The Materials Life Cycle

Fundamentals of Life Cycle Assessment

Strumenti dell'Ingegneria per l'Industria 4.0

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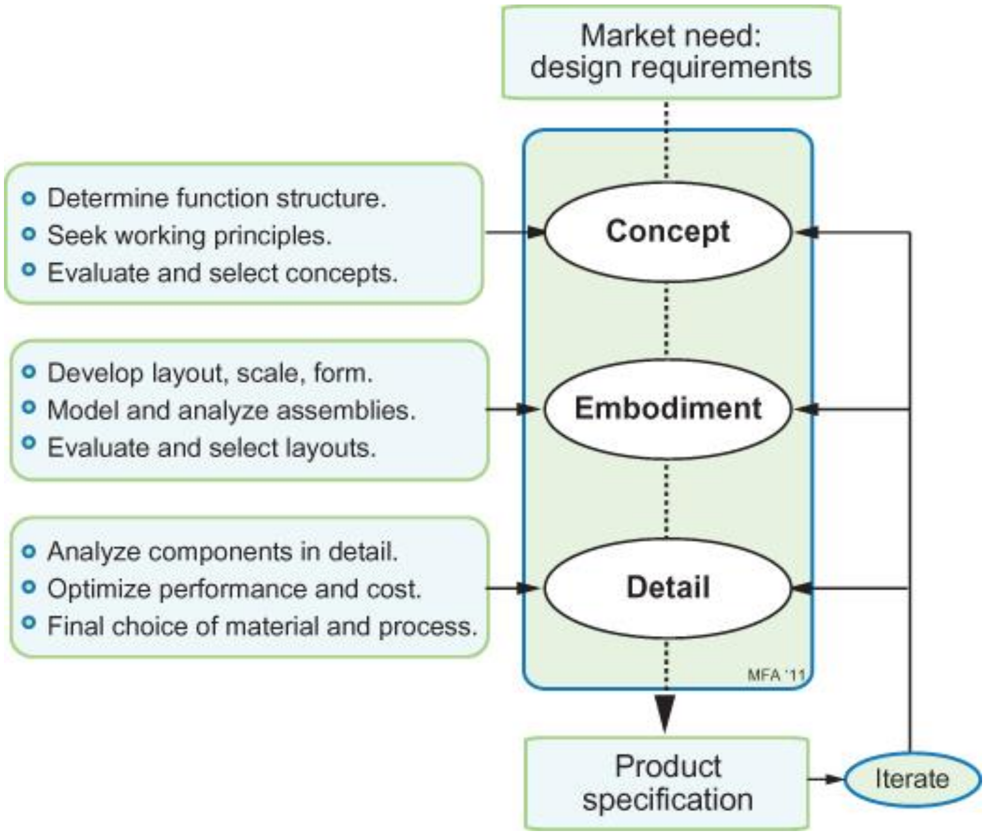
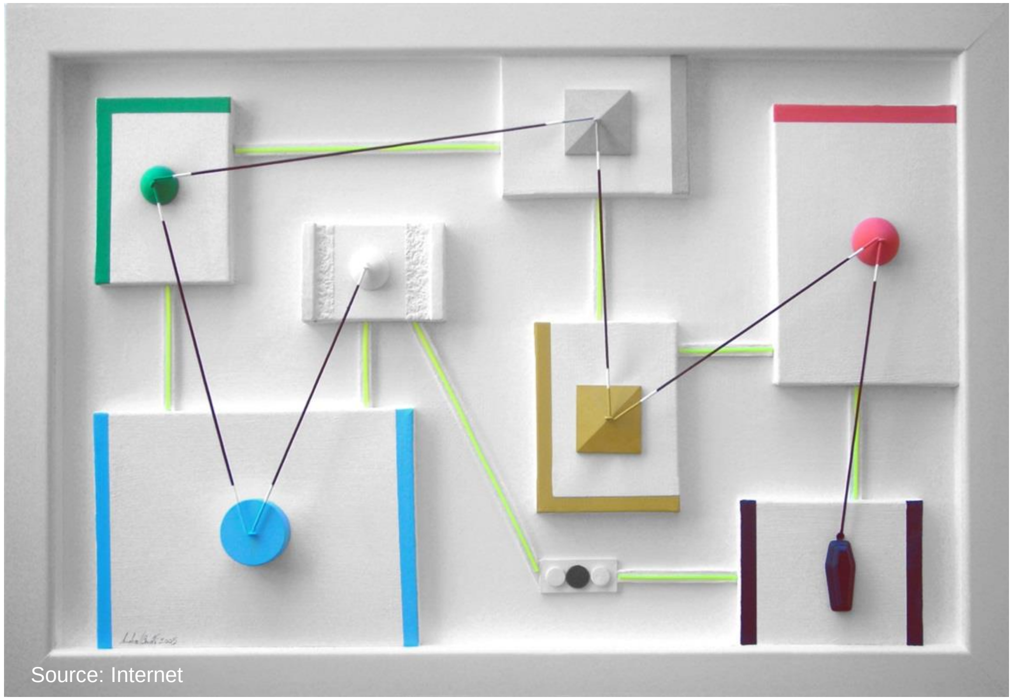
The design process



- The starting point of a design is a *market need* or a *new idea*.
- The end point is the *full specification of a product* that fills the need or embodies the idea.
- The environmental impact that a product has over its subsequent life is largely determined by decisions taken during the design process.
- The concept, the embodiment, the detail, and the choice of materials and manufacturing process all play a role.
- A complete assessment of this impact requires *a scrutiny of the entire life cycle.*

The cycle of life

- The idea of a *life cycle* has its roots in the biological sciences.
- Living organisms are born; they develop, mature, grow old, and, ultimately, die.

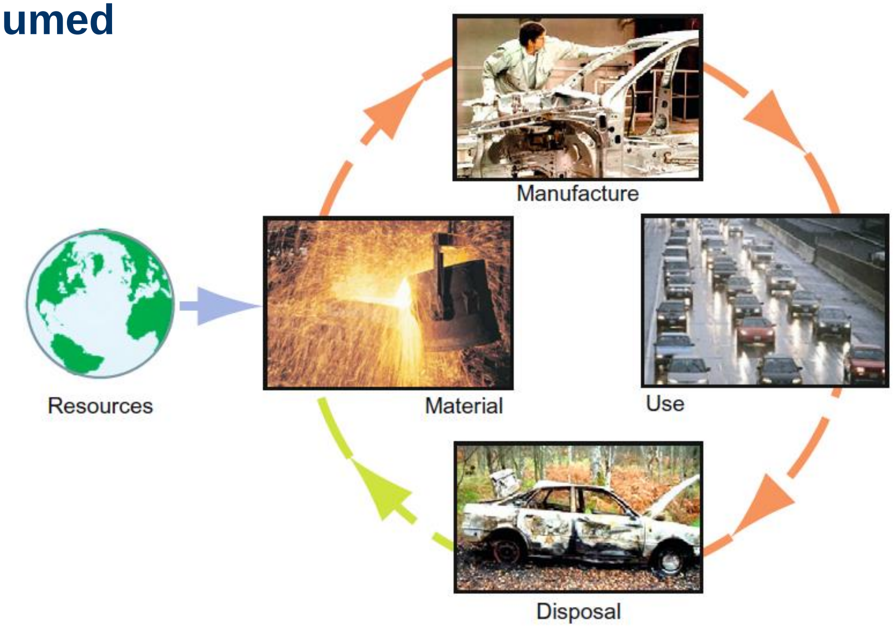

Source: Internet

The materials Life Cycle

- The materials of engineering have a life cycle.
  - They are created from ores and feedstock.
  - These are manufactured into products that are distributed and used.
  - Products have a finite life, at the end of which they become scrap.
  - Some materials can enter a second life as recycled content in a new product.

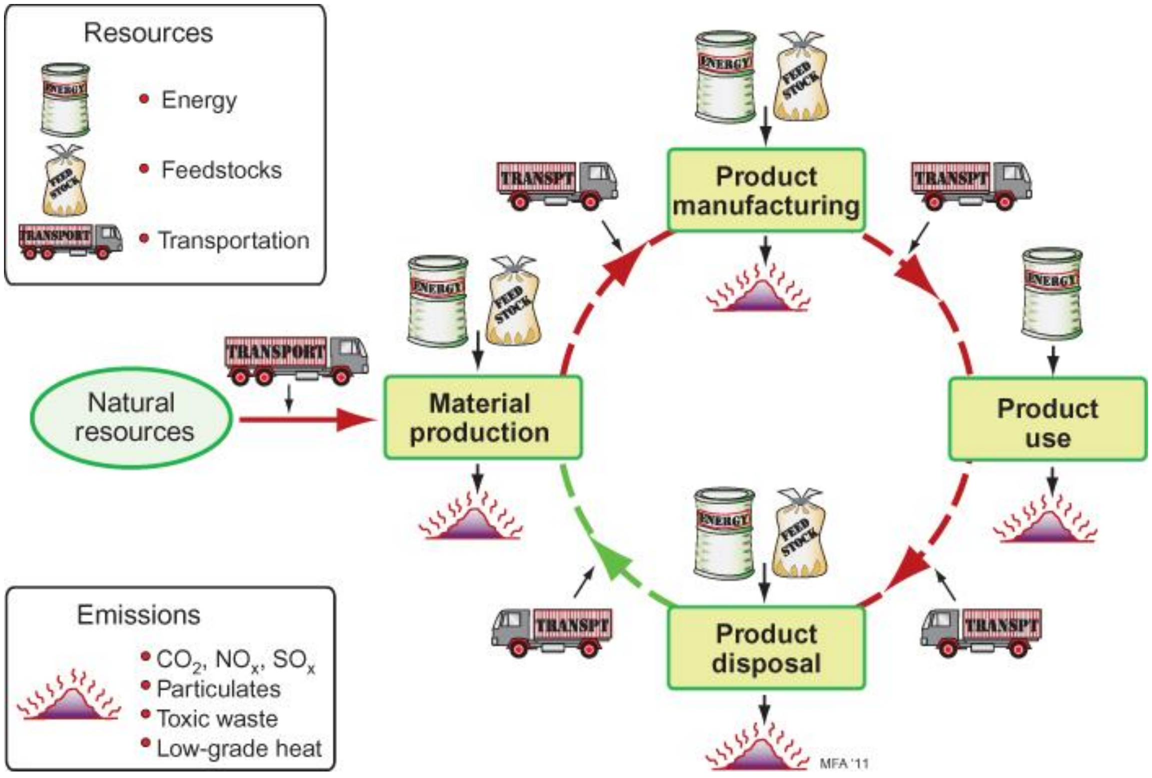
- Life-cycle assessment (LCA) traces this progression, documenting the **resources consumed** and the **emissions excreted** during each phase of life.

- LCA is a technique to assess **environmental impacts** associated with all the stages of a **product's life.**



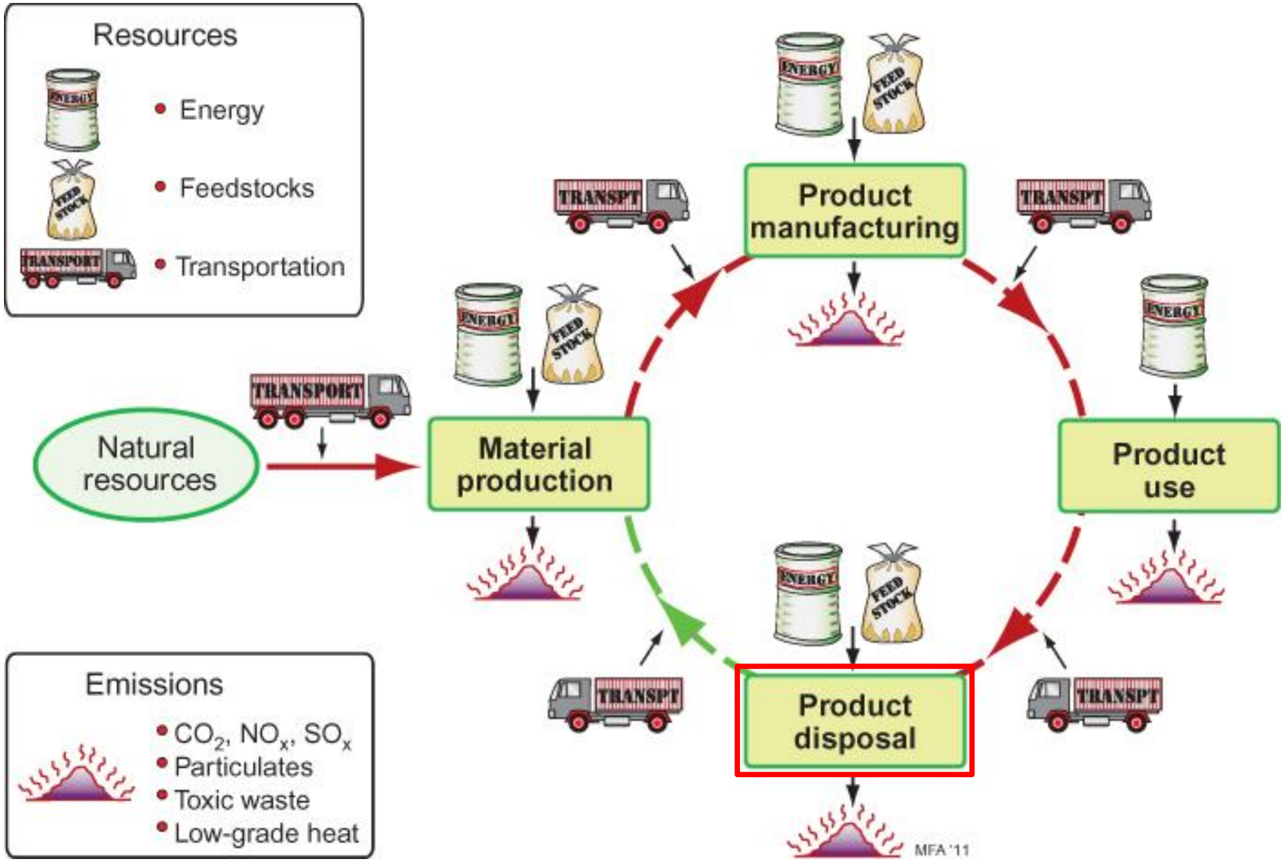
The materials Life Cycle

- Energy and materials are consumed in each phase, generating waste heat and solid, liquid, and gaseous emissions.
- The sum of these unwanted by-products now often exceeds the capacity of the environment to absorb them.
- The study of resource consumption, emissions, and their impacts is called LCA.



The materials Life Cycle

- Product disposal: a fraction of the materials the products contain perhaps entering a **recycling loop**, the rest committed to **incineration or landfill**.



Life Cycle Assessment

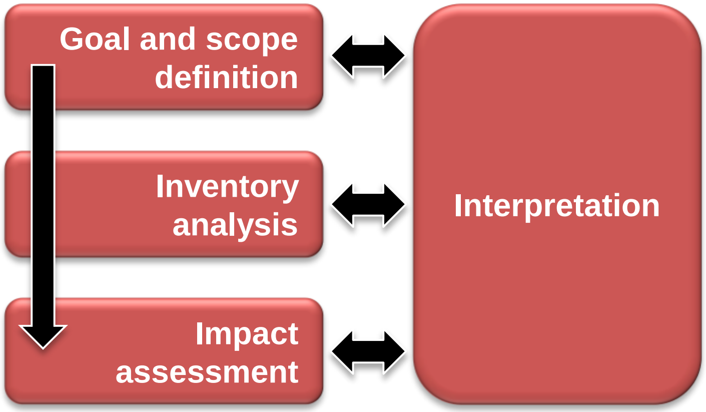
- LCA is issued by the International Standards Organization (ISO 14040 and its subsections 14041, 14042, and 14043).

- These prescribe procedures for “defining goal and scope of the assessment, compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential impacts associated with those inputs and outputs; interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.”

