Selection of materials to reduce environmental impact: a case study on refrigerator insulation

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The creation and use of any engineering product carries with it environmental penalties. There is a growing recognition that the minimization of these penalties must become a primary design objective. Some of the considerations – and difficulties – in selection of materials to minimize environmental impacts are discussed. A design strategy is developed which relates traditional design objectives with environmental impact indicators. The selection of insulation for refrigerators is used to illustrate the approach. Copyright © 1996 Elsevier Science Ltd.

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Introduction: material use and the environment
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 – the demands for stiffer, stronger, lighter, cheaper materials – remain one of 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 10 years or more – requiring sustained investment.

Until recently, these were the principal evolutionary forces of materials technology. But our damaging impact on the environment can no longer be ignored. Any manufacturing process carries with it an environmental impact. For each type of impact, a natural recovery-rate exists (though it may vary enormously from tropical jungle to high sierra), implying that a steady state is possible, at least in principle. Increasingly, concern is expressed that present-day processes cause impact at a rate which exceeds the capacity for recovery, leading to accumulation of damage.

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. Minimizing the damage requires the selection of materials and processes which are less toxic, and can give products which are easier to recycle, lighter and less energy-intensive; and this must be achieved without compromising product quality. Different materials differ greatly in their impact: by almost any measure, cadmium is damaging, wood is benign.

There are two alternative views on how the negative impacts of materials on the environment should be countered. The first is to treat environmental damage as a design constraint, listing permissible levels of impact and insisting that the actual impact level does not exceed this target. The second is to treat the minimization of environmental impact as an objective. It is unrealistic to think of it as the only objective, since minimizing cost is always a consideration also. But if a value can be placed on each sort of impact, allowing the formulation of a set of ‘exchange-rates’, converting impact to dollars, the application of optimization methods is possible.

To reach this goal, a need must be met: that for quantitative accounting methods for environmental impact. They do not need to be exact: useful conclusions can be drawn from approximate data. The measures may require debate and will change with time, but techniques for obtaining them are only a little more difficult than those established for energy accounting or for estimating cost.

This paper concerns one route towards achieving these goals. It describes how an established methodology for materials selection might be adapted to the task of minimizing the environmental impact of material usage. In doing so, it is helpful to divide origins of environmental impact in engineering production and use into three broad classes.

1. Inefficient use of materials: the best defence against waste and the problems of its disposal is to decrease the amount of waste that is produced in the first place by efficient design.

2. Consumption of non-renewable resources: the life cycle of any engineering structure involves the consumption of energy and materials, both very much derived from non-renewable resources.

3. Specific damage to air, water and land, by chemical contamination, particulates and solid waste.

To explore ways of choosing materials to minimize environmental impact it is helpful first to examine how materials are selected to meet a design specification.
Materials selection methodology
Function, objective and constraints
Any engineering component has a function: to carry bending moments, to contain a pressure, to transmit heat, etc. In designing the component, the designer has an objective, to make it as cheap as possible, or as light, or as safe, perhaps. This must be achieved subject to constraints: that the component can carry the given loads without failure, that certain dimensions are fixed, and that its cost is within certain limits. Function, objective and constraints (Table 1) define the boundary conditions for selecting a material and – in the case of load-bearing components – a shape for its cross-section.

The optimal selection of material for an engineering component is usually overconstrained; and, additionally, it must commonly meet several compound objectives. Methods for achieving this, based on the use of material indices and selection charts, are developed below.

The index-and-chart method
Two concepts are used in the selection procedure. The first is that of 'performance indices' which isolate the combination of material properties and shape information that maximize performance; the second is that of materials-selection charts. These are discussed in detail elsewhere. The main features are summarized briefly here.

