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THE DEVELOPMENT AND USE OF A METHODOLOGY FOR THE ENVIRONMENTALLY-CONSCIOUS SELECTION OF MATERIALS

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ABSTRACT

A materials selection methodology and its software implementation, developed to aid the designer in making environmentally conscious decisions early in the design process, is described.

NOMENCLATURE

A = area
a = width
b = depth
C = constant
E = Young's modulus
E_I = eco-indicator
I = second moment of area
J = heat flux
M = material index
m = mass
S = stiffness
t = thickness
ΔT = temperature difference
$\Delta T / \Delta x$ = temperature gradient
λ = thermal conductivity
ρ = density

1 INTRODUCTION

The creation and use of any engineering product carries with it an environmental burden. There is a growing recognition that the minimisation of this burden must become a primary design objective. Materials contribute to it in their production, in the use of products made from them and in the disposal of these products. The minimisation of the environmental burden requires the selection of materials which are less toxic, can give products which — without compromising product quality — are more easily recycled, which are lighter and less energy intensive, and which, where possible, use renewable or non-critical resources. This paper describes the development and use of a software-based design tool, the Cambridge Eco-Selector, which aids the environmentally-conscious selection of materials.

2 THE DESIGN PROCESS AND ENVIRONMENTAL IMPACT EVALUATION

The essential steps in the design process are described in the flow chart of Figure 1. 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. Finally, the product is manufactured, distributed, used and — when it reaches the end of its lifetime — the materials it contains may be reused, recycled, incinerated or committed to landfill.

The environmental impact of a product is frequently explored using the techniques of Life-Cycle Assessment (LCA). An LCA, as the name implies, examines the whole life-cycle of the product (manufacture, use and disposal — represented as the bottom three boxes in Figure 1) and the total eco-impact it creates. LCA requires information of the life-history of the product at a level of precision which is only available after the product has been produced; it is a tool for the evaluation and comparison of existing products, rather than one which guides the design of those which are new. But decisions taken in the early stages of design lead to commitments which cannot easily be changed later, and for this decision-making, LCA comes too late. Instead, a design tool is required which guides environmental awareness and exploits the information available early in the design process — the “concept” and “embodiment” stages of Figure 1. The Eco-Selector described here, seeks to achieve this.

3 THE CAMBRIDGE ECO-SELECTOR

An environmental impact evaluation tool for the early design stages must be designed to cope with broad but imprecise information such as the *function* of the component, its *size* and its intended *use*. The tool described below, the Cambridge Eco-Selector, aims to achieve this by building and expanding on an established methodology for materials selection implemented in the Cambridge Materials Selector (CMS). CMS allows the relative performance of materials in a given application to be evaluated objectively using *material indices* — a grouping of material properties which characterises performance — and *material property charts* (Ashby, 1992).

It is unrealistic to think of minimising the environmental impact of material production and usage as the only objective, since minimising cost is always a consideration too. The *value function* method for materials selection already built into the methodology can allow an optimum compromise to be reached (Ashby, 1997). A description of the value function method is, however, beyond the scope of this paper.

3.1 MATERIAL SELECTION CHARTS AND MATERIAL INDICES

Optimisation is achieved by the use of *material indices*. These are groups of material properties which characterise performance. They allow ranking of potential candidates: the materials with the largest values of an index maximise 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 catalogue, with derivations, can be found in Ashby (1992).

Indices are used with *material selection charts*. These are plots of one material property or a combination of material properties against another. Material indices can be plotted on a material selection chart to compare the performance of different materials for a given application. The procedure allows a ranking of materials according to their function per unit weight, or function per unit cost or, as described here, *function per unit environmental impact*.

Figure 6 shows an example: for a flat panel, high bending stiffness per unit mass and low environmental impact is achieved by seeking materials with high values of the index $\mathrm{M} = E^{1/3}/E_I\,\rho$, where E_I is the eco-indicator (IDEMAT, 1996), a measure of the total eco-burden associated with the production of a unit mass (1 kg) of material based on data from a life-cycle assessment — the higher the indicator-value, the greater the environmental impact.

These ideas are best illustrated by a case study. One is presented in the next section.

