2006-1934: TEACHING STUDENTS ABOUT THE ENVIRONMENTAL IMPACT OF MATERIAL CHOICE IN DESIGN

Helen McLachlan, Granta Design

Dr Helen McLachlan is Granta's product manager for education. She also has a PhD in materials science from the University of Cambridge.

Patrick Coulter, Granta Design

Dr Patrick Coulter is a director at Granta. He also has PH.D. in polymer science from the University of Cambridge.

Mike Ashby, University of Cambridge

Professor Mike Ashby FRS is Royal Society Research Professor in the Department of Engineering at the University of Cambridge and is a Visiting Professor of Design at the Royal College of Art, London, UK. His interests include materials selection in design, process modelling and the study of the properties of composites and foams. He has written and co-written leading textbooks in the field, as well as over 200 papers on mechanisms of plasticity and fracture, powder compaction, mechanisms of wear, methodologies for materials selection, and the modelling of material shaping processes, among other topics. He is also co-founder of Granta and directs development of Granta's CES EduPack.

Teaching Students About The Environmental Impact Of Material Choice In Design

Abstract
Engineers make things out of materials and the more things they make, the greater the damage to the environment. Today's student engineers need to know how to minimize this environmental damage through their choice of materials.

This paper presents a rational, practical methodology for achieving environmentally sound material selection. It is well understood that there are four phases to the life cycle of materials: material production, manufacturing, use, and disposal. Each phase has an impact on the environment. By limiting the impact of the most dominant of these life phases, a product becomes more "green". To assist both teaching and implementation of the methodology, a software tool, the new Eco Edition of CES EduPack, is discussed. The tool has three teaching levels: Level 1 introduces environmental factors such as embodied energy, CO_2 creation, and recyclability for around 60 of the most common materials. More materials and environmental parameters are added at Level 2. The third and highest level, Level 3, has over 70 properties for over 3,000 materials allowing material optimization for real designs on economic, environmental, and technical grounds. The method is illustrated with case studies.

The Problem

The nature of the problem is brought into focus by examining the materials lifecycle, sketched in Figure 1. Ore and feedstock are processed to give materials; these are manufactured into products that are used, and, at the end of their lives, disposed, a fraction perhaps entering a recycling loop, the rest committed to incineration or landfill. Energy and materials are consumed at each point in this cycle (we shall call them "phases"), with an associated penalty of heat, gaseous (CO_2, SO_x, NO_x), liquid and solid waste. Three important questions arise from this picture and none have obvious answers: How much damage, on some sort of absolute scale, does each of these wastes represent? Where in the cycle does the damage occur? And if we know the answers to the first two questions, how do we select materials to minimize the impact?

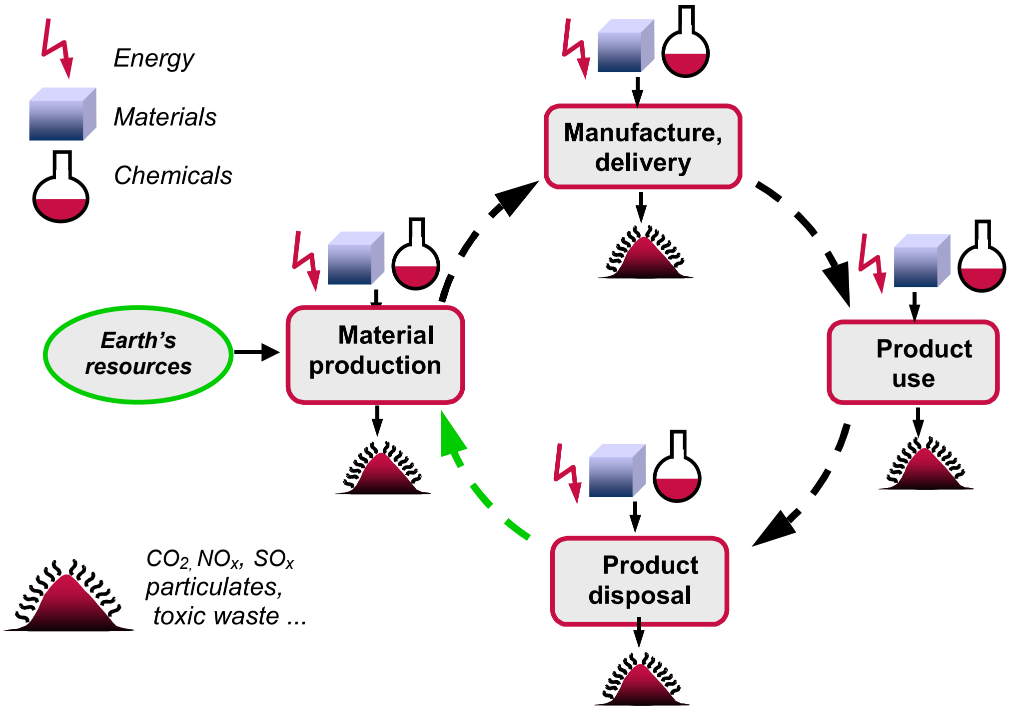

Figure 1. The Materials Life Cycle.

