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Eco-selection:

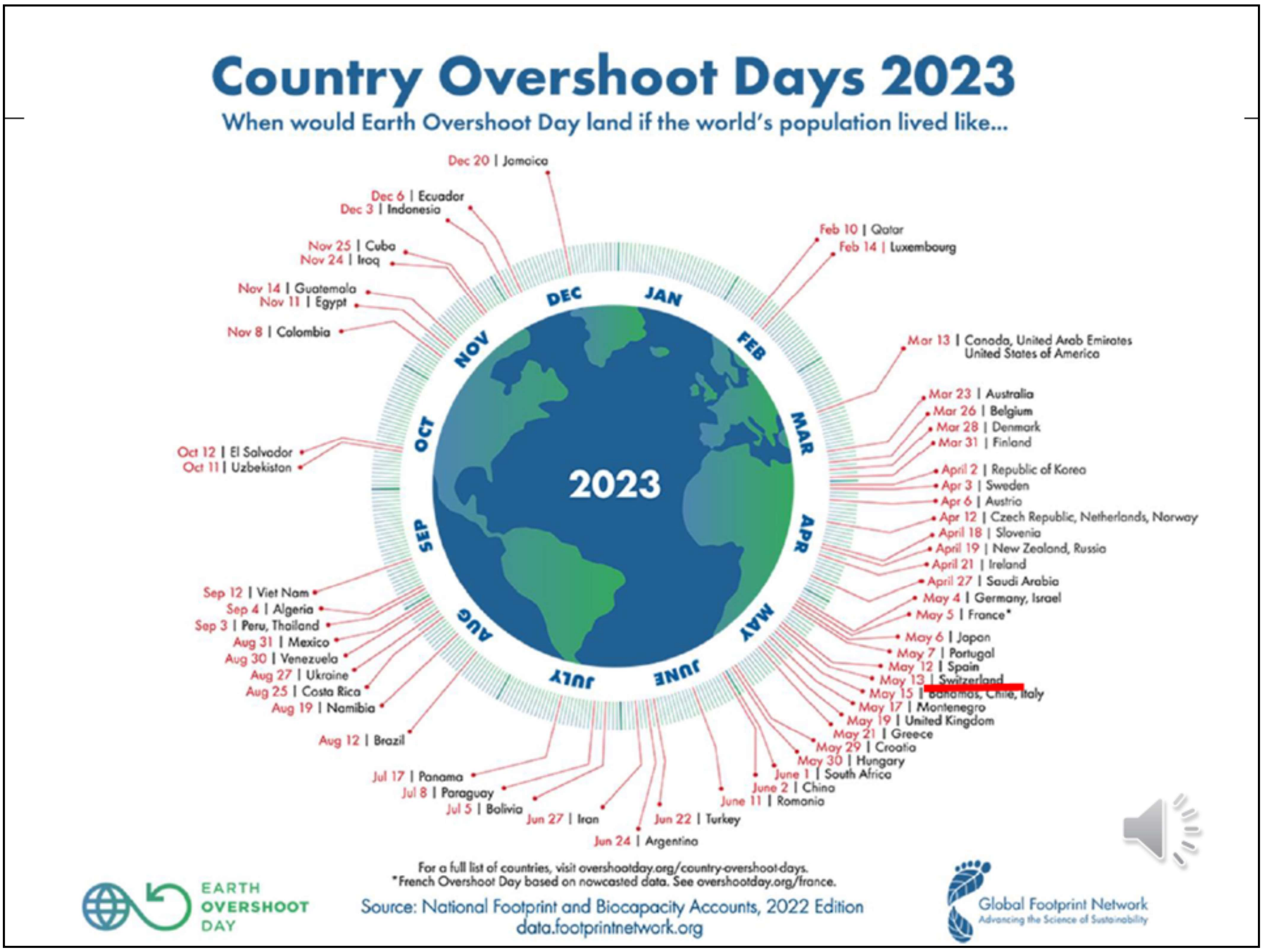
environmentally informed material choice

Outline

- Material consumption and the material life-cycle
- LCA, problems and solutions
- Analysis of products
- Strategy for materials selection

More info:
- "Materials: engineering, science, processing and design", **Chapter 20**
- "Materials Selection in Mechanical Design", **Chapter 16**

All human activity has some impact on the environment in which we live. The environment has some capacity to cope with this, so that a certain level of impact can be absorbed without lasting damage. But it is clear that current human activities exceed this threshold with increasing frequency, diminishing the quality of the world in which we now live and threatening the well-being of future generations. Thus the objective of **minimizing the impact of material production, use and disposal on the environment** in which we live is now seen as of central importance. This is a complex and sometimes emotional subject, one in which a proper perspective is important. This Unit introduces the topic and the way the EduPack, and the more specialised ECO-Selector, can be used to explore eco-friendly material options in a common-sense way. The frame lists the principal points.


Country Overshoot Days 2023
When would Earth Overshoot Day land if the world's population lived like...
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Dec 6 | Ecuador
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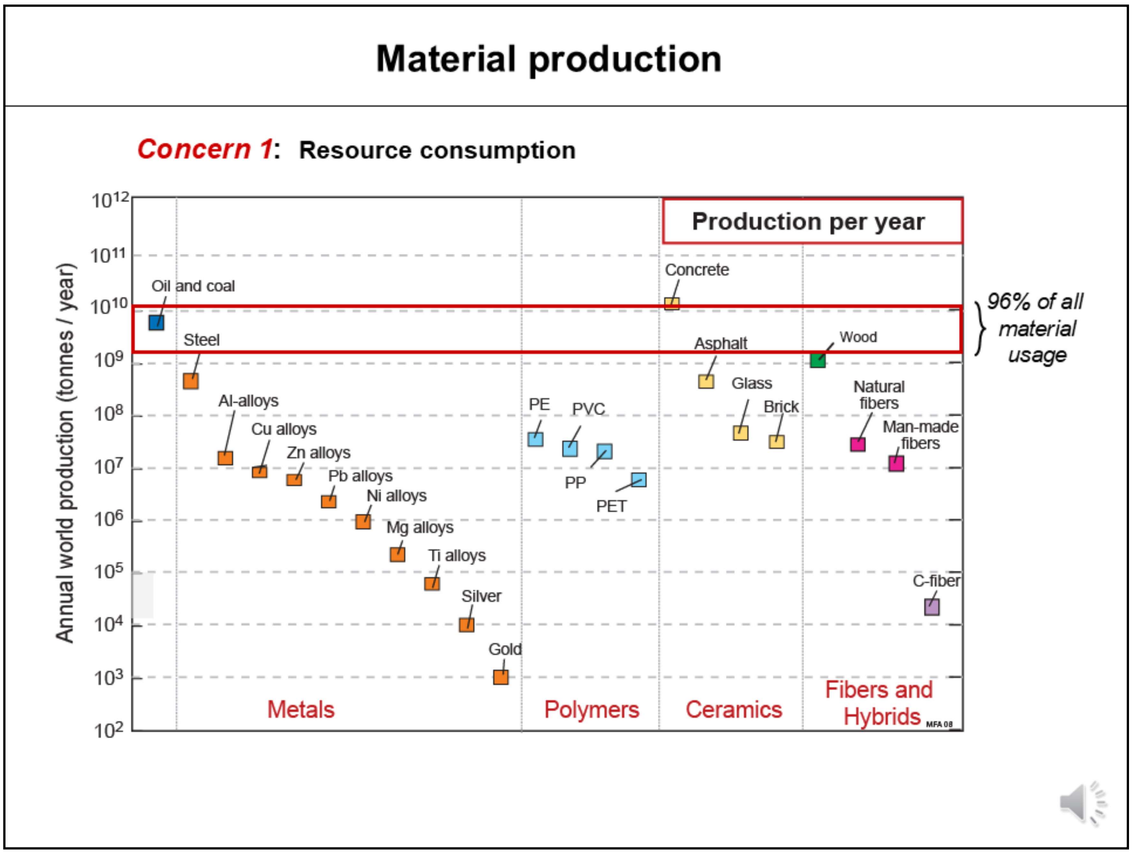
Nov 25 | Cuba
Nov 24 | Iraq
Nov 14 | Guatemala
Nov 11 | Egypt
Nov 8 | Colombia
Oct 12 | El Salvador
Oct 11 | Uzbekistan
Sep 12 | Viet Nam
Sep 4 | Algeria
Sep 3 | Peru, Thailand
Aug 31 | Mexico
Aug 30 | Venezuela
Aug 27 | Ukraine
Aug 25 | Costa Rica
Aug 19 | Namibia
Aug 12 | Brazil
Jul 17 | Panama
Jul 8 | Paraguay
Jul 5 | Bolivia
Jun 27 | Iran
Jun 24 | Argentina
Jun 22 | Turkey
Feb 10 | Qatar
Feb 14 | Luxembourg
Mar 13 | Canada, United Arab Emirates United States of America
Mar 23 | Australia
Mar 26 | Belgium
Mar 28 | Denmark
Mar 31 | Finland
April 2 | Republic of Korea
Apr 3 | Sweden
Apr 6 | Austria
Apr 12 | Czech Republic, Netherlands, Norway
April 18 | Slovenia
April 19 | New Zealand, Russia
April 21 | Ireland
April 27 | Saudi Arabia
May 4 | Germany, Israel
May 5 | France*
May 6 | Japan
May 7 | Portugal
May 12 | Spain
May 13 | Switzerland
May 15 | Bahamas, Chile, Italy
May 17 | Montenegro
May 19 | United Kingdom
May 21 | Greece
May 29 | Croatia
May 30 | Hungary
June 1 | South Africa
June 2 | China
June 11 | Romania
For a full list of countries, visit overshootday.org/country-overshoot-days.
*French Overshoot Day based on nowcasted data. See overshootday.org/france.
EARTH OVERSHOOT DAY
Source: National Footprint and Biocapacity Accounts, 2022 Edition
data.footprintnetwork.org
Global Footprint Network
Advancing the Science of Sustainability

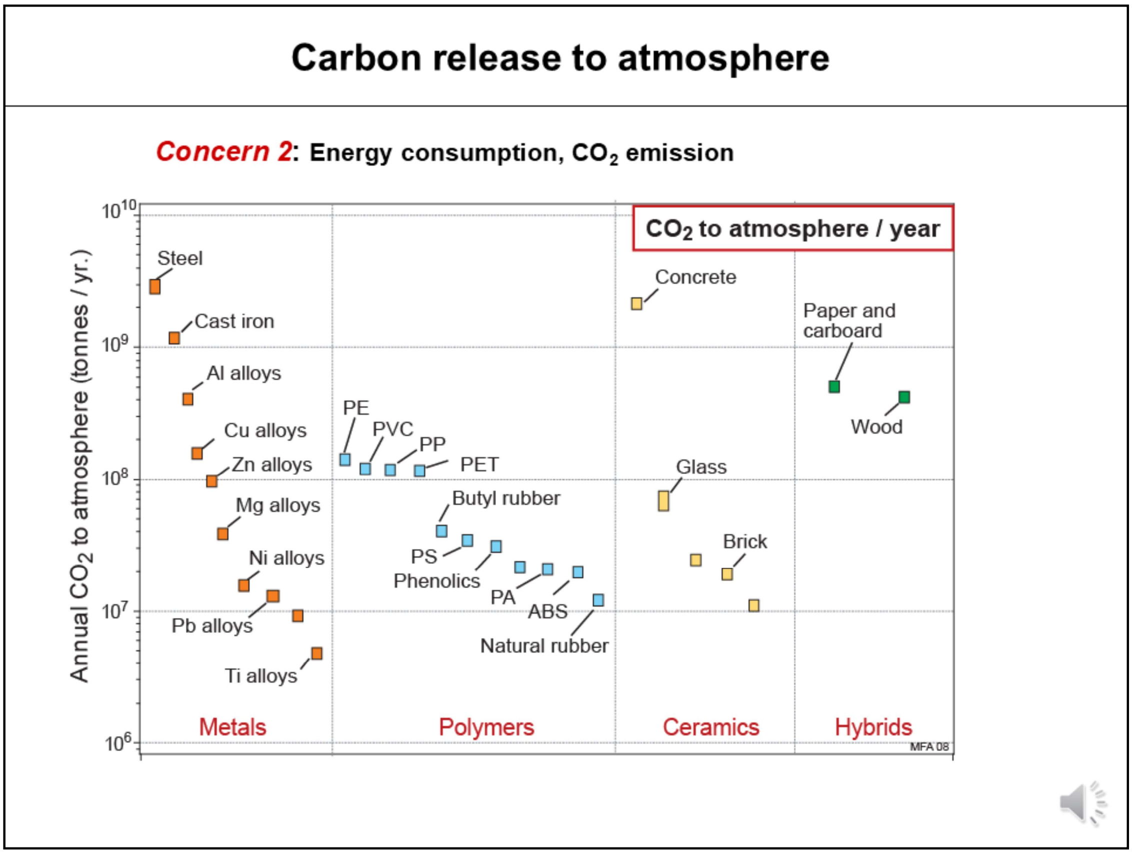


Speaking globally, we consume roughly 10 billion (10^{10}) tonnes of engineering materials per year. This bar-chart shows the **annual world production** of the materials that are used in the greatest quantities. On the extreme left, for calibration, are hydrocarbon fuels – oil and coal – of which we currently consume about 9 billion tonnes per year. Next, moving to the right, are metals. The scale is logarithmic, making it appear that the consumption of steel (the first metal) is only a little greater than that of aluminum (the next); in reality, the consumption of steel exceeds, by a factor of ten, that of all other metals combined. Polymers come next: today the combined consumption of commodity polymers polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP) and polyethylene-terephthalate, (PET) begins to approach that of steel.

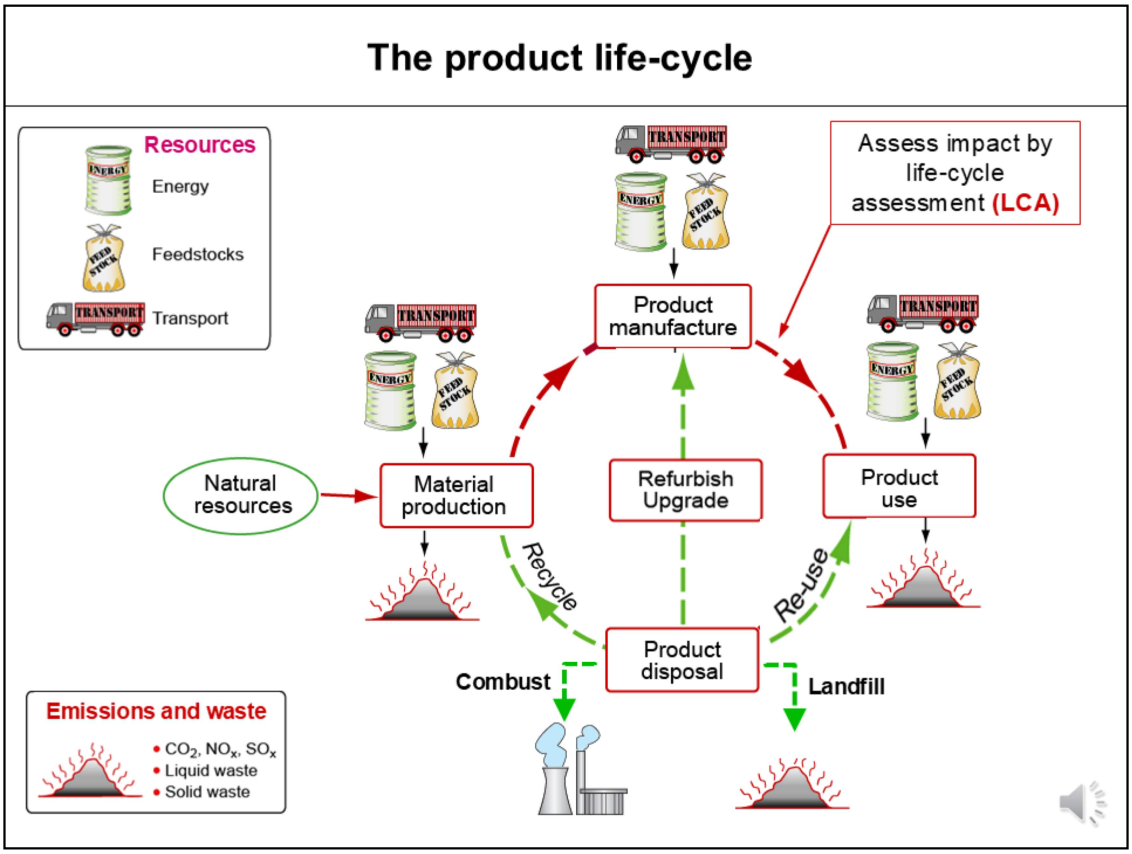
The really big ones, though, are the materials of the construction industry. Steel is one of these, but the consumption of wood for construction purposes exceeds that of steel even when measured in tonnes per year (as in the diagram), and since it is a factor of 10 lighter, if measured in m^3/year, wood totally eclipses steel. Bigger still is the consumption of concrete, which exceeds that of all other materials combined. The other big ones are asphalt (roads) and glass.

The remaining columns show the production of natural and artifical fibers, ending with carbon fiber. Just 20 years ago this material would not have crept onto the bottom of this chart. Today its consumption is approaching that of titanium and is growing fast.

The columns on this figure describe broad classes of materials, so – out of the many thousands of materials now available – they probably include 99.9% of all consumption when measured in tonnes. This is important when we come to consider the impact of materials on the environment, since impact scales with consumption.

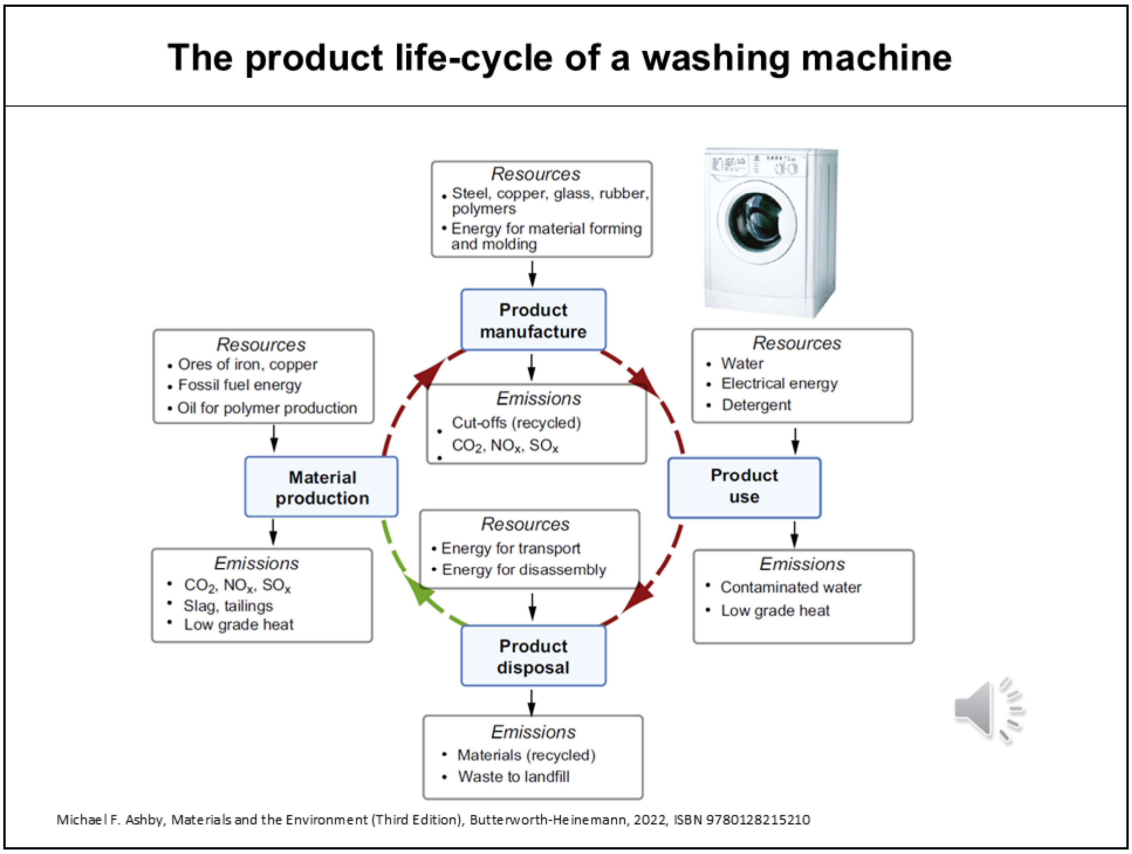


Carbon release to atmosphere caused by the production of materials is calculated by multiplying the annual production (last frame) by the embodied energy of the material (defined and plotted in later frames). This is what it looks like. The order changes a little from that of the last frame, but not much. If you want a BIG change in the contribution of material production to the carbon problem, it is these materials on which attention must focus.

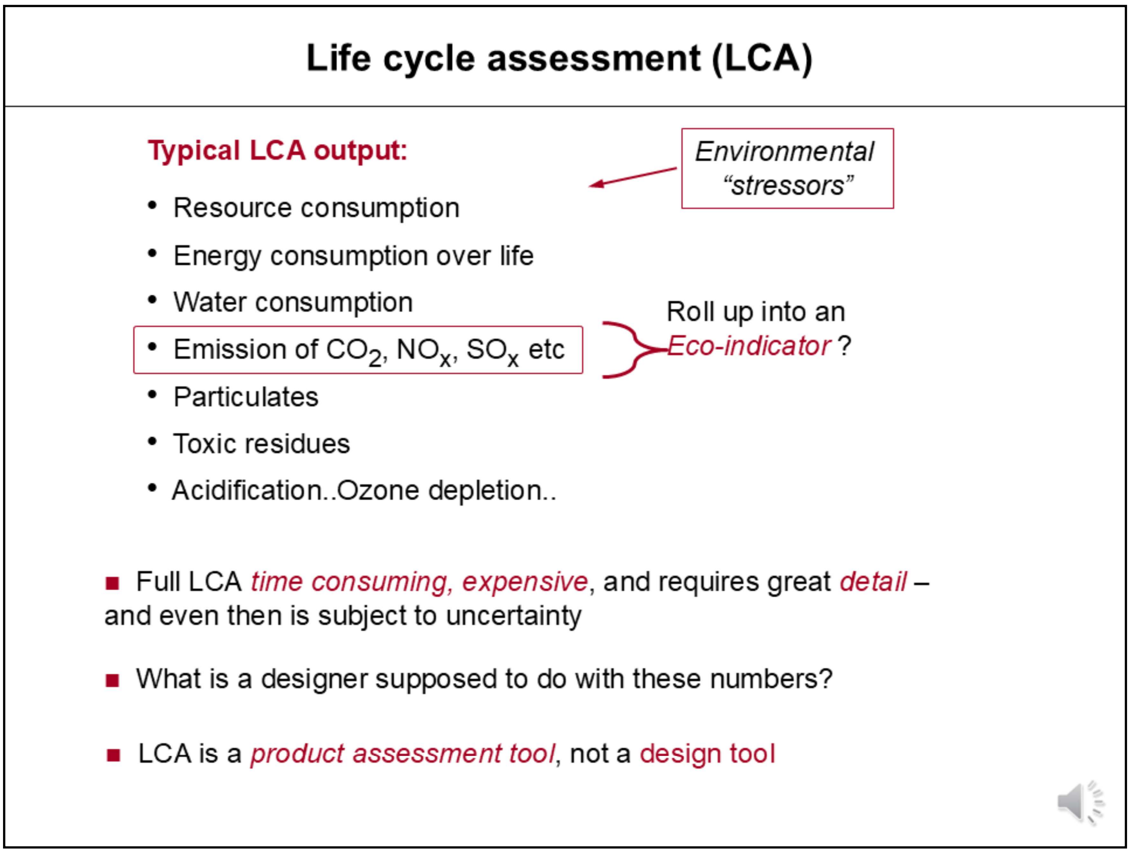


This frame shows the materials lifecycle. Ore and feedstock, drawn from the earth's resources, are processed to give materials. These are manufactured into products that are used, and, at the end of their lives, discarded, a fraction perhaps entering a recycling loop, the rest committed to incineration or land-fill. Energy and materials are consumed at each point in this cycle (we shall call them "phases"), with an associated penalty of CO_2 , SO_x, NO_x and other emissions – heat, and gaseous, liquid and solid waste, collectively called environmental "*stressors*". These are assessed by the technique of **life-cycle analysis (LCA).**

ISO 14000 of the International Standards Organization defines a family of standards for environmental management systems. It contains the set IS0 14040, 14041, 14042 and 14043 published between 1997 and 2000, prescribing broad procedures for conducting the four steps of an LCA: setting *goals and scope, inventory compilation, impact assessment* and *interpretation*. The standard is an attempt to bring uniform practice and objectivity into life-cycle assessment and its interpretation, but implementation is cumbersome and expensive.

