A methodology and support tool for environmentally conscious design and manufacture.

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A Methodology and Support Tool For Environmentally Conscious Design and Manufacture

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'The problems arising from material usage,
high energy consumption and waste generation
urgently need engineering solutions to repair and
protect the environment.'

Engineering Council

'70 - 80% of a products future environmental
impact can be determined during the early low-cost
design phase of its development.'

Design Council

Dedicated to environmental researchers past, present and future.

Abstract

Environmental concerns are now firmly on the agenda for engineers and designers. In recent years an increasing barrage of legislation accompanied by the public's increasing awareness of, and concern for, the environment is forcing industry to respond.
Energy and resource consumption reduction have long been the concerns of industry but this narrow view is no longer appropriate with much more complex life-cycle environmental issues such as design for disassembly and environmentally conscious processing becoming apparent.

In response many tools have been developed in recent years to assist engineers and designers in their attempts to address the emerging environmental problems. The most universally adopted is that of Life-Cycle Analysis or LCA. This procedure assesses the complete life-cycle environmental burdens of product or system with a view to evaluating and implementing opportunities to effect improvements. The initial stages of LCA which include initiation, inventory and impact assessment are well developed disciplines and standardised frameworks are appearing. However the improvement stage of LCA, in which changes in design are considered is currently an active field of investigation as attempts are made to develop efficient and reliable methods.
The integration of LCA principles into current design and materials selection procedures, and thus completion of the improvement stage, is a task which needs addressing. Methods exist in the form of frameworks, guidelines, matrices and computer based tools, but all have drawbacks and 'blind spots'.

This research looks at the problems facing designers and engineers both in terms of environmental concerns and the logistics of integrating these new concerns into current product development practices. Environmental problems are reviewed and responsibilities and possible solutions are identified. Environmental analysis procedures are explained and the process of LCA is studied in detail. The development of environmental design is discussed which leads to the presentation of the possibilities for integration of Design for the Environment (DFE) into current practices.
Through a critical review of current practices in environmental design the following important unfulfilled needs are identified: the difficulty in comparing different design options in environmental terms; providing guidance in identifying appropriate product design strategies for different products; helping to train/advise engineers and designers in the use of environmentally sound products and materials and the development of tools which actively offer advice to designers and engineers.

In fulfilling these needs this research presents a contribution to knowledge in the field of environmentally conscious design and manufacture in three ways:
Development of a novel matrix-based method of environmental design,
Integration of environmental concerns into the materials selection process and
The development of a computer support tool for environmentally conscious design and manufacture.
Validation of the research is presented through examples and the conduction of a user survey.

Finally this thesis summarises the conclusions drawn from the research and identifies areas of further work which will increase the knowledge base, scope and applicability of the work carried out.

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Glossary of Terms

Artificial Intelligence (AI)

A branch of computer science concerned with the design and implementation of programs which are capable of emulating human cognitive skills such as problem solving, visual perception and language understanding.

Concurrent Engineering

Simultaneous design of all components of the product system including processes and distribution networks. Concurrent design utilises an integrated approach using teams of specialists from various disciplines.

Cradle-to-Grave

An approach to product design or analysis which acknowledges that environmental concerns may emerge at any stage of the products life cycle. A full cradle-to-grave approach will span from extraction of raw materials at source to the eventual disposal of the product.

Design Matrices

Paper based design tools which uses a matrices to allow the consideration of the sometimes complex interrelation of different design requirements and product life-cycle stages

Design for Environment (DFE)

The process of considering all the possible environmental implications of a product or system using the principles of concurrent engineering. DFE can be considered as both an explicit concurrent engineering imperative and an underlying theme running through all DFX disciplines.

Design for X (DFX)

Design for X. An approach to implementing the principles of Concurrent Engineering. It focuses on a limited number of vital elements at a time. X may be assembly, quality, environment etc.

Eco-Indicators

A method of attributing environmental impact to a material, product or system. Eco-indicators may be a single overall figure or may be presented as a number of separate elements.

End-of-Pipe Strategies

Reactive rather than proactive measures. E.g. treating waste water rather than trying to prevent its occurrence.

Environmental Auditing

A management tool comprising a systematic, documented, periodic and objective evaluation of how well the environmental organisation, management and equipment are performing

Environmentally Conscious Design (ECD)

Design considerations are flavoured from the very conceptual stages so that the product is developed in an environmentally conscious manner.

Environmentally Conscious Design and Manufacture (ECDM)

A progression of ECD along the design model and into the manufacturing process. The design of products will have an effect on the manufacturing processes used.

Environmental Impact Assessment (EIA)

A decision making process that attempts to define the environmental consequences associated with specific actions before that action is taken and potentially irreversible adverse environmental changes result.

Expert Systems (ES)

A computer program that represents and reasons with knowledge of some specialist subject with a view to solving problems or giving advice.

Green Design

General term usually used to mean environmental design. Green design considers one or a number of environmental issues in isolation. It does not consider the environmental impact of the product as a whole.

KADS Methodology

A structured methodology for analysis and design of knowledge-based systems.

Knowledge-Based Systems

Any system which performs a task by applying rules of thumb to a symbolic representation of knowledge.

Life-Cycle Assessment (LCA)

An accounting system for assigning specific costs to a product or system within a physical life-cycle framework.

Material Indices

A system of representing constraints related to mechanical function such as strength or stiffness used in materials selection exercises.

Materials Selection Charts

Charts used to plot material indices, thus allowing a graphical representation of the relative performance of a given group of materials.

Maximum Allowable Concentration (MAC)

A system of representing the safe limits of pollutants in air. Can be used in the calculation of eco-indicators.

OvD

A system of representing the safe limits of pollutants in water. Can be used in the calculation of eco-indicators.

Pollution

Any by-product or unwanted residual produced by human activity. These residuals include both hazardous and non-hazardous substances released to all media.

Product Classification

A system of identifying the characteristics of a product which will affect the impact it has on the environment at each life-cycle stage.

Product Life-Cycle

All aspects of the manufacture, use, servicing and disposal of a product. Beginning with the extraction of materials and ending in the eventual disposal of the product.

Sustainability

The ability to meet our current needs without compromising the ability of future generations to meet their needs.

System Boundaries

A definition of the extent of systems or activities. These boundaries are used in LCA and dictate the areas for design and analysis.

Units Acidification

An aggregated method of presenting the contribution of a product or system to the occurrence of acid rain. Calculated from the amounts of the pollutants which are known to cause acidification. Presented as a single figure to allow easy comparison of different cases.

Units Polluted Air

An aggregated method of presenting the extent of pollution to the atmosphere created by a product or system. Presented as a single figure to allow easy comparison of different cases.

Units Polluted Water

An aggregated method of presenting the extent of pollution to water created by a product or system. Presented as a single figure to allow easy comparison of different cases.

Acknowledgements

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Declaration

I declare while registered as a candidate for the University's research Degree, I have not been a registered candidate or enrolled student for another award of the University or other Academic or Professional organisation. I further declare that no material contained in this thesis has been used in any other submission for an academic award.

Leigh Holloway

Chapter 1

Engineering and the Environment

Engineering and the Environment

1.1 Background

With the beginning of the industrial revolution in the 18th century, the whole idea of our ability to produce and consume goods changed. We could make much more than we had ever been able to before. Utilisation and consumption of resources were the main aim and the age of mass production was born. One of the major driving forces behind this revolution was engineering and that revolution continues to this day - but with a difference. As early as the 1880s Ruskin was warning of the effects this had on the environment. Now society has recognised that our production and consumption of goods and resources must be reconciled with environmental imperatives: such as air quality, water quality, waste management and resource conservation. This realisation is changing the priorities and agenda of engineering.

The fact of our very existence consumes massive amounts of resources and degrades the environment around the world. Products and services once seen as a luxury are now deemed 'essential' by much of the developed world and it is this increase in consumerism that has lead to an increase in demand, consumption, pollution and waste. **Alders** (1991) cites a report published by the National Institute of Public Health and Environment in December 1988 entitled 'Concern for Tomorrow', an overview of the environmental problems in the Netherlands. The conclusions were:

- Emission discharges of numerous compounds and substances must be reduced by between 70 and 90 percent on current levels;
- this could not be achieved by using the available technical end-of-pipe measures;
- other measures were required to affect the changes in peoples behaviour patterns.

There is much support for this with works by the likes of **Burall** (1991) and **MacKenzie** (1991) both of whom identify the need for changes in the way we produce and consume in order to curb environmental problems. **Mendias & Sliter** (1994) also argued that these new environmental concerns ' ....necessitates that another element be added to the design, manufacturing testing and maintenance of products' Starting in the late 50s and in later publications **Papanek** (1971) said 'by creating a whole new species of permanent garbage to clutter up the landscape , and by choosing materials and processes that pollute the air we breath, designers have become a dangerous breed'.

Alders (1991) then goes on to say that in order to achieve the objective that

'within the period of one generation we must solve our environmental problems and we must put an end to the process, whereby we transfer our problems elsewhere or shift the burden to the shoulders of later generations.'

The following significant principles should be added to the basis of environmental policies:

1. Integrate life-cycle management, aimed at closing the cycle from raw material to product, with as few leaks as possible.
2. Energy conservation, aimed at reducing the overall consumption of energy from non renewable sources.
3. Enhancement of quality, aimed at increasing the time spent by materials in the cycle of production and products.

Although Alders work was originally carried out in, and aimed at, the Netherlands his principles are now accepted throughout the developed world. However it is now generally accepted that life-cycle management should close the cycle from raw material and beyond the production stage to disposal.

Banks (1976) stated 'Protection of the environment and preservation of environmental resources to the maximum feasible degree are highly important to man's future well-being', and now many engineering organisations are now beginning to recognise this. **Forrest & Szekely** (1991) discussed the apparent environmental problems and possible solutions being adopted by the primary metals industry. Not only the metals industry are in the spotlight as **Guyot** (1994) showed with her review of the strong environmental opposition facing the plastics industry. People want, and indeed need, products and services. **Hindle & Payne** (1991) summarise this by stating 'People want products which do the job for which they have been purchased, and which are easy and convenient to use. They also want products which are absolutely safe and which do not impact on the environment in any way. The problem for society is that there is no way in which this Utopia can be achieved.' The key to the problem is to keep a balance between environmental considerations and other actions needed to improve the overall 'quality of life'.

1.2 Environmental Problems

It has only been in recent years that we have realised the effect that our actions are having on the environment and the diversity and complexity of these problems is bewildering.

The main areas of concern are: air pollution, land contamination, water pollution and non-renewable resource consumption. Within each of these are a number of particular problems.

1.2.1 Air Pollution

By releasing pollutant gases into the atmosphere we insulate the earth and prevent some of the suns heat from escaping (CO_2 & NO_X: the greenhouse effect), damage the ozone layer which in turn reduces protection from ultraviolet radiation (CFCs: ozone depletion) and produce acidic rain which leads to deforestation (SO_Xs & NO_Xs). Clearly there are a number of direct or consequential public health issues which are also important here. The effect of particulates in the form of dust and smoke also have a great effect on our everyday lives as well as the eco-systems around us. Most manufacturing industries contribute significantly to this particular pollution problem as does power generation (coal and oil fired power stations) and also traffic.

The existence of areas of thinning ozone has been accepted for may years but only very recently has global warming been officially recognised.

1.2.2 Land Contamination

The pollution problems faced on land are contamination of soils, by heavy metals, poisonous substances etc. and the ever increasing amount of landfill waste. Land contamination is a very serious issue with redevelopment costs estimated at £105.96 million in 1992/93, **Mumma** (1995) Contaminated land can occur as the result of many engineering operations from mining of raw materials to waste disposal. The particular types of materials that occur at end of line waste streams and contaminate land depend upon the particular country, area or engineering sector in question. (For example 'Almost 70% of all plastic waste in Germany now ends up in landfill sites. But plastics are far too precious to throw away and can be used in more appropriate ways.'[1]). The dumping of waste in landfill sites can also cause problems with vermin, odour, litter and produce large amounts of methane landfill gas.

1.2.3 Water Pollution

Many industrial practices use large amounts of water in production facilities and as a result the amount of 'clean' water available cannot meet demand. Again, world-wide, the engineering industry is responsible for much of this pollution. Large amounts of water are used in many industrial processes. Much of this water is contaminated to a high level and needs expensive treatment to render it ‘useable’ again. Certain amounts of liquid waste (chemicals etc.) are lawfully discharged directly into rivers, waterways and the sea. If humans and animals come into contact with this water before it has been treated it can result in many toxicological effects

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[1] **BASF Report (1993)**

such as abnormal skin colour, damage to the immune system, slowing of the conduction of nervous impulses, interference with respiration or chromosomal abnormalities

1.2.4 Non-renewable Resource Consumption

The problem of using non-renewable raw materials has been highlighted by predictions that our reserves of oil, natural gas and coal will not last indefinitely. Indeed at the current rate of consumption it seems that these resources have a very limited life. The search for new sustainable sources of raw materials is already underway. Most of the materials used in engineering utilise non-renewable resources. We have finite amounts of iron and aluminium ore etc. and we must take this into consideration we making new products. It has been suggested that throughput of materials and energy need to be reduced by a factor of twenty or more **Manzini** (1994).