Teaching students to identify eco-impact

The first of these questions has led 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 criticized by some. The grounds for criticism are that there is no agreement on normalization or weighting factors used to calculate them and that the method is opaque since the indicator value has no simple physical significance. At the time of writing there is no general agreement on how best to used eco-data in design. But on one point there is international agreement (Kyoto Protocol, 1997) [1]: that the developed nations should progressively reduce CO2 emissions – a considerable challenge in times of industrial growth, increasing affluence, and growing population. Thus there is a certain logic in using CO2 emission as the "indicator", though it is more usual at present to use energy.

The CES EduPack Eco Edition[2] contains data for both energy and CO2 burdens associated with the material production. At level 3, the specialized Eco-Selector database contains much more detail. Both are designed to guide selection for all four of the life-phases of Figure 1.

It is generally true that one of the four phases of life shown in Figure 1 dominates the picture. Simplifying for a moment, let us take energy consumption as a measure of both the inputs and undesired by-products of each phase and use it for a character-appraisal of use-sectors. Figure 2 presents the evidence, using this measure. For products that consume energy during their life, it is almost always the Use phase that dominates, accounting for 80% or more of the total life-energy (top row). For passive structures (bridges, roads, unheated buildings like car-parks) it is the production phase that overwhelmingly dominates. In rarer instances it is the manufacturing phase or disposal phase (bottom row). If large changes are to be achieved, it is the dominant phase that must be the target; a reduction by a factor of 2, even of 10, in any other makes little significant difference to the total.

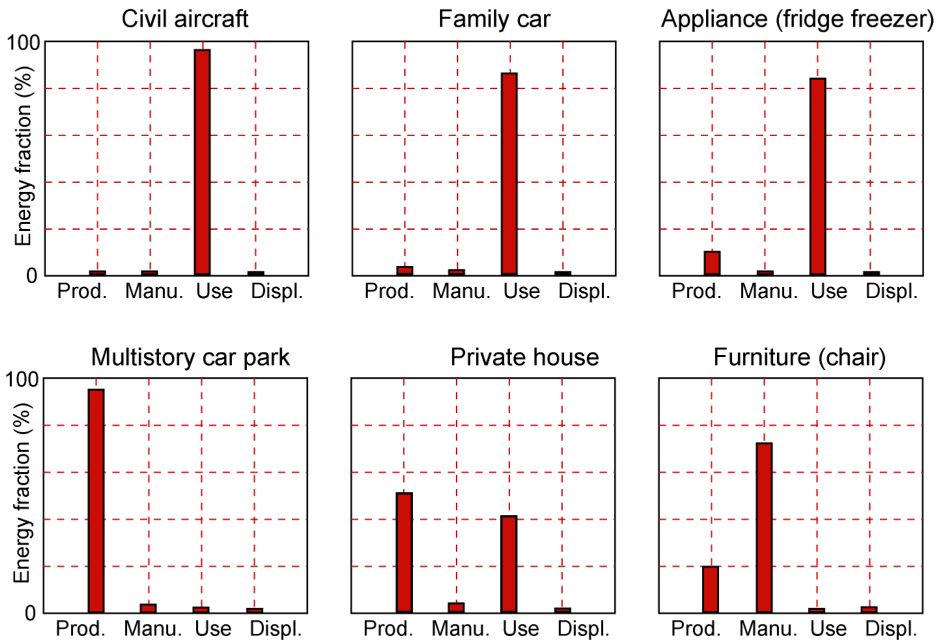

Figure 2. Approximate values for the energy consumed at each phase of Figure 1 for a range of products.[3]

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 the effective use of the data. Figure 3 illustrates the reasoning.