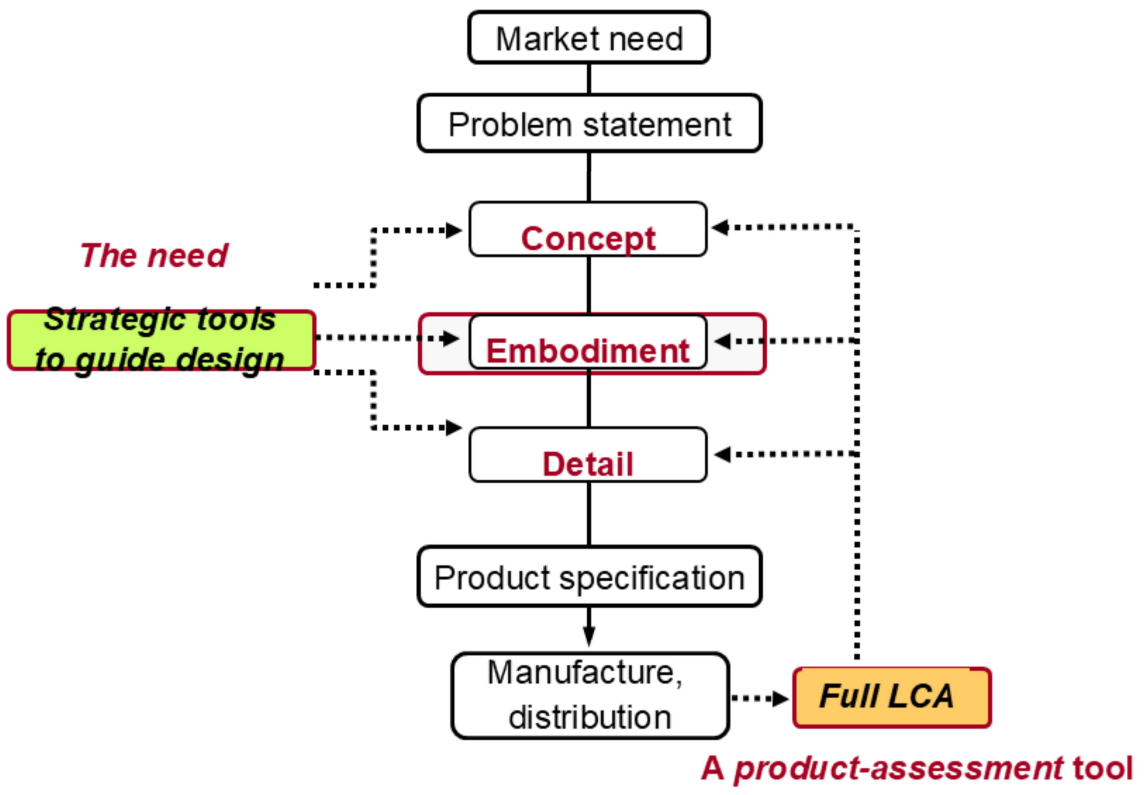


This frame shows the materials lifecycle of a washing machine.



The upper part of this frame lists the **typical ouput** of an LCA. A full LCA is time-consuming and expensive and it cannot cope with the problem that 80% of the environmental burden of a product is determined in the early stages of design when many decisions are still fluid. And there is a second problem: what is a designer supposed to do with this information? How are $C0_2$ and $S0_x$ productions to be balanced against resource depletion, toxicity or ease of recycling when choosing a material? This question has lead to efforts to condense the eco-information about a material into a single measure or **eco-indicator**, giving the designer a simple, numeric ranking. The use of a single-valued indicator is criticised by some. The grounds for criticism are that there is no agreement on normalisation or weighting factors used to calculate them and that the method is opaque since the indicator value has no simple physical significance.

LCA in the context of design

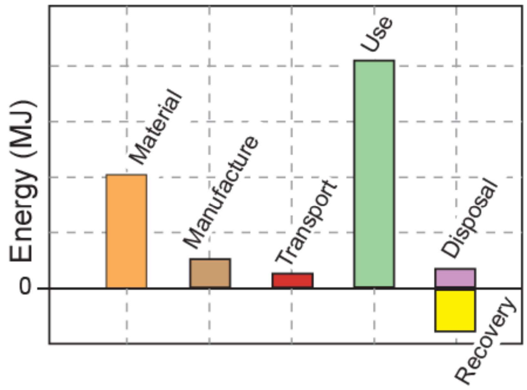


Here we reproduce the design flow-chart introduced Unit 3. A full LCA is not much help in developing the design, for the reasons given on the last frame: it is a **product assessment tool**, not a **design tool.** This has led to the development of more approximate methods that seek to combine acceptable cost with sufficient accuracy to guide decision-making, the choice of materials being one of these decisions. The are described in the next frame.

Developing strategies for guiding design

Need: **Eco-audit** that combines acceptable cost with sufficient precision to guide decision-making

- **1 resource – *energy*** **1 emission – *CO_2***
- **Distinguish life-phases**

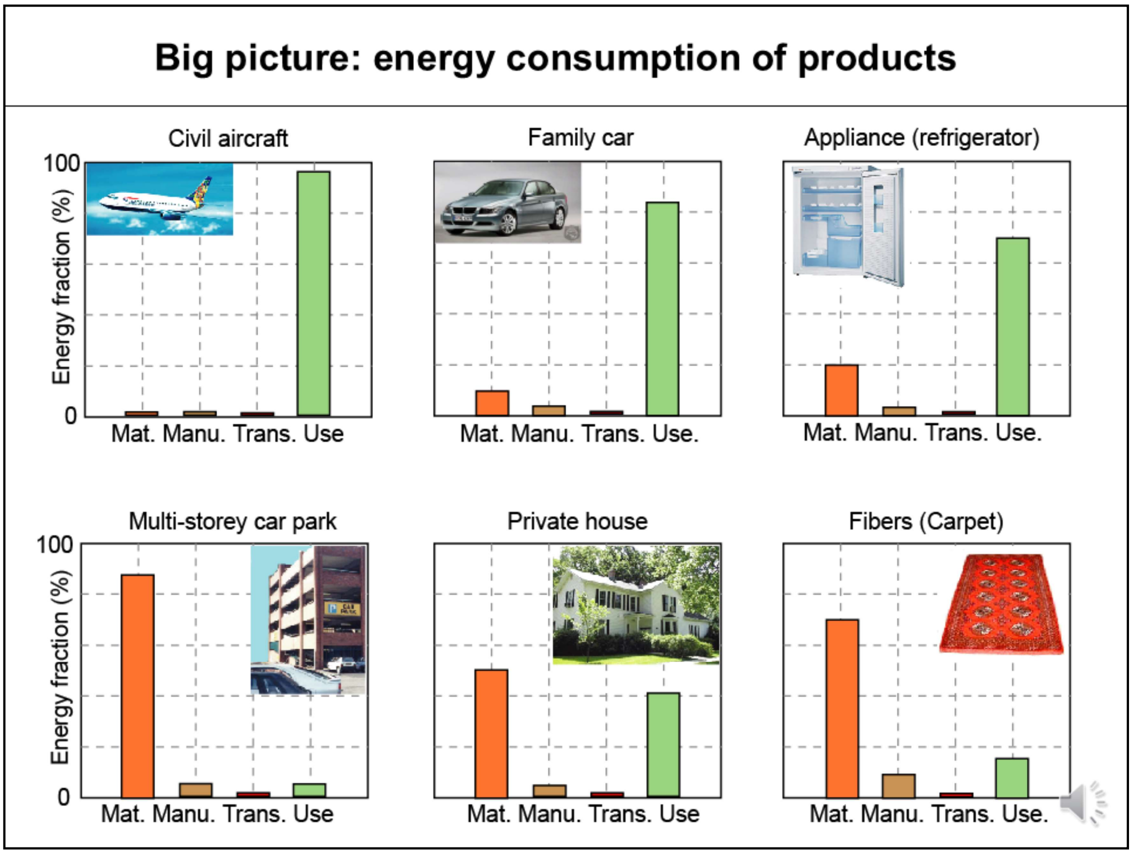


The strategy for guiding design has 3 steps.

The **first step** is one of simplification, developing a tool that is approximate but retains sufficient discrimination to differentiate between alternative choices. A spectrum of levels of analysis exist, ranging from a simple **eco-screening** against a list of banned or undesirable materials and processes to a **full LCA**, with overheads of time and cost. In between lie methods that are less rigorous; they are approximate but fast.

The **second step** is to select a single measure of eco-stress. On one point there is some international agreement: the Kyoto Protocol of 1997 committed the developed nations that signed it to progressively reduce **carbon emissions,** meaning **CO_2.** At the national level the focus is more on reducing **energy consumption**, but since this and CO_2 production are closely related, they are nearly equivalent. Thus there is a certain logic in basing design decisions on energy consumption or CO_2 generation; they carry more conviction than the use of a more obscure indicator. We shall follow this route, using energy as our measure.

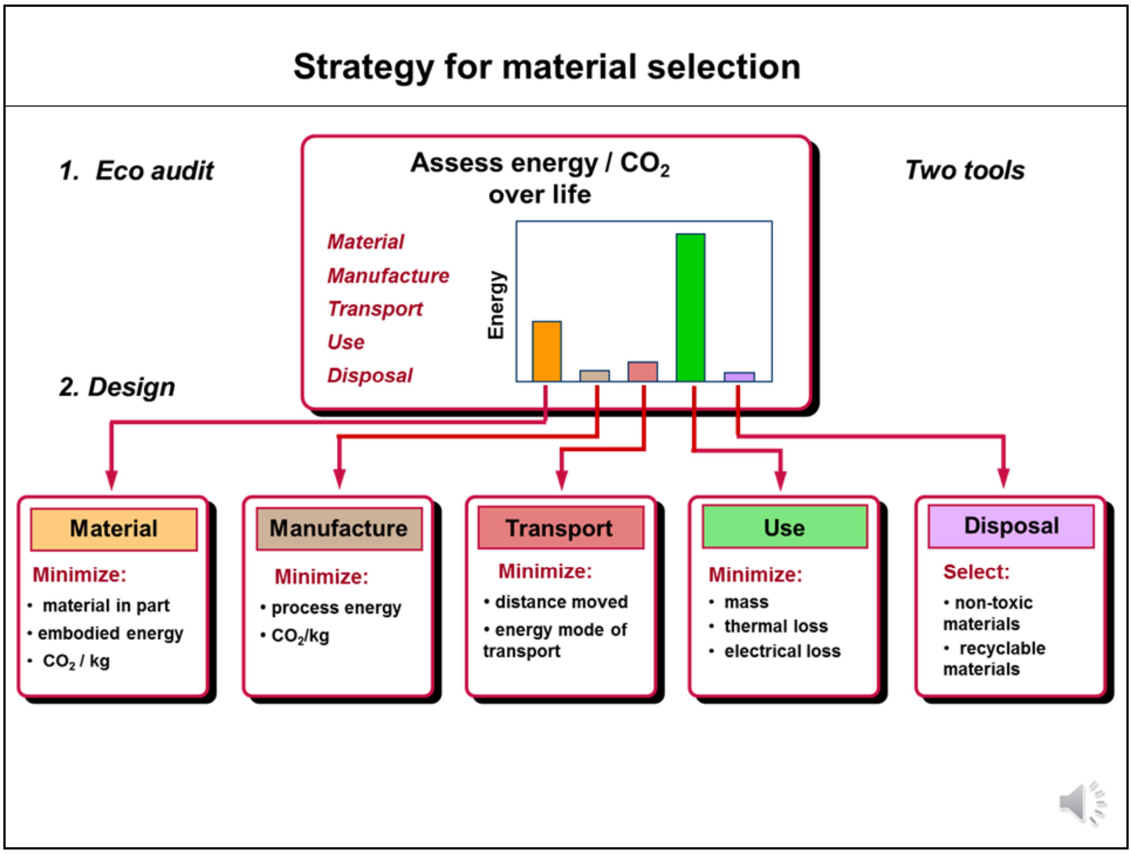
The **third step** is to separate the contributions of the phases of life because subsequent action depends on which is the dominant one. If it is that a material production, then choosing a material with low "embodied energy" (defined on a later frame) is the way forward. But if it is the use phase, then choosing a material to make use less energy-intensive is the is the right approach – even if it has a higher embodied energy.



This overhead shows the **breakdown of energy usage over life**, assigning a fraction of the total life-energy demands of a product to material creation, product manufacture, transport and product use and disposal. Product disposal can take many different forms, some carrying an energy penalty, some allowing energy recycling or recovery.

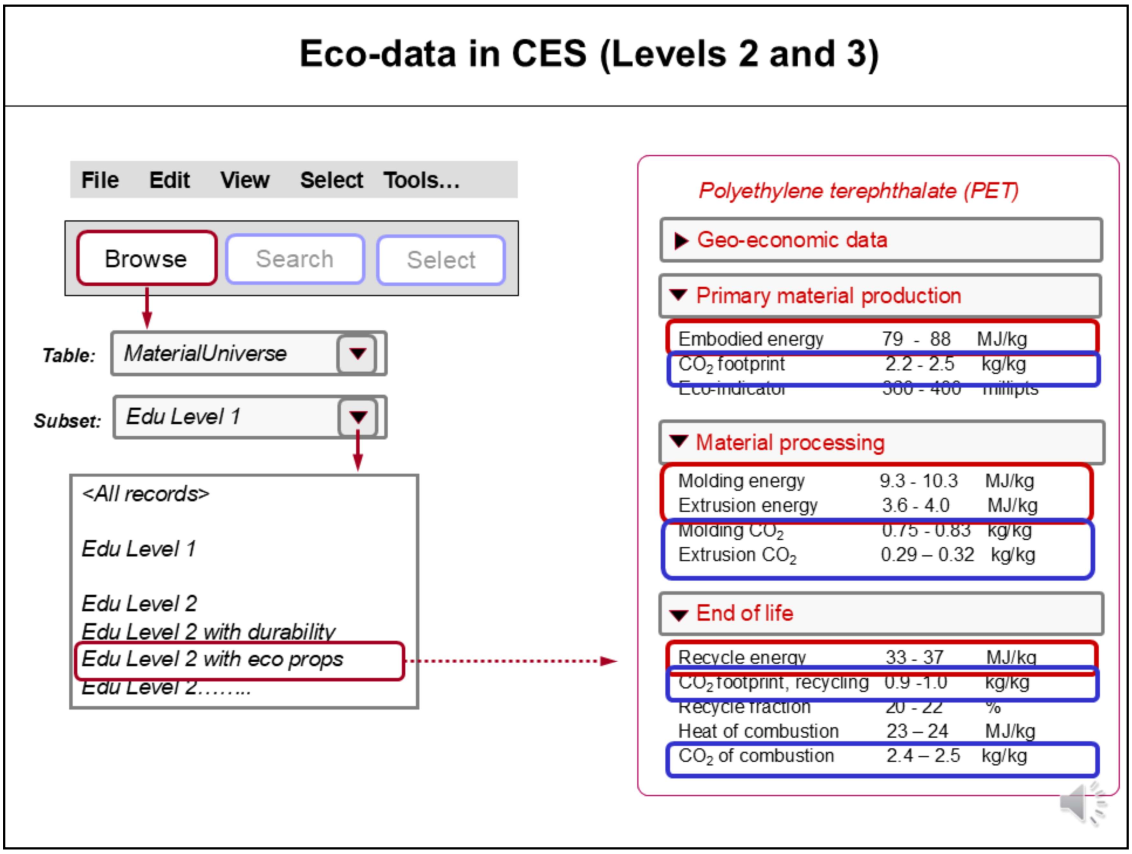
When this distinction is made, it is frequently found that one of phases dominates the picture, as in the those of this frame. The upper row shows an approximate energy breakdown for three classes of energy-using products: a civil aircraft, a family car and an appliance. For all three the use-phase consumes more energy than the sum of all the others. The lower row shows products that still require energy during the use-phase of life, but not as intensively as those of the upper row. For these, the embodied energies of the materials of which they are made generally make the largest contribution.

Two conclusions can be drawn. The first: one phase frequently dominates, accounting for 60% or more of the energy – often much more. If large energy savings are to be achieved, it is the dominant phase that becomes the first target since it is here that a given fractional reduction makes the biggest contribution. The second: when differences are as great as those of shown here, great precision is not necessary – modest changes to the input data leave the ranking unchanged.



For selection to **minimize eco-impact** we must first ask: which phase of the life cycle of the product under consideration makes the largest impact on the environment? The answer guides material selection.

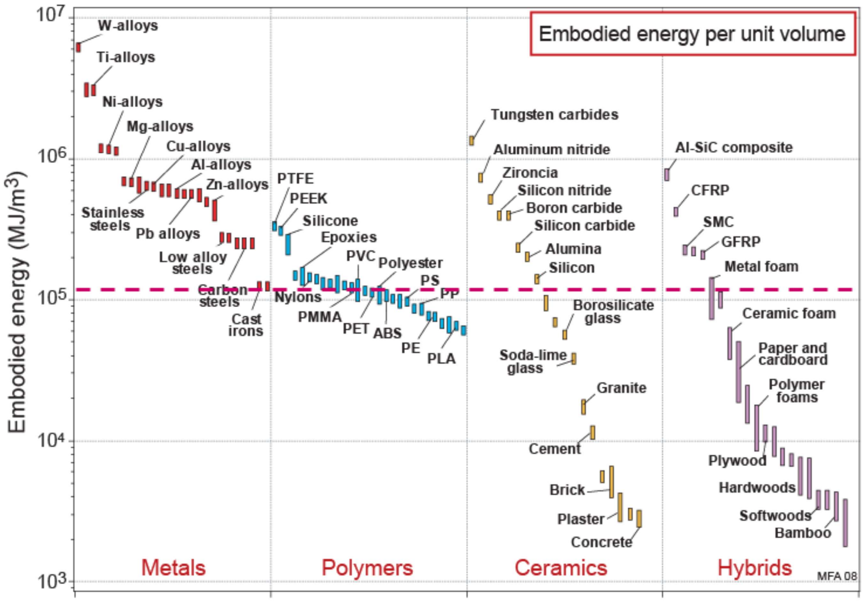
To carry out an eco-audit we need **data** for the energy and CO_2 footprints of materials. That comes next.



Eco properties are displayed by selecting the Subset "**Materials with Eco properties**" at Level 2, or by opening the CES Level 3 Eco-selector.

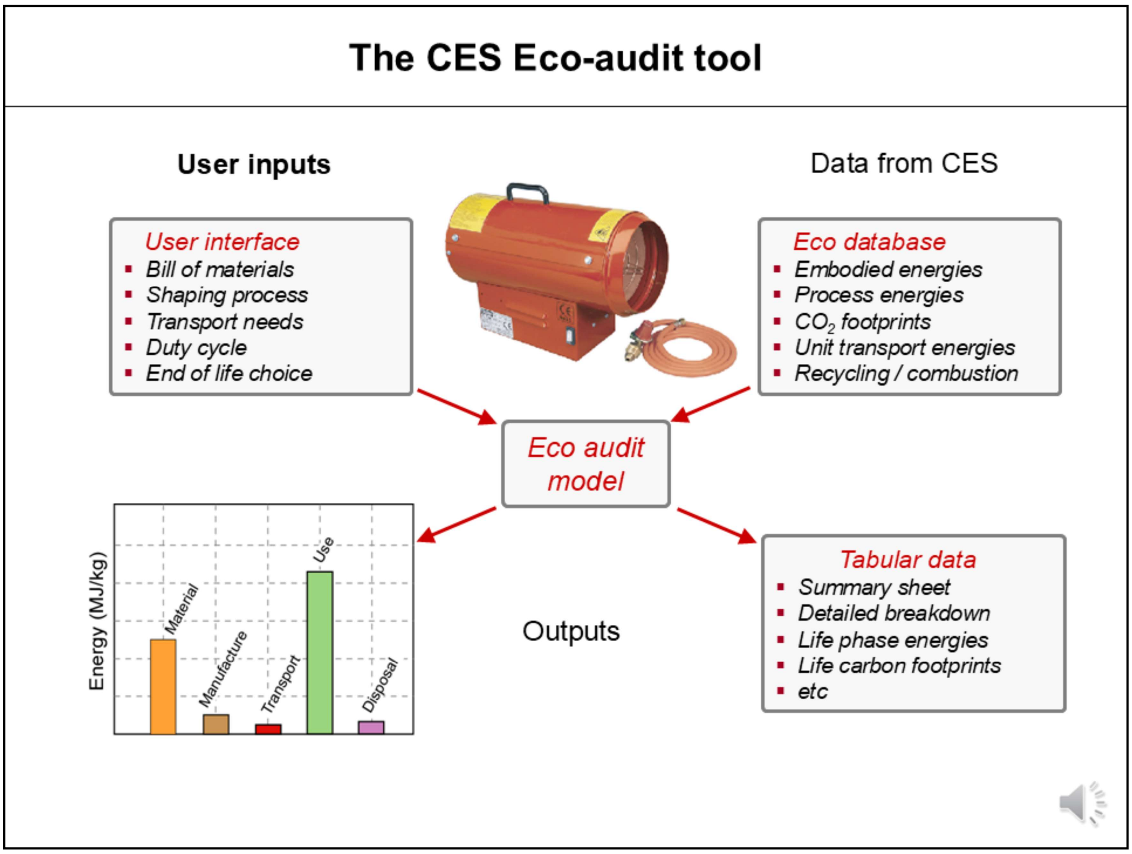
The **Browse** button lets you explore the contents by roaming through its "tree". Scrolling down to Materials with Eco-properties opens the Eco database. The records contain data for eco-properties, some shown here, in addition to all the other data for mechanical, thermal, electrical attributes.

Plotting eco data: embodied energies



Embodied energies of materials are compared in the the CES bar charts in this frame. That on the left is a plot of energy per unit mass (units: MJ/kg). Among metals, the light alloys based on aluminum, magnesium and titanium have the highest values, approaching 1000 MJ/kg for titanium on this chart, but precious metals lie much higher still. Polymers all cluster around 100 MJ/kg, less than the light alloys, but considerably more than steels and cast irons, with energies between 20 and 40 MJ/kg. Technical ceramics such as aluminum nitride have high energies; those for glass, cement, brick and concrete are much lower. Composites, too, have a wide spread. High performance composites – here we think of CFRP (carbon-fiber reinforced polymers) – lie at the top, well above most metals. At the other extreme paper, plywood and timber are comparable with the other materials of the construction industry.

But is embodied **energy per unit mass** the proper basis of comparison? Suppose, instead, the comparison is made using **energy per unit volume** (chart on the right, made using the Advanced facility of CES to create the product Embodied energy x Density). Now metals as a family lie above the others. Polymers cluster around a value that is lower than most metals – by this measure the are not the energy-hungry materials they are sometimes made out to be. The non-metallic materials of construction – concrete, brick, wood – lie far below all of them. CFRP is now comparable with aluminum.

