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TEACHING RESOURCES

CES EduPack for Eco Design

CES EduPack for Eco Design —A White Paper

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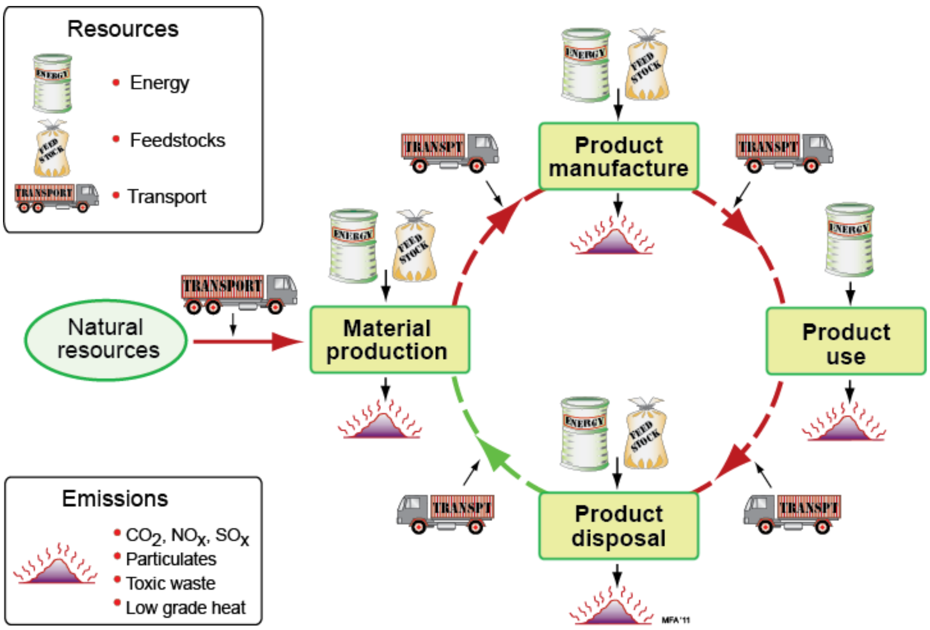

Abstract

Concern for the damaging effect of human activity on the environment prompts efforts to analyze and correct them. The focus of this report is on the role of materials and processes in this, and on data, methods, and supporting software to support design to minimize the damage. The approach is a broad one, seeking to develop a resource that, although approximate, has wide applicability. This is only possible if prerequisites of strict procedure and exactitude are relaxed. The method allows greater rigor and precision to be incorporated as the data to enable them becomes available.

The report introduces the problem, describes the CES EduPack software that incorporates the method, and the MaterialUniverse data that supports it. The data and a version of the software appropriate for teaching are also available as the CES EduPack Eco Design Edition. Here we document sources of the data, the ways in which estimates have been made for the numerous

materials for which no eco-data are available, and illustrate the use of the system for selection. Numerous further examples can be found in the text “Materials and the Environment”, Ashby (second edition, 2012).

Contents

1. Introduction: the material's life-cycle

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 quality of life and threatening the well-being of future generations. The position is dramatized by the following statement: at a global growth rate of 3% per year we will mine, process, and dispose of more "stuff" in the next 25 years than in the entire history of human civilization. *Design for the environment* (Eekels, 1993; Fiskel and Wapman, 1994) is generally interpreted as the effort to adjust our present product design efforts to correct known, measurable, environmental degradation; the time-scale of this thinking is ten years or so, an average product's expected life. *Design for sustainability* is the longer view: that of adaptation to a lifestyle that meets present needs without compromising the needs of future generations (Brundlandt, 1987). The time-scale here is less clear—it is measured in decades or centuries—and the adaptation required is much greater. This report focuses on the role of materials and processes in achieving both of these.

The nature of the problem is brought into focus by examining the materials lifecycle, sketched in Figure 1. Ore and feedstock, most of them non-renewable, 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 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 and other emissions—heat, and gaseous, liquid, and solid waste.

The problem, crudely put, is that the sum of these unwanted by-products now often exceeds the capacity of the environment to absorb them. Some of the injury is local, and its origins can be traced and remedial action taken. Some is national, some global, and here remedial action has wider social and organizational prerequisites. Much present environmental legislation aims at modest reductions in the damaging activity; a regulation requiring 20% reduction in—say—the average gasoline consumption of passenger cars is seen by car-makers as a major challenge.

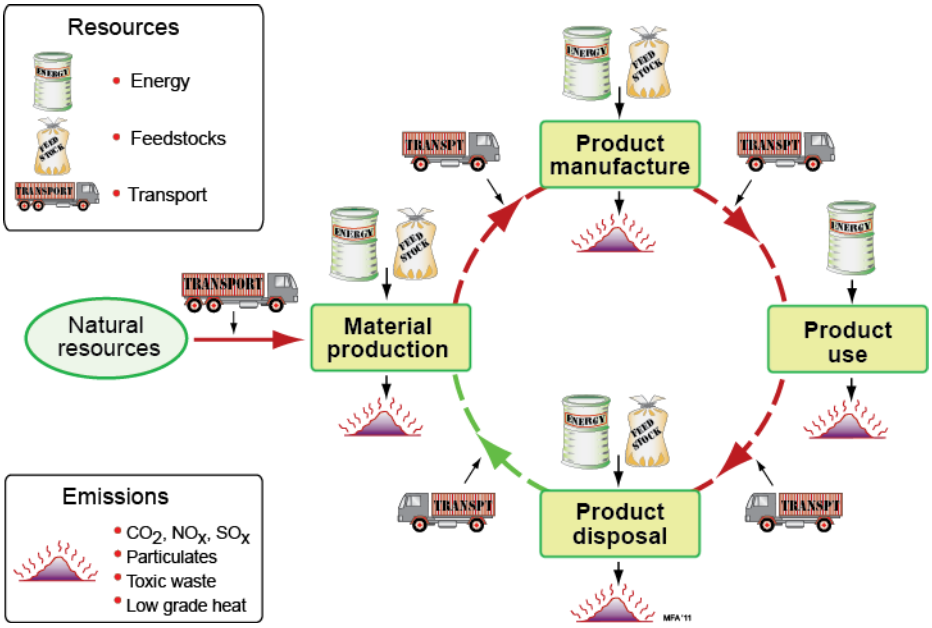

Figure 1. The material life-cycle. Ore and feedstock are mined and processed to yield a material. This is manufactured into a product that is used and at the end of its life, discarded or recycled. Energy and materials are consumed in each phase, generating waste.

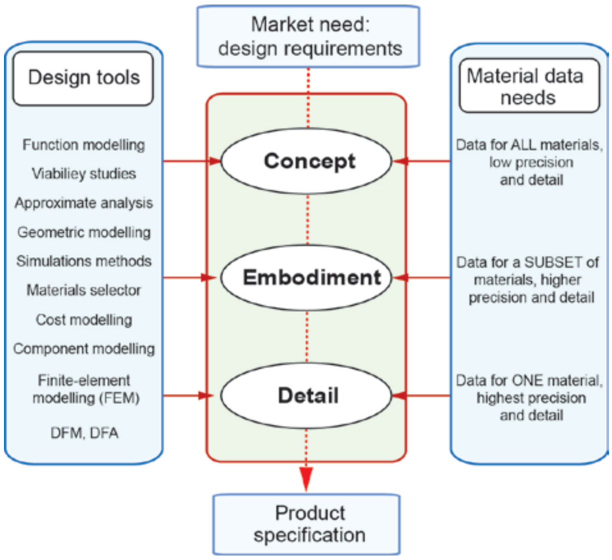

Figure 2. The design flow-chart showing need, concept generation, embodiment, and detailing. On the left: *the design tools that support the process.* On the right: *the material data-needs.*

Sustainability requires solutions of a completely different kind. Even conservative estimates of the adjustment needed to restore long-term equilibrium with the environment envisage a reduction in the flows of Figure 1 by a factor of four (see, for example, von Weizsäcker et al, 1997); some say ten (Schmidt-Bleek, 1997). Population growth and the growth of the expectations of this population more than cancel any modest savings that the developed nations may achieve. It is here that the challenge is greatest, requiring difficult adaptation, and one for which no generally-agreed solutions yet exist. But it remains the long-term driver of eco-design, to be retained as background to any creative thinking.

2. Materials selection in design

The design process

The essential steps in the design process are described in the flow chart of Figure 2 (Cross, 2000; French 1985; Pahl and Beitz, 1997; Ullman, 1992; Ulrich and Eppinger, 1995). A market need is identified. Concepts to fill it are developed and critically reviewed. Promising concepts pass to the embodiment or “layout” stage, where the most suitable is selected for detailed design, analysis, production, planning, and costing. The output is a product specification, enabling prototyping, testing, and the establishment of full production.

The environmental impact of a product is frequently explored using the techniques of Life Cycle Assessment (LCA). An LCA analysis, as the name implies, examines the life cycle of a product and assesses the eco-impact it creates. This requires information of the life-history of the product at a level of precision that is only available after the product has been produced and used. It is a tool for the evaluation and comparison of existing products, rather than one that guides the design of those that are new. The difficulty is that decisions taken in the early stages of design lead to commitments that cannot easily be changed later; for this early decision-making, LCA comes too late. Instead a design tool is required that guides environmental awareness and exploits the information available early in the design process—the “concept” and “embodiment” stages of Figure 2.