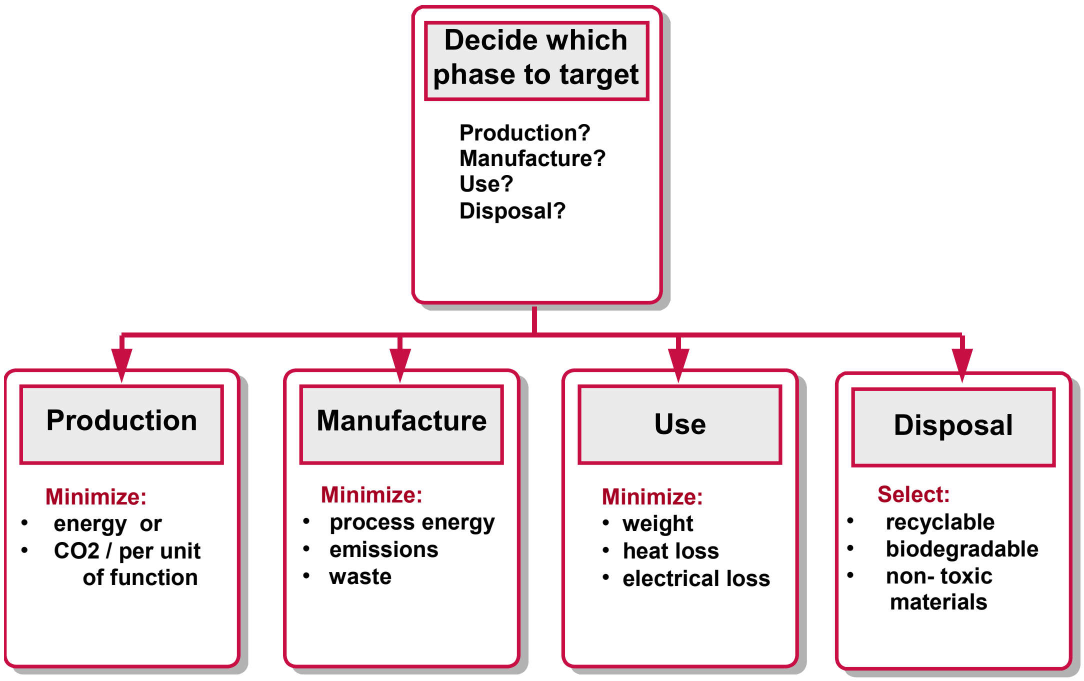

Figure 3. Once the phase of life to be targeted is identified this guides the method of selection to minimise the impact of the phase on the environment.

The material production phase. If material production is the dominant phase of life in terms of environmental impact, then it becomes the first target. Drink containers provide an example: they consume materials and energy during material extraction and container-production, but, apart from transport and possible refrigeration, not thereafter. Here, selection of material to minimize the embodied energy and using less of it are the ways forward.

Th***e product-manufacture phase.*** The energy required to shape a material is usually much less than that to create it in the first place. Certainly it is important to save energy in production. But higher priority often attaches to the local impact of emissions and toxic waste during manufacture, and this depends crucially on local circumstances. Clean manufacture is the answer here.

The product-use phase. The eco-impact of the use phase of energy-using products has nothing to do with the embodied energy of the materials themselves – indeed, minimizing this may frequently have the opposite effect on use-energy. Use-energy depends on mechanical, thermal and electrical efficiencies; it is minimized by maximizing these. Fuel efficiency in transport systems (measured, say, by MJ/km) correlates closely with the mass of the vehicle itself; the objective then becomes that of minimizing mass. Energy efficiency in refrigeration or heating systems is achieved by minimizing the heat flux into or out of the system; the objective is then that of minimizing thermal conductivity or thermal inertia. Energy efficiency in electrical generation, transmission and conversion is maximized by minimizing the ohmic losses in the conductor; here the objective is to minimize electrical resistance while meeting necessary constraints on strength, cost etc. Material selection to meet these objectives is well documented in standard texts listed under Further reading.

The product disposal phase. The environmental consequences of the final phase of product life have many aspects. The ideal is summarized in the following guidelines.

- Avoid toxic materials such as heavy metals and organo-metallic compounds that, in landfill cause long-term contamination of soil and ground water.
- Examine the use of materials that cannot be recycled, since recycling can save both material and energy; but do so with the influence they have on the other phases of life in mind.
- Seek to maximize recycling of materials for which this is possible, even though recycling may be difficult to achieve for the reasons already discussed.
- When recycling is impractical seek to recover energy by controlled combustion (incineration).
- Consider the use of materials that are biodegradable or photodegradable, although these are ineffectual in landfills because the conditions within them inhibit rather than promote degradation; they do, however, work for surface refuse.

Implementing this requires information of toxicity, potential for recycling, controlled combustion and bio-degradability. The CES software provides simple checks of each of these.

Example: Design of a drinks container minimizing eco-impact.

A good example is selecting the material for use as a container for a liquid: it illustrates the method and the tools needed to implement it, and makes an excellent introduction for students before they move on to working on more complicated problems either as homework assignments or as projects. The student will need an introduction to the concepts outlined above and will need to have some knowledge of the EduPack software.

On the left of Figure 4 is an inventory of the principle materials, manufacturing methods and use and disposal information about a milk container. On the right is list of the additional information required to allow an approximate energy audit. The need, then, is for a tool to provide this. Granta Design's CES EduPack Eco-Edition offers this.