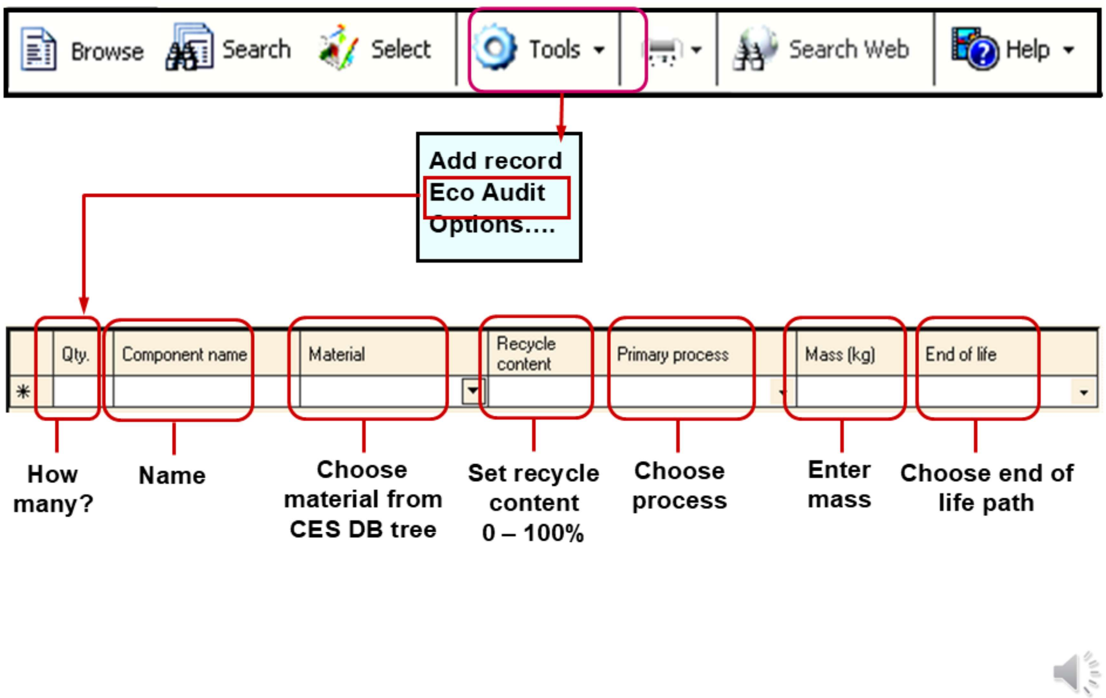


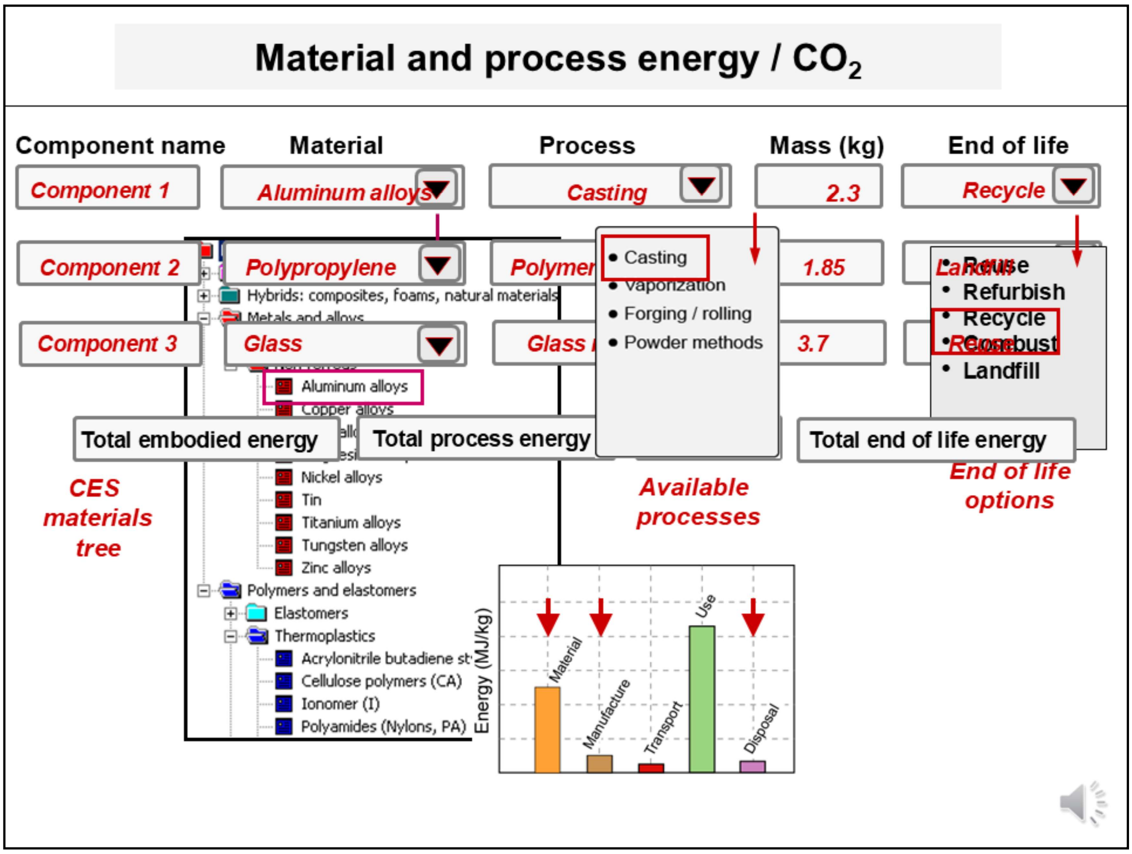
The **CES Eco-audit Tool** is opened from the Tools menu at the top of the CES screen. This frame shows how the **eco-audit** of a product works. The *inputs* are of two types. The first are drawn from a user-entered *bill of materials*, *process choice*, *transport requirements*, *duty cycle* (the details of the energy and intensity of use) and *disposal route*, shown at the top left.

Data for embodied energies, process energies, recycle energies and carbon intensities are drawn from a database of material properties; those for the energy and carbon intensity of transport and the use-energy are drawn from the CES database of eco-attributes of materials. The *outputs* are the energy or carbon footprint of each phase of life, presented as bar charts and in tabular form.

The next 4 frames illustrate the use of the Eco-audit too.

The Audit tool



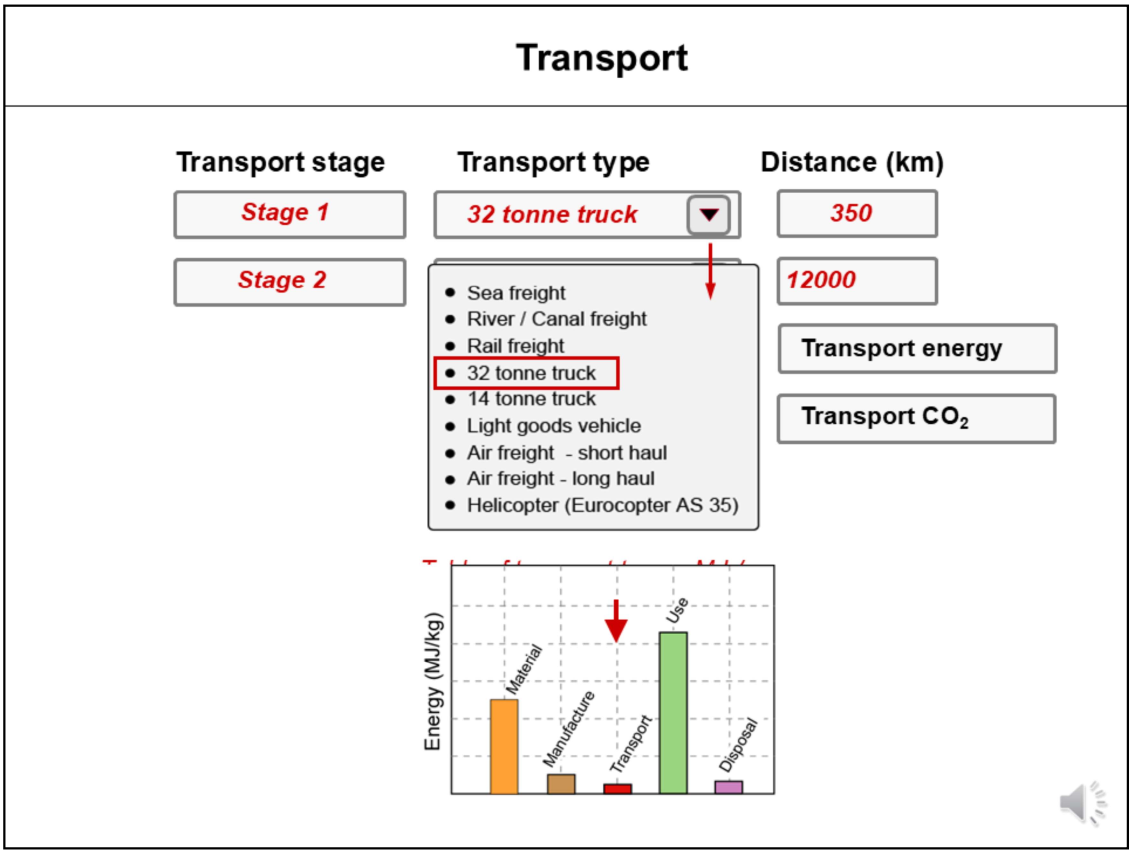


Materials, processes and end-of-life choice are entered in the way shown here. A **bill of materials** is drawn up, listing the mass of each component used in the product and the material of which it is made, as on the left. Data for the embodied energy (MJ/kg) and CO2 (kg/kg) per unit mass for each material is retrieved from the database – here. Multiplying the mass of each component by its embodied energy and summing gives the total material energy – the first bar of the bar-chart.

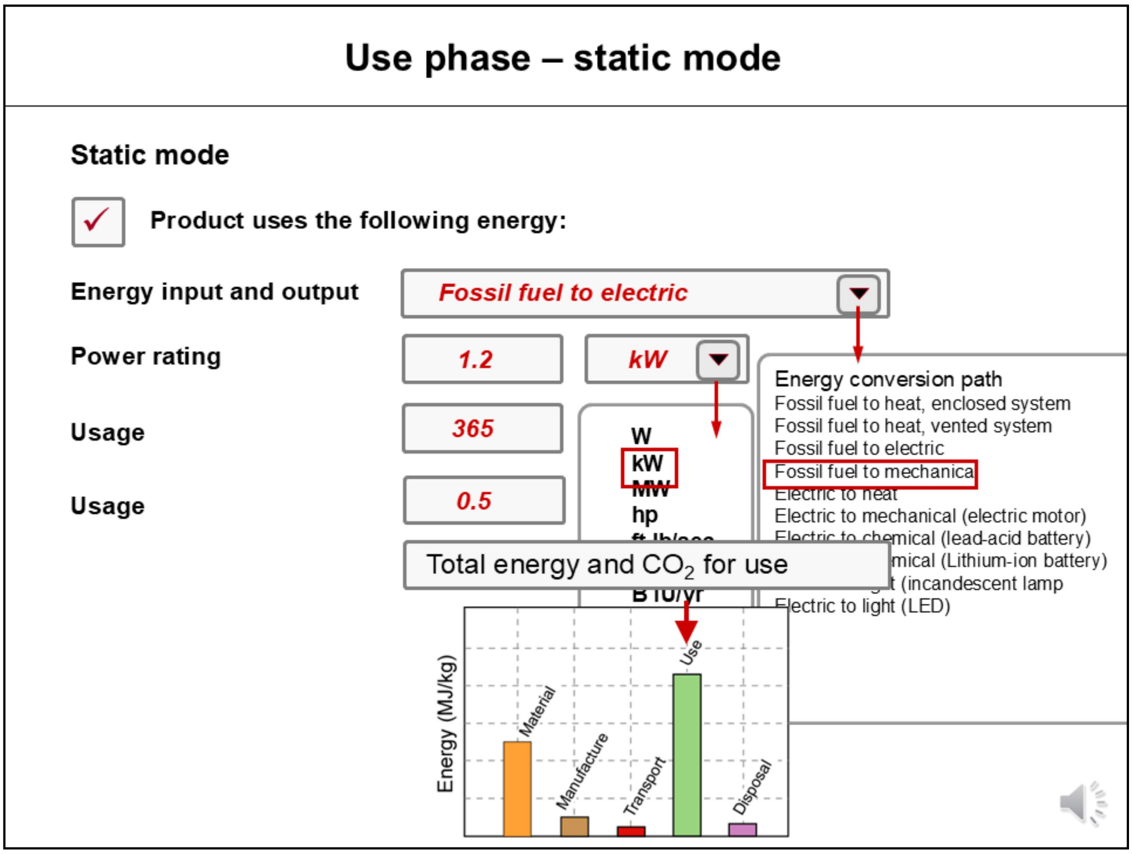
The audit focuses on primary **shaping processes** since they are generally the most energy-intensive steps of manufacture. These are listed against each material, shown here. The process energies and CO_2 per unit mass are retrieved from the database. Multiplying the mass of each component by its primary shaping energy and summing gives an estimate of the total processing energy – the second bar of the bar-chart.

On a first appraisal of the product it is frequently sufficient to enter data for the components with the greatest mass, accounting for perhaps 95% of the total. The residue is included by adding an entry for "residual components" giving it the mass required to bring the total to 100% and selecting a proxy material and process: "polycarbonate" and "molding" are good choices because their energies and CO_2 lie in the mid range of those for commodity materials.

Finally, the **end-of-life** choice is selected from the list of 5 options, listed here.



This step estimates the energy for **transportation** of the product from manufacturing site to point of sale. The energy demands of chosen transport in 0.9 MJ/tonne.km, retrieved from a look-up table in CES, is multiplied by the mass of the product and the distance travelled to give the travel energy. Carbon footprint is calculated in a similar way.

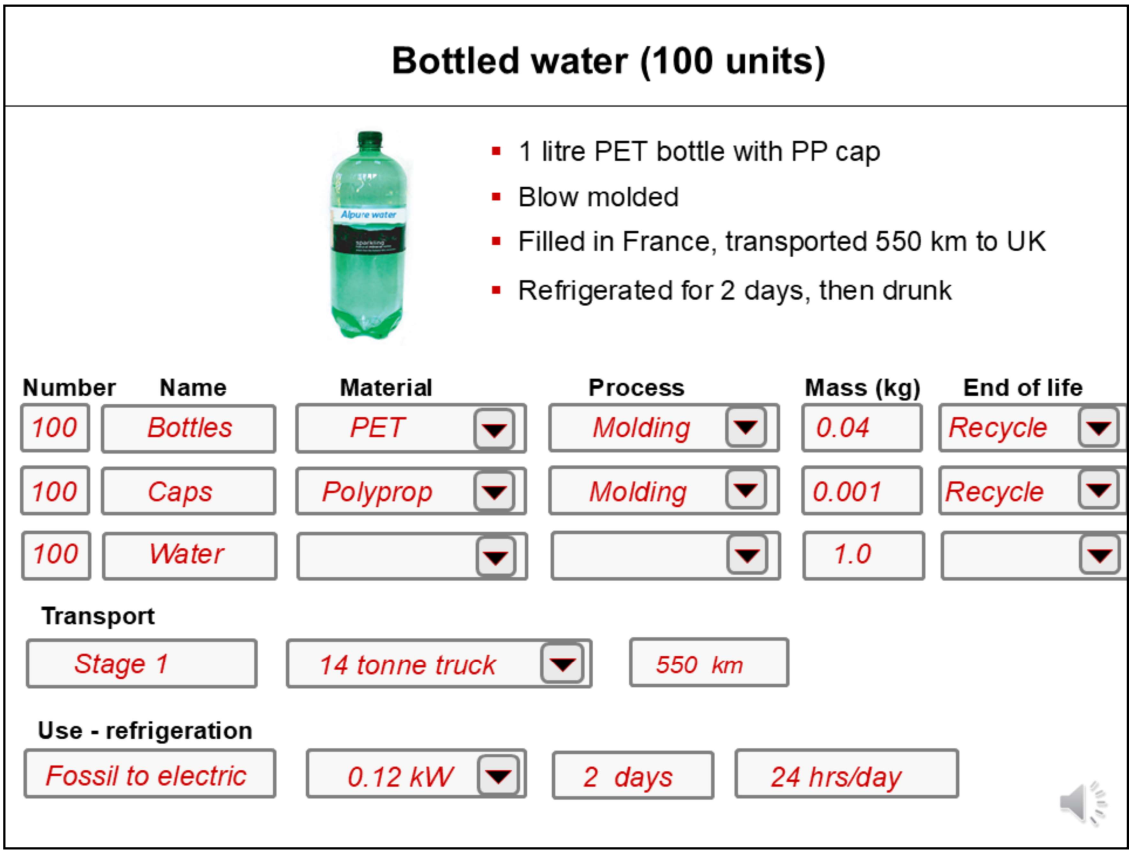


The **use phase** requires a little explanation. There are two different classes of contribution.

Most products require energy to perform their function: electrically powered products like hairdryers, electric kettles, refrigerators, power tools and space heaters are examples. Even apparently non-powered products like household furnishings or unheated buildings still consume some energy in cleaning, lighting and maintenance. The first class of contribution, then, relates to the power consumed by, or on behalf of, the product itself.

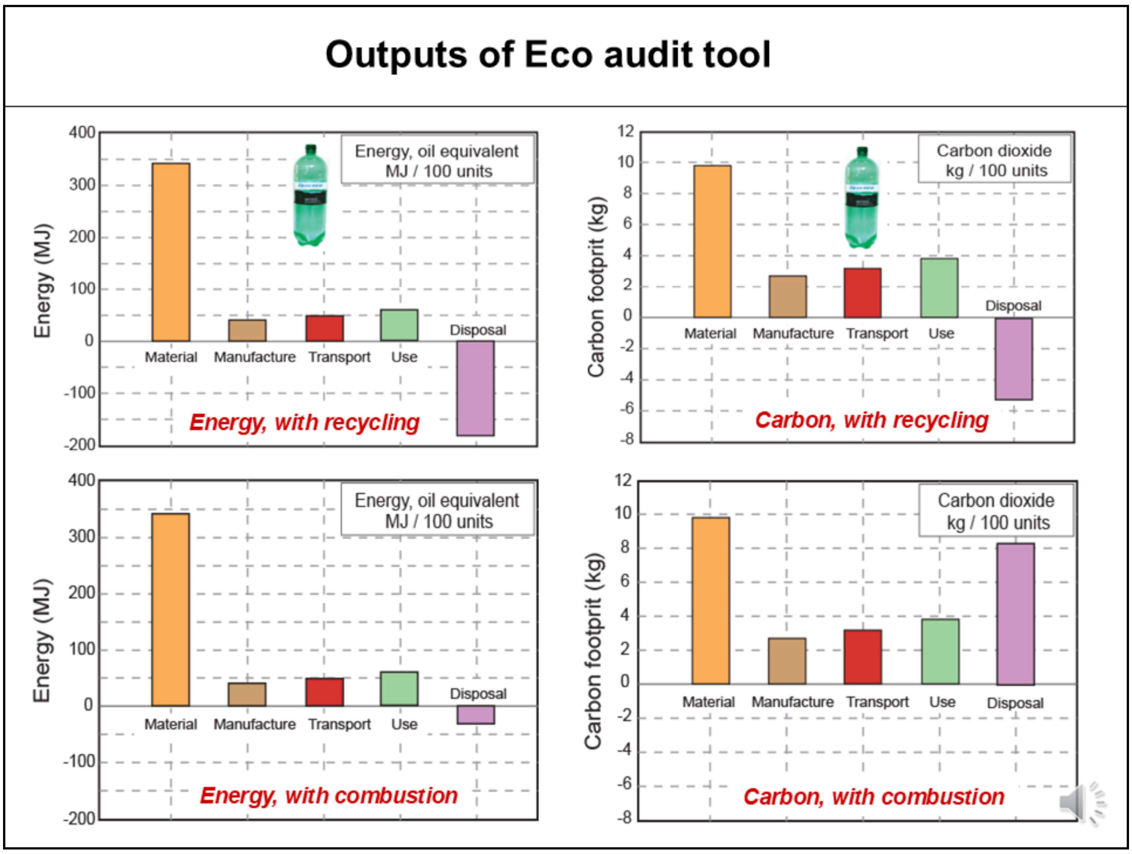
The second class is associated with transport. Products that form part of a transport system or are carried around in one add to its mass and thereby augment its energy consumption and CO2 burden. This carries an energy and CO_2 penalty per unit weight and distance. Multiplying this by the product weight and the distance over which it is carried gives an estimate of the associated use-phase energy and CO_2.

All energies are related back to primary energy, meaning oil, via oil-equivalent factors for energy conversion. Retrieving these and multiplying by the power and the duty cycle – the usage over the product life – gives an estimate of the oil-equivalent energy of use.



Here is an extremely simple example to illustrate how the Eco-audit tool works. One brand of **bottled water** – we will call it *Alpure* – is sold in 1-liter PET bottles with polypropylene caps. One bottle weighs 40 grams; its cap weighs 1 gram. The bottles and caps are molded, filled with water in the French Alps and transported 550 km to London, England, by 14 tonne truck. Once there they are refrigerated for 2 days, on average before consumption. We use these data for the case study, taking 100 bottles as the unit of study, requiring 1 m^3 of refrigerated space.

At end of life the bottles are recycled.



The outputs are bar-charts of energy and CO_2 over life. The upper two show the contributions to energy and carbon from the phases of life when the bottles are recycled after use. What do we learn? The largest contribution to energy consumption and CO_2 generation derives from the production of the polymers used to make the bottle. The second largest is that of the short, 2-day, refrigeration. The seemingly extravagant part of the life cycle – that of transporting water, 1 kg per bottle, 550 km from the source to the consumer – contributes 10% of the total energy and 17 % of the total carbon. So the conclusion: use less material for the bottle, or choose one with a lower embodied energy and carbon footprint.

The lower pair of bar charts shows the contributions when the bottles are combusted for heat recovery at end of life. The heat of combustion, less an efficiency factor, is recovered but instead of saving carbon, all that associated with the PET of the bottle is released into the atmosphere.

An overall reassessment of the eco-impact of the bottles should, of course, explore ways of reducing energy and carbon in all phases of life, not just one, seeking the most efficient molding methods, the least energy intensive transport mode (32 tonne truck, barge) and – an obvious step – minimizing the refrigeration time.

Jug kettle: materials, process, use, end of life

2 kW jug kettle
Made SE Asia
Air freight to UK
Life: 3 years

Bill of materials

No	Component	Material	Process	Mass kg	End of life
1	Housing	Polypropylene	Polymer molding	0.91	Recycle
4	Small steel parts	Steel	Def. processing	0.12	Recycle
1	Small aluminum parts	Aluminum	Def. processing	0.08	Recycle
1	Glass jug	Glass (Pyrex)	Molded	0.33	Recycle
1	Heating element	Ni-Cr alloy	Def. processing	0.026	Recycle
1	Electronics and LED	Electronics	Assembled	0.007	Recycle
1	Cable sheath, 1 meter	PVC	Polymer extrusion	0.12	Landfill
1	Cable core, 1 meter	Copper	Def. processing	0.035	Recycle
1	Plug body	Phenolic	Polymer molding	0.037	Landfill
3	Plug pins	Brass	Def. processing	0.03	Recycle
1	Packaging, padding	Polymer foam	Polymer molding	0.015	Landfill
1	Packaging, box	Cardboard	Construction	0.125	Landfill
1	Other components	*Proxy material:* Polycarbonate	*Proxy process:* Polymer molding	0.04	Landfill

Transport

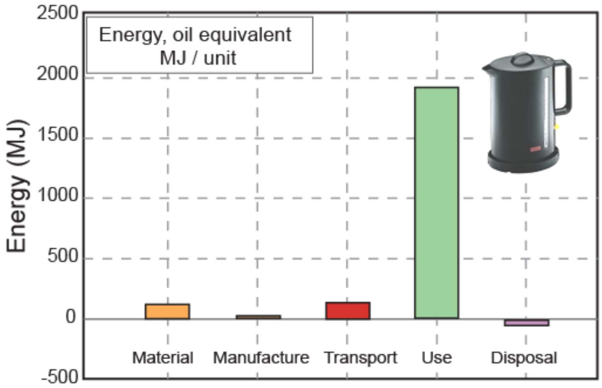
- 12,000 km, air freight
- 250 km 14 tonne truck

Use

- 6 minutes per day
- 300 days per year
- 3 years

Here is a second example: a 2 kW **electric jug-kettle**. The kettle is manufactured in South-east Asia and transported to Europe by air freight, a distance of 12,000 km. The table lists the bill of materials. The kettle boils 1 liter of water in 3 minutes. It is used to do this, on average, twice per day 300 days per year over a life of 3 years. At end of life metal and some plastic parts are recycled; the rest is sent to landfill.