Materials selection

Unbiased materials selection is best achieved by considering *all* materials to be viable candidates until shown to be otherwise. Efficient selection (Ashby, 2005) involves four

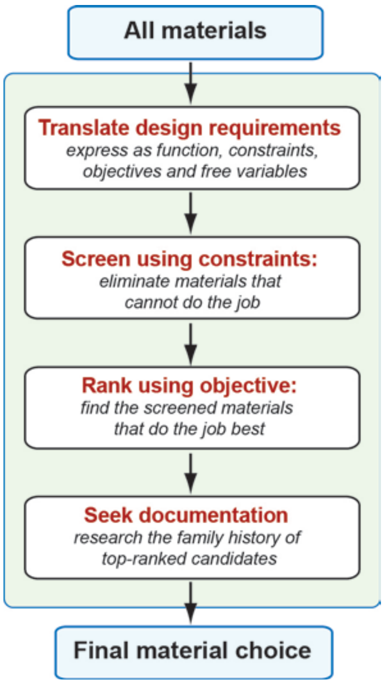

Figure 3. The strategy for materials selection. The four main steps—translation, screening, ranking, and supporting information—are shown here.

steps, which we here call *translation, screening, ranking,* and *supporting information* (Figure 3). The steps can be likened to those in selecting a candidate for a job. The company needs are first analyzed and *translated* into a job specification. The job is advertised, defining essential skills and experience, thereby *screening-out* potential applicants unable to meet the job requirements and allowing a shortlist to be drawn up. Applicants submit CVs, which allows candidates to the *ranked* by the strength of evidence that they can do the job effectively and efficiently. References and interviews are then sought for the short-listed candidates, building a file of *supporting information*.

Texts on material selection (Dieter, 1991; Charles et al, 1997; Budinski and Budinski,1999; Farag, 1989; Lewis, 1990; Ashby, 2005) describe how these steps are implemented to select materials and processes. In the translation step the design requirements are reformulated as constraints on material properties and process attributes and as one or more objectives: minimization of cost, or of weight, or of environmental impact, for instance. In screening, these constraints are used to eliminate materials that cannot meet the requirements. It is effectively performed using a computerized database containing material attributes: values for physical, mechanical, thermal, and electrical properties; and—in a database for eco-selection—attributes relating to the environmental impact of the production of the material itself: its energy content, the greenhouse and acidification gases created by its production, its toxicity, and so forth. The design requirement that "the service temperature of a candidate material must be greater than 250^{o}C" imposes the limit that the maximum service temperature of any viable candidate must be greater than this; the design requirement of "electrical insulation" imposes a limit on electrical resistivity, and so forth. Attribute limits are the analog of the job advertisement that requires that the applicant "must have a valid driving license", or "a degree in computer science". They do not, however, provide any level of performance optimization.

Ranking is achieved by the use of *material indices* derived from the objective mentioned above. These are groupings of material properties that characterize performance: the materials with the largest values of an index maximize some aspect of performance. The specific stiffness, E/ρ, is one such index (E is Young's modulus and ρ the density); the specific strength σ_y / ρ is another (σ_y is the yield strength). There are many material indices, each measuring some aspect of efficiency for a given function; a catalog, with derivations, can be found in Ashby (2005). They are the analog of the job advertisement that states that "typing speed and accuracy are a priority", or that "preference will be given to those with a proven track record of success in this environment", implying that applicants will be ranked by these criteria.

Indices are used with *material selection charts*. These are plots of one material property or a combination of material properties against another shown schematically in Figure 4. Material indices can be plotted on a material selection chart, identifying materials that have attractive values of the index. The procedure allows ranking of materials according to cost per unit of function, mass per unit of function or, as described below, *environmental impact per unit of function*.

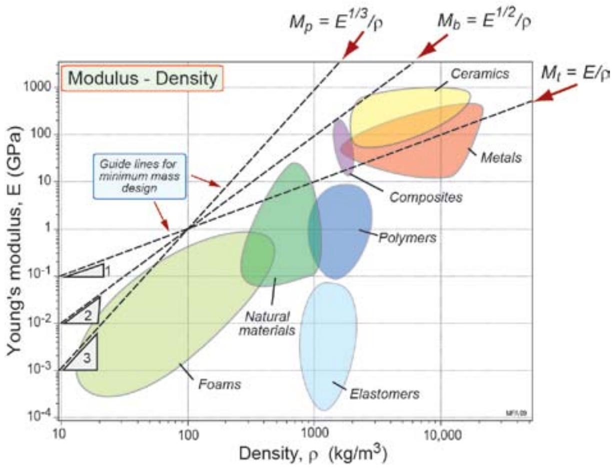

Figure 4. A schematic E – ρ chart showing guidelines for selecting materials for light, stiff structures.

The output of the screening and ranking steps is a ranked short-list of materials that satisfy the quantifiable requirements of the design. To proceed further we seek a detailed profile of the top-ranked candidates: their supporting information (Figure 3, second box from the bottom). Typically, it is non-quantifiable information: examples of its use, design guidelines, failure analyses, processing information, or details of availability and pricing. Supporting information helps narrow the short list to a final choice, allowing a definitive match to be made between design requirements and material attributes. The parallel, in filling a job, is that of taking up references and conducting interviews—an opportunity to probe deeply into the character and potential of the candidate.

It is, of course, unrealistic to think of minimizing the environmental impact of material production and usage as the only objective, there are always other considerations: cost, reliability, performance. The method of *penalty-functions* for materials selection, built into the methodology, allows an optimum compromise to be reached (Ashby, 2005).

3. Material and energy-consuming systems

The most obvious ways to conserve materials is to make products smaller, make them last longer, and recycle them when they finally reach the end of their lives. But the seemingly obvious can sometimes be deceptive. Materials and energy form part of a complex and highly interactive system, of which Figure 5 is a cartoon. Here primary catalysts of consumption such as *new technology*, *planned obsolescence, increasing wealth and education*, and *population growth* influence aspects of product use and, through these, the consumption of materials and energy and the by-products that these produce. The connecting lines indicate influences; a green line suggests positive, broadly desirable influence; red line suggests negative, undesirable influence, and red-green suggests that the driver has the capacity for both positive and negative influence.

The diagram brings out the complexity. Follow, for instance the lines of influence of *new technology* and its consequences. It offers more material and energy-efficient products, but by also offering new functionality

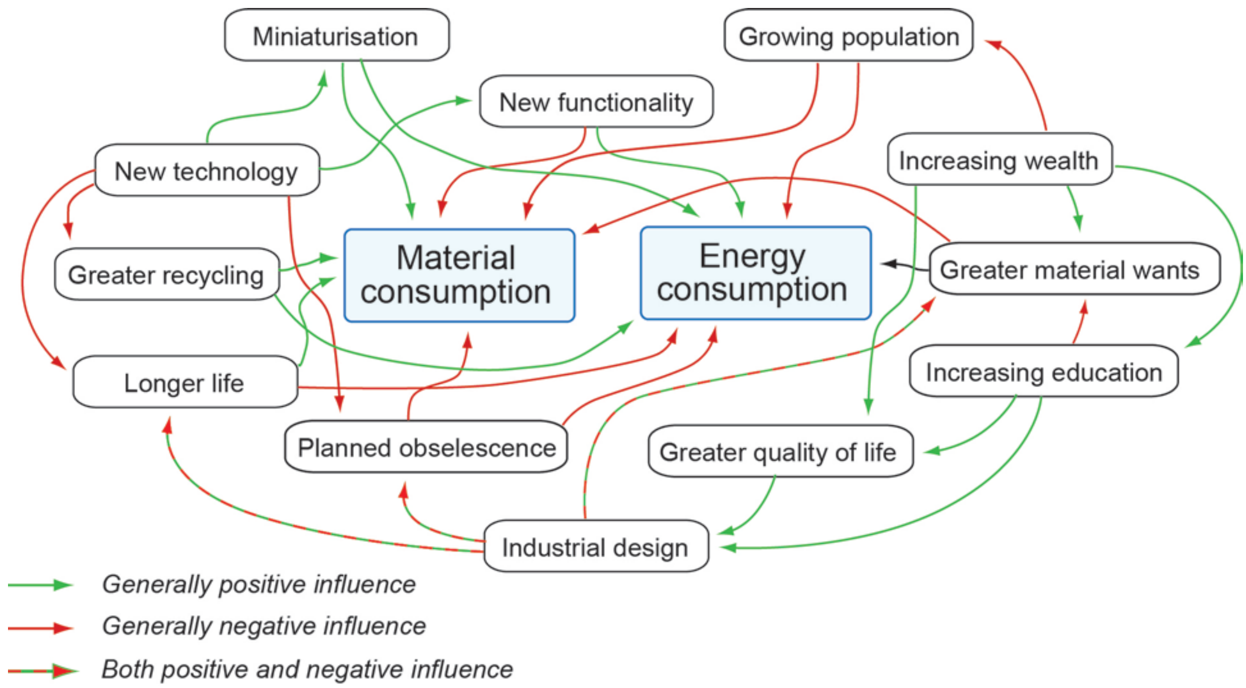

Figure 5. The influences on consumption of materials and energy. It is essential to see eco-design as a systems problem, not solved by simple choosing "good" and avoiding "bad" materials, but rather that of matching the material to the system requirements.

