University of BRISTOL

Theme: Sustainable Materials and Manufacturing

Lecture 2: Material selection for Eco-design

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Room 0.56 Queen’s Building

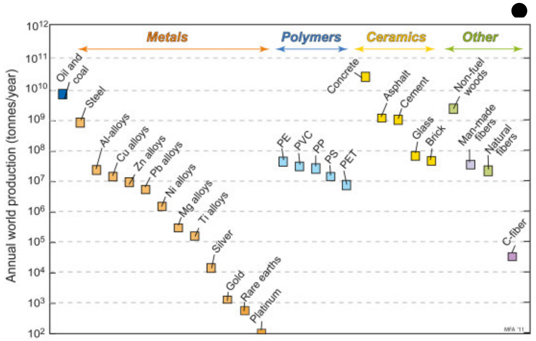
Today's Lecture Contents

- Material life cycle
- Sustainable material selection

Previously – Materials Consumption

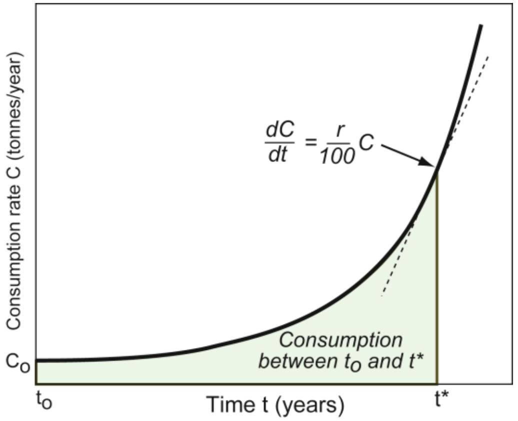
Materials Consumption

- Collossal amounts used
- Mainly oil/coal
- Unsustainable



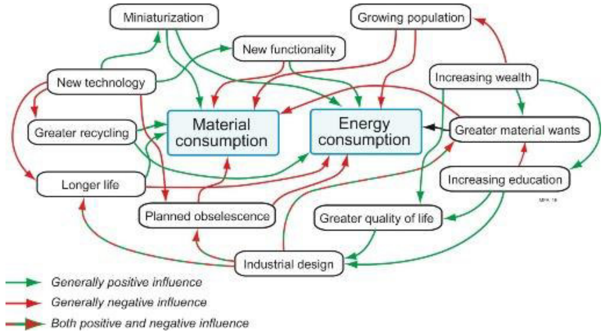
Rates

- Exponential
- Population
- Living standards



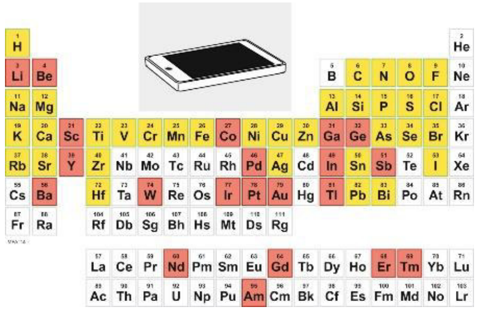
Materials Eco-system

- Catalysts to consumption
- Interconnected
- Unintended consequences

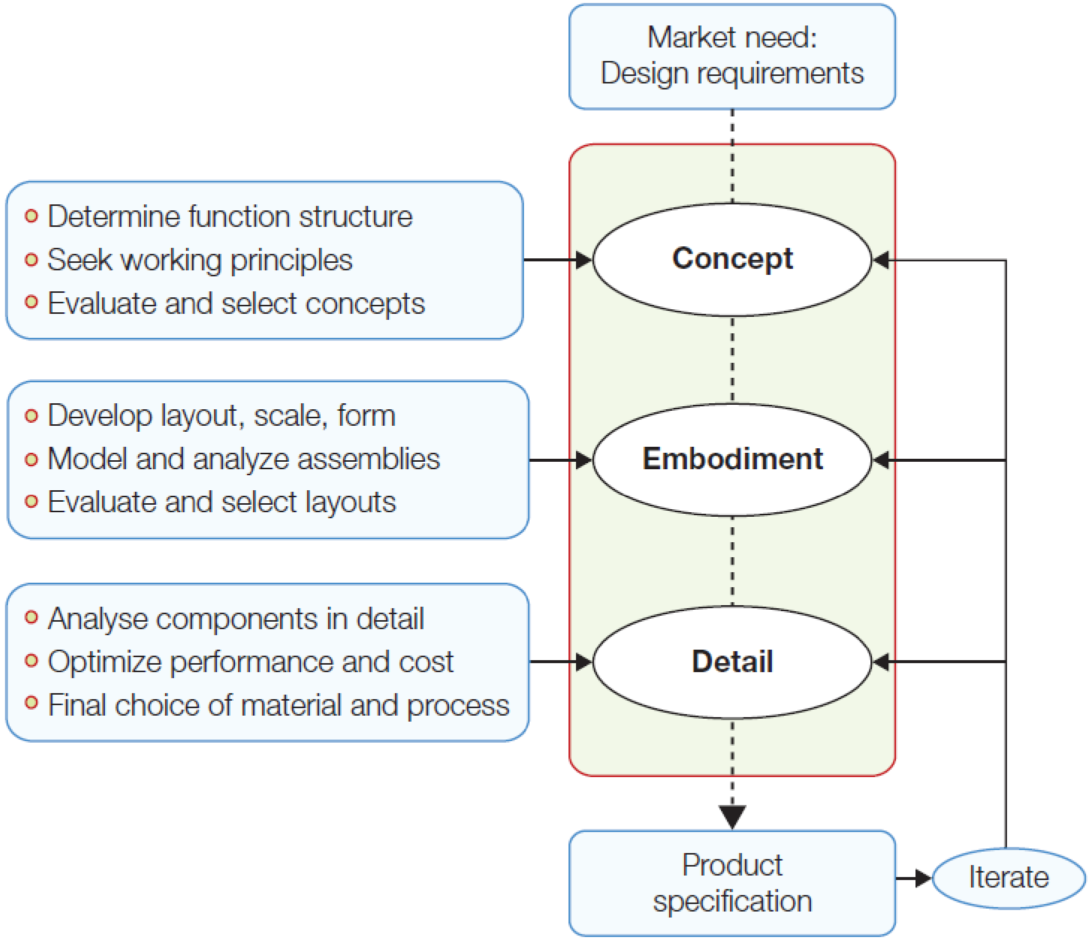


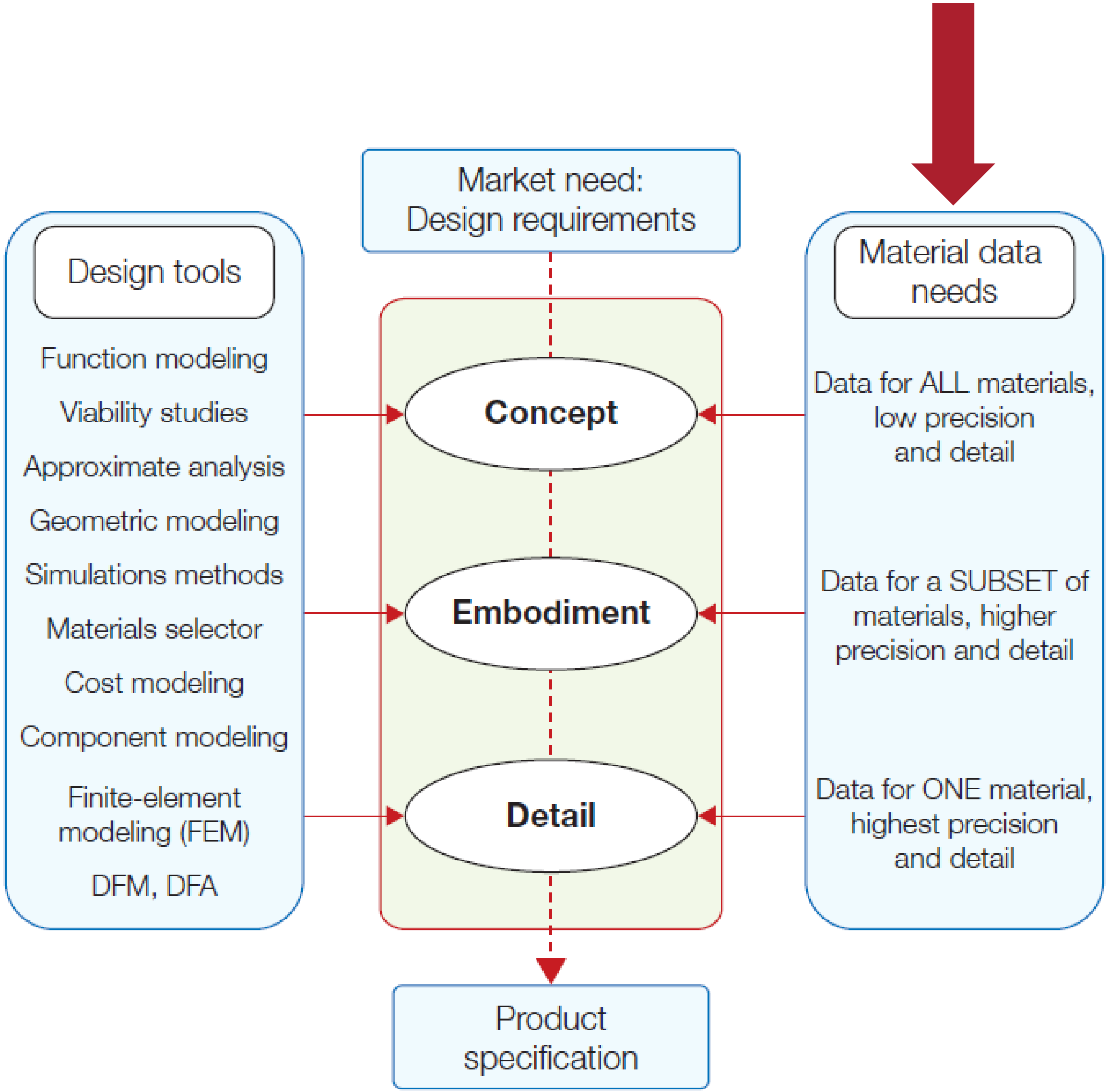
Strategic (critical) materials

- Global distribution
- Security of supply
- Niche uses



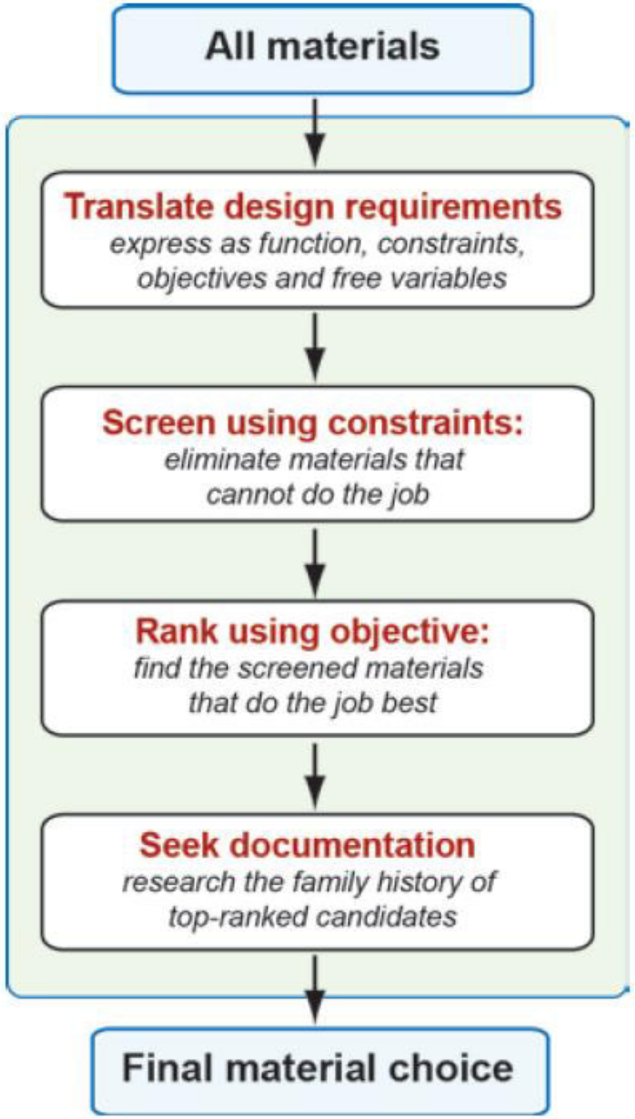
The design process





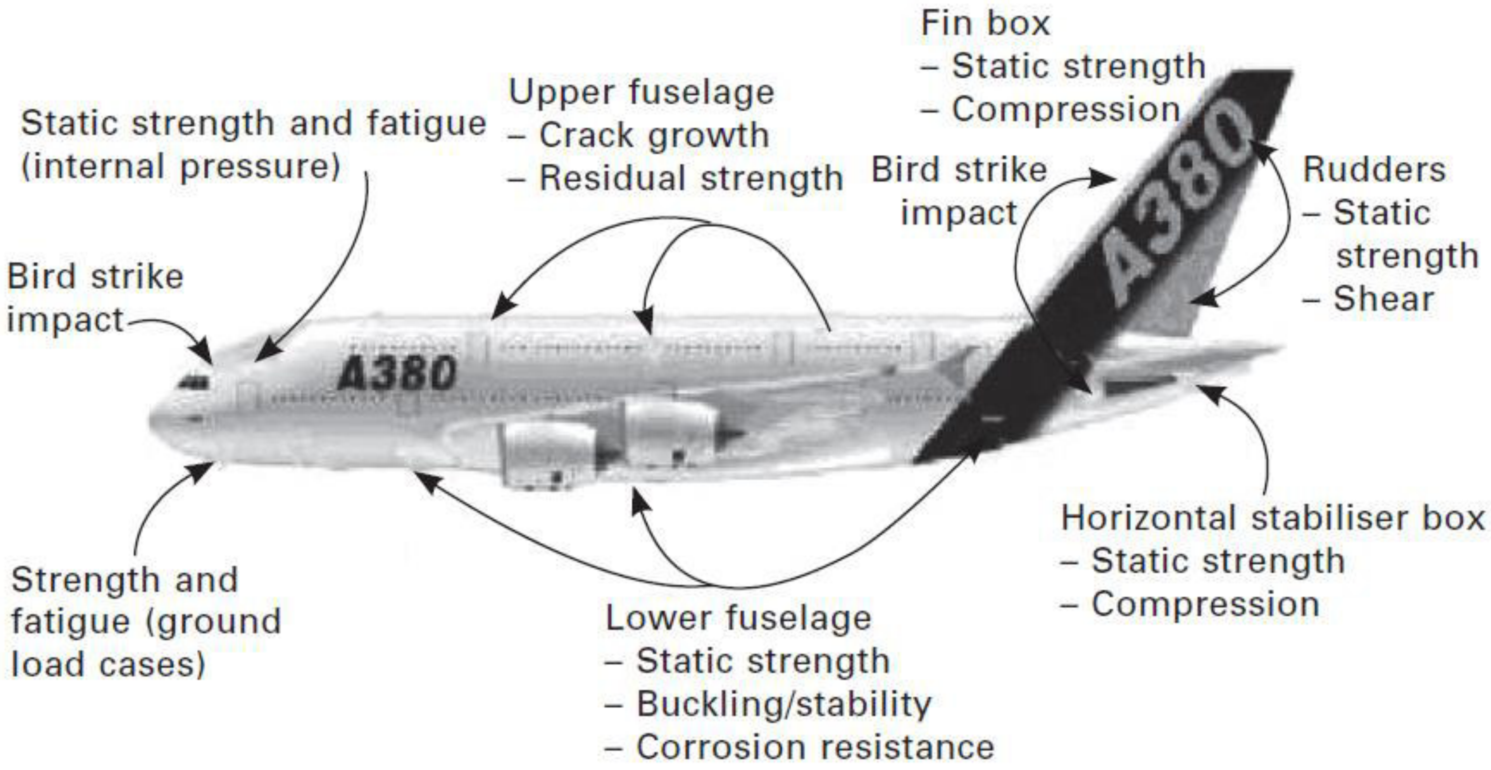
University of Bristol students improve manual washing machine design
https://www.bbc.co.uk/news/uk-england-bristol-61641123