- The study must (according to the ISO standards) examine energy and material flows in raw material acquisition, processing and manufacture, distribution and storage (transport, refrigeration, and so forth), use, maintenance and repair, recycling options, and waste management.

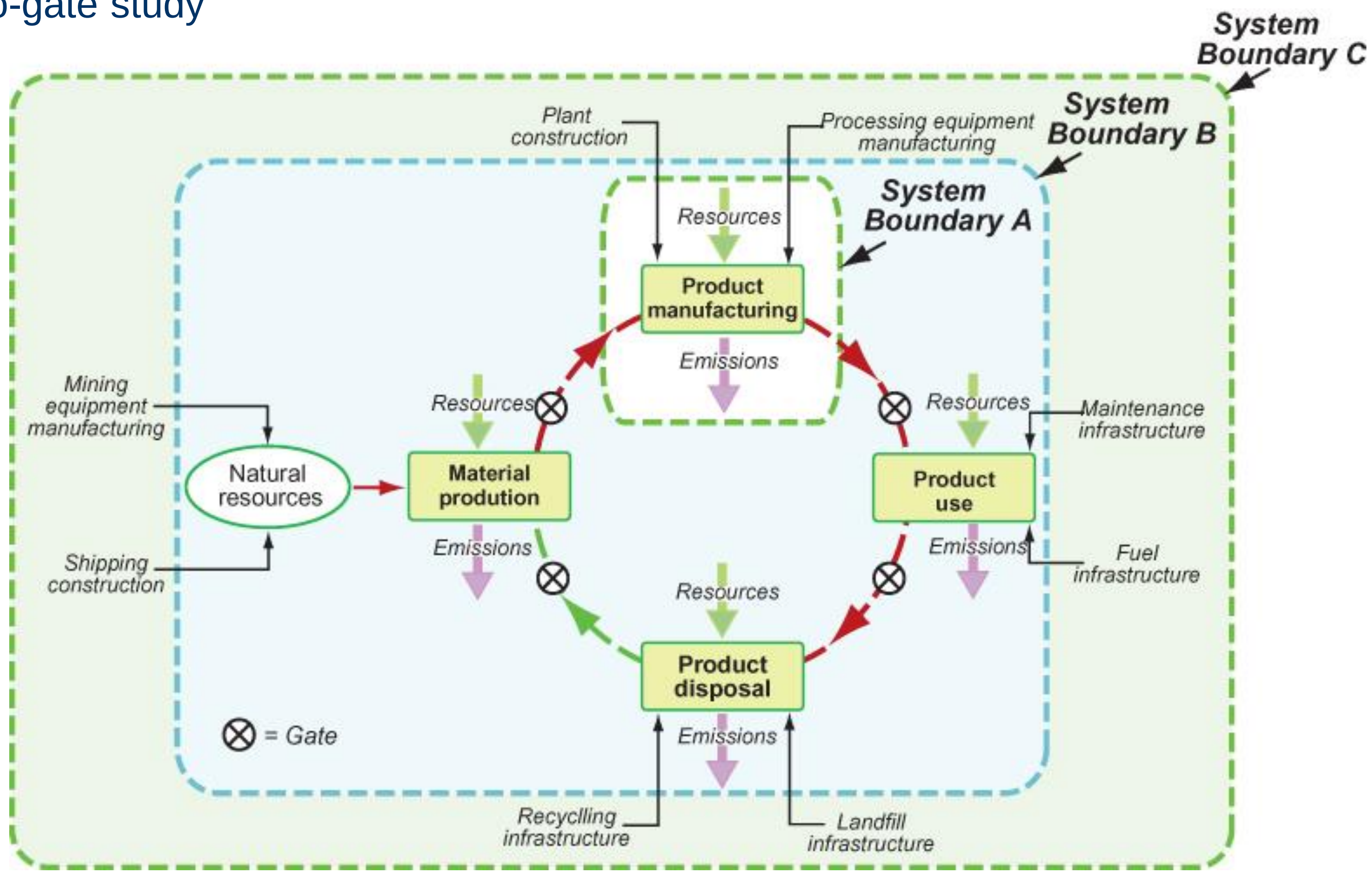
Life Cycle Assessment: 4 main steps

- Goals and scope
  - Why do the assessment?
    What is the subject, and
    which bit(s) of its life are assessed?
- Inventory compilation
  - What resources are consumed,
    what emissions excreted?
- Impact assessment
  - What do these do to the environment?
  - Particularly, what bad things do they do?
- Interpretation
  - What do the results mean and what is to be done about them?



Goal and scope: system boundaries

- Craddle-to-grave study
- Gate-to-gate study



LCA system boundaries with the flows of resources and emissions across them.

Goal and scope: system boundaries

- Gate-to-gate: study in which the scope is limited to the activity inside the box labeled as “System Boundary A”.

- If the broader goal is to assess the resource consumption and emissions of the product over its entire life, the boundary must enclose all four phases (System Boundary B). The scope becomes that of product birth to product death, including, at birth, the ores and feedstock that are drawn from the Earth’s resources and, at death, the consequences of disposal.

- Some LCA proponents see a still more ambitious goal and grander scope (System Boundary C).

Inventory analysis

- Data collection: amassing an inventory of the resource flows passing into the system and the emissions passing out, *per unit of useful output.*

- But how is this data to be measured? *The inventory analysis assesses resource consumption and emissions per functional unit.*

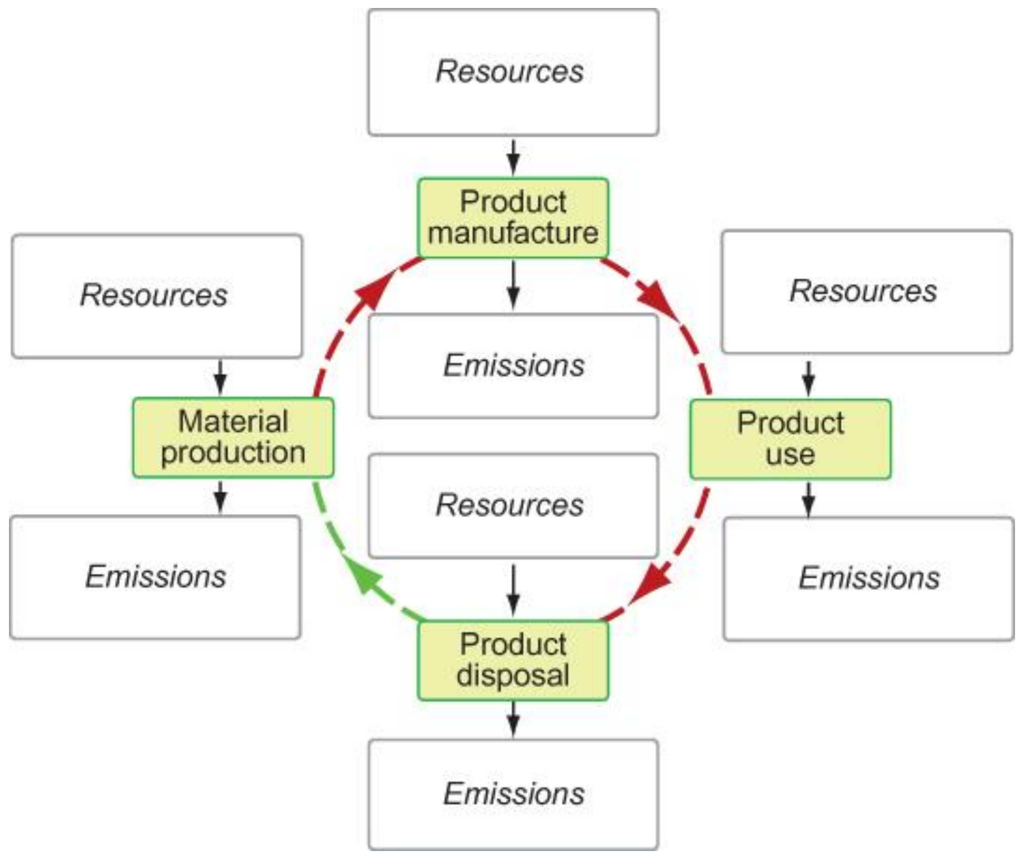
- The function of a container for a soft drink (a plastic water bottle, a beer can) is to contain fluid. The bottle maker might measure resource flows per bottle, but if it is concerned with environmental or economic consequences of its entire life, it is the eco-impact (or cost) per unit volume of fluid contained that is the proper measure.

- The output of manufacture is a component or product; here kilograms or product units may be used. It is in the use phase that the function becomes important and here the real measure - that per unit of function - becomes the logical one.

- *Level of detail* of the assessment.

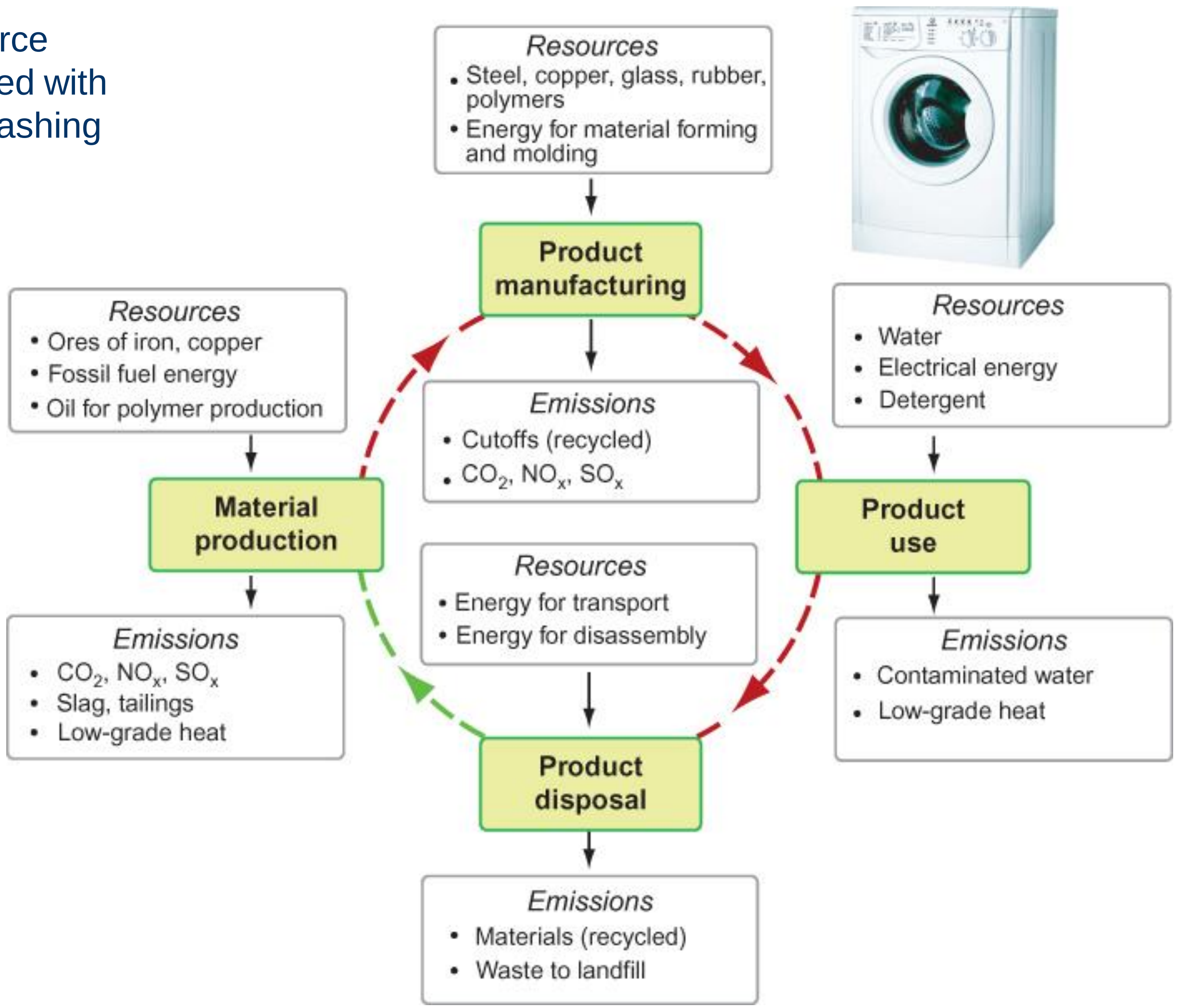
Inventory analysis

A template for listing the principal resources and emissions associated with the life of a product.



Inventory analysis

The principle resource emissions associated with the life cycle of a washing machine



Impact assessment

- The inventory, once assembled, lists resource consumption and emissions, but they are not equally malignant.
- Some have a greater impact than others. Impact categories include *resource depletion, global warming potential, ozone depletion, acidification, eutrophication, human toxicity*, and more.
- Each impact is calculated by multiplying the quantity of each inventory item by an *impact assessment factor* - a measure of how a given inventory type contributes to each impact category.

Gas	Impact assessment factor
Carbon dioxide, CO_2	1
Carbon monoxide, CO	1.6
Methane, CH_4	21
Di-nitrous monoxide, N_2O	256

Global warming potential impact assessment factors

- The overall impact contribution of a product to each category is found by multiplying the quantity emitted by the appropriate impact assessment factor and summing the contributions of all the components of the product for all four phases of life.

Interpretation

The final questions:

- What do these inventory and impact values mean?
- What should be done to reduce their damaging qualities?

- The ISO standard requires answers to these questions but gives little guidance about how to reach them.

- All this makes a full LCA a time-consuming matter requiring experts.

- A full LCA is not something to embark on lightly.

Output analysis

- Example of a partial LCA for the production of aluminum cans (it stops at the exit gate of the manufacturing plant, so this is a *cradle-to-gate* study).
- Functional unit: 1000 cans.
- Three blocks of data.