Performance indices. The idea of performance indices in assessing the merits of a particular material in any design is a powerful one. The design of a mechanical component is specified by four groupings of variables: the functional requirements (need to carry loads, transmit heat etc.) F; the specifications on geometry, G; the properties of the material of which it is made, M; and the section shape, S. The performance P of the component can be described by an equation with the form

\[ P = f(F, G, M, S) \]  

where \( P \) may be its mass, or volume, or cost, or life, for example; and ' \( f \)' means 'a function of'. Optimum design can be considered to be selection of the material and geometry which maximize (or minimize) \( P \). The optimization is subject to constraints, some of them imposed by the material properties. The four groups of parameters in equation (1) are said to be 'separable' when the equation can be written

\[ P = f_1(F).f_2(G).f_3(M).f_4(S) \]  

where \( f_1, f_2, f_3 \) and \( f_4 \) are functions. When the groups are separable, the optimum choice of material becomes independent of the details of the design: it is the same for all geometries \( G \), and all values of the functional requirements \( F \). Then the optimum material can be identified without solving the complete design problem, or even knowing all the details of \( F \) and \( G \). This enables considerable simplification: the performance for all \( F \), \( G \) and \( S \) is maximized by maximizing \( f_3(M) \), which is called the 'performance index'. Experience shows that the groups usually are separable. Numerous examples are given elsewhere. The steps in deriving an index are as follows:

1. Identify the PRIMARY FUNCTION of the component for which a material is sought. A beam carries bending moments; a heat-exchanger tube transmits heat; a bus-bar transmits electric current.
2. Write down an equation for the OBJECTIVE; it is called the 'objective function'. The objective is the first and most important quantity to be minimized or maximized. Commonly, it is weight or cost; but it could be energy dissipated in \( \ell R \) heating (a bus-bar), or environmental impact (refrigerator insulation materials) – it depends on the application. In general, the objective function contains one or more free variables: dimensions (such as the cross-section of the beam or the wall thickness of the heat-exchanger tube) which are not specified, and which we are free to choose.
3. Eliminate the free variable(s) in this equation by using the CONSTRAINTS. They are the design requirements which must be met, and which therefore limit the optimization process of step (2). Commonly these are: a required value for the stiffness \( S \); a required value for the safe load \( F \), or moment \( M \) or torque \( T \) or pressure \( p \) that can be supported; a limit on operating temperature \( T_{\text{max}} \); or on resistance to sudden fracture, measured by the fracture toughness \( K_c \).
4. Read-off the grouping of material properties (called the PERFORMANCE INDEX) which maximize the value of the objective.

Applying the criteria: selection charts
Figure 1 shows the steps involved in a single selection stage. Typically, we have a performance index, \( M \), made up of two or more properties \( P_1 \) and \( P_2 \) – in this

- Table 1 Function, objectives and constraints

<table>
<thead>
<tr>
<th>Function</th>
<th>What does component do?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective</td>
<td>What is to be maximized or minimized?</td>
</tr>
<tr>
<td>Constraints</td>
<td>What non-negotiable conditions are to be met?</td>
</tr>
<tr>
<td></td>
<td>What negotiable but desirable conditions ...?</td>
</tr>
</tbody>
</table>

Figure 1 A material-selection chart
example they are Young’s modulus, $E$ and density, $\rho$. We create a selection chart with axes of $P_1$ and $P_2$. The performance index, $M$, plots as a diagonal line on the chart. Its slope is important. A simple performance index, typically, has the form

$$M = \frac{P_1}{P_2^2}$$

(3)

The default axes of the charts are logarithmic. Taking logs of the above equation gives:

$$\log P_1 = n \log P_2 + \log M$$

(3a)

A line of slope $n$ on the log-log plot describes the index; its position is determined by the value of $M$. Moving the line changes the value. The selection is optimized by moving the line to the highest value of $M$ which still leaves a viable subset of materials exposed.

Environmental impact versus functional performance

The index-and-chart method outlined above can be readily extended for the case of compound objectives: the task of meeting two objectives in one design. For this scenario the design is best analysed by forming the performance index for each objective in turn, and combining the two in an appropriate way to form a value function. This procedure can be applied to environmental design. Here, an environmental objective is formed and its performance index, $M_1$, is calculated; the result giving a measure of environmental impact. Environmental impact can then be compared with the traditional function (design) objective (characterized by the index $M_2$), by making a chart with these quantities as the axes. Selection is made by plotting coupling contours onto the selection chart, as illustrated in Figure 2. A coupling contour is a plot of the value function by

$$V = C_e M_1 + M_2$$

(4)

Here, $C_e$ is the appropriate exchange (coupling) constant; it can be thought of as a weighting factor, or – more precisely – as ‘the relative value of environmental impact and performance’. The power of this method is that potential materials are compared with a reference material (A in Figure 2) in the light of both performance indices. All materials that lie on a contour have the same overall value (e.g. life-cost) as the reference material. All materials that lie above the line have a lower life-cost and are a better choice while those that lie below are worse. The slope of the contour is dependent on $C_e$; its position depends on $V$.