Material selection process

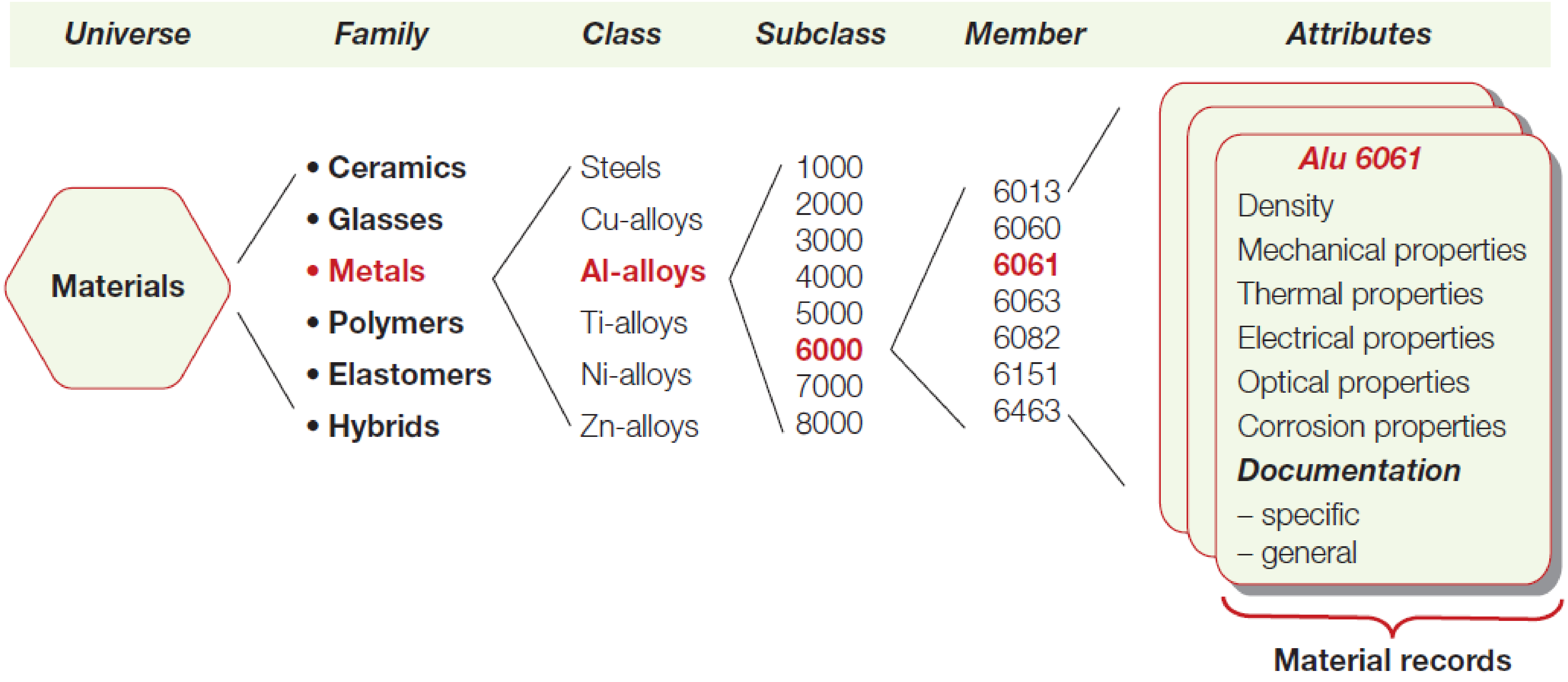


- **Translation:** Design requirements are reformulated as constraints on material properties and process attributes and as one or more objectives
  - minimization of cost, or of weight, or of environmental impact
- **Screening:** constraints are used to eliminate materials that cannot meet the requirements
- **Ranking:** achieved by the use of material indices
- **Supporting information:** seeking documentation for the top-ranked candidates