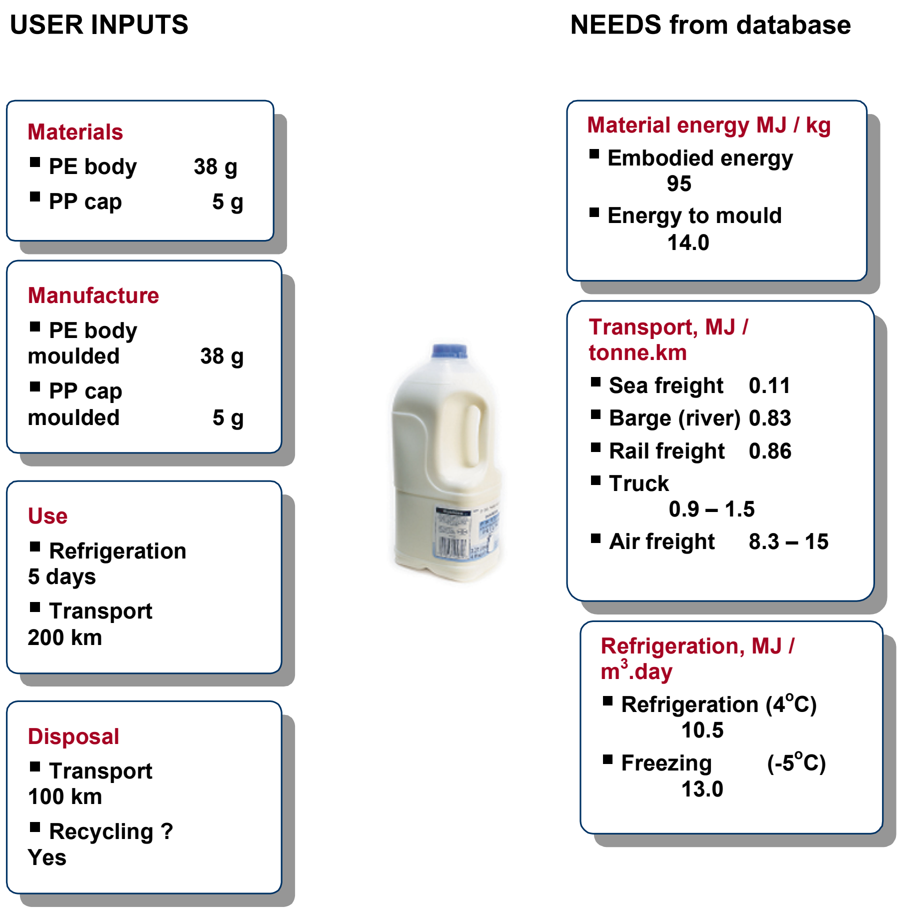

Figure 4. Information needed to analyze the which phase of the life cycle has the highest eco-impact.

Figure 5 shows an example of part of an EduPack record at level 2, here for polyethylene. Numeric properties are reported as ranges (material properties have permitted range of values because of latitude in permitted compositions and methods of production). Non-numeric properties are shown as rankings: here, very poor, poor, average, good, very good. Ideally, structured data should contain no "holes" – missing data – because this compromises its use for selection. (The CES EduPack databases have no holes.) Links provide the connections to processes that can be used to shape, join and surface-treat PE.

On the left of Figure 5 are data for thermo-mechanical design – mechanical, thermal and electrical properties. On the right are data for eco-properties. The production of 1 kilogram of polyethylene consumes energy and is associated with undesired gas emissions, among which is CO_2. The quantities can be large, as shown here – each kilogram of PE generates some 2 kilograms of CO_2.

Polyethylene (PE) - $(CH_2\text{-}CH_2\text{-})_n$

General Properties				
Density	939	-	960	kg/m ^{3}
Price	1.3	-	1.45	US $/kg
Mechanical Properties				
Young's Modulus	0.6	-	0.9	GPa
Elastic Limit	17.9	-	29	MPa
Tensile Strength	20	-	45	MPa
Elongation	200	-	800	%
Hardness - Vickers	5.4	-	8.7	HV
Fracture Toughness	1.4	-	1.7	MPa.m $^{1/2}$
Thermal Properties				
Max Service Temp	100	-	120	C
Thermal Expansion	126	-	198	10^{-6}/K
Specific Heat	1810	-	1880	J/kg.K
Thermal Conductivity	0.4	-	0.44	W/m.K
Electrical Properties				
Resistivity	3×10^{22}	-	3×10^{24}	$\mu\Omega$.cm
Dielectric constant	2.2	-	2.4	

Eco - properties: production			
Embodied energy	77	-	85 MJ/kg
Carbon dioxide	1.9	-	2.2 kg/kg
Recycle ?	✓		
Eco - properties: manufacture			
Injection / blow moulding	12	-	15 MJ/kg
Polymer extrusion	3	-	5 MJ/kg

Environmental notes. PE is FDA compliant- it is so non -toxic that it can be embedded in the human body (heart valves, hip-joint cups, artificial artery).

Figure 5. Part of an EduPack record at level 2.

Figure 6 shows part of record from the level 3 Eco Edition Database, again for polyethylene. The specialized ECO-Edition database contains much more detail. It is designed to guide selection for all four of the life-phases of Figure 1. It contains 2900 materials, with:

- detailed design data for thermo-mechanical design
- data giving an eco-profile of the material, including embodied energy and undesired gas emissions: CO_2, NO_x, SO_x and CH_4.
- end of life information such as an estimate of *recycle energy*. And an indication of whether the material can or cannot be *recycled*, *down-cycled, biodegraded*, *incinerated* or committed to *landfill*.

Material: Medium density PE (branched homopolymer)

Production energy and emissions				
Production Energy	84	-	93	MJ/kg
Carbon Dioxide	2.2	-	2.4	kg/kg
Nitrogen Oxides	11.4	-	12.6	g/kg
Sulphur Oxides	8.6	-	9.5	g/kg
Eco - Indicators				
Eco Indicator	340	-	380	millipoints / kg
EPS value	722	-	798	
Manufacture at 30% efficiency				
Min. Energy to Melt	2.8	-	3.1	MJ/kg
End of life				
Recycle	✓			
Downcycle	✓			
Biodegrade	x			
Incinerate	✓			
Landfill	✓			
Recycling Energy	35	-	40	MJ/kg
Recycle fraction of current supply	3	-	4	%
Bio - data				
Toxicity rating	Non -toxic			
FDA approved (skin & food contact)	✓			
WEEE prohibited material	x			