Table 1. Use matrix of product classes.

	High load factor	**Modest load factor**	**Low load factor**
Primary power-consuming	Family car Train set Aircraft	Television Freezer	Coffee maker Vacuum cleaner Washing machine
Secondary power-consuming	Housing (heat, light)	Car-park (light)	Household dishes Clothing (washing)
Non power-consuming	Bridges Roads	Furniture Bicycle	Canoe Tent

Energy Intensive

Material intensive

High impact **Low impact**

it creates obsolescence and the desire to replace a product that has useful life left in it. Electronic products are prime examples of this: 80% are discarded while still functional. And observe, even at this simple level, the consequences of *longer life*—a seemingly obvious measure. It can certainly help to conserve materials (a positive influence) but, in an era in which new technology delivers more energy-efficient products (particularly true of cars, electronics, household appliances today), extending the life of old products can have a negative influence on energy consumption.

As a final example, consider the bi-valent influence of industrial design. The lasting designs of the past are evidence of its ability to create products that are treasured and conserved. But today it is frequently used as a potent tool to stimulate consumption by deliberate obsolescence, creating the perception that "new" is desirable and that even slightly "old" is unappealing.

The use-patterns of products

Table 1 suggests a matrix of product use-patterns. Those in the first row require energy to perform their primary function. Those in the second could function without energy but, for reasons of comfort, convenience, or safety, consume energy to provide a secondary function. Those in the last row provide their primary function without any need for energy other than human effort. The load factor across the top is an approximate indicator of the intensity of use—one that will, of course, vary widely.

The choice of materials and processes influences all phases of Figure 1: *production*, through the drainage of resources and the undesired by-products of refinement; *manufacture*, through the level of efficiency and cleanness of the shaping, joining, and finishing processes; *use,* through the ability to conserve energy through light-weight design, higher thermal efficiency and lower energy drainage; and (finally) *disposal* through a greater ability to allow disassembly and recycling. Our aim has been to create a tool to assist the designer in minimizing the undesired consequences of the four phases.

It is generally true that one of the four phases of 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 6 presents the evidence, using this measure. It has two significant features, with important implications. First, one phase almost always dominates, accounting for 80% or more of the energy—often much more. If large changes are to be achieved, it is this 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. The second: when differences are as great as those of Figure 6, precision is not the issue—an error of a factor of 2 changes very little. It is the nature of people who *measure* things to wish to do so with precision, and precise data must be the ultimate goal. But it is possible to move forward without it: precise judgments can be drawn from imprecise data.

4. The Granta eco data

Table 2 lists eco attributes included in Granta's MaterialUniverse data module for research and industrial product development. This data is available for these applications via the industrial CES Selector software. It is also available to support teaching through the CES EduPack Eco Design Edition. We now describe this data.

Geo-economic data

The first block of data shown in Table 2 contains information about the resource base from which the material is drawn and the rate at which it is being exploited. The *annual world production* is simply the mass of the material extracted annually from ores or feedstock. The *reserves* (listed for elements only) are estimates of today's known economically recoverable ores or feedstock from which the material is extracted or created. The *resource base* (not listed in the database because of its uncertainty) is an estimate of what this quantity might become if all possible sources, including those not yet assayed, were known.

Taken at their face value the reserves and the resource base allow estimates of the resource life—the time to exhaust the resource—by dividing them by the annual world production. But, although such calculations are possible, they are futile. The reserves are estimates made by mining companies who, for economic reasons, have little interest in declaring known reserves extending beyond a ten-year time-scale. The resource base is still less well defined: historically, improved exploitation technology has often expanded the resource base faster than exploitation has diminished it.

Table 2. Eco-data for engineering materials.

Geo-economic data for principal component	
Principal component (material name)	
Annual world production (tonnes/yr)	
Reserves (tonnes)	
Typical exploited ore grade (%)	
Minimum economic ore grade (%)	
Abundance in earth's crust (ppm)	
Abundance in sea water (ppm)	
Material production: energy and emissions	
Production energy (MJ/kg)	
CO_2 creation (kg/kg)	
NO_x creation (kg/kg)	
SO_x creation (kg/kg)	
Indicators for principal component	
Eco-indicator 95	
Eco-indicator 99	
EPS value	
Material processing energy at 30% efficiency	
Minimum energy to melt (MJ/kg)	
Minimum energy to vaporise (MJ/kg)	
Minimum energy to deform 90% (MJ/kg)	
End of life	
Recycle	(yes/no)
Down-cycle	(yes/no)
Biodegrade	(yes/no)
Incinerate	(yes/no)
Landfill	(yes/no)
Recycling energy (MJ/kg)	
Recycle as fraction of current supply (%)	
Bio-data	
Toxicity rating (non-toxic, slightly toxic, toxic, very toxic)	
Approved for skin and food contact (yes/no)	
Sustainability	
A renewable resource	(yes/no)
Possible substitutes for principal component	
Text	

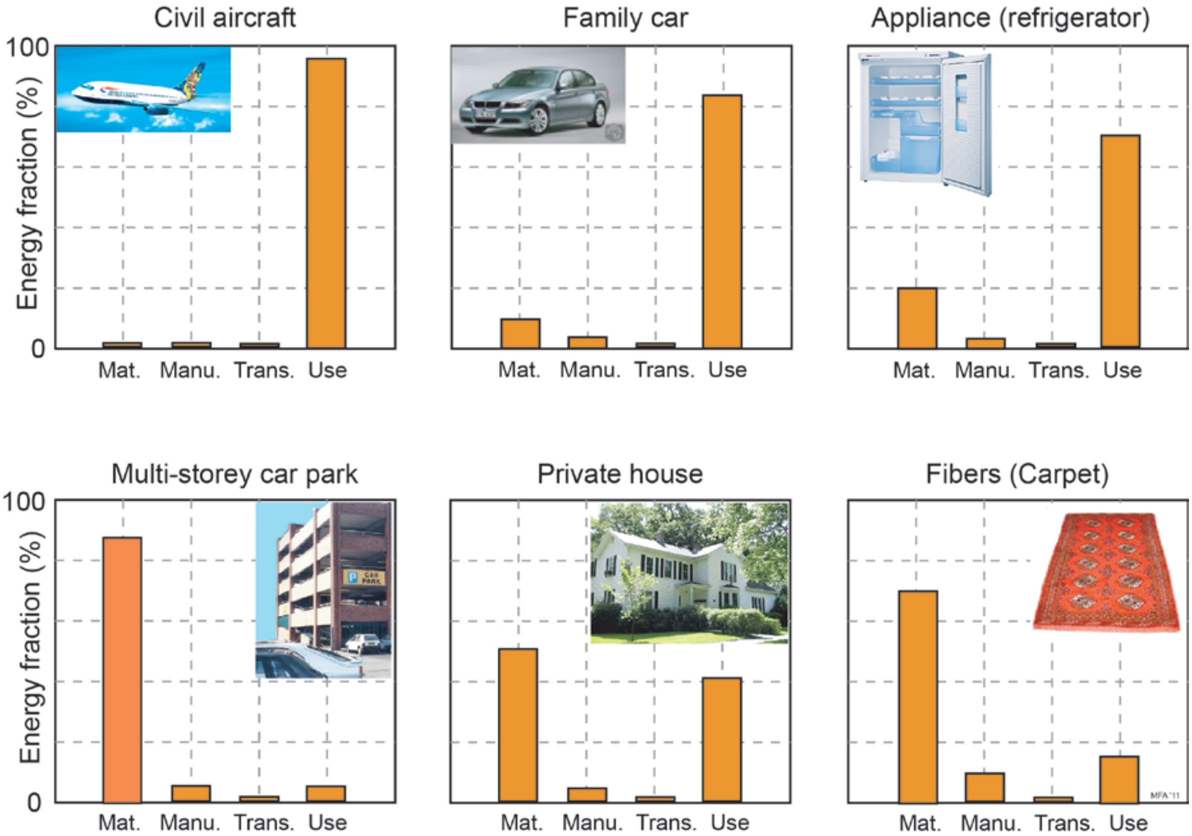

Figure 6. Approximate values for the energy consumed at each phase of Figure 1 for a range of products (data from Bey, 2000).

All this sounds like an argument for dismissing data for reserves and resources completely. They must be viewed in a very critical way—it is easy to be misled by them. But there is an ultimate point at which consumption will outstrip the rate of discovery of recoverable ore, and at that point use patterns must start to change. Material reserves will never "run out", but as the resource base diminishes, the material cost will rise, making their lower-value uses untenable. The data now available are an inadequate indicator, but the continuing near-exponential growth in consumption makes conclusions less sensitive to this than might be thought. Current values for these quantities are given to allow comparisons between materials, and to enable the user to make his or her own judgment.