Material selection for aircraft construction

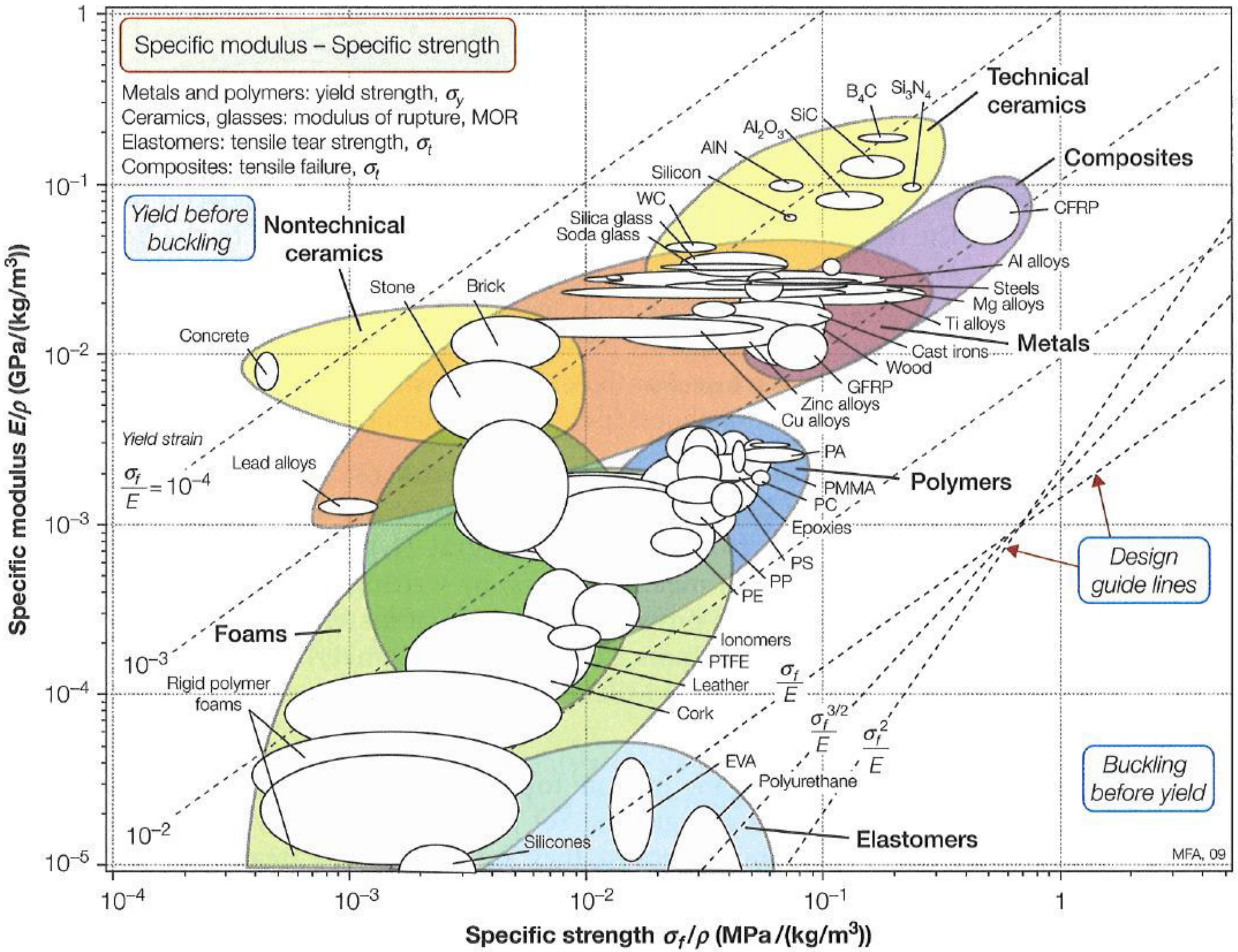


Material selection

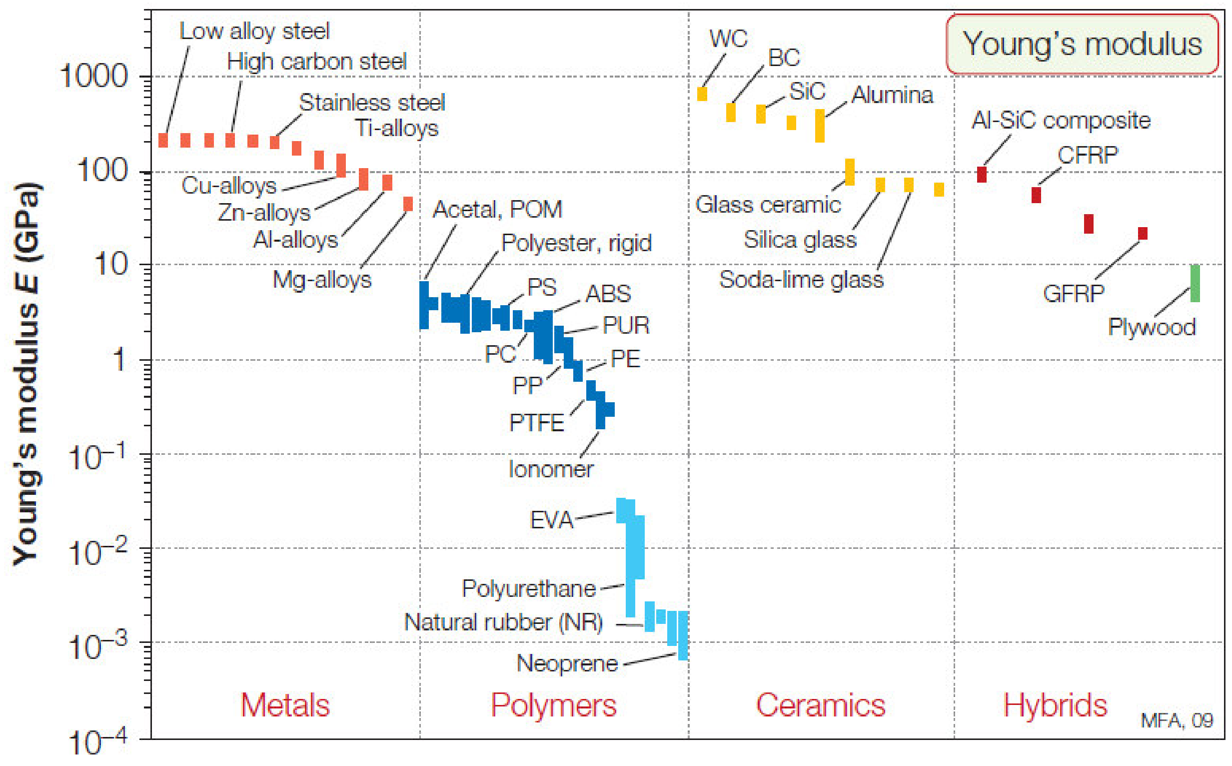


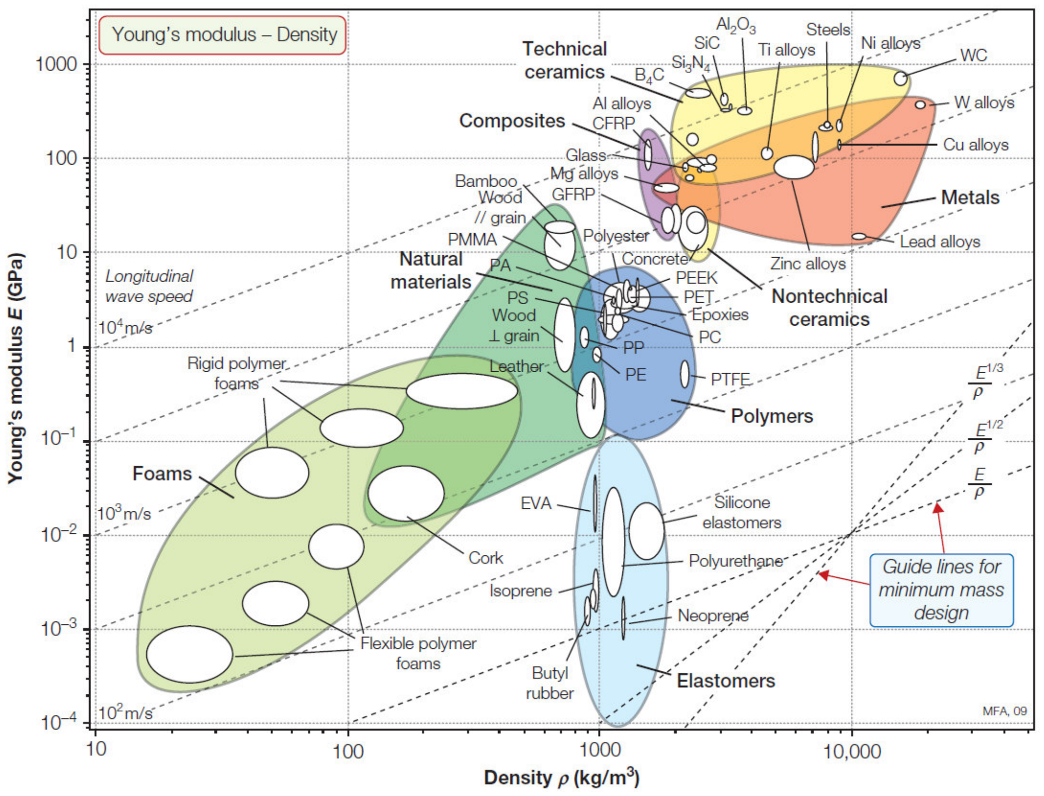
Time machine to last year

Specific Modulus – Specific Strength



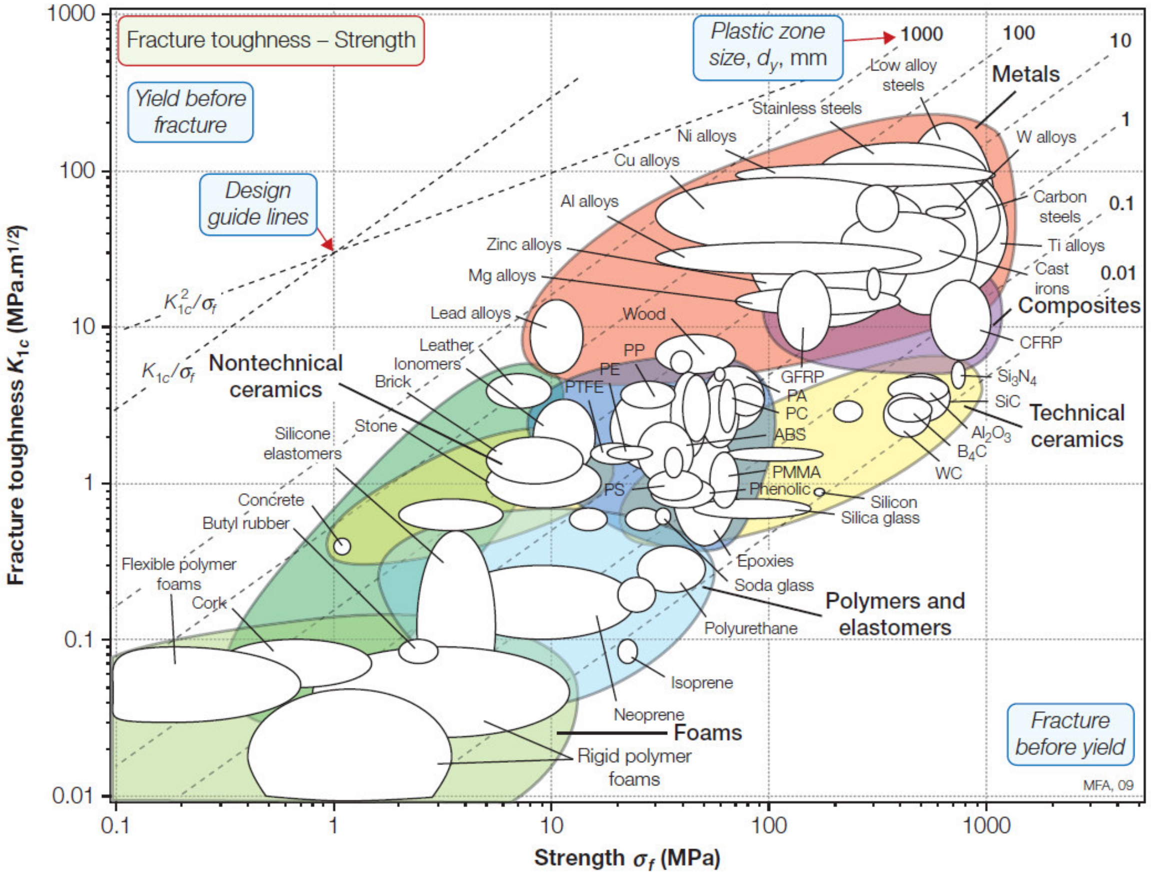
Mechanical property of materials

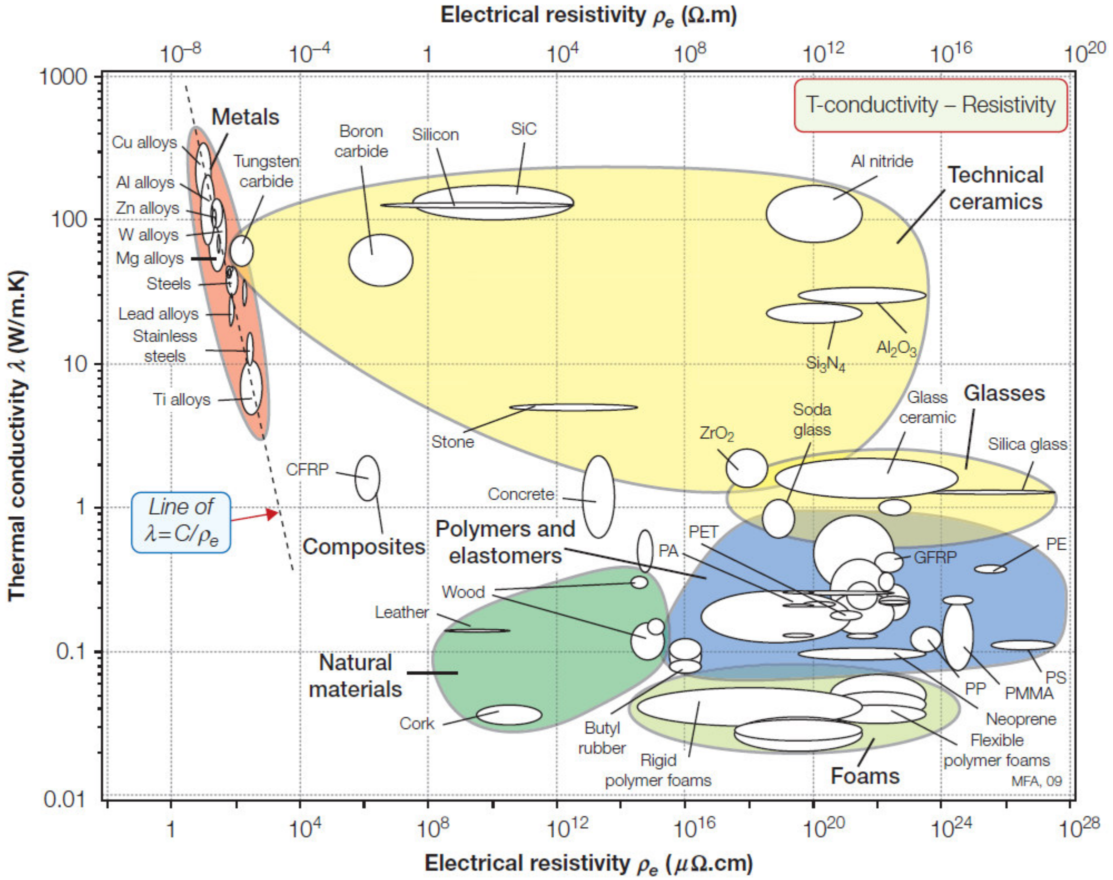




Selection depends on function of design
(*e.g.* support load while minimising mass)

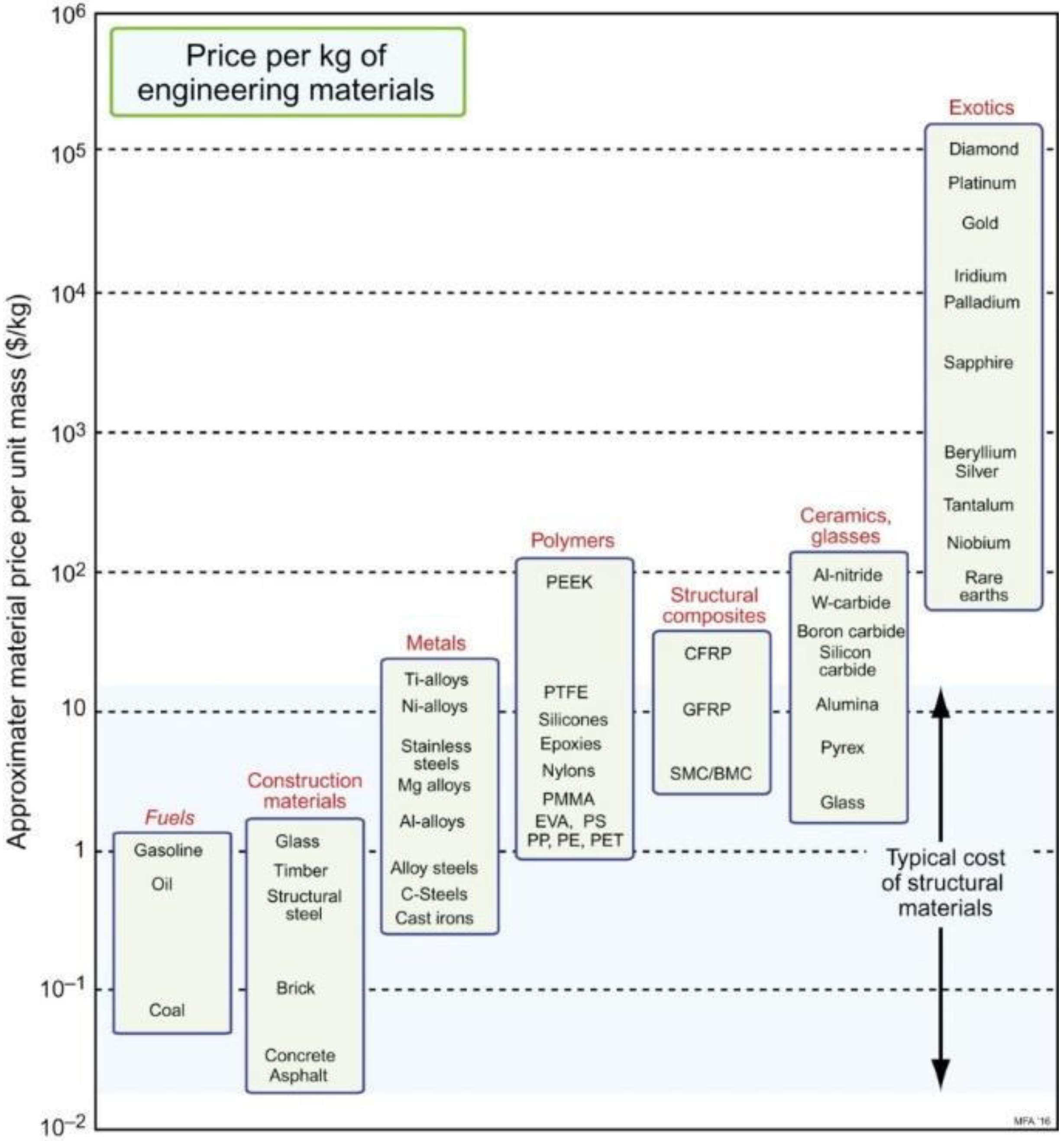
Other properties





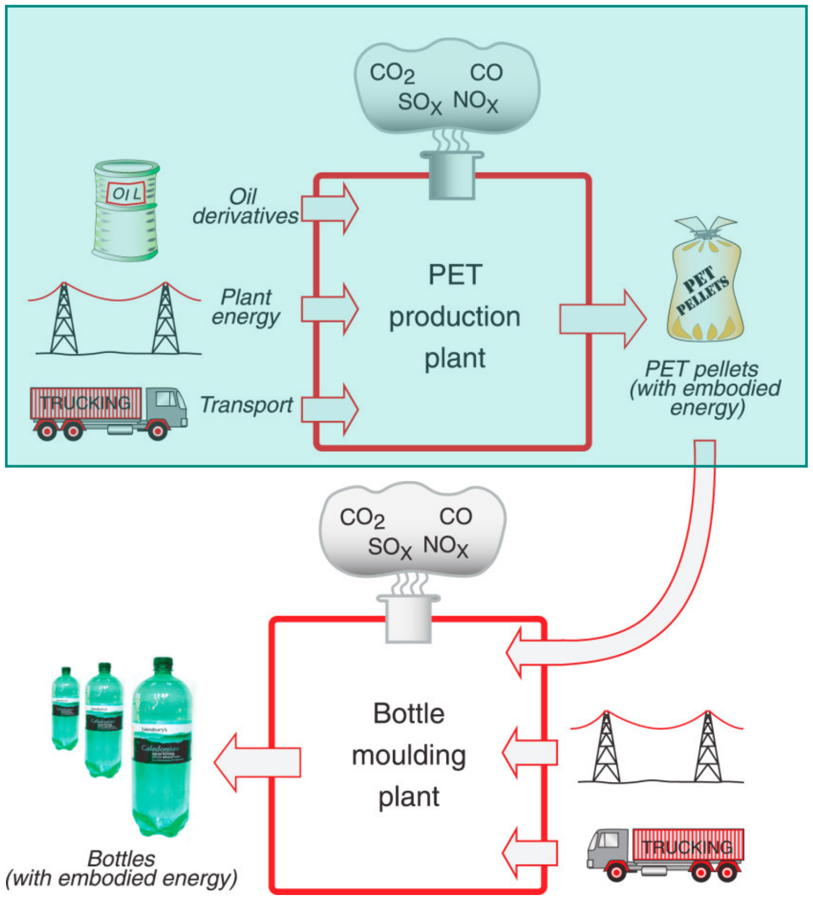
Material usage

- Market price is common measure for comparison.
- Shaded areas – includes most widely used materials for structural products.
- End users of materials are manufacturing industries.
- They decide which material they will purchase and adapt for their products.



Embodied Energy

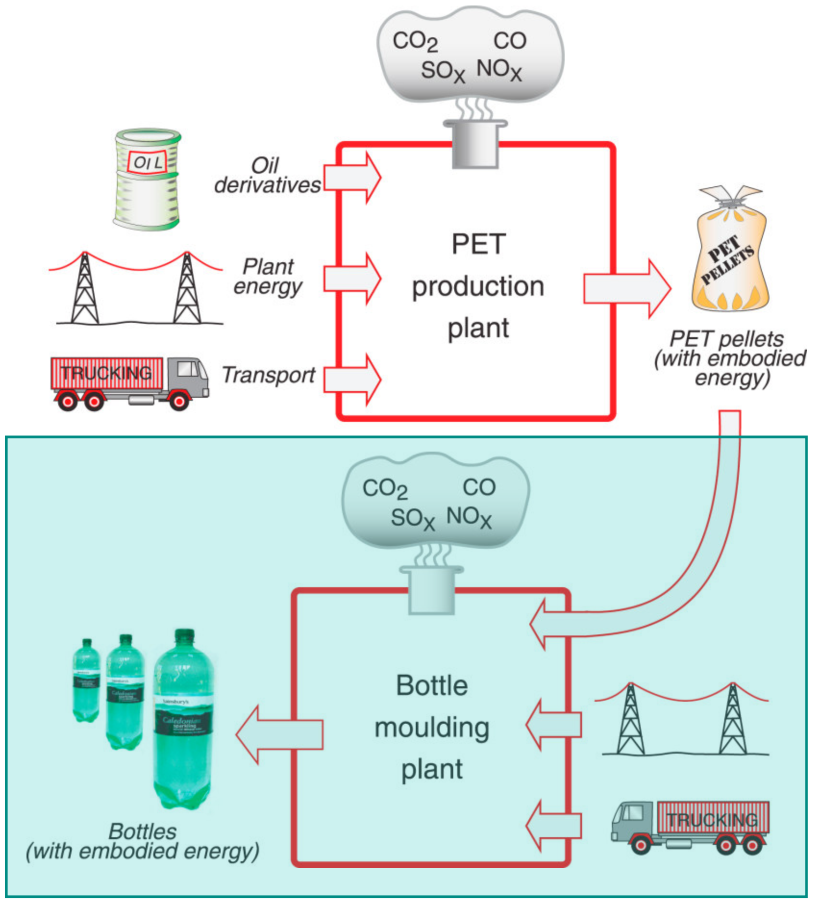
- Energy committed to creating 1kg of usable material
  - Steel stock, PET pellets, cement powder, *etc.* measured in MJ/kg
  - CO_2 footprint = associated release of CO_2 measured in kg/kg
- Embodied energies assessed by input-output analysis.
  - Found by monitoring over fixed period total energy input to production plant (including embodied energy of feedstock)
- Inputs:
  - oil derivatives (naphtha) other feedstocks, direct power
    (electricity is 34% efficient), energy of transporting feedstock.
- Output:
  - Hourly output of usable PET granules
- Embodied energy (Hm) of PET (MJ/kg)
  - $(H_m)_{PET} = \frac{\sum energies\ entering\ plant\ per\ hour}{Mass\ of\ PET\ granules\ produced\ per\ hour}$



An input-output diagram for PET Production and recycling (see Fig. 20.4)