Aluminum cans, per 1000 units

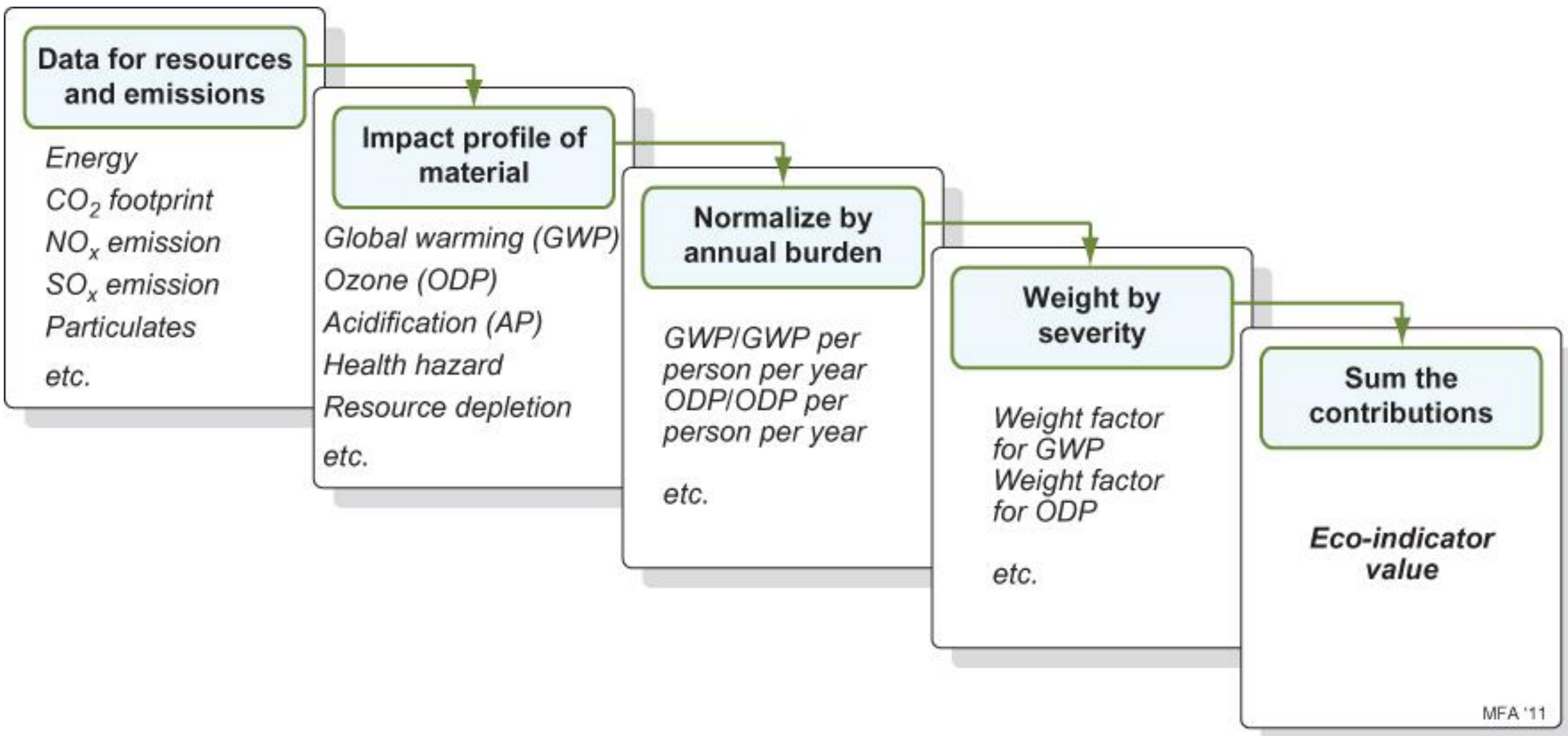
Resource consumption	Bauxite	59	kg
	Oil fuels	148	MJ
	Electricity	1572	MJ
	Energy in feedstocks	512	MJ
	Water use	1149	kg
Emissions inventory	Emissions: CO_2	211	kg
	Emissions: CO	0.2	kg
	Emissions: NO_x	1.1	kg
	Emissions: SO_x	1.8	kg
	Particulates	2.47	kg
Impact assessment	Ozone depletion potential	0.2×10^{-9}	
	Global warming potential	1.1×10^{-9}	
	Acidification potential	0.8×10^{-9}	
	Human toxicity potential	0.3×10^{-9}	

Accuracy

- The results are subject to considerable uncertainty.
- *Resource* and *energy* inputs can be monitored in a straightforward and reasonably precise way.
- The *emissions* rely more heavily on sophisticated monitoring equipment; few are known to better than 10%.
- Assessments of *impacts* depend on values for the marginal effect of each emission on each impact category; many of these have much greater uncertainties.

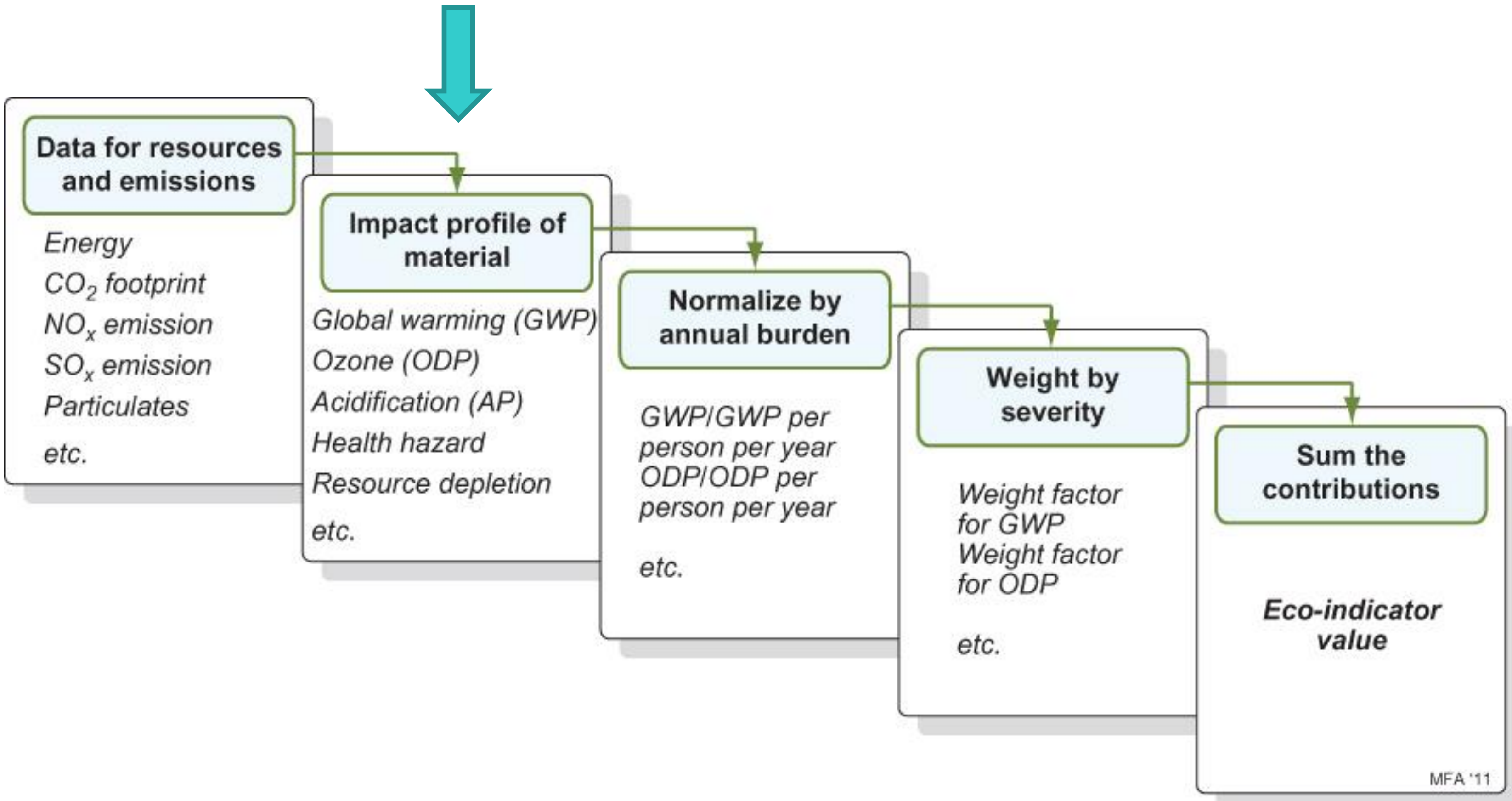
Aggregated measures: eco-indicators

- What to do with these numbers?
- Efforts to condense the LCA output into a single measure, or *eco-indicator.*
- Four steps are necessary.



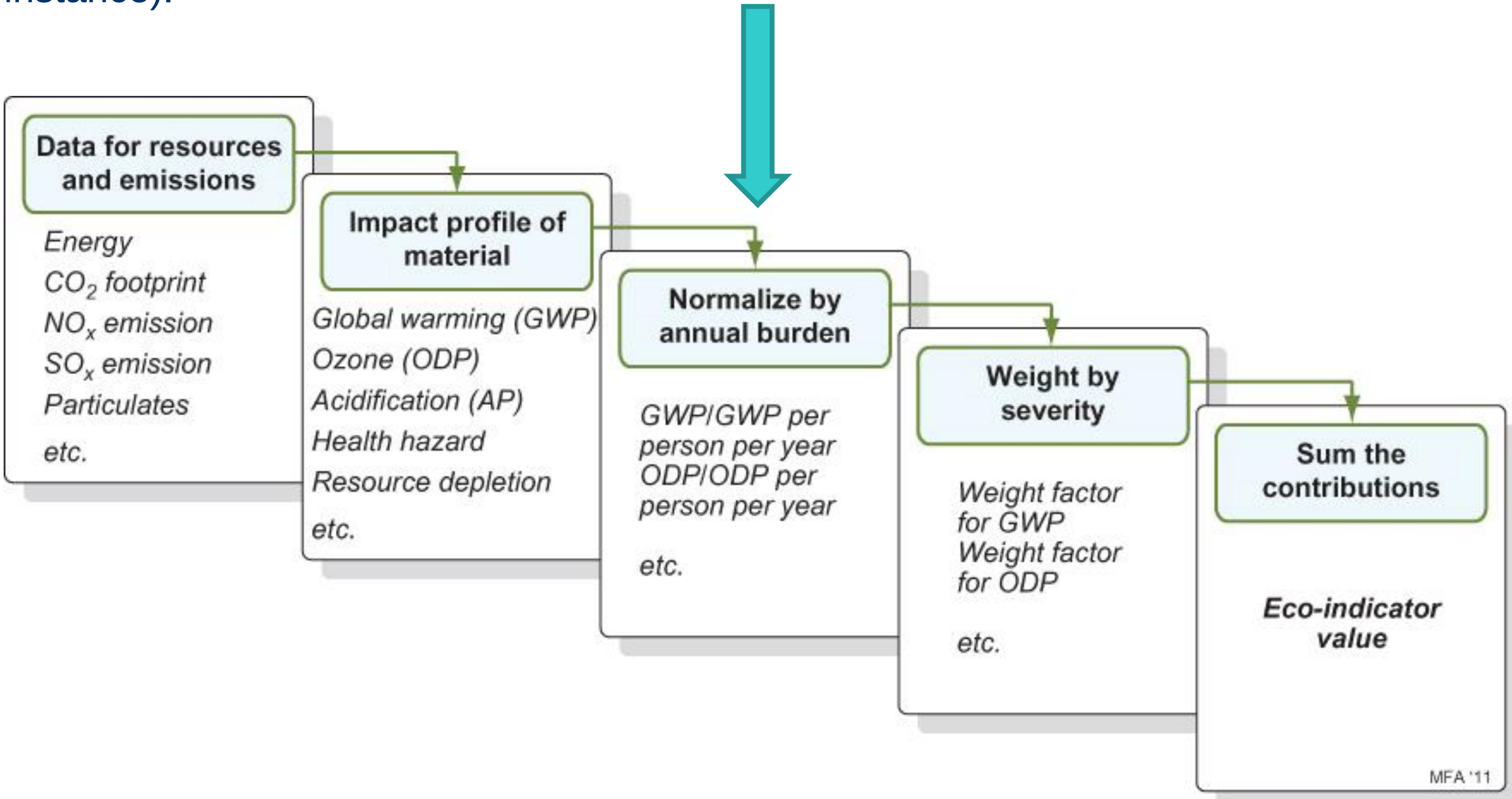
Aggregated measures: eco-indicators

1) The first is that of *classification* of the data according to the impact each causes (global warming, ozone depletion, acidification, etc.).



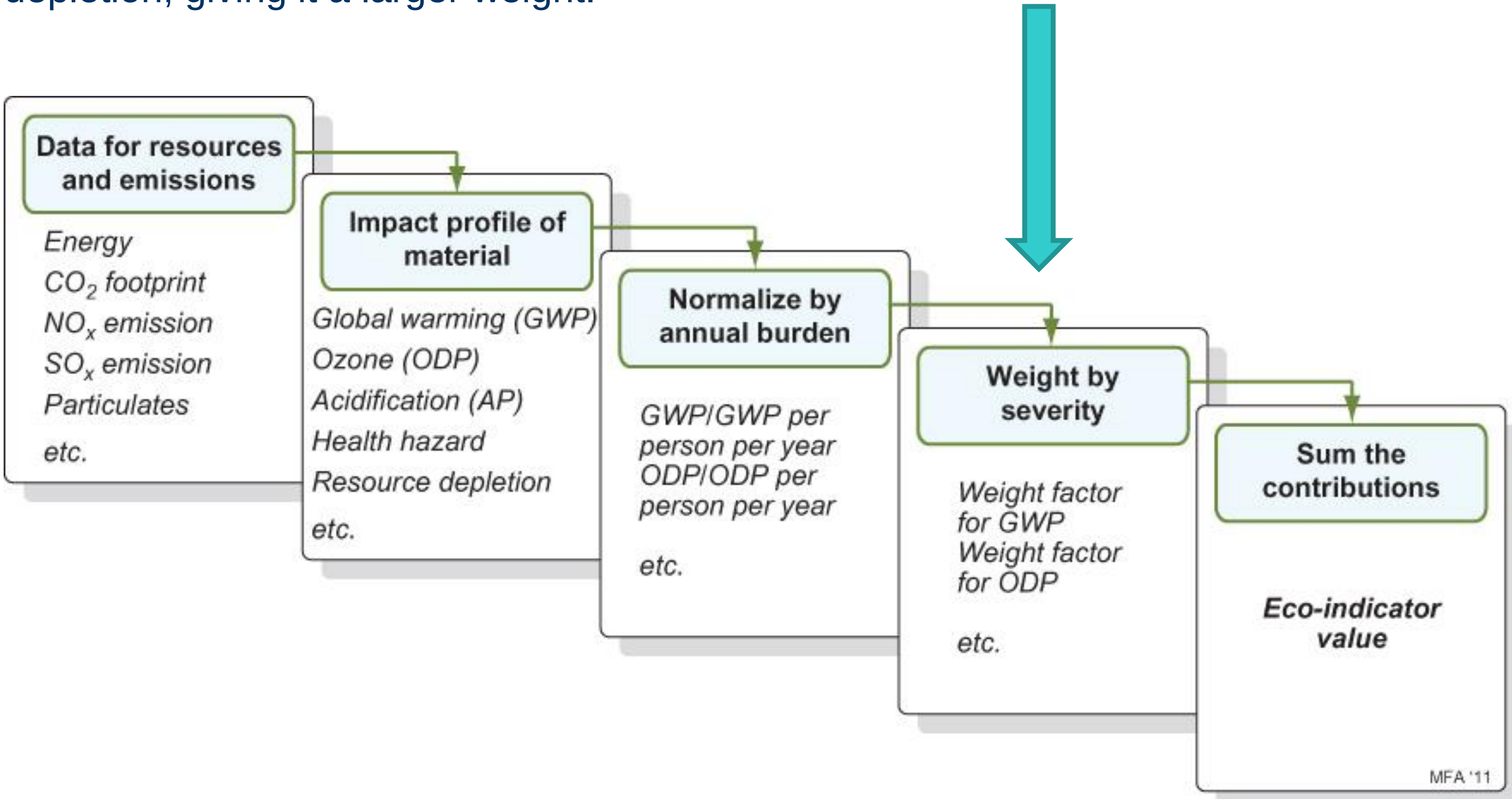
Aggregated measures: eco-indicators

2) The second step is that of *normalization* to remove the units (of which there are several in the LCA report) and reduce them to a common scale (0 –100, for instance).