The method is best explained by means of an example. Consider the insulation of refrigerators. The manufacturer may wish to minimize the cost of the material, while, on the other hand, a consumer may want to minimize the energy lost over the lifetime by conduction through the refrigerator walls. These objectives can be transformed into performance indices that are given by $M_1$ and $M_2$, respectively. By relating the energy losses to a cost through the price of electrical energy a total lifetime cost can be established. Then the value, $V$, in equation (4) becomes the total lifetime cost and $C_e$ is the cost of electrical energy.

Furthermore, the value function method can also be used to relate seemingly unrelated objective functions. Again using a refrigerator as an example we consider the increase in amount of money a consumer is prepared to pay for an increase in fire resistance. The performance index which minimizes the cost of material is once again given by $M_2$ in equation (4). The performance index which gives a measure of fire resistance is $M_1$. The exchange constant is found as follows. Note that for the general case and a fixed value of $V$

$$\Delta C = C_e \Delta M_1$$

that is, $C_e$ measures the change in cost, $\Delta C$ for a given change in $M_1$, at constant $V$. Then for our example, $C_e$ is the increase in price a consumer is prepared to pay for an increase in fire resistance. These examples are discussed in more detail in the following section.

Simple measures of impact: a case study on refrigerator insulation

Environmental impact is difficult to quantify. One component of this impact relates to the energy content of the material, and that can be quantified. We shall use this, together with the energy dissipated during the life of a component and fire resistance of a material, as examples in the design of insulation for refrigerators, returning to the more general measures of environmental damage at the end of the paper.

Materials for refrigerator insulation
Many refrigerators use polyurethane foam as the insulation material. We choose a polyurethane foam with

* Chloro-fluorocarbon foams (CFCs) are not considered in this case study, as they have been excluded for use in refrigerators in Europe and other countries. However, it should be noted that their thermal conductivities are among the lowest available for foamed materials.
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**Table 2** Design requirement for insulation

<table>
<thead>
<tr>
<th>Function</th>
<th>Refrigerator insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Objectives</strong></td>
<td></td>
</tr>
<tr>
<td>Functional</td>
<td>Minimize cost of insulation while satisfying constraints</td>
</tr>
<tr>
<td>Environmental</td>
<td>Minimize energy consumption over lifetime</td>
</tr>
<tr>
<td>Safety</td>
<td>Material needs to have good fire resistance</td>
</tr>
<tr>
<td><strong>Constraints</strong></td>
<td></td>
</tr>
<tr>
<td>Thickness ≤ 2 cm</td>
<td></td>
</tr>
<tr>
<td>Lifetime &gt; 10 years</td>
<td></td>
</tr>
<tr>
<td>Outside/inside temperature</td>
<td>≥ 16°C</td>
</tr>
</tbody>
</table>

\[
U_{\text{TOT}} = xpq + \frac{\lambda \Delta T}{x} t_i = \frac{1}{M_2} \frac{\Delta T}{x} + \frac{x}{M_3} \tag{5}
\]

with \( M_2 = 1/\lambda \) and \( M_3 = 1/qp \), and where \( \lambda \) is the thermal conductivity of the material, \( x \) is its wall thickness (2 cm), \( t_i \) is the lifetime of the insulation (10 years), \( q \) is its energy content and \( p \) is its density. \( \Delta T \) is the temperature difference between the inside and the outside of the insulation layer. Each \( M \) is a performance index, to be maximized if each contribution was treated separately. Figure 4 shows the contribution from each energy to the total by plotting \( M_2 \) against \( M_1 \). The better the material, the greater the value on each axis. Superimposed on the chart is a contour of total energy using polyurethane from (density 80 kg/m³) as a reference. This is obtained directly from equation (5) but plots as a curve because of logarithmic scales. All materials which cut through such a line have the same energy associated with them over their lifetime. The contour, for this example, is near-vertical, indicating that the energy content of the material is small compared with the energy losses over the lifetime. Therefore, to a good approximation, the total energy associated with a material can be measured solely in terms of energy losses over the lifetime of the refrigerator.