Processing Energy

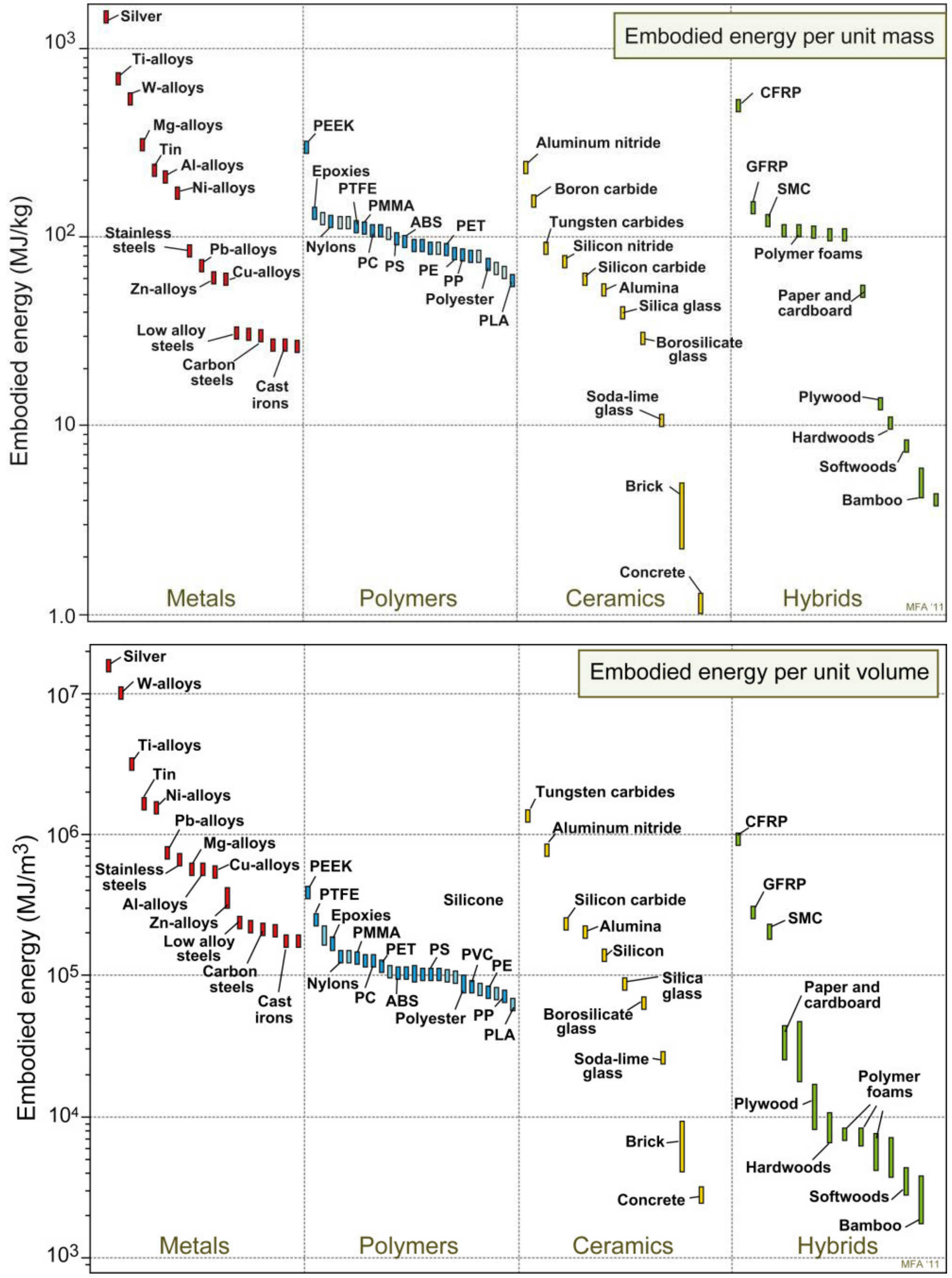
- Energy (MJ) used to shape, join, finish 1kg of usable material to create component or product.
  - Polymers (moulded or extruded), metals (cast, forged), ceramics (powder method)
  - Energy associated with process measured in MJ/kg
- Processing energy (H_p) of PET (bottles)
- Inputs:
  - PET granules (after transportation to blow moulding facility) (H_m)
  - oil derivatives (fuel) other feedstocks, direct power
- Output
  - Energy committed per bottle produced
- Many steps before bottle reaches consumer (and used)
  - Collection, filtration, water/ingredients monitoring, transportation of drink and bottles to bottling plant, labelling, delivery to central warehouse, distribution to retailers, possible refrigeration.



An input-output diagram for PET Production and bottle manufacture (see Fig. 20.4)

Charts for Embodied Energy

- Compared per unit mass, metals (especially steels) appear attractive (lower energy)
- Compared on a volume basis, ranking changes (polymers lower than metals)
- Light alloys (aluminium, magnesium, titanium) have high energies by either measure
- How to make meaningful comparisons and minimise embodied energy?

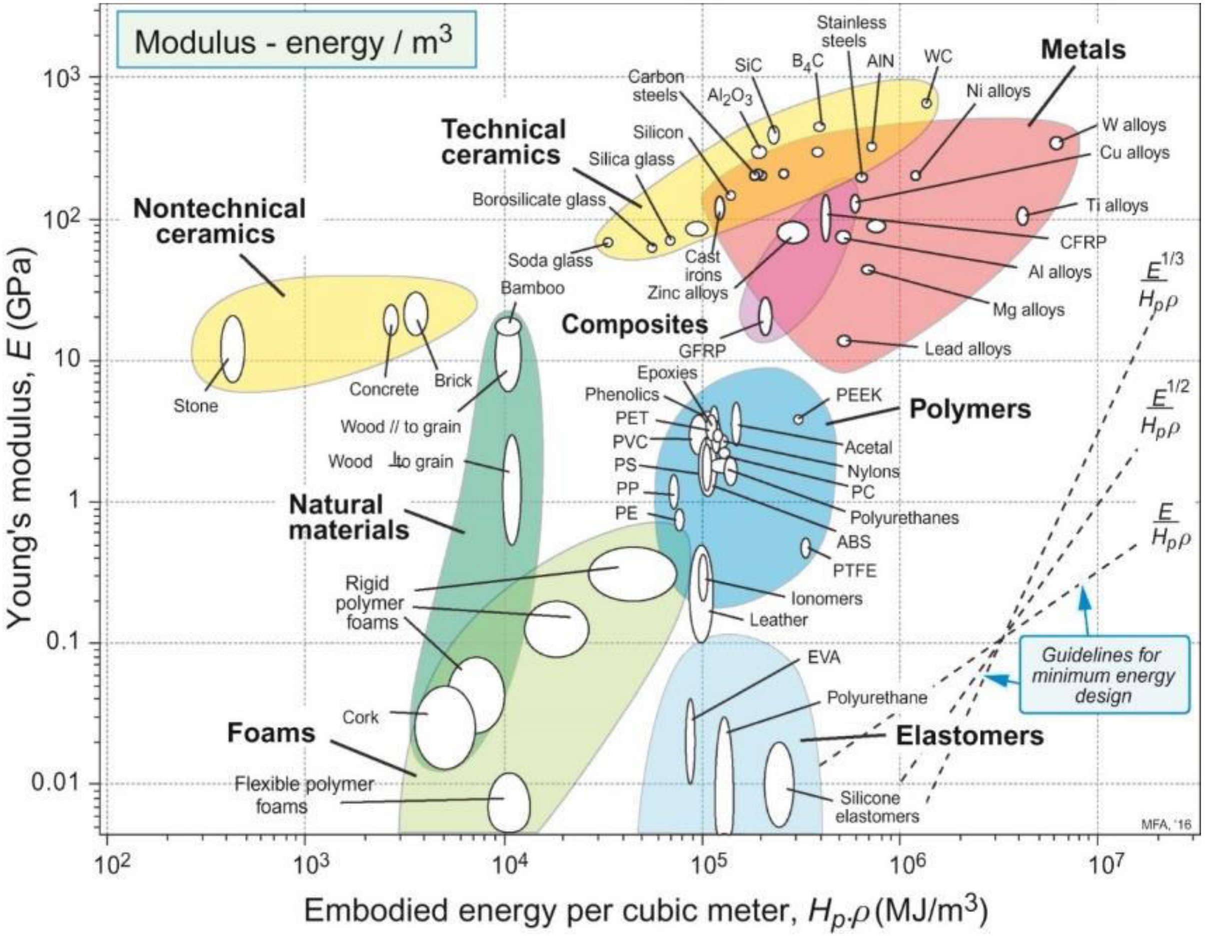


Bar charts of embodied energy of basic materials (see Fig. 20.8, 20.9)

Embodied Energy in Structural Design

- If objective to minimise energy embodied in product and provide structural functionality then need equivalent charts
- Plots of modulus and strength *versus* $H_m.\rho$ (slopes are common performance indices)

$$(H_m.\rho)/E,\ (H_m.\rho)/E^{1/2},\ (H_m.\rho)/E^{1/3}.$$

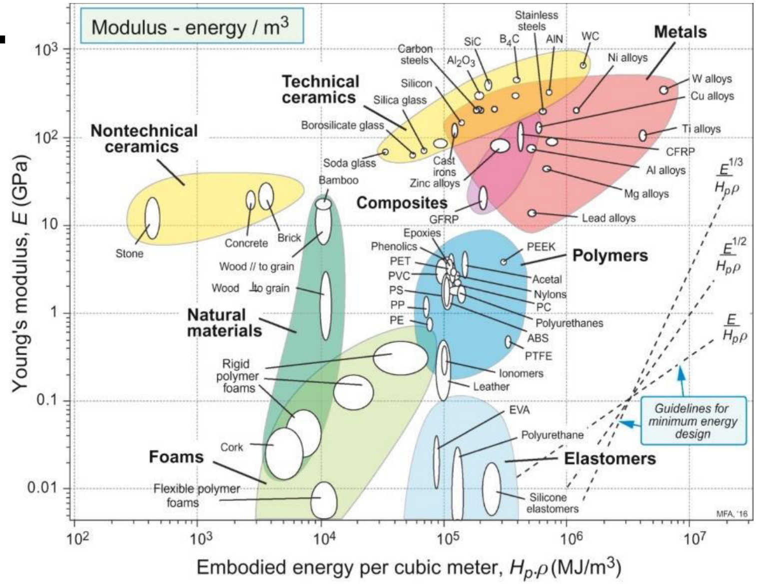


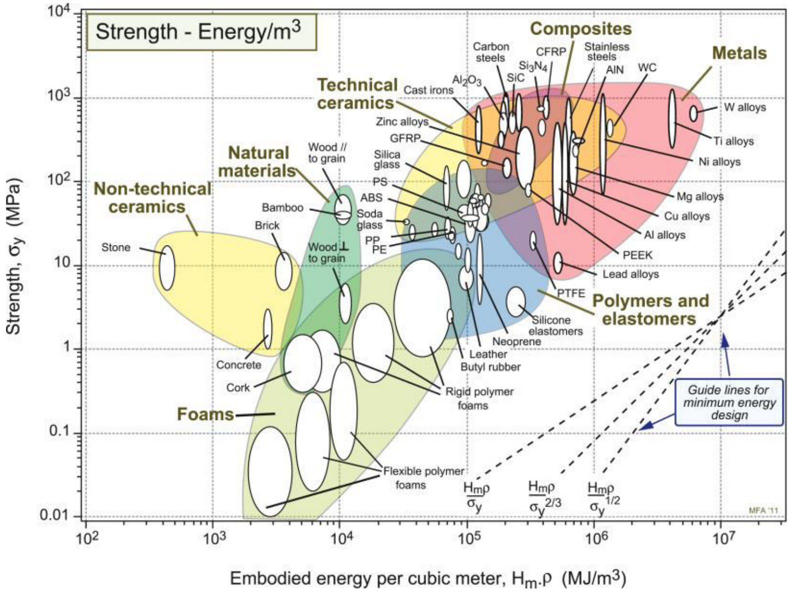
Plots of modulus-embodied energy and strength-embodied energy (see Fig. 20.10, 20.11)

Embodied Energy in Structural Design

- Selection depends on function of design (*e.g.* support load while minimising mass)
- If objective to minimise energy embodied in product and provide structural functionality then need equivalent charts
- Plots of modulus and strength *versus* $H_m.\rho$ (slopes are common performance indices)

$$(H_m.\rho)/E,\ (H_m.\rho)/E^{1/2},\ (H_m.\rho)/E^{1/3}.$$



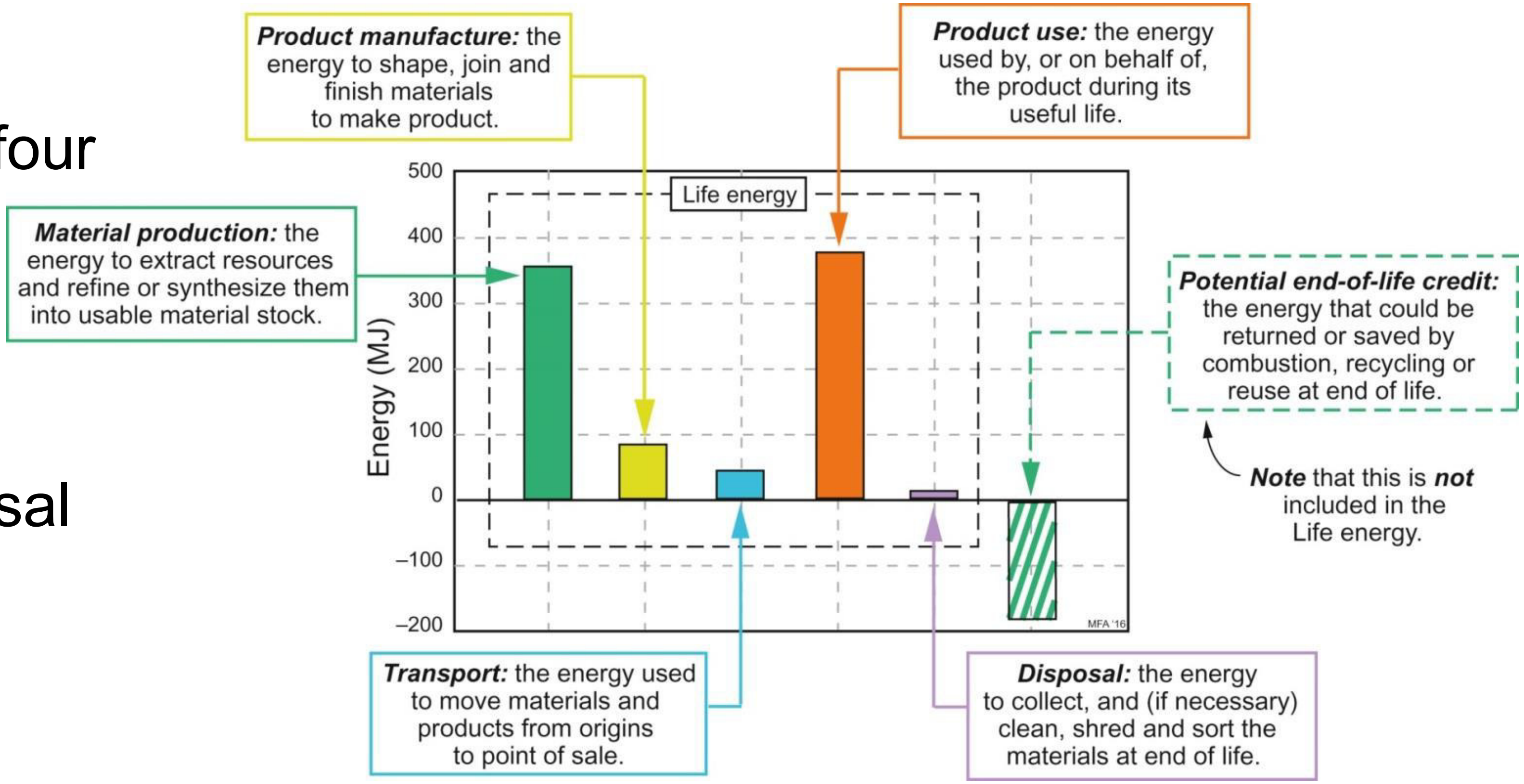


Plots of modulus-embodied energy and strength-embodied energy (see Fig. 20.10, 20.11)

Energy fingerprint

- Consider how products consume energy in each of four phases of life cycle

- Some phases are harder to estimate (*e.g.* product disposal phase)