Aggregated measures: eco-indicators

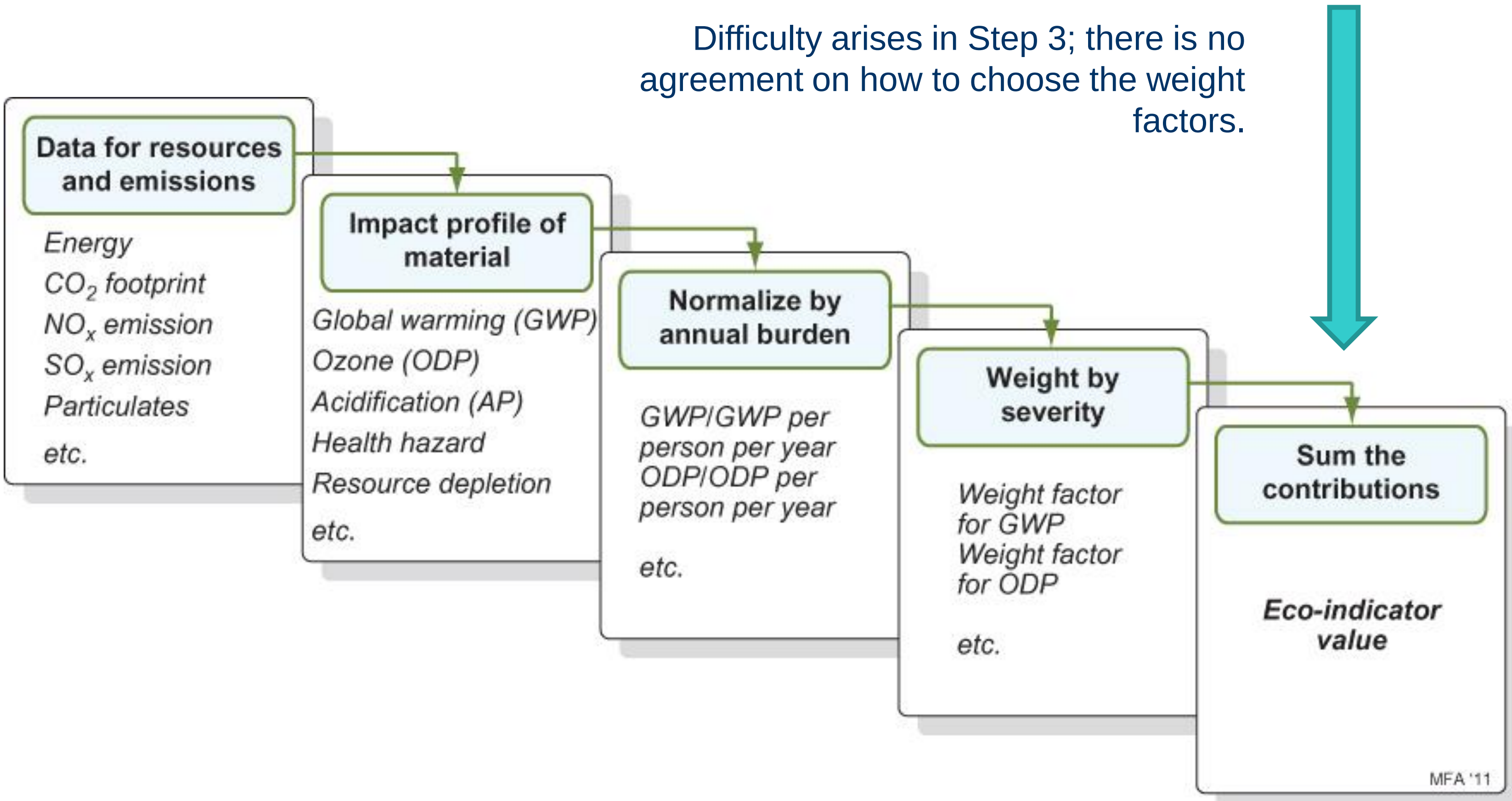
3) The third step is that of *weighting* to reflect the perceived seriousness of each impact; thus global warming might be seen as more serious than resource depletion, giving it a larger weight.



Aggregated measures: eco-indicators

4) In the final step, the weighted, normalized measures are *summed* to give the indicator.

Difficulty arises in Step 3; there is no agreement on how to choose the weight factors.



Aggregated measures: eco-indicators

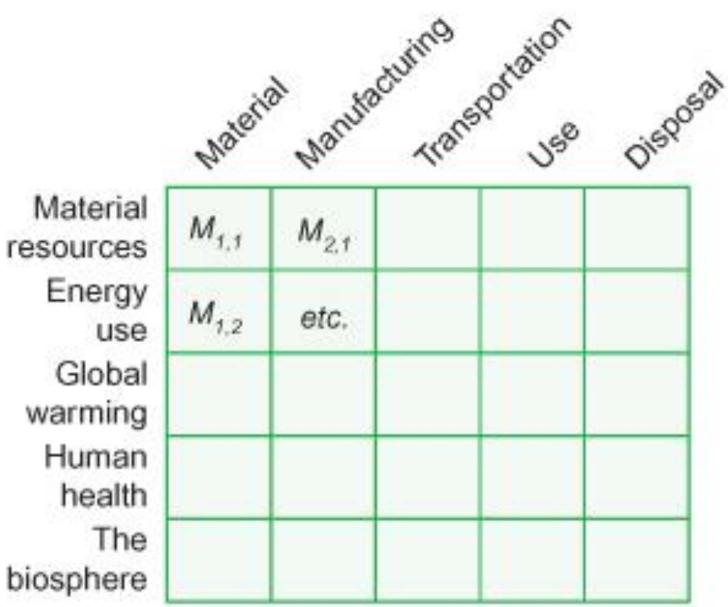
- The use of a single-valued indicator is criticized by some.

  The grounds for criticism are that:

- there is no agreement on normalization or weighting factors,
- the method is opaque since the indicator value has no simple physical significance,
- defending design decisions based on a measurable quantity such as *energy consumption* or *CO2 release to atmosphere* carry more conviction than doing so with an indicator.

Streamlined LCA

- The complexity of an LCA makes it, for many purposes, unworkable.
- *Streamlined LCA* attempts to overcome this problem by basing the study on a reduced and simplified inventory of resources, accepting a degree of approximation while retaining enough precision to guide decision making.
- Matrix method: from quantitative to qualitative analysis. An integer between 0 (highest impact) and 4 (least impact) is assigned to each matrix element M_{ij}, based on experience.



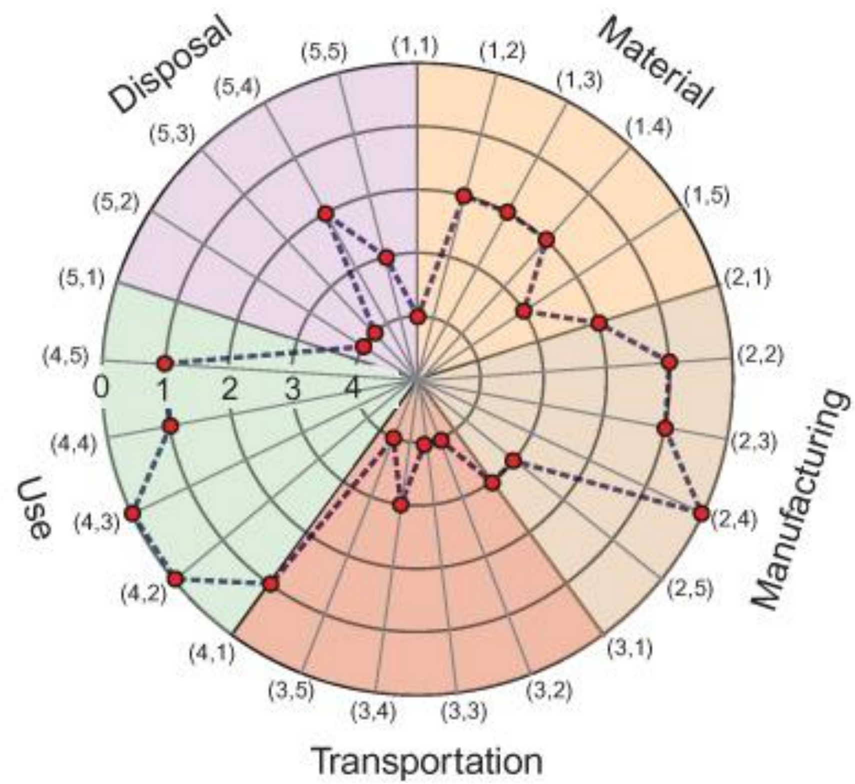
The overall *Environmentally Responsible Product Rating* is the sum of the matrix elements:

$$R_{erp} = \sum_i \sum_j M_{ij}$$

Streamlined LCA

- An example of a streamlined LCA matrix and a target plot displaying the rankings in each element of the matrix. In this example the use phase gets poor ratings.

	Material	Manufacturing	Transportation	Use	Disposal
Material resources	$M_{1,1}$	$M_{2,1}$			
Energy use	$M_{1,2}$	etc.			
Global warming					
Human health					
The biosphere					



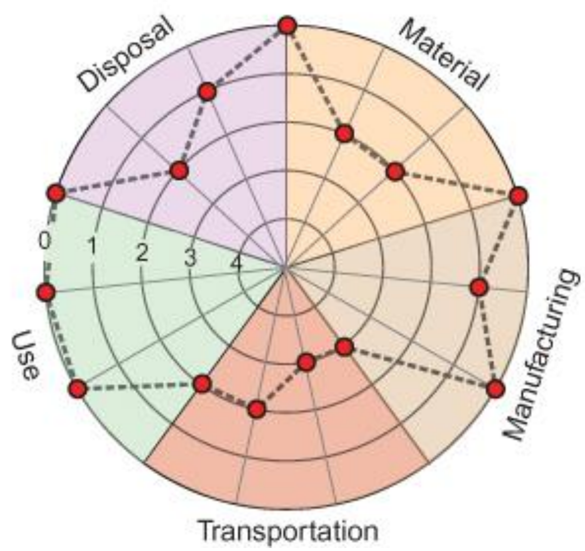
Streamlined LCA

- The assessment matrices and the target plots for cars of the 1950s and of 1990s.

1950s automobile

	Material	Manufacturing	Transportation	Use	Disposal
Material efficiency	0	0	3	2	0
Energy efficiency	2	1	3	0	2
Carbon efficiency	2	0	2	0	1

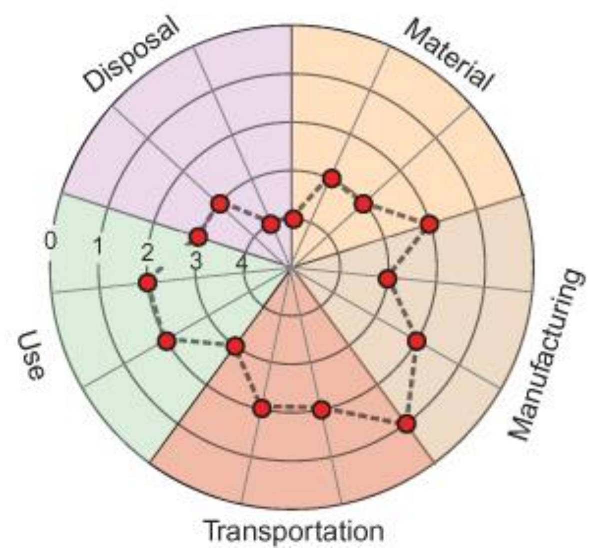
$R_{erp} = 18$



1990s automobile

	Material	Manufacturing	Transportation	Use	Disposal
Material efficiency	4	2	1	3	3
Energy efficiency	3	3	2	2	3
Carbon efficiency	3	2	2	2	4

$R_{erp} = 39$



A strategy for eco-selection of materials

- *"What if?"* exploration of alternatives.

- It is necessary to strip off much of the detail, multiple targeting, and complexity of method that makes standard LCA techniques so cumbersome.

- A possible approach:

1) **Adopt simple metrics of environmental stress.**

→ Energy and/or CO_2 footprint.

The two are related and are easy understandable.

Energy is the easiest to monitor, it can be measured with relative precision, and it can be used as a proxy for CO_2.

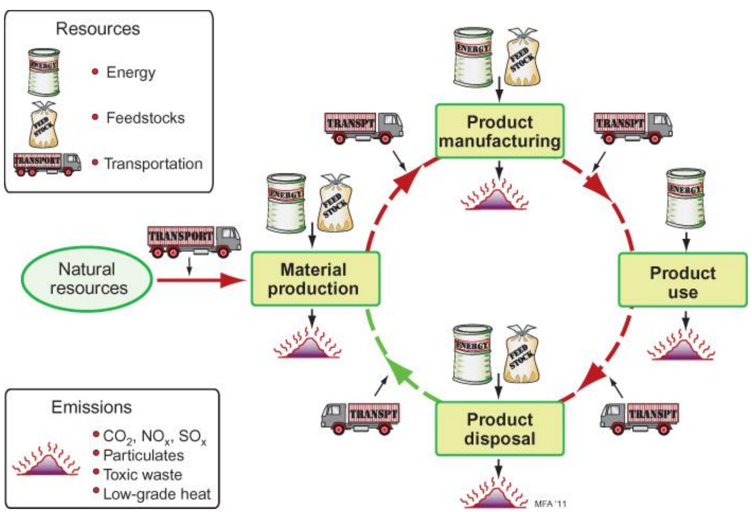
One resource, one emission

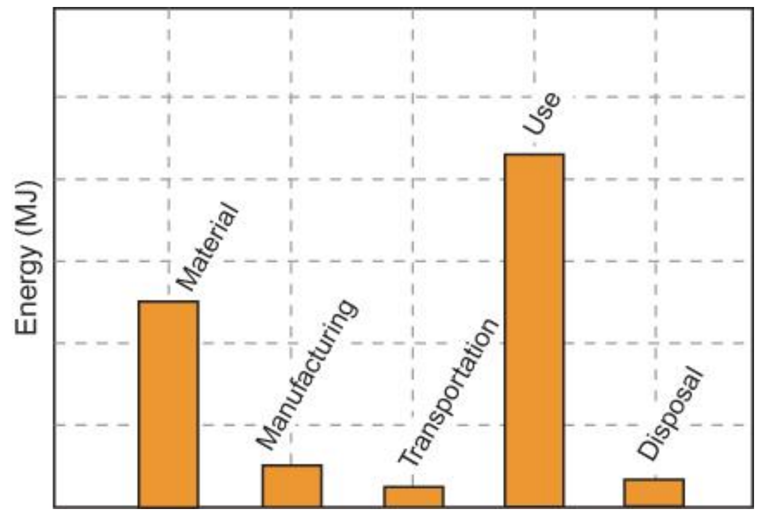
It is now standard practice to report official fuel economy figures for cars (e.g., Combined: 5.9 -6.4 liter/100 km, CO_2 emissions: 143 - 154 g/km) and energy ratings for appliances (e.g., 330 kWhr/year, efficiency rating: A).

A strategy for eco-selection of materials

2) ***Distinguish the phases of life.***

→ Breakdown of energy into that associated with each life phase.

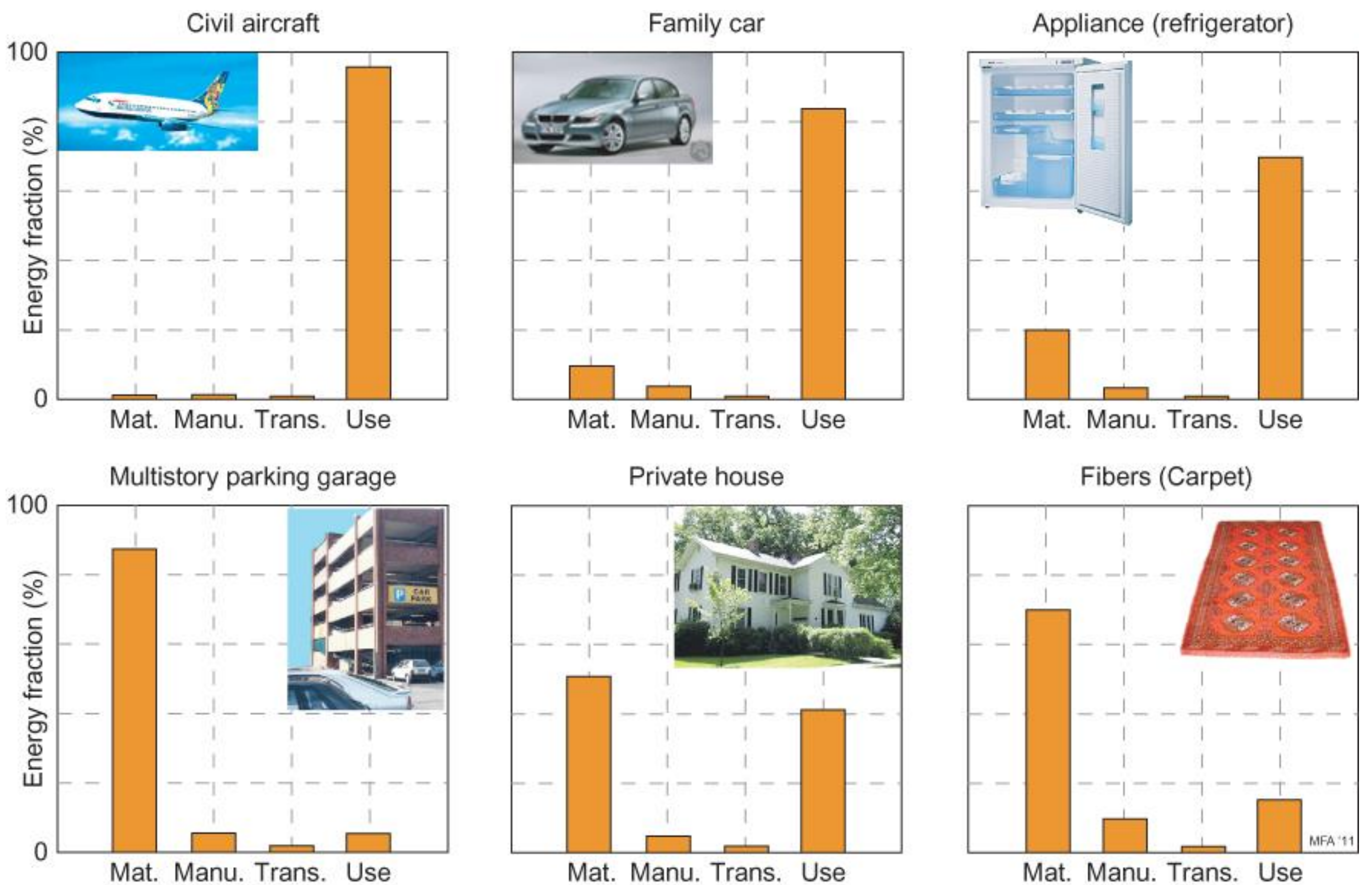




Product disposal can take many different forms,
some carrying an energy penalty, some allowing energy recycling or recovery.