Eco audit: the jug kettle



What do we learn?

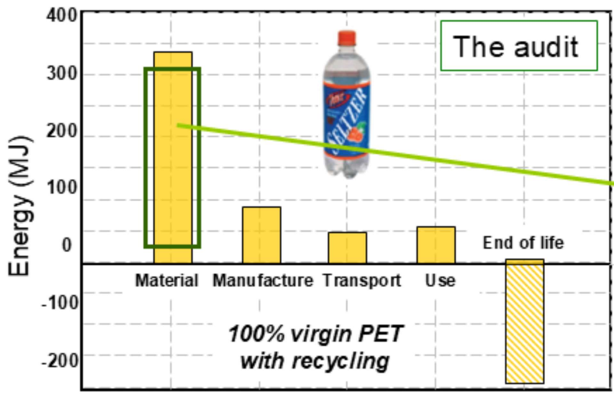
Little gained by change of material for its own sake
Much gained by insulation – double wall with foam or vacuum

The frame shows the **energy breakdown**. The first two bars – materials (120 MJ) and manufacture (10 MJ) – are calculated from the data in the table by multiplying the embodied energy by the mass for each component, and summing. Air freight consumes 8.3 MJ/tonne.km, giving 129 MJ/kettle for the 12,000 km transport. The duty cycle (6 minutes per day, 300 days for 3 years) at full power consumes 180 kW.hr of electrical power. The corresponding consumption of fossil fuel and emission of CO_2 depends on the energy mix and conversion efficiency of the host country. CES allows you to choose this.

The use-phase of life consumes far more energy than all the others put together. Despite using it for only 6 minutes per day, the electric power (or, rather, the oil equivalent of the electric power) accounts for 88% of the total. Improving eco-performance here has to focus on this use energy – even a large change, 50% reduction, say, in any of the others makes insignificant difference. Heat is lost through the kettle wall. Selecting a polymer with lower thermal conductivity or using an insulated double wall could help here – it would increase the embodied energy of the material bar, but even doubling this leaves it small. A full vacuum insulation would be the ultimate answer – the water not used when the kettle is boiled would then remain hot for long enough to be useful the next time it is needed. The seeming extravagance of air-freight accounts for only 6% of the total energy. Using sea freight instead increase the distance to 17,000 km but reduces the transport energy per kettle to a mere 0.2% of the total.

This dominance of the use-phase of energy (and of CO2 emission) is characteristic of small electrically powered appliances. Further examples can be found in the next case study and the exercises at the end of this chapter.

Eco-selection for a fizzy drink bottle



Material dominates

Minimize embodied energy

Design brief

Improve green credentials of bottle

⇨

Translation

Constraints

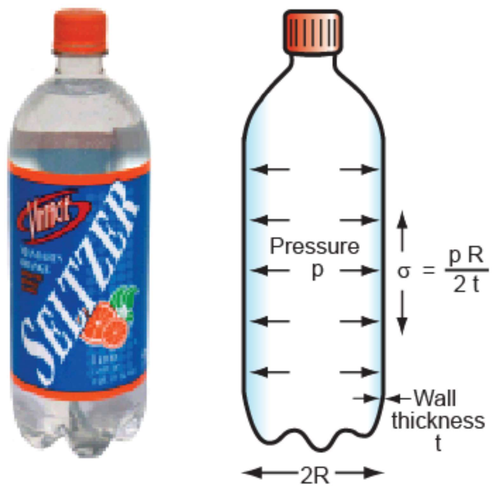
- **Able to be molded**
- **Transparent / translucent**
- **Able to contain pressure**

Objectives

- **Minimize embodied energy of bottle**
- **Minimize material cost of bottle**

Here is an example: systematic selection for the carbonated drink bottle. In its present form it is made of polyethylene terephthalate, PET. The audit shows that the material-energy of the bottle itself is the phase of life that consumes the most energy and releases the most carbon. The design brief is to improve the eco-profile of the bottle, which must at the same time be transparent (or at least translucent) so that the contents are visible, and the bottle must withstand the internal pressure and any accidental overloads without yield or bursting. The objective is to minimize the embodied energy per bottle.

Modelling the bottle



R = Bottle radius
t = Thickness of bottle wall
p = Internal pressure
σ_y = Yield strength of material
ρ = Density of material
H_m = Embodied energy of material/kg
E = Embodied energy/m^2 of wall
C_m = Material cost per kg

Cylindrical pressure vessel

- Circumferential stress $\sigma = \frac{pR}{t} < \sigma_y$
- Embodied energy per unit area of wall

$$E = tH_m\rho = pR\frac{H_m\rho}{\sigma_y}$$

Embodied energy / kg of material

- Find material with lowest energy, seek largest

$$\frac{\sigma_y}{H_m\rho}$$

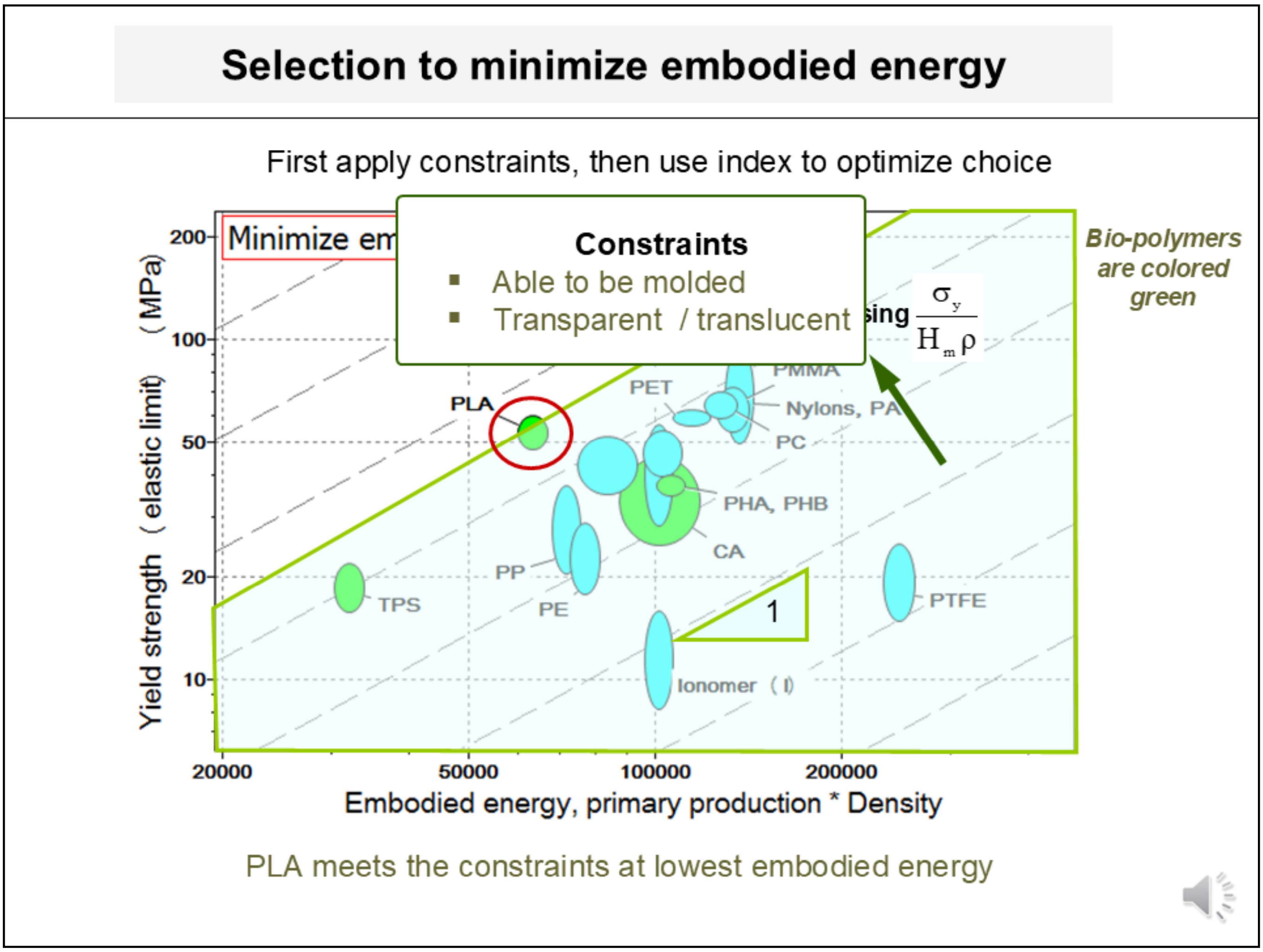
- Find material with lowest cost, seek largest

$$\frac{\sigma_y}{C_m\rho}$$

Price / kg of material

The bottle is modelled as a cylindrical pressure vessel. The internal pressure p creates a stress in the wall of the bottle, as indicated in the diagram. The circumferential stress is the larger one – its value is listed at the top. This stress must not exceed the yield strength of the material of the bottle, setting a minimum value for the wall thickness, t.

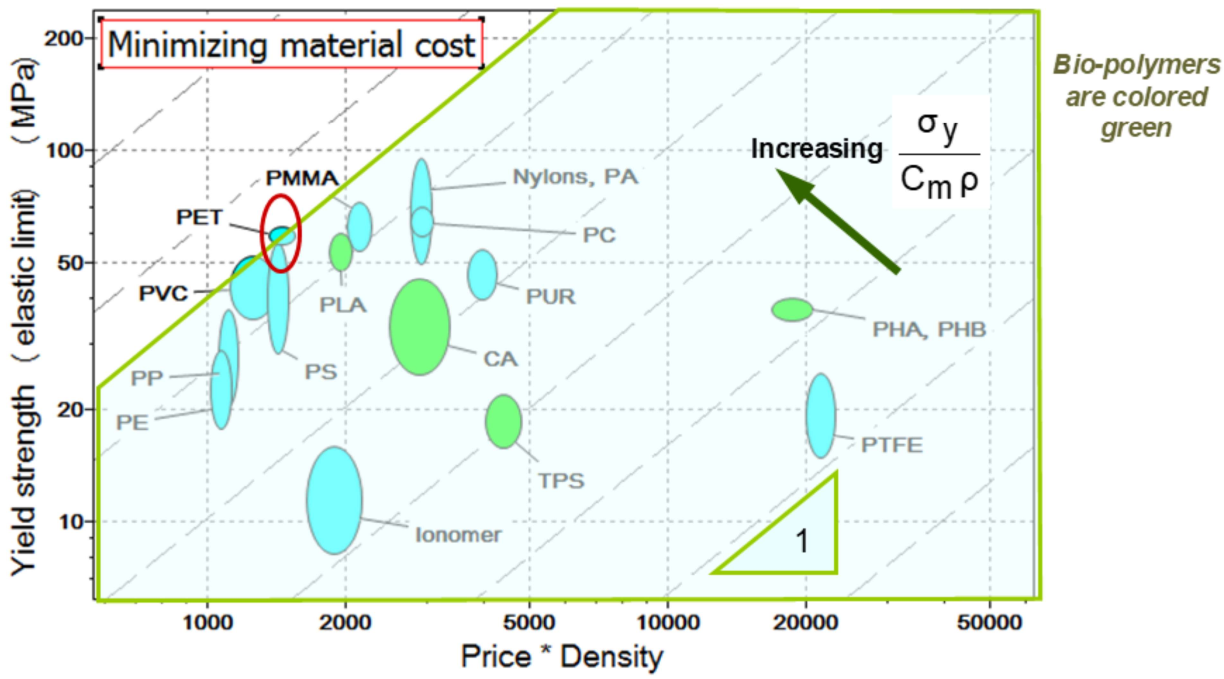
The embodied energy E of the bottle per unit area of wall is given by the second expression. The pressure p and the bottle radius R are fixed by the design. The energy E is minimized by seeking materials with the lowest value of the material property group $H_m\rho/\sigma_y$, or the maximum value of its reciprocal. The quantity is the **material index** for the problem.



This is a chart of **yield strength vs. embodied energy per unit volume** for polymers that are translucent or transparent. The contours show the index from the previous frame. Biopolymers are shown in green to distinguish them from those that are derived from oil, shown in blue. Two of these – polylactide, PLA and polyhydroxyalkanoates (PHA) perform exceptionally well. PLA, in particular, offers a reduction of embodied energy per bottle of about 40%.

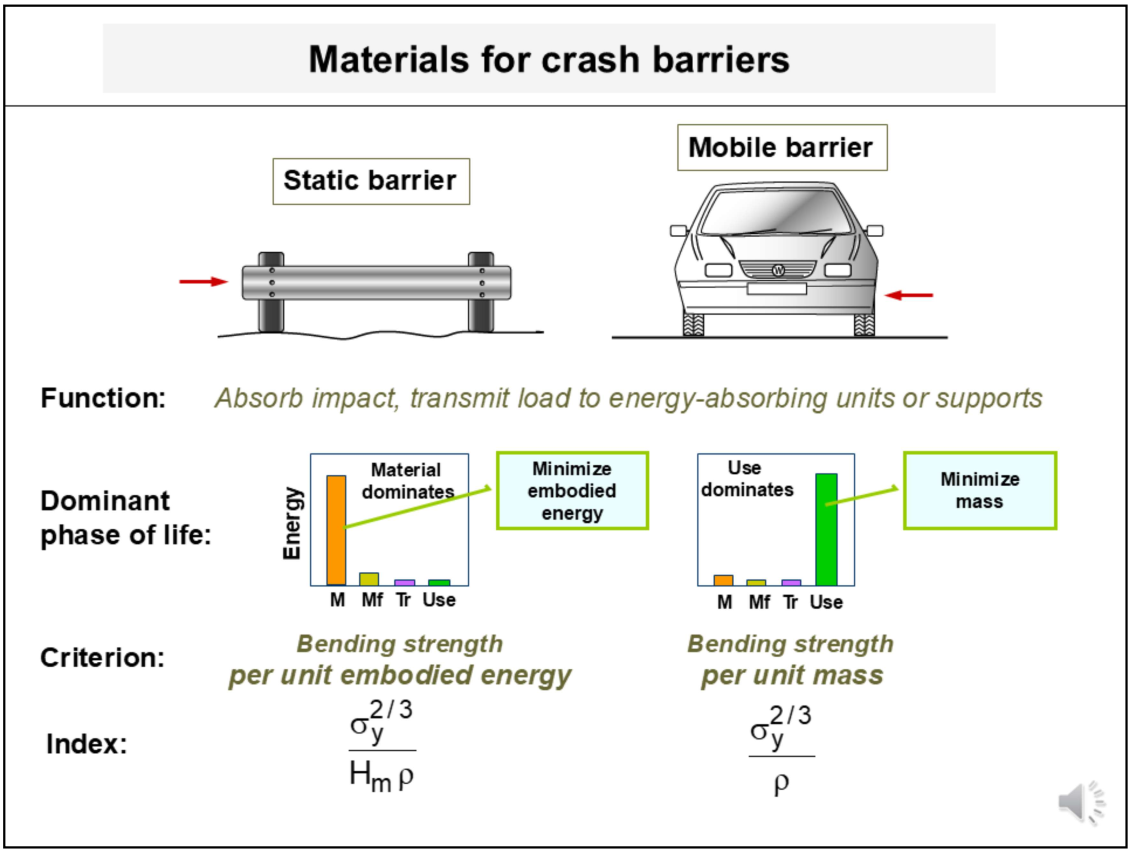
Selection to minimize cost

Can't ignore cost



PET meets the constraints at lowest cost

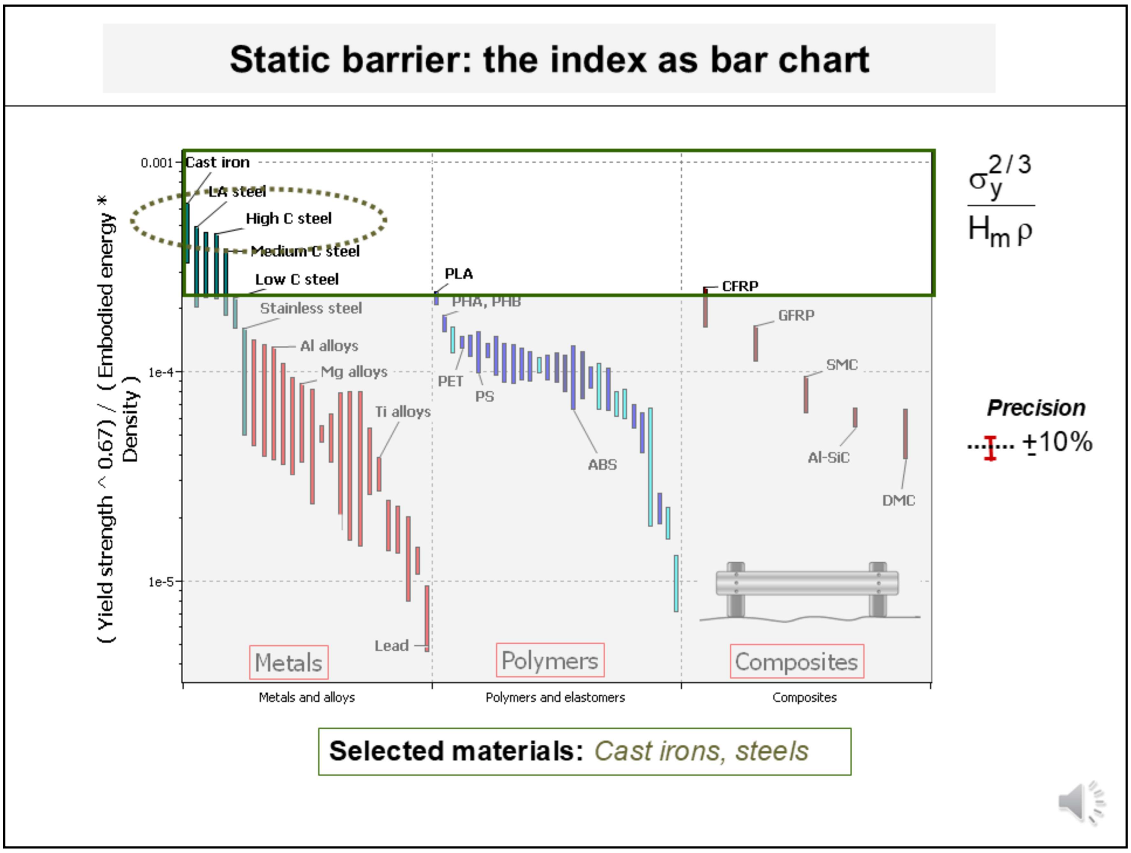
Why, then, are so few bottles made of PLA? Here is a chart of **yield strength vs. cost per unit volume** for the bottle. The contours show the material cost per unit area of bottle wall. By this criterion the bio-polymers (green) do not do so well. The cheapest material is PET – the material of choice for almost all pressurized drink bottles..



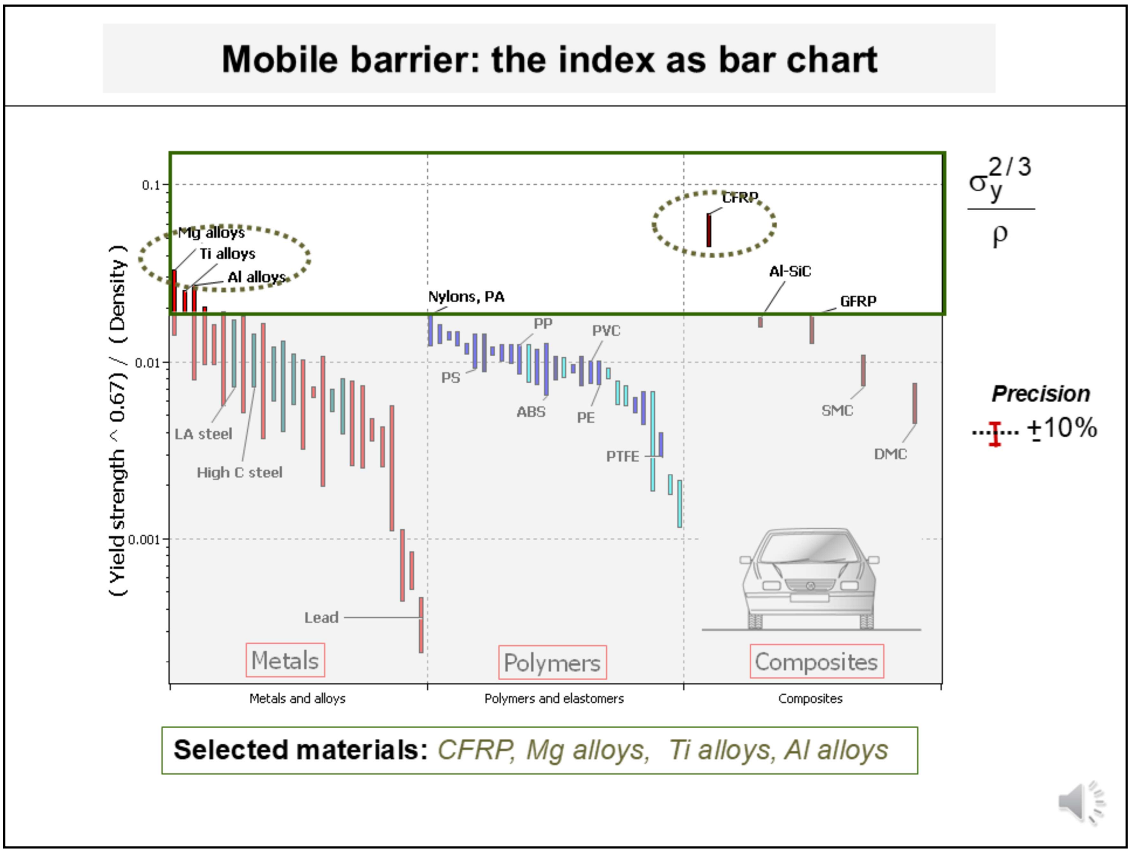
Crash barriers. Barriers to protect driver and passengers of road vehicles are of two types: those that are static – the central divider of a freeway, for instance – and those that move – the fender of the vehicle itself (this frame). The static type line tens of thousands of miles of road. Once in place they consume no energy, create no CO_2 and last a long time. The dominant phases of their life in the sense of Frame 4 are those of material production and manufacture. The fender, by contrast, is part of the vehicle; it adds to its weight and thus to its fuel consumption. The dominant phase here is that of use. This means that, if eco-design is the objective, the criteria for selecting materials for the two sorts of barrier will differ.

This frame shows the two types of barrier and a schematic eco-audit for each. For the static barrier on the left it is the material phase of life that is dominant., making the reduction of material energy the objective in redesign. For the mobile barrier on the right it is the contribution of the barrier mass to the mass of the vehicle that, over life, results in the largest commitment of energy, making a reduction in mass the objective in redesign.

In use (that is, in a crash situation) the barriers are loaded in bending – they must be strong enough in bending to transmit the load to the supports of the road barrier or to the energy-absorbing crush units on the car. The bottom line shows the relevant index. That for the static barrier on the left characterizes materials with low embodied energy per unit bending strength; that on the right characterizes low mass per unit bending strength. Both are plotted on the frames that follow.



The Y-axis of this chart is the index for the static barrier, made with CES EduPack Level 2. The green selection box isolates the materials with the largest values of this index. They are all **ferrous alloys – steels** and **cast irons**. They minimize the life-energy of a static barrier by minimizing the most energy-intensive phase – that of material extraction, casting and rolling.



The Y-axis of this chart is the index for the mobile barrier, again made with CES EduPack Level 2. The green selection box isolates the materials with the largest values of this index: **CFRP** and **light alloys**. They minimize the life-energy of a mobile barrier by minimizing the most energy-intensive phase – that of product use.