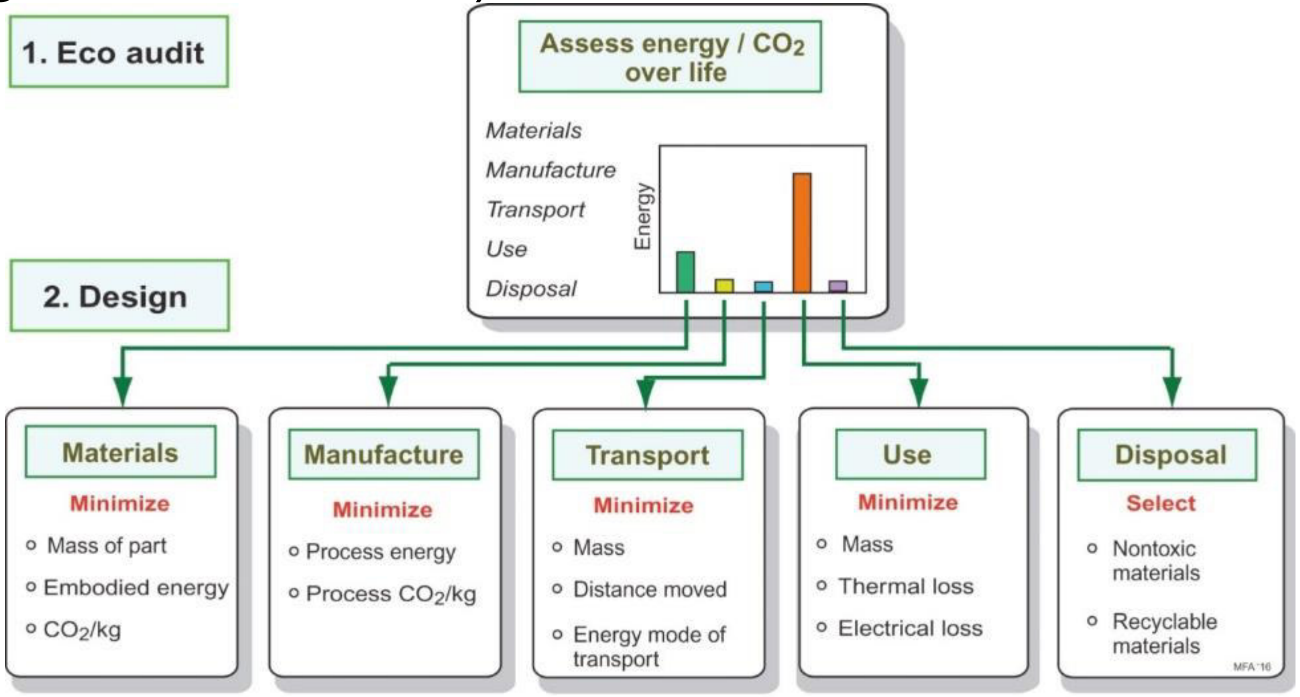
Output of an eco-audit: energy fingerprint of product (Ashby: Materials Section in Mechanical Design, Fig. 14.4)

Eco-audit

- If material production consumes more energy than other phases then it becomes first target (e.g. drinks containers – see later).
- Large civil structures (buildings, bridges, roads) are material intensive (embodied energy of materials is largest commitment).
- Architects and civil engineers focus

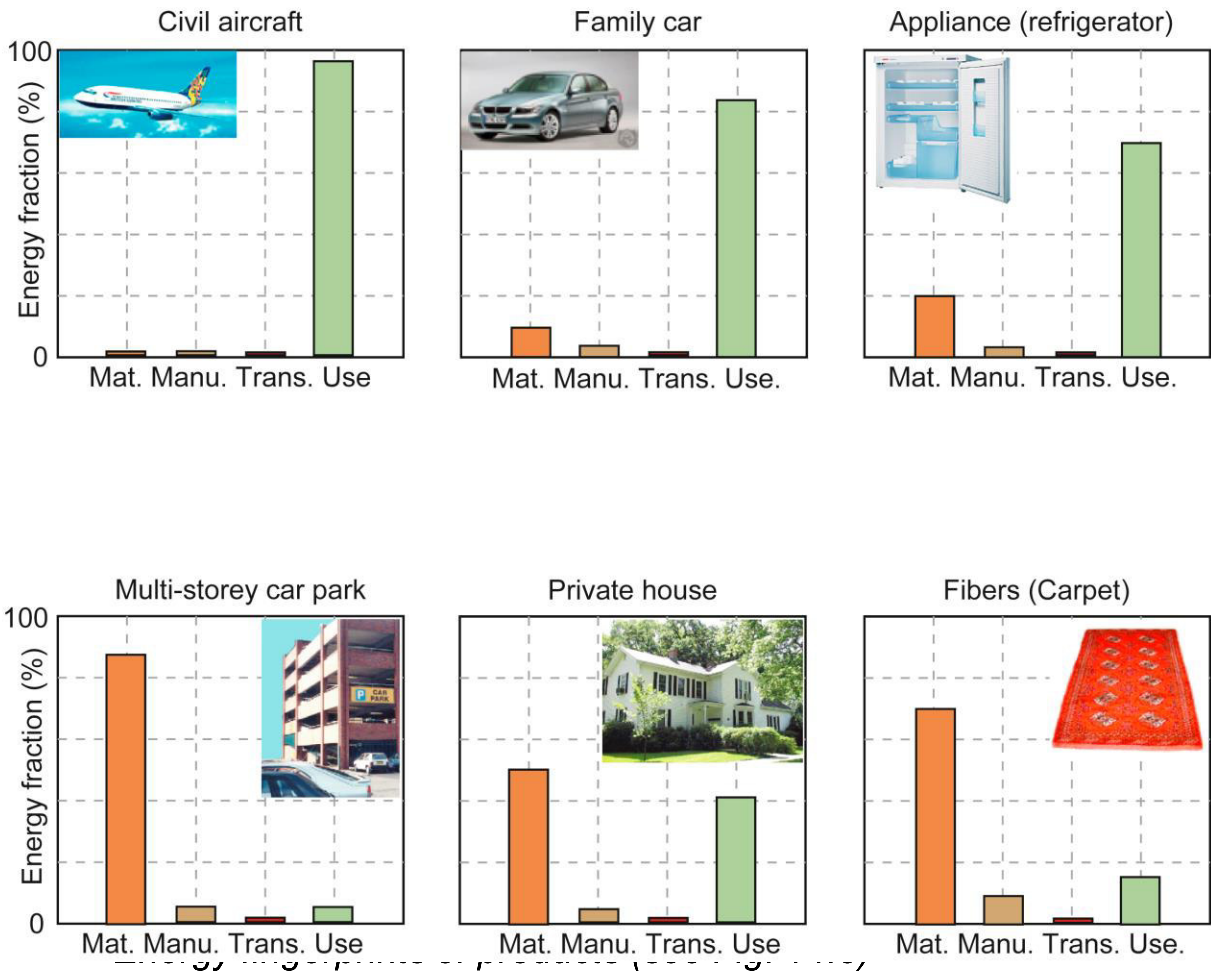
  on embodied energy as well as

  thermal efficiency of structures.



Design for environment (see Fig. 20.12)

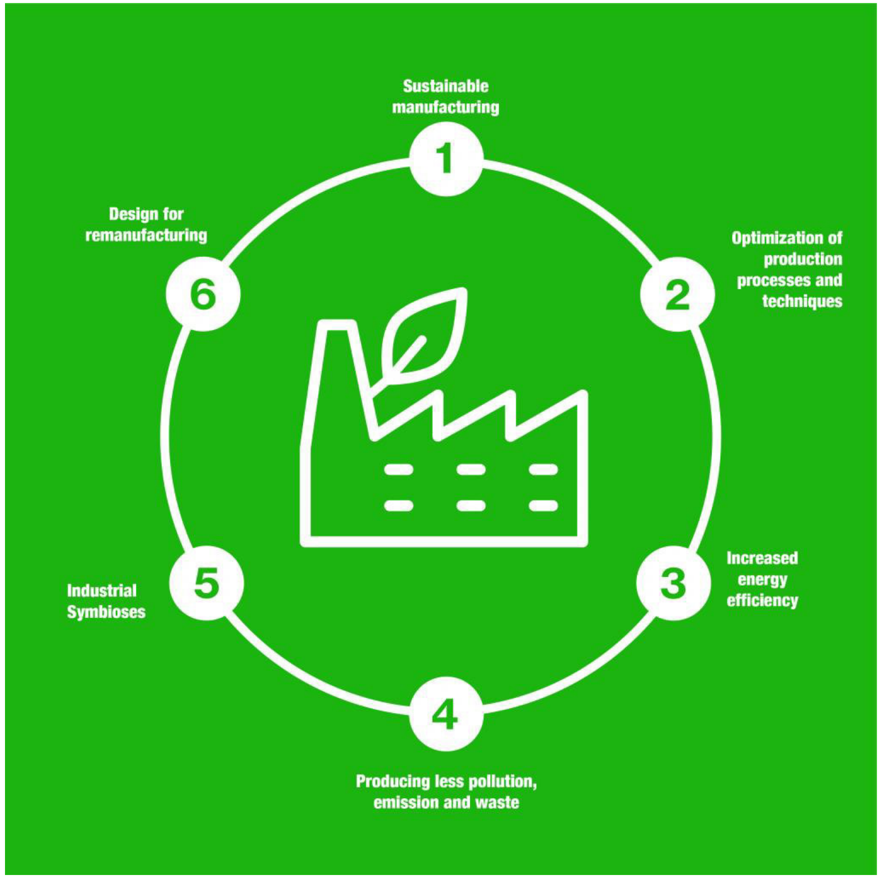
Energy Demands of Products



- To achieve large changes **dominant phase** must be first target
- Some products consume energy during use (dominates life energy)
- Others depend less heavily on energy, but **material intensive** (embodied energy of material dominates)
- Eco-impact of use phase unrelated to embodied energy of materials.
- Minimising one may have opposite effect on another energy (depends on mechanical, thermal, electrical efficiencies).

Product Manufacture Phase

- Energy required to shape a material usually much less than that to create it originally.
- Important to save energy in production.
- Higher priority often to minimise local impact of emissions or toxic waste.
- **Sustainable manufacturing** is the creation of manufactured products that use a process to minimise negative environmental impacts, conserve energy and natural resources, are safe for employees, communities and consumers.



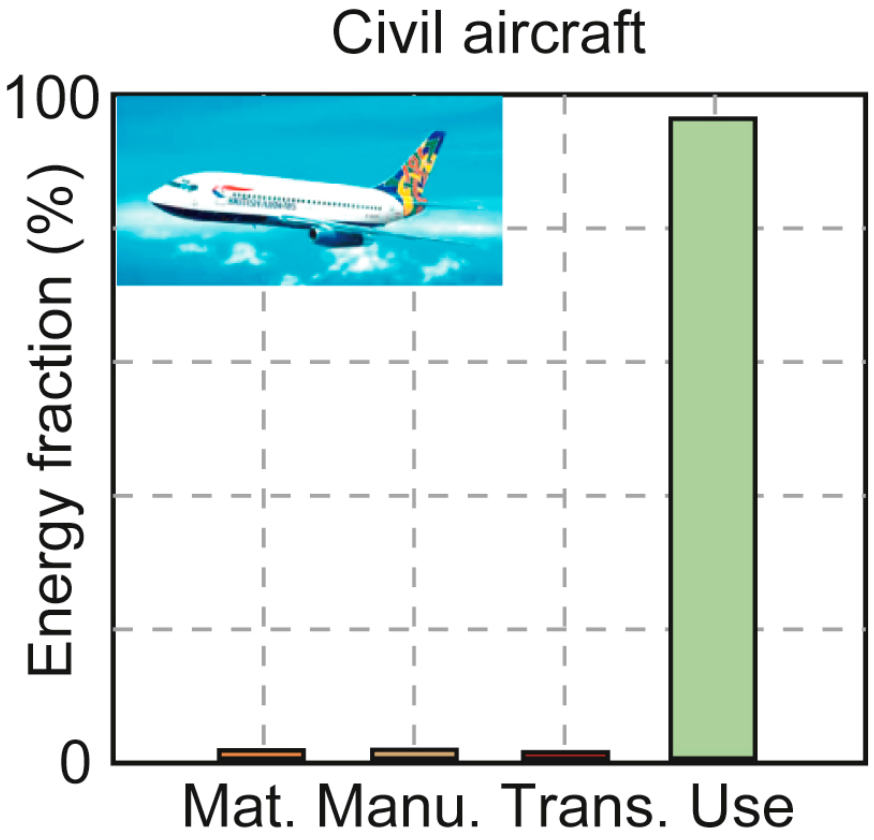
Transport

- Energy involved with transportation occurs throughout a manufacturing process.
- Raw materials are transported to factory from source.
- Haulage of additives, chemical feedstocks, packaging.
- Movement of product for assembly, finishing.
- Transportation to distribution centre or retailer.
- Collection for disposal.

Transport	Energy requirement MJ/tonne-km
Sea freight	0.16
Barge	0.36
Rail freight	0.25
2-axle truck (14t)	1.5
3-axle truck (24t)	1.1
4-axle truck (32t)	0.94
Air freight	6.9-15 (size/type aircraft)

Product use phase

- Tabulate main components of product (with material and weight)
  - Estimate embodied energy (multiply masses by H_m and H_p and sum them)
  - Transport costs (distance and energy used)
  - Use energy estimated from power, duty cycle, power source



Energy fingerprints of products (see Fig. 14.5)

https://www.bbc.co.uk/news/uk-england-derbyshire-60068786

Eco-data

Geo-economic data for principal component
- Principal component (material name)
- Annual world production (tonnes/yr)
- Reserves (tonnes)
- Typical exploited ore grade (%)
- Minimum economic ore grade (%)
- Abundance in earth's crust (ppm)
- Abundance in sea water (ppm)

Material production: energy and emissions
- Production energy (MJ/kg)
- CO_2 creation (kg/kg)
- NO_x creation (kg/kg)
- SO_x creation (kg/kg)

Indicators for principal component
- Eco-indicator 95
- Eco-indicator 99
- EPS value

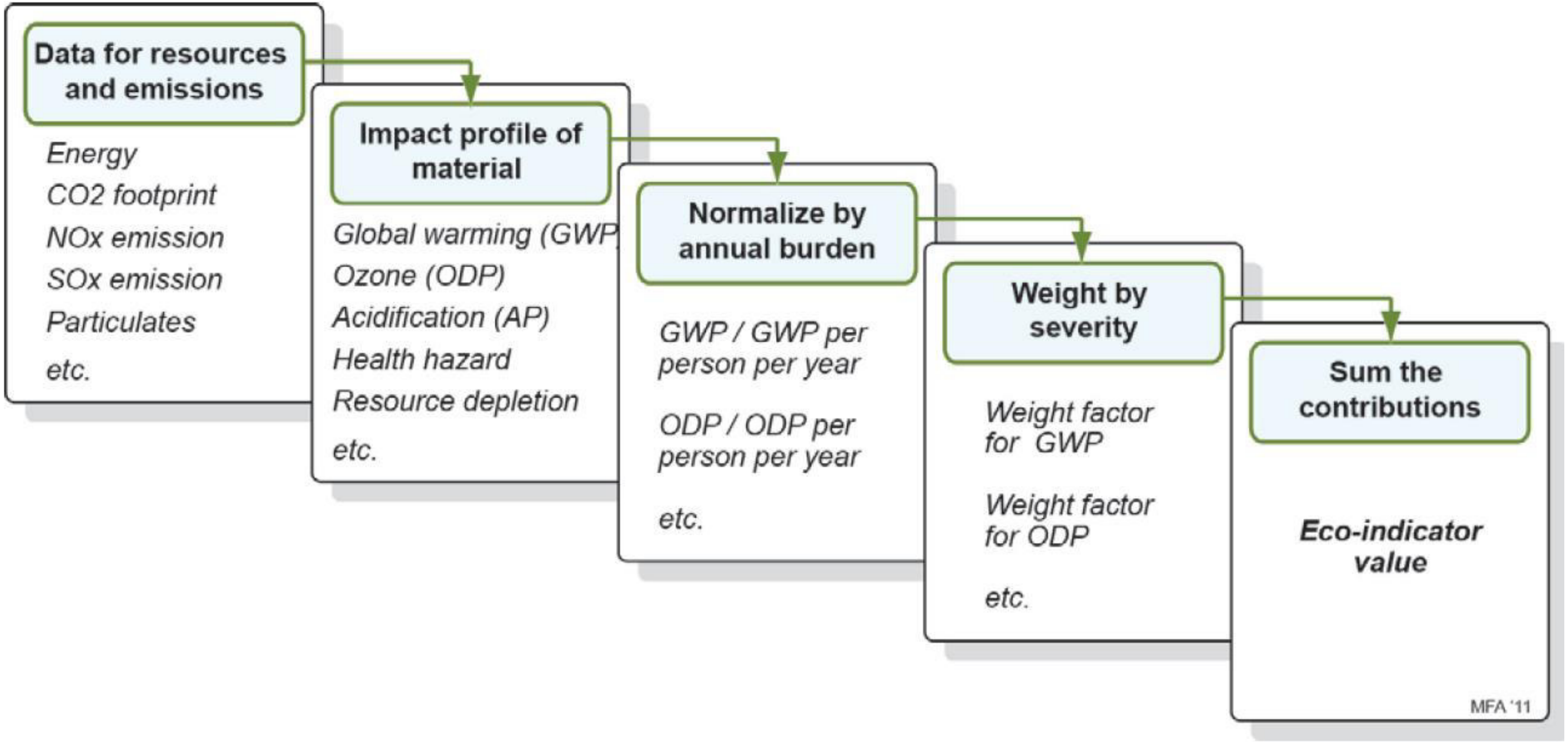
End of life
- Recycle (yes/no)
- Down-cycle (yes/no)
- Biodegrade (yes/no)
- Incinerate (yes/no)
- Landfill (yes/no)
- Recycling energy (MJ/kg)
- Recycle as fraction of current supply (%)