All of the environmental concerns outlined above are an integral part of the process of engineering. Table 1.1 contains more detailed information about pollutants and their effects. Through careful design and development programmes 'Engineers have the potential and the duty to be major influence in the achievement of the primary goals of the future: a sustainable habitat for all life, and one that continues to allow mankind to achieve his potential and to enjoy the process of living'. **WFEO** (1992)

Problem	Environmental Significance	Some Main Pollutants
Global Warming	Stratospheric accumulation of some gases as a result of human activities may be changing the Earth's energy balance, leading to damaging climate change	Carbon Dioxide Methane Nitrous Oxide
Stratospheric Ozone Depletion	Degradation products of CFC's etc. react with and destroy the stratospheric ozone layer one of whose functions is to protect the Earth's surface from excess UV sunlight	Chloroflurocarbons - CFC 11 - CFC 12 - CFC 113 Halons Chlorinated Solvents
Acid Rain	Reactions of acidic ions with water in the atmosphere acidifies precipitation resulting in acidification of surface water and soils, damaging aquatic life, trees and other vegetation, and also contributing to damage to the built environment	Sulphur Dioxide Nitrogen Oxides Hydrogen Chloride Hydrogen Fluorides
Water Quality	Pollution of ground water, rivers, lakes, estuaries and the sea affects not only the ecosystems within those waters, but also ecosystems, including those occupied by people, that are dependent on them	Organometallics Other Inorganics Gross Organic Load Suspended Solids Nitrates and Phosphates Unwanted organisms [VOCs, POs, Heavy Metals]

Table 1.1 Examples of Major Environmental Problems **CEST** (1991)

Problem	**Environmental Significance**	**Some Main Pollutants**
Heavy Metals	Metals and their compounds persist in the environment and build up in organisms, particularly those near the top of the food chain, with a range of toxic effects	Mercury Lead Cadmium Copper, Nickel, Zinc [Al, Co, Cr]
Persistent Organics	Some compounds do not bio-degrade in the environment leading to possible accumulation in organisms and to toxic effects. Adverse effects are not always proven hence emphasis is placed on 'persistence' of these compounds in the environment	Organochlorine Insecticides Pesticides Polychor, Biphenyls Plasticisers Organosilicones Polybrominated Compounds [Detergents, plastics, pharmaceuticals, chlor. prods, bioproducts]
Air Quality	In addition to the other air problems (global warming, ozone depletion and acid rain) particulates and smogs have adverse effects on health and natural and built environments	Particulates Mineral Dust Metallurgical Oxides Carbon Black [NOx, SO_2 VOCs Heavy Metals]
Noise/Vibration	Negligible ecological impact; adverse amenity and psychological/social impact at normal levels; physiological impact at high (work place) levels	Transportation Noise Industrial and Construction Neighbourhood

Table 1.1 Examples of Major Environmental Problems **CEST** (1991)

Problem	**Environmental Significance**	
Visual Impact/Amenity	Loss of social and cultural heritage. Inadequate planning/design that causes a change in physical appearance	
Waste Management	Extent of air/water/soil pollution problems caused by waste disposal make this a problem area in its own right	
Contaminated Land	Risks to potential users of the site (presence of toxic and/or explosive, substances) are central to the UK approach. Ground water protection is also a concern in other countries	
Major Spills and Incidents	Acute short/medium term disruption to local environment. Significant impact on public environmental consciousness	
GMO's Releases from Technology	Concerns about potential for genetically modified organisms (GMOs) to out perform natural populations, for unexpected gene transfer or for the activation of silent genes or appearance of new pests	

Table 1.1 Examples of Major Environmental Problems **CEST** (1991)

Problem	Environmental Significance	Some Main Pollutants
Visual Impact/Amenity	Loss of social and cultural heritage. Inadequate planning/design that causes a change in physical appearance	Loss of Architectural, Archaeological and Historical Sites Loss of Landscape, Flora and Fauna
Waste Management	Extent of air/water/soil pollution problems caused by waste disposal make this a problem area in its own right	Household Industrial Effluent Hazardous, Special & Agricultural Waste Mines, Quarries and Constructional Waste Power Station Ash Sewage Sludge, Clinical Waste
Contaminated Land	Risks to potential users of the site (presence of toxic and/or explosive, substances) are central to the UK approach. Ground water protection is also a concern in other countries	Heavy Metals Oils, Tars and Phenols Asbestos Methane Combustibles, Aggressive Inorganics
Major Spills and Incidents	Acute short/medium term disruption to local environment. Significant impact on public environmental consciousness	Marine Oil Spills Chemical Incidents Gas Explosions
GMO's Releases from Technology	Concerns about potential for genetically modified organisms (GMOs) to out perform natural populations, for unexpected gene transfer or for the activation of silent genes or appearance of new pests	Plants Micro-organisms Animals

Table 1.1 Examples of Major Environmental Problems **CEST** (1991)

1.3 Possible Solutions

In order to reduce the environmental effects of our actions we must first start by assessing and identifying their effects. Every industrial, and many non-industrial, activity being carried out in the world today has a very definite effect on the environment in which we live. There are a number of ways in which we can try and provide solutions to our environmental problems and a specific order in which we should carry them out. First on the list is Environmental Auditing: this is a well established discipline.

1.3.1 Environmental Auditing

'A widely used definition of Environmental Auditing (EA) states that it is a management tool comprising a systematic, documented, periodic and objective evaluation of how well the environmental organisation, management and equipment are performing.' **Mumma** (1995).

An EA programme helps to identify potential and actual environmental incidents and ensures that mechanisms and management systems exist to allow a pro-active approach to the environment.

It is usually a corporation level action and is concerned mainly with the structure around which an audit is carried out. In the UK the procedures for auditing are contained within the British Standard B7750 and the newly written ISO 14000 series of standards. EA and its associated management strategy are very closely linked to those of quality with BS 7750 being based around the British Standard for Quality Management Systems: BS5750.

There are many stages to an EA each of which have specific structures too detailed to discuss in this work. **Lloyds Register** (1992) have summarised what is needed by an EA programme in order to achieve environmental excellence:

- ensuring that the organisation has a clear understanding of the impact that its processes, products and waste have on the environment.

- demonstrating that procedures, systems and responsibility for action exist to protect the environment - staff have to be empowered to act
- providing evidence that action to protect the environment is taken at all levels in the organisation
- identifying and assessing pollution that may have been caused by normal operation, accidents or third-party activities
- demonstrating compliance with national and EC legislation as well as corporate policy.

Frienz (1989), **Reed** (1987) and **Varney** (1989) have discussed different aspects of EA; planning & implementation, practice and benefits respectively. One very important area of EA is that of presenting the results. If the results of the audit are not collated and communicated effectively then much of the impetus to be gained from the study can be lost. **Rhodes** (1986) shows that there are a number of factors which should be taken into account when delivering the results of EAs: fundamentals such as accuracy, clarity, conciseness, timeliness and tone. Coverage such as directors, managers, environmental management and business area management and finally, confidentiality.

In many cases it is the information gathered in an EA that will be the starting point for change in the environmental policies and performances of many companies. Areas of environmental concern highlighted by the audit can be looked at in more detail and plans for their improvement drawn up. Emission of contaminated waste water may be excessive or energy and material utilisation efficiency for specific processes may be unsatisfactory. Problems such as these may be picked up by environmental audits and if rectified can result in a drop in environmental impact. It is often the environmental impact of a particular process or system which will dictate the seriousness of the problem and the alacrity with which it is addressed.

The associated process of Environmental Impact Assessment is another of the possible solution which can be adopted to help engineers move towards sustainable development. This will be discussed in detail in a later chapter.

1.3.2 Legislation

The options for considering environmental factors in industrial practices discussed in the previous sections are voluntary decisions on the part of the company or organisation involved. This is with the exception of EIA which is 'required by law for specific activities for the biogeophysical environment and for human welfare.' **Engineering Council** (1994). Legislation is in many cases the driving force which pushes organisations into action, and in the case of the environment this is no different. Engineers and designers, as well as most other members of industry have a duty to know the law and how it applies to them.

1.3.3 Environmental Legislation

Until the late 1980's Town and Country Planning Law was the only comprehensive body of law which dealt with the environment. Since then there has been a constant barrage of environmental legislation from Europe and the UK. (Environmental legislation from other countries and continents is used in the legislative process of Europe. For example the Californian emissions regulations for vehicles are use by European car manufactures as past experience has shown that these very strict regulations tend to be introduced in Europe at a later date.) There is a large amount of environmental legislation applicable to industry as a whole and just as much again which deals with specific industrial sectors. In general the environmental legislation which affects industry covers, polluting emissions (air, water, land, noise etc.), waste management and disposal, energy consumption and use of natural resources. UK and European law are very closely linked with main UK legislation being driven chiefly by laws agreed by the member states of the European Union (EU).

EU legislation takes three forms **Engineering Council** (1994):

- **Regulations** enter directly into force in national law in Member States
- **Directives** bind Member States to achieving particular results but allow national governments to decide on the way in which they are implemented.
- **Decisions** are binding in their entirety and are often used to commit EU Member States to international agreements.

The main areas covered by legislation are: Air quality and emissions; Hazardous substances; Water quality, pollution and treatment and particularly detailed legislation covering Waste Management practices. Commenting on the UK experience **Mumma** (1995) points out that 'The main body of environmental law is currently contained in a few major statutes and judicial decisions.' and summarises it in the following manner:

The Environmental Protection Act 1990 (EPA) makes provisions for integrated pollution control, a comprehensive system of waste management, and statutory control over genetically modified substances. The Water Resources Act 1991 and the Water Industry Act 1991 contain the law on water pollution control while The Clean Air Act 1993 deals with the law on dark smoke emissions. In 1995 the introduction of the Environment Act changed the administration and responsibility for the enforcement of these laws with the separate bodies being brought together into The Environment Agency.

The main driving force behind the legislation are the penalties imposed if the law is broken. This in itself drives industry to make environmental considerations. Other laws such as Landfill Tax and Integrated Pollution Control are also pushing industry to take a more serious attitude towards the environment. But perhaps the biggest step in legislation is the move towards the idea of 'the polluter pays' which is already being introduced in a number of European countries. The main principle is that the producer becomes responsible for the product after disposal 'with a movement to return products to the manufacturer at the end of their useful lives.' **Devon** (1993).

It is strategies such as this which will push manufacturers to use materials which are recyclable and to assemble them in such a way that they can be easily disassembled at the end of life. Legislation rather than being a negative aspect of environmental management and design, can be, if interpreted and anticipated correctly, the perfect platform for innovative change within industry.

Through the introduction of legislation and a shift in consumer perception the demand for environmentally friendly products and processes is increasing. Recent legislation shows a general shift towards improving industries environmental performance and, as with most legislation, the incentive is financial. Fines and levies will be imposed on offenders and in some cases operations may be closed down.

Figure 1.1 summaries the regulatory process which is being put in place, to improve environmental performance and keep industry competitive *(Taken from 'Towards Sustainability')* **Warmer** (1996).

Many of the strategies that industry will have to adopt as a result of this legislation make good economic and business sense. It is clear that those companies that can, and do, ride the environmental tide will prosper; those that ignore it will surely suffer.

Legislation is constantly changing and being updated, however more detailed information on environmental legislation may be found in books such as those by **Mumma** (1995) and **Leeson** (1996) and papers such as those by **Hermann** (1994) & **Holloway** (1997).

1.4 Future Responsibilities

Burall (1991) argues that 'now legislation to alleviate environmental problems is being introduced in many countries, the effect on industry world-wide will be increasingly apparent.' This is undoubtedly true and environmental consideration will no longer be a moral decision on

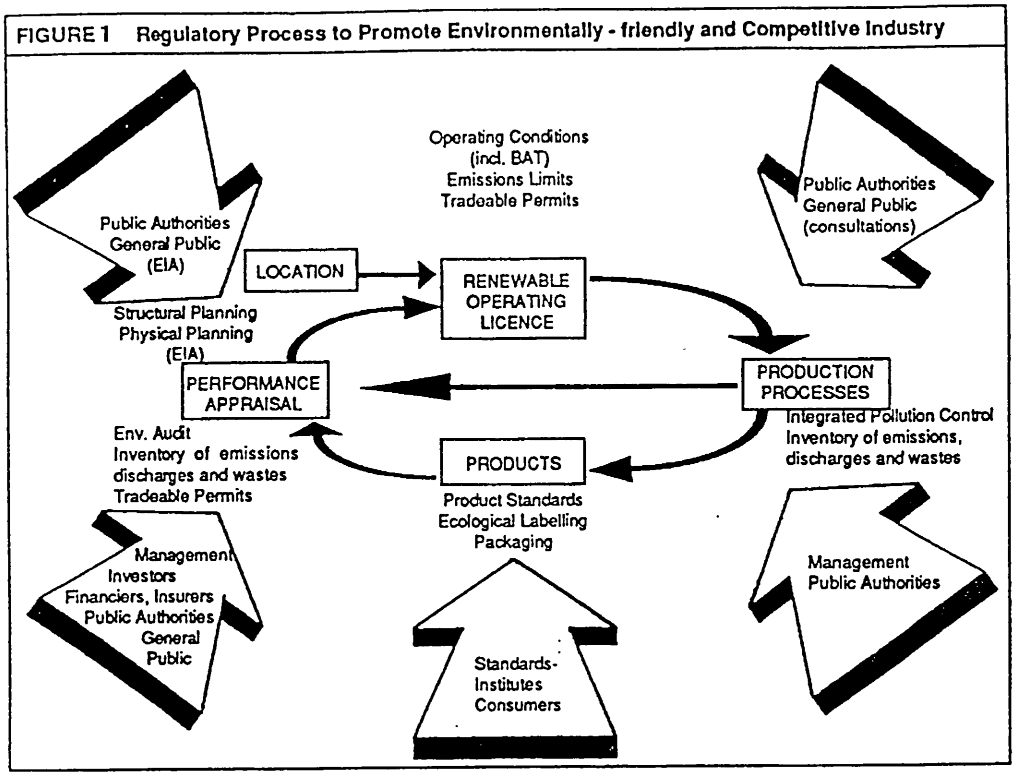


Figure 1.1 The Regulatory Process to Promote Environmentally Friendly and Competitive Industry

the part of individuals within organisations but will become a whole philosophy in itself. **Duncan** (1995) identifies the first main step we need to take as 'The first step towards a solution is simply recognising the source of the problem.' This is the first step in the move towards sustainable development which will not be easy. **Dewberry & Goggin**(1995) point out that as a target, sustainability 'consists of a broad range of external material and cultural factors' and it is this which will be the biggest hurdle to overcome. It is, however, possible at this stage to identify future responsibilities for engineers and industry as a whole. The **Engineering Council** (1994), suggest that engineers have a responsibility for ensuring that:

- their own perception of environmental problems is as accurate as possible
- they are able to analyse different aspects of a problem and address the whole issue, not

merely the point source problem;

- they help reduce the imprecision and uncertainty associated with environmental issues, by communicating using simple, consistent and accurate language in reports and presentations;
- they should work closely with government, business, academia, environmentalists and the public. They should learn how different participants perceive the environment and make environmental decisions, and explore how to develop and communicate solutions to common problems.
- they achieve a balance between so-called 'high tech' (e.g. photovoltaic cells) and 'low-tech' (e.g. efficient charcoal stoves) applications for resolving environmental problems, aiming at all times to identify the most *appropriate* solutions for particular circumstances.
- they identify, as far as possible, all the facts relevant to an issue and explain the advantages of alternative solutions so that these are understood by the deciding authority.

1.5 Chapter Summary

We have to learn from our past mistakes and engineers must now be prepared to attempt to eradicate or reduce existing environmental hazards and to develop a wide understanding of the impact of new developments. This chapter has outlined the pollution problems facing industry and shown that the task of reducing our impact on the environment is by no means an easy one. Some high level solutions such as auditing and legislation have been outlined and future responsibilities of industry discussed briefly.