The long reach of legislation - Standards

Standards. ISO 14000 of the International Organization for Standardization (ISO) defines a family of standards for environmental management systems.3 It contains the set ISO 14040, 14041, 14042, and 14043 published between 1997 and 2000, prescribing broad but vague.

The standard is an attempt to bring uniform practice and objectivity into life-cycle assessment (LCA) and its interpretation, but it is not binding in any way.

ISO 14025 is a standard guiding the reporting of LCA data as an environmental product declaration (EPD)4 or a climate

Michael F. Ashby, Materials and the Environment (Third Edition), Butterworth-Heinemann, 2022, ISBN 9780128215210

This final frame summarizes the main findings of this Unit.

The long reach of legislation – European legistation

Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) (2006) requires manufacturers to manage risks from chemicals and to find substitutes for those that are most dangerous.

The list of restricted substances. A few examples of restrictions
that affect materials. Some are draconian: a total ban. Others are mild: keep it

asbestos (prohibited)
flame retardant compounds (limit 0.1%)
arsenic compounds (prohibited in wood products)
cadmium compounds (0.25% in galvanization, 0.01% in electronics)
chromium, hexavalent compounds (limited to 0.1% in electronics)
lead compounds (limit 0.1% in electronics)

…..

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This final frame summarizes the main findings of this Unit.

The long reach of legislation – European legistation

There are many more EU directives that influence the choice of materials.
Here, briefly, are some of them.

The **Product Liability Directive** (1985) imposes liability responsibility for damage caused by defective products.

The **Landfill Directive** (1999) sets rules for dealing with hazardous and nonhazardous wastes, banning the landfilling of many products, among them tires.

The **Volatile Organic Compounds (VOC)** Directive (1999) limits the emissions of VOCs from organic solvents in paints and cleaning fluids.

End-of-Life Vehicles (ELV) Directive (2000) sets norms for recovering materials from dead cars. The initial target was that 80% by weight must be recycled or reused. In 2015, the target was raised to 95%. The idea is to encourage redesign to maximize ease of disassembly.

This final frame summarizes the main findings of this Unit.

The long reach of legislation – European legistation

Restriction of Hazardous Substances (RoHS and RoSH2) Directive (2002 and 2011) bans the sale of new electrical and electronic equipment containing more than set levels of lead, cadmium, mercury, …..

Waste Electrical and Electronic Equipment (WEEE, 2002) sets collection, recycling, and recovery targets for electrical goods. Producers must pay for the collection, recovery, and safe disposal of their products and meet certain recycling targets.

The **Energy-Using Products (EuP, 2003**) and Energy-Related Products (2009) Directives impose eco-design requirements for products that use energyd appliances, electronic equipment, pumps, motors, and the likedand for products that are energy related even if they don't use itddouble glazing, faucets, and showers, for example.

The **Battery Directive** (2006) bans the sale of some classes of batteries …

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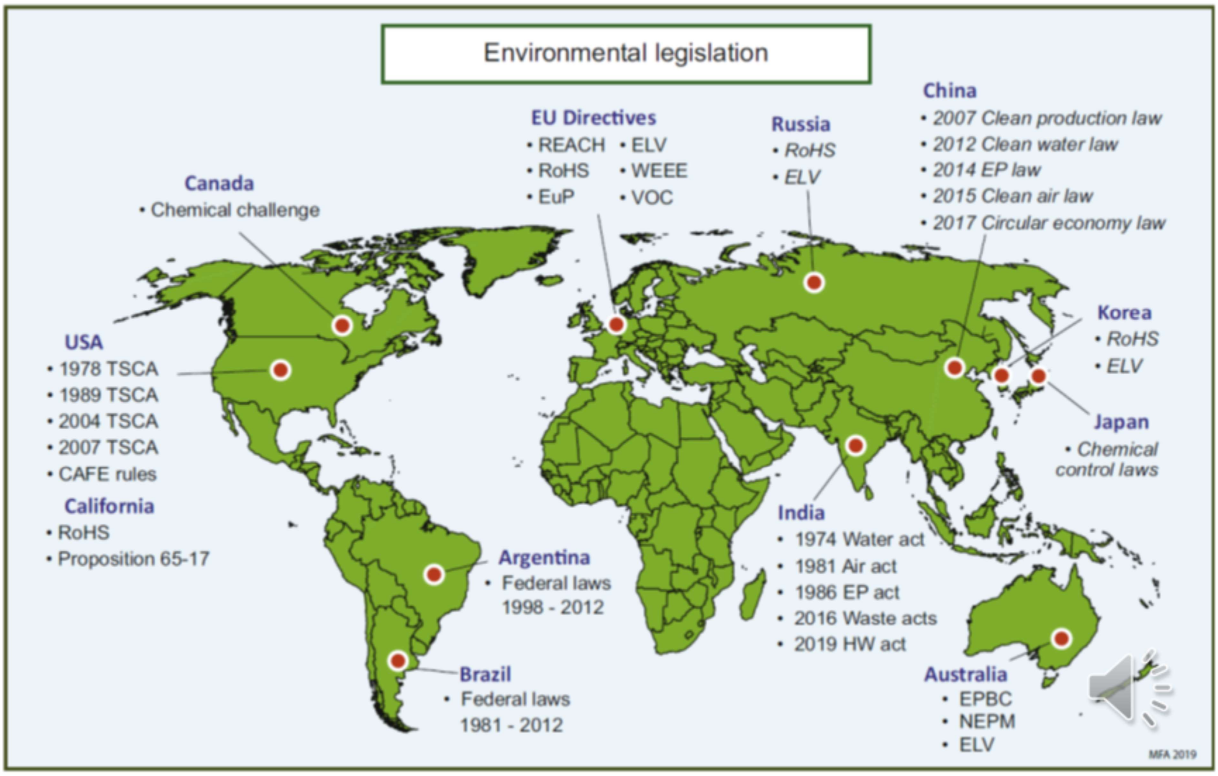
This final frame summarizes the main findings of this Unit.

The long reach of legislation – worldwide



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This final frame summarizes the main findings of this Unit.

The long reach of legislation

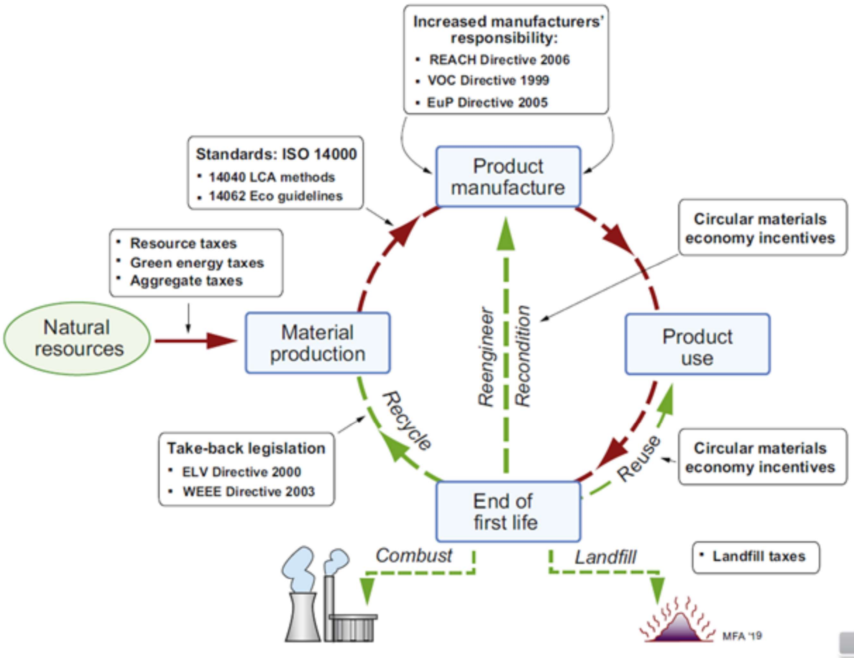

FIGURE 5.3 *Interventions and other mechanisms that influence the flows in the material life cycle.*

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This final frame summarizes the main findings of this Unit.

So what?

- Eco-informed material choice is part of the eco-design process
- An eco-audit identifies the most damaging phase of life and identifies strategies for overcoming it
- Systematic strategies, using material indices, optimize material choice to minimize life energy
- The CES EduPack software allows the strategy to be implemented and documents the steps taken to minimize eco-impact.

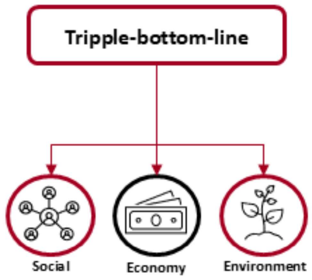
This final frame summarizes the main findings of this Unit.

Critical Raw Materials

global ressources informed material choice

Challenges to today's society

Sustainability Framework in industrial context



UN: the way forward

Yet, we must ask **how** are these goals achieved?
In part, each goal can be achieved via technological solution.

Current challenges faced by society can be broken down into three distinct categories:

- **Social**
- **Economic**
- **Environmental (Ecological)**

Acknowledging this the UN developed 17 sustainable development goals. These aim to **improve** each aspect of the triple bottom line.

Material flows in strategic technology

There are now many materials that are key to the deployment of technology that will help to solve these problems. These are often referred to as **technology materials**.

↓

Each group of materials in the figure has an associated supply risk. We can see that some of these groups, notably the **Heavy Rare Earth Elements (HREEs)** and **Light Rare Earth Elements (LREEs)**, are high risk.

↓

How do we **categorise** these materials and how can we **mitigate** these risks without sacrificing technological capability and efficiency?

LREE - La, Ce, Pr, Nd, Sm
HREE - Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Y

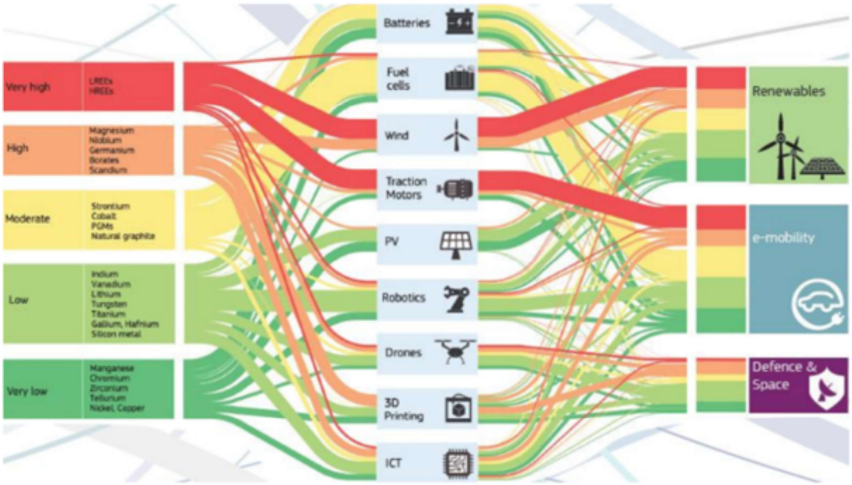


Fig 1 European Commission, Critical materials for strategic technologies and sectors in the EU – a foresight study 2020

These are just a few examples of how these materials are used in technology. They are used much more extensively in practice.

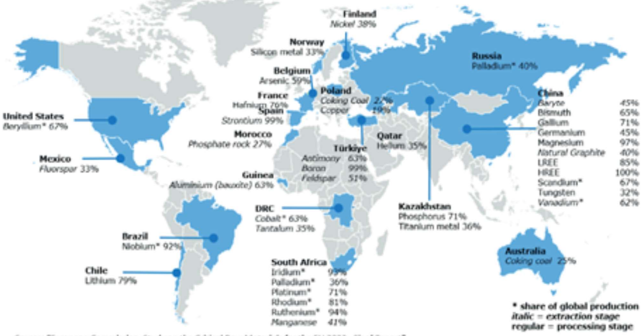
The REE are split into two groups, the Light Rare Earth Elements (LREE - La, Ce, Pr, Nd, Sm) and Heavy Rare Earth Elements (HREE - Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Y), both for physico-chemical and commercial reasons. For more see here, for instance, Rare Earth Elements | CRM Alliance

Critical Raw Materials

There is an inherent **risk** to the **supply** of any material. In order to be able to continue developing and deploying key technologies it is vital to mitigate or avoid this.

Countries and other entities began creating lists of materials that had a high associated **supply risk** and were also of high **economic importance**.

Groups of materials of particularly high economic importance and supply risk are referred to **as Critical Raw Materials** (**CRMs**). Different countries have different lists of CRMs depending on access to domestic supply, geopolitics and economic strength nationally. Such lists are reviewed every 3-4 years.



Source: "European Commission, Study on the Critical Raw Materials for the EU 2023– Final Report"

"Strategic Raw materials" and "Critical Raw materials" are sometimes used interchangeably. Often, however, "strategic" refers more to military purposes or how relevant they are for "strategic technologies". Copper and Nickel do not meet the CRM thresholds but are on the CRM list as Strategic Raw Materials (European Critical Raw Materials Act 2023).

Economic importance is not strictly evaluated based on GDP but rather the contribution to the economy the material creates both directly and indirectly.

"Strategic raw materials" and "Critical raw materials" are sometimes used interchangeably. Often, however, "strategic" refers more to military purposes.

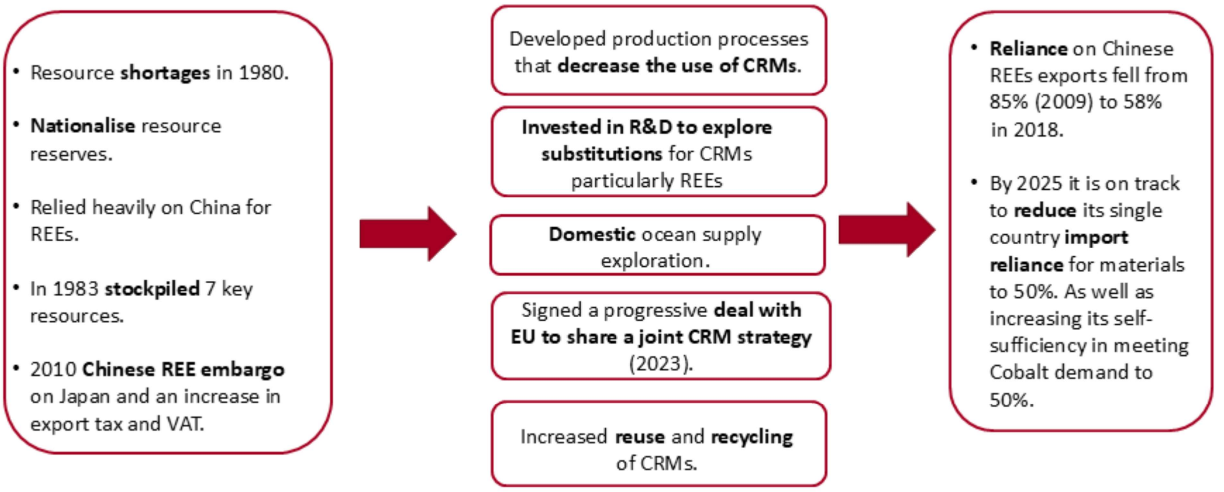
Important: In the EU, it is not the same! "Strategic raw materials" are a subset of critical raw materials that are, amongst others, defined by their expected demand growth and their relevance for "strategic technologies"

Criticality broader view

The scope for criticality assessment can be different, be that at a level of economy, sector, technology, company, product. For an individual company in the EU the whole list of critical raw materials might not be applicable.

The level of criticality depends on the probability of the supply disruption and vulnerability to supply disruption (or economic importance), which can be influenced by geopolitical, geological, economic, technical, social and environmental factors.

Example of Rare Earth Elements (REE) strategy in Japan



In the mid 1980 with demand growing and domestic supplies waning many countries began to nationalise resource reserves.

Japan, a country that relied heavily on China for resource exports, recognised the potential impact that reduced resource supply could have.
As a result, in 1983 Japan began to stockpile 7 resources including, Cobalt, Tungsten and Vanadium. The Chinese also increased export taxes on REEs.
In 2010 China placed an REE embargo on Japan, a result of tensions surrounding the Diaoyu Islands and the detention of a Chinese boat captain.

Reaction: Japanese government cooperated with companies to focus on mitigating the impact of import over reliance. As a result companies such as Toyota and Mitsubishi began to focus on decreasing the use of CRMs and looking for substitutes. They also created strategies to reuse and recycle materials as well as establishing domestic supplies. Recently, submarine exploration found and have established 6 deposits of CRMs in the ocean.
Results: In 2018 Japan had decreased its reliance on Chinese REEs from 85% in 2009 to 58%. By 2025 it is on track to reduce its single country import reliance for materials to 50% as well as increasing its self-sufficiency in meeting Cobalt demand to 50%. It has also increased its reserves to 180 days of domestic consumption from 60 and recently signed a deal with the EU to collaborate in meeting CRM challenges.

Result of CRM control to the Triple-bottom-line

Tripple-bottom-line → *Japan*

Economy

- **Diversified** resource supply reduces risk of material shortages. e.g. Japanese supply REEs from Australian mine - Lynas Rare Earth.
- **Innovative technology** with less CRMs can increase competitiveness
- Lessened **reliance** on **single exporters** stabilises industrial economies as commodity volatility and production bottlenecks (a result of supply shortage) are reduced.

Social

- Exploration of new technologies domestically helps engagement of **local communities.**
- Mining conditions in another industrialized country, such as Australia are under scrutiny of international and local regulations - an impact on **workers** can be better controlled.

Environment

- More stable supply of technology materials (CRMs) in Japan means less risk of disruption for production of **sustainable/green technologies.**
- Seabed mining is in exploratory stage, while an idea of bringing more reliable domestic supply is a very attractive one, can cause **environmental disruption.**
- Recycling and reuse reduces strain on **environment.**

Assessing criticality

Criticality assessments are developed to raise awareness of CRMs and carried out by governments, companies and even individuals.

If a company uses its own criticality assessment, each company-specific mitigation steps influences the individual criticality score; if it e.g. uses a national list as a reference, this is not necessarily the case.

The EU evaluates the criticality of a material by aggregating into single values of supply risk and the economic importance. A threshold is then defined for both axes. If a material is found to be above both thresholds – it is considered critical.

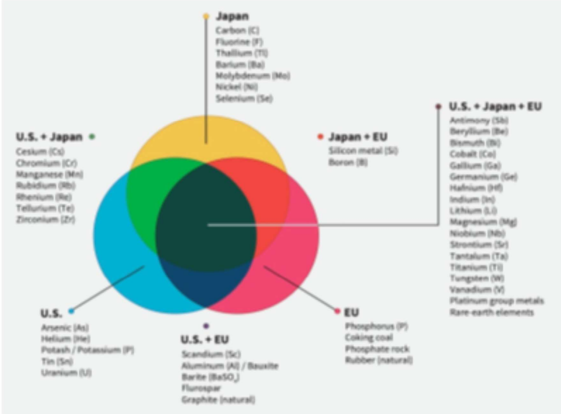
Supply risk categories in Raw Material Supply Risk Assessments
- more information in Helbig C. et al (2021, 3)

Challenges with criticality assessment

> "Raw material criticality is the field of study that evaluates the economic and technical dependency on a certain material, as well as the probability of supply disruptions, for a defined stakeholder group within a certain time frame". (Schrijvers et al, 2020, 2).

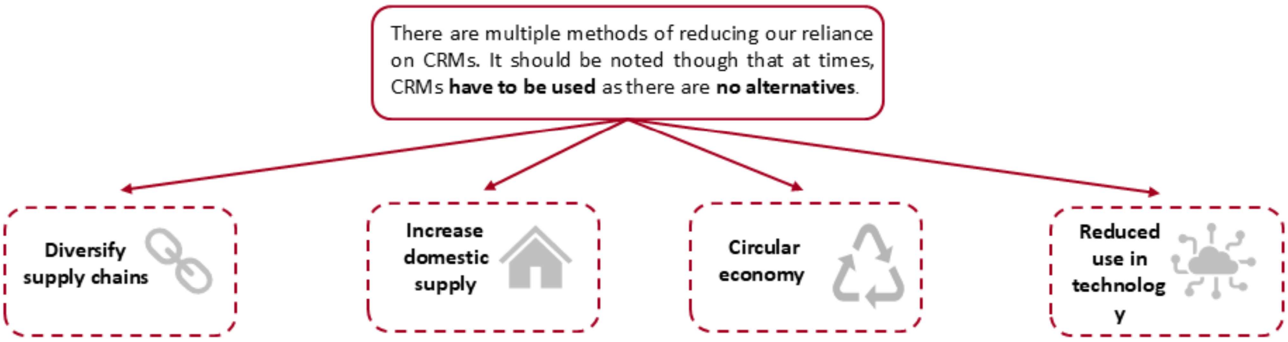
Issues with criticality evaluation:

- Differences in goals and scope, leading to different priorities and indicators, not always transparent enough and limited by availability of quality data, yet also reflect individual cases.
- Comprehensive review of criticality assessment methods is provided here: (Schrijvers et al, 2020)



Comparison of CRM lists for the US, EU and Japan
- more information in (Nakano J., 2021).

Methods of mitigating criticality



Reduces reliance on specific exporting nations. This means potential risk of governance and negative social impact are reduced.

By investing in domestic supply the need to import materials from other nations is decreased.

Materials can either be reintegrated into the same technology by recycling or reused for different purposes in a degraded form.

Recycling can reduce supply risk, yet is not easy to increase recycling of certain elements as they are found in small quantities and their recycling rates are low at the moment.

Yet, a recycled content declaration requirement would apply from 1 January2027, for instance, to industrial, EV and automotive batteries containing cobalt, lead, lithium or nickel in active materials with mandatory minimum levels of recycled content from 2030. These targets should encourage market of secondary materials.

Regulation (EU) 2023/ of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC (europa.eu)

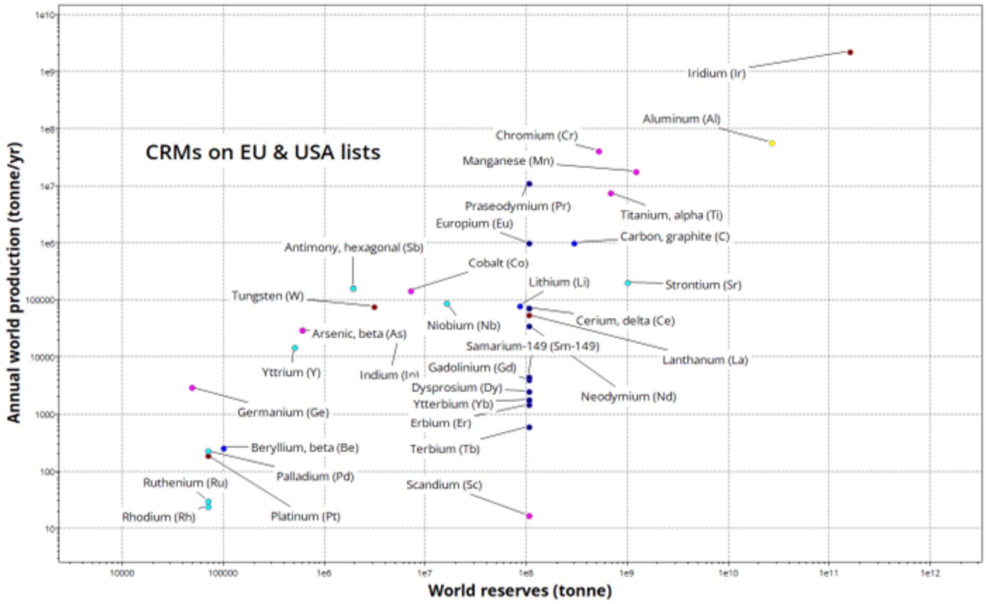
The quantity of a material used could be reduced; examples include cathode technologies that now can use significantly less Cobalt.

Evaluating criticality with Ansys Granta EduPack

Can check to see if an element is on either the EU or US critical raw material list in the Element record.