Bio-data
- Toxicity rating (non-toxic, slightly toxic, toxic, very toxic)
- Approved for skin and food contact (yes/no)

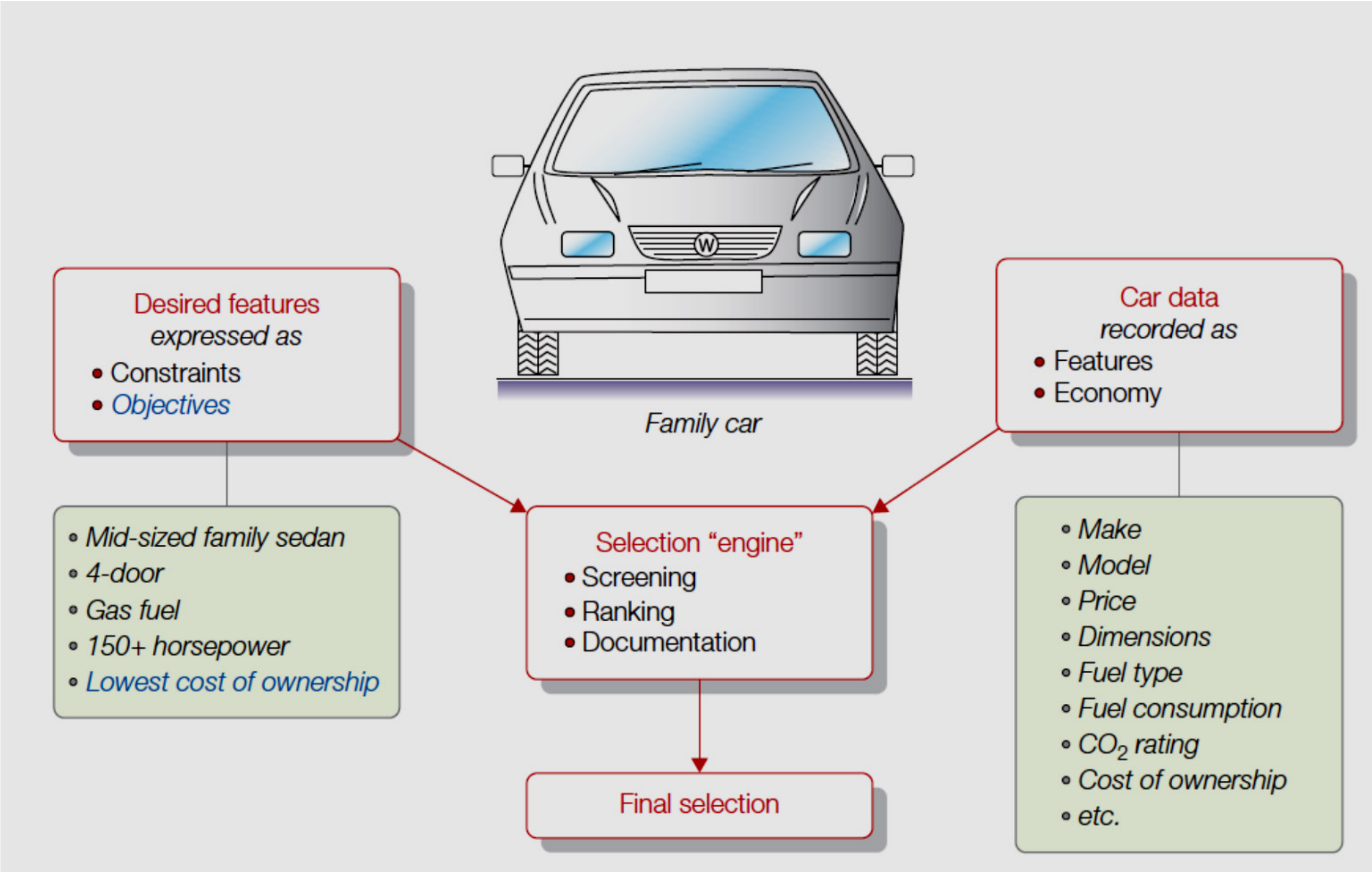
Sustainability
- A renewable resource (yes/no)

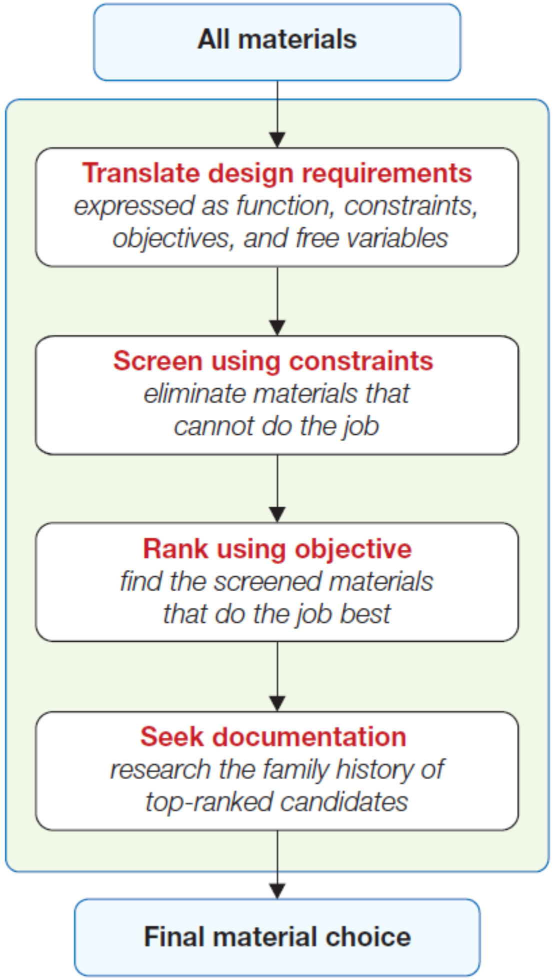
Possible substitutes for principal component
- Text

Eco-indicator



Choosing a Car - Material selection process





Case Study – Drinks Containers

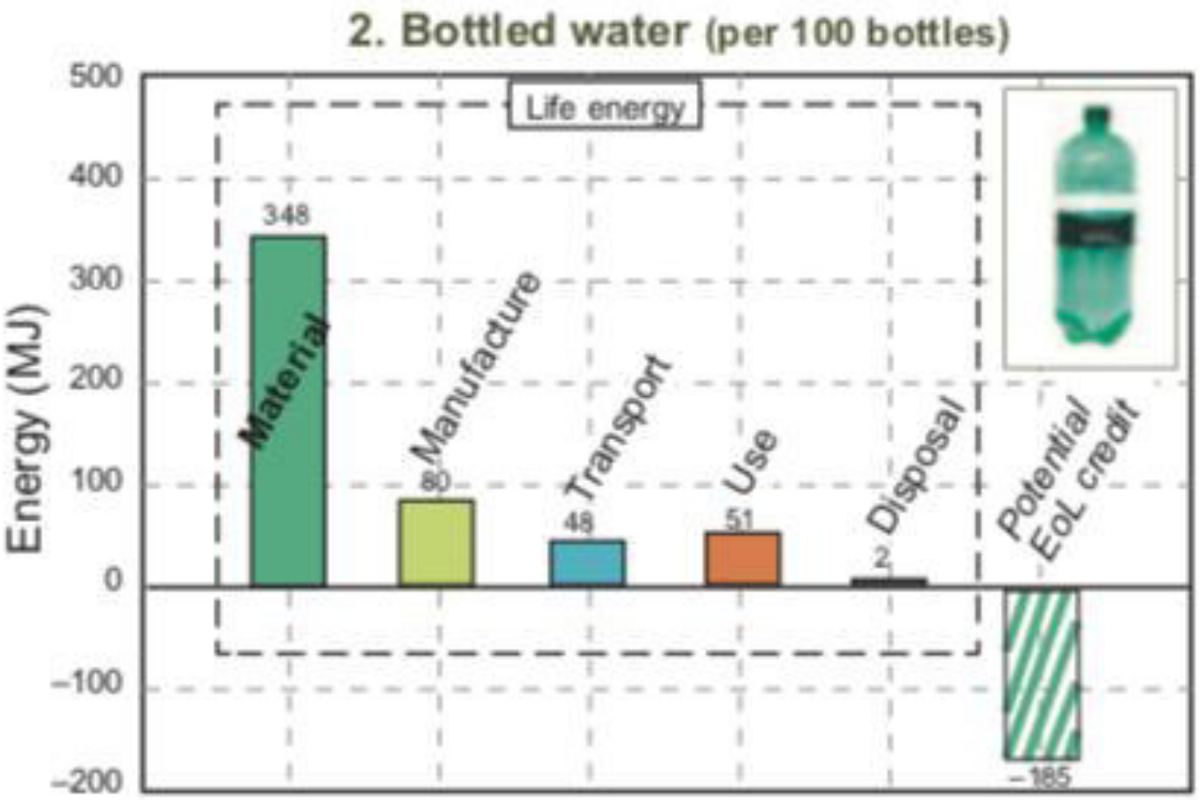
- Compare glass, PE, PET, aluminium, steel.
- Which has the lowest energy penalty and carbon footprint?

Case studies: liquid containers
Materials selection in Mechanical Design (Fig. 14.9)

Table 15.3 Design Requirements for the Containers

Function	Container for cold drink
Constraint	Must be recyclable
Objective	Minimize embodied energy per unit capacity
Free variable	Choice of material

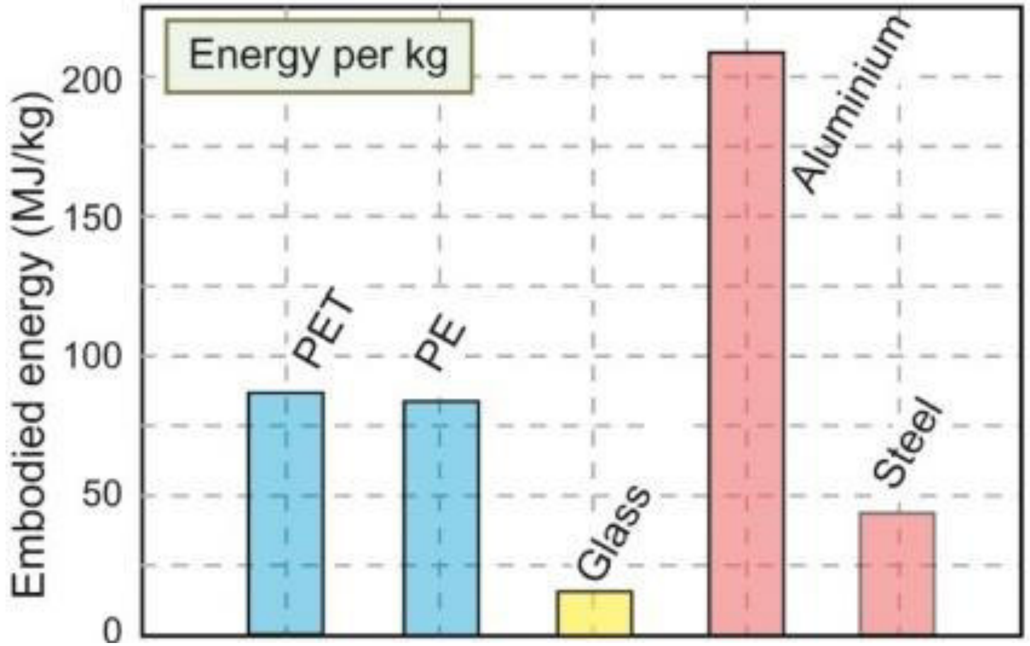
Case Study – Drinks Containers



- Drinks containers consume materials and energy during material extraction, container production (little afterwards).
- Selecting materials with low embodied energy and using less of them would be best way forward.

Case Study – Drinks Containers

Container type	Material	Mass (g)	Embodied energy (MJ/kg)
PET 400 ml bottle	PET	25	84
PET 1 litre milk bottle	HDPE	38	81
Glass 750 ml bottle	Soda glass	325	15.5
Al 440 ml can	5000 series Al alloy	20	210
Steel 440 ml can	Plain carbon steel	45	32