As an indicator of the limits that technology might sooner or later address, we list, for the elements, the *abundance in the earth's crust and oceans*. If recovery of a material were sufficiently important, processes might be necessary to extract them from "ores" with these minute yields. It is already done for a few; magnesium is economically extractable from seawater, as is bromine; aluminum and silicon are so abundant in the Earth's crust that they could be extracted almost anywhere. The data are presented as a reminder of this aspect of resource distribution.

What is economic at present? The range of concentrations of currently-mined reserves—the *typical exploited ore grade*—is given as one indicator; more significant is the *minimum economic ore grade*, also given, since it is the measure of where extraction cost and market value come into balance. But this, too, must be heavily qualified. Ore grades vary enormously—those viable at the highest grade are usually small in volume, and, for various reasons (geographical, or chemical), unable to meet market needs; the leaner ores may be more accessible, so that the market comes into equilibrium despite the differences in sourcing.

Material production: energy and emissions

Most of the energy consumed in the four phases of Figure 1 is derived from fossil fuels.

Some is consumed in that state—as gas, oil, coal, or coke. Much is first converted to electricity and then used. The European average conversion efficiency is about 30%. Not all electricity is generated from fossil fuels—there are contributions from hydroelectric, nuclear, and wind/wave generation. But with some exceptions (e.g., Norway at 70% hydro) the predominant energy sources remain fossil fuels.

The fossil-fuel energy consumed in making one kilogram of material is called its *embodied energy*. Some of the energy is stored in the created material and can be reused, in one sense or another, at the end of life. Polymers made from oil (as most are) contain energy in another sense—that of the oil that enters the production as a primary feedstock. Natural materials such as wood, similarly, contain "intrinsic" or "contained" energy, this time derived from solar radiation absorbed during growth.

Views differ on whether the intrinsic energy should be included in the embodied energy or not. There is a sense in which not only polymers and woods, but also metals, carry intrinsic energy that could—by chemical reaction or by burning the metal in the form of finely-divided powder—be recovered, so omitting it when reporting embodied energy for polymers but including it for metals seems inconsistent. For this reason we have chosen to include intrinsic energy from non-renewable resources in reporting production energies, which generally lie in the range 50–500 MJ/kg.

The existence of intrinsic energy has another consequence: that the energy to recycle a material is sometimes much less than that required for its first production, because the intrinsic energy is retained. The *recycling energy*, listed in the database, is—despite its approximate nature—a useful indicator of the viability of recycling. Typical values lie in the range 10–100 MJ/kg.

The production of 1 kg of material is associated with *undesired gas emissions*, among which CO_2 , NO_x, SO_x and CH_4 cause general concern (global warming, acidification, ozone-layer depletion). The quantities can be large—each kg of aluminum produced by using energy from fossil fuels creates some 9 kg of CO_2, 40 grams of NO_x and 90 grams of SO_x. Production is generally associated with other undesirable outputs, particularly toxic wastes and particulates, but these can, in principle, be dealt with at source.

Wood, bamboo, and other plant-based materials, too, contain intrinsic energy, but unlike man-made materials it derives from sunlight, not from non-renewable resources. The embodied energy data for these materials does not include this intrinsic energy, and the emissions take account of the CO_2 absorbed during their growth.

Material processing energies at 30% efficiency

Many processes depend on casting, evaporation, or deformation. It is helpful to have a feel for the approximate magnitudes of energies required by these.

Melting. To melt a material, it must first be raised to its melting point, requiring a minimum input of the heat $C_p(T_m - T_o)$, and then caused to melt, requiring the latent heat of melting, L_m

$$H_{min} = C_p(T_m - T_0) + L_m \qquad (1)$$

where H_{min} is the minimum energy per kilogram for melting, C_p is the specific heat, T_m is the melting point, and T_o is the ambient temperature. A close correlation exists between L_m and $C_p\, T_m$

$$L_m \approx 0.4\, C_p T_m \qquad (2)$$

and for metals and alloys $T_m >> T_o$ giving

$$H_{min} \approx 1.4\, C_p T_m \qquad (3)$$

Assuming efficiency of 30%, the estimated energy to melt one kilogram, H^*_{min} , is

$$H^*_m \approx 4.2\, C_p T_m \qquad (4)$$

the asterisk recalling that it is an estimate. For metals and alloys, the quantity H^*_{min} lies in the range 0.4 to 4 MJ/kg.

Vaporization. As a rule of thumb the latent heat of vaporization, L_v, is larger than that for melting, L_m, by a factor of 24 ± 5, and the boiling point T_b is larger than the melting point, T_m, by a factor 2.1 ± 0.5. Using the same assumptions as before, we find an estimate for the energy to evaporate 1 kg of material (as in PVD processing) to be

$$H_v^* \approx 38\, C_p T_m \qquad (5)$$

again assuming an efficiency of 30%. For metals and alloys, the quantity H_v^* lies in the range 3 to 30 MJ/kg.

Deformation. Deformation processes like rolling or forging generally involve large strains. Assuming an average flow-strength of $(\sigma_y + \sigma_{uts})/2$, a strain of $\varepsilon = 90\%$, and an efficiency factor of 30%, we find the work of deformation per kg to be

$$W_D^* \approx 1.5(\sigma_y + \sigma_{uts})\varepsilon = 1.35(\sigma_y + \sigma_{uts}) \quad (6)$$

where σ_y is the yield strength and σ_{uts} is the tensile strength. For metals and alloys, the quantity W_D^* lies in the range 0.01 to 1 MJ/kg.

We conclude that casting or deformation require processing energies that are small compared to the embodied energy of the material being processed, but the larger process energies required for vapor-phase processing may become comparable with those for material production.

End of life

Quantification of the process of material *recycling* is difficult. Recycling costs energy, and this energy carries its burden of gases. But the *recycle energy* is generally small compared to the initial embodied energy, making recycling—when it is possible at all—an energy-efficient proposition. It may not, however, be one that is cost efficient; that depends on the degree to which the material has become dispersed. In-house scrap, generated at the point of production or manufacture is localized and is already recycled efficiently (near 100% recovery). Widely distributed "scrap"—material contained in discarded products—is a much more expensive proposition to collect, separate, and clean.

Many materials cannot be recycled, although they may still be reused in a lower-grade activity; continuous-fiber composites, for instance, cannot be re-separated economically into fiber and polymer in order to recycle them, though they can be chopped and used as fillers. Most other materials require an input of virgin material to avoid build-up of uncontrollable impurities. Thus the fraction of a material production that can ultimately re-enter the cycle of Figure 1 depends both on the material itself and on the product into which has been incorporated. Despite this complexity, some data for the fraction re-entering the cycle of Figure 1 are available and—where this is so—it is listed as *recycle as fraction of current supply*. More usually, the position is characterized by indicating simply whether the material can or cannot be *recycled*, *down-cycled, biodegraded*, *incinerated,* or committed to *landfill*.

Bio-data

Some materials are toxic, creating potential problems during production, during use, and during disposal. The database ranks toxicity on a four-point scale: *non-toxic, slightly toxic, toxic,* and *very toxic*. More pertinent, often, is information about whether a material can be used in contact with skin or food, for children's toys, or for storing medical supplies. An indication of this is approval by the Federal Drug Administration (FDA) or equivalent bodies. The database indicates this under the heading *approved for skin and food contact*.

Sustainability, and possible substitutes

The record ends with an indication of whether or not the material derives from a renewable resource, and a list of alternatives should its use be undesirable.

Aggregated measures: eco-indicators

A designer, seeking to cope with many interdependent decisions that any design involves, inevitably finds it hard to know how

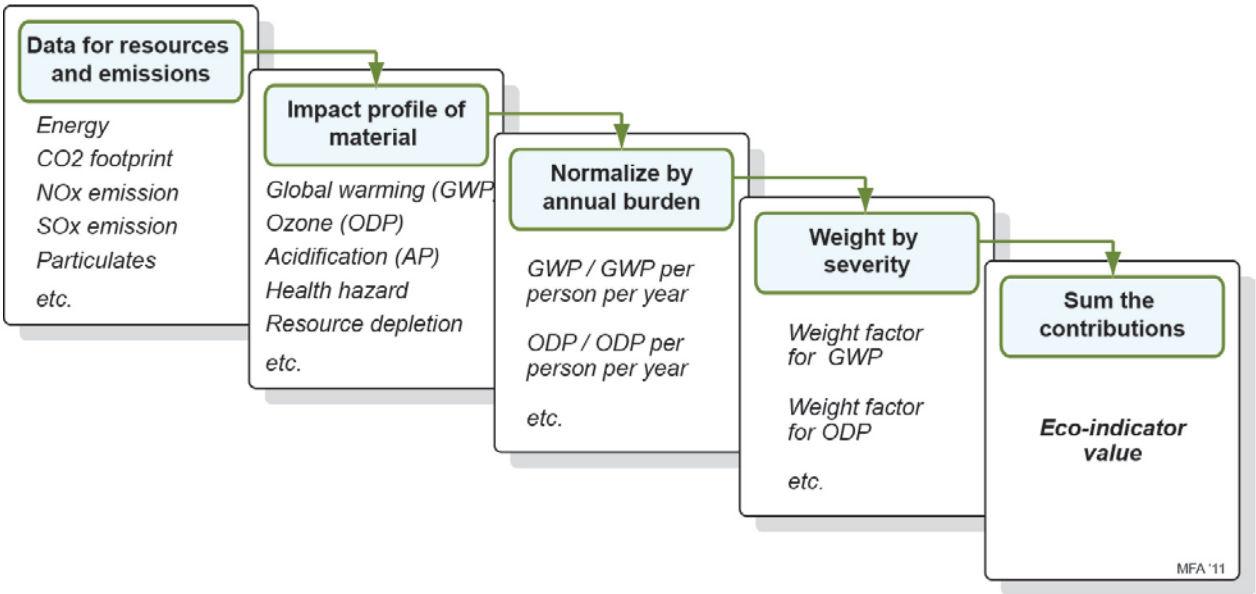

Figure 7. The steps in calculating an eco-indicator. Difficulty arises in step 3: there is no agreement on how to choose the weight factors.

best to use data of the type listed in Table 2. How are CO_2 and $S0_O$ productions to be balanced against resource depletion, toxicity, or ease of recycling?

