Chapter 16

Forces for change

16.1 Introduction and synopsis

Materials are evolving faster now than at any previous time in history. The speed of change was suggested by Figure 1.2: new polymers, elastomers, ceramics and composites are under development; and new processing routes offer cheaper, more reproducible production of conventional materials. These changes are driven by a number of forces. First, there is the *marker-pull:* the demand from industry for materials which are lighter, stiffer, stronger, tougher, cheaper and more tolerant of extremes of temperature and environment. Then there is the *science-push:* the curiosity-driven researches of materials experts in the laboratories of universities, industries and government. Beyond this, there are *global issues:* the desire of society to minimize environmental damage, to save energy, and to reuse rather than discard. Finally, there is the driving force of what might be called *mega-projects:* historically, the Manhattan Project, the space-race and various defence programmes; today, one might think of alternative energy technology, the problems of maintaining an ageing infrastructure of drainage, roads, bridges and aircraft, and environmental problems associated with industrialization.

This chapter examines these forces for change and the directions in which they push materials and their deployment.

16.2 The market pull: economy versus performance

The end-users of materials are the manufacturing industries. They decide which material they will purchase, and adapt their designs to make best use of them. Their decisions are based on the nature of their products. Materials for large civil structures (which might weigh 10 000 tonnes or more) must be cheap; economy is the overriding consideration. By contrast, the cost of the materials for biomredical applications (an artificial heart valve, for instance) is almost irrelevant; performance, not economy, dictates the choice.

The market price of a product has several contributions. One is the cost of the materials of which the product is made, but there is also the cost of the research and development which went into its design, the cost of manufacture and marketing and the perceived value associated with fashion, scarcity, lack of competition and such like. When the material costs are a large part of the market value (50%, say) — that is, when the value added to the material is small — the manufacturer seeks to economize on materials to increase profit or market share. When, by contrast, material costs are a tiny fraction of the market value (1%, say), the manufacturer seeks the materials which will most improve the performance of the produce with little concern for their cost.

With this background, examine Figures 16.1 and 16.2. The vertical axis is the price per unit weight (£/kg or $/kg), applied to both materials and products: it gives a common measure by which