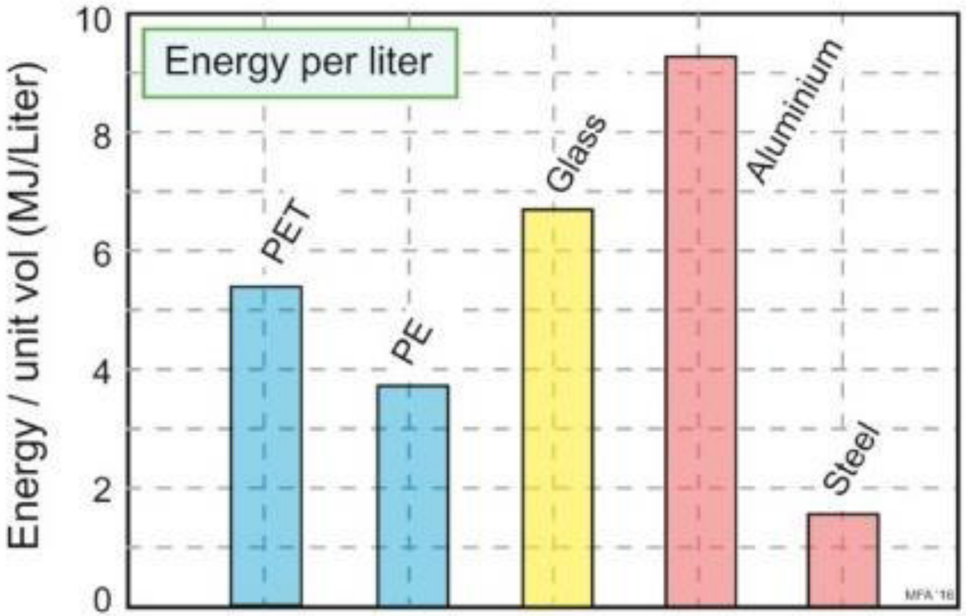
Normalising for volume

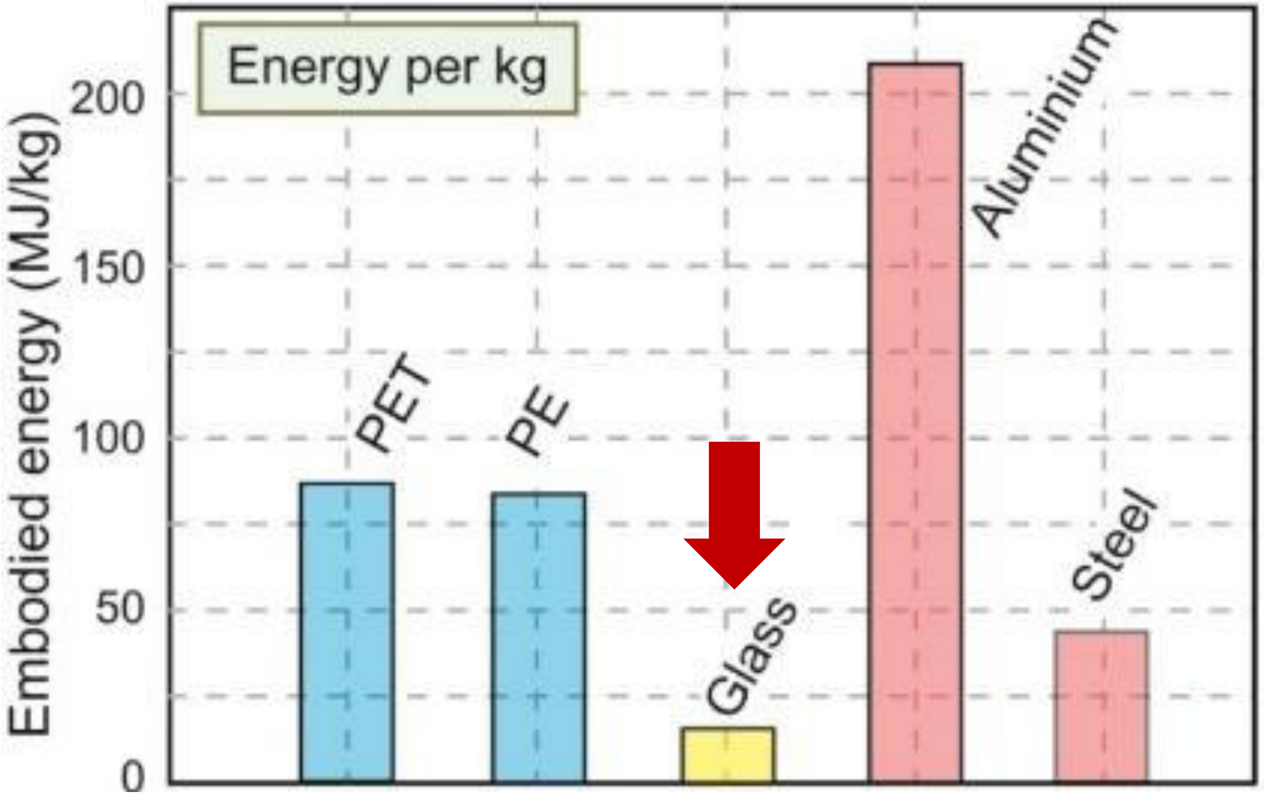
Container type	Material	Mass (g)	Mass/litre (g/L)
PET 400 ml bottle	PET	25	62
PET 1 litre milk bottle	HDPE	38	38
Glass 750 ml bottle	Soda glass	325	433
Al 440 ml can	5000 series Al alloy	20	45
Steel 440 ml can	Plain carbon steel	45	102

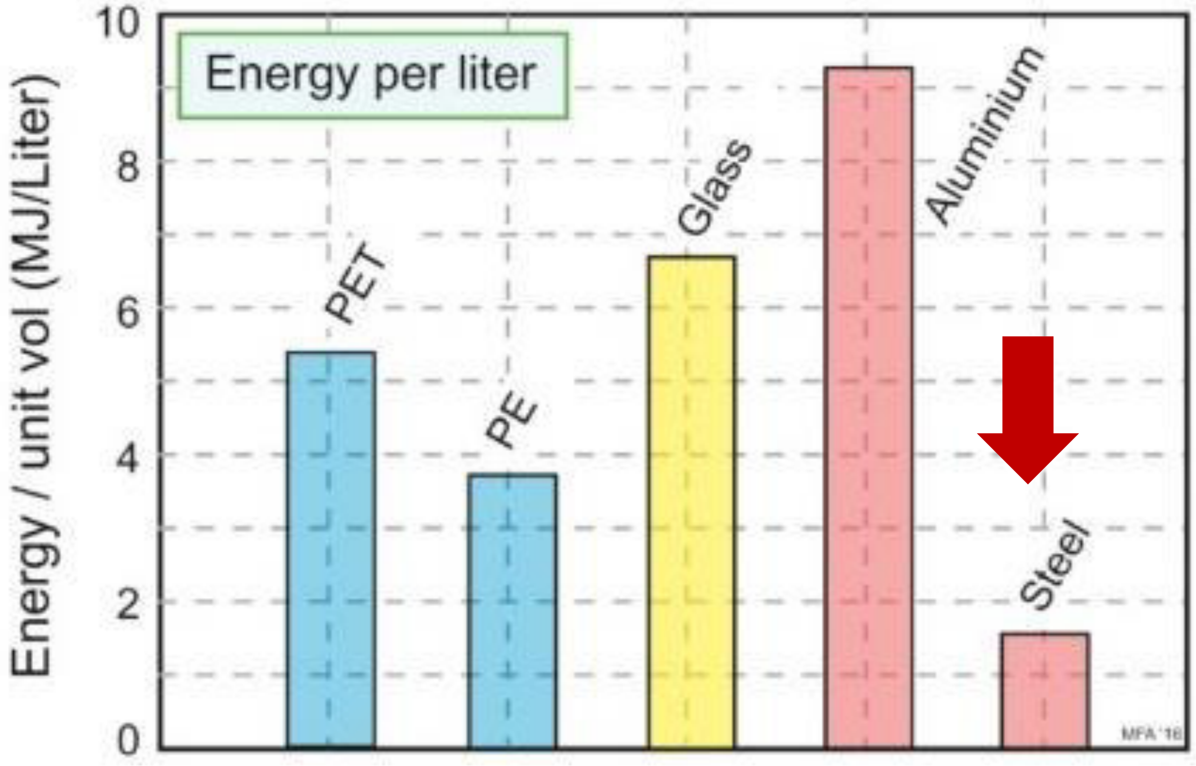
Energy per litre

Material	Mass/litre (g/L)	Embodied energy (MJ/kg)	Energy/Litre (MJ/L)
PET	62	84	5.3
HDPE	38	81	3.1
Soda glass	433	15.5	8.2
5000 series Al alloy	45	210	9.0
Plain carbon steel	102	32	**2.4**

- Must take density into account to enable comparisons to be made.
- Steel container has lowest energy penalty per unit volume.
- Aluminium container has highest energy penalty per unit volume.




Energy per kg
Embodied energy (MJ/kg)
0
50
100
150
200
PET
PE
Glass
Aluminium
Steel


Energy per liter
Energy / unit vol (MJ/Liter)
0
2
4
6
8
10
PET
PE
Glass
Aluminium
Steel

Guardian – Disposable cups

https://www.theguardian.com/environment/2024/jan/22/disposable-coffee-cups-environmental-impact

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Environment ▶ Climate crisis Wildlife Energy Pollution

Our unequal earth
Waste

The disposable cup crisis: what's the environmental impact of a to-go coffee?

Styrofoam cups

- Today, the US produces about 3m tons of polystyrene every year.
- 80% of it ends up in the trash (including about 25bn cups each year). That translates to the material taking up about a third of landfill space.
- As garbage, polystyrene takes about 500 years to break down.
- Manufacturing a single Styrofoam cup leads to about **33g of CO2** emissions. That’s the equivalent of driving about a 10th of a mile
- Equivalent to about **21m tons of CO2** – or about the same amount that 4.5m cars emit each year.

Reusable cups?

- That said, even reusable cups have climate impacts: they too have to be made, and additionally must be washed with hot water between uses.
- A reusable cup has to be used between 20 and 100 times to offset the emissions produced to make it
- Reusable is still the way to go, but there’s no need to overload on dozens of mugs and thermoses.

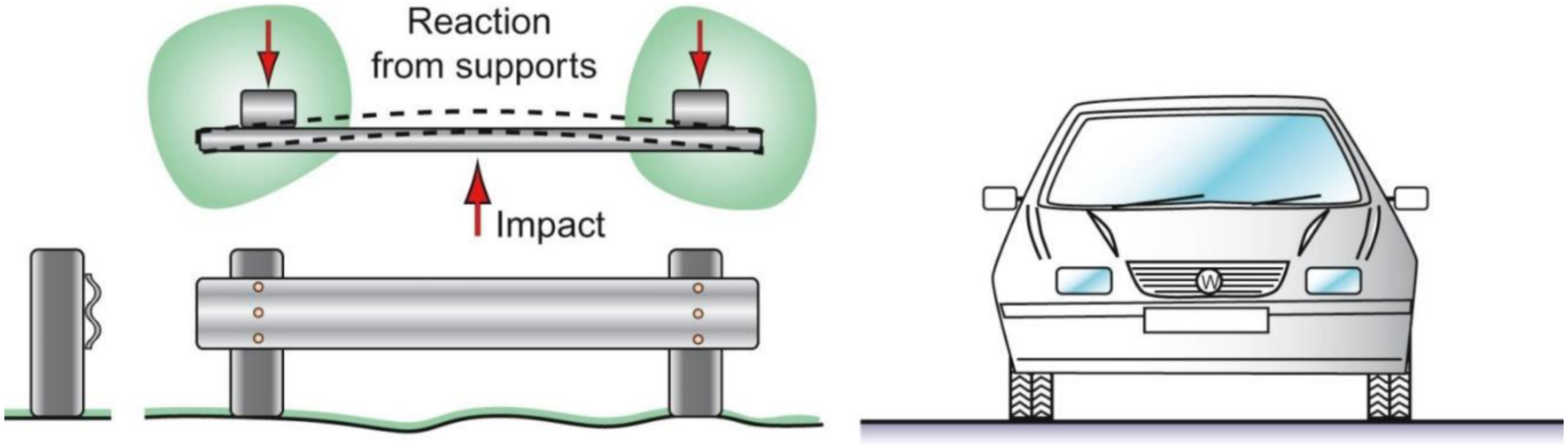
Dilbert on the environment

Single use Vapes

- https://www.theguardian.com/society/2023/sep/08/call-for-uk-ban-on-single-use-vapes-as-more-than-5m-discarded-each-week
- Five million single-use vapes are being thrown away in the UK every week
- This amounts to eight vapes a second being discarded, with the lithium in the products enough to create 5,000 electric car batteries a year.

Case Study 2 – Crash Protection

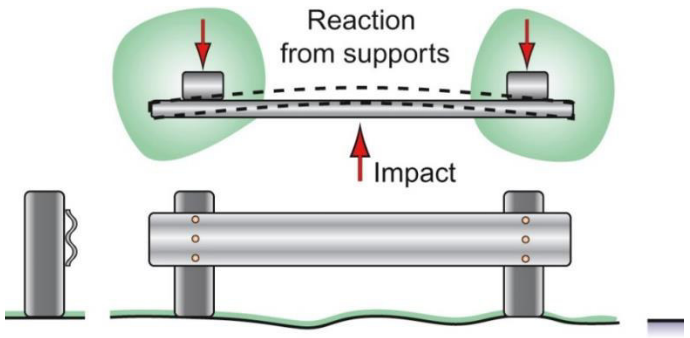
- Barriers protect driver and passengers of road vehicles.
- Two types: static (central barrier separating two lanes) and moveable (vehicle bumper).



Case studies: two crash barriers (see Fig. 14.10)

Static Crash Barrier

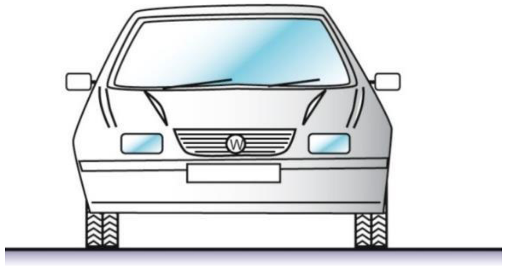
- Static type – lines tens of thousands of miles of road.
- Once in place, consume no energy, create no CO_2, long lasting.
- Dominant phases in life are material production and manufacture.



Case studies: two crash barriers (see Fig. 14.10)

Dynamic Crash Barrier

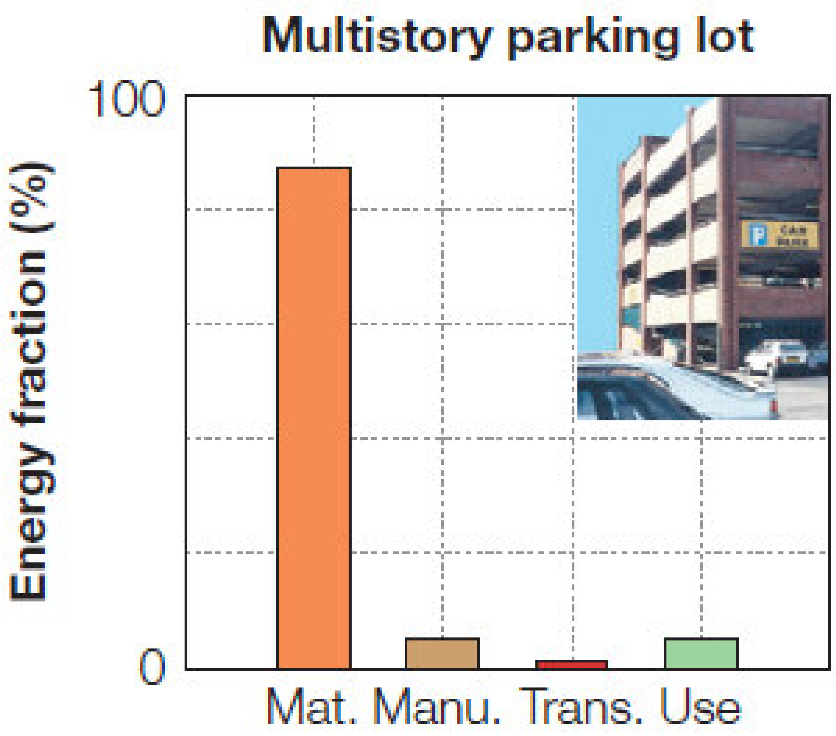
- Mobile barrier (bumper) – part of vehicle,
- Adds to weight, and fuel consumption
- Dominant phase in life is use phase.

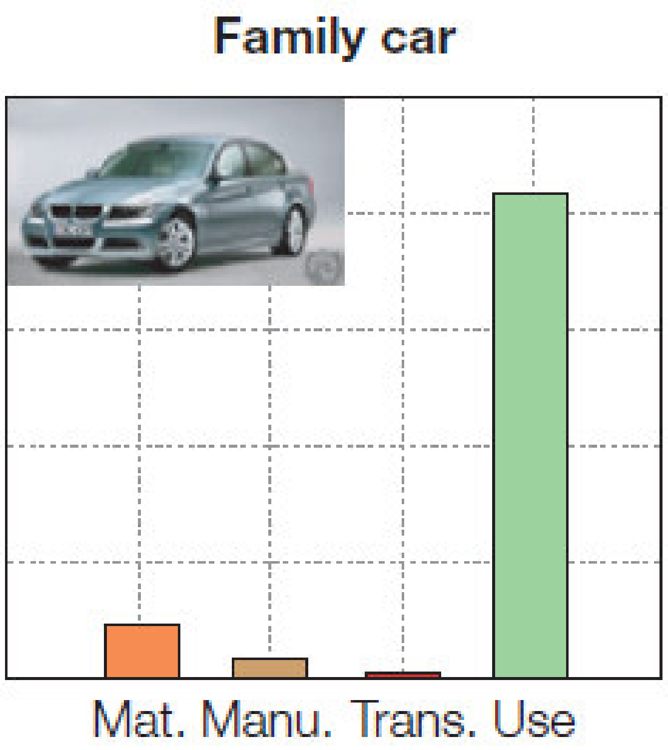


Case Studies – Crash Barrier

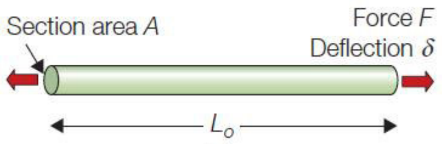
- If eco-design is the objective, criteria for selecting materials for two barriers differ.
- Function of barrier transfers load from point of impact to support structure.
- Either
  - 1. structure collapses, absorbing energy or
  - 2. barrier and supports react against vehicle, energy absorbed in crush elements (designed into vehicle).
- Barrier must have adequate strength (σ_y), ability to be shaped/joined cheaply, and recyclable.