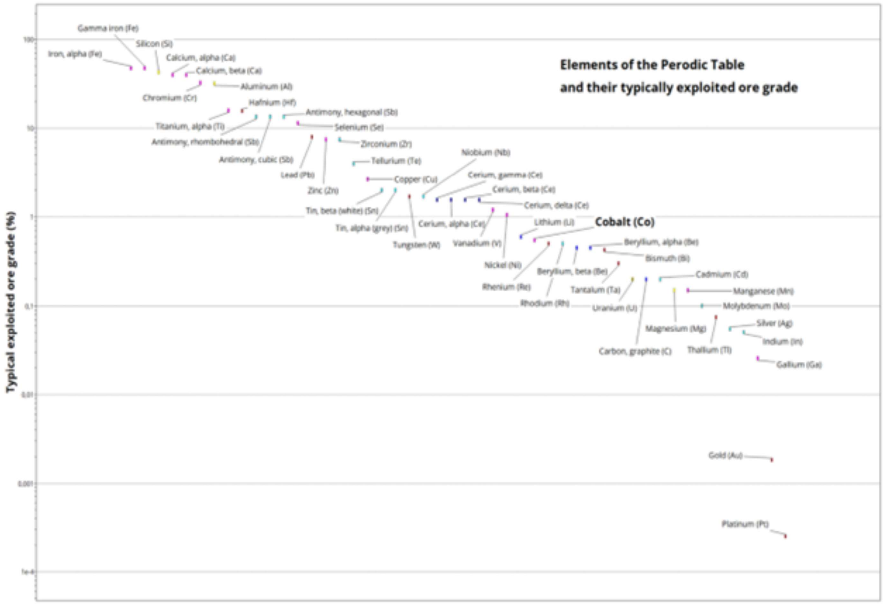
Can also see if more than 5% of a material contains critical elements in the Material record.

Analyzing CRMs data with Ansys Granta EduPack



Slide is made with Ansys Granta EduPack Version 2024 R1

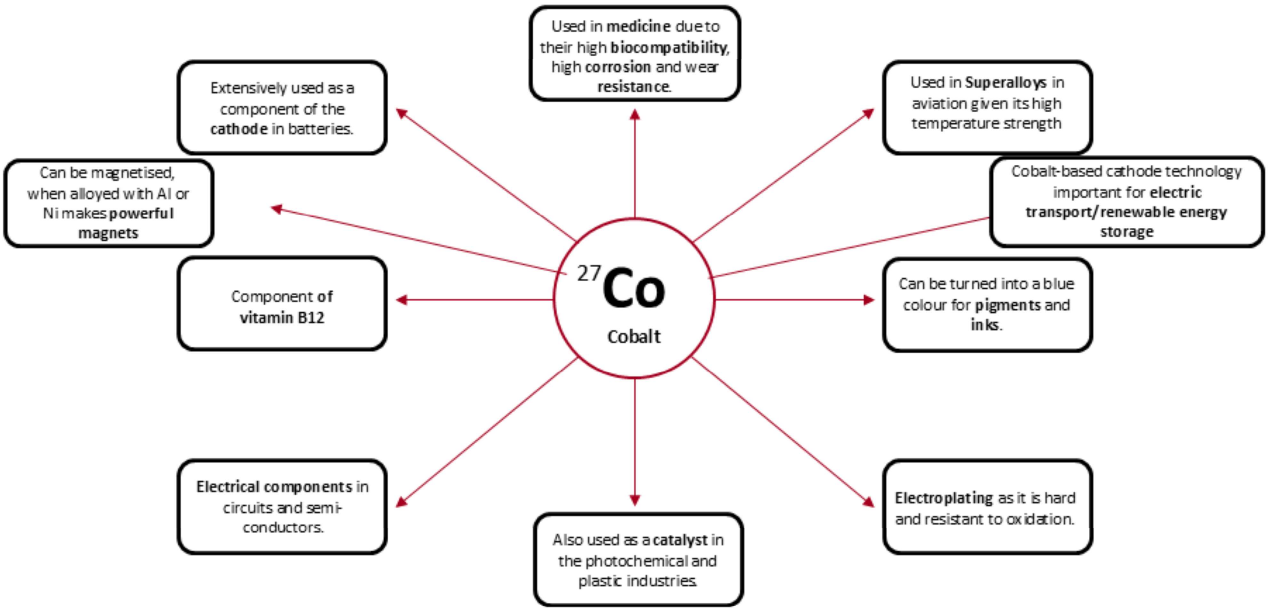
Ore grades & Elements in Ansys Granta EduPack



The ore grade is an indicator for the abundance of each element in the extracted rock. Cobalt has a varied grade and is difficult to extract and process.

Slide is prepared with Version 2024 R1 EduPack

The many uses of Cobalt

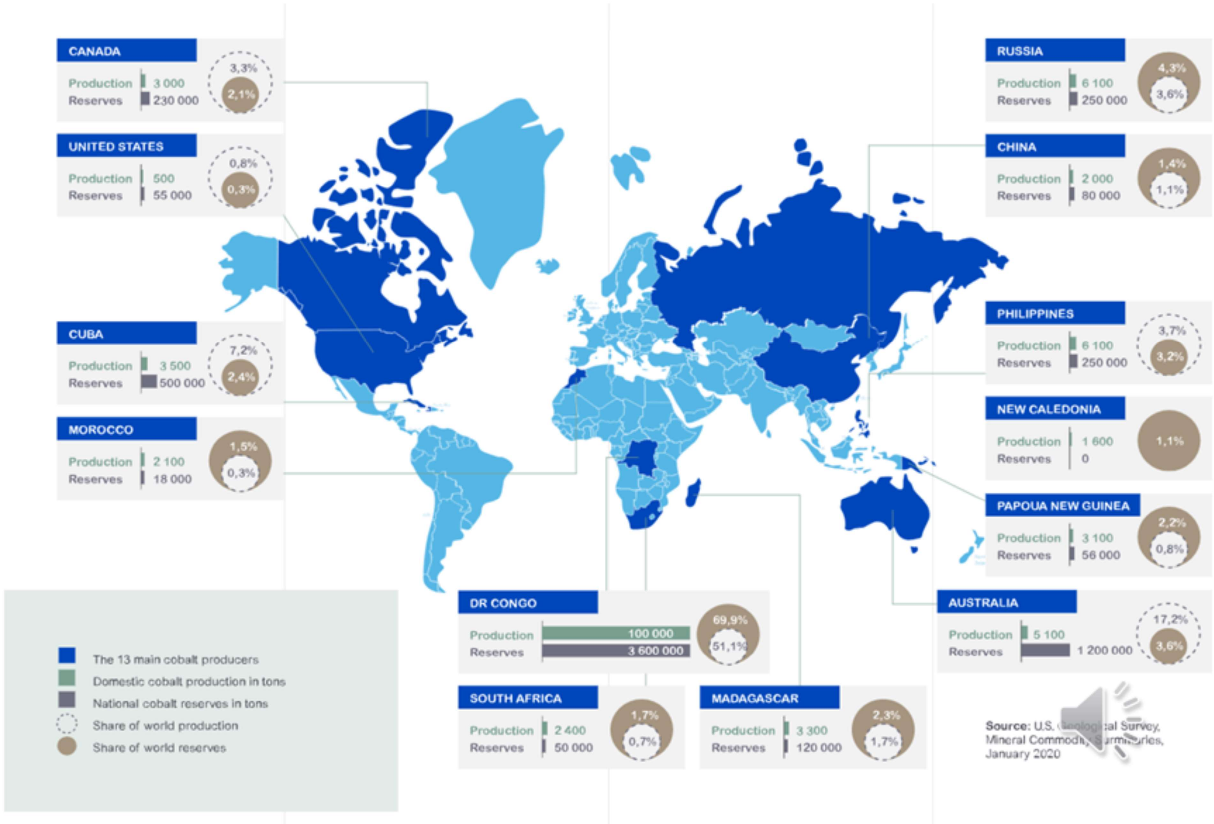


https://www.omlus.com/wp-content/uploads/2017/12/Cobalt-Institute-60-yrs-1024x561.png - a modified figure from this source

Cobalt (Co) is critical for many high-tech applications, in particular, high-strength materials, magnets and rechargeable batteries. The majority of world cobalt output arises as a by-product of extracting other metals, such as nickel (Ni) and copper (Cu). Significant differences in cobalt ores makes it challenging to develop a single extraction or a single treatment process.

Quentin Dehaine, Laurens T. Tijsseling, Hylke J. Glass, Tuomo Törmänen, Alan R. Butcher,
Geometallurgy of cobalt ores: A review,
Minerals Engineering,
Volume 160,
2021,
106656,
ISSN 0892-6875,
https://doi.org/10.1016/j.mineng.2020.106656.

World Cobalt production and reserves in 2019



https://www.cobaltinstitute.org/about-cobalt/cobalt-life-cycle/

The problems with Cobalt

Cobalt has a wide range of applications and is used **extensively** in **sustainable** technologies. **Demand** has significantly **increased** year-on-year.

The **DR Congo** has more Cobalt deposits than every other nation combined.
Co mines in the DRC are mostly owned **by foreign companies**; China dominates refining (2/3 of world production).

The DR Congo relies heavily on 'artisanal' mining. This essentially refers to:

- **Child Labor**
- **Slave Labor**
- **Extremely low salary**
- **Use of hands or pickaxe and shovel**
- **No safety equipment**

Cobalt is a **gamma emitter** and is therefore, radioactive. Complications of unsafe extraction conditions have been shown to include:

- **Cancer**
- **Thyroid issues**
- **Vomiting and heart complications**
- **Asma and pneumonia**
- **Damage to water supply and ecology**

The breakdown

Issues:

- Cobalt is a technology material, and it is therefore of **economic importance. Demand** has greatly increased.
- Extraction grade material is sourced mainly from the DR Congo. The human rights abuses and poor governance in the DR Congo creates a **supply risk and lead to negative social consequences**.

- It is important to note that here the supply risk is **not** a result of the limited reserves, but rather the risk of reliance on a country with **poor governance** and working conditions.
- This creates **reputational risk** for companies, supplying materials from this region, affecting their brand value.

Mitigation:

- Technologies that are **less reliant** on Cobalt could be developed, e.g. **substitution**.
- **Diversification of supply chain and increase of its transparency, potentially via certification** route.
- **Exploration of domestic supply.**
- Increase **reuse** (and recycling) and promote material **circularity,** decreasing demand of primary production.
- **Opportunities for social investments to combat** negative social consequences.

Summary

Groups of materials of particularly high economic importance and supply risk are referred to as Critical Raw Materials (CRMs).

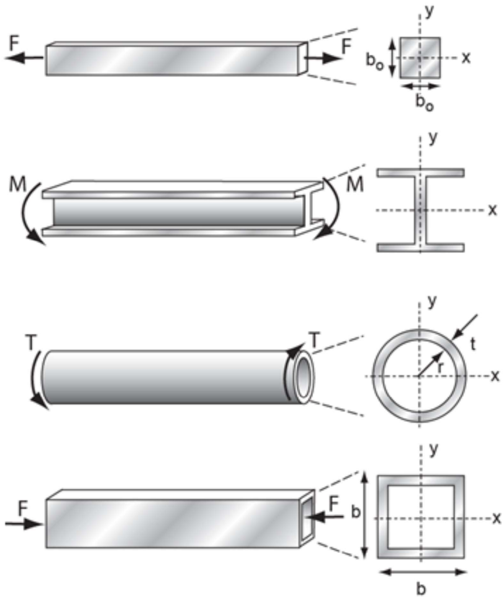
Different countries have different lists of CRMs depending on access to domestic supply, geopolitics and economic strength nationally.

There are different methods for criticality assessment, varied in goals and scopes, using different indicators.

Example of Cobalt shows high importance of CRMs and complex challenges in many cases.

Structural sections:

shape in action

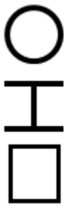


Structural sections

When materials are loaded in bending, in torsion, or are used as slender columns, ***section shape*** becomes important

Shape = cross section formed to a

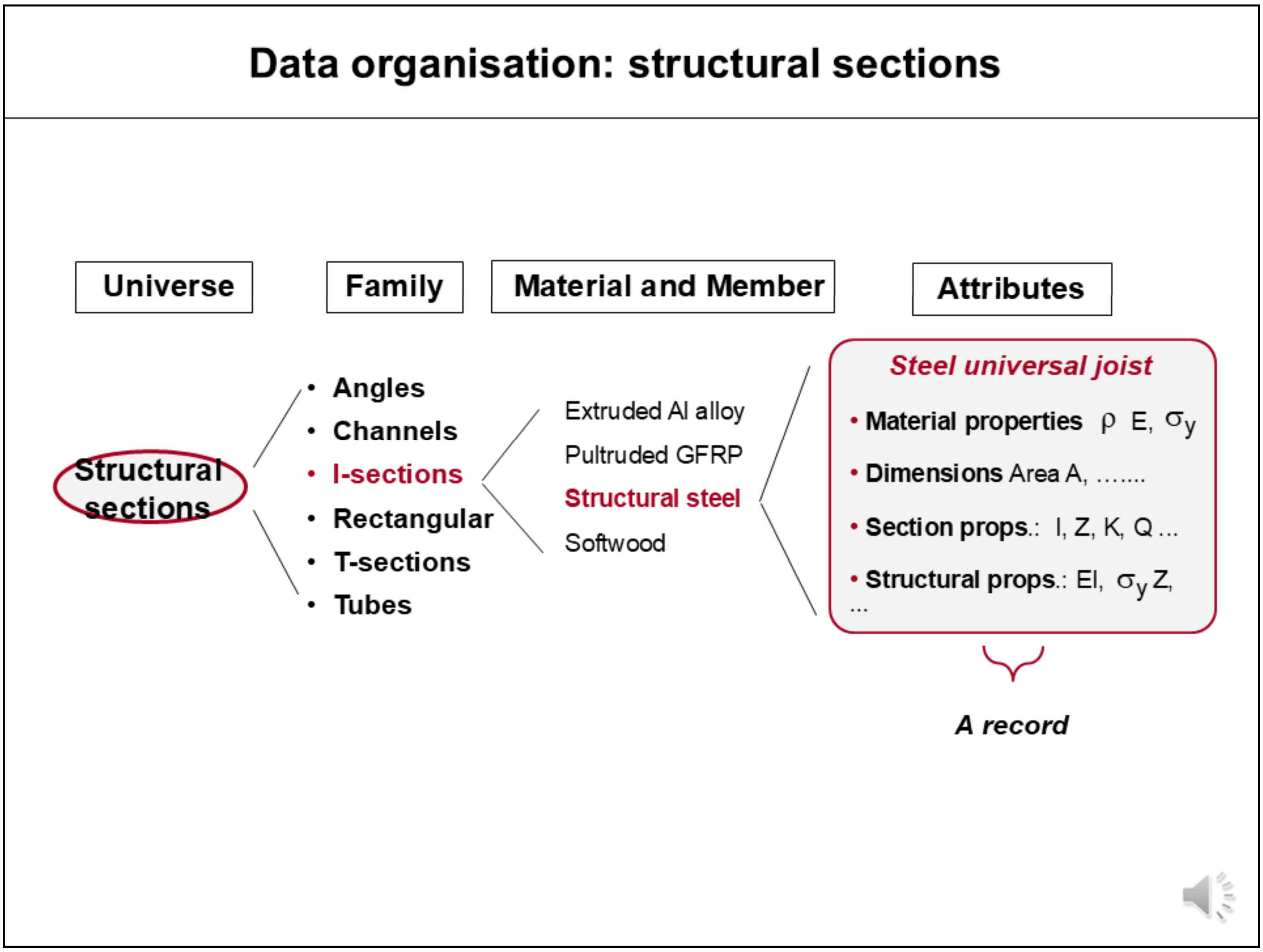
- Tube
- I-section
- Hollow box



All increase

- Second moment of area I
- Section modulus Z
- Bending stiffness $E\,I$
- Bending strength $\sigma_y\,Z$ *(called YZ in the database)*

When components carry bending, torsion or compressive loads, both the **area of the cross-section** and its **shape** are important. By *shape* we mean that the cross-section is formed to a tube, I-section or the like. *Efficient shapes* use the least material to achieve a given stiffness or strength – they have high values of the second moment o area, I, section modulus, Z, and other moments. It might seem that the way forward is to first choose the shape, then form the material into that shape. But some materials are routinely made into efficient shapes are some or not, either because of manufacturing difficulties or because they buckle too easily. So material and shape are coupled, requiring a method of choosing them together.



Standard sections are widely available in **structural steel, extruded aluminum alloy, pultruded GFRP** and **wood**. They have the shape shown here – rectangular, box, cylinder, tube, I-sections, U-sections and angles. A good way to get a feel for how shape efficiency is used in practice is to examine these. The CES structural sections database contains 1881 records covering the full range of standard sections. The data organization is shown here. The first level – the families – refers to shape. The choice of shape, it will be remembered, is dependent on the way the section will be loaded: I, L an U-sections are good in bending but poor in torsion; closed circular and box sections carry both torsion and bending well. The second level of the tree is the material – here we list the four for which standard sections are widely available. Each of these comes in many different sizes, and for each size there is a set of attributes. The records in the database detail these attributes: material properties, dimensions, section properties such as I and Z, and structural properties such as E.I and σ_y.Z.

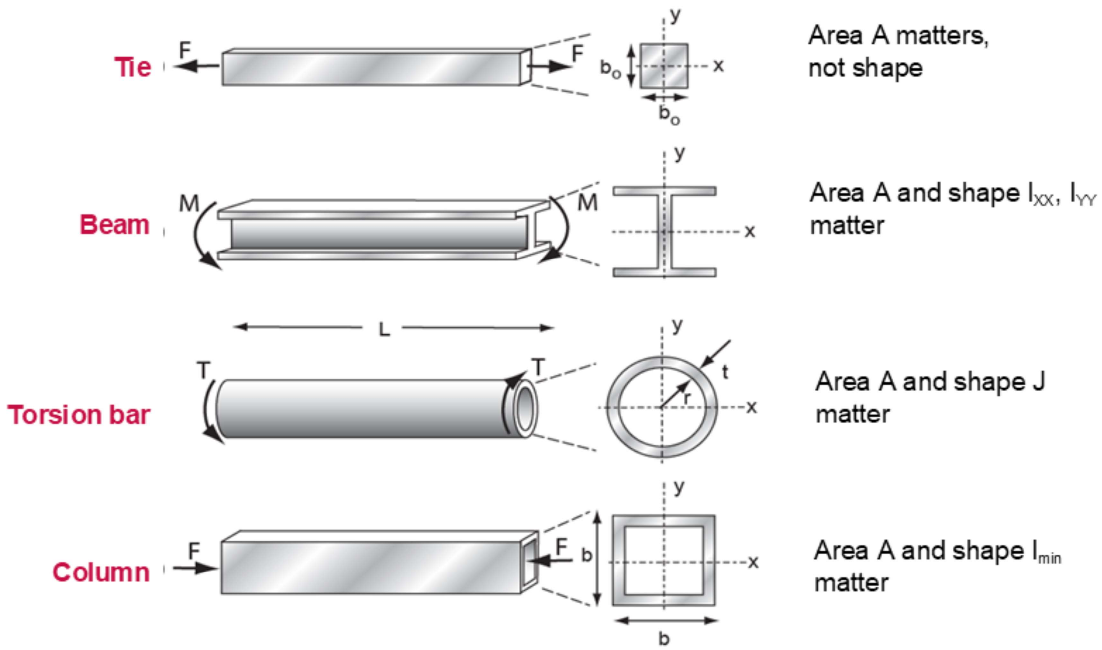
Shape efficiency

- When materials are loaded in bending, in torsion, or are used as slender columns, section shape becomes important
- "**Shape**" = cross section formed to a
  - tubes
  - I-sections
  - tubes
  - hollow box-section
  - sandwich panels
  - ribbed panels
- "**Efficient**" = use least material for given stiffness or strength
- Shapes to which a material can be formed are limited by the material itself
- Goals: understand the limits to shape
  develop methods for co-selecting material and shape

In many applications section shape is not a variable. But when components carry bending, torsion or compressive loads, both the area of the cross-section and its shape are important. By *shape* we mean that the cross-section is formed to a tube, I-section or the like. *Efficient shapes* use the least material to achieve a given stiffness or strength. It might seem that the way forward is to first choose the shape, then form the material into that shape. But some materials are routinely made into efficient shapes are some or not, either because of manufacturing difficulties or because they buckle too easily (more on that later). So material and shape are coupled, requiring a method of choosing them together.

Shape and mode of loading

Standard structural members



Certain materials can be made to certain shapes: what is the best combination?

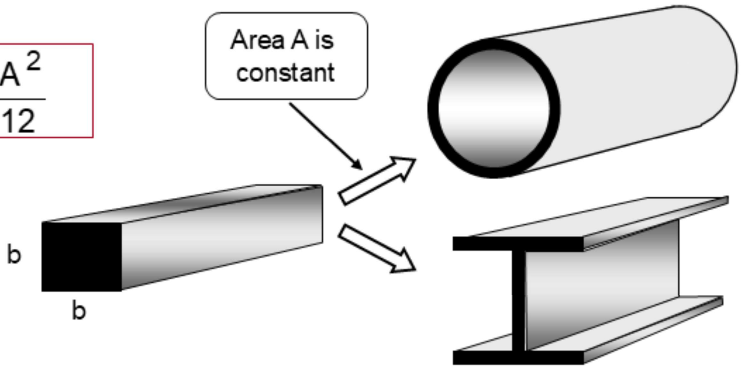
The choice of section shape is linked to the mode of loading. I-sections resist bending but are poor in torsion. Tubes resist torsion well. Tubes and box sections are good as columns, though I-sections are often used because their entire surface can be reached for painting and inspection, whereas the inner surface of tubes and boxes cannot.

Shape efficiency: bending stiffness

- Take ratio of bending stiffness S of shaped section to that (S_o) of a neutral reference section of the same cross-section area
- Define a standard reference section: a solid square with area $A = b^2$
- Second moment of area is I; stiffness scales as EI.

$$I_o = \frac{b^4}{12} = \frac{A^2}{12}$$

Area $A = b^2$



$$I = \int y^2 b(y)\,dy$$

Area A and modulus E unchanged

- Define **shape factor for elastic bending,** measuring efficiency, as

$$\varphi_e = \frac{S}{S_o} = \frac{EI}{EI_o} = 12\,\frac{I}{A^2}$$

The obvious way to measure shape efficiency is to compare the behaviour of a shaped section with that of a standard section with the same area – and thus the same mass of material per unit length. We take the standard section to be a *solid square*. If the square section is reshaped into a tube or I-section, the cross section area stays the same but the bending stiffness increases. Bending stiffness is proportional to EI where E is Young's modulus and I is the second moment of area of the cross section. The standard and the shaped beam are the same material, so E does not change. The second moment I increases from

$$I_o = \frac{A^2}{12}$$

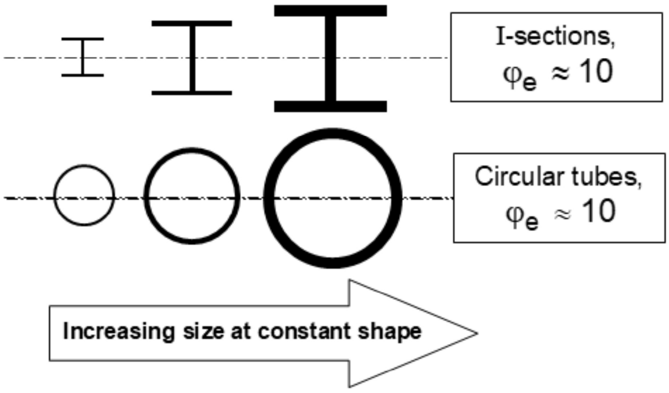
to I, so the bending stiffness inc e factor

$$\varphi_e = \frac{I}{I_o} = \frac{12I}{A^2}$$

The quantity ϕ_e measures e shape when stiffness is the goal.

Properties of the shape factor

- The shape factor is dimensionless -- a pure number.
- It characterizes shape.