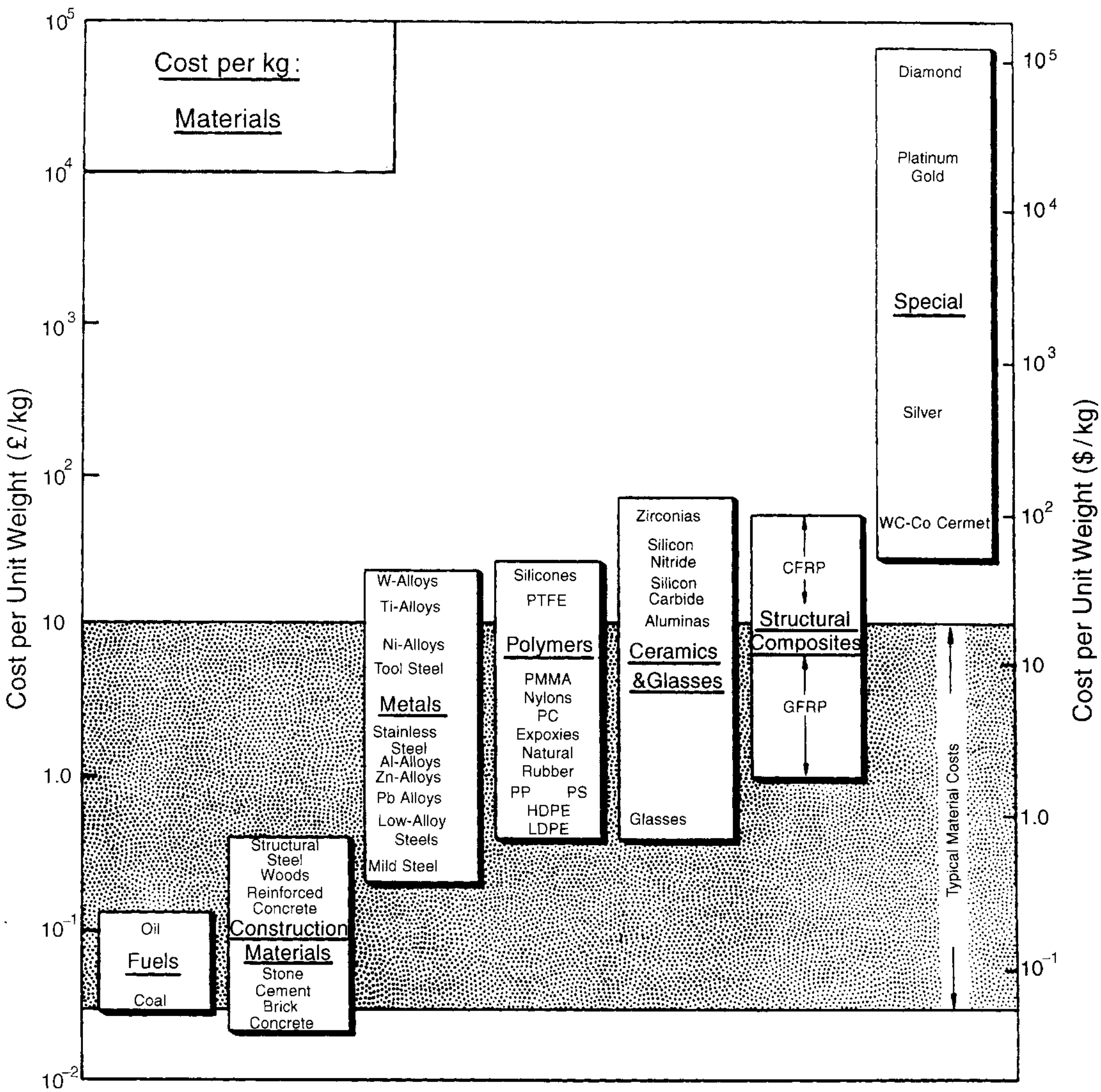

Fig. 16.1 The cost-per-unit-weight diagrams for materials. The shaded band spans the range in which lie the widely used commodity materials of manufacture and construction.

materials and products can be compared. The measure is a crude one but has the great merit that it is unambiguous, easily determined, and bears some relationship to value-added. A product with a price/kg which is twice that of its materials is material-intensive and is sensitive to material costs; one with a price/kg which is 100 times that of its materials is insensitive to material costs, and is probably performance-driven rather than cost-driven. On this scale the cost per kg of a contact lens differs from that of a glass bottle by a factor of 10^5, even though both are made of almost the same glass; the cost per kg of a heart valve differs from that of a plastic bottle by a similar factor, even though both are made of polyethylene. There is obviously something to be learned here.

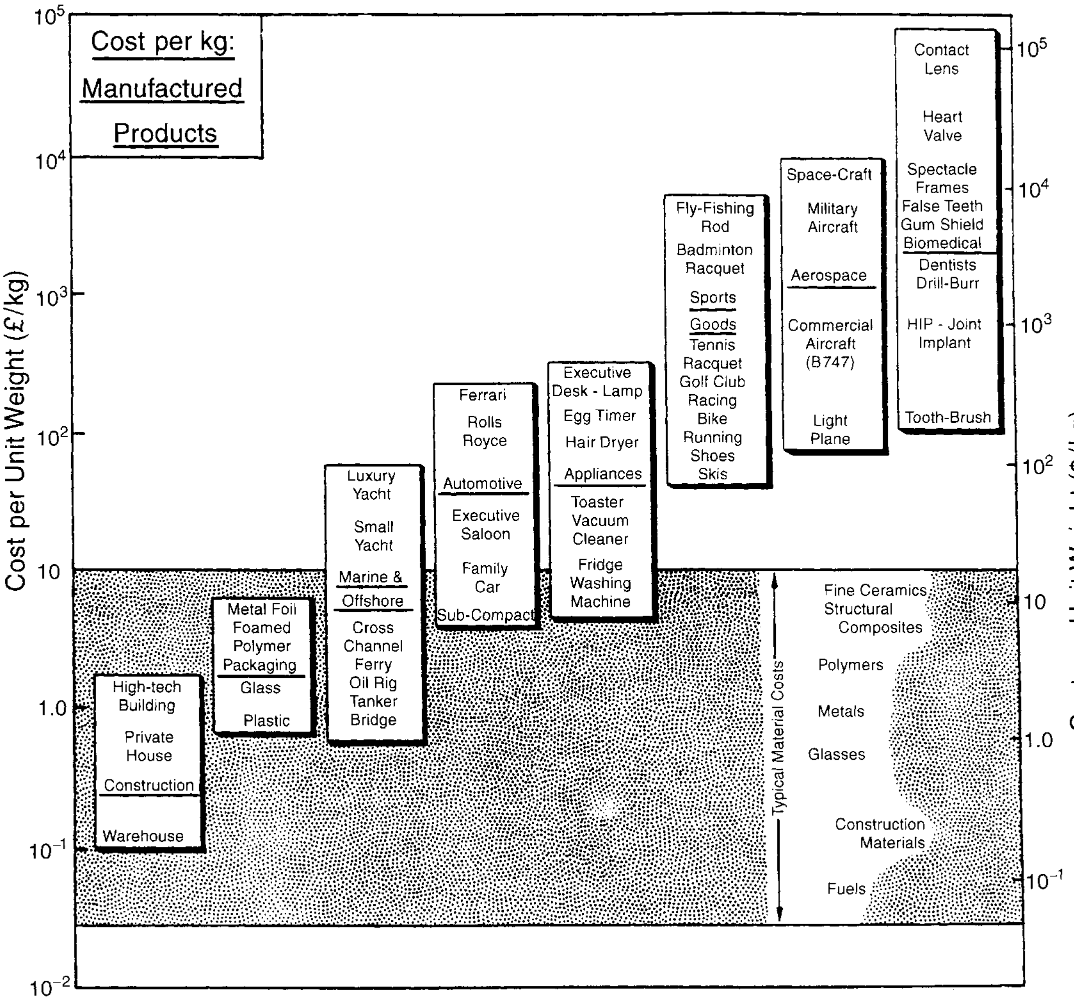

Fig. 16.2 The cost-per-unit-weight diagram for products. The shaded band spans the range in which lie most of the materials of which they are made. Products in the shaded band are material-intensive; those above it are not.