Figure 6. Part of record from the level 3 Eco Edition Database

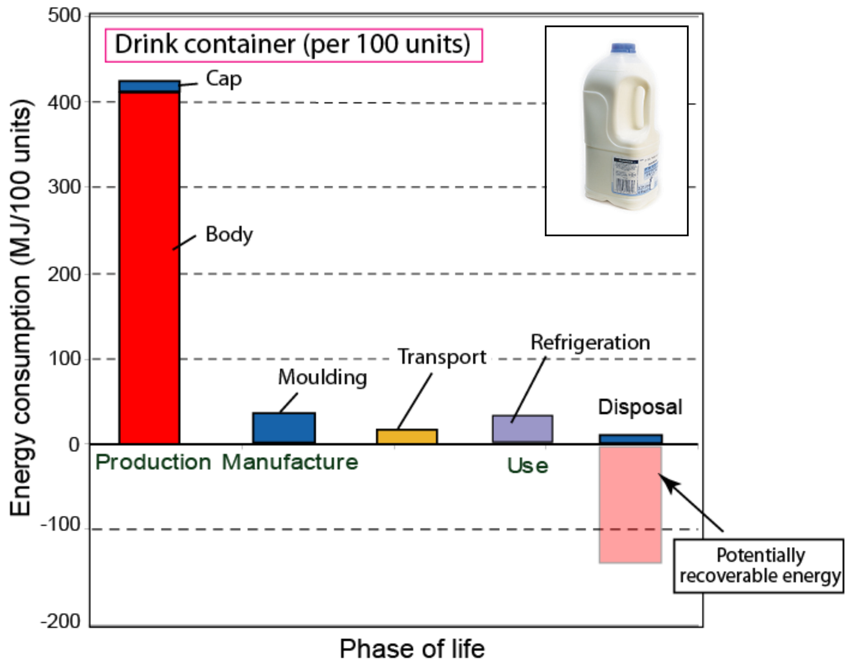

Figure 7. Energy Consumption for the Different Phases of Life for a Milk Container.

Figure 7 shows the result of the analysis of the milk container: an energy-portrait. From left to right: the embodied energy (the energy required to make the materials), the energy required for molding, transport, refrigeration, and the energy that could be recovered by incineration or saved by recycling if this is possible.
As already said, the analysis includes only the larger contributions, and uses approximate data. But errors of a factor of 2 or more do not alter the main feature of the portrait: the embodied energy of the polyethylene is the dominant contribution.

Teaching students how to minimize environmental impact

The second stage now is for the students to identify what can be done to decrease the eco-impact.

In the case of the drinks container it is the production phase that dominates the energy consumption of the product it is this phase of life that should be targeted to reduce eco-impact. This can be achieved by choosing a material that has less embodied energy than the current choice. Materials that are commonly used to hold liquids are, glass, plastics, such as PE and PET and metals such as steel and aluminum.

The energy associated with the production of one kilogram of a material is H_p (the embodied energy), and per unit volume is $H_p\rho$, where ρ is the density of the material. The bar-charts in Figures 8 and 9 show these two quantities for ceramics, hybrids (here, composites), metals and polymers, generated from the CES EduPack level 2 database. The materials used for containing liquids are highlighted. On an "energy per kg" basis (Figure 8) steel and glass have relatively low values. Polymer production carries a much higher burden than does steel. Aluminum and the other light alloys carry the highest penalty of all.

If instead these same materials are compared on a "energy per m3" basis (Figure 9) the conclusions change: glass is still the lowest, but now commodity polymers such as PE and PP carry a *lower* burden than steel. Again the arrows show the materials of the containers. Now the two polymer containers well below steel and only just above glass. Aluminum is again the worst performer.