4 CASE STUDY: THE MONITOR CHASSIS

Monitor chassis are currently made of fire-retardant polystyrene (PS). It has been suggested that the substitution of a magnesium alloy (Mg) or an aluminium alloy (Al) could increase recyclability and lengthen chassis-life, allowing the possibility of reuse. This case study compares the three materials from a mechanical, thermal and environmental perspective.

The approach is based on developing sets of *material indices* for performance-limiting aspects of the design (Ashby, 1992; Ashby and Cebon, 1996; CMS, 1995). The first index relates to the mass of the chassis: its outer faces, mechanically speaking, act as flat panels loaded in bending, and they must be stiff and strong enough to do this task adequately. The second relates to heat-transfer, important because the electronics contained in the chassis must not overheat. The third æ and the one of principal interest here æ concerns the ecological impact ("eco-burden") associated with the material of which the chassis is made. The overall aim is to establish whether the use of magnesium (Mg) or aluminium (Al) for the chassis can give a product which equals or surpasses the performance of the current PS chassis in mass and heat-transfer, and do so with a lesser eco-burden.

4.1 DESIGN REQUIREMENTS

The monitor chassis encases and supports the cathode ray tube (CRT) and associated electronics. These, and the loads imposed externally during normal use, cause the flat panels which form the chassis-walls to be loaded in bending. The structure must be stiff and strong enough to support these bending loads and have heat-transfer properties which are adequate to prevent overheating. It is also known that the natural vibration frequencies of the chassis must be high to avoid the excitation of resonances. The current PS chassis achieves these goals, but cannot readily be recycled, and is made of a material which creates, in its manufacture, an above-average eco-burden. A substitute must equal or surpass PS in its mechanical and thermal performance and exceed it in recyclability with a lower eco-burden. The design requirements are summarised in Table 1.

4.2 THE METHOD

The Mass. The index for selecting materials for low-mass panels of specified stiffness, S, is found as follows (Ashby, 1992; Ashby and Cebon 1996). The mass of a panel of dimensions $a * b * t$ ($a < b$, with a, b and t as the width, the depth and the thickness respectively) is

$$m = a.b.t.\rho \tag{1}$$

where ρ is the density of the material of the panel. Its stiffness is

$$S = C_1 \frac{E.I}{b^2} = C_2 \frac{E.a.t^3}{b^2} \tag{2}$$

where E is Young's modulus, I is the second moment of area, and C_1 and C_2 are constants. The minimum thickness of the panel which meets the stiffness constraint is thus

$$t = \left(\frac{S.b^2}{C_2 E.a}\right)^{1/3}. \tag{3}$$

Substituting this into equation (1) gives

$$m = a^{2/3}.b^{5/3}.(\frac{S}{C_2 E})^{1/3}.\rho \tag{4}$$

Thus the best materials for a flat panel loaded in bending and of minimum weight, with a constraint on stiffness, are those with the highest value of the material index

$$M_1 = \frac{E^{1/3}}{\rho} \tag{5}$$

By a similar argument, the best materials which will perform the same function, but with a constraint on strength, are those with the highest value of the material index

$$M_2 = \frac{\sigma^{1/2}}{\rho} \tag{6}$$

The constraints (a) and (b) in Table 1 require that the substitute for PS has values of M_1 and M_2 which at least equal those of PS itself. If they fail to do this, they will be heavier than the existing panels.

Heat Transfer. The heat-transfer rate through a panel (assuming that conduction is controlling) is measured by the heat flux

$$J = A\lambda \frac{\Delta T}{\Delta x} \tag{7}$$

where A is the area of the panel, λ is the thermal conductivity and $\Delta T / \Delta x$ is the temperature gradient. If the stiffness constraint is assumed to be limiting, then the heat-diffusion distance, Δx, is equal to the thickness of the panel, given by equation (3). Inserting this into equation (7) gives an expression for the temperature difference, ΔT, caused by a heat-flux, J,

$$\Delta T = \frac{J}{a.b.\lambda}\left(\frac{S.b^2}{C_2 E.a}\right)^{1/3} \tag{8}$$

and the relevant index is

$$M_3 = \lambda E^{1/3} \tag{9}$$

If, instead, the strength constraint is limiting, then the relevant index is

$$M_4 = \lambda \sigma^{1/2} \tag{10}$$

The constraint (c) in Table 1 requires that the substitute for PS has values of M_3 and M_4 which at least equal those of PS itself.