Look first at the price per unit weight of materials (Figure 16.1). The bulk, 'commodity' materials of construction and manufacture lie in the shaded band; they all cost between £0.05 and £10/kg, or \$0.7 and \$16/kg. Construction materials like brick, concrete, wood and structural steel, lie at the lower end; high-tech materials, like titanium alloys, lie at the upper. Polymers span a similar range: polyethylene at the bottom, polytetrafluorethylene (PTFE) near the top. Composites lie higher, with GFRP at the bottom and CFRP at the top of the range. Engineering ceramics, at present, lie higher still, though this will change as production increases. Only the low-volume 'exotic' materials lie much above the shaded band.

The price per kg of products (Figure 16.2) shows a different distribution. Eight market sectors are shown, covering much of the manufacturing industry. The shaded band on this figure spans the cost of commodity materials, exactly as in the previous figure. Sectors and their products within the shaded band shave the characteristic that material cost is a major fraction of product price: about 50% in civil construction, large marine structures and some consumer packaging, falling to perhaps 20% as the top of the band is approached (family car — around 25%). The value added in converting material to product in these sectors is relatively low, but the market volume is large. These constraints condition the choice of materials: they must meet modest performance requirements at the lowest possible cost. The associated market sectors generate a driving force for improved processing of conventional materials in order to reduce cost without loss of performance, or to increase reliability at no increase in cost. For these sectors, incremental improvements in well-tried materials are far more important than revolutionary research-findings. Slight improvements in steels, in precision manufacturing methods, or in lubrication technology are quickly assimilated and used.

The products in the upper half of the diagram are technically more sophisticated. The materials of which they are made account for less than 10% — sometimes less than 1% — of the price of the product. The value added to the material during manufacture is high. Product competitiveness is closely linked to material performance. Designers in these sectors have greater freedom in their choice of material and there is a readier acceptance of new materials with attractive property-profiles. The market-pull here is for performance, with cost as a secondary consideration. These smaller volume, higher value-added sectors drive the development of new or improved materials with enhanced performance: materials which are lighter, or stiffer, or stronger, or tougher, or expand less, or conduct better — or all of these at once.

The sectors have been ordered to form an ascending sequence, prompting the question: what does the horizontal axis measure? Many factors are involved here, one of which can be identified as 'information content'. The accumulated knowledge involved in the production of a contact lens or a heart valve is clearly greater than that in a beer-glass or a plastic bottle. The sectors on the left make few demands on the materials they employ; those on the right push materials to their limits, and at the same time demand the highest reliability. These features make them information-intensive. But there are also other factors: market size, competition (or lack of it), perceived value, fashion and taste, and so on. For this reason the diagram should not be over-interpreted: it is a help in structuring information, but it is not a quantitative tool.

The manufacturing industry, even in times of recession, has substantial resources; and it is in the interests of government to support their needs. The market pull is, ultimately, the strongest force for change.

16.3 The science-push: curiosity-driven research

Curiosity may kill cats, but it is the life-blood of innovative engineering. Technically advanced countries sustain the flow of new ideas by supporting research in three kinds of organization: universities, government laboratories and industrial research laboratories. Some of the scientists and engineers working in these institutions are encouraged to pursue ideas which may have no immediate economic objective, but which can evolve into the materials and manufacturing methods of future decades. Numerous now-commercial materials started in this way. Aluminium, in the time of Napoleon III, was a scientific wonder — he commissioned a set of aluminium spoons for which he paid more than those of solid silver. Aluminium was not, at that time, a commercial success; now it is. Titanium, more recently, has had a similar history. Amorphous (= non-crystalline) metals, now important in transformer technology and in recording-heads of tape decks, were, for years, of only academic interest. It seems improbable that superconductors or semiconductors would have been discovered in response to market forces alone; it took long-term curiosity-driven research to carry them to the point that they became commercially attractive. Polyethylene was discovered by chemists studying the effect of pressure on chemical reactions, not by the sales or marketing departments of multinational corporations. History is dotted with examples of materials and processes which have developed from the inquisitiveness of individuals.

What new ideas are churning in the minds of the materials scientists of today? There are many, some already on the verge of commercialization, others for which the potential is not yet clear. Some, at least, will provide opportunities for innovation; the best may create new markets.