A strategy for eco-selection of materials

- It is frequently found that one of the phases dominates the picture.



The use phase consumes more energy than the sum of all the other phases.

Embodied energies of the materials of which products are made make the largest contribution.

A strategy for eco-selection of materials

- If large energy savings are to be achieved, the dominant phase becomes the first target, since a given fractional reduction makes the biggest contribution.
- When differences are so great, great precision is not necessary, since modest changes to the input data leave the ranking unchanged.
- Precise judgments can be drawn from imprecise data.

3) ***Base the subsequent action on the energy or carbon breakdown.***

- Dominant phase: material production

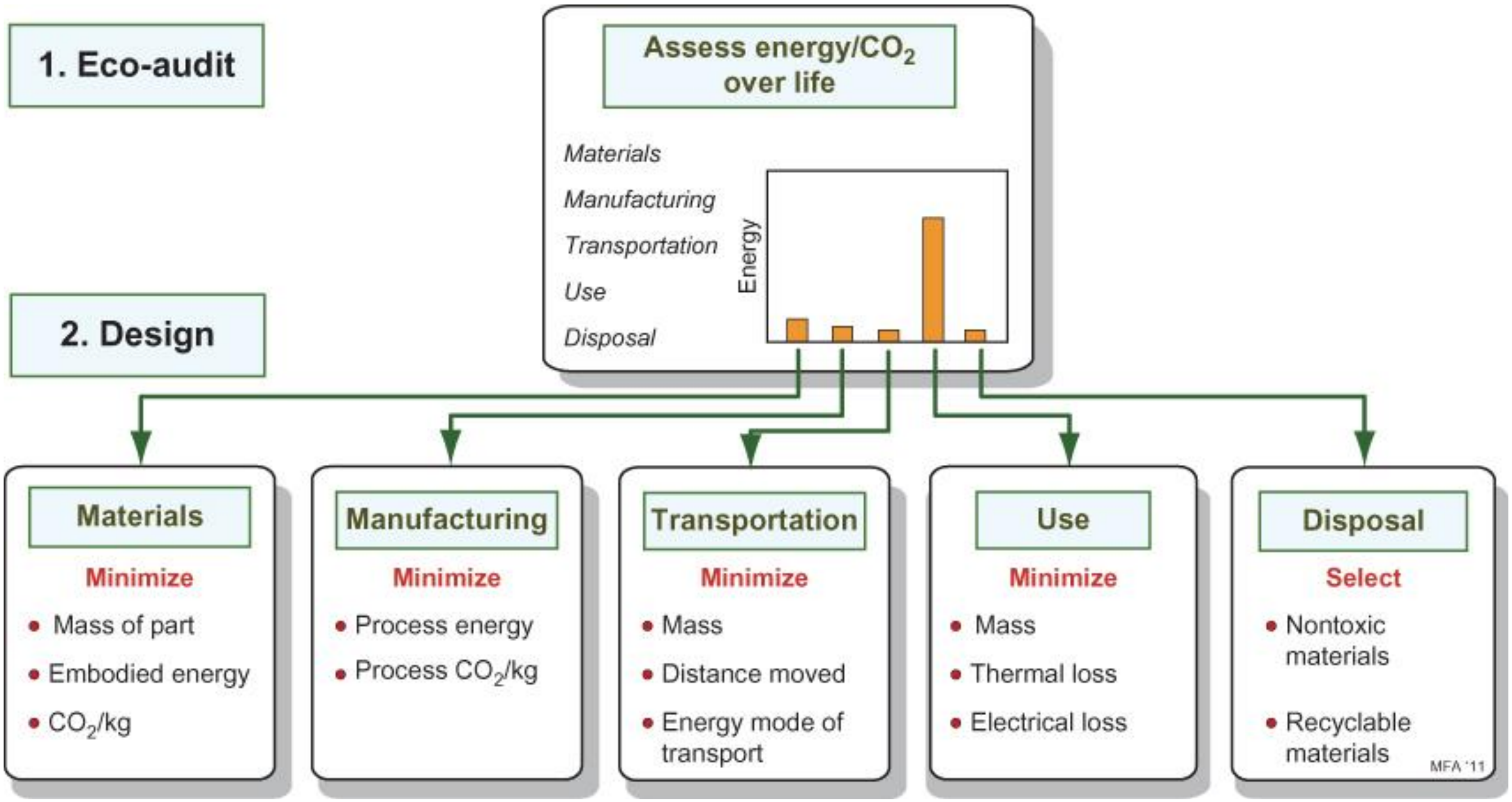
  → choose materials with low embodied energy, minimize the used amounts.
- Dominant phase: manufacture

  → reduce processing energy.
- Dominant phase: transport

  → seek a more efficient transport mode, reduce distances.
- Dominant phase: use

  → minimize mass, increase thermal efficiency, reduce electrical losses, etc.

A strategy for eco-selection of materials



Eco-Data

- Decisions need data.
- Engineering eco-properties.
- The precision of a great deal of eco-data is low.
- The values of some are known to within 10%, others with even less certainty.
- How much precision do you need to deal with a given problem?
- The answer: just enough to distinguish the viable alternatives.
- Often that does not require much. *Precise judgments can be based on imprecise data*.

Introduction

- The engineering (i.e. mechanical, thermal) properties of materials are well characterized. They are measured with sophisticated equipment according to internationally accepted standards and are reported in widely accessible handbooks and databases.

- They are not *exact*, but their *precision* is reported.

- Additional properties are needed to incorporate eco-objectives into the design process. They include measures of the energy committed and carbon released into the atmosphere when a material is extracted or synthesized - its *embodied energy* and *carbon footprint* - and similar data for processing of the material to create a shaped part.

- Take embodied energy as an example. It is the energy to produce unit mass (usually, 1 kg) of a material from, well, whatever it is made from.

- Embodied energy is an upstart with a brief and not very creditable history. There are no sophisticated test machines to measure it. International standards, detailed in ISO 14040, lay out procedures, but these are vague and not easily applied.

- The distinctions they reveal and the decisions drawn from them must be *significant*, meaning that they must stand despite the imprecision of the data on which they are based.

Eco-data: An example

Aluminum alloys

Eco properties: material	
Global production, main component	37×10^6 metric ton/yr
Reserves	2.0×10^9 metric ton
Embodied energy, primary production	200–220 MJ/kg
CO_2 footprint, primary production	11–13 kg/kg
Water usage	495–1490 l/kg
Eco-indicator	710 millipoints/kg
Eco properties: processing	
Casting energy	11–12.2 MJ/kg
Casting CO_2 footprint	0.82–0.91 kg/kg
Deformation processing energy	3.3–6.8 MJ/kg
Deformation processing CO_2 footprint	0.19–0.23 kg/kg
End of life	
Embodied energy, recycling	22–39 MJ/kg
CO_2 footprint, recycling	1.9–2.3 kg/kg
Recycle fraction in current supply	41–45%

Geo-economic data: information about the resource base from which the material is drawn, and the rate at which it is being exploited.

- *Annual world production* is the mass of the material extracted annually from ores or feedstock.
- *Reserve* is the currently reported sizes of the economically–recoverable from which the material is extracted or created.

Eco-data

- Aluminum: embodied energy 200 - 220 MJ/kg.
- The ranges allow “best-case” and “worst-case” scenarios to be explored.
- When point (single-valued) data is needed, take the mean of the range.

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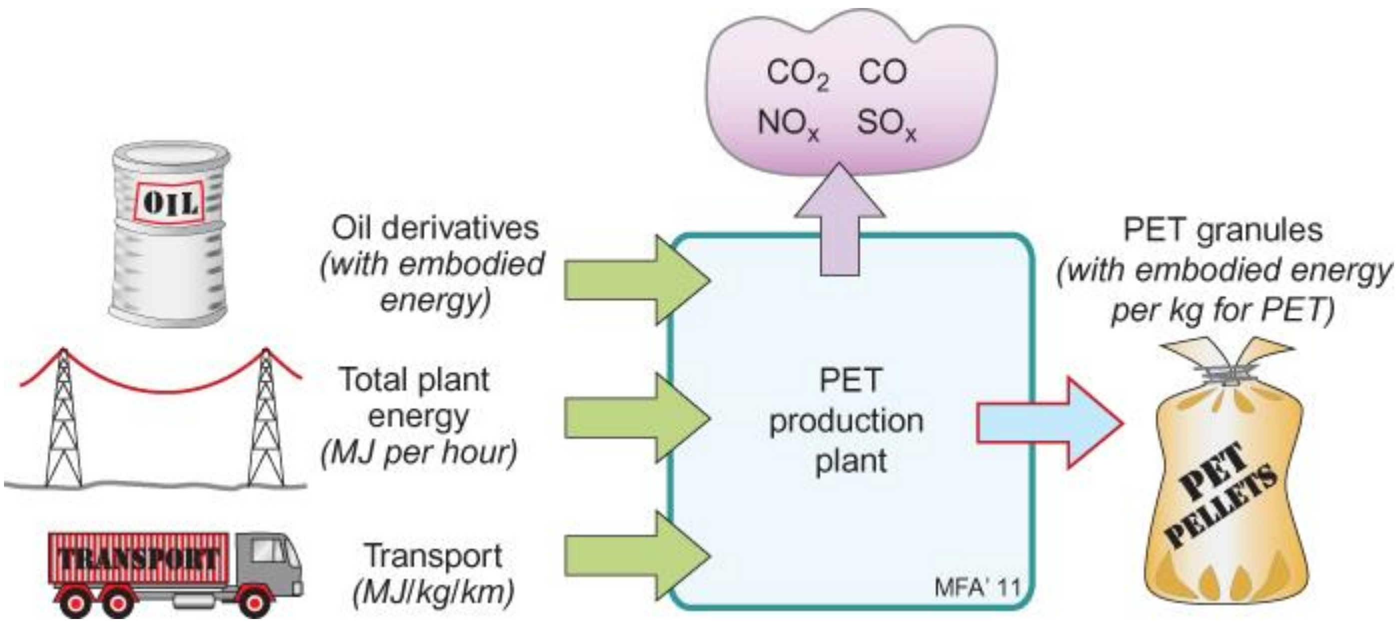
Embodied energy and CO_2 footprint

- The *embodied energy* is the energy that must be committed to create 1 kg of usable material -1 kg of steel stock, or of PET pellets, or of cement powder - measured in MJ/kg.
- The *CO_2 footprint* is the associated release of *CO_2* into the atmosphere, in kg/kg. The embodied energy and the CO_2 footprint of a material are assessed in a similar way.



$$(H_m)_{PET} = \frac{\sum \text{Energies entering plant per hour}}{\text{Mass of PET granules produced per hour}}$$

Embodied energy and CO_2 footprint

- Embodied energies are more properly assessed by input/output analysis. For a material such as ingot iron, cement powder, or PET granules, the embodied energy/kg is found by monitoring over a fixed period of time the total energy input to the production plant and dividing this total by the quantity of usable material shipped out of the plant.

- The material inputs to any processing operation are referred to as feedstock. They can be inorganic or organic:

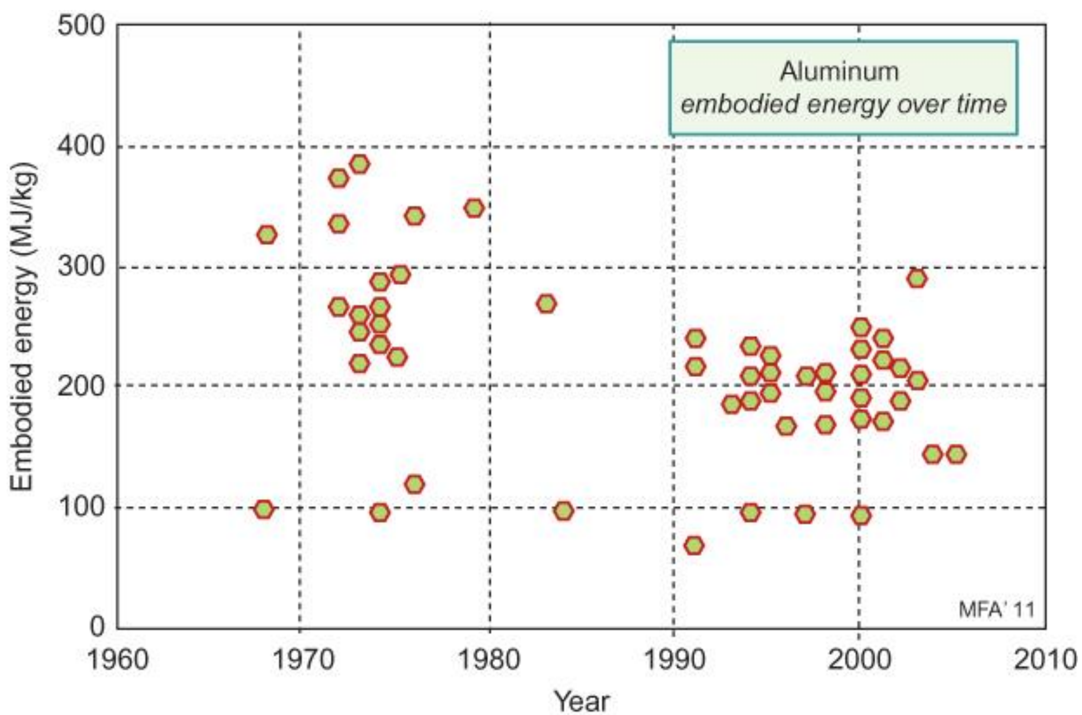
  - *Inorganic feedstock* is straightforward because, during processing, they appear either in the final product or in the waste output.
  - *Organic feedstock* can be used either as a material input or as a fuel input.

- In describing the embodied energy of materials or products it is important to include feedstock energies in the total because they represent a demand for a resource to support the system of production.

- The carbon emissions consequent on the creation of unit mass of material include those associated with transport, the generation of the electric power used by the plant, and that of feedstock and hydrocarbon fuels.