Eco-burden. The performance of the chassis depends on the criteria discussed so far - if these are not met, the substitute is not acceptable. If they are, the question becomes one of the relative environmental impact of the two materials. This is evaluated using two further material indices, derived in ways which parallel those for the mass. High stiffness per unit weight and low environmental impact is achieved by seeking materials with high values of the index

$$M_5 = \frac{E^{1/3}}{E_I \rho} \tag{11}$$

Here E_I is the *eco-indicator*, a measure of the total eco-burden associated with the production of a unit mass (1kg) of material. The derivation of these indicators is difficult and requires a great deal of detailed information about energy, green-house gasses and waste of all sorts. At this early point in our study we have drawn on the limited but well-documented data of the IDEMAT software (IDEMAT, 1996) for values for E_I. Incorporating this into the reasoning for material indices gives, when high stiffness per unit mass is the constraint, the index given above; when strength per unit mass is the constraint, the index becomes

$$M_6 = \frac{\sigma^{1/2}}{E_I \rho}. \tag{12}$$

4.3 THE EVALUATION

Figures 2 to 7 show the six material indices as bar-charts for the two classes of materials relevant to this study: polymers (including PS) and metals (among them, Al and Mg). The figures are constructed using the Cambridge Eco-Selector which contains physical, mechanical, thermal and eco-data for 267 materials of five classes (ceramics, composites, metals, natural materials and polymers). The first pair of figures show the indices M_1 and M_2. They allow a comparison of PS, Al and Mg on a mass basis. The three materials are labelled. By either criterion, the Mg chassis is lighter than Al or PS.

The second pair of figures plot the indices M_3 and M_4, allowing the materials to be compared on the basis of heat-transfer. Once more, the Mg panel exceeds the performance of PS; Al performs even better.

The last pair of figures show the eco-indices M_5 and M_6. Here, five materials are identified. The first is a fire-retardant PS (the material of which the chassis is currently made); the second and third are both Al and the fourth and fifth are both Mg. For both Al and Mg a value of eco-indicator for recycled material is used in addition to a value for virgin material. It is clear that while the virgin Mg is comparable in its eco-burden with PS, the recycled Mg is substantially better.

Table 2 below shows a summarised comparison of the three candidate materials: fire-retardant PS, Mg and Al. The winner in each category is marked by a “1”, the loser by a “3” or a “5” in the case of the eco-performance. Those in between are graded in order of decreasing performance.

The evaluation of the three alternative materials suggests that Mg alloys provide both from a mechanical and environmental point of view an alternative to fire-retardant PS as long as recycled Mg is used.

5 CONCLUSION

The methodology for environmentally conscious materials selection described in this paper is still under development. It will be developed further, tested and refined by analysis of case studies in collaboration with industrial and academic partners. It builds on a well-tried methodology and software system. It has potential as a tool for suggesting ecologically-sound materials selection at an early design stage when the details required for conventional life-cycle assessment are still unresolved.

ACKNOWLEDGEMENTS

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REFERENCES

Ashby, M.F. 1992, “Materials Selection in Mechanical Design”, Butterworth Heinemann, Oxford, UK.

Ashby, M.F. and Cebon, D. 1996, “Case Studies in Materials Selection”, Granta Design, Cambridge, UK.

Ashby, M.F. 1997, “Materials Selection: Multiple Constraints and Compound Objectives”, ASTM STP 1311 on Computerisation/Networking of Material Databases, ASTM.

CMS Software 1995, Granta Design Limited, Trumpington Mews, 40B High Street, Trumpington, Cambridge CB2 2LS, UK.

IDEMAT Software 1996, Faculty of Industrial Design Engineering, Delft University of Technology, Jaffalaan 9, 2628 BX Delft, The Netherlands.