Monolithic ceramics, now produced in commercial quantities, offer high hardness, chemical stability, wear resistance and resistance to extreme temperatures. Their use as substrates for microcircuits is established; their use in wear-resistant applications is growing, and their use in heat engines is being explored. The emphasis in the development of *composite materials* is shifting towards those which can support loads at higher temperatures. Metal-matrix composites (example: the aluminium containing particles or fibres of silicon-carbide of Section 14.7) and intermetallic-matrix composites (titanium-aluminide or molybdenum-disilicide containing silicon-carbide, for instance) can do this. So, potentially, can ceramic-matrix composites (alumina with silicon carbide fibres) though the extreme brittleness of these materials requires new design techniques. Metallic foams, up to 90% less dense than the parent metal, promise light, stiff sandwich structures competing with composites.

A number of new techniques of *surface engineering* allows the alloying, coating or heat treating of a thin surface layer of a component, modifying its properties to enhance its performance. They include: laser hardening, coatings of well-adhering polymers and ceramics, ion implantation, and even the deposition of ultra-hard carbon films with a structure and properties like those of diamond. New *bio-materials*, designed to be implanted in the human body, have structures onto which growing tissue will bond without rejection. New *polymers* which can be used at temperatures up to 350°C allow plastics to replace metals in even more applications — the inlet manifold of the automobile engine, for example. New *elastomers* are flexible but strong and tough; they allow better seals, elastic hinges, and resilient coatings. Techniques for producing *functionally-graded materials* can give tailored gradients of composition and structure through a component so that it could be corrosion resistant on the outer surface, tough in the middle and hard on the inner surface. *'Intelligent' materials* which can sense and report their condition (via embedded sensors) allow safety margins to be reduced. New *adhesives* could displace rivets and spot-welds; the glue-bonded automobile is a real possibility. And new techniques of *mathematical modelling* and *process control* allow much tighter control of composition and structure in manufacture, reducing cost and increasing reliability and safety.

All these and many more are in the pipeline. They have the potential to enable new design, or, more often, potential for the redesign of a product which already has a market, increasing its market share. Some are already commercial or near commercial; others may not become commercially viable for two decades. The designer must stay alert.

16.4 Materials and the environment: green design

Technical progress and environmental stewardship are not incompatible goals. History contains many examples of civilizations that have adopted environmentally conscious life-styles while making technological and sociological progress. But since the start of the industrial revolution, the acceleration of industrial development has overwhelmed the environment, with local and global consequences which cannot be ignored.

There is a growing pressure to reduce and reverse this environmental impact. It requires processes which are less toxic and products which are lighter, less energy-intensive and easier to recycle; and this must be achieved without compromising product quality. New technologies must (and can) be developed which allow an increase in production with diminished impact on the environment. Concern for the environment must be injected into the design process — brought 'behind the drawing-board', so to speak — taking a life-cycle view of the product which includes manufacture, distribution, use and final disposal.

Energy-content as a measure of environmental impact

All materials contain energy (Table 16.1). Energy is used to mine, refine, and shape metals; it is consumed in the firing of ceramics and cements; and it is intrinsic to oil-based polymers and elastomers. When you use a material, you are using energy, and energy carries with it an environmental penalty: CO_2, oxides of nitrogen, sulphur compounds, dust, waste heat. Energy is only one of the eco-influences of material production and use, but it is one which is easier to quantify than most others. We take it as an example.

Performance indices which include energy content are derived in the same way as those for weight or cost (Chapter 5). An example: the selection of a material for a beam which must meet a stiffness constraint, at minimum energy content. If the energy content per kilogram of a material is q (data in Table 16.1), that per unit volume is ρq where ρ is the density of the material. Repeating the derivations of Chapter 5 but with the objective of minimizing the energy content of the beam rather than its mass leads to performance equations and material indices which are simply those of Chapter 5 with ρ replaced by ρq. Thus the best materials to minimize energy content of a beam of specified stiffness and length are those with large values of the index

$$M = \frac{E^{1/2}}{\rho q} \tag{16.1}$$

where E is the modulus of the material of the beam. The stiff tie of minimum energy content is best made of a material of high $E/\rho q$; the stiff plate, of a material with high $E^{1/3}/\rho q$.

Strength works the same way. The best choice of material for a beam of specified bending strength and minimum energy content is that with the highest value of

$$M = \frac{\sigma_f^{2/3}}{\rho q} \tag{16.2}$$

where σ_f is the failure strength of the beam-material. The equivalent calculation for the tie gives the index $\sigma_f/\rho q$; that for a plate gives $\sigma_f^{1/2}/\rho q$. The calculation is easily adapted to include shape; then the indices of Table 8.1 apply, with ρ replaced by ρq.

Figures 16.3 and 16.4 are a pair of Materials Selection Charts for minimizing energy content per unit of function. The first show modulus, E, plotted against energy content, ρq; the design guide-lines give the slopes for three of the commonest performance indices. The second shows strength σ_f (defined as in Chapter 4) against ρq; again, design guide-lines give the slopes.