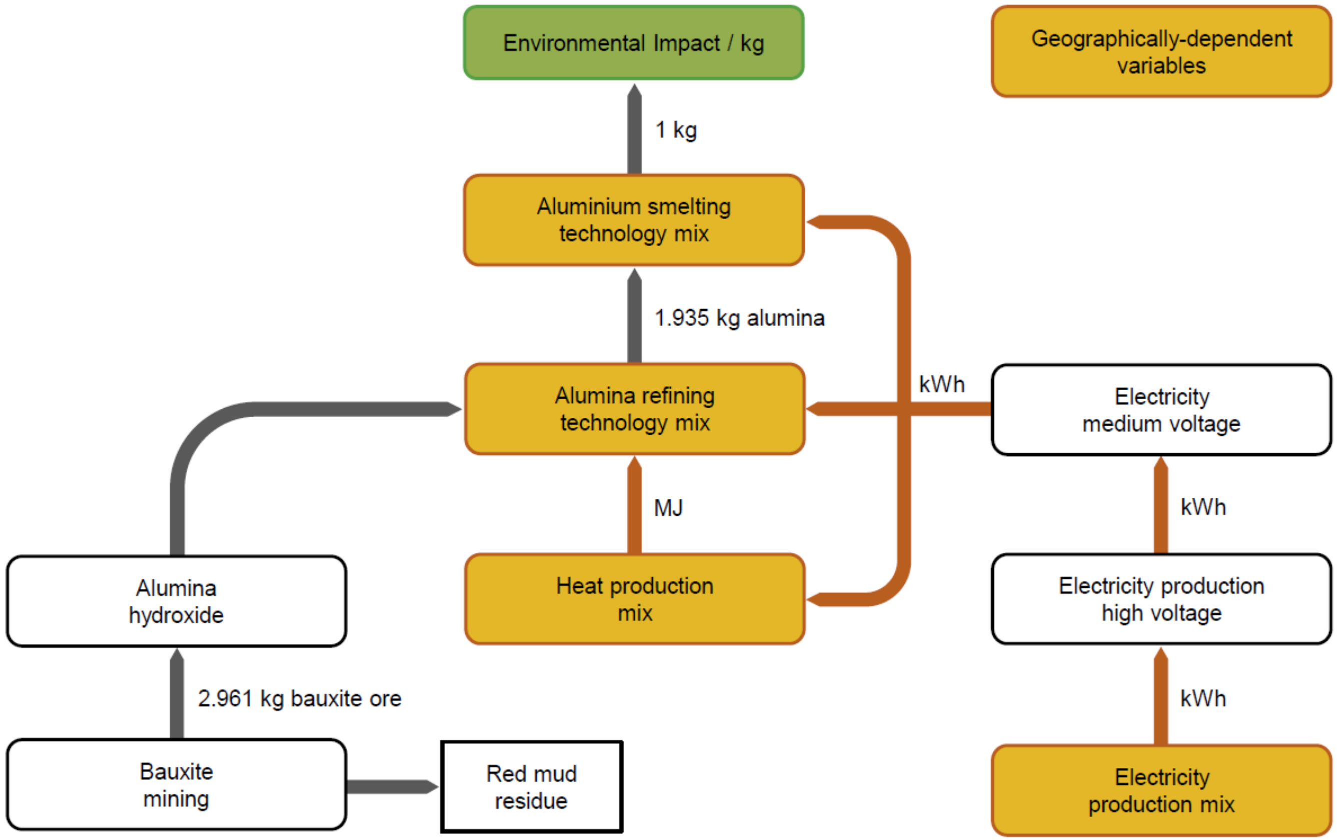
- The CO_2 footprint, with the usual units of (kg of CO_2)/kg, is then the sum of all the contributions per unit mass of usable material exiting the plant.

Data precision



- Data for the embodied energy of aluminum.
- The mean is 204 MJ/kg, with a standard deviation of 58 MJ/kg.
- Using the best-characterized data only gives a mean of 210 MJ/kg with a standard deviation of 20 MJ/kg.

Geographically-dependent variability: Aluminium production

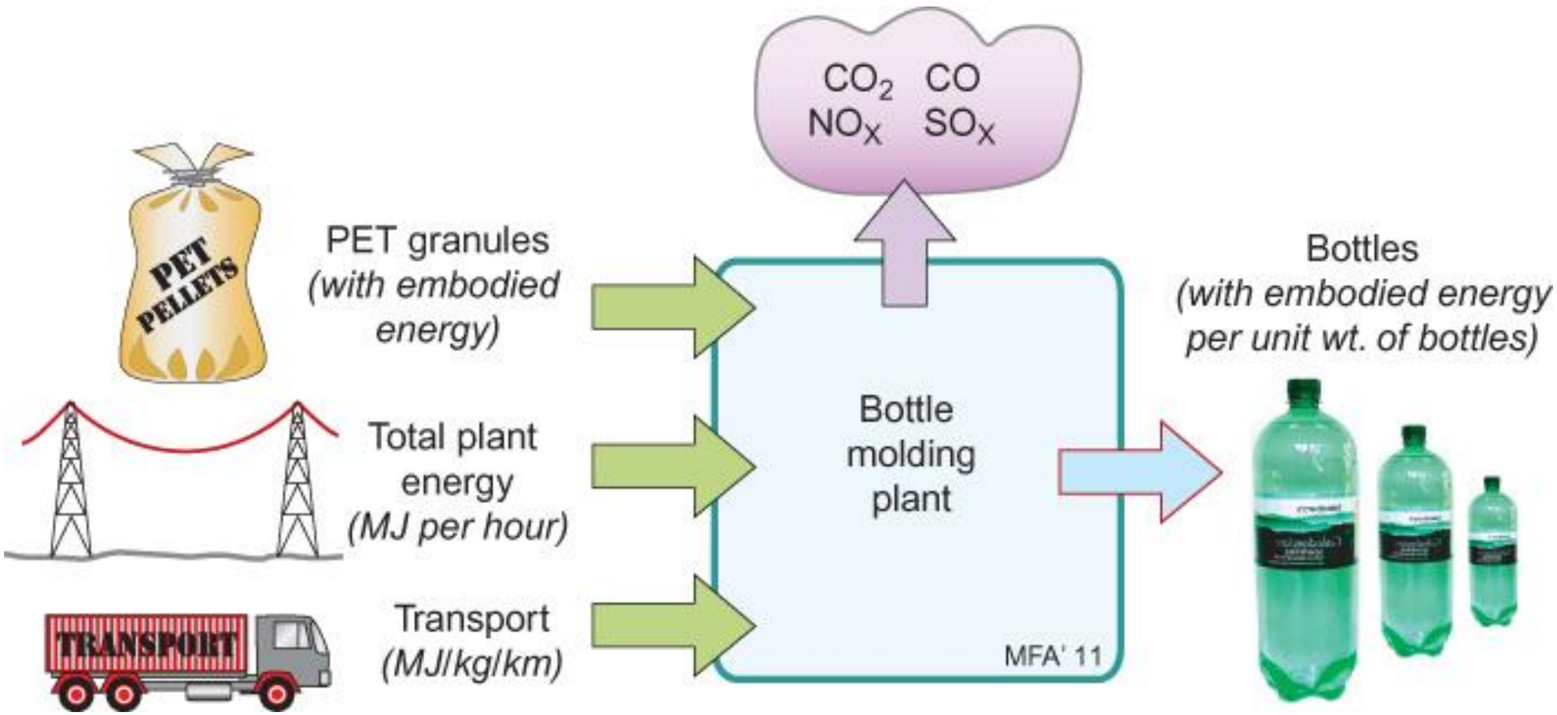


Scenario	Bauxite mining (Ecopoints/kg)	Alumina refining (Ecopoints/kg)	Aluminium smelting (Ecopoints/kg)	Total (Ecopoints/kg)
MIN	0.005	0.150	0.356	0.511
MAX	0.005	0.219	1.876	2.100
AVG	0.005	0.185	1.116	1.306

Ingarao et al,
J. Cleaner Production 176 (2018) 261-275

Eco-properties: Processing energy

- Product manufacture requires that materials be shaped, joined, and finished.
- The processing energy associated with a material is the energy, in MJ/kg, used to do this.
- The availability and precision of data for processing are particularly poor due to differences in processing equipment and manufacturing practice.



Processing energy

Shaping of metals

Casting
Forging, rolling (deformation processing)
Metal powder processing
Vapor-phase methods

Shaping of polymers

Polymer molding (thermo-forming, injection molding, etc.)
Polymer extrusion
Polymer machining

Shaping of ceramics

Ceramic powder forming

Shaping of glasses

Glass molding

Shaping of composites

Simple composite molding
Advanced composite molding

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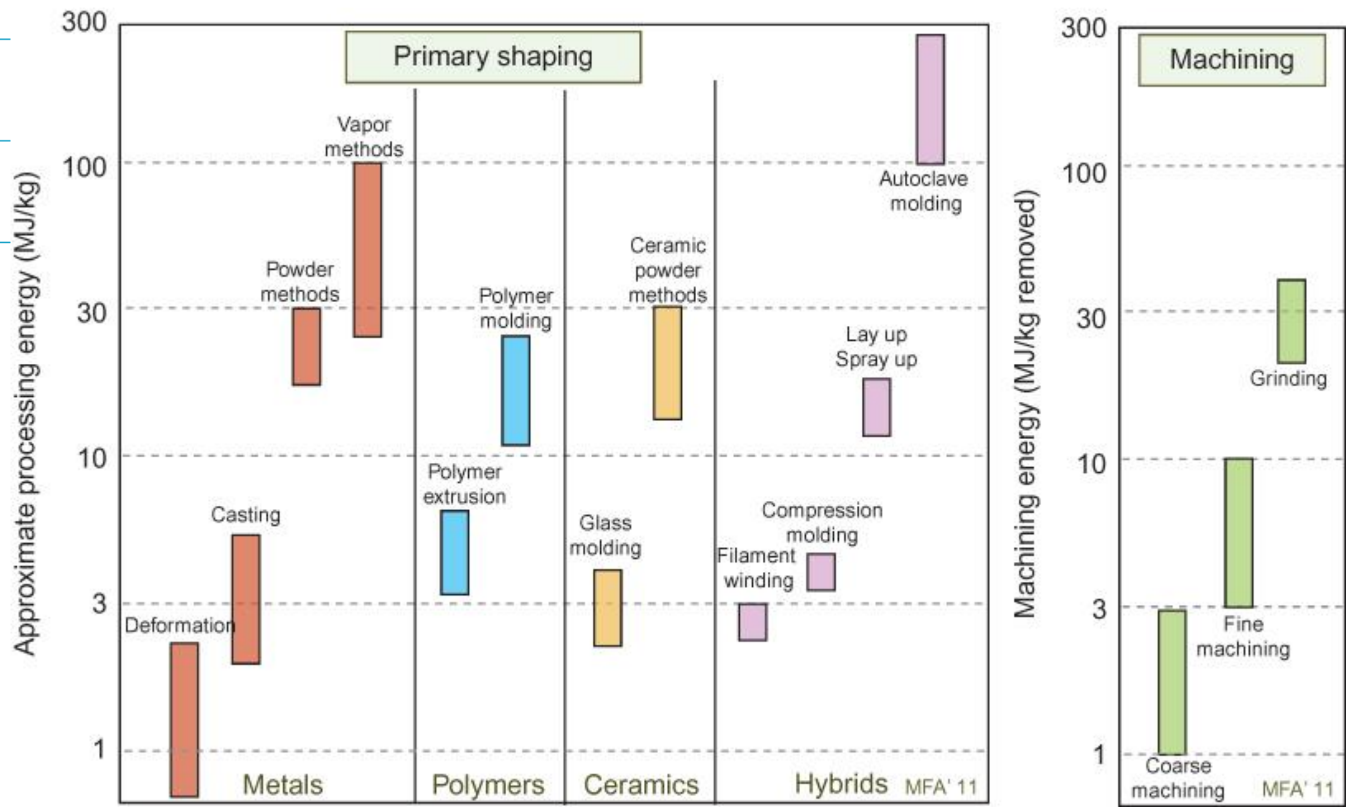
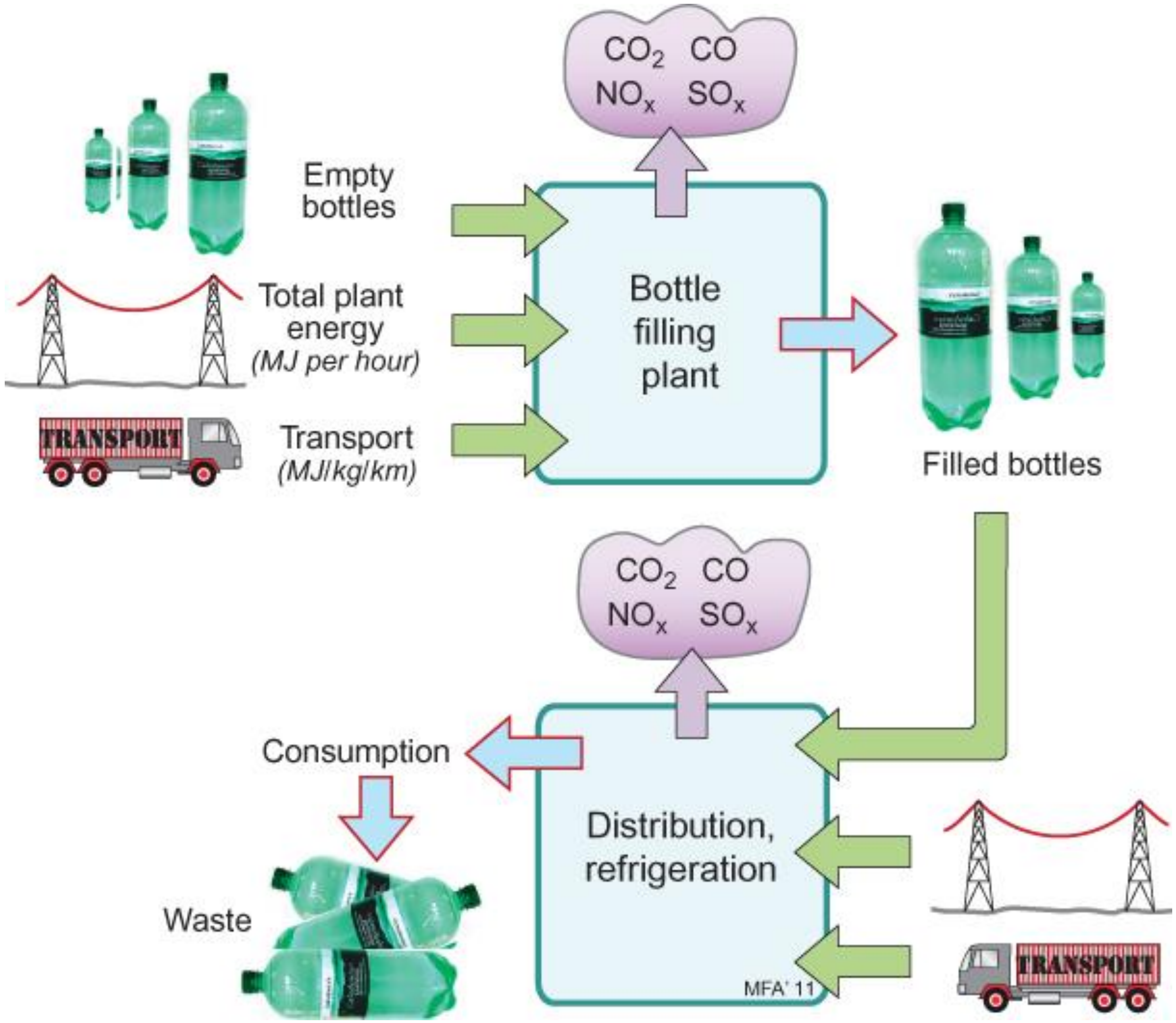


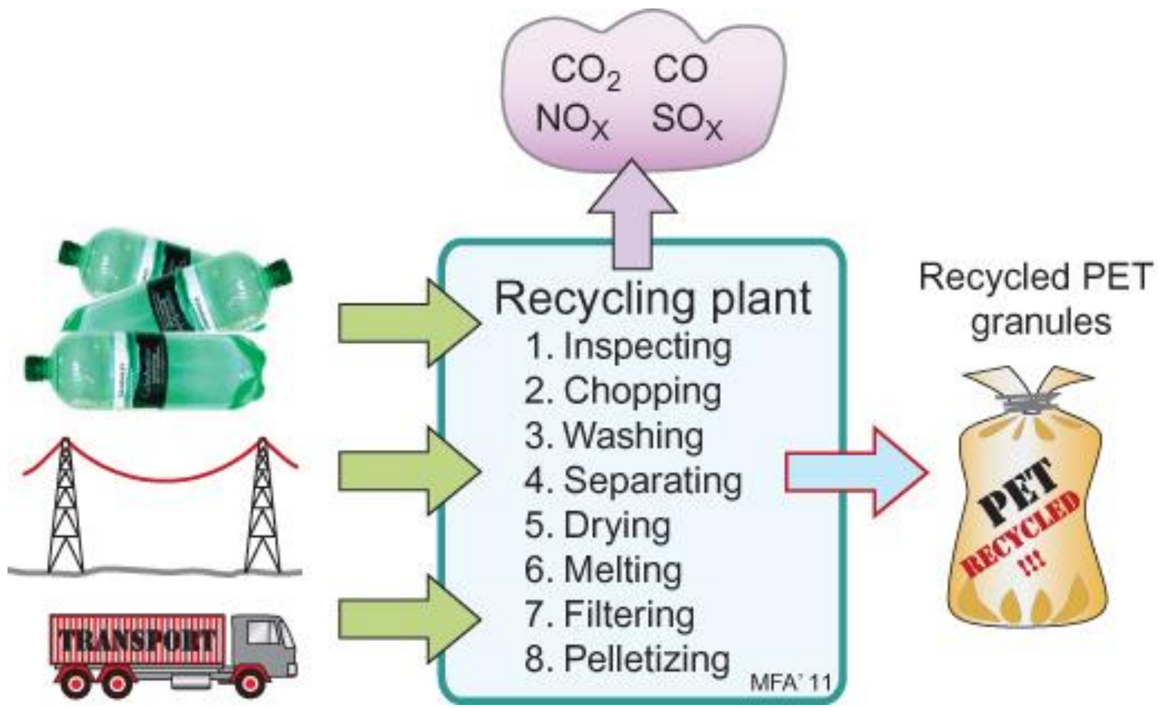
Use phase



The *use phase* of PET water bottles: filling, distribution, and refrigeration.