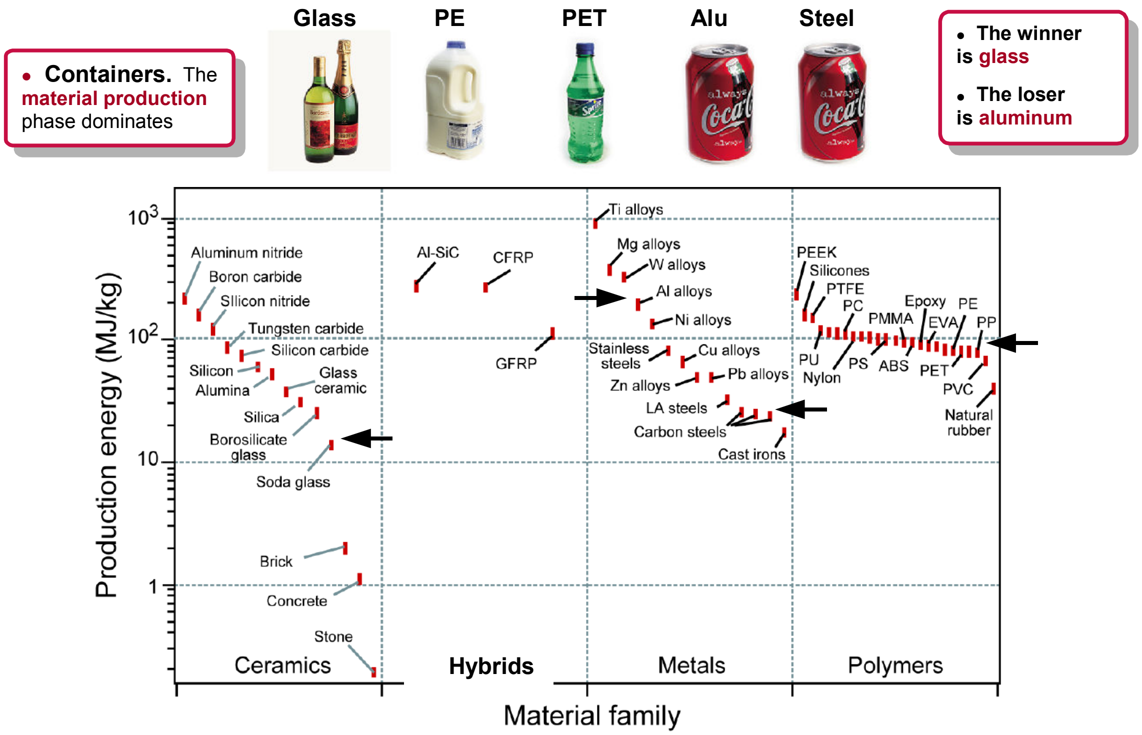

Figure 8. Bar chart of embodied energy of basic materials by weight.

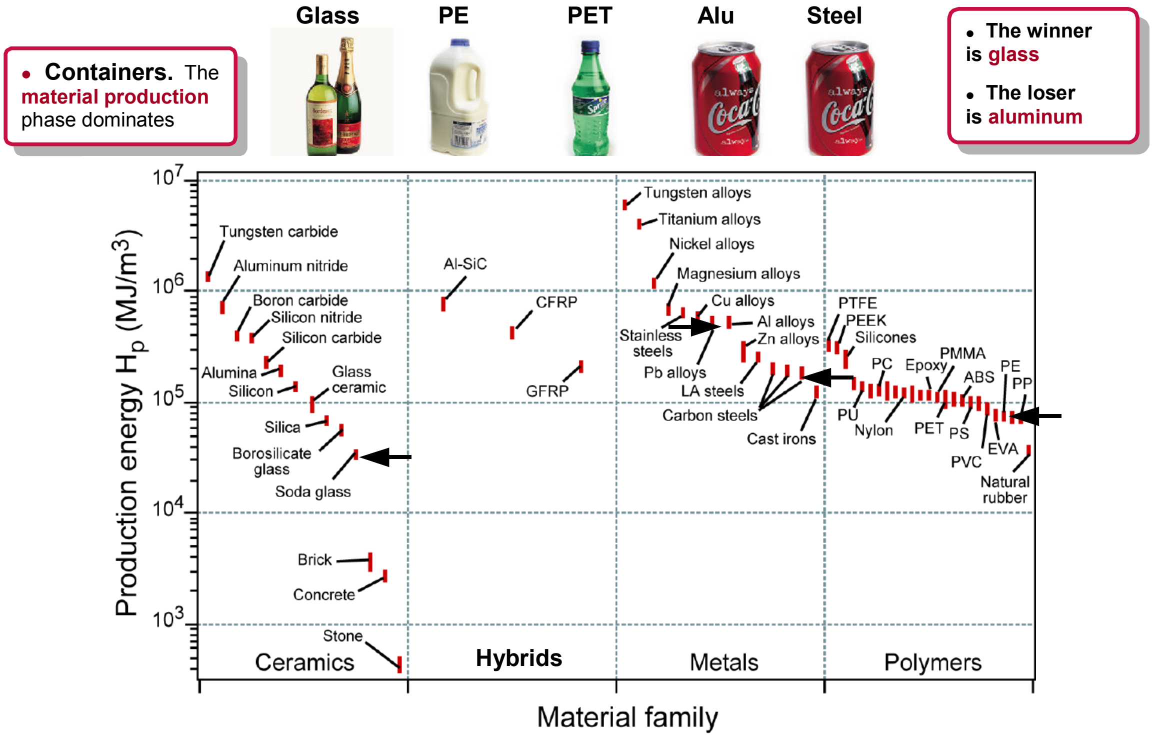

Figure 9. Bar chart of embodied energy of basic materials by volume.

However, is comparison “per kg” or “per m^3” the right way to do it? To deal with environmental impact at the production phase properly we must seek to minimize the energy, the CO_2 burden or the eco-indicator value *per unit of function.* The masses of five competing container-types, the material of which they are made, and the specific energy content of each are listed in Table 1. Their production involves molding or deformation; approximate energies for each are listed. All five of the materials can be recycled. The bottom row gives the result, calculated from the data in the rows above. The steel can is the most energy-efficient, followed by polyethylene. Glass, although it has the lowest energy per kg of material (Figure 8), has a much high energy per unit of function (almost as high as aluminum) because glass bottles are so heavy.

Function: ***contain 1 litre of fluid***

	Glass	*PE*	*PET*	*Alu*	*Steel*
Container type					
Mass *g*	325	38	25	20	45
Mass/litre *g/litre*	433	38	62	45	102
Energy/mass *MJ/kg*	14	80	84	200	23
Energy/litre *MJ/litre*	8.2	3.2	5.4	9.0	2.4

- **The winner is steel**
- **The loosers are glass and aluminum**

Table 1. Eco-Impact per Unit of Function.