- Each of these is roughly 10 times stiffer in bending than a solid square section of the same cross-sectional area

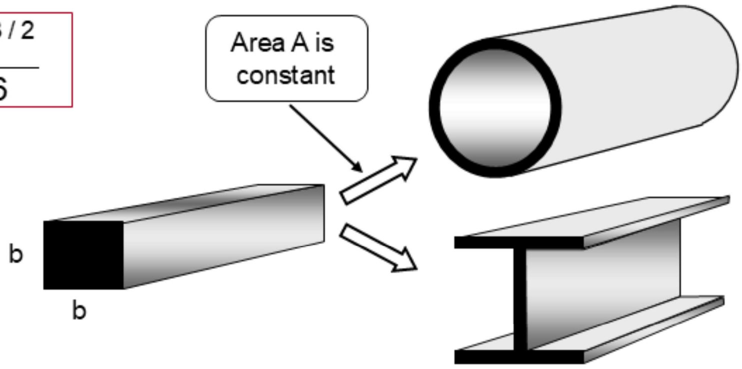
Area A has dimensions (m2) but shape ϕ_e , does not – it is a pure number. The frame shows I-sections and tubes with ϕ_e = 10, meaning that they are 10 times stiffer in bending than a solid square section of the same area. The three I-sections differ in size, but all have the same shape factor – each is a magnified version of the one on its left. The same is true of the tubes.

Shape efficiency: bending strength

- Take ratio of bending strength F_f of shaped section to that ($F_{f,o}$) of a neutral reference section of the same cross-section area
- Section modulus of area is Z; strength scales as $\sigma_y Z$

$$Z_o = \frac{b^3}{6} = \frac{A^{3/2}}{6}$$

Area $A = b^2$



$$Z = \frac{I}{y_{max}}$$

Area A and yield strength σ_y unchanged

- Define **shape factor for onset of plasticity (failure),** measuring efficiency, as

$$\varphi_f = \frac{F_f}{F_{fo}} = \frac{\sigma_y Z}{\sigma_y Z_o} = 6\frac{Z}{A^{3/2}}$$

A parallel argument leads to the definition of the shape factor for the onset of yield or failure in bending. Here the act of shaping increases the section modulus Z. The efficiency is the ratio of this to the value

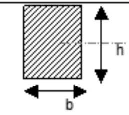
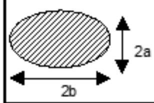
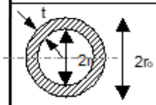
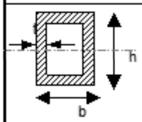
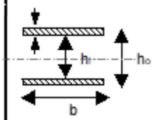
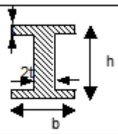
$$Z = \frac{A^{3/2}}{6}$$

for the solid square section, giving the shape factor

$$\varphi_f = \frac{Z}{Z_o} = \frac{6\,Z}{A^{3/2}}$$

The quantity ϕ_f measures the efficiency of the shape when strength is the goal. Shapes with high ϕ_e have high ϕ_f as well. Similar shape factors characterise stiffness and strength in torsion. See book from Ashby for further reference.

Tabulation of shape factors

Section shape	Area A m	Second moment I, m^4	Elastic shape factor
	bh	$\frac{bh^3}{12}$	$\frac{h}{b}$
	πab	$\frac{\pi}{4}a^3b$	$\frac{3}{\pi}\frac{a}{b}$
	$\pi(r_o^2 - r_i^2)$ $\approx 2\pi rt$	$\frac{\pi}{4}(r_o^4 - r_i^4)$ $\approx \pi r^3 t$	$\frac{3}{\pi}\left(\frac{r}{t}\right)$ $(r >> t)$
	$2t(h+b)$ $(h, b >> t)$	$\frac{1}{6}h^3 t(1 + 3\frac{b}{h})$	$\frac{1}{2}\frac{h}{t}\frac{(1+3b/h)}{(1+b/h)^2}$ $(h, b >> t)$
	$b(h_o - h_i)$ $\approx 2bt$ $(h, b >> t)$	$\frac{b}{12}(h_o^3 - h_i^3)$ $\approx \frac{1}{2}bth_o^2$	$\frac{3}{2}\frac{h_o^2}{bt}$ $(h, b >> t)$
	$2t(h+b)$ $(h, b >> t)$	$\frac{1}{6}h^3 t(1 + 3\frac{b}{h})$	$\frac{1}{2}\frac{h}{t}\frac{(1+3b/h)}{(1+b/h)^2}$ $(h, b >> t)$

The quantities I, Z and A can all be calculated from the dimensions of the section, allowing φ*e* to be calculated when these are known. This frame shows a small part of a larger table listing these. Note that the square section has a shape factor of 1; that for a solid circular section is very close to 1 (3/π = 0.95). That for thin wall tubes, box and I-sections is much larger.

Limits for Shape Factors φ_e and φ_f

- There is an upper limit to shape factor for each material

Material	Max φ_e	Max φ_f
Steels	65	13
Aluminium alloys	44	10
GFRP and CFRP	39	9
Unreinforced polymers	12	5
Woods	8	3
Elastomers	<6	-
Other materials	..can calculate	

- Limit set by: (a) manufacturing constraints
  (b) local buckling

- Theoretical limit:

$$\varphi_e \approx 2\sqrt{\frac{E}{\sigma_y}}$$

Modulus (E)

Yield strength (σ_y)

The table lists empirical upper limits for shape factors for a number of materials. The limit is sometimes set by manufacturing constraints. But if these are overcome there is a practical upper limit related to the tendency of the section to buckle. Buckling is an unpredictable mode of failure, influenced by small geometric imperfections, and it can be catastrophic. Yielding is benign – it gives warning. The more slender the structure the more easily it buckles. So the upper limit on slenderness and thus on ϕe , is set by the requirement that the structure yields before it buckles catastrophically, giving the equation shown on this frame.

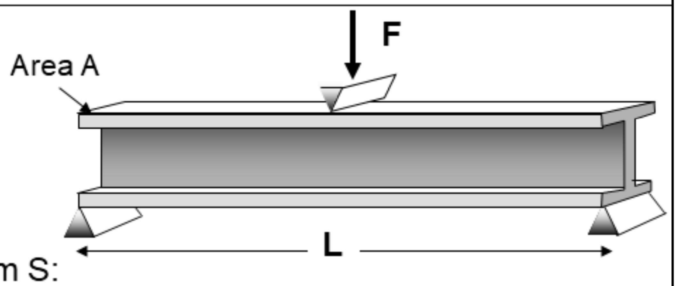
Indices that include shape

Function — *Beam* (shaped section).

Objective — *Minimise mass*, m, where:

$$m = A L \rho$$

Constraint — *Bending stiffness* of the beam S:



$$S = \frac{C E I}{L^3}$$

I is the second moment of area:

$$\varphi_e = 12 \frac{I}{A^2} \qquad A = \left(\frac{12\, I}{\varphi_e}\right)^{1/2}$$

m = mass
A = area
L = length
ρ = density
b = edge length
S = stiffness
I = second moment of area
E = Youngs Modulus

Combining the equations gives:

$$m = \left(\frac{12\ S\ L^5}{C}\right)^{1/2} \left(\frac{\rho}{(\varphi_e E)^{1/2}}\right)$$

Chose materials with smallest $\left(\frac{\rho}{(\varphi_e E)^{1/2}}\right)$

The derivation here parallels that for a light stiff being given in Unit 4. The only difference is that, for the square beam of Unit 4

$$I_o = A^2/12$$

whereas for the shape beam

$$I = \varphi_e A^2/12.$$

The resulting equation for the metric m shows how the mass of the beam depends on the mechanical constraint it must meet (S) on the section shape (φ_e) and on the material of which its made ($\rho/E^{1/2}$). The quantity $\rho /(\varphi_e E)^{1/2}$ can be thought as a “**shaped-material index”.**

Selecting material-shape combinations

- Materials for stiff, *shaped* beams of minimum weight
- Fixed shape (φ_e fixed): choose materials with low $\dfrac{\rho}{E^{1/2}}$
- Shape φ_e a variable: choose materials with low $\dfrac{\rho}{(\varphi_e E)^{1/2}}$

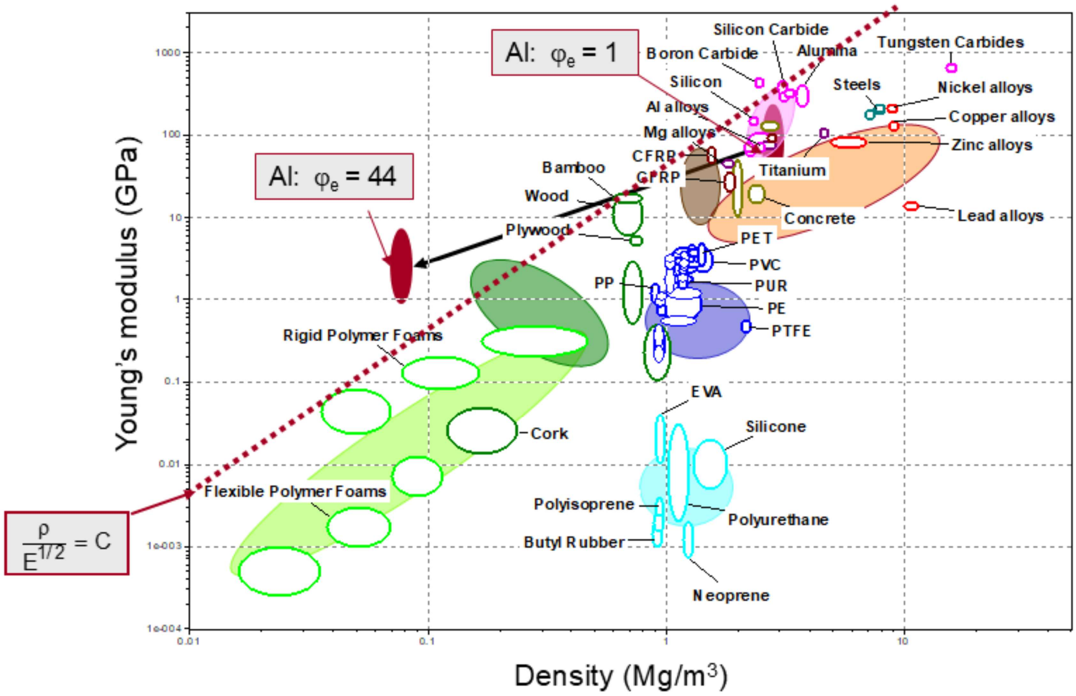
Material	ρ, Mg/m³	E, GPa	$\varphi_{e,max}$	$\rho / E^{1/2}$	$\rho / (\varphi_{e,max} E)^{1/2}$
1020 Steel	7.85	205	65	0.55	0.068
6061 T4 Al	2.70	70	44	0.32	0.049
GFRP	1.75	28	39	0.35	0.053
Wood (oak)	0.9	13	8	0.25	0.088

- Commentary: Fixed shape (up to $\varphi_e = 8$): wood is best
  Maximum shape ($\varphi_e = \varphi_{e,max}$): Al-alloy is best
  Steel recovers some performance through high $\varphi_{e,max}$

The table shows an example of the comparison of materials for light stiff beams. When materials are compared with the same shape, it is sufficient to rank them by their value of $\rho/E^{1/2}$. But when their shapes differ, they must be ranked by $\rho/(\varphi_e E)^{1/2}$. The table shows that when these four materials are compared at constant shape (which must be less than φ_e =8 because timber is not available in more efficient shapes than this) then timber is the lightest. But if each material is shaped to its maximum value of φ_e , the lightest beam is that made of aluminum alloy; GFRP is close behind; and the steel beam is slightly lighter than the wooden one.

Shape on selection charts

- Note that $\dfrac{\rho}{(\varphi_e E)^{1/2}} = \dfrac{\rho/\varphi_e}{(E/\varphi_e)^{1/2}}$ New material with $\begin{cases} \rho^* = \rho/\varphi_e \\ E^* = E/\varphi_e \end{cases}$



The same comparison can be performed **graphically** – and this gives an interesting insight into the structural efficiency of wood. The shaped-material index can be re-expressed in terms of

$$\rho^* = \rho/\varphi_e \quad \text{and}$$
$$E^* = E/\varphi_e$$

The shape of the material can be thought of as a new material with "properties" ρ* and E* allowing it to be plotted on the E-ρ chart as shown here. The construction is shown here for aluminum, first as a solid square section when it lies at the values of ρ and E of aluminum, and second at the point $(E/\varphi_e, \rho/\varphi_e)$.

A selection line for the index $E^{1/2}/\rho$ is shown. Shaping has carried the aluminum across the line, into a region not occupied by an unshaped materials.

The main points

- When materials carry bending, torsion or axial compression, the section shape becomes important.

- The "shape efficiency" is the amount of material needed to carry the load. It is measured by the shape factor, φ.

- If two materials have the *same* shape, the standard indices for bending (eg $\rho / E^{1/2}$) guide the choice.

- If materials can be made -- or are available -- in different shapes, then indices which include the shape (eg $\rho / (\varphi E)^{1/2}$) guide the choice.

- The CES Structural Sections database allows standard sections to be explored and selected

So what?

- The CES Bio-materials DB presents natural and bio-materials in familiar format
- Comparison with man-made materials
- Displays the remarkable properties of natural materials,
- Stimulates thinking about replacement and mimicry

For more information

- White Paper: **The CES database of natural, bio and engineering materials"**
  (download from CES Help or from the Granta Design web site)

This brief introduction to the **CES Biomaterials database** gives a flavor of how it can be used to explore the properties of natural materials and compare them with those of man-made materials. It provides a tool to engage the interest of students, and allows exercises and project work.

Materials in Industrial design

why do consumers buy products?

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Outline

- **Why is Industrial Design important?**
- **What gives a product its character?**
- **Making charts for sensory properties**
- **Design: creating associations and perceptions**

Resources:

- "Materials Selection in Mechanical Design", 3rd edition by M.F. Ashby, Butterworth Heinemann, Oxford UK, 2006, **Chapter 17**.
- "Materials and Design, the Art and Acience of Materials Selection in Product Design", by Mike Ashby and Kara Johnson Butterworth Heinemann, Oxford UK, 2002, ISBN 0-7506-5554-2

This is the outline of the Unit. The relevant chapters of the Texts are listed.

Product value

A product has a **cost** C — *the true **cost** of manufacture, marketing etc.*

a **price** P — *the **price** at which it is offered to the consumer*

a **value** V — *what the consumer thinks it is **worth***

My Parker pens, 8 euros each

Do they write 375 times better?

Parker special edition 3000 euros

Product success requires that C < P < V

What determines **cost**? — *Technical design, materials, processes*

What determines **value**? — *Both technical and industrial design;*
-- aesthetics, associations, perceptions

This Unit concerns industrial design – the aspect of design that relates to the **visual, tactile**, and **aesthetic** qualities of a product. Successful products use materials not only to fulfil a function, but also to provide satisfaction. The pens on the left cost 8 Euros each. Those on the right cost about 3000 Euros. Do they write 375 times better? Unlikely – those on the left write perfectly well. Yet there is a market for the expensive pens. Why? It is a question of **aesthetics, associations** and **perceptions,** words that are explained in a moment. Our interest is in exploring how materials are used to provide these. We start by examining the ingredients of product design, shown on the next viewgraph.

Why is industrial design important ?

Product maturity and market saturation

- As products mature and markets saturate, the products of competing manufacturers converge technically -- hardly differ in performance or cost

⇨ ID allows differentiation, enhanced value

Corporate identity

- Corporate and product identity are partly created and largely maintained through innovative industrial design

⇨ ID creates corporate image

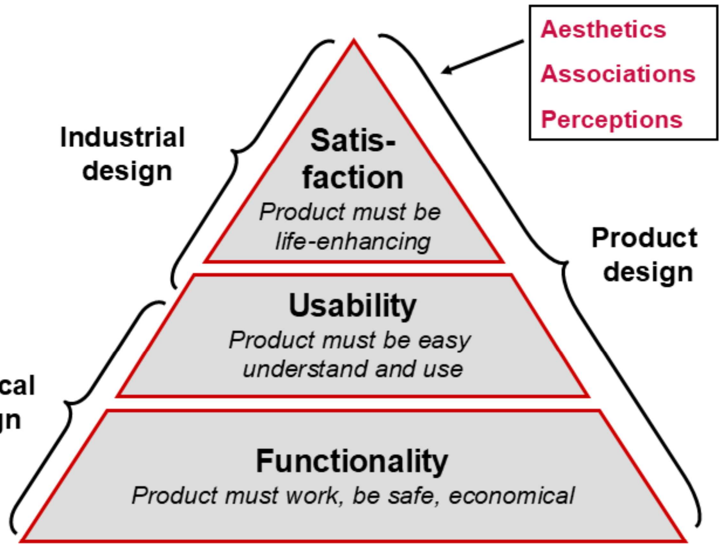
The environment, in the broadest sense

- Products are part of our environment. Products that give no sensual satisfaction damage the environment

⇨ ID contributes to quality of life

Why is industrial design important? Because it is central to creating product identity, maintaining corporate image and providing the consumer with products that satisfy.

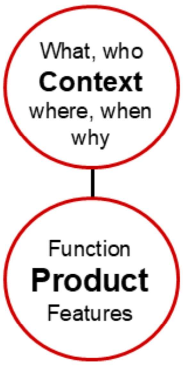
Technical, industrial and product design



Example: the car

What are the ingredients of a successful product? First, its **functionality**: the product must work well, be safe and economical. Second, its **usability**: good functionality is not much use if the consumer for whom the product is intended is unable to make it work. Functionality and usability alone are not enough. To succeed in today's markets, in which many nearly identical products compete, the product must give **satisfaction**, be life-enhancing. And here these three words appear again – satisfaction has to do with aesthetics, associations and perceptions. Product design, then, requires a combination of technical and industrial design.

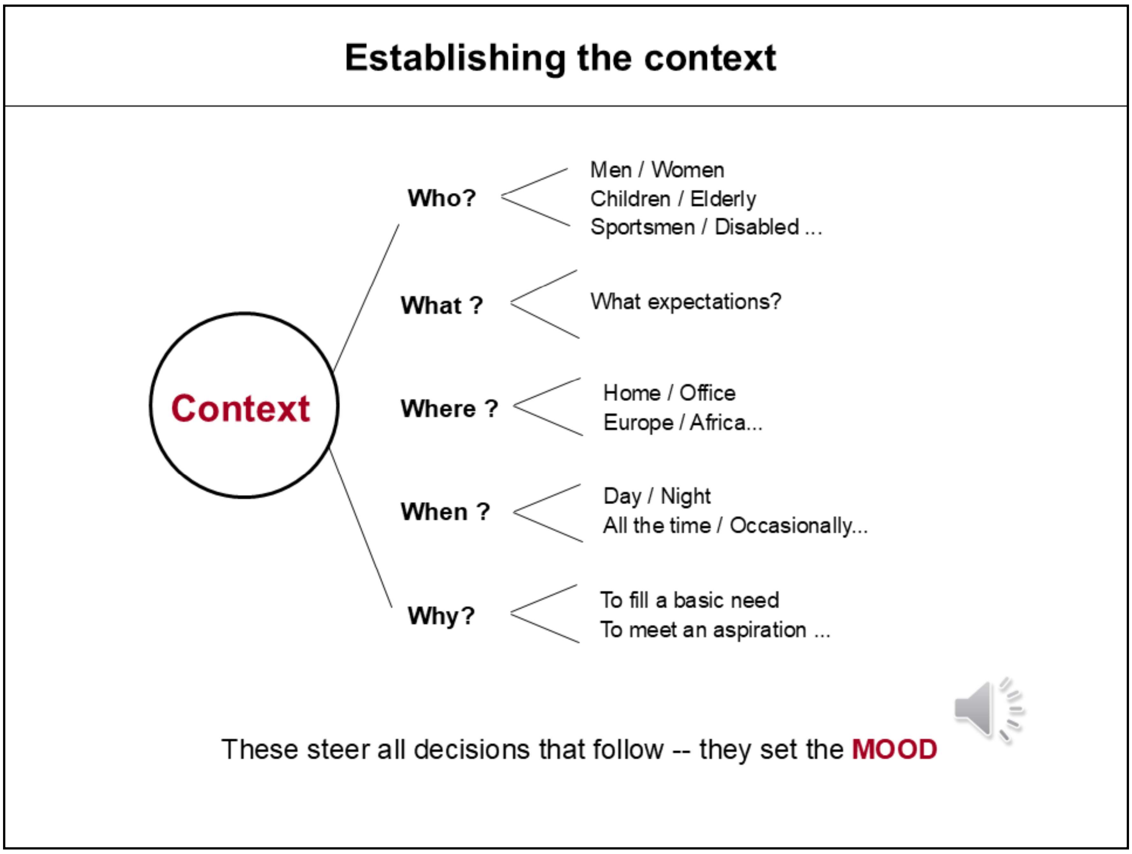
What gives a product its character?



So let us examine what gives a product its character. The **product** – central circle in this diagram – performs a function for which a market need exists. The first step is to characterise this market, seeking answers to five questions that establish the **context**:

- **What?**
- **Who?**
- **Where?**
- **Why?**
- **When?**

The next frame elaborates.



Here context is explained in more detail.

What? What function is the product designed to perform?

Who? Who are the target consumers – men, women, children, the elderly, people that are active or disabled?

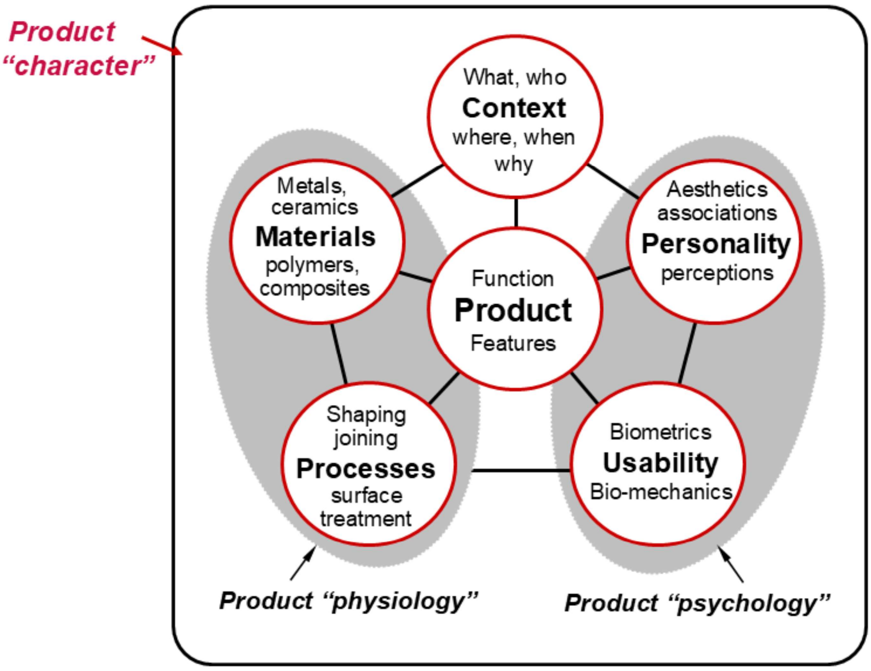
Where? Will the product be used in the home, the office, indoors, outside…..?

Why? Does the product fill a basic need, is it a life-style statement, is it bought to enhance self-image….?