Energy is consumed in transport and refrigeration.

Recycling and end-of-life



- The product is transported to the point of sale, passes to the consumer, is used, and, ultimately, reaches the end of its useful life.
- The existence of embodied energy has another consequence: that the energy to recycle a material is sometimes much less than that required for its first production because the embodied energy is retained.

Energy intensity

- The energy intensity of fossil fuels and their carbon footprints.

Fuel type	kg OE*	MJ/liter	MJ/kg	CO_2 (kg/liter)	CO_2 (kg/kg)	CO_2 (kg/MJ)
Coal, lignite	0.45	—	18–22	—	1.6	0.080
Coal, anthracite	0.72	—	30–34	—	2.9	0.088
Crude oil	1.0	38	44	3.1	3.0	0.070
Diesel	1.0	38	44	3.1	3.2	0.071
Gasoline	1.05	35	45	2.9	2.89	0.065
Kerosene	1.0	35	46	3.0	3.0	0.068
Ethanol	0.71	23	31	2.8	2.6	0.083
LNG	1.2	25	55	3.03	3.03	0.055
Hydrogen	2.7	8.5	120	0	0	0

**Kilograms oil equivalent (the kg of oil with the same energy content)*

- Electricity is the most convenient form of energy. Today most electricity is still generated by burning fossil fuels, but the pressure on these fuels and the problems caused by the emissions they release are urging governments to switch to nuclear and renewable sources, and most of these generate electric power.

- The *energy mix* in a country's electricity supply is the proportional contribution of each source to the total → CES Method.

Energy mix

- Electricity generation

Country	Fossil fuel %	Nuclear %	Renewables %	Efficiency[a] %	MJ_{oe}[b] per kWh[d]	CO_2,[c] kg per kWh[d]
Australia	92	0	8	33	10.0	0.71
China	83	2	15	32	9.3	0.66
France	10	78	12	40	0.9	0.06
India	81	2.5	16.5	27	10.8	0.77
Japan	61	27	12	41	5.4	0.38
Norway	1	0	99	—	0	0
UK	75	19	6	40	6.6	0.47
USA	71	19	10	36	7.1	0.50
OEDC (Europe)	62	22	16	39	5.7	0.41
World average	**67**	**14**	**19**	**36**	**6.7**	**0.48**

**Data from IEA (2008)*

(a) Conversion efficiency of fossil fuel to electricity

(b) MJ_{oe} of fossil fuel (oil equivalent) used in energy mix per kWh of delivered electricity from all sources

(c) CO_2 release per kWh of delivered electricity from all sources

(d) 1 kWhr is 3.6 $MJ_{electric}$

Transport

- Manufacturing is now globalized. Products are made where it is cheapest to do so and then transported, frequently over large distances, to the point of sale.
- Transport is an energy-conversion process: primary energy (oil, gas, coal) is converted into mechanical power and thus motion, sometimes with an intermediate conversion to electrical power.
- As in any energy conversion process, there are losses.
- The energy and CO_2 costs of transport.

Transportation type and fuel	Energy (MJ/metric ton · km$^+$)	Carbon footprint (kg CO_2/metric ton · km$^+$)
Ocean shipping—Diesel	0.16	0.015
Coastal shipping—Diesel	0.27	0.019
Barge—Diesel	0.36	0.028
Rail—Diesel	0.25	0.019
Articulated HGV (up to 55 metric tons)—Diesel	0.71	0.05
40 metric ton truck—Diesel	0.82	0.06
32 metric ton truck—Diesel	0.94	0.067
14 metric ton truck—Diesel	1.5	0.11
Light goods vehicle—Diesel	2.5	0.18
Family car—Diesel	1.4–2.0	0.1–0.14
Family car—Gasoline	2.2–3.0	0.14–0.19
Family car—LPG	3.9	0.18
Family car—Hybrid gasoline-electric	1.55	0.10
Super sports car and SUV—Gasoline	4.8	0.31
Long haul aircraft—Kerosene	6.5	0.45
Short haul aircraft—Kerosene	11–15	0.76
Helicopter (Eurocopter AS 350)—Kerosene	55	3.30

**Data sources are listed under Further reading.*

$^+$1 ton · mile = 1.46 metric ton · km

Material property charts

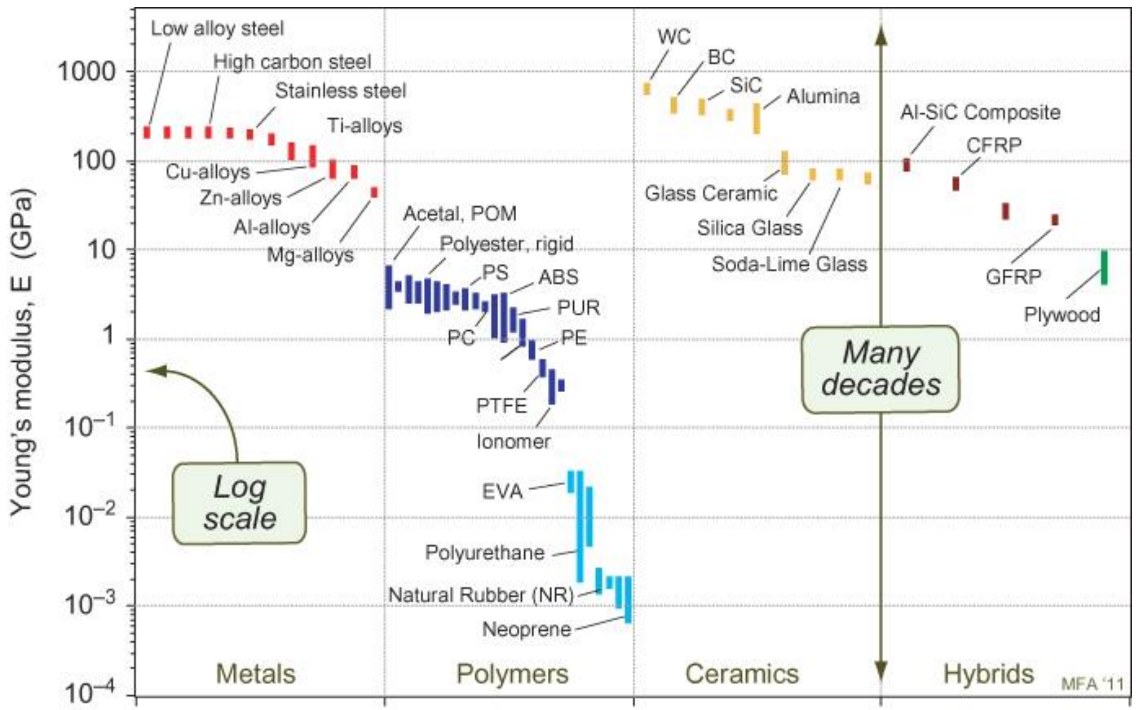
Property charts are of two types:

- *bar charts*
- *bubble charts*

A bar chart is simply a plot of the value ranges of one property.

The largest range makes sense to plot them on logarithmic scales.

The length of each bar shows the range of the property for each of the materials, segregated by family.

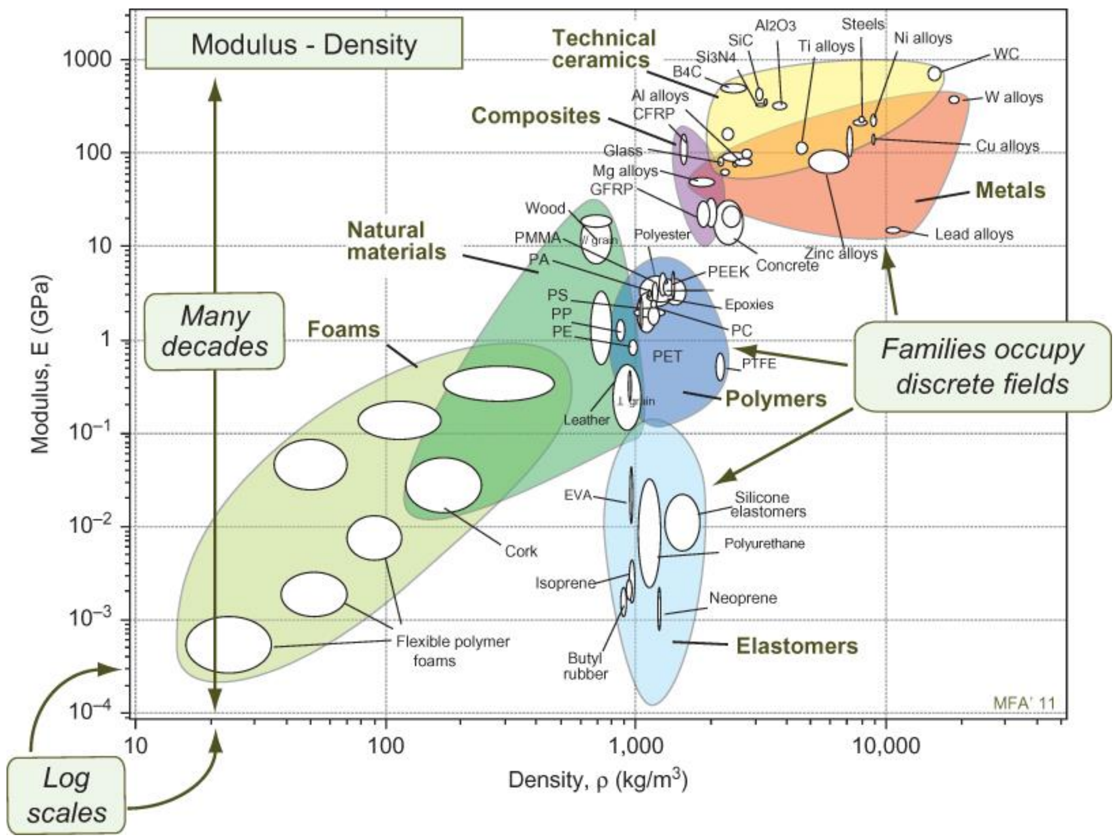


Material property charts

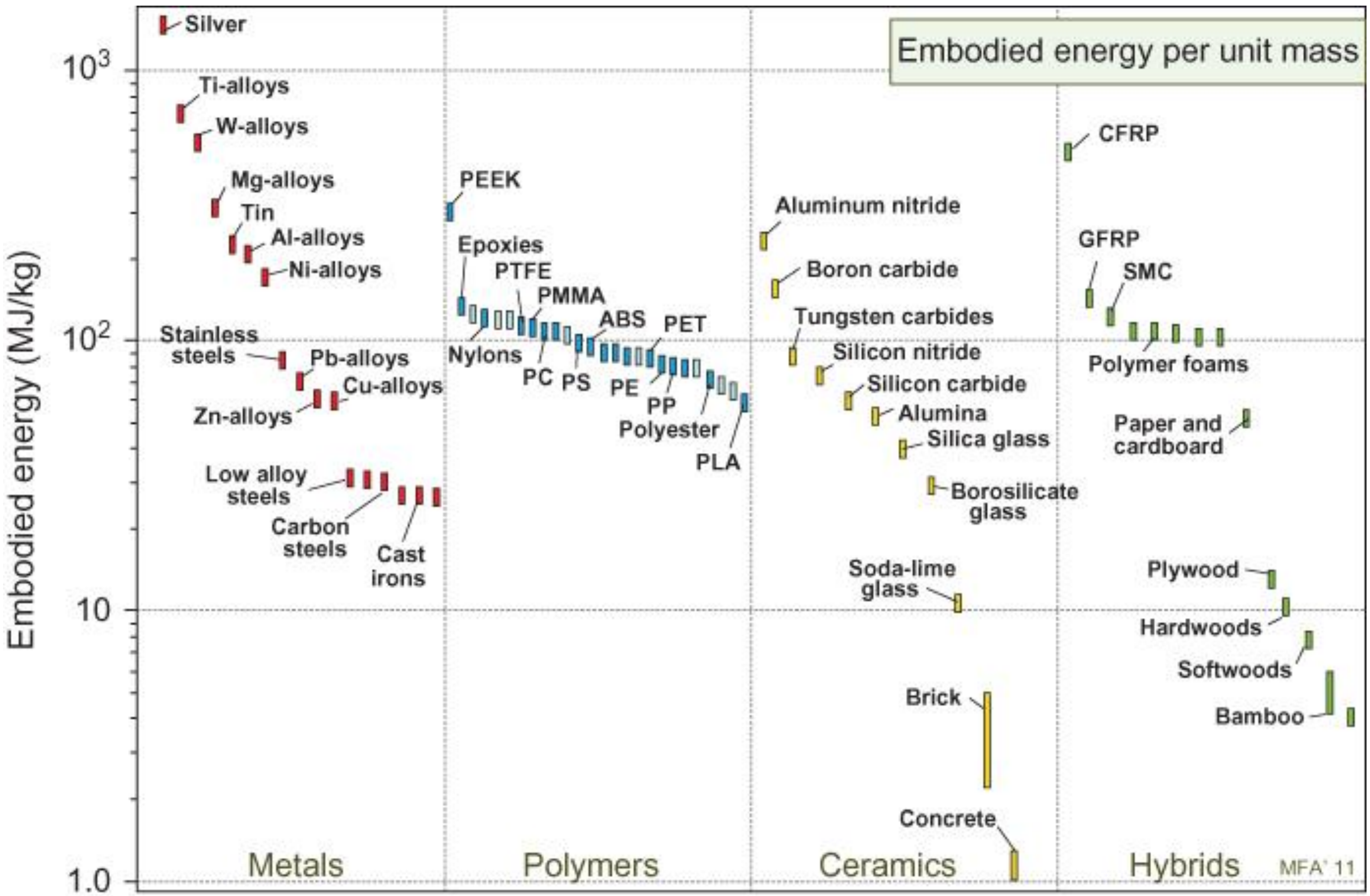
In bubble charts, families occupy discrete areas of the chart.
More information are given.