The charts are used in exactly the same way as before. Energy consumption, and the potential for saving, are significant when large quantities of material are used, as they are in civil construction. The reader can quickly establish that the most energy-efficient beam, whether the design is based on stiffness or on strength, is that made of wood; steel, even with a large shape factor, consumes far more. Columns of brick or stone are more energy-efficient than concrete, though more labour intensive.

Table 16.1 Energy content and eco-indicator values for materials

Class	*Material*	*Energy/wt* *q (MJ/kg)*	*Energy/vol* *ρq(GJ/m*^{3}*)*	*Eco-indicator* *(millipoints/kg)*
Metals	Titanium and alloys	555–565	2400–2880	80–100 (est.)
	Magnesium and alloys	410–420	717–756	20–30 (est.)
	Cast irons	60–260	468–1500	3–10
	Aluminium and alloys	290–305	754–884	10–18
	Stainless steels	110–120	825–972	16–18
	Copper and alloys	95–115	712–1035	60–85
	Zinc and alloys	67–73	348–525	60–85 (est.)
	Carbon steels	50–60	390–468	4.0–4.3
	Lead and alloys	28–32	300–360	60–85 (est.)
Polymers	Nylon 66	170–180	187–216	12–14
	Polypropylene	108–113	95–102	3.2–3.4
	H.D. polyethylene	103–120	97–116	2.8–3.0
	L.D. polyethylene	80–104	73–94	3.7–3.9
	Polystyrene	96–140	96–154	8.0–8.5
	PVC	67–92	87–147	4.2–4.3
	Synthetic rubber	120–140	108–126	13–15
	Natural rubber	5.5–6.5	5–6	14–16
Ceramics and glasses	Glasses	13–23	32–57	2.0–2.2
	Glass fibres	38–64	95–160	2.1–2.3
	Bone china	270	540–580	1.0–1.5 (est.)
	Bricks	3.4–6.0	6.8–12	0.5–1.0
	Refractories	1–50	3–100	10–20 (est.)
	Pottery	6–15	12–30	0.5–1.5
	Cement	4.5–8.0	9–18	1.0–2.0 (est.)
	Concrete	3–6	7–15	0.6–1.0 (est.)
	Stone	1.8–4.0	4–8.8	0.5–1.0
	Gravel	0.1	0.2–0.4	0.2–0.5
Composites (estimates)	GFRP	90–120	160–220	12–12 (est.)
	CFRP	130–300	230–540	20–25 (est.)
Other	Hard and soft woods	1.8–4.0	1.2–3.6	0.6–0.8
	Reinforced concrete	8–20	20–50	1.5–2.5 (est.)
	Crude oil	44	38–40	—
	Coal	29	27–30	—
	Natural gas		0.033–0.039	—

(1 MJ = 0.278 kWh = 9.48×10^2 Btu)

Most polymers are derived from oil. This leads to statements that they are energy-intensive, with implications for their future. The two charts show that, per unit of function in bending (the commonest mode of loading), most polymers are less energy-intensive than primary aluminium, magnesium or titanium, and that several are competitive with steel. Most of the energy consumed in the production of light alloys such as aluminium and magnesium is used to reduce the ore to the elemental metal, so that these materials, when recycled, are much less energy intensive. Efficient collection and recycling makes important contributions to energy saving.

Eco-indicators

Energy content, as said earlier, is only one measure of the environmental impact of material usage. In many circumstances it is not the important one; the emission of a toxic by-product, the difficulty