This perception has led to efforts to condense the eco-information about a material into a single measure or *indicator*, giving the designer a simple, numeric ranking.

To do this, four steps are necessary, shown in Figure 7. The first is that of *classification* of the data listed in Table 2 according to the impact each causes (global warming, ozone depletion, acidification etc.). The second step is that of *normalization* to remove the units (of which there are several in Table 2) and reduce them to a common scale (0-100, for instance). The third step is that of *weighting* to reflect the perceived seriousness of each impact, based on the classification of Step 1: thus global warming might be seen as more serious than resource depletion, giving it a larger weight. In the final step, the weighted, normalized measures are *summed* to give the indicator. Details can be found in EPS (1993), Idemat (1997), EDIP (1998), and Wenzel et al (1997).

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*, that the method is opaque since the indicator value has no simple physical significance, and that defending design decisions based on a measurable quantity like energy consumption or CO_2 generation carries more conviction than doing so with an indicator.

The system we have developed is intended to provide information in whatever format the designer chooses to use it. For this reason we have included data for two indicators where values are available: the Dutch eco-indicator and the Swedish EPS indicator. 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): that the developed nations should progressively reduce CO_2 emissions—a considerable challenge in times of industrial growth, increasing affluence and growing population. Thus there is a certain logic in using CO_2 emission as the "indicator", though it is more usual at present to use energy.

* The different normalization and weight factors used in the Idemat, EDIP, and EPS methods, for instance, lead to radically different rankings of materials.

Table 3. Data sources for eco-attributes of materials.

Nature of data	Origins
World production, reserves and resources, prices for commodities	US GS Mineral Commodity Summaries (1996, 1998, 2000) www.plasticstechnology.com/pricing/resins
Abundance in sea water and the Earth's crust	Emsley J. (1998)
Average and minimum ore grade	Smithells, C.J. (1998) US GS Mineral Commodity Summaries (1996, 1998, 2000)
Embodied Energy	Allen & Alting (1986) APME (1992 –1999) Boustead & Hancock (1979) Boustead model 4 (1999) BUWAL (1996) Frischknecht R.(1996) Plastics Industry (2000) Szargut et al (1988) Szokolay (1980) Weivel and Stritz (1995)
Recycle Energy	Chapman & Roberts (1993) Plastics Industry (2000)
Recycling information	www.recycle-steel.org, etc.
Eco-indicator	Goedkoop et al (2000)
EPS value	EPS (1993)
Standards	ISO 14001 (1996) ISO 14040 (1997, 1998, 1999)

Sources of data

The raw data on which later manipulations are based are drawn from a number of sources, catalogued in Table 3. Some take the form of publications or reports, some as software, some are available online. The sources and their nature are listed in the References section of this report.

5. Data estimates

Life cycle assessment (LCA) techniques*, now documented in standards (ISO 14040, 1997, 1998) analyze the eco-impact of products once they are in service. These techniques have acquired a degree of rigor, and now deliver essential data documenting the way materials influence the flows of energy and undesired outputs of Figure 1. But if applied with full rigor, they are both time-consuming and expensive. Streamlined LCA relaxes the rigor to allow an affordable first-look. But all of these require that the product already exists, has lived, and died; without information derived from the product in service, LCA methods, relying as they do on a quantitative breakdown of material and process-content of the product, cannot be applied. LCA methods are an essential intermediate step in eco-accountability, generating generally accepted information and establishing the credentials of an ability to analyze the eco-influence of products. But it is clearly better to design-in the qualities we seek from the very start rather than searching for ways to introduce them into a product that is already in production. This is the goal of eco-design.

Taking a material and process standpoint, three requirements emerge for an eco-design tool. First, the tool should help with the concept stage when details are not yet set, and to do this it must be based on *function*, not on *quantity*. The second is practicality: if designers are really going to use eco-information in their work, the data must be

*See, for example, Goedkoop et al 2000 (Eco-indicator method); EPS, 1993 (Environmental Priorities Strategy); MIPS – Schmidt-Bleek 1997, 1998, 1999 (Material Intensity per Service Unit method); Wenzel et al 1997, EDIP, 1998 (EDIP method); Bey, 2000 (Oil Point method).

Table 4. The classification used for estimation.

Material families and classes
Ceramics
Ceramic
Cement and concrete
Metals
Alloy
Element
Element (research purity)
Metal
Polymers
Elastomers
Thermoplastic
Thermoset

Material families and classes
Natural Materials
Natural materials (general)
Wood
Composites
Composite
Ceramic-based composite
Metal-based composite
Polymer-based composite
Wood-based composite

easy to find, instantly accessible, and include—even if approximately—as wide a range of materials and processes as possible. The third follows from this; eco-data of any sort exist only for a tiny handful of materials and processes (perhaps 100 out of 60,000 or more); the advice offered by LCA practitioners to those who ask for data for a non-documented material is "assume it is like one that *is* documented". This sits badly with the precision demanded by other aspects of LCA, and supposes a deep enough knowledge of materials to be able to make an appropriate choice. So the third requirement is that of developing more credible estimates, allowing greater confidence in the data and the application of the method.

This cannot be achieved without some sacrifice of rigor. There is no suggestion here that loss of rigor is desirable. The suggestion, rather, is that the best way forward lies in an adaptable approach, incorporating breadth, using approximate methods based on the best currently available data, but with the capacity to replace approximations with more precise methods and data as these become available. It is this approach that we develop here.

Filling the holes: data estimation.

We have tried to find better ways for estimating missing data than that mentioned earlier: the use, as a substitute, of data for a "similar" material that *is* characterized. This begs the question: what does "similar" mean? Belonging to the same material class (meaning polymer, or metal, or ceramic), certainly, but after that? Similar strength? Similar thermal conductivity? There are ways of defining "similarity" but—without exploration—it is not obvious which way is helpful here.

Exploration is possible by searching for correlations, using physical reasoning to guide the choice. Taking *embodied energy* (units MJ/kg) as an example, the correlation might be expected with the minimum economic ore-grade: the lower the grade, the greater the mass of useless material that must be moved or crushed or sifted to recover it. In fact, we find the correlation too poor to be of any use. Another possibility is that of price. One might have lower expectations of this—price is influenced not only by the real cost of production but also by market forces. But we find that, on segregating materials into the families and classes of Table 4, the correlation between embodied energy and price averaged over eight years (evening out some of the speculative elements) is remarkably strong. Not, perhaps, so surprising—it has been suggested that, if an international currency independent of nationality were needed, energy might be the answer.

Mathematical fits to the data have been used to fill holes for commercially pure metals, for polymers, and for ceramics. No claim is made that these are particularly precise, only that they are better—considerably better—than the simple guess at a “similarity”.

Alloys, polymer blends, and composites are treated by assuming (when no direct measurements are available) that a lower bound for energy and gas emissions is given by a linear combination of data for their constituents—“a rule of mixtures”. (For metallic alloys even this does not always work: stainless steels, for example, are not made by mixing commercially pure nickel and chromium into iron but by using much cheaper ferro-chrome as alloy agents). The lower bound underestimates real energy inputs because the process used to create the alloy from its ingredients itself requires energy, but—as discussed in Section 3—this is usually small. As a bound it is useful, capturing (for instance) the effect of including rare-earths and other alloying agents in otherwise cheap hosts. Composites are treated in a similar way: the energy value is the weighted sum of the constituents, ignoring processing, and should again be seen as a lower bound.

6. Using the data

The eco attributes are available within the MaterialUniverse data, accessible via the CES Selector software for research and industrial applications, and for teaching via its incorporation into the CES EduPack Eco Design Edition. It can be used for *retrieval*—as a reference source for environmental and other information about a given material process—or it can be used for *rational selection.* Retrieval is simply a case of browsing or searching the database and choosing the material of interest. The result is illustrated in Table 5, which shows eco-attributes for one grade of aluminum.

Table 5. The eco-attributes of one grade of aluminum alloy.