The following chapters of this work will go on to look at how these problems are being addressed and suggest how to improve further our efforts to curb the ever growing environmental problems we face today through careful design and development of products and systems.

Chapter 2

Environmental Analysis

Environmental Analysis

2.1 Introduction

Over recent years environmental analysis has been carried out in a number of different ways. Many of these ways were very divergent and would deliver widely differing results for the same study. In an attempt to tackle this methodologies for environmental analyses have been developed and are reaching a stage of standardisation.

This chapter will look at the way in which environmental analysis is now carried out, point out some of the limitations and attempt to predict how the techniques will develop.

2.2 The Cradle-to-Grave Approach

To asses the true effect of a product or system on the environment, consideration must be given to *all* the stages of its life cycle. Focusing on just one or two of the impacts such as use or recyclability will give an incomplete and misleading picture of its overall performance. The cradle-to-grave approach acknowledges that environmental concerns may emerge at any stage of the products life cycle. A full cradle-to-grave approach will span from extraction of raw materials at source to the eventual disposal of the product (landfill, incineration or recycling). The exact impact of a product or system may be impossible to assess and many research institutions are attempting to develop cradle-to-grave eco-balance equations. It has been shown, however, that although energy consumption is relatively easy to calculate with some degree of accuracy other aspects of environmental performance are harder to establish. Attempting to compare different types of impact such as water pollution and noise is very difficult and at present no agreed set ways of comparison exist. Because of this it is very complex to compare products with different environmental profiles.

At present the cradle-to-grave approach provides a useful framework and checklist for ensuring every aspect of the product is considered. It may become practical to consider only the areas of greatest importance and ensure the performance of the others meet certain standards.

The most widely used technique for conducting 'cradle-to-grave' studies is Life Cycle Analysis (LCA). LCA is basically an accounting method which will assess a given attribute or group of attributes over the whole life-cycle of a product or system. It can be used to assess many facets of a product but is usually linked with the assessment of environmental effects, and so in many cases it is called Environmental Impact Assessment.

2.3 Environmental Impact Assessment & Life Cycle Analysis

Environmental Impact Assessment (EIA) and Life Cycle Analysis (LCA) are given many names, 'Environmental Assessment', 'Environmental Cost Attribution', 'Eco-balancing' and 'Cradle-to-Grave Assessments'. These are all terms which refer to a process described by **Lein** (1992) as 'a decision making process that attempts to define the environmental consequences associated with specific human action before that action is taken, and potentially irreversible adverse environmental changes result'. This is very much an ideal definition, in that in many cases the EIA or LCA is carried out in retrospect thus only highlighting an existing problem. Some see EIA as a separate and integral part of LCA, in that LCA has been defined by **SETAC** (1991) as 'The life-cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material usage and environmental releases, to assess the impacts of those energy and material uses and releases to the environment, and to evaluate and implement opportunities to effect environmental improvements. The assessment includes the entire life-cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing transportation, and distribution; use/re-use/maintenance; recycling; and final disposal .' **Rowcliffe** (1991) has argued that 'LCA is likely to become the most influential environmental management tool of the 1990's.' Although SETAC have attempted to standardise LCA it is still seen as 'a developing technique without a universally accepted methodology.' **Holloway** (1991) and it has also been shown by practical application that 'Some of the best known examples of Life Cycle Analyses are those for which the findings have been hotly contested.' **Holloway** (1991)

2.3.1 LCA Techniques & Studies

As relatively little is known about the effects on the environment of certain systems and their associated outputs, LCA or EIA can be used as a guidance tool to investigate and define ways of reducing that burden. Such studies may provide the basis for a wide range of further work, for example;

Eco-Labelling Schemes
Waste Minimisation Initiatives
Pollution Prevention Programmes
Eco-Design
Energy Conservation etc.

At present LCA is a developing science without a universally accepted methodology thus different studies may deliver different results. When developing methodologies it is important to remember the limitations of the process and the possible conflict of aims. However a study of current LCA Methodologies adopted by different schemes, **Beevers**(1993), **Russel** (1992), **Richards** (1992), **Boustead** (1992), **Boustead** (1992), **Shaw et al.**(1992) has revealed that there is a common trend developing.

2.3.2 Carrying out an LCA

In order to carry out an LCA study all the stages of the system must be included from extraction of raw materials to final disposal. A complete LCA involves three main steps **Boustead** (1991):

1. measuring or calculating an inventory of the inputs and outputs from any industrial system,
2. identifying the link between the measured inputs and outputs and the environmental parameter of concern,
3. Finding a solution to the problem.

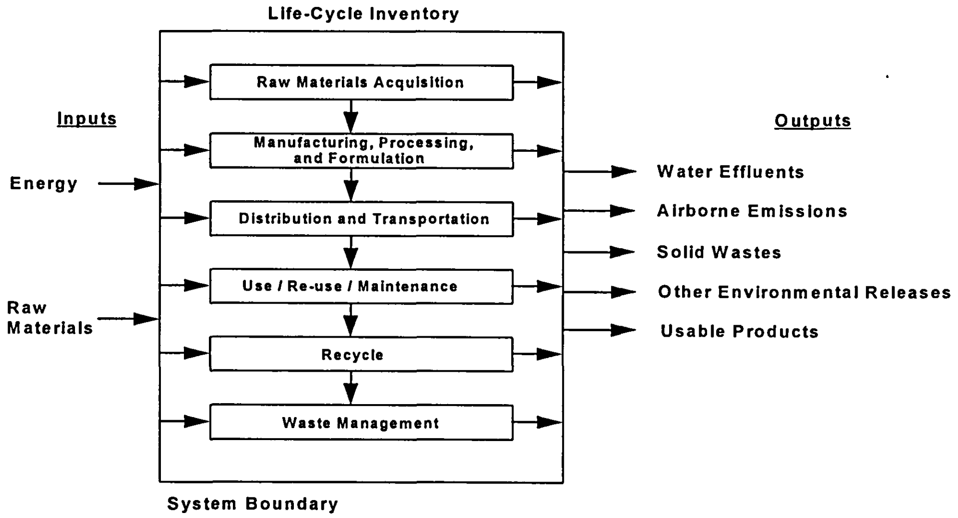
Fussler (1993) has proposed that LCA studies consist of four basic elements known as the 4 I's:

1. Initiation - define the scope, goal and system boundaries of the study
2. Inventory - carry out an LCA study of the product system
3. Impact - classify all the relevant environmental data and calculate actual environmental effects
4. Improvement - having identified the areas for improvement, modify the design specification.

Although it is accepted that LCA is still a developing discipline the most widely used standard is that developed by SETAC and shown in figure 2.1

The scope of the LCA should include all the feedback loops which are apparent and deal with both energy and material flow. As can be seen each process is a sink for either energy , materials or both. 'The core idea is to analyse the estimated life-cycle cost of the product..' **Ishii & Mukherjee** (1992), in this case the cost is to the environment.

Once an LCA study has been carried out and all the stages of the complete cycle, including inputs and outputs identified, Environmental Impact Assessment (EIA) may be utilised to assess the true cost of the product to the environment. EIA may be seen as a separate discipline but is an integral part of any LCA study. The inventory stage of an LCA will identify all the raw materials used, energy consumed and products discharged into the environment within the boundaries of a specified system. To make use of the results they are categorised into actual effects on the environment. Figure. 2.2 shows how an EIA will address the impact analysis stage of the life cycle assessment. By grouping the different emissions and wastes generated by a product system an EIA is able to present the amount of resource depletion, acidification of water or atmosphere, ozone depleting emissions etc. and allows more meaningful interpretation of LCA results. It must be remembered, however, that grouping data in such a way may lead to valuable detail being hidden. Therefore it is essential that all the discrete data is available to the concerned parties as well as any results that have been grouped or aggregated.



A Technical Framework for Life-Cycle Assessments, SETAC Foundation for Environmental Education, Inc January 1991

Figure 2.1 The SETAC LCA Framework

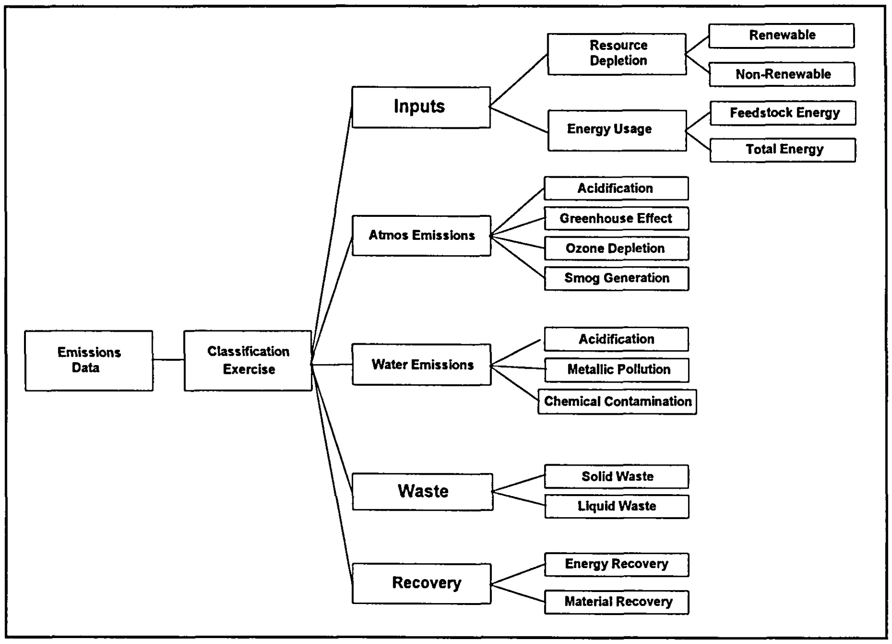


Figure 2.2 Grouping Emissions using an Environmental Impact Assessment

2.3.3 Stages of an LCA

All LCA studies, independent of which method is used will involve the following stages:

2.3.3.1 Study Definition

Before undertaking any assessment study it is vital that the participating body understand what can and cannot be achieved and how to achieve it.

Firstly the end objective must be clearly defined. The statement of the end objective should cover all the stages of interest be they Cradle-to-Grave or otherwise and most importantly be non-ambiguous. The sensitivity of the systems should also be defined e.g. Insignificant emissions of less than say 5% may be omitted. As already mentioned different studies deliver different results and recommendations, thus an end objective is needed to aid development of the correct methodology and present the results of the study in the correct context.

After documenting the end objective the difference between the system and it products should be stated and the system boundary defined. A system is a 'collection of operations which together perform some defined function and a product is the output of that system' **Boustead** (1991). The system consumes energy and raw materials. The system environment is 'the source of all the inputs and sink of all the outputs. In a true life-cycle analysis there is no useful output'. **Boustead** (1991)

The definition of the system boundary is very important as all consumption's and emissions occur within that boundary. Without proper definition the study may become 'lost' or 'meaningless' and the results obtained cannot be held within the appropriate context. 'The choice of system, the definition of its boundaries and the identification of the component sub-systems are the most difficult problems faced by the analyst' **Russel** (1992) The system environment may be represented as in Fig. 2.3

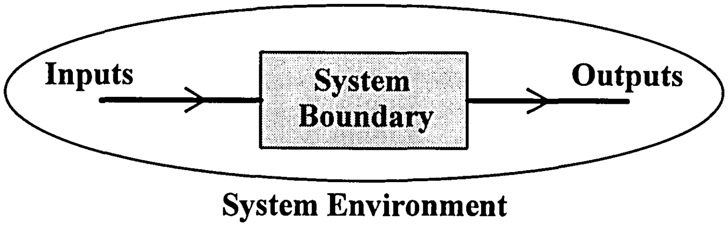


Figure 2.3 Definition of System Boundaries and Environment

The definition of the system boundary will involve elements such as :

1) Which wastes to include and in what order, impact measure, (toxicity etc.) quantity or regulatory category.

2) Impacts of associated activities.

3) Consideration of avoidable impacts.

4) Economic impacts (if applicable).

5) First, second or third order energy analysis.

2.3.3.2 Methodology

After clear definition of the system boundaries and its end objective, the methodology of analysis must be considered. At present there is no standard LCA methodology but those which have been used **Holloway** (1991), **Assies** (1992) and **Russel** (1992) show strong similarities and a definite *'direction'*.

The starting point of any methodology should be the construction of a detailed flow chart. The details identified in this chart should correspond only to operations for which data is available, (defining steps with no known data can lead to a break down of the methodology).

A methodology can be separated into the following operations;

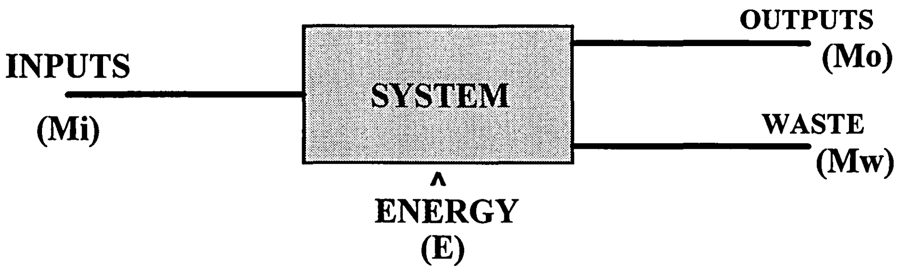
1) Definition of Objective and System Boundaries.
2) Construction of Flow Chart.
3) Collection of Data.
4) Assessment of Data.
5) Calculation.
6) Results Analysis.
7) Presentation of Results.

Each of these steps is equally important if the methodology is to succeed.

When completed the flow chart may be turned into a material balance. At this stage the importance of defining the system boundary becomes apparent. Without overall boundary of the system there are an almost endless series of sub-systems each with their own boundaries and material balances are needed across each and every sub-system boundary. As seen in figure 2.4 although potentially very complex, the material balance may be simplified somewhat and consists of, basically inputs and outputs.

2.3.3.3 LCA Data

When finalised the flow chart will be the guide for data collection. Each of the stages in the diagram should be taken separately and the relevant data collected in as much detail as is needed or is possible. Once again there is no fixed method for data acquisition but there are two main approaches; Primary and Secondary Acquisition.



Mass Balance : Mi = Mo + Mw

Normalised waste output = Mw/Mo

Normalised system energy = E/Mo

Normalised raw materials = Mi/Mo

Figure 2.4 Material Balancing

Primary data acquisition (PDA) is actual monitoring of processes etc. This may be very expensive and time consuming but can be made easier by the use of data questionnaires. Questionnaires of a fixed format are distributed to manufacturers and completed by the specific company carrying out that particular process **Boustead**(1991). It must be noted that data gained by these means may not be of the required integrity and quality if the questionnaire study is not monitored.