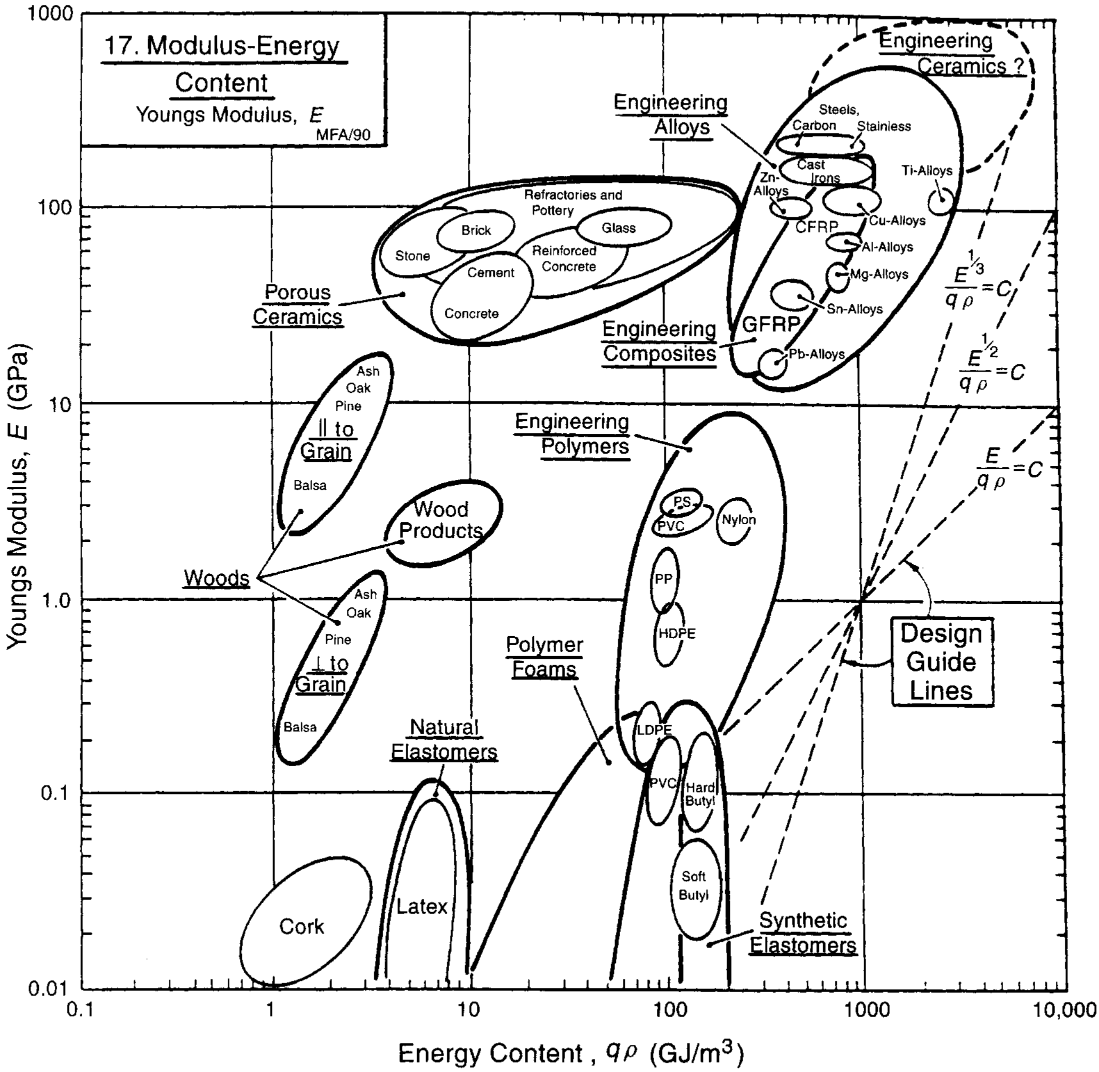

Fig. 16.3 The modulus versus energy-content chart, with guide-lines for selecting materials for stiff structures at minimum energy-content. It is an example of charts which allow selection to minimize environmental impact.

of recycling, or the resistance to biodegrading can be the real environmental threat. Table 16.2, as an example, lists the eco-profile associated with the production of 1 kg of aluminium from bauxite. Energy is a contribution, and linked to energy is the consumption of certain resources and the production of greenhouse gasses such as CO_2, CH_4 and CO. But there are other contributions too: acidification (SO_X, NO_X) particulates, solid waste etc. They are measured in strange units and the numbers in these units vary by enormous factors. Which are important and which are not? What is the designer to do with information like this? In this form it is not helpful.

What does the designer need? Ideally, a single number characterizing, in a properly balanced way, the eco-impact associated with the production of 1 kg of each material. We deal with cost in exactly

