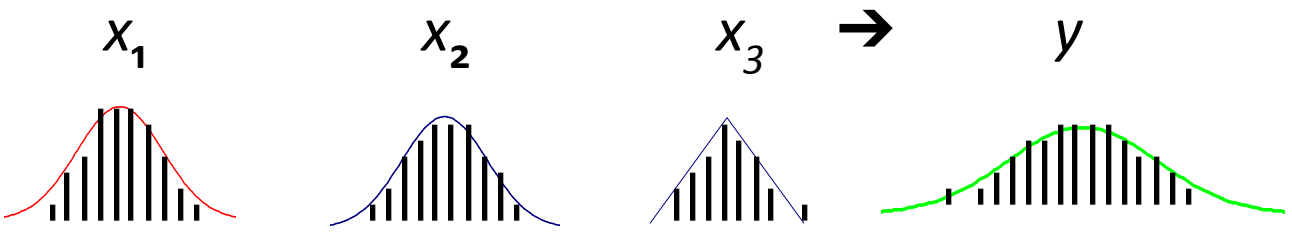
Monte-Carlo simulation

Propagation of uncertainties throughout the calculations

1. **Expression of uncertainty associated with each input variable**
2. **Random value for each input variable according to its associated probability distribution**
3. **Calculation of output variable**
4. **Steps 2 – 3 are repeated many times (1000+ iterations)**
5. **Distribution curve for the output variable**



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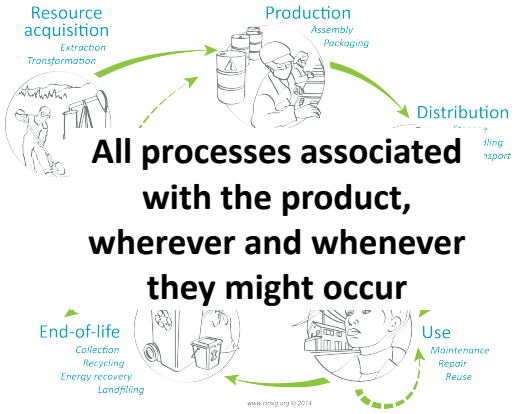
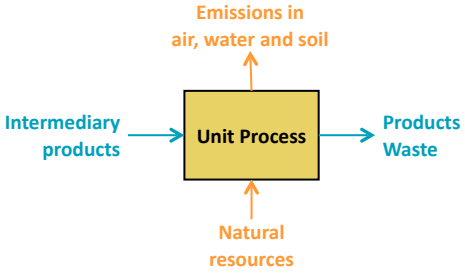
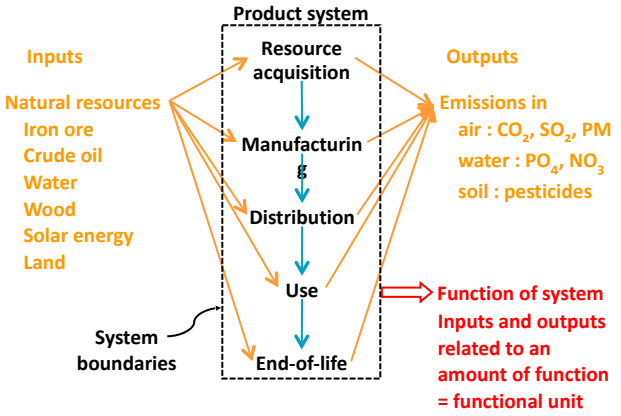
LCA in brief

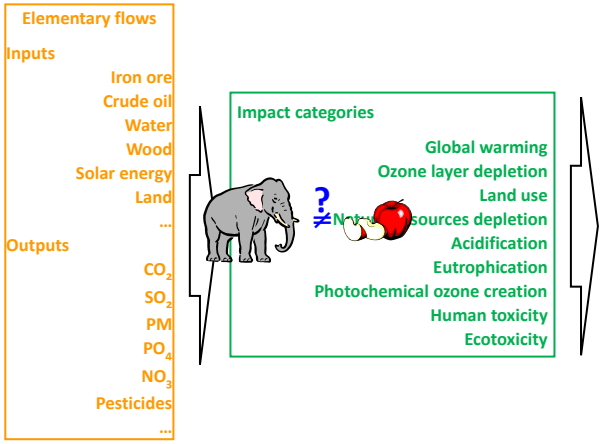


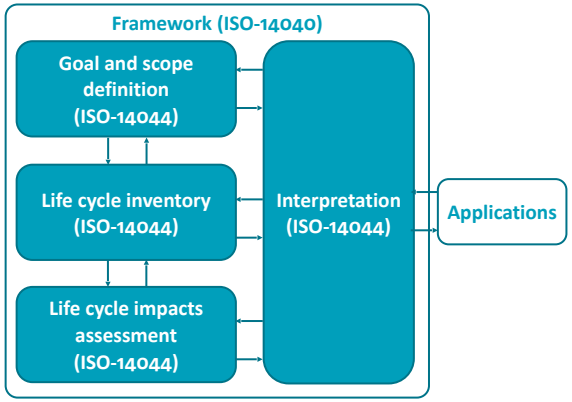
All processes associated with the product, wherever and whenever they might occur



The inputs and outputs of processes, exchanged between processes or with the environment, can be quantified, compared and aggregated







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