The calculation can be adapted to minimize cost, rather than energy. Equation (5), the value function, becomes, instead

\[
C_{\text{TOT}} = xC_{\text{w}}p + \frac{\lambda \Delta T}{x} t_i C_E = \frac{1}{M_1} \frac{\Delta T}{x} + \frac{x}{M_2} \tag{6}
\]

with \( M_1 = 1/C_{\text{w}}p \) and \( M_2 = 1/\lambda \). The cost of energy, \( C_E \), has been introduced to convert energy losses to an energy cost. In practice, this is the cost of electricity to the consumer. Here, a figure of £10/GJ is assumed for illustrative purposes.

Figure 5 shows a chart of \( M_1 \) against \( M_2 \). Traditionally the best materials would have been chosen on cost alone as indicated by large values of \( M_1 \). On environmental grounds the best materials have large values of \( M_2 \). However, the two competing objectives...
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Figure 4  Insulation reduces the loss of energy from a refrigerator, but contains energy itself. The contour shows all materials with the same life-energy as polyurethane (density 0.08 Mg/m$^3$). The total life-energy contour is near-vertical, indicating that energy content of the material is small compared with energy losses over the lifetime.

Safety aspects are often considered alongside environmental concerns. Fire resistance, in particular, could be identified as an issue for which consumers are prepared to pay a premium. If the amount of money could be identified for which customers are willing to pay extra for an increase in fire resistance the analysis above could be adapted to two separate objectives. The lifetime cost calculations assumed that the cost of electrical energy, $C_e$, was known. To relate fire resistance to cost of material it is necessary to determine the perceived increase in value to the consumer associated with an increase in fire resistance. Then

$$\text{Increase in value} = \text{value added due to increase in fire resistance} - \text{increase in material costs}$$

Here, it is proposed that customers are prepared to pay for fire resistance. We examine three levels of this willingness: £10, £30 and £100 per 10% increase in fire resistance. A useful measure of fire resistance in polymeric foams is the oxygen index. This figure gives the percentage of oxygen in the atmosphere needed to sustain burning, the larger the figure the more fire-resistant the material. Figure 6 shows a chart of $M_1$ versus $M_2$ where the latter is the oxygen index. Superimposed on the chart are three contours of constant value using polyurethane (0.08) as the reference material. Each contour is associated with a different perceived value of fire resistance. The lower contour is given by the lowest premium for a 10% increase in fire resistance, that is, only £10. The middle contour is for £30 and the upper one for £100. An indication of the appropriate accurate figure could be obtained from consumer surveys. The trend of each contour is easily explained. At high values of fire resistance (large $M_2$) the material cost is higher (low $M_1$), as expected from the increase in price a consumer is prepared to pay. On the other hand, materials with worse fire resistance than polyurethane (0.08) are cheaper. The contour represents a curve of constant value.

The two limits of perceived value are also examined on this chart. If customers do not value fire resistance at all, i.e. they are willing to pay £0 for increase in fire resistance, the contour of constant value is a horizontal line passing through the reference material (polyurethane 0.08). Conversely, the greater the premium a consumer is prepared to pay for an increase in fire resistance, the more vertical the contour becomes, again passing through the reference material.

Results

The lifetime cost of a refrigerator with polyurethane (0.08) as an insulation material is equal to approximately £600. It is made up of £40 on PU (0.08), £200 on the rest of refrigerator and £360 on energy losses over 10 years, as calculated by inserting the constants in equation (6).

The results of the selection strategy are summarized in Table 4. Each row corresponds to a different environmental indicator. The first row shows the relative lifetime cost of alternative foams compared to a refrigeration system with polyurethane (0.08) as insulation material. The second row shows the relative life-energy of the same foams, and the third row shows the relative fire resistance of the foams, as measured by the oxygen index.
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Figure 5 Insulation reduces the loss of energy (which has a value in £) from the refrigerator, but has an intrinsic cost itself. The choice which minimizes the life-cost of the system can be made with this chart, again allowing for a constraint on total thickness.

The phenolic foam of density 35 kg/m³ shows a lifetime cost saving of 20% (£120) over PU (0.08).

The second row shows the results of added value to the consumer, for the same cost, associated with an increase in fire resistance. The results are normalized to the cost of a refrigerator with PU (0.08), i.e. £250.