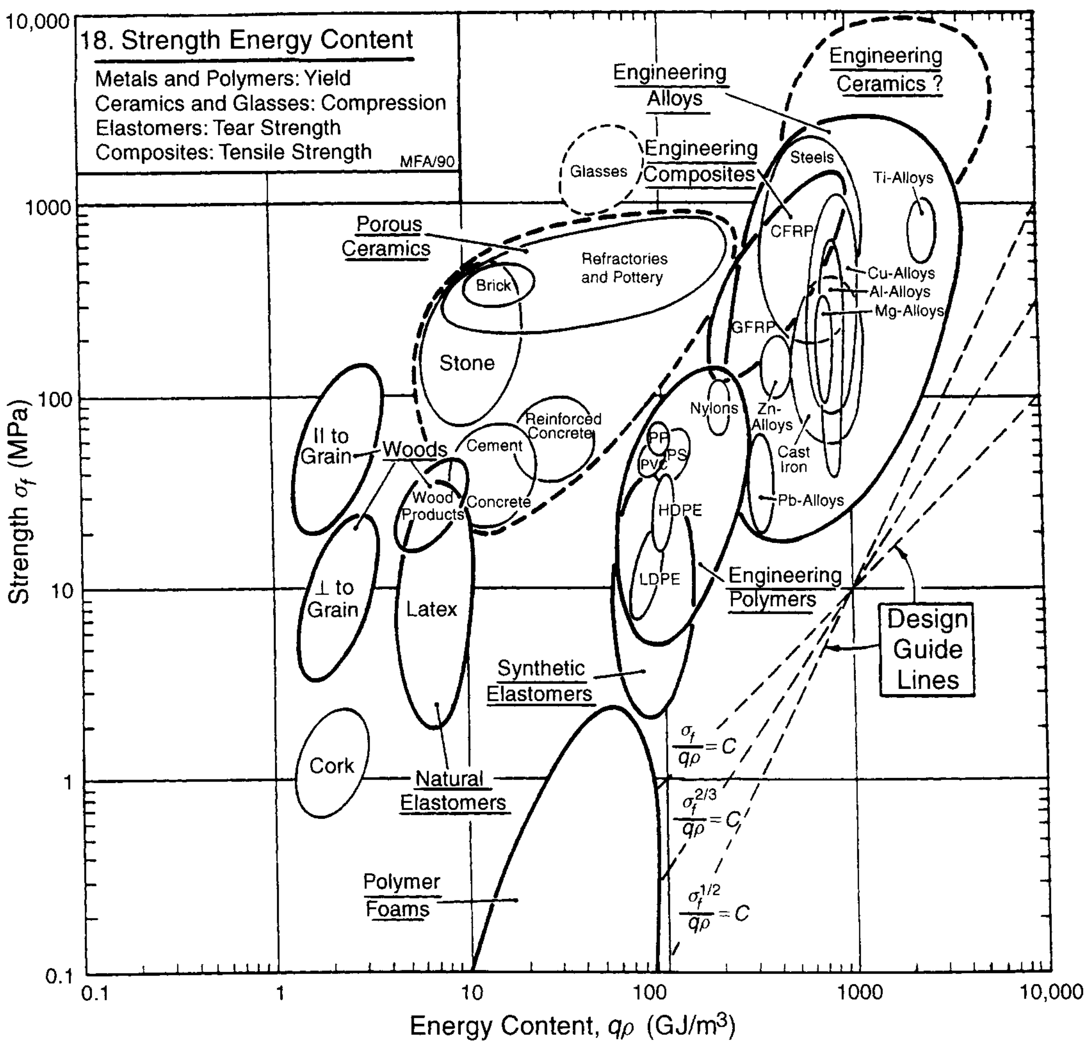

Fig. 16.4 The strength versus energy-content chart, with guide-lines for selecting materials for strong structures at minimum energy-content.

this way — it is, after all, an aggregated measure of the costs of resources, labour, capital and energy required to make 1 kg of material. Can a similar aggregate be constructed for eco-burden?

Efforts are underway in Europe to devise such a lumped measure, called the *eco-indicator* value, associated with the manufacture or processing of 1 kg of each material. Evaluating it involves three steps (Figure 16.5). First, values for the individual contributions of Table 16.2 are normalized to remove the strange units. To do this, the contribution is divided by the average contribution per (European) person per year. Thus the energy is normalized by the energy consumption per person per year (the total European energy consumption per year divided by the population). Second, the normalized contributions are weighted to take account of the severity of the problems they cause. Thus if acidification is a serious problem it is weighted heavily, and if summer smog is not a problem

Table 16.2 Eco-profile: production of 1 kg of aluminium from bauxite

Environmental load	*Value*	*Units* (all per kg)*
Energy	220	MJ
Resources	2.0	kg
Greenhouse	10.6	GWP
Ozone	0	ODP
Acidification	0.11	AP
Eutrophication	0.002	NP
Heavy metals	0	Pb equiv.
Carciogenicity	0	PAH equiv
Wintersmog	0.13	SO_2 equiv
Summersmog	0.003	POCP
Pesticides	0	kg
Solid	0.083	kg

*Units (all per kg):
MJ = megajoules of energy
GWP = global warming potential relative to 1 kg of CO_2
ODP = ozone depletion potential relative to 1 kg of CFC-111
AP = acidification potential relative to 1 kg of SO_2
NP = nutrification potential relative to 1 kg of PO_4
Pb equiv. = heavy metal toxicity relative to 1 kg of Pb ion
POCP = photochemical oxidant formation relative to 1 kg of ethylene
SO_2 equiv. = equivalent smog-potential relative to 1 kg of SO_2