FIGURES

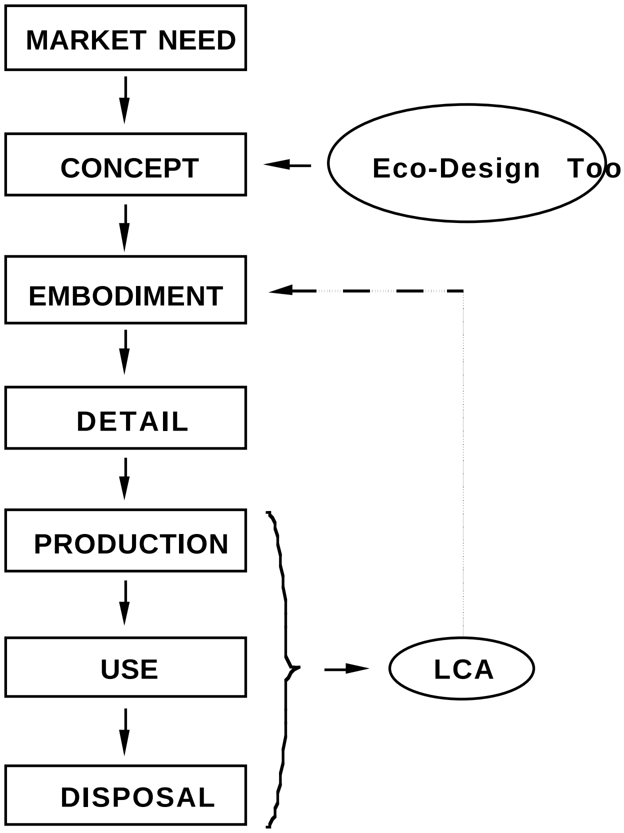

Fig. 1 The design process, life-cycle assessment (LCA) and eco-design tools.

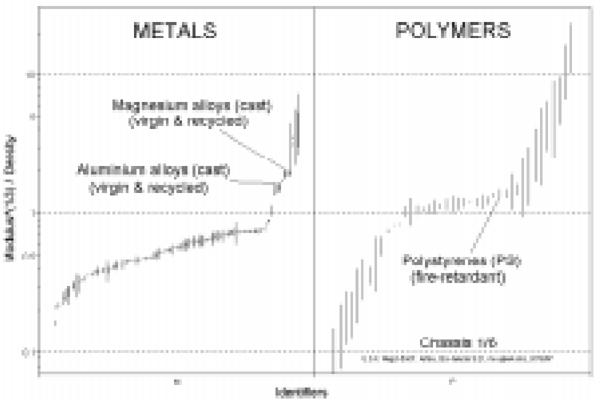

Fig. 2 A chart of M_1 against polymer and metal identifiers.

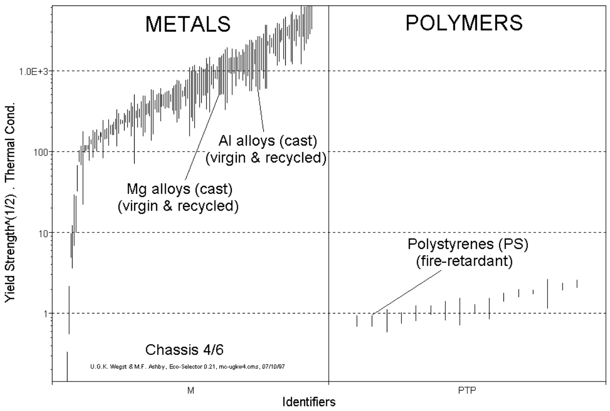

Fig. 5 A chart of M_4 against polymer and metal identifiers.

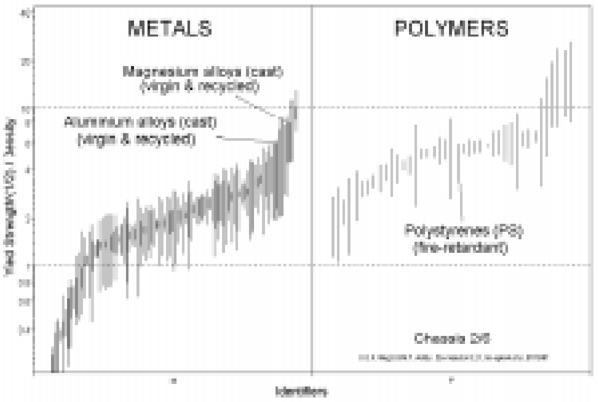

Fig. 3 A chart of M_2 against polymer and metal identifiers.