Case Study: Crash Barriers

This case study is one that could easily be used with students as either a class homework or the ideas could be implemented as part of a larger project. They would need to be aware of the phases of life and how different factors minimize the eco-impact of each one. They would also need some knowledge of the CES EduPack.

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 (Figure 10). The static type lines 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 Figure 2 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, Figure 11.

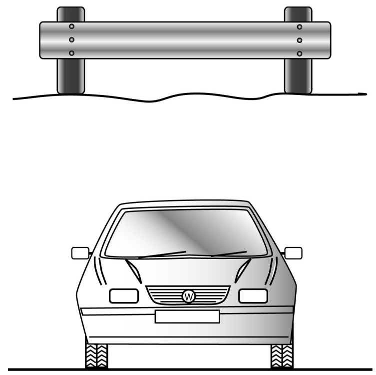

Figure 10: Two crash barriers, one static, the other – the fender – attached to something that moves. Different eco-criteria are needed for each.

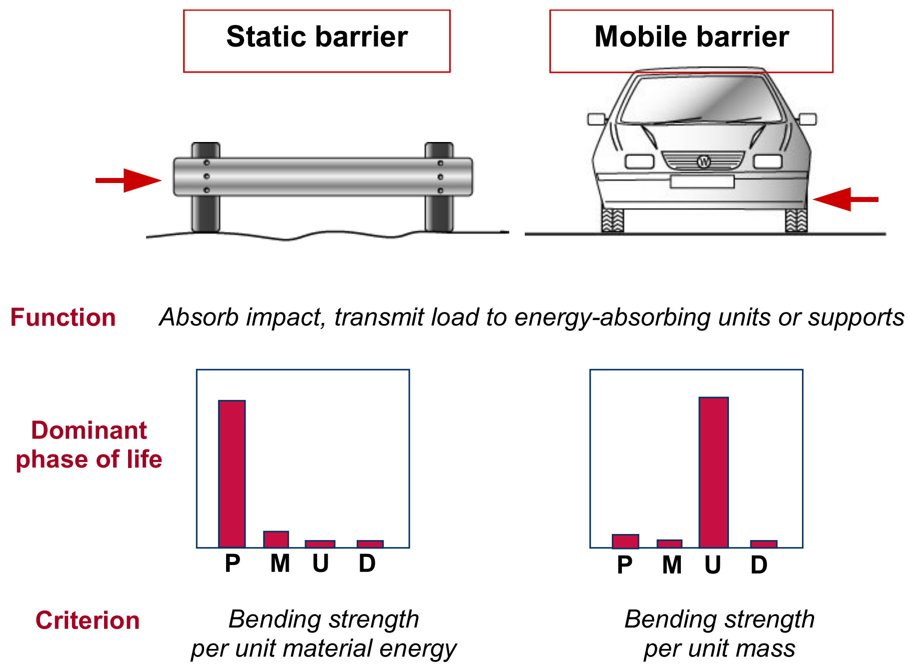

Figure 11. Which phase of life dominates for the two types of barrier?

In an impact the barrier is loaded in bending. Its function is to transfer load from the point of impact to the support structure where reaction from the foundation or from crush-elements in the vehicle support or absorb it. Standard analysis shows that the best choice of materials to transmit a given bending load at *minimum production energy* are those with a high value of the quantity

$$M_1 = \frac{\sigma_{ts}^{2/3}}{H_p \rho}$$

where σ_{ts} is the tensile strength, H_p is the production energy per kg of material and ρ is its density. To do so at *minimum weight* requires instead materials with large values of

$$M_2 = \frac{\sigma_{ts}^{2/3}}{\rho}$$

Details of how to perform these calculations can be found in Materials Selection and Mechanical Design by MF Ashby[4]. Once the performance metrics have been calculated they can be plotted as indices onto material property charts to select the best material.

The charts in Figures 12 and 13 show this. These charts have been generated using CES EduPack Eco Edition at level 2. Figure 12 guides the selection for static barriers. It shows that production energy (for a given load bearing capacity) is minimized by making the barrier from carbon steel or cast iron; nothing else comes close.

Figure 13 guides selection for the mobile barrier. Here CFRP (continuous fiber carbon-epoxy, for instance) excels in its strength per unit weight, but it is not recyclable. Heavier, but recyclable, are alloys of magnesium, titanium and aluminum. Polymers, which rank poorly on the first figure, now become candidates – even without reinforcement, they can be as good as steel.