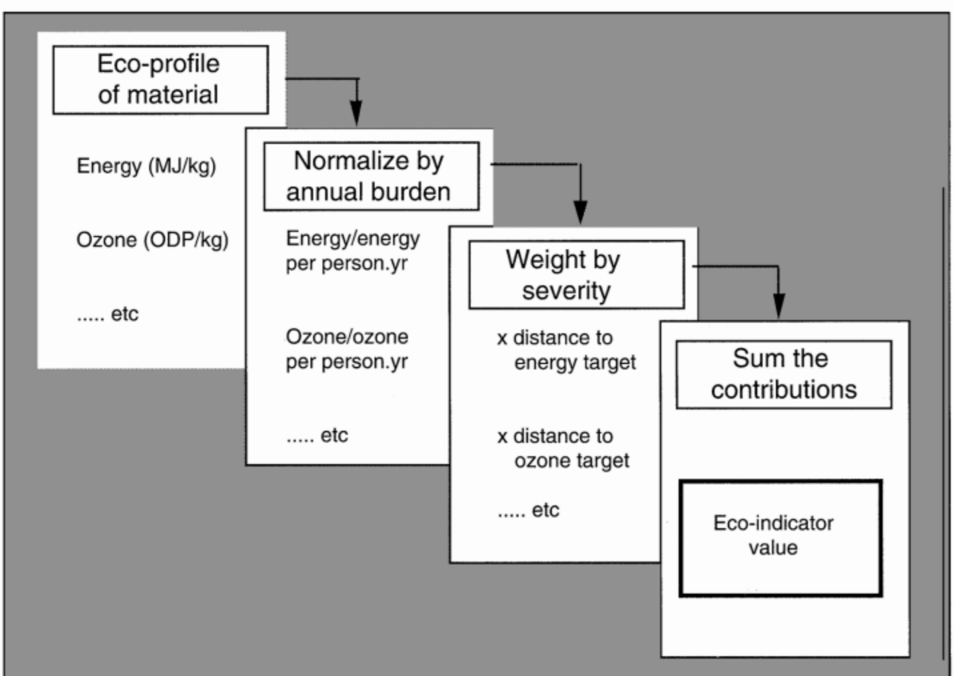

Fig. 16.5 The steps in deriving an eco-indicator value for a material or process. The raw data are first normalized by the average output per European person per year, then weighted by the severity of their effect, then summed. For details, see Goedkoop *et al.* (1995).

it is given a light weight. Finally, the weighted, normalized contributes are *summed* to give the eco-indicator value. There is a lot more to it than that, but this outline gives the essentials. The last column of Table 16.1 lists values based on weight-factors appropriate to a European nation. A high value means that the use of 1 kg of the material carries a high eco-burden; a low value, a low one.

These eco-indicators (symbol: I_e) are only an approximate measure of the eco-burden, but they are a useful one because they allow the initial election of material to minimize overall eco-impact per unit of function. The reasoning, as with energy in the last section, follows the method of Chapter 5. This leads to a set of indices which are simply those given above with ρq replaced by ρI_e.

Despite often-expressed reservations about the low resolution of eco-indicators, several large industries now use them to guide the selection of materials and processes. As the documentation of the eco profile of materials improves and broader agreement is reached on procedures for normalizing and weighting, it can be expected that their use will grow. The right way to exploit them is that described here, seeking materials which minimize the eco-impact, not per unit of weight, but per unit of function.

16.5 The pressure to recycle and reuse

There are many good reasons for not throwing things away. Discarded materials damage the environment; they are a form of pollution. Materials removed from the manufacturing cycle must be replaced by drawing on a natural resource. And materials contain energy, lost when they are dumped. Recycling is obviously desirable. But in a market economy it will happen only if there is profit to be made. What is needed to allow this?

Look, first, at where recycling works well and where it does not. *Primary scrap* — the turnings, trimmings and tailings which are a by-product of manufacture — has high value: it is virtually all recycled. That is because it is uncontaminated and because it is not dispersed. *Secondary scrap* has been through a consumption cycle — the paper of newsprint, the aluminium of a drink-can, the steel of an automobile — all are contaminated by other materials to which they are joined; by corrosion products; by ink and paint. And they are dispersed, some, like the tungsten in the filaments of lamp bulbs, very widely dispersed. In this form they are worth nothing or less-than-nothing, meaning that the cost of collection is greater than the value of the scrap itself. Yet this is by far the largest component of the material cycle. Newsprint and bottles are present examples: in a free market it is not economic to recycle either of these. Recycling *does* take place, but it relies on social conscience and good will, local subsidies and publicity. It is precarious for just those reasons.

Two things can change all that. Legislation (a departure from a true free market economy) is the obvious one. A deposit or 'dispersal cost', built into the price of each product, profoundly changes the economics and effectiveness of recycling; numerous societies have tried it, and it works. The other is design. The great obstacles in recycling are recognition, separation and decontamination; all are problems the designer can address. Finger-printing materials by colour or emblem or bar code allows recognition. Design for disassembly and the avoidance of mutually contaminating combinations allow economic separation. Clever chemistry (strippable paints; soluble glues) help with decontamination. And finally: design to by-pass the need to recycle: longer primary life; and more thought, at the initial design stage, of secondary usage.

16.6 Summary and conclusions

Powerful forces drive the development of new and improved materials, encourage substitution, and modify the way in which materials are produced and used. Market forces, historically the most influential, remain the strongest. The ingenuity of research scientists, too, drives change by revealing a remarkable spectrum of new materials with exciting possibilities, though the time it takes to develop and commercialize them is long: typically 15 years from laboratory to market.

Until recently, these were the evolutionary forces of materials technology. But man's damaging impact on the environment can no longer be ignored. Materials contribute to this damage at three points: in their production, in the use of products made from them, and in the disposal of these products. Concern about this, backed by legislation, already drives the development of new processing routes, the elimination of particularly damaging materials, and requirements for more effective recycling. The need, today, is to inject concern for environmental friendliness into the design process. Only the designer can do that.

16.7 Further reading

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