WROUGHT ALUMINIUM PURE, 1-0

Geo-Economic Data for Principal Component			
Principal Component	Aluminium		
Annual world production	3.7e7	- 3.8e7	tonne/yr
Reserves	2e10	- 2.2e10	tonne
Typical exploited ore grade	30	- 34	%
Minimum economic ore grade	25	- 39	%
Abundance in earth's crust	7.8e4	- 8.6e4	ppm
Abundance in seawater	2.5e-4	- 2.8e-4	ppm
Material production: energy and emissions			
Embodied energy	1.9e2	- 2.1e2	MJ/kg
Carbon footprint	* 9.0	- 10.0	kg/kg
Nitrogen oxides	* 72	- 79	g/kg
Sulphur oxides	* 1.2e2	- 1.4e2	g/kg
Water usage	495	- 1490	l/kg
Indicators for principal component			
Eco Indicator	710	- 780	mmillipoints/kg
Material processing energy			
Extrusion	1.5	- 1.6	MJ/kg
Rolling	0.9	- 1.0	MJ/kg
Metal powder forming	24	- 27	MJ/kg
End of life			
Recycle	True		
Downcycle	True		
Biodegrade	False		
Incinerate	False		
Landfill	True		
Recycling Energy	* 17	- 20	MJ/kg
Recycle fraction in current supply		55	%
Bio-data			
Toxicity rating		Non-toxic	
Approve for skin & food contact	True		
Sustainability			
A renewable resource?	No		

Possible Substitutes for Principal Component

Copper can replace aluminum in electrical applications. Magnesium, titanium, and steel can substitute for aluminum in structural and ground transportation uses. Composites, wood, and steel can substitute for aluminum in construction. Glass, plastics, paper, and steel can substitute for aluminum in packaging.

Rational selection is typically a two-stage process in which we must first ask—as we did in Section 2—which phase of the life cycle of the product under consideration makes the largest impact on the environment? This *audit* process is described in our separate paper “The CES EduPack Eco Audit Tool—A White Paper”. The answer guides (Figure 8) the effective use of the data in substituting of selecting materials, as we now discuss.

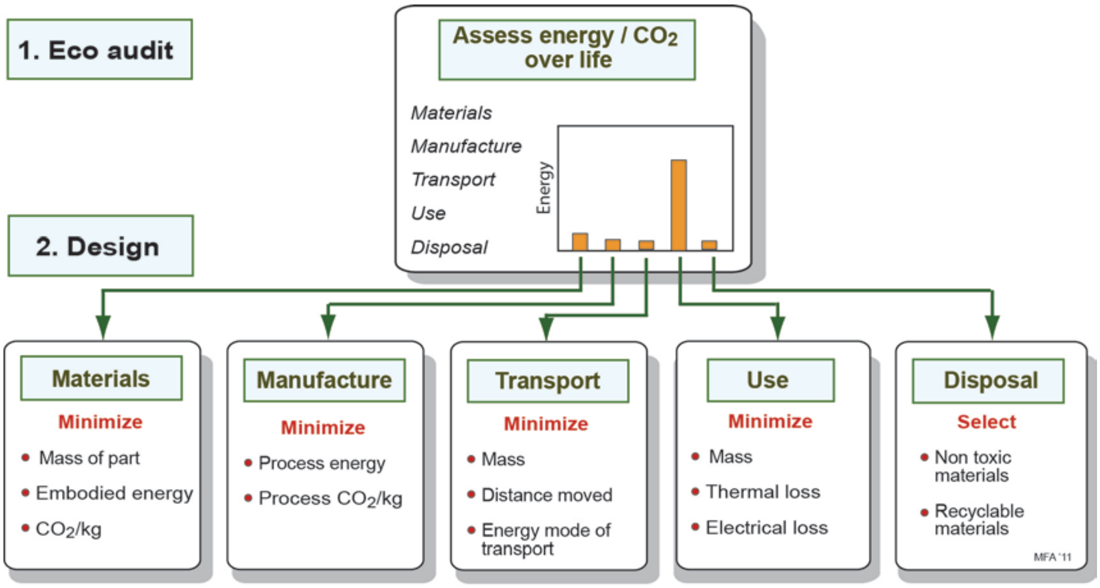

Figure 8. Rational use of the eco data starts with an analysis of the phase of life to be targeted. The decision then guides the method of selection to minimize the impact of the phase on the environment.

The material production phase

If material production is the dominant phase of life it is this that we must target. Drink containers (Figure 9) provide an example: they consume materials and energy during material extraction and container-production, but (apart from transport, which is minor) not thereafter.

Figure 9. Containers for liquids: glass, polyethylene, PET, and aluminum. All can be recycled. Which carries the low penalty of embodied energy?

We use the energy consumed in extracting and refining the material (the embodied energy of Table 2) as the measure; CO_2, NO_x and SO_x emissions are related to it, although not in a simple way. The energy associated with the production of one kilogram of a material is H_m, that per unit volume is $H_m\rho$ where ρ is the density of the material. The bar-charts of Figures 10(a) and (b) show these two quantities for ceramics, metals, polymers and composites. On a "per kg" basis (upper chart) glass, the material of the first container, carries the lowest penalty. Steel is higher. Polymer production carries a much higher burden than does steel. Aluminum and the other light alloys carry the highest penalty of all. But if these same materials are compared on a "per m^3" basis (lower chart) the conclusions change: glass is still the lowest, but now commodity polymers such as PE and PP carry a *lower* burden than steel; the composite GFRP is only a little higher. But is comparison "per kg" or "per m^3" the right way to do it? Rarely. 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.*

To select materials with the lowest eco-impact per unit of function we make use of *performance indices.* Performance indices that include energy content, CO_2 burden or eco-indicator are derived in the same way as those for weight or cost. Thus the best materials to minimize embodied energy of a beam of specified stiffness and length are those with large values of the following index:

$$\boxed{M = \frac{E^{1/2}}{H_m\rho}} \quad (7)$$

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 $E/H_m\rho$; the stiff plate, of a material with high $E^{1/3}/H_m\rho$ and so on.

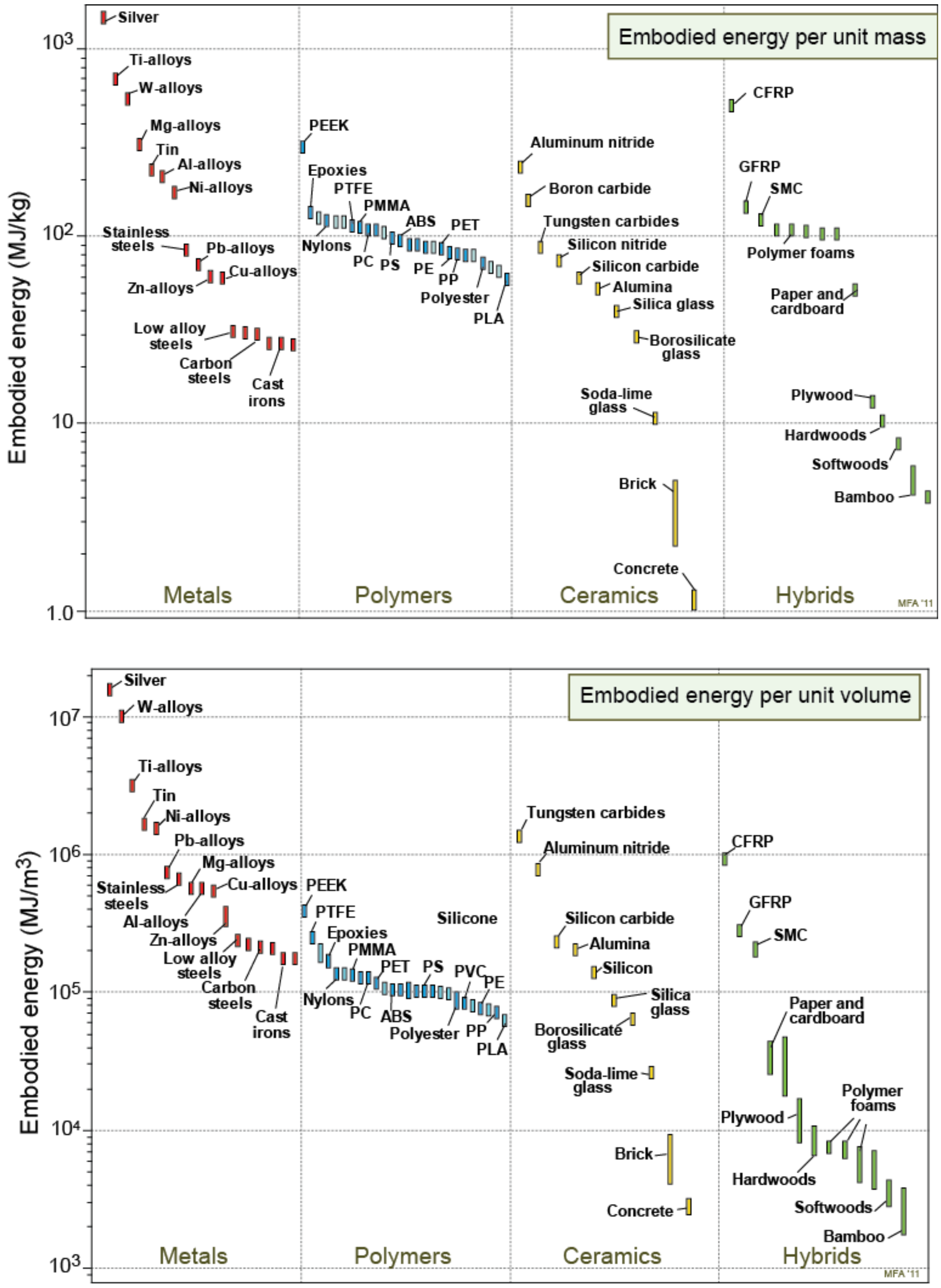

Figure 10 (a) and (b). The energy per unit mass and per unit volume associated with material production, plotted with CES EduPack.