Secondary data acquisition (SDA) is the use of collated information resulting from the studies mentioned above. Until recently data of good integrity had been difficult to find but as LCA becomes more common place the required data will become more readily available. **Boustead** (1992), **Habersatter** (1990), **Steinhage** (1990) and **Geodkoop** (1992). It is very important to use a recognised source for study data. There should also be a certain amount of information available concerning the data used such as:

- type of process (technology, system boundaries)

- type of information (annual mean value for branch, industry average, random sample etc.)
- the age of the data
- source (The industry itself, environmental authority, literature etc.)
- the representivity of the data (best, worst or average technology)
- how allocations have been made (per kg, per tonne, per MJ etc.)
- the completeness of the information (have all emissions been included; what is missing; which substances are most common in the summation parameters).

'To control the completeness of the information requires a degree of knowledge within the field' **Chalmers** (1992).

2.3.3.4 Data Assessment and Calculation

The data assessment is the core of the LCA and the criteria on which the data is to be judged will have a great bearing on the outcome of the study. Single Criteria options have been adopted, as in the German *'Blue Angel'* Eco-Labelling Scheme, but it is becoming obvious that such approaches are too simplistic 'As the complexity of real systems increase the inadequacy of a single criterion methodology to help decision making has been widely admitted'..*and...*' Decision making consists of the comparative examination of more than one alternative action.' **Diakoulaki & Koumoutsos** (1991)

If the comparison is based on only one simplified criterion, or there is no comparison being made, then the calculation of the data is simple. It is collected and represented in the appropriate manner. (see 2.3.3.6 Presentation of Results).

The problem which arises with Multiple Criteria Analysis (MCA) is the confliction of the different impacts and the essence of a good methodology is one which resolves this. MCA has been in development over the past 15 years and today appears as one of the fastest growing areas in operational research, **Diakoulaki & Koumoutsos** (1991) & **Eyerer** (1991), providing a great variety of methodological tools to deal with vastly diverse problems.

As with all LCAs it is very unlikely that a single product or process will be assessed. The real advantage of LCA is in comparative studies aimed at finding the best alternative for an application or, at a lower level, the best material / processing for a product. (*'Best'* implies resulting in the lowest environmental impact). The bare methodology of calculation is straight forward and simple but an extension of the method is used in MCA This method involves evaluating the differences 'which exist among the performance of different actions with reference to the spread of scores observed at a given criterion', **Diakoulaki & Koumoutsos** (1991).

2.3.3.5 Analysis of Results

The analysis of the results should include an ' evaluation of the reliability of the LCA as well as an analysis of the environmental profile' **Assies** (1992). It must be noted that many LCA results do not relate directly to environmental issues and must be interpreted with great caution. There is currently no accepted way to present the results of a study, but the essential elements of what is necessary are becoming clear.

A large number of parameters need to be described fully, the energy and raw material requirements as well as solid waste and emissions to air and water should be included. This data forms the basis of the required complete description. Combining data to reduce the number of parameters seems the sensible way forward if we are to present results which are comprehensible to non specialists. It is often meaningful to add data together for variables which are measured in the same units, but it must be recognised that although summation may simplify matters it may also may hide much of the detailed and valuable information.

2.3.3.5.1 Aggregation of Results

Aggregation or summation may clearly be applied to economic aspects and energy consumption but in considering emissions to the environment the approach is less than clear.

Some past LCAs have summed together all emissions to the atmosphere and water thus giving the same impact weighting factors to very different emissions. 'This is obviously not satisfactory but an ideal system is hard to define' **Holloway** (1991).

Weighting factors may be introduced, such as aggregation used in pollution classification, **Porteous** (1992), EC Directive 76/464/EEC (1982) and **Horvath et al.** (1995) and emissions then added together to give a total contribution to the environmental problem. However, for many emissions the environment effects are varied and summation would be a complex and inaccurate exercise. While a quantitative risk assessment can be appropriate and necessary in gauging the effects of a particular product it would be an impractical exercise to produce similar results for every emission for every step of a life cycle.

Currently the grouping which is used in LCA studies takes emissions to like media (i.e. emissions to air or emissions to water) utilises a form of weighting factor for each specific emission (e.g. carbon monoxide or nitrogen oxides) and produces groups of summed emissions such as:

- Energy Usage.
- Units Polluted Water (UPW)
- Units Polluted Air (UPA)
- Units Acidification (UA)
- Solid Waste (by weight or volume)

For example UPW would be calculated using the following equation:

$$UPW\,(\mathrm{m}^3) = \sum_{n}^{1} \frac{Ammount\ of\ Emission_x\,(mg)}{O.V.D_x\,(mg\,/\,m^3)}$$

Where:

x is the emission (e.g. heavy metals) and n is the total number of emission to water

UPA would be calculated using the following equation:

$$UPA(m^3) = \sum_{n}^{1} \frac{Value\ of\ Emission_x(mg)}{MAC_x(mg/m^3)}$$

Where:

x is the emission (e.g. SO_x) and n is the total number of emission to air

O.v.D norms are '...Dutch norms for maximum levels at the inlet of drinking water into purification plants'. (In this work we are using the Dutch definitions as they are readily available, but other documented legislative data may be used as it may vary from country to country).

MAC values are '...the definition of acceptable levels in working conditions by the Dutch Labour Inspection', **Goedkoop & de Keijser** (1992) and are used for airborne emissions. If we define polluted air or water as air or water which is lost to human consumption without first needing treatment, then the MAC and O.v.D values offer comprehensive data for calculation. These parameters will give an environmental profile of the product and processing which may be assessed with relative ease. Where justified by its importance, a more detailed analysis of one or more streams may be appropriate for a second more in-depth study.

If summation is considered to be too simplistic the most satisfactory approach may be to identify the environmental problems that need to be considered and collect only the appropriate data for analysis. A balanced course for the first pass of an LCA is :

- Note quantitative data for emissions.
- Sum data only where meaningful to do so.
- Note general environmental characteristics such as toxicity or persistence of material.
- Assign non-summable emissions to broad risk categories.

2.3.3.6 Presentation of Results

When presenting the final results of a study it is of the utmost importance to show the actual system and its boundaries such that the results may be viewed in context.

The results may be presented in many formats the two most useful of which seem to be:

1) Tables of actual data. - Table 2.1

2) Graphs representing data - Figures 2.5 and 2.6

The overall results presentation will consist of a table of listings giving emission name, whether to air or water and actual amount emitted. Any waste products produced should be listed and disposal routes outlined. E.g. If waste is to be recycled by incineration, and energy recovery applied, it should be stated whether this energy gain has been included in the overall energy balance calculation. Also included should be a list of materials / components for which no environmentally relevant information is available.

Waterborne Emissions (mg)	
Ammonia	0.005
BOD	70.3
COD	929
Cyanide	0.0109
Dissolved Organics	35.3
Dissolved Solids	384.5
Fe	1.0899
Fluorides	0.015
Fluorines	0.3609
HCl	20
Hydrocarbons	322.8
Lead	0.005
Metals	646
NH_3	0.0693
Na	0.001661
Nitrates	0.05021
Oil	148.8
Other Nitrogen	11.8
Phenols	0.00327
Phosphates	0.048
SO_4	0.00036
Suspended Solids	417.9
Tar	0.01

Table 2.1 Table of Emissions Data

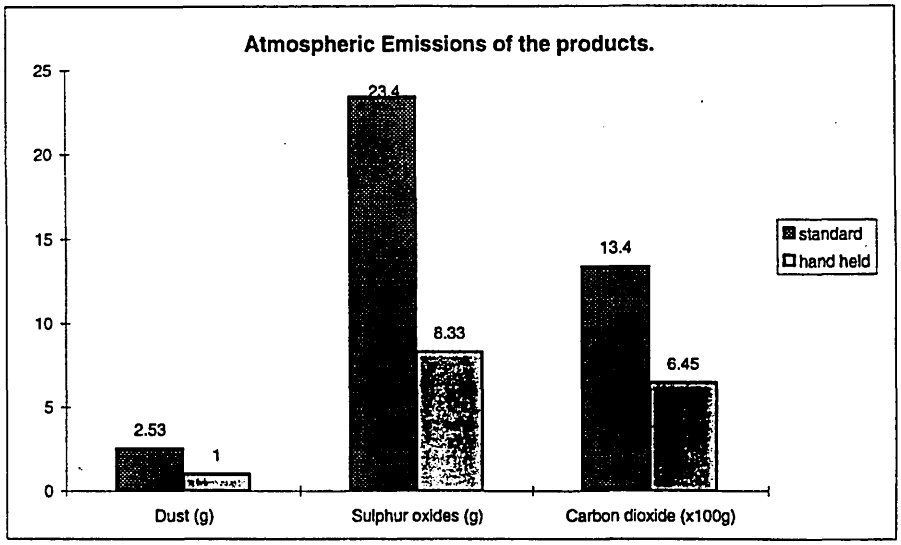


Figure 2.5 Graphical Representation of Atmospheric Emissions Data

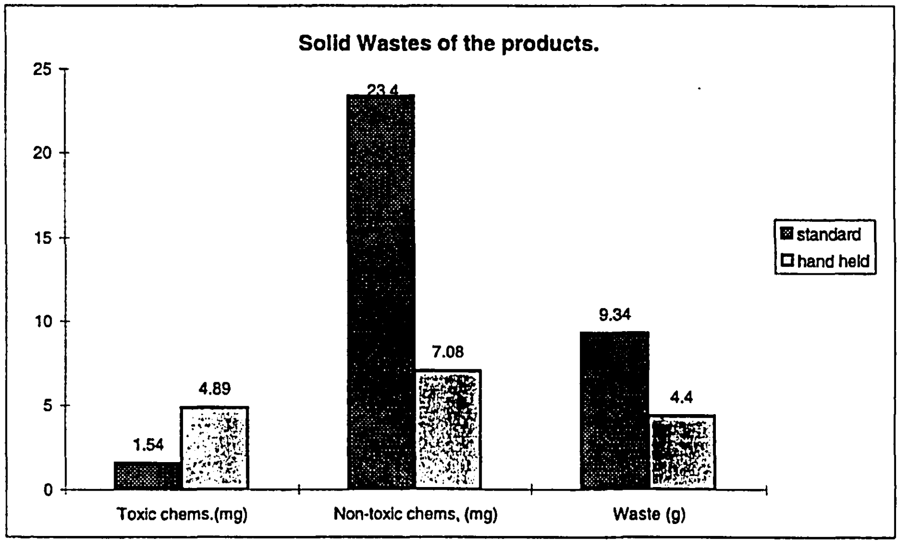


Figure 2.6 Graphical Representation of Solid Waste Data

If emissions have been summed and grouped, the group headings and values should be listed. A graphical representation of these groupings can aid assessment of the system especially if there are two or more products being compared.

It is of utmost importance if a grouping exercise has taken place, that a fully documented table of ungrouped emissions is presented. This will stop any vital detail being hidden from the data used in the summing exercise.

2.3.4 Limitations of LCA Studies

There are a considerable number of limitations and problems which may arise while undertaking an LCA study. These problems may occur during any and all stages of the exercise.

PREPARATION

- Definition of the end objective and system boundaries must be full and accurate.
- An understanding of how the LCA has been conducted is essential to a proper understanding of the results.
- The flow charts constructed to represent systems must be comprehensive and accurate.
- Reliability of data may not be 100% especially if elicited through a second party.

METHODOLOGY

- Emissions which occur over a long period of time are difficult to assess. E.g. Emissions arising from landfill.
- Non-renewable resources consumption is near impossible to assess at this time.
- Many assumptions used in the study are not supported by evidence.

RESULTS

- Summation of non-appropriate emissions can lead to conflicting results.
- There is a temptation to force results to a bottom line conclusion, which can lead to results being harder for non-specialists to understand

2.3.5 The Future of LCA

Overall discussions on LCA methodologies seem to be pointing towards a general method which is bringing together the underlying similarities in present work.

That LCA is still in development does not imply that the full development of LCA methodology has to be awaited before any further studies are carried out. A general framework for LCA will bring more transparency to the routes that may be followed in conducting such an exercise and give more impetus to the results, **Assies** (1992). Guidelines relating to different applications of LCA should also be considered.

Although LCA is not a fully developed science the results being delivered are allowing us to learn more about product life cycles and their effect on the environment and may result in a positive impact on the development of new products.

2.3.5.1 Simplification of LCA

Billett (1996) has shown that the future of LCA may be the use of abridged or streamlined methods. By making a number of assumptions the method of LCA may be simplified greatly.

Billett shows that typical assumptions may be:

- using expert judgement, ignore any part that is less than 5 per cent
- exclude leachate from the disposal phase
- exclude any other than first order problems during extraction
- use generic data where actual data is not available

He then goes on to offer a practical approach to LCA as:

- if data is available use generic data
- if data is missing use parallel study data if available
- If data cannot be found use related data you can obtain to make an engineering estimate of the missing data
- If worst comes to worst use price as a basic metaphor for environmental impact.

All these assumption will obviously have a large impact on the results of the LCA study but as **Billet** (1996) points out 'Although the assumptions made to streamline the life cycle analysis must surely reduce the accuracy, one comes to realise that this is probably not all that important because of the somewhat arbitrary nature of LCA in the first place'.

2.6 Chapter Summary

Given that agreement can be reached on the main stages of the Life Cycle Analysis, and this looks very likely, LCA will emerge as an extremely useful tool in future design and production exercises and should influence a wide ranging section of industry from packaging manufacturers to civil engineers.

As this chapter has shown LCA is a complex but comprehensible tool which has an essential place in environmental assessment and improvement studies. The technique is still under development and has a number of limitations but standardisation is occurring and the tool is becoming more widely used. Although through simplification of the method it may become more widely adopted.

Whether it is called LCA, EIA or cradle-to-grave there is one thing that is certain about this type of study, it is now an integral part of any environmental management or environmental improvement programme. As **Fouhy** (1993) points out 'Once dismissed as a public relations ploy by environmentalists, LCA has become scientifically rigorous, providing a way to de-fuse environmental debates by answering emotionalism with data.' This is certainly true but this rigorous scientific approach may be the downfall of LCA. A balance must be struck between practicality and accuracy.

Chapter 3

The Development of Environmental Design

The Development of Environmental Design

3.1 Introduction

In the past environmental concerns were very often dealt with in retrospect. The problem was only addressed after the event, using techniques such as LCA and EIA, and as a result was much more difficult to rectify. Modern design and manufacturing techniques now attempt to address problems before they occur through careful consideration of the whole life-cycle of a product or system. This philosophy is characterised by the shift in recent years from analysis to prevention in many aspects of engineering. This shift has been brought about by the recognition of the disadvantages of traditional design practices and has lead to the development of concurrent engineering.

3.2 Concurrent Engineering

'Concurrent engineering grew out of the recognition that the traditional sequential approach to the design and manufacturing process has serious drawbacks when applied to the modern day product market place' **Barker** (1995).

A large portion of a product cost is determined at the design stage hence organisations can benefit by adopting a concurrent approach to pinpoint problems at this stage. **Sohlenius** (1992) characterises concurrent engineering (CE) as 'a way of work where the various engineering activities in the product and production development process are integrated and performed as much as possible in parallel rather than in sequence', as does **Carter** (1994).

There are many considerations that may be addressed at the design stage. In, for example, a mechanical based product these downstream fields will include areas such as manufacture, assembly and so on. Financial cost is always an important consideration. **Cha & Guio** (1993) look at the way in which design decisions can affect the overall life-cycle cost of a product.

3.2.1 CE and the Environment

In the past environmental problems and design and manufacturing were treated very much independently with little or no concern given to the environment during the course of product development. As our understanding and awareness of these problems develops it is becoming apparent that design and manufacturing can have a very immediate effect on the environment. It has been accepted for many years that design dictates a large proportion (up to 70%) of a products cost, **Andreasen et al.** (1983), and it is not unreasonable to appreciate that a considerable portion of the environmental life-cycle costs are also directly affected by the design process. By consideration of the potential problems before they arise designers may 'significantly reduce life-cycle expenditures, be they financial, environmental or otherwise.' **Holloway et al.** (1994). This approach will eventually replace the current 'end-of-pipe' measures which have been the traditional way of dealing with environmental problems. Figure 3.1, **Eco2-Irn** (1994), shows how only 20% of the environmental impact of a product can be addressed using end-of-pipe measures. (Interestingly it also claims that 80% of environmental damage is caused by only 20% of the products currently in use, although these figures are not linked to the former in any way). Most 'environmental engineering' however still focuses on waste treatment processes and it has become clear that adopting an approach which attempts to prevent pollution and waste during the design stages can be much more effective ,**Hendrickson et al.** (1994). The integration of environmental concerns into the framework of CE is given many names but is commonly known as 'green' design.

3.3 What is Environmental Design?

Terms such as Environmental Design, 'Green' Design, Design for the Environment and

Environmentally Conscious Design are used alternatively to refer to a concept which has been defined as:

'Design carried out within current product development frameworks, that addresses all the environmental impacts associated with a product or system throughout its complete life cycle, with a view to reducing these impacts to a minimum but without compromising other criteria such as function, quality, cost and appearance.' **Eco2-Irn** (1994)

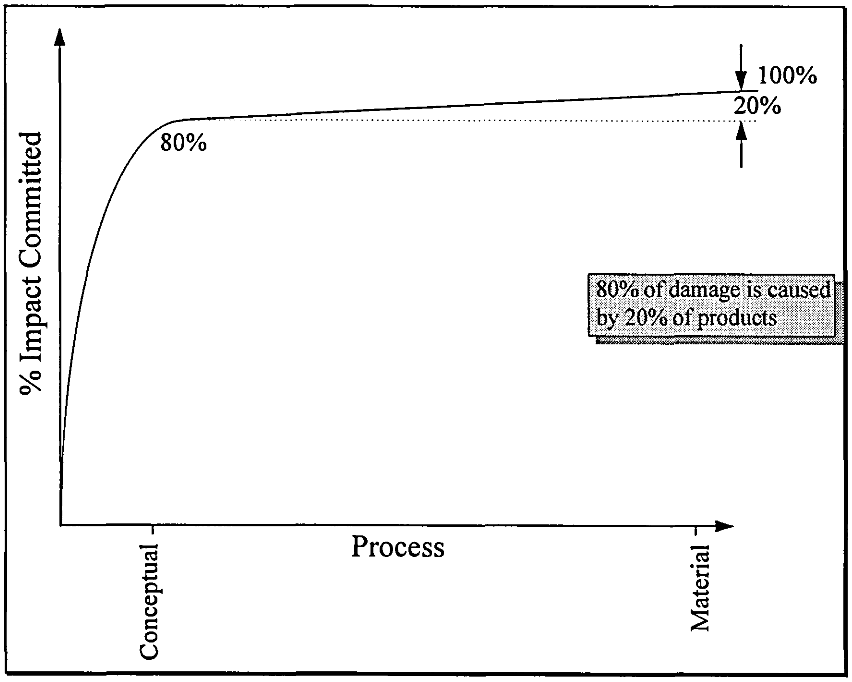


Figure 3.1 Effectiveness of End-of-Pipe Measures Eco2-Irn (1994)

When using the different terms relating to environmental design it is useful to specify their place within the move towards sustainability. Figure 3.2 shows how different terms are used to describe different types of environmental design and how they relate to each other.

From this figure we can see that there are a number of different design practices and philosophies used, having different names and different places within the whole scope of sustainability.

3.3.1 Green Design

Green design is the simplest form of environmentally conscious design. As can be seen from figure 3.2 it can be a number of different things but usually focuses on single-issues, **Werner**(1993). For example, hairspray manufacturers now claim to have green hairsprays because they no longer contain CFCs. Detergent manufacturers claim 'green' products because they use bio-degradable surface agents and some product manufacturers claim 'green' design as they use recycled materials in their packaging. Though a step in the right direction, this is not a definitive solution. A green design can contain one or a number of single actions that go towards altering the product's environmental impact.

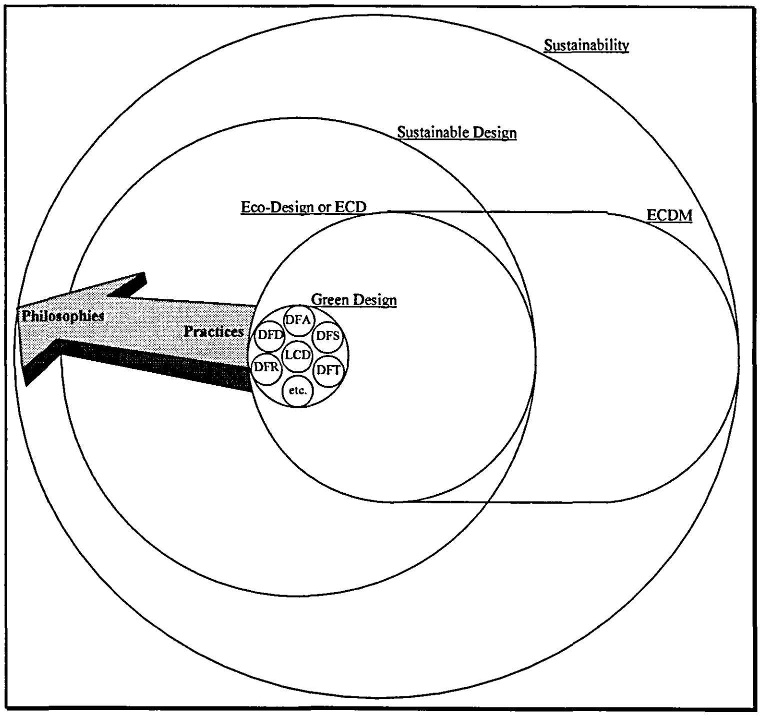


Figure 3.2 Relationships between Design Practices/Philosophies **Eco2-Irn** (1995)

Most of these actions can be seen as design for 'X' where X is a focus such as quality, recyclability or disassembly. Application of each of these DFX strategies will have specific environmental implications and gains.

3.3.2 DFX

Much work has been carried out in this area, the most well established being DFA, **Lund & Kahler** (1985), **Bralla** (1986), **Boothroyd & Dewhurst** (1987). Each is a technique which slots into the design process at some stage. Although some of the DFX techniques are not specifically related to the environment, taking the environment into account when applying these techniques may result in environmental gains. However, practising all of these techniques, will not necessarily produce a completely environmentally sound product. Practising one, or a small number of these environmentally potent techniques is said to be practising Green Design.

McAloone & Holloway (1996), suggest that 'The way in which these environmental requirements can be considered in design is to add them predominantly to the natural flow of the design process in the form of environmentally weighted DFX steps'. They also present a design model detailing this inclusion of DFX steps as shown in Figure 3.3.

At each stage of the design process many considerations must be made between different functions within the organisation and the designer may have a DFX hurdle to overcome. Each of the DFX disciplines will have particular significance at different stages of the design process.

This adds a new task to the designers schedule and may appear to add to the design time, but is argued by **Jones** (1992) that it can be seen as being cost & time saving, and a quality enhancing activity in the long run.

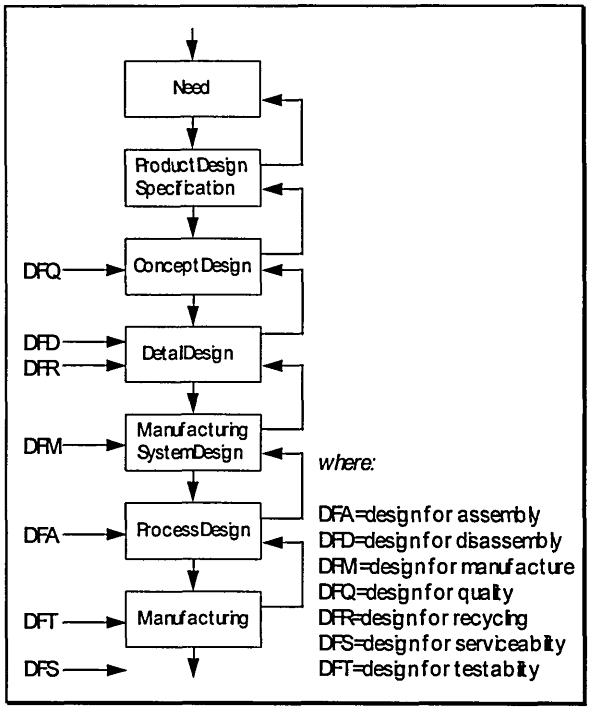


Figure 3.3 Example of the Application of 'DFX' to a Design Process

3.3.2.1 Environmental Implications of DFX Strategies

As each of the DFX strategies is applied to the design process they will result in specific environmental gains.

3.3.2.2 DFA

The concept of Design for Assembly **Boothroyd** (1982) is that all the discrete component parts within a product will be designed so that they are easily assembled and the assembly related cost is significantly reduced. In terms of the environment design for assembly will reap certain benefits. DFA will reduce the amount of energy used in assembling a product. In some instances it will also mean that the product is more recyclable because there may be a reduction in mix of materials and fasteners used may be of the snap-fit type which speeds up assembly but also can aid disassembly.

3.3.2.3 DFD

Design for Disassembly involves developing products which are easy to take apart and thus facilitate recycling and removal of hazardous materials, **Hanft & Kroll** (1995), and is thus closely linked to DFR, **Wilder** (1990). By promoting recycling waste is reduced and the consumption of raw material is decreased. DFD typically results in less bonding of dissimilar materials and the use of non permanent fastenings. Many methods for DFD are in development such as the method proposed by **Simon** (1993) in which a decision tree is used in conjunction with design indices.

3.3.2.4 DFM

Design for Manufacture or Manufacturability aims at reducing product development times by avoiding design errors and features difficult to machine before process planning begins, **Hyeon et al.** (1991). By considering this the amount of energy and time used to manufacture a product is reduced. The amount of waste produced will also reduce as a consequence of the careful planning. These aspects have obvious environmental advantages.

3.3.2.5 DFQ

Design for Quality, **Hubka** (1989), is another developing DFX discipline. Again it aims to reduce the amount of errors made during the design, production and ultimately use of a product. DFQ can be seen as an overall design concept as it is a very wide ranging discipline. By designing for quality products will last longer and be more reliable. In turn this will reduce the amount of maintenance needed over their life-cycle and in many cases increase that life-cycle significantly. The environmental effects are again very significant. Reduction in materials and energy use, increase in life expectancy etc. all of which will reduce pollution and life-cycle environmental burdens.

3.3.2.6 DFR

Design for recyclability, **Leach** (1990), recognises that eventually every product will wear out or become obsolete. Although many of the materials used in manufacturing are from non-renewable sources difficulties in retrieving and re-using them has lead to their disposal in landfill sites. New technologies are enabling an increasing number of materials to be successfully recycled, be it directly or indirectly. To successfully design for recyclability a number of points must be observed:

- Reduce number of different materials used
- Avoid use of composite materials
- Replace toxic materials with non-hazardous alternatives
- Reduce complexity of products
- Promote infrastructures geared towards recycling

The ease with which consumers may deposit this waste for recycling contributes greatly towards its success.

3.3.2.7 DFS

Sometimes referred to as design for reliability and maintainability, **Dewhurst & Abbatiello** (1996), the discipline of Design for Serviceability is one which many manufacturers are taking on board. The trend of disposability is now being discouraged, **MacKenzie** (1991) and consumer are demanding better quality longer lasting products. By careful design products may be easy to service, with the 'disposable' being easily, quickly and cheaply replaced. By designing in this way the amount of materials and energy used by a product throughout its life-cycle may be reduced.

3.3.2.8 DFT

When manufacturing products, if they are not tested at regular intervals faults can be very difficult and expensive to rectify when they are brought to light. By designing for testability, **Drury** (1996), problems which do occur are highlighted early on in the process and are easily addressed. If a computer, for example, is not tested until it has been fully assembled then any fault which occurs will require time, materials and energy to rectify as the whole machine may need stripping down.

3.3.2.9 DFE

The final DFX strategy that can be applied is Design for Environment. This is a broad approach which considers the impacts of a product throughout its entire life cycle, **Fiskel & Wapman** (1994). Some see DFE as an explicit DFX step whereas others see it as an implicit part of carrying out a number of environmentally related DFX steps. In practice DFE imposes on designers the need to consider a products manufacture, distribution, use and ultimate disposal. Some see DFE becoming a responsibility of designers to make choices that are ecologically sound, **Eekels** (1993).

The concept of DFE and its relationships with DFX disciplines will discussed in greater detail later in this work.

3.3.3 Eco-Design/Environmentally Conscious Design (ECD)

These two principles are thought to be one and the same. The difference here is that design considerations are flavoured from the very conceptual stages so that the product is developed in an environmentally conscious manner. Again this area has become particularly active in recent years, **Dewberry & Goggin** (1995), **Potter** (1991) & **McAloone & Evans** (1995). There are not simply physical design mileposts (although these may still exist), but in Eco-Design/ECD the environment is considered inherently at each stage of the design process. This may be achieved by corporate strategy; decision-making tools; or on-line CAD tools such as that being developed by **Poyner & Simon** (1995). This fashion of design implies a shift from the original practice of cost-led design to environment-led design. (In reality, cost must still be high on the agenda, or the design would never leave the drawing board.)

3.3.4 Environmentally Conscious Design & Manufacture (ECDM)

This is the progression of ECD along the design model into the manufacturing process. Design of products also affects the manufacturing process, and ECDM should consider the environmental impact of product designs on their production processes.

3.3.5 Sustainable Design

'A sustainable product must generate capital for future generations to offset its use of non-renewable resources.' **Simon** (1995). Sustainability is more a direction than an action. We must always try and move towards sustainability, but never believe that we are there. The main question here is how can this be interpreted into a design principle? Again work is being carried out in this area and amongst others **Keoleian & Menerey** (1994), **Devon** (1993) and **Alting & Jorgrnsen** (1993) are trying to address this problem.

3.3.6 Sustainability

This is seen as being the ultimate goal; everything we consume goes complete circle, is renewable and has a further use. This is seen as being the boundary within which sustainable design fits.

3.4 The Principles of Environmental Design

For purposes of simplicity environmentally conscious design and manufacturing will be referred to from this point forward as environmental design.

Designers have a crucial role to play in achieving a more sustainable economic and social order. The complexity and importance of the designers role is highlighted by the business and ethical issues which are raised when studying environmental issues. There is a need for a holistic approach to solutions, **Sullivan & Young** (1995) & **Fava** (1993). It is of little or no use making one part of the process *'green'* if the rest is unacceptably damaging, and designers must ensure that by providing one set of solutions to an environmental problem does not create or increase others. Designers must grasp this concept fully to design truly *'green'* products as they have great influence over every aspect of the products life, from manufacture and ease of repair to use and final disposal.

'Designing for green markets and with an eye on likely future legislative demands does not invalidate the traditional criteria for good design, but it does demand that some are given different weightings and that new considerations are also taken into account', **Burall** (1991). A designer can no longer design a product in isolation from the affect materials, production route and use will have on the environment or without thinking through the implications of eventual disposal. Life Cycle Analysis, which was discussed in detail earlier, is an integral part of environmental design .

3.4.1 Using LCA for Environmental Design

As LCA is the most widely used tool or technique for assessing the whole-life environmental impact of a product or system it follows that it also widely used in environmental design. ‘Life cycle inventory results can be used to identify areas for improving product and packaging systems in terms of reducing energy usage, resource usage and environmental releases.’ **Rethmeyer** (1993).

During the eighties and early nineties public awareness of the environment grew which increased industries effort to demonstrate that their products had an improved environmental performance, **Fava** (1993). LCA was an approach which helped industry with the development of environmentally friendly products, processes and activities and thus became an integral part of 'green' design.

LCA when used in environmental design is sometimes referred to as environmental life-cycle design. This is closely linked with concurrent engineering design methods such as that demonstrated by **Shaw et al.** (1992). Life cycle design is used for a number of reasons such as reducing energy, **Shaw et al.** (1992), achieving a compatible materials balance for recycling, **Muller et al.** (1993), or generally identify improvements in the environmental performance of a product system, **Sullivan & Young** (1995).

As life cycle design can cover specific singular aspects of environmentally conscious design and manufacture, such as designing for disassembly or waste minimisation throughout the life-cycle, **Fava** (1991) suggests that it is important to 'apply a Life Cycle Inventory (LCI) framework in each product development stage,' This will allow the important environmental problems to be recognised and addressed fully. It is very important when using life cycle design methods that the key issues are addressed, **Holloway** (1996). The key to good environmental design is the identification of the main areas of environmental impact and the use of the correct design strategies in order to adequately address the problems. A good example of this is the automotive industry. Use of LCA in automotive design highlights the real environmental problem areas as shown in figure 3.4.

This graph shows that over 70% of a vehicles energy requirement is in use through the burning of hydrocarbon based fuel (Nearly 18,000 litres in an average lifetime). Other studies have suggested that the figure for in-use energy requirement may be well over 80%, **Holloway et al.** (1996). It is the usage cycle of the vehicle that manufacturers should be addressing with the greatest urgency.

In this case the recycling of materials and disassembly studies can only reduce the energy requirement of a vehicle by small amounts. Indeed it has been suggested that even if a vehicle were totally recycled the resultant net energy return would save only 5% of that used in total, **Holloway et al.** (1996).

It seems that the strategies that car manufacturers should be adopting are those of improving engine efficiency and reducing weight. **Fussler & Krummenacher** (1991) have shown that in automobile design the lightest always wins.

Many organisations have explicit goals to design environmentally conscious products, **Diaz-Calderon et al.** (1994). These organisations must use LCA or Life Cycle Design to identify the areas or greatest environmental sensitivity and thus reap the greatest rewards through adopting the correct environmental design strategies.

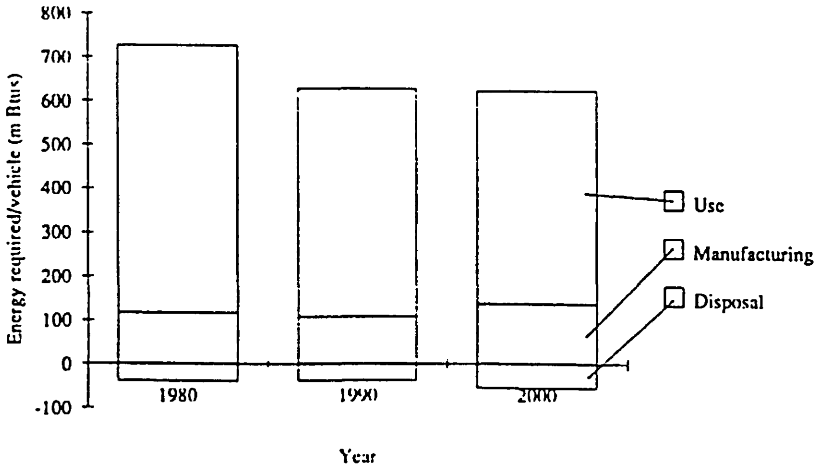


Figure 3.4 Typical Energy Requirements of Vehicles

3.4.2 Environmental Design Guidelines

There is a danger of over simplifying what makes a design environmentally acceptable. For example designing a product with a long life cycle should not mean that too long a life will prevent benefits being gained from new materials or technologies. Aiming to build in as much flexibility as is possible will reduce the risk of loosing opportunities from scientific

Guideline	Description
Consider every stage of the products life cycle in environmental terms	When designing a new product or system, or even redesigning and old one, EVERY stage of the life cycle should be considered. From extraction of raw materials at source through processing, use and on to ultimate disposal. Only by doing this can the full environment impact of a design be considered.
Increase efficiency in the use of materials energy and any other resources	One of the most straightforward ways of reducing the environmental impact of a product or system is to reduce the amount of resources consumed. These resources may be materials or energy etc. As well as reducing the environmental effect, increasing efficiency in resource usage make good financial sense.
Use recycled, renewable and biodegradable materials	Designers should make attempts to use recycled materials. With new technologies being developed recycled materials are becoming more suitable for everyday applications with their mechanical properties being similar if not the same as those of virgin materials. If recycled materials are not available then designers should try to use materials from renewable sources. It must be remembered that the rate of consumption of these renewable materials should not outstrip the rate at which they can be replenished. Biodegradable materials are also environmentally acceptable as they break down and leave no harmful waste when put into landfill sites.
Choose materials that will minimise other environmental damage or pollution	If recycled materials etc. cannot be used then the material choice should be made with a view to reducing environmental damage. What may be very similar materials in mechanical or aesthetic terms will usually exhibit a very different environmental performance. Through careful material selection the environmental impact of a product or system may be minimised.
Ensure that the life expectancy of the product is appropriate, try to extend this as much as possible	Through many different design decisions the life expectancy of a product may be extended. Designing for ease of maintenance and serviceability is one approach while designing for reliability and quality is another. When attempting to extend the life expectancy of a product it must be noted that changes in future technology may benefit the particular product or system. Therefore the way in which the product is designed must take this into account so that the benefits may be had when they become available.
Consider the actual use of the product with a view to minimising the long term environmental effects.	The effects of a product or systems usage may be the biggest contributor to the overall environmental damage caused. To this end designers must look at the projected usage information and take this into account. For example why design items such as electric tooth brushes which use energy when traditional manual ones perform the same function but use no energy at all in use. Also it is only the head of the tooth brush which wears out so why not make it detachable, on the manual brush, and replace only that part. The materials and resources needed to make the handles are then saved.
Design for ease of recycling, reuse or re-manufacture	When a product has reached the end of its useful life strategies such as design for recycling, reuse or remanufacture will influence the final disposal options. By designing in such features the materials present within a product are much more likely to be recovered. Fixings such as bonding or welding should be avoided and the mix of materials within a product should be reduced or the mixture made compatible for recycling. Remanufacture allows the less worn, usually steady state, components within a design to be reused again saving resources and reducing pollution.

***Table 3.1 Summary of General Environmental Design Guidelines* - Holloway et al.** (1996)

discoveries, legislation and changes in consumer perceptions. More fundamental questions will be raised if two major environmental objectives clash. Environmentally responsible decisions will rarely be straightforward, and the pros and cons will always have to be considered and balanced carefully.

Table 3.1, **Holloway et al.** (1996), summaries and describes general environmental design guidelines.

3.4.3 The Paradox of Environmental Design

The guidelines shown in the previous section will help designers to design products which are more environmentally benign. However designers must avoid attempting to make simplistic assumptions and in some cases there may be a paradox between environmental fact and belief. What people believe to be the more environmentally friendly option is not always so.

For example many people believe paper bags to be more environmentally friendly than plastic ones. The decision being made on the basis of assumptions such as wood is a renewable resource, paper is easily recycled and plastic is not, plastic uses oil as its base which is a finite resource etc. The West German Environmental Protection Agency concluded the following.

Plastic Bag	**Paper Bag**
1/3 energy of that used in paper bag	3 times the energy of plastic bag and more processing pollution
17 Kg SO_2 per 50,000 bags	80 - 230 Kg SO_2 per 50,000 bags
Less CO and HC emissions	More CO and HC emissions
More likely to be re-used	More likely to be thrown away

When these results are considered along with other information such as; plastic can now be easily recycled, plastics can be made form different renewable resources such as plant derivatives and plastic can now be made bio-degradable thus reducing the litter problem, it becomes obvious that environmental decisions are not always clear cut.

3.5 Chapter Summary

This chapter has shown that environmental design may use the principles of concurrent engineering and the tools of LCA and EIA to move away from curing a problem and towards prevention of the problem before it occurs.

It may be carried out at a number of different levels within the overall concept of sustainabilty and each level will have its own methods and benefits in terms of reducing environmental damage.

Using the techniques described in this chapter allows designers to make sound environmental decisions and increase their understanding of the affect that their work has on the environment. However environmental design guidelines and methodologies such as LCA will not present designers with clear cut answers and, as always, it will be up to the design team to weigh up the overall benefits of the different alternatives, find out the facts and make sensible decisions.

Chapter 4

Integrating Environmental Concerns into Current Design Practices

Integrating Environmental Concerns into Current Design Practices

4.1 Introduction

Traditionally design has been concerned largely with function, appearance and cost but it is now becoming apparent that environmental concerns must be integrated into current design practices. This chapter will look at the way in which current design methods and practices can be adopted and adapted in terms of environmental design. The use of concurrent engineering and DFX disciplines is studied and the need for both tools and frameworks to support environmental design is discussed.

4.2 The Process of Environmental Design

In order to do this successfully design, practices must be defined and analysed with a view to introducing these 'extra' concerns but without completely re-thinking the way in which products are designed as many of the methods which already exist are perfectly suited for adaptation. Design cannot be defined easily, it is both a scientific as well as an artistic process. 'Design establishes and defines solutions to, and pertinent structures for, problems not solved before, or new solutions to problems which have previously been solved in different ways', **Blummich** (1970). The inclusion of environmental concerns in the design process requires the development of these pertinent structures and new solutions to address problems which have not been dealt with, in any great depth, before. The problem of environmental impact is not a new one, but until recently it was seen as a moral decision on the part of the designer and not an integral part of the design process.

Good design requires synthesis and analysis. 'Analysis is the simplification of the real world through use of models, while synthesis is concerned with assembling elements into a workable whole', **Dieter** (1986). Thus in order to design something successfully we must be able to calculate as much about its life-cycle as is necessary to address the defined objectives. It is this life-cycle approach which is needed to predict the full environmental impact of a design. In environmental design the analysis is achieved through the use of tools such as LCA, while synthesis is a complex balance of all the possible solutions to achieve a design which is both economically and environmentally viable.

Any design process may be considered as the following steps:

1. Recognition of a need
2. Analysis of the problem
3. Gathering of information
4. Conceptualisation of solutions
5. Evaluation of alternatives
6. Detailed design
7. Communication of the design configuration

Environmental design is no different and will follow the same pattern. By looking at design in this way it becomes easier to see how environmental concerns may be integrated.

4.2.1 Recognition of Needs

When considering the initial step of recognition of a need it is important to make some clear definitions in environmental design. Environmental design is 'design which addresses all the environmental impacts of a product throughout the complete life cycle of the product, without unduly compromising other criteria such as function, quality cost and appearance', **Eco2-IRN** (1994). Environmental design does not tackle the subject of sustainable development and aims to reduce the impact of products made within current design and product development frameworks. The whole question of 'do we really *need* this product?' is a far more complex social issue and is encompassed in sustainable development theory. The initial stage in developing a design is this definition of the need while also stating that the environmental impact should be kept to a minimum or specific environmental problems addressed.

4.2.2 Analysis of the Problem

The next stage, analysis of the problem, can again be very easily applied in environmental design. The analysis of any apparent environmental problems should be included in the overall analysis of the design. In some cases specialist techniques and tools may be required to fully analyse these environmental problems. Simplified environmental impact assessments may be used here.

4.2.3 Gathering of Information

It is the next stage of the design process, gathering of information, were environmental concerns will begin to noticeably affect the design process. The 'extra' amount of information needed to support environmental design is one of the main factors behind its delayed development and acceptance. Not only is it time consuming, but it adds to development times and in most cases is still a very costly exercise.

As discussed earlier the information may difficult if not impossible to collect and therefore assumptions have to be made.

4.2.4 Conceptualisation, Evaluation and Detailed Design

Conceptualisation, evaluation of alternatives and detailed design will all make use of LCA and EIA studies. At each of these stages the environmental information is introduced as would any other information and is another factor to be considered in the trade-offs made when designing a product. Comparative LCA studies may be used in the evaluation of one design compared with another and detailed design may deal with specifics such as fastenings and material types which may affect disassembly and recycling practices.

4.2.5 Communication of the Design

When finally communicating the design it is important to outline the environmental advantages offered. Communication of the design in terms of detailed drawings and specifications may not offer opportunities to outline the environmental factors easily and efficiently. These factors may therefore be better communicated in separate environmental specific documents. Using the information gathered in the previous stages, in particular evaluation of alternatives, designers may show how the proposed design helps alleviate certain environmental burdens.

4.3 Developing Environmental Design Methods

As can be seen the ' product development process entails a series of activities which start with the recognition of an opportunity and end with the introduction of a product into the market place. Throughout the process there exists the potential for reducing the environmental impact of the product being developed.', **Kusz** (1991).There is therefore a need for acting on the potential to develop a means of implementing a whole range of environmental ideas into design. **Jakobsen** (1991) believes that designers must adapt an integrated design procedure which enables them to interrelate a number of traditionally independent disciplines.

4.3.1 Adapting Current Design Methods & Philosophies

Many of the design methods and philosophies currently in use can be easily adapted to include environmental concerns and it seems that the environment is just another concern that can be mapped onto the design process. It has been questioned whether the study of the environmental impacts of a product is not simply environmental research, i.e. a matter of gathering information which a designer might use in the same way as looking up the density of water? This is certainly a logical view point but design is based upon the gathering and use of such information. Without this type of information designers could not be expected to produce a product which performs the required function. So although environmental impact is a field of environmental research is it also an integral part of design and as such should be considered in the context of design and also design research. (It is through including environmental concerns in the design process that the ultimate aim of environmental design may be achieved, a move towards sustainable development).

4.3.2 Jakobsen's Design Model

Environmental design is no different to any other design strategy in that there are a number of trade-offs which have to be made when considering the design as a whole. In the traditional design process **Jakobsen** (1991) has shown that there is an inherent relationship between function, material, production method and shape. Figure 4.1 shows Jakobsen's concept of this interrelation. Each of the four elements are directly related to the remaining three in such a way that when a designer is considering , for example, production method the choice will be affected by the shape of the component, the material from which it will be made and the function it will have to perform. The process is cyclic, with all the requirements being checked against each other until a satisfactory solution is achieved.

By utilising this design model 'the different relationships of the matrix must be collected, studied, developed and finally expressed in a normal way', **Jakobsen** (1991).

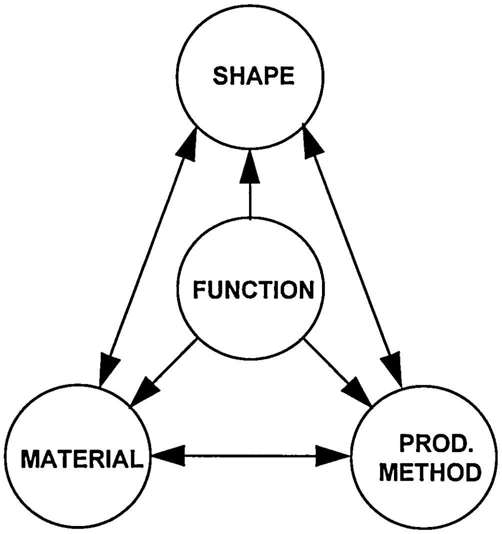


Figure 4.1 Jakobsen's Model of Interrelation

4.3.3 Adapting Jakobsen's Model

Using Jakobsen's Model as a basis the idea of interrelation of different design requirements may be extended to include environmental concerns. In the same way that function, material, shape and production method are all dependent on each other they are also influences on, and influenced by, environmental concerns. Figure 4.2 shows an adaptation of Jakobsen's Model which integrates environmental concerns into the cyclic design procedure. As the diagram shows, environmental concerns are not directly related to all the other elements in design. There are strong direct relationships between environmental impact and function, material and production method. There is, however only an indirect link between environmental concerns and shape and it can be seen that this indirect link is affected by material, function and production method.

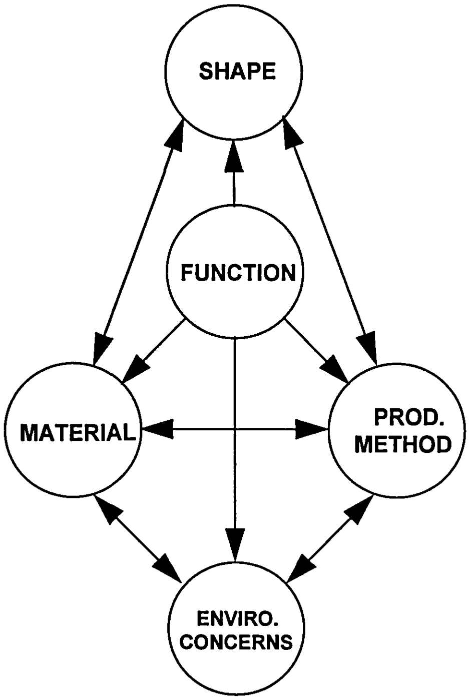


Figure 4.2 Environmental Adaptation of Jakobsen's Model - **Holloway et al.** (1994)

Representing the integration of environmental concerns in this way allows us to see how they affect other decisions. However Figure 4.2 represents the situation in a general manner. To fully appreciate the complex links between the differing elements of design Figure 4.2 must be developed further and will be discussed later.

4.3 Environmental Design Principles

The problem to be addressed seems not can but how we integrate environmental concerns into the design process. Recently much work has been carried out on the development of environmental design strategies and philosophies. CERES (the Coalition for Environmentally Responsible Economies) drew up the Valdez Principles in 1989, figure 4.3.

4.3.1 The Valdez Principles

These principles outline 10 steps for producing and marketing environmentally friendly products. It is the first 6 points which can be addressed by environmental design, the other 4 are more deeply involved with environmental management. Since the Valdez Principles were authored it has become widely accepted that they cover the general goals of environmental design. Many organisations have now drawn up environmental design guidelines similar to those developed by the American EPA, **Keoleian & Menerey** (1993), which are:

- Product system life extension
- Material life extension
- Material Selection
- Reduced material intensiveness
- Process management
- Efficient distribution
- Improved management practices

These guidelines are very general and cover the whole spectrum of product development, from design to distribution and management but it can be seen that 'these strategies go a long way to successfully addressing the Valdez Principles', **Holloway et al.** (1994) **.**

4.4 Adapting Concurrent Engineering

Many of the environmental concerns which need to be taken into account require a life cycle approach to design. For example the environmental impacts of material choice will be apparent from the extraction of the raw material, through processing, in some cases use, and also the final disposal. If the consideration of environmental factors is to be successfully integrated into the design process following the guidelines suggested by Jakobsen and also utilising a life cycle approach, the ideas and strategies embodied in concurrent engineering undoubtedly offer the best opportunities. Concurrent engineering ' imposes upon designers the need for

The Valdez Principles

1) **Protection of the Biosphere**
Companies will minimise the release of any pollutant that may endanger air, water or earth.

2) **Sustainable Use of Natural Resources**
Companies will make sustainable use of renewable natural resources, including the protection of wildlife habitats, open spaces, and wilderness.

3) **Reduction and Disposal of Waste**
Companies will minimise waste and recycle wherever possible.

4) **Wise Use of Energy**
Companies will use environmentally safe energy sources and invest in energy conservation.

5) **Risk Reduction**
Companies will minimise environmental health risk to employees and local communities.

6) **Marketing of Safe Products and Services**
Companies will sell products or services that minimise adverse environmental impacts and are safe for the consumers use.

7) **Damage Compensation**
Companies will take responsibility through cleanup and compensation for environmental harm

8) **Disclosure**
Companies will disclose to employee and community incidents that cause environmental harm or pose health or safety hazards.

9) **Environmental Directors**
At least one member of the board will be qualified to represent environmental interests and a senior executive for environmental affairs will be appointed.

10) **Annual Audit**
Companies will conduct an annual self-evaluation of progress in implementing these principles and make results of independent environmental audit available to the public.

Figure 4.3 The Valdez Principles

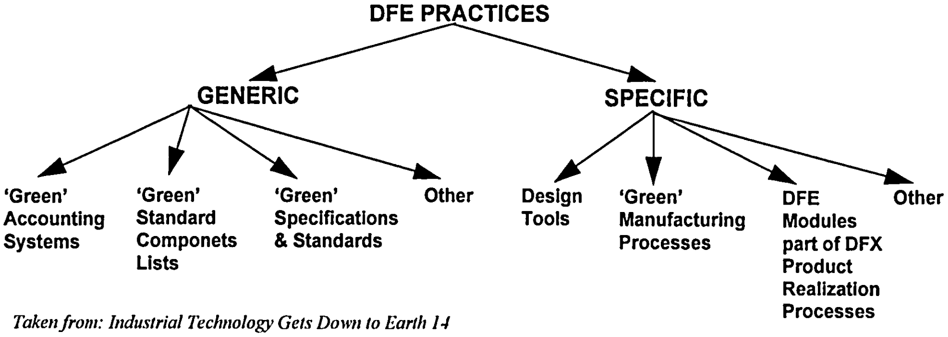
simultaneous consideration of product design, function, manufacturing and cost while also taking into account later-stage considerations such as reliability, quality and environmental impact.' **Holloway et al.** (1994).

4.4.1 DFX Strategies

Allenby (1994) has identified that in developing a DFX methodology the environmental concerns as outlined in the Valdez Principles may be addresses by separating environmental design practices into two streams:

1. Generic concerns
2. Specific concerns

As Figure 4.4 shows the generic concerns deal mainly with 'green' management practices and the environmental commitment of the company while the specific concerns deal with the concept of DFE and supportive tools. Allenby's view of the specific DFE practices is similar to Andreasen's Design for Assembly work in that it deals with DFE as a 'module of existing product realisation processes, specifically the "Design for X" systems', **Andreasen** (1983). Although Allenby terms these DFE practices as 'specific' the objectives may be drawn from a general central core of environmental design strategies, **Holloway et al.** (1994), be they the Valdez Principles, American EPA Environmental Design Strategies or others. In developing DFE modules as part of an overall DFX product realisation strategy 'the challenge is to create modules which, in keeping with industrial ecology theory, are broad, comprehensive and system-based yet can be defined well enough to be integrated into current design practices', **Allenby** (1994).



Taken from: Industrial Technology Gets Down to Earth 14

Figure 4.4 DFE Practices

On the whole DFE is not, as yet, a well-established concept and as Allenby has shown it seems to be an overriding theme in concurrent engineering rather than an explicit DFX step. If this is the case then it seems sensible to look at existing design frameworks and adapt them. As with existing design frameworks a framework for DFE, according to **Kusz** (1991) 'should communicate the design process and highlight the importance of that process and its management in the development of effective competitive strategies'.

Before these concurrent engineering frameworks can be adapted it is important that the concept of DFE is clarified. Is it a theme implicit in carrying out a group of 'greened' DFX steps or is it an explicit concurrent engineering imperative in itself. This may become clearer by looking at the way in which DFE is linked with other DFX disciplines.

4.4.2 Links with DFE and DFX disciplines.

Many of the Design for X strategies have common or linking features. They all have the common goal of addressing life cycle concerns at the design stage therefore dealing with potential problems before they occur, but many of the individual perspectives are inextricably linked. In this way it can be seen that DFE is a part of concurrent engineering and that the value of work in the area of DFE is less if it is not considered within the frame of concurrent engineering. Just as in concurrent engineering there are a number of design experts in areas such as quality, cost, reliability and so on, there may be a need for a specialist in the environment. However, **Hoffman** (1995) states '....it is also imperative that the overall objectives of a DFE strategy be integrated into the thinking of the other design specialities', which is a plausible concept and could reduce the need for a single DFE specialist. The combined environmental knowledge of the other specialists may suffice.

Design for	Ass.	Cost	Disass.	Disposal	Env.	Man.	Quality	Recycling	Reliability
Assembly									
Cost	2								
Disassembly	3	2							
Disposal	2	1	3						
Environment	2	2	3	3					
Manufacture	3	3	2	2	3				
Quality	2	2	2	1	2	2			
Recycling	3	1	3	3	3	2	1		
Reliability	1	2	1	1	2	2	3	1	

1 - weak link 3 - strong link

Table 4.1 Links between DFX Imperatives

The fact that DFE can be thought of as part of so many other areas of the design process is an indication of how basic and pervasive a subject it is. Table 4.1, developed through this research, shows how all the current DFX imperatives are linked and overlap and how these are linked with DFE. The differing DFX imperatives have different things in common. In the table a weak or tertiary link between imperatives is indicated by 1, a medium or secondary link by 2 and a strong or primary relationship by 3.

For example Design for Assembly and Design for Cost exhibit a secondary relationship. Design for assembly is basically concerned with assembling a product in the most efficient way. This means that time, energy consumption and in some cases material usage are all reduced to an optimum level. This obviously ties in with the aims of Design for Cost which aims to reduce the financial cost of a product to a minimum.

Design for Assembly has strong links with Design for Disassembly for the obvious reasons and so on. Studying the table it is interesting to note that Design for Environment is the only imperative which has no weak links with any of the others.

Many of the ideas within DFE are conducive to good practice in both engineering and business terms. Design for Recycling and Design for Environment exhibit strong relationships as recycling is an area which can reduce the environmental impacts of overall product systems, reclaim materials, thus reducing demand on virgin sources and eliminating pollution caused by raw material extraction. This type of relationship exists between DFE and disassembly, disposal, manufacture and recycling. DFE also has secondary links with other DFX imperatives. For example design for reliability aims at reducing maintenance, parts failure etc. which in turn will reduce material usage and energy usage, two of the main aims in environmental design.

4.5 What is DFE?

It can be argued that by taking the idea of DFE and 'deconstructing and integrating it into manufacturing, assembly, cost, quality etc. that it is in fact subordinate to those interests', **Narotzky** (1995) , but by making DFE an explicit step in design development it may well restructure design itself and help in its integration.

It is therefore very important to look at DFE in two ways:

1. As an explicit concurrent engineering imperative and
2. As an underlying theme running through all DFX disciplines.(This is supported by the concepts discussed earlier in this work where it was shown that each DFX discipline will have specific environmental implications.)

'Isolating any aspect of concurrent engineering is only a useful approach for focusing ones attention on a subset of issues', **Mitchell** (1995). Having studied the apparent links between DFE and other DFX imperatives, as Jakobsen interrelation theory suggests, it seems inappropriate to treat any aspect as a separate imperative, for example design for cost separate from design for assembly/disassembly (the life cycle cost being affected by the economic efficiency of assembly/disassembly, and the ease of assembly/disassembly being affected by the premium one can afford to realise this goal). Thus, while it may be necessary to consider one aspect as a separate imperative so as to focus attention on a smaller, more manageable, subset of problems, the optimum solution can only be achieved by resolving all the issues across the full breadth of the design. In other words by being truly concurrent, which in practice, for large problems, means the iterative consideration of separate imperatives as outlined by Jakobsen.

In summary there are two ways of looking at DFE and its relationships with other concurrent engineering imperatives, explicitly and as a part of a larger whole. DFE should be an integral part of all concurrent engineering activities and has such wide reaching consequences it may become the dominant imperative in many design development exercises. However it is also very important to consider it explicitly to help raise awareness of its importance, to increase our understanding of its requirements, affects and implications and to ensure that the required standard in this area are achieved be they moral, legal or otherwise.

4.6 Frameworks to Support DFE

Having established that DFE can be integrated into concurrent engineering design procedures, it is necessary to develop a framework and infrastructure for DFE within these procedures such that it may be implemented in a systematic way. Headway in standardising certain elements of DFE has already been made. As discussed earlier LCA has been standardised by SETAC into four basic elements, known as the 4 I's (**Fussler** 1993):

- Initiation - define the scope, goals and system boundaries of the study
- Inventory - gather all the relevant information about the product system
- Impact - classify all the relevant environmental data and calculate actual environmental effects
- Improvement - having identified the areas for improvement, modify the design specification

In studying areas such as LCA we must be careful not to confuse it with DFE. LCA is a tool for use in DFE but not a framework for DFE itself. It has been suggested that 'a number of recent papers have...confused the analysis of a product with its design', **Simon** (1995). LCA is an analysis process which may be used in the design or re-design of products but which must not be confused with design. As Simon suggests there are two ways of looking at LCA and DFE, 'design or re-design is included in the improvement stage, thus subsuming design within LCA.' and 'to subsume LCA within design (or new product development) by mentioning it as a "tool" which designers will use at some stage'. When developing supportive frameworks for DFE it would seem that LCA should be viewed as the latter and used in conjunction with other tools and strategies which also subsume themselves within design practices. Existing product development frameworks such as the TRIAD Product Development Process Conceptual Framework, **Design Management Institute** (1989), offer themselves to DFE as they show the potential to apply LCA concepts, EIA studies and achieve the goals of the Valdez Principles. The TRIAD Product Development Process Conceptual Framework is similar to the basic design process presented in section 4.2 and is defined as the following:

1. ***Recognition*** Recognising the existence of a business problem or opportunity
2. ***Analysis*** Analysing a problem in order to develop a strategy for its solution
3. ***Definition*** Defining what characteristics the product must have in order to solve the problem
4. ***Exploration*** Exploring many possible options for achieving the defined objectives
5. ***Selection*** Evaluating the options and selecting the one that will be pursued
6. ***Refinement*** Perfecting the selected option through attention to every detail
7. ***Specification*** Final verification and specification of manufacturing related details
8. ***Implementing*** Procurement, tooling and manufacturing

9. ***Bring the product to market***

4.6.1 A Simple DFE Framework

This framework may be utilised to support DFE practices by mapping environmental concerns onto each step. If this is done the following DFE oriented product development framework results:

1. ***Recognition*** Recognising the existence of environmental problems or opportunities which can be addressed through design
2. ***Analysis*** Using LCA and similar "tools" in order to identify the causes of the problems or opportunities and develop strategies for their solutions
3. ***Definition*** Defining what environment affecting characteristics the product must have to solve the problems or exploit the opportunities
4. ***Exploration*** Exploring as many possible options for achieving the defined objectives using DFE strategies
5. ***Selection*** Evaluating the options using environmental impact assessment and selecting the one that is most environmentally and economically acceptable and will be pursued
6. ***Refinement*** Perfecting the selected option through attention to every detail and exploration of any additional environmental design strategy that may be applied
7. ***Specification*** Final verification and specification of manufacturing related details and explanations of their environmental advantages
8. ***Implementation*** Procurement, tooling and manufacturing all taking into account environmental concerns
9. ***Bringing the product to the market*** Packaging, distribution and, if applicable, after sales service should all take environmental concerns into account. Communication of the environmental problems and opportunities to the consumer.

The development of simple, straightforward, environmentally based product development frameworks is relatively easy, if we do not look at the deeper issues such as patterns of consumerism and the difference between consumer 'wants' or 'needs'. The process, as with design itself, will be iterative. As more of these exercises are carried out the experience gained will help in the refinement of DFE frameworks.

4.6.2 Infrastructure to Support DFE

One very important area which must not be overlooked is the infrastructure which must be in place in order to support DFE exercises.

There must be both infrastructures for designers to gain and assess the information that they require, and also infrastructures which support environmentally responsible actions on the part of the consumer in using and disposing of products.

In terms of design and product development , there is a need for environmentally relevant data, environmental management schemes, such as ISO 14000, and also legislation to push organisations into considering the environmental consequences of their actions. While on the consumer side there is a need for a collection and recycling infrastructure which will allow the adoption of design strategies, such as Design for Recycling and Design for Disassembly. The speed with which these infrastructures are put in place, and the number of people that will use them may depend heavily on education in, and awareness of, environmental concerns.

4.7 Support Tools for DFE

As with many design disciplines the use of support tools will structure and accelerate environmental design. Just as tools such as CAD and finite element analysis are used to accelerate mechanical design practices tools need to be developed and adopted for environmental design.

Tools which assist Design for Assembly, **Boothroyd & Dewhurst** (1987), do exist and, although useful have little effect in terms of reducing overall environmental impact.

In recent years work in developing tools to support DFE has increased. Such tools are discussed in detail in a later chapter.

4.8 Chapter Summary

This chapter has shown that many of the current frameworks and practices used in design lend themselves to DFE. The idea that there is an interrelation between the environment and all stages of product development and use is one which is becoming more widely accepted. Concurrent engineering represents one of the most attractive opportunities to DFE as the 'infusion of environmental knowledge of downstream activities into the design process will be the only way in which designers can generate 'green' product solutions rapidly and correctly', **Holloway et al.** (1994) . The different elements needed to develop DFE are already in place, it is now a case of integrating these into a single product development strategy and making DFE common place. As **Jakobsen** (1991) concludes 'In good designs, there exists a harmonic relationship between geometric shape, material and the production method used. In order to achieve this harmony it is necessary to use a procedure which considers the treatment of these elements as an integrated activity'.

In environmental design this integrated activity is DFE. Figure 4.4 shows how each of the separate elements of environmental design are integrated and form DFE which is itself an integral part of concurrent engineering.

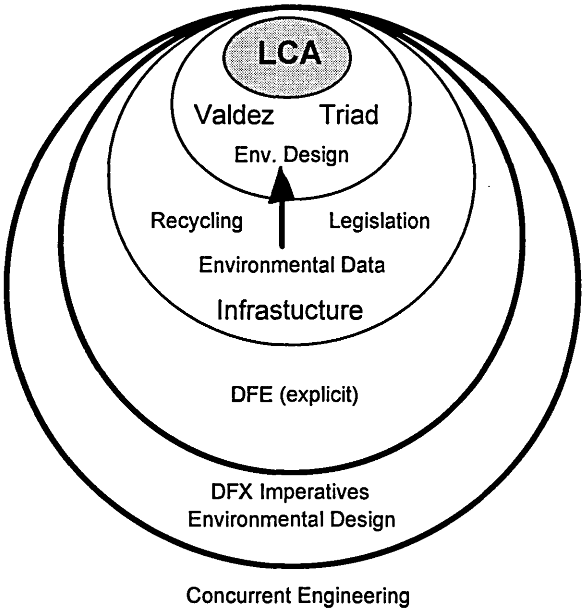


Figure 4.4 Elements of DFE within Concurrent Engineering

Chapter 5

A Critical Review of Current Practices in Environmental Design

A Critical Review of Current Practices in Environmental Design

5.1 Introduction

In the previous chapter the integration of environmental concerns into current design practices was discussed and the need for support to achieve this goal was identified. This support will come in many forms but was summarised as being the need for frameworks, methods and tools which promote environmental design.

This chapter will look at current practices in the field of environmental design. Existing and developing frameworks, methods and tools will be discussed and the overall needs within environmental design, at this time, are identified.

5.2 Current Environmental Design Practices

It has now become generally accepted that most of the environmental impacts of a product or system are set long before manufacture or use. Until recently most of these impacts were considered in retrospect and as a result 'companies spent too much time fixing problems instead of preventing them,' **Keoleian & Menerey** (1993). Some organisations are still looking an end-of-pipe measures such as recycling, **Nutter** (1993), which have their place but do not deal with the whole issue of environmentally friendly design, as discussed in chapter 3.

Front End Environmental Analysis, **Coogan** (1993), is a method which is now generally accepted as being required, in which the potential problems are addressed before they occur. As Coogan points out, meeting mechanical, financial and environmental criteria concurrently represents a formidable challenge and usually results in trade offs making use of the available information. This idea was discussed in detail in chapter 4. There are many different systems and methodologies which now deal with environmental design such as **Fiskel** (1993), **Braden**

& Allenby (1993), **Ryding et al.** (1993) **Rydberg** (1993), **Chen** (1995) and **Navinchandra** (1991). Each of these systems and methods attempts to provide a framework, infrastructure or guidelines within which designers and organisations may work. The advantages offered by these systems are the structuring and in some cases accelerating of the consideration of environmental factors in design. 'The best of these technical methodologies begin to incorporate the characteristics which the study of industrial ecology indicates are critical if environmentally appropriate decisions are to be made.' **Braden & Allenby** (1993). Although all the methodologies have their own specifics and anomalies they are all loosely based on a framework such as that documented by **Olesen & Keldmann** (1993), figure 5.1. The principles of concurrent engineering are also applied as considerations about later life performance are made at the design stage.

The following sections of this chapter will look at some of the more prominent and stimulating methods in use and under development and discuss their advantages and disadvantages.

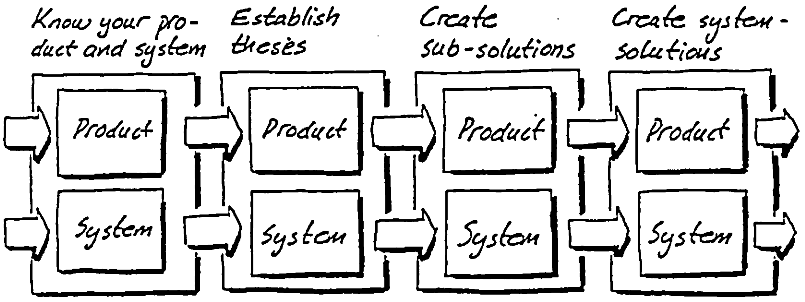


Figure 5.1 The Activities within a DFE Approach

5.2.1 End-of-Pipe Strategies

There are many end-of-pipe strategies which designers and organisations have been adopting for a number of years. Disciplines such as waste management, water treatment and air pollution control all produce environmental benefits but deal with the problems in retrospect rather than attempting to reduce the possibility of the problem occurring in the first place.

These strategies are all an integral part of environmental design when balanced against each other and the particular characteristics of the life-cycle of the product or system are taken into account. The problems arise when they are used in an attempt to reduce overall environmental impact without considering the life-cycle as a whole. Prevention is better than cure and has both environmental and financial benefits. Environmental problems should be considered at the design stage where the greatest advantages can be gained.

5.2.2 Design for Recyclability and Disassembly

Recently the technology available to recycle materials has advanced considerably. Materials such as steel and aluminium have had supportive infrastructures for recycling in place for many years, as has glass and paper, but now polymers are becoming increasing more recyclable. This design strategy goes some way towards improving environmental performance but is concerned solely with recovery of materials. Many factors have driven this approach, not least the increasing cost of dumping waste, **Lascelles** (1995), and the introduction of producer responsibility. Recycling encourages use of certain materials and reducing the overall mix, **Ertel et al.** (1993), and therefore restricts designers (as most design criteria do). Recycling requires energy in collection, separation, cleaning, re-processing and so on. This extra energy usage and resultant pollution means that in some cases recycled materials have a very large environmental impact. Also 100% recycling may not always result in the optimum environmental solution. Recycling paper has an environmental optimum of approximately 60%, **Ryding et al**. (1993). Another problem is that the percentage of recycling cannot be guaranteed and therefore the overall benefit of recycling is not quantifiable. Figure 5.2 shows the general trend in recent years has moved away from material reclamation and towards overall material reduction which has clearly quantifiable effects.

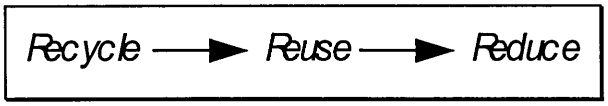


Figure 5.2 Trends in Material Reclamation

Disassembly has much the same criticisms aimed at it. It requires energy and time at the end of the product life and in most cases is not currently economically viable, **Dowie** (1994). The degree to which disassembly takes place can never be guaranteed, although work at Manchester Metropolitan University, **Dowie** (1994), has helped guide designers towards making disassembly more cost effective, which may promote its adoption by organisations.

5.2.3 Other End-of-Life Strategies

Many other end-of-life measures such as disposability and design for degradability must be considered in the overall whole of environmental design. These measures tends to be relatively easy to address and as such are used by companies to demonstrate their 'green' practices. As discussed in chapter 3 these end of pipe approaches may only address a very small percentage of the overall life-cycle environmental impact, depending on the life-cycle pattern of the product or system in question.

5.3 Environmental Design Frameworks

Much work has been carried out on environmental design frameworks and generally they follow a very similar pattern. Work by **Kusz** (1991), **Olesen & Keldmann** (1991), **Braden & Allenby** (1993), **Fiskel** (1993), **Hendrickson et al.** (1994), **Hoffmann** (1995) and **Sheng et al.** (1995) have all demonstrated the need for a structured framework within which environmental design may be carried out. Each of these frameworks is based upon the use of LCA as discussed earlier. **Hoffmannn** (1995), shows a tiered approach, for design and manufacture of electronic goods, which operates as shown in figure 5.3.

Within this framework a number of questions must be asked in order to integrate environmental concerns into the design process. Hoffmann suggests that these questions and criteria be derived using expert opinion, and that each design