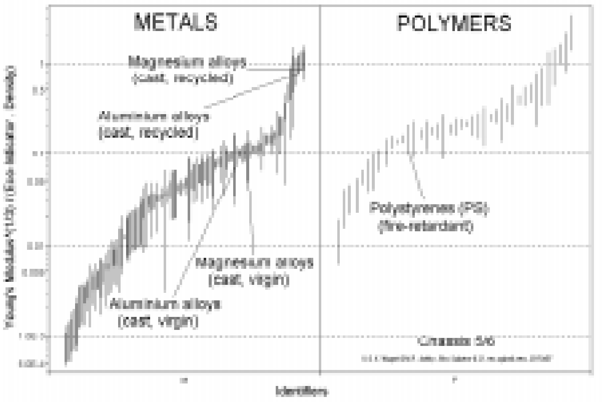

Fig. 6 A chart of M_5 against polymer and metal identifiers.

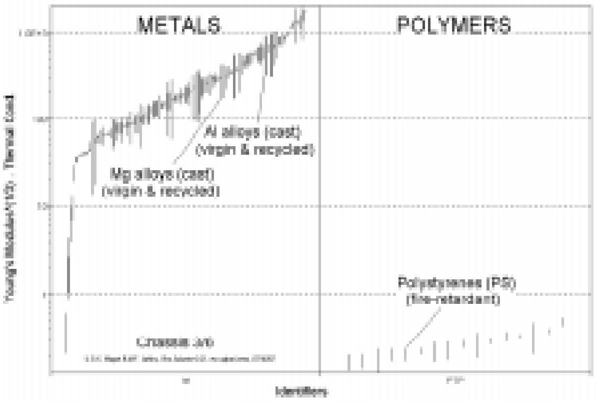

Fig. 4 A chart of M_3 against polymer and metal identifiers.

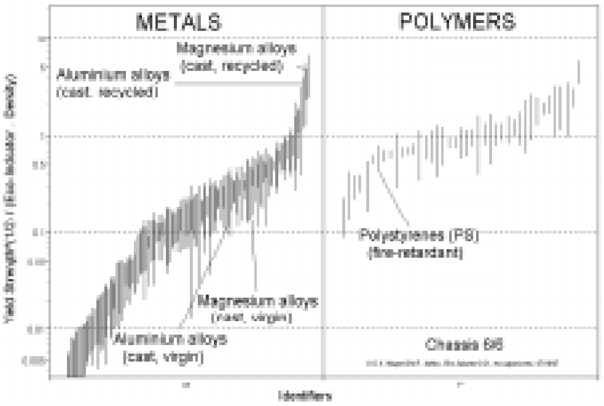

Fig. 7 A chart of M_6 against polymer and metal identifiers.

TABLES

FUNCTION	Plate loaded in bending
OBJECTIVE	Minimise environmental impact
CONSTRAINTS	Match or exceed the properties of fire-retardant polystyrenes (PS): a) Bending stiffness per unit mass b) Bending strength per unit mass c) Heat transfer

Table 1 The design requirements for a monitor chassis.

MATERIAL / PERFORMANCE	**Stiffness**	**Strength**	**Thermal**	**Eco**
Fire-retardant Polystyrenes	3	3	3	2
Aluminium Alloys (virgin)	2	2	1	5
Aluminium Alloys (recycled)	2	2	1	3
Magnesium Alloys (virgin)	1	1	2	4
Magnesium Alloys (recycled)	1	1	2	1

Table 2 Performance of the three candidate materials fire-retardant PS, Mg alloys and Al alloys. The winner in each category is marked by a “1”, the loser by a “3” or a “5” in the case of the eco-performance. Those in between are graded in order of decreasing performance.