Overall:

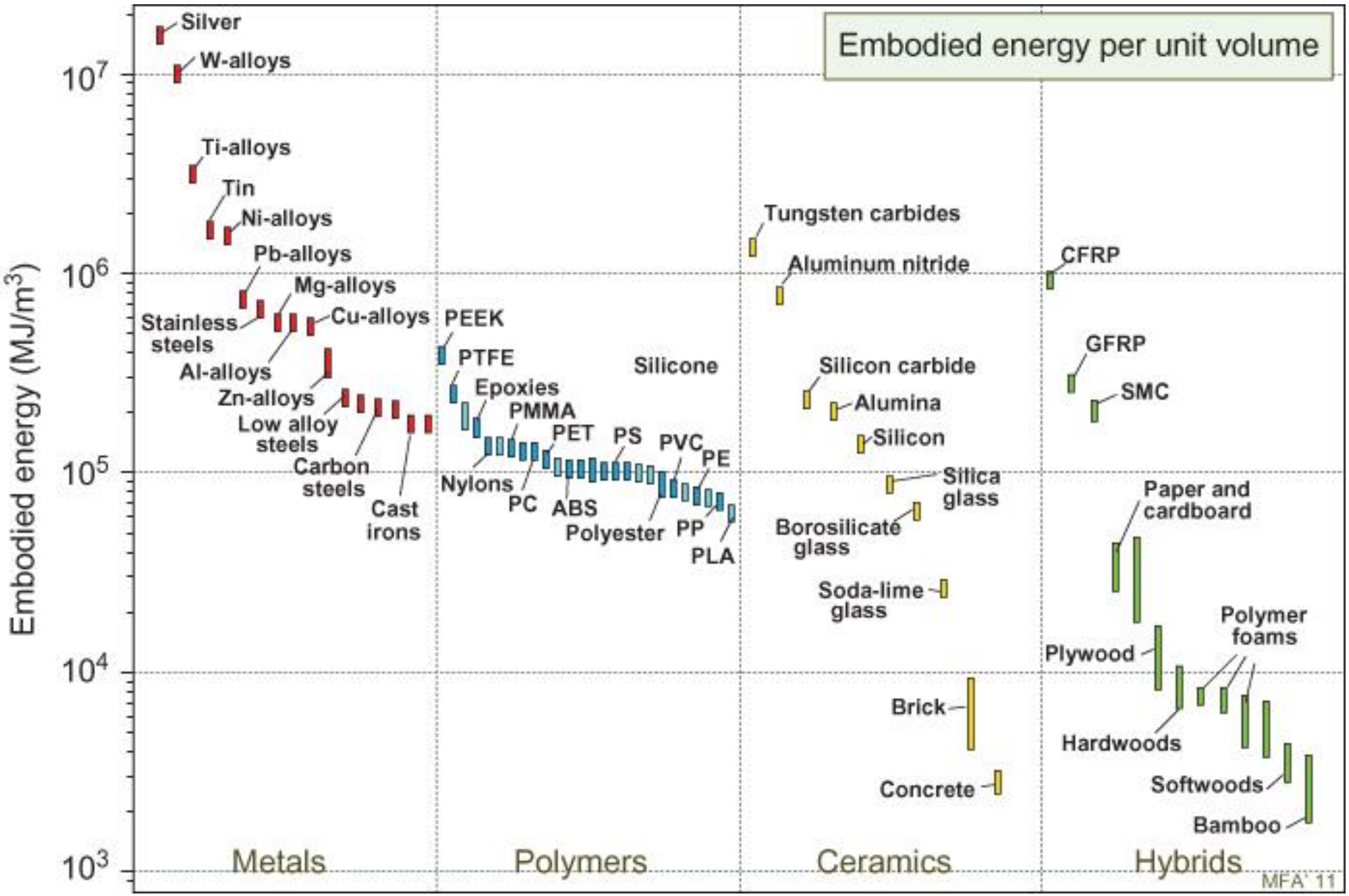
- The charts give an overview of the physical, mechanical, and functional properties of materials, presenting the information in an compact way.
- They reveal aspects of the physical origins of properties.
- They become a tool for optimized selection of materials to meet given design requirements, and they help us understand the use of materials in existing products.



Embodied energy

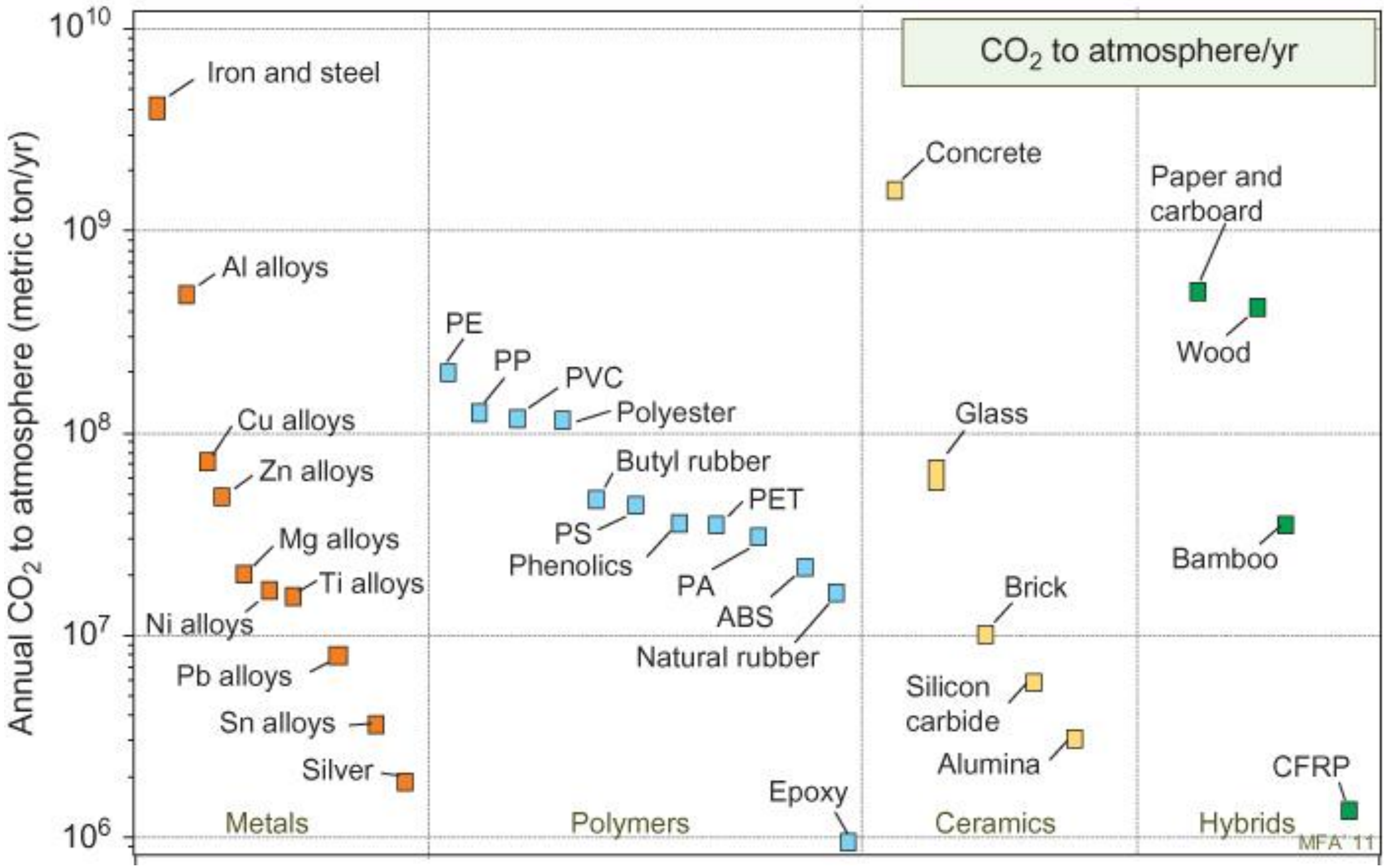


Embodied energy

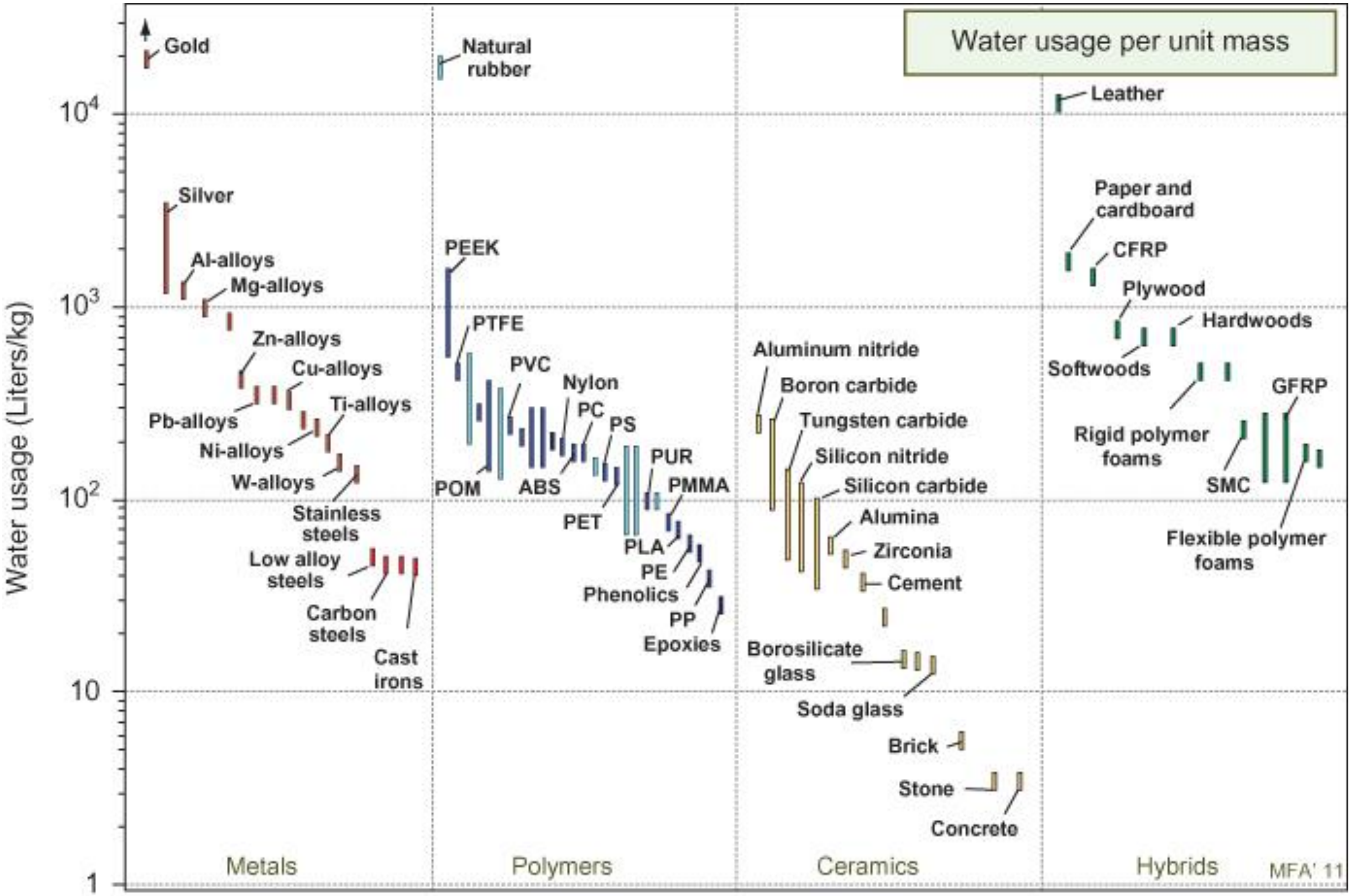


Carbon footprint

Which materials contribute the most?

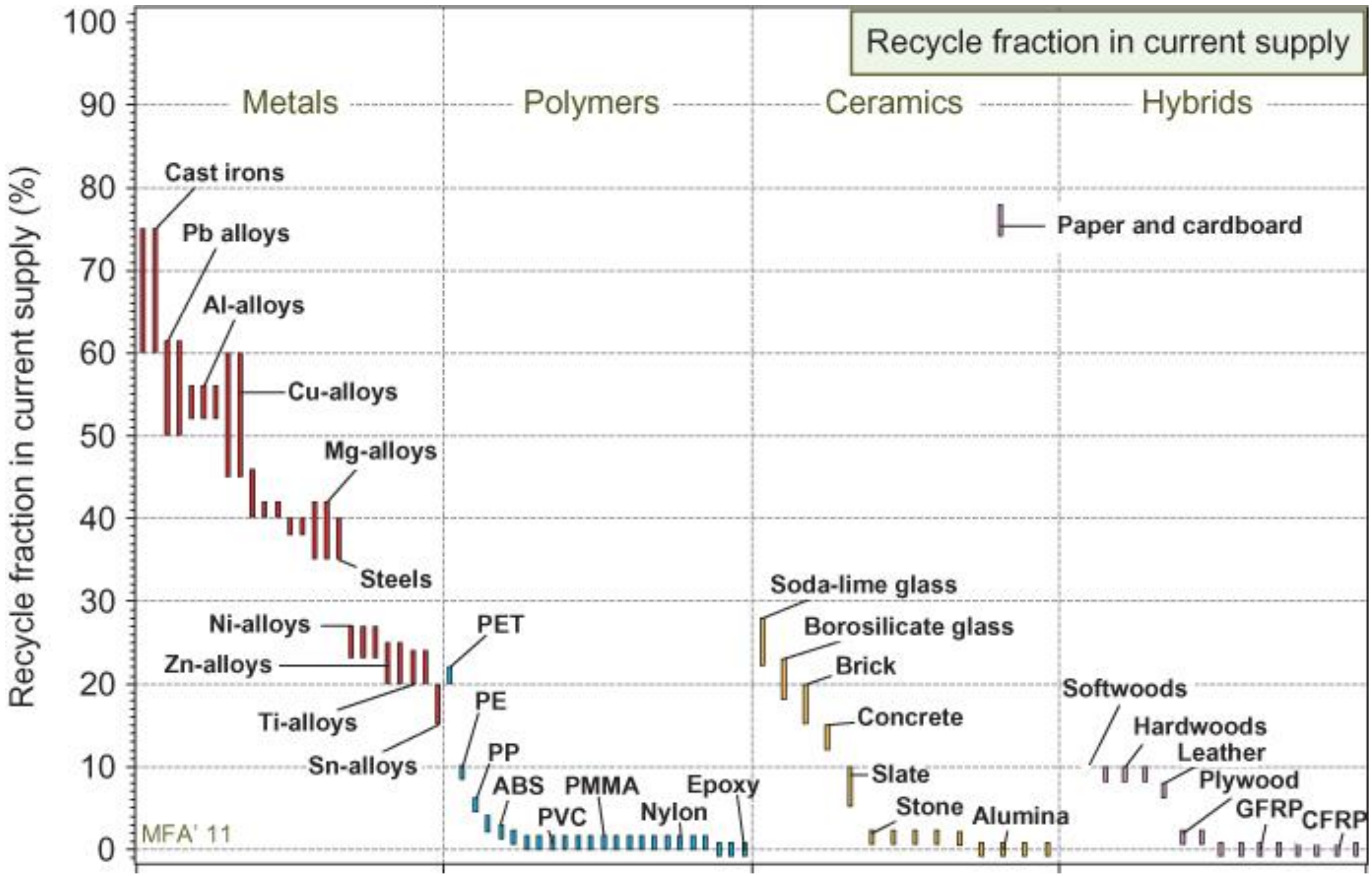


Water usage



Water usage bar chart.
The demands of water for material are small compared with those for agriculture.

Recycling



Recycle fraction bar chart. Metals are extensively recycled. Most other materials are not.

References and further readings

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  Eco-Informed Material Choice

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- David Dornfeld, Editor

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- **Handbook on Life Cycle Assessment**

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