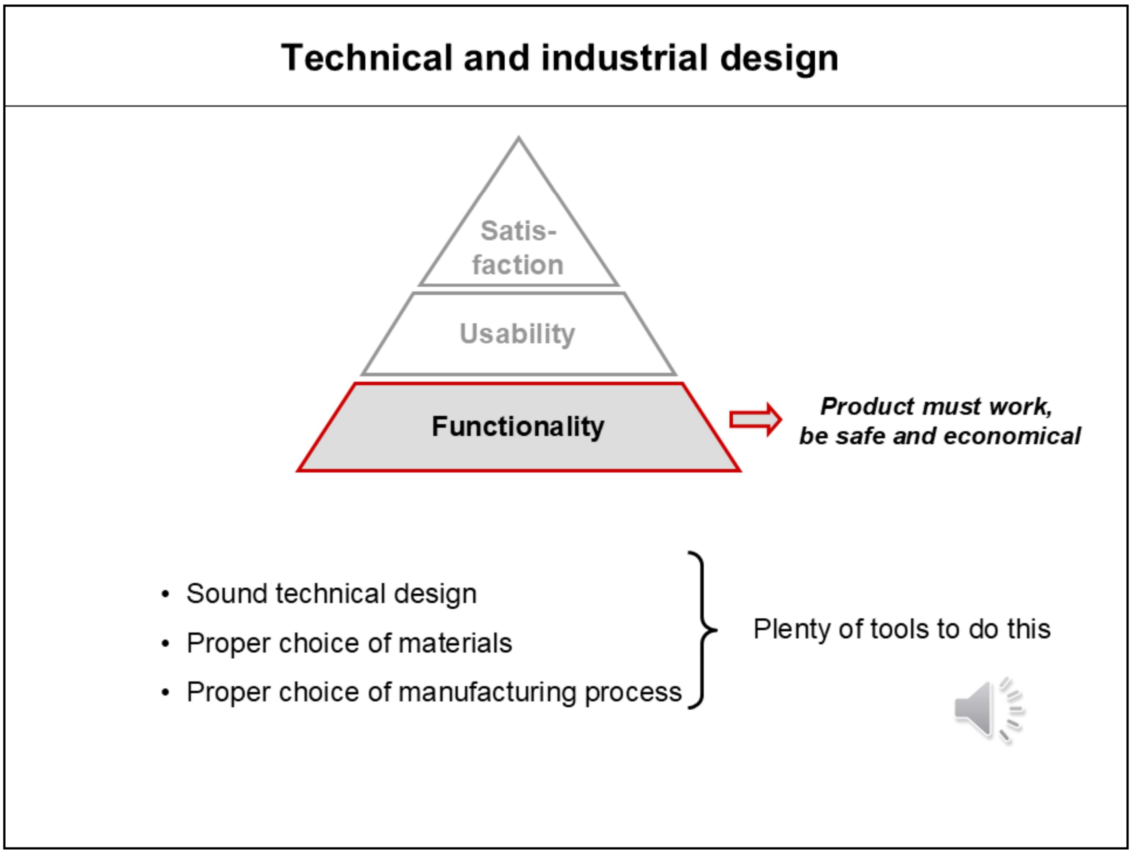
When? When will the product be used: continuously or only occasionally? During the day or at night?

The answers to these questions do not "design" the product, but they define the context, and inform or influence all the decisions that follow: they set the mood.

What gives a product its character?

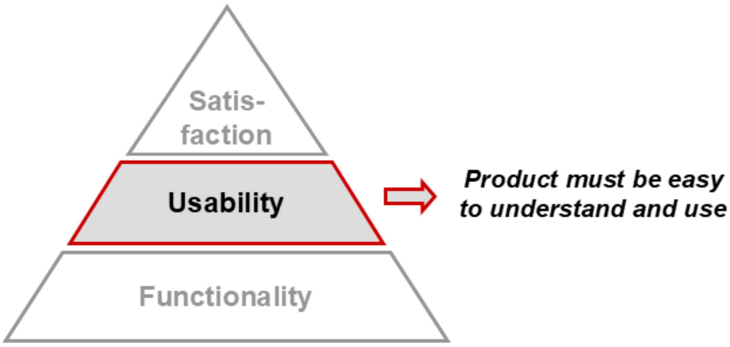


Back to product character. Products are made of **materials**, shaped by **processes**, shown on the left. They provide the flesh and bones so to speak; they create what you might call the physiology of the product. **Usability**, as we have said, is important. It is a question of matching the product to the physical and mental capabilities of the user. And finally there is **personality** – the visual and tactile qualities of the product, its associations and they way it is perceived. They create what you might call the psychology of the product. The whole combination create the **product character.**



What determines product value? **Functionality,** provided by sound technical design, clearly plays a role. The requirements pyramid shown here has this as its base: the product must work properly, be safe and economical.

Usability ("ergonomics")



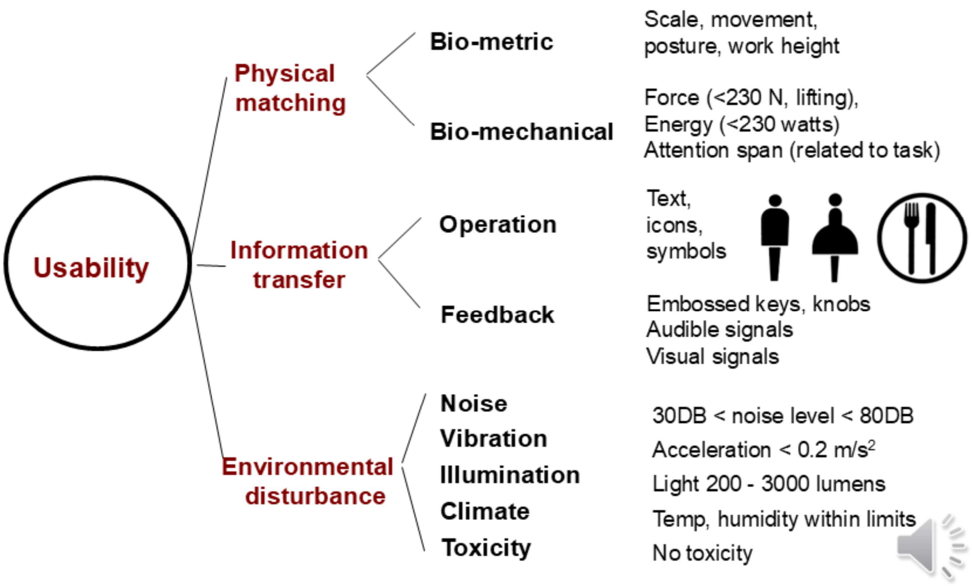
Three aspects

- Interaction with the **human body** -- biometrics
- Interaction with the **mind** -- intelligibility
- Interaction with the human **environment**

Now much researched

Functionality alone is not enough: the product must be easy to understand and operate, and these are questions of **usability**, the second tier of the figure. This has three aspects, listed here.

Usability ("ergonomics")

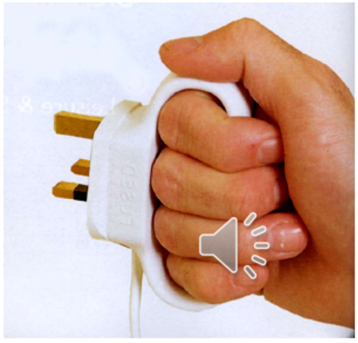


Aspects of usability are classified here following the broad families listed on the previous frame.

Examples of bio-mechanical matching

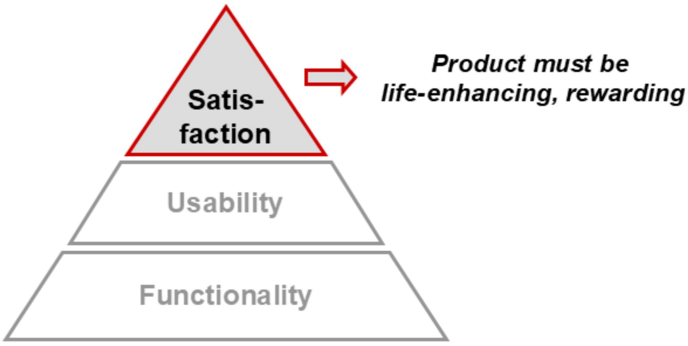




Examples of design to provide usability to compensate for impaired hand and wrist actions.

Industrial design and satisfaction

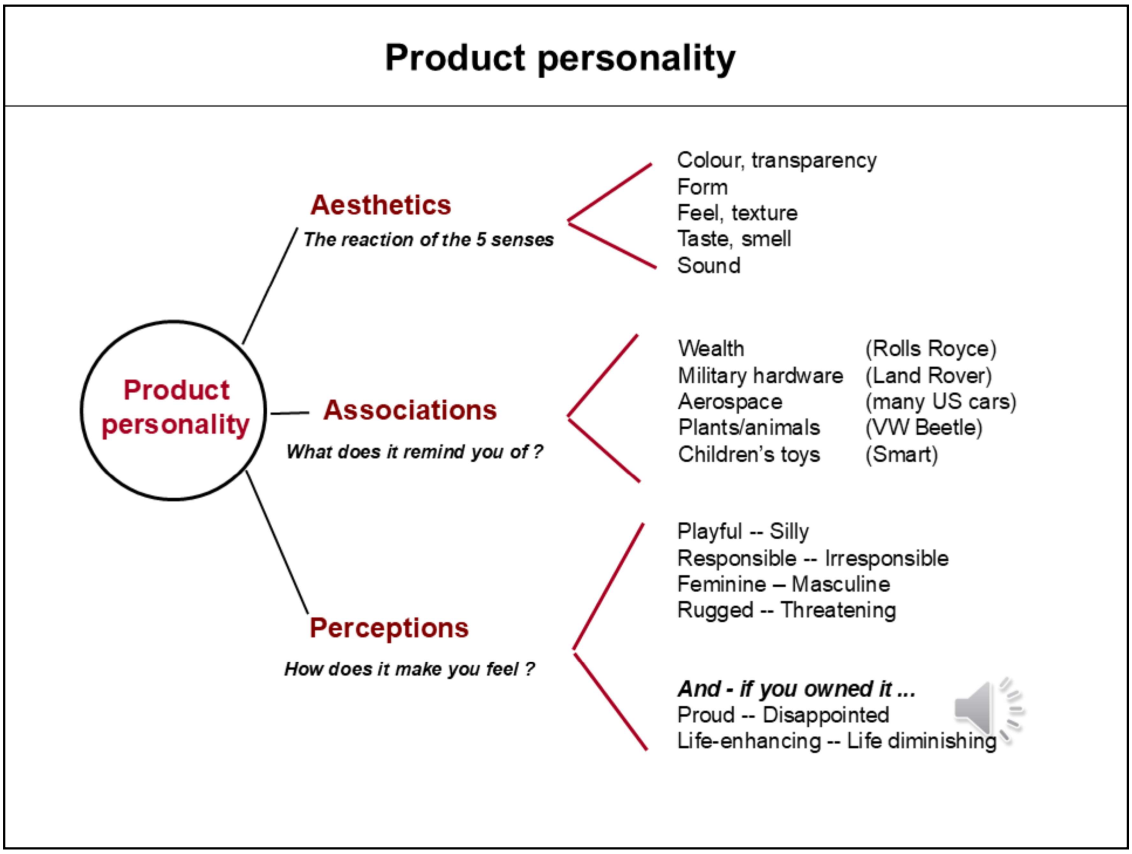


Three facets

- **Aesthetics** -- appealing to the senses -- sight, hearing, feel, taste, smell
- **Associations** -- what does it remind you of ? What does it suggest ?
- **Perceptions** -- what is your reaction to it ? How does it make you feel ?

The third tier of the pyramid is the requirement that the product gives **satisfaction**: that it enhances the life of its owner. The lower part of the pyramid tends to be called "Technical design", the upper part, "Industrial design" suggesting that they are separate activities. It is better to think of think of all three tiers as part of a single process that we shall call "Product design".

Creating satisfaction has three facets, listed here. They are explored in the frames that follow.



We are interested here in product personality and the ways in which materials contribute to it. It is a question of aesthetics, associations and perceptions.

Anaesthetics dull the five senses. **Aesthetics** stimulate them. I will use the word here to mean just that: the reaction of the five senses. Thus aesthetics refers to colour, form, feel, texture, sound, smell and taste.

Associations: what does the product suggest or remind you of? Wealth? A Rolls Royce is designed to do just that. Military hardware? SUVs like Land Rover exploit the form and colour of military vehicles to suggest ruggedness. Aerospace? American cars of the 1970s derived their styling from aircraft and rockets. Assigning associations is not controversial – most people would agree with those interpretations.

Perceptions are another matter. What are your feelings about the product? Does it strike you as feminine or masculine – and do you like it if it does? Is it desirably rugged or undesirably threatening? Attractively playful or just silly? Here different user perceive products differently; the skilful designer creates associations and perceptions that are appeal to the user group for which the product is intended.

Material personalities

NO intrinsic personality*?*
-- materials acquire one through the way they are used?

Wood in fine furniture -- *craftsmanship*
in railway sleepers -- *cheap utility*

Gold in jewelry -- *luxury, wealth*
in micro-circuits -- *technical efficiency*

Glass in a camera lens -- *precision engineering*
in beer bottle -- *disposable packaging*

But ...

Materials contribute to **product personality**, but can the material itself be said to have a personality? At first sight – no. A material is like an actor – it can take on many characters; it depends on how it is used. The overhead lists three examples in which a material, when used in different ways, carries different associations and perceptions.

But wait. The image in the lower part of this frame show a product with a solemn and – one hopes – dignified function. Polished hardwood, bronze fittings seem appropriate to the occasion on which it is to be used. But if I told you that this one was made of plastic – of expanded polystyrene – would you feel the same about it? It becomes a bin, something to put rubbish in.

So materials do, it seems, have a personality – a shy one, to be coaxed out by the designer. The next overhead gives some examples.

Material moods

Wood, leather

- **Aesthetics:** tactile, warm, textured, it ages well
- **Associations** of fine furniture, musical instruments
- **Perceptions** of craftsmanship, tradition, heritage, quality

Metals

- **Aesthetics:** cold, clean, hard, stiff, strong, often ages well
- **Associations** of machinery, precision instruments, weapons
- **Perceptions** of strength, precision, durability, quality

Ceramics and glass

- **Aesthetics:** hard, abrasion resistant, permanence of colour
- **Associations** of culture, luxury, sophistication
- **Perceptions** of refinement, quality

Polymers

"Cheap plastic imitation"

- **Aesthetics:** colourful, warm, soft, smooth, flexible, do not age gracefully
- **Associations** of mass production, substitutes for metals, glass, wood
- **Perceptions**: deceptive, cheap, imitation ....but adaptable.

The overhead gives examples of aesthetics, associations and perceptions of material classes. The perceptions are, as explained earlier, a matter of background, culture and taste – one possible set is listed here. With that background we shall examine some products to see how materials have been used.

Aesthetic properties

Warm / Cold

Heat drain $Q = \sqrt{\rho \lambda C_p}$

Density, Thermal conductivity, Specific heat

Soft / Hard

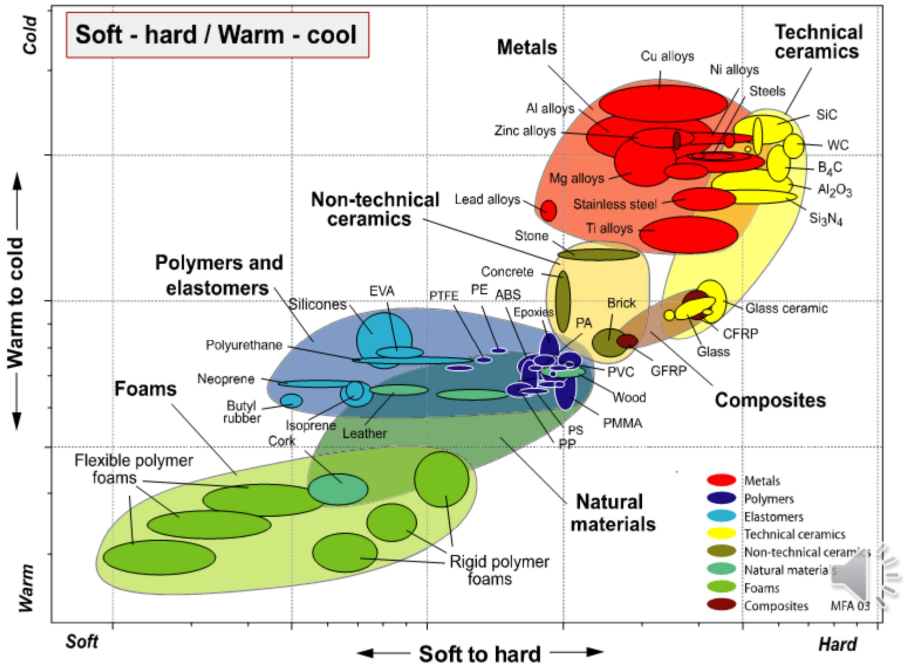
Soft/Hard $S = \sqrt{E H}$

Modulus, Hardness

Perceiving material properties

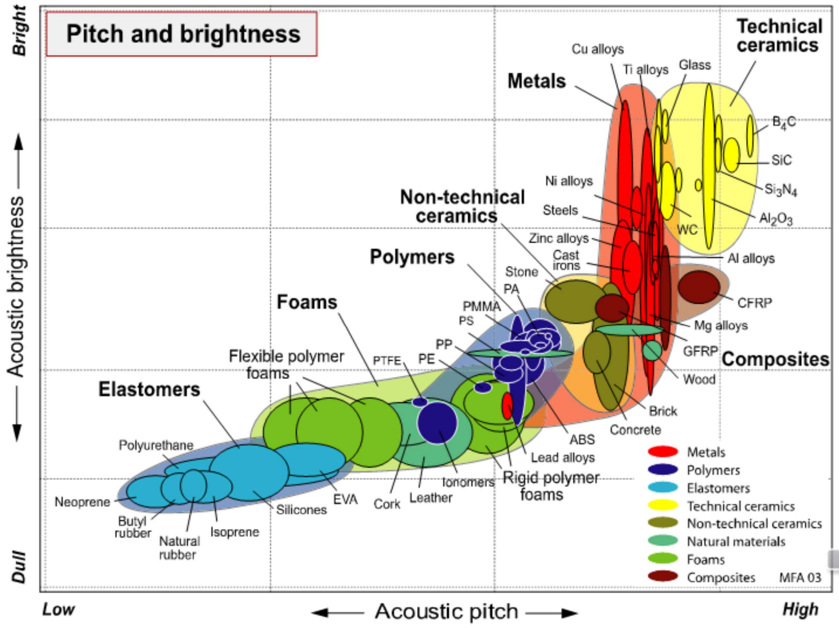
- The Design database is unique in that it has Aesthetic properties, such as Sensorial ones
- These are subjective but can actually be quantified by using other material properties
- The feeling of warm and cold when you touch a material depends on thermal conductivity etc
- How soft a material feels depends on hardness and stiffness, for example

Warm/Cold - Soft/Hard

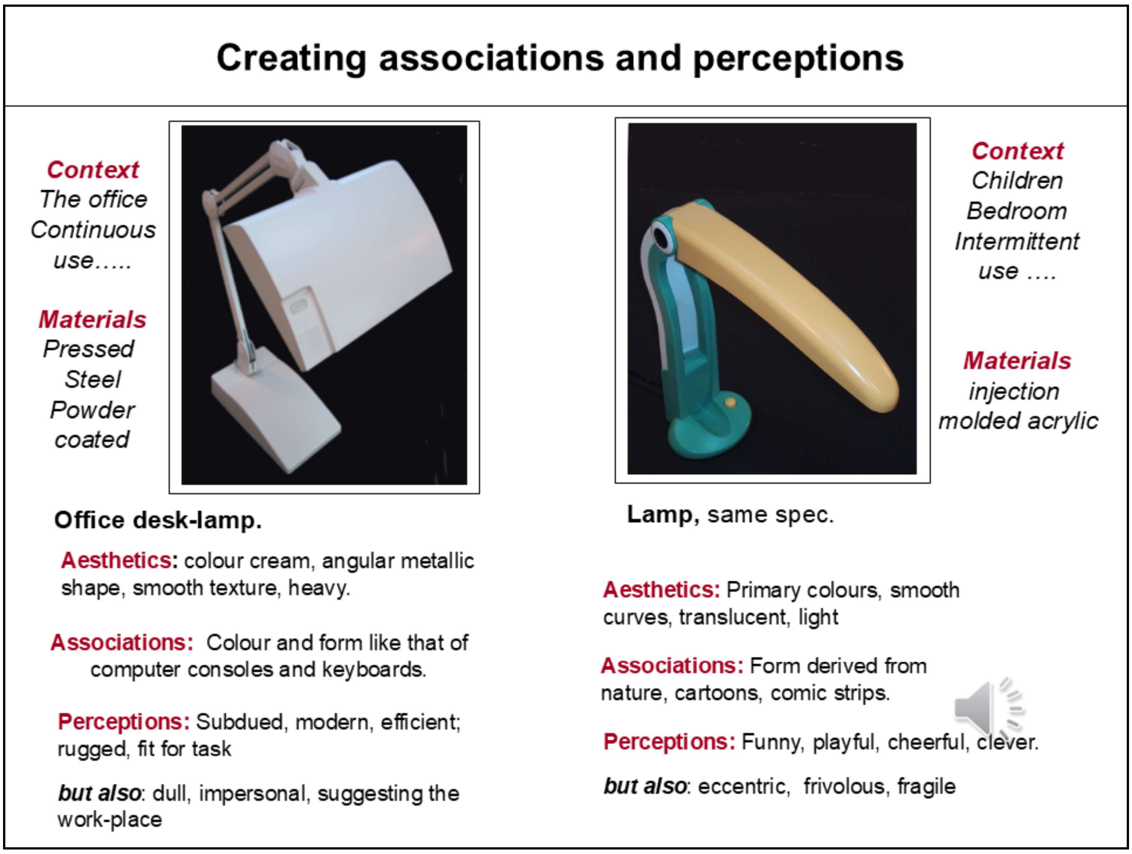


Some of these qualities can be measured and quantified. The sensation of softness has to do with elastic modulus and strength – an appropriate combination of these properties can be used to rank materials on a scale of **soft to hard**. The sensation of warmth of a material has to do with thermal conductivity and specific heat – an appropriate combination of these can be used to rank materials on a scale of **warm to cold**. The result (constructed with the CES software) is shown here (for details see *Materials and Design*, referenced on frame 2 of this Unit).

Acoustic pitch and brightness



Acoustic behaviour, too, can be quantified. Pitch has to do with modulus and density, brightness with internal damping. Appropriate combinations of these can be used to classify materials on scales of **pitch and brightness**, as shown here (for details see *Materials and Design*, referenced on frame 2 of this Unit).



Here is an example of designs to create **associations** and **perceptions**.

The lamp on the left is designed for the office (the *where* ?), will be used by executives (*who* ?) and probably remain on all day (*when* ?). Aesthetics, associations and perceptions are listed. To achieve these, the designer has used pressed steel, powder coated – the same materials that computer cases are made from.

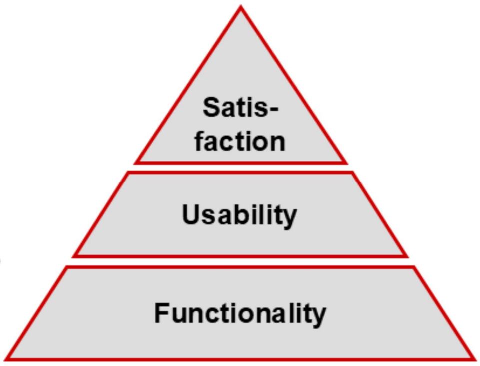
The lamp on the right has the same technical specification as that on the left, but in every other way it is different. It is intended for a child's bedroom (when folded it acts as a night-light), and for intermittent use only. This context has led the designer to develop a different set of aesthetics (curved form, pastel colours), associations (nature, cartoon characters ..) and perceptions (funny, playful…). To do this he or she has chosen translucent, injection moulded, acrylic as the principal material.

So what? 1

(1) See product as a whole

(2) Think of it in more than one way

- What does the product do?
- Who will use it? Where? When? Why?
- What are their aspirations, self-image…?



(3) The element of satisfaction is central to contemporary product design

What messages can be drawn from all this? The first is a way to think about product design:

- **Context**: who is it designed for, and why?
- **Product character**: is it functional? Is it usable? Does is give satisfaction – at least to the consumers at which it is aimed?

So what? 2

Train yourself - look at products and ask:

- What aesthetics? Why?
- What associations? How did the designer do it? Why?
- What perceptions? What made you perceive it that way? How (intentionally or unintentionally) did the designer do it?
- And finally: what was the designer trying to say?

What further messages? It is rewarding to train yourself to analyse products – particularly those that appeal to you.

- **Aesthetics**: what materials, colors, forms has the designer used, and why?
- **Associations**: what does the product suggest? What do you think of when you look at it or pick it up?
- **Perceptions**: what is your reaction to the product? If you like or dislike it, why?
- And finally: what is the **designer trying to say**?

Computer Exercises