Reminder


Multistory parking lot
100
0
Energy fraction (%)
Mat. Manu. Trans. Use


Family car
Mat. Manu. Trans. Use

Material indices



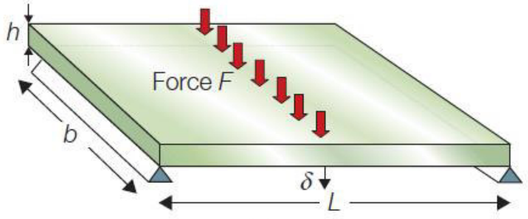
(a)

$$m \geq (F^*)(L)\left(\frac{\rho}{\sigma_f}\right)$$

Material properties

Functional constraint

Geometric constraint



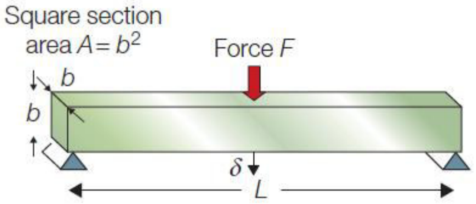
(b)

$$m = \left(\frac{12S^*}{C_1 b}\right)^{1/3}(bL^2)\left(\frac{\rho}{E^{1/3}}\right)$$

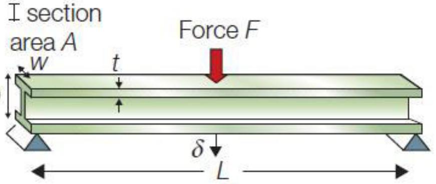
Material properties

Functional constraint

Geometric constraints



(c)

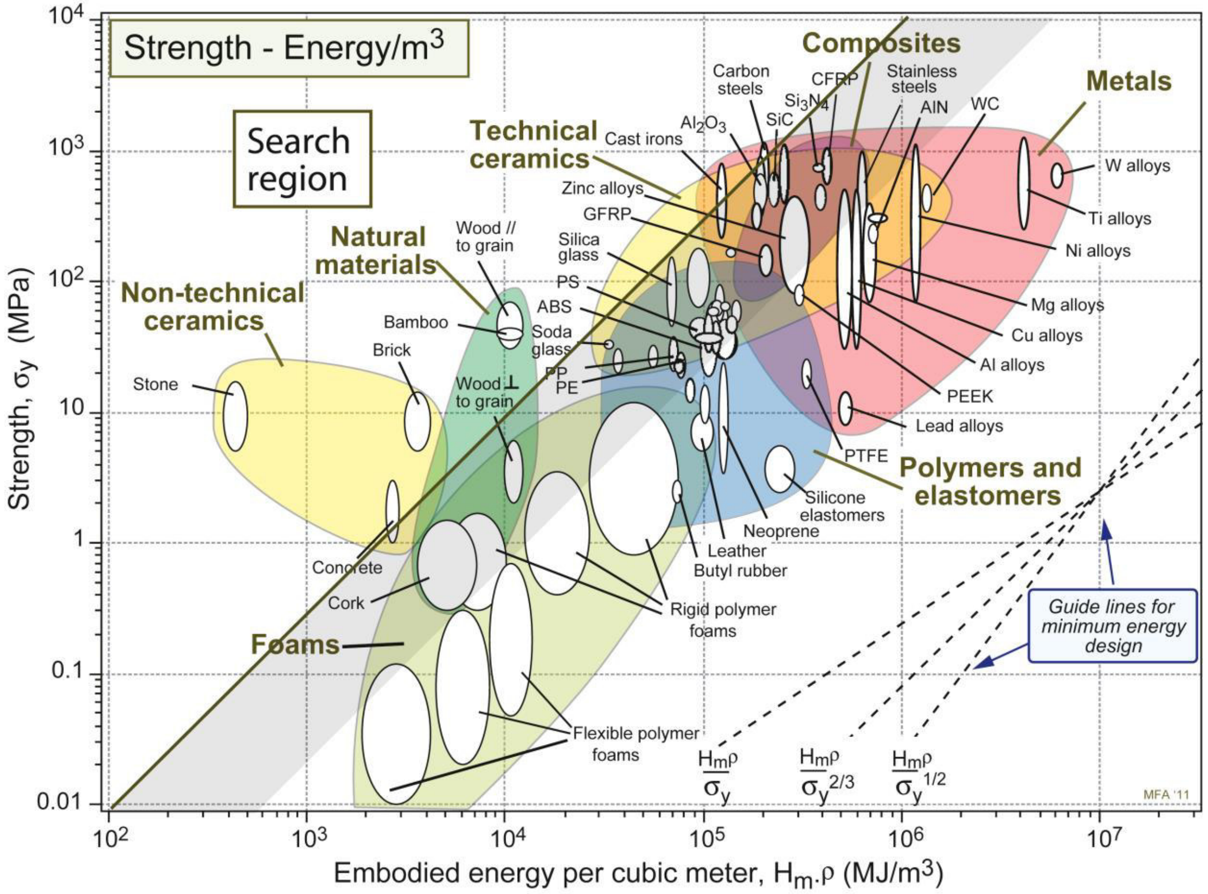


(d)

$$M_{b_1} = \frac{E^{1/2}}{\rho} \qquad M_{b_2} = \frac{\sigma_y^{2/3}}{\rho}$$

Materials Selection for Static Barrier

- For static barrier, **embodied energy** (not weight) is the problem.
- If objective is minimum embodied energy then require materials with $M_2 = \frac{\sigma_y^{\frac{2}{3}}}{H_m \rho}$

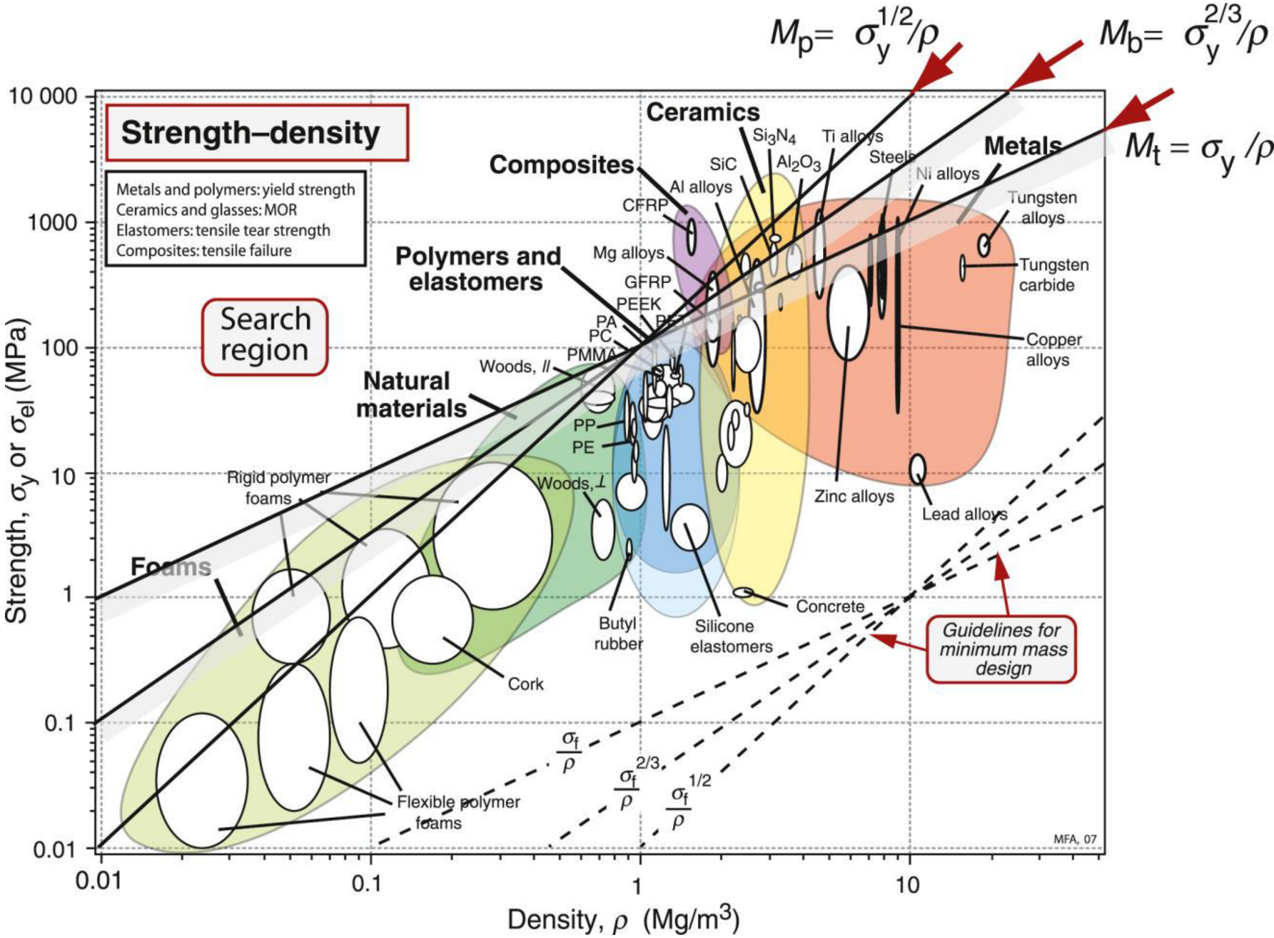


- Leaving aside brittle ceramics, Hm minimised using carbon steel, cast iron, wood.

Selection chart for strength with minimum production energy (see Fig. 14.8)

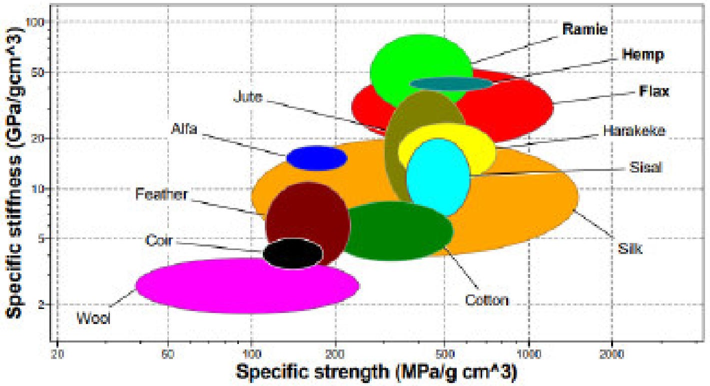
Materials Selection for Car Bumper

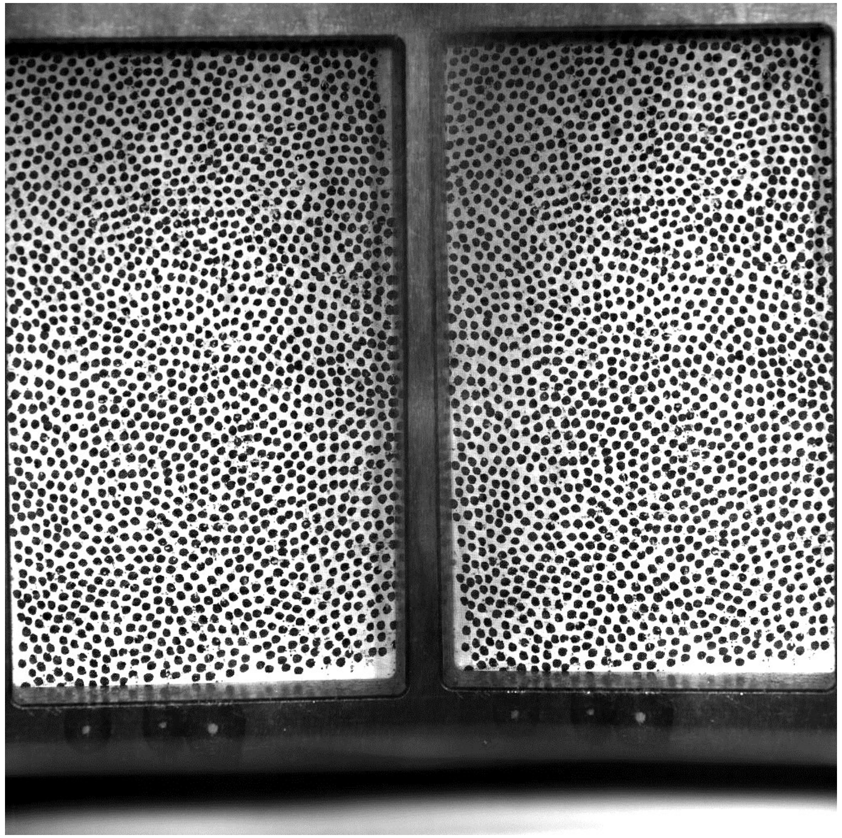
- Material must meet constraints with minimum mass (reduces use energy).
- For strength loaded in bending, materials with high values of index M1 = $\frac{\sigma_y^{\frac{2}{3}}}{\rho}$
- CFRP leads the way (with suitable choice of matrix).

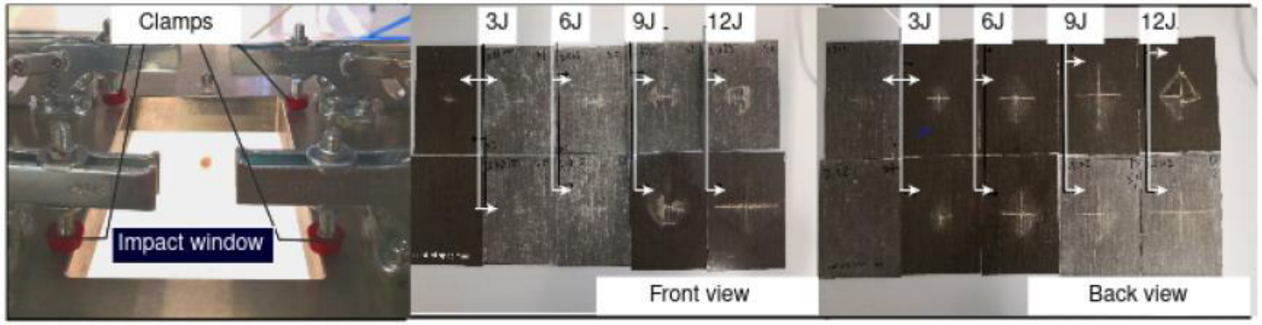


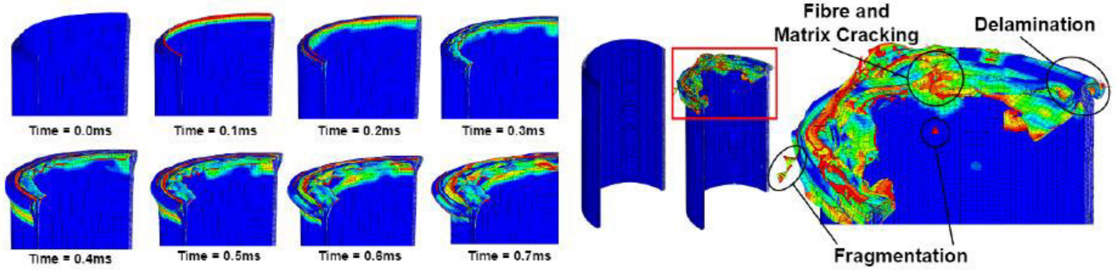
Strength-density chart with selected indices (see Fig. 7.8)

Research project









Summary

- Rational selection of materials to meet environmental objectives
  - identifying the phase of product life that causes the greatest concern
  - production, manufacture, use, or disposal
- If material production is the phase of concern
  - selection is based on minimizing production energy
- If it is the use phase
  - Selection is based instead on lightweighting

Summary

- Material selection process translates design requirement to final product
- The embodied energy and process energy reflect energy committed to producing and finishing 1 kg of usable material/product.
- Use of material selection chart to minimise environmental impact
- Charts of mechanical properties in terms of embodied energy (as a function of mass or volume) allow meaningful comparisons to be made to minimise embodied energy