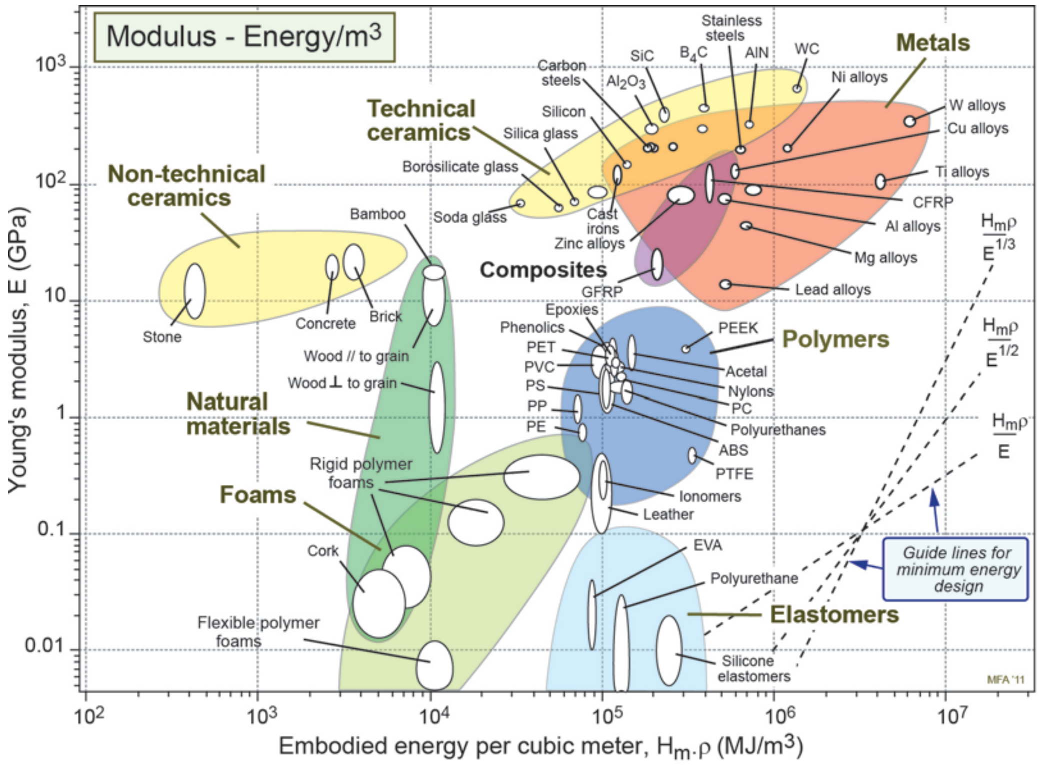

Figure 11. A selection chart for stiffness at minimum embodied energy. It is used in ways detailed in Ashby (2011).

Selection for a constraint on strength works similarly. The best materials for a beam of specified bending strength and minimum energy content maximize:

$$M = \frac{\sigma_f^{2/3}}{H_m \rho} \qquad (8)$$

where σ_f is the failure strength of the beam-material. Other indices follow in a similar way. Table 6 contains examples of other indices for eco-selection to minimize impact during the production phase of life. Materials with the lowest values of these, and which meet all other design constraints, are the best choice to meet the functions listed here. The method of deriving them is fully documented elsewhere (Ashby 2011). The CES EduPack search engine allows these combinations to be created, and combined with other constraints to enable an optimized selection. Once a short-list of potential candidates is established, supporting information can be sought for them via the references at the end of this report or through the built-in web-links library of the software.

Table 6. Examples of indices to minimize impact in the production phase.

Function	MAXIMIZE*
Minimum energy content for given tensile stiffness	$E / H_m \rho$
Minimum CO_2 emissions for given tensile strength	$\sigma_y / [CO_2] \rho$
Minimum energy for given bending stiffness (beam)	$E^{1/2} / H_m \rho$
Minimum energy for given bending stiffness (panel)	$E^{1/3} / H_m \rho$
Minimum CO_2 for given bending strength (beam)	$\sigma_f^{2/3} / [CO_2] \rho$
Minimum CO_2 for given bending strength (panel)	$\sigma_f^{1/2} / [CO_2] \rho$
Minimum eco-indicator points for given thermal conduction	$\lambda / I_e \rho$

* H_m = embodied energy content per kg;
$[CO_2]$ = CO_2 production / kg;
I_e = eco-indicator / kg;
E = Young's modulus;
σ_{ts} = tensile strength;
ρ = density.

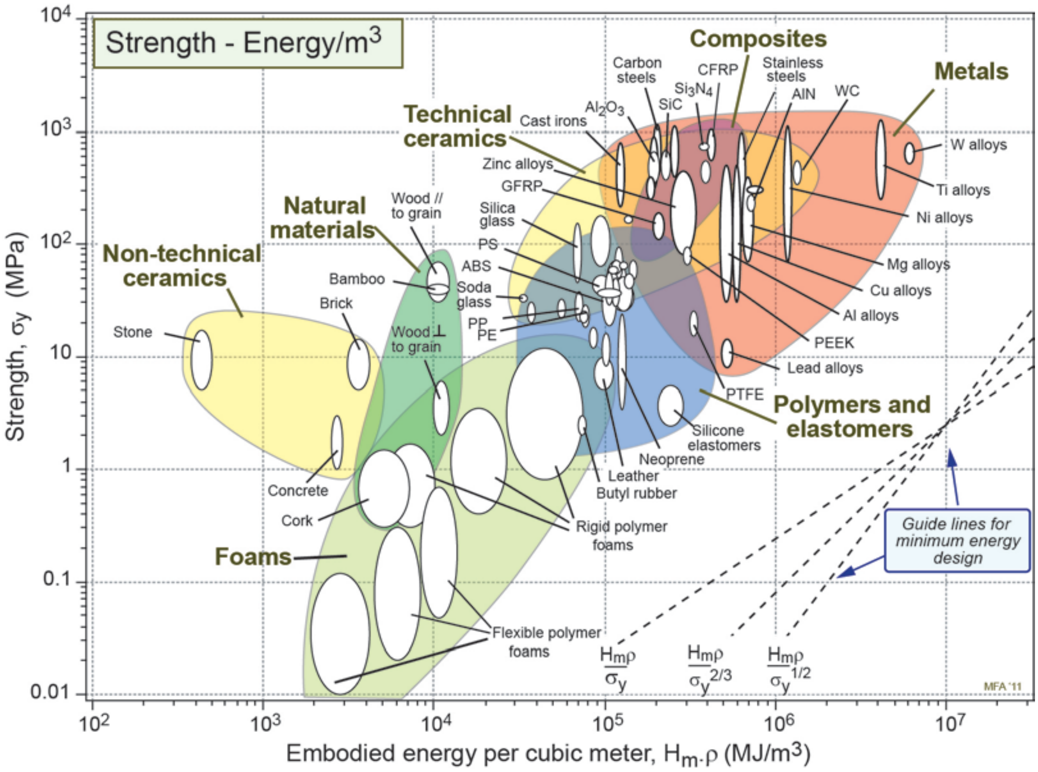

Figure 12. A selection chart for strength at minimum embodied energy. It is used in ways detailed in Ashby (2011).

Figures 11 and 12 are a pair of materials selection charts for minimizing embodied energy H_p per unit of function (similar charts for CO_2 burden can be made using the CES EduPack software). The first shows modulus *E* plotted against $H_m \rho$; the guide-lines give the slopes for three of the commonest performance indices. The second shows strength σ_f plotted against $H_m \rho$; again, guide-lines give the slopes. The two charts give a survey of data for minimum energy design. They are used in exactly the same way as the $E - \rho$ and $\sigma_f - \rho$ charts for minimum mass design.

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 carry a lower energy penalty than primary aluminum, magnesium, or titanium, and that several are competitive with steel.

The product-manufacture phase

Vapor-forming methods are energy-intensive, casting and deformation processing are less so. 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. Paper making (to take an example) uses very large quantities of water. Historically the waste water was heavily polluted with alkalis and particulates, devastating the river systems into which it was dumped. Today, the best paper mills discharge water that is as clean and pure as it was when it entered. Production sites of many heavily industrialized countries are terminally polluted; those producing the same materials elsewhere, using best-practice methods, have no such problems. Clean manufacture is the answer here.