Again the phenolic foam rates highly. For the same cost refrigerator, phenolic foams are 29% better in value for money in terms of fire resistance.

Discussion
Before phenolic (0.035) foam is confirmed as a better environmental foam for insulation in refrigerators other...
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Table 4  Results of environmental insulation material selection

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy efficiency</th>
<th>Toxicity</th>
<th>Gaseous emission</th>
<th>Specific toxic emission</th>
<th>Dioxin emission</th>
<th>Material life-cycle cost</th>
<th>Material retrieval cost</th>
<th>Emission to be expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU</td>
<td>0.08</td>
<td>1</td>
<td>0.99</td>
<td></td>
<td></td>
<td>1.12</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>PVC</td>
<td>0.028</td>
<td>1.04</td>
<td>0.96</td>
<td></td>
<td></td>
<td>0.93</td>
<td>0.91</td>
<td>0.80</td>
</tr>
<tr>
<td>Phenolic foam</td>
<td>0.035</td>
<td>0.88</td>
<td>1.29</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Factors should be examined. These include material properties such as ease of recycling, biodegradability and toxicity. The manufacturing process should be examined to identify the amount of gaseous emissions (NOx, SOx, CO2) and other contaminants. In addition, the toxicity of component chemicals and the finished material could be analysed.

The selection chart method outlined here, whereby a traditional functional objective is plotted against an environmental impact objective, could be applied to all these environmental measures. The objectives are plotted in terms of performance indices. The two or more objectives are combined to give a value function by expressing one in terms of the other via an exchange constant. Cx. Examples considered here include the energy loss for the insulation material which is converted into a cost using the cost of energy, and fire safety, which is converted to cost with a perceived benefit. But before this can be done, data of sufficient accuracy are required. If stored in ranges (lower and upper bounds) the data do not need to be exact. This, at the present time, is the most urgent need.

Having identified the most energy-efficient material for refrigerator insulation there is still a question of the mechanism or market forces that will cause this design solution to be chosen. One possible scenario is that manufacturers, themselves, will make a marketing decision to promote the design that gives the best lifetime energy performance, even though there may be a penalty on the initial purchase cost. This approach becomes more viable if the government makes it mandatory for every refrigerator manufacturer to state the lifetime energy-efficiency of their refrigeratory so that a potential customer is more confident about the decisions on lifetime costs.

Conclusions and challenges
If engineers are to minimize the environmental impact of the products they design, they require tools and methods to guide their choice of material and process. Ideally, this methodology should point, in any given application, to the subgroup of materials which perform best by environment-sensitive criteria.

This paper outlines one approach to the problem and illustrates it by taking two restricted measures of impact, the energy content and the fire resistance of the material. 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 of recycling, or the resistance to biodegrading can be the real environmental threat. The chart method could be used here too, if appropriate charts could be constructed. And therein lies the challenge: devising quantitative measures of environmental impact (generalized replacements for qp) against which design-limiting properties (strength or thermal conductivity) can be plotted.

One candidate is cost: the cost, per m³ of material, of exactly reversing the damage that creating, using and disposing of the materials has caused. The difficulties involved can be seen by attempting to apply it to our restrictive case. The cost of energy is, of course, known; it is currently about £10 per GJ. But the energy content of a material measures more than that: it also includes a measure of the CO2, SO2 and H2S produced, the depletion of a natural energy resource, and the dust and slag produced. Energy content was chosen for the charts shown here because it has this greater dimension.

It is clear that a need exists for quantitative accounting methods for environmental impact. As mentioned earlier, they need not be exact. As with energy content, different materials differ greatly. Useful conclusions can be drawn from approximate data. The measures will require debate and will change with time, but techniques for obtaining them are only a little more difficult than those established for energy or cost accounting. These, with methods like those described in this paper, are a logical step forward in environmentally conscious engineering.

References
1 Forrest, D. and Szekely, J. Journal of Metals 1991, December, 23
3 Geiser, K. The greening of industry. Technology Review 1991, August/September
11 Weaver, P. M. and Ashby, M. F. The optimal selection of material and shape. Journal of Engineering Design 1996, 7 (2)
12 Ashby, M. F. Materials Selection: Multiple Constraints and Objectives. Cambridge University Engineering Dept Report CUE/E-C-MATS/TR229, September 1995