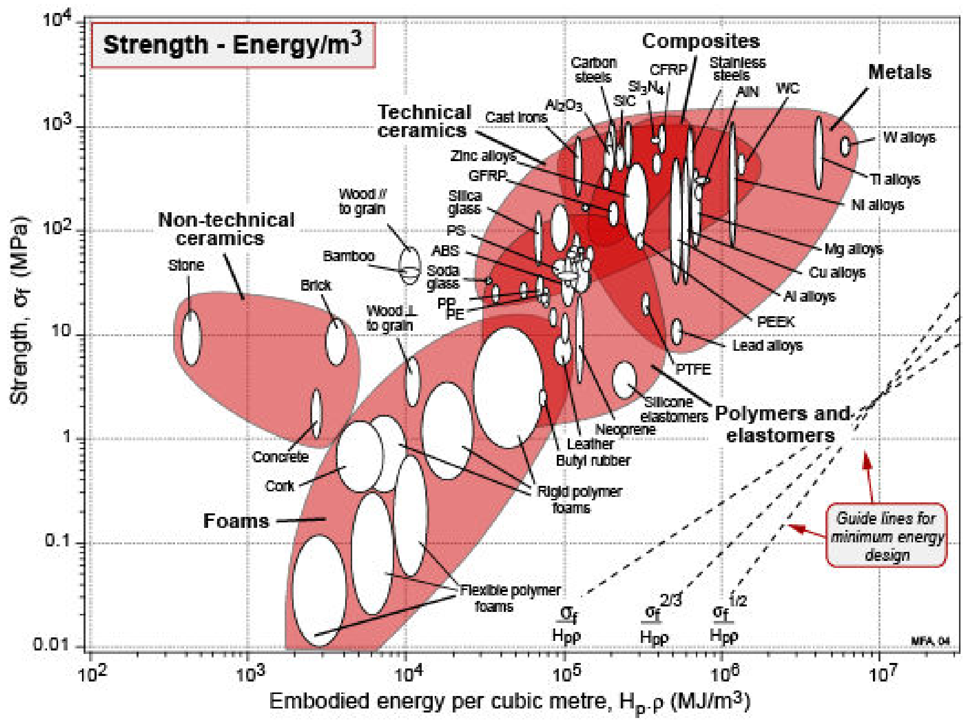

Figure 12. The chart of strength and embodied energy; it is used to select materials for strength at minimum embodied energy.

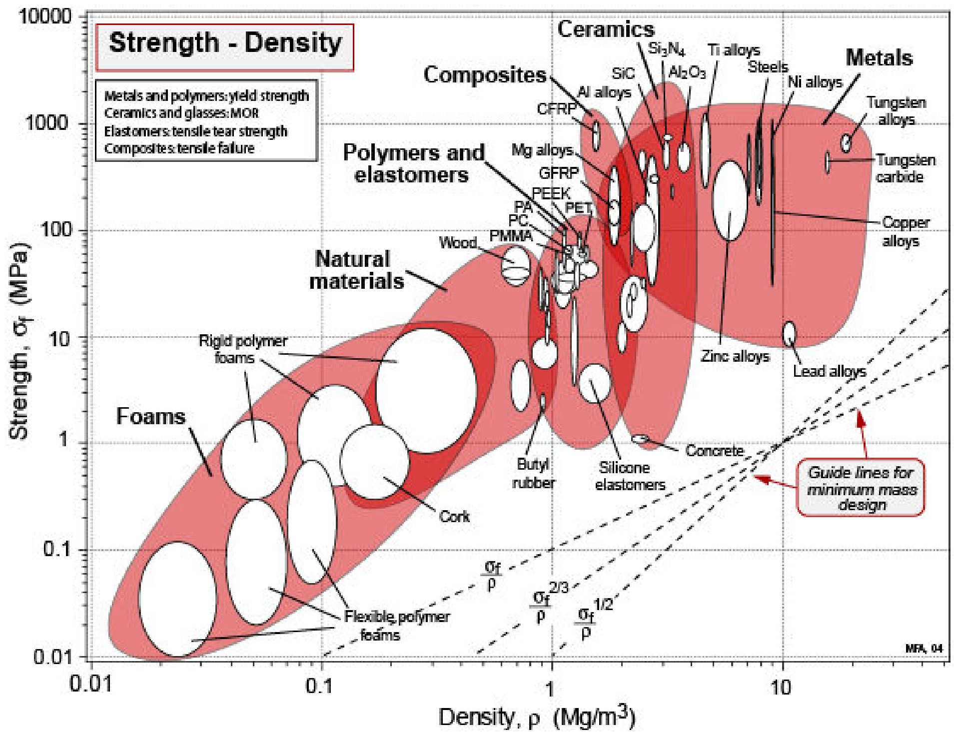

Figure 13. The chart of strength and density; it is used to select materials for strength at minimum weight.

Conclusion

Rational selection of materials to meet environmental objectives starts by identifying the phase of product-life that causes greatest concern: production, manufacture, use or disposal. Dealing with all of these requires data not only for the obvious eco-attributes (energy, CO_2 and other emissions, toxicity, ability to be recycled and the like) but also data for mechanical, thermal, electrical and chemical properties. Thus if material production is the phase of concern, selection is based on minimizing their embodied energy or the associated emissions (CO_2 production for example). But if it is the use-phase that is of concern, selection is based instead on light-weight, excellence as a thermal insulator, or as an electrical conductor (while meeting other constraints on stiffness, strength, cost etc). The CES Eco-database provides data to enable this. Students can identify which phase of life is the most dominant using simple techniques outlined here. They can then look at what can be changed to reduce the eco-impact. This is a simple but effective way of introducing green design to students. Projects based on everyday objects such as car fenders, drinks containers or small appliances (such as a small hairdryer) engage the students and encourages them to think about the wider implications of green design on everyday life.

Acknowledgements

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