The use phase

The eco-impact of the use phase of energy-consuming products has nothing to do with the energy content 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.

The product disposal phase

The environmental consequences of the final phase of product life has many aspects. The aggregation of these into the single “indicator” does not appear to be a helpful path to follow. Most energy consumed in the production of metals such as steel, aluminum, or magnesium is used to reduce the ore to elemental metal, so that these materials, when recycled, require much less energy. Efficient collection and recycling makes important contributions to energy saving. Limited data are available for recycle energies, and for the fraction of current supply currently met by recycling. The simple Boolean (yes/no) classification in Table 2 signals that a given material can be recycled, reused in a lower grade activity, bio-degraded, incinerated, or committed to landfill.

7. Case studies

The methods are illustrated below by case studies.

The energy content of containers

The problem. The containers of Figure 9 are examples of products for which the first and second phases of life—material production and product manufacture—are ones that consume energy. Thus material selection to minimize energy and consequent gas and particle emissions focuses on these. Table 7 summarizes the requirements.

Table 7. Design requirements for the containers.

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

The masses of five competing container types, the material of which they are made, and their specific energy contents are listed in Tables 8(a) and (b). Production involves molding or deformation; approximate energies for each are listed. All five of the materials can be recycled. Which type carries the lowest energy penalty per unit of fluid contained?

The method and results. A comparison of the energies in Tables 8 (a) and (b) shows that the energy to shape the container is always less than that to produce the material in the first place. Only in the case of glass is the forming energy significant. The dominant phase is that of material production. Summing the two energies for each material and multiplying by the container-mass per liter of capacity gives the ranking shown in the second last column of Table 8 (a). The steel container carries the lowest energy penalty, glass and aluminum the highest.

Crash barriers

The problem. 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 13).

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 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 is use. So, if eco-design is the objective, the criteria for selecting materials for the two sorts of barrier will differ.

Table 8(a). Details of the containers.

Container type	Material	Mass, g	Mass / litre, g	Energy/litre MJ/litre
PET 400 ml bottle	PET	25	62	5.4
PE 1 litre milk bottle	High density PE	38	38	3.2
Glass 750 ml bottle	Soda glass	325	433	8.2
Al 440 ml can	5000 series Al alloy	20	45	9.0
Steel 440 ml can	Plain carbon steel	45	102	2.4

Table 8(b). Data for the materials of the containers (MaterialUniverse data).

Material	Embodied energy MJ/kg	Forming method	Forming energy MJ/kg
PET	84	Molding	3.1
PE	80	Molding	3.1
Soda glass	14	Molding	4.9
5000 series Al alloy	200	Deep drawing	0.13
Plain carbon steel	23	Deep drawing	0.15

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 (Table 9). We have seen that to transmit a bending load at minimum embodied energy requires materials that maximize:

$$\boxed{M_1 = \frac{\sigma_{ts}^{2/3}}{H_m \rho}} \qquad (9)$$

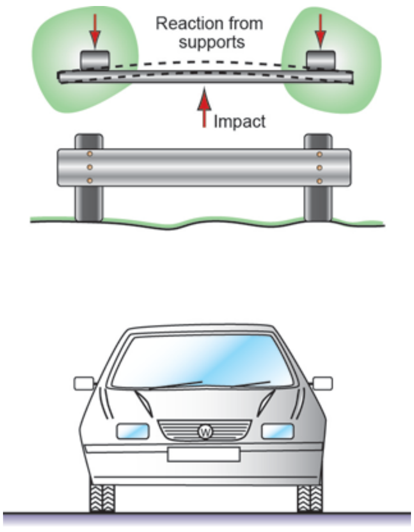

Figure 13. Two crash barriers, one static, the other—the fender—attached to something that moves. Different eco-criteria are needed.

Table 9. Design requirements for the crash barriers.

Function	Crash barrier
Constraints	Must be recyclable
Objective	Maximize strength per unit embodied energy, or Maximize strength per unit mass
Free variables	Choice of material

To do so at minimum weight requires instead materials with large values of:

$$\boxed{M_2 = \frac{\sigma_{ts}^{2/3}}{\rho}} \qquad (10)$$

Figure 14 plots these two quantities for metals, polymers, and polymer-matrix composites. The top figure guides the selection for static barriers. It shows that embodied energy (for a given load bearing capacity) is minimized by making the barrier from carbon steel or cast iron; nothing else comes close. The second figure 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.

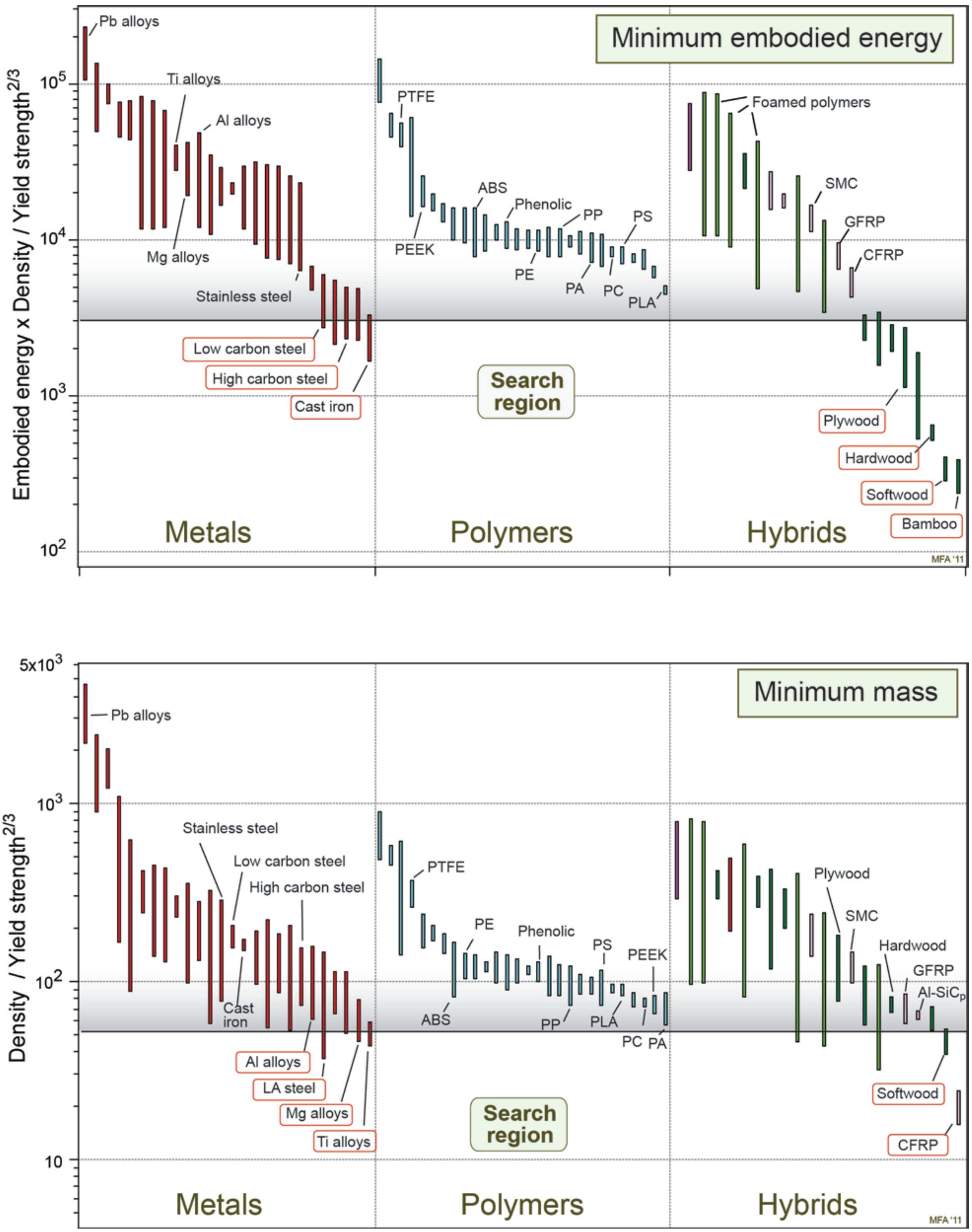

Figure 14. (Top) Material choice for the static barrier is guided by the bending strength per unit of embodied energy. Cast irons, carbon steels, or low alloy steels are the best choice. (Here the number of materials has been limited to 50 for clarity). (Bottom) Material choice for the mobile barrier is guided by bending strength per unit mass. CFRP is the best choice, followed by magnesium, titanium, and aluminum alloys.

8. Summary and conclusions

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 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.). CES EduPack provides this data package, managed by a sophisticated search-engine.

The database contains about 3,000 materials. Each record is “full” meaning that all attributes have values. This is achieved through the use of estimation procedures, using correlations between attributes to approximate those that are missing. All estimates are flagged as such, distinguishing real from estimated values. The user can edit the database, allowing estimates to be replaced by real data as this becomes available.

This report summarizes the philosophy, the attribute-definitions, the estimation methods, and the procedure for using the system, both as a simple data source, and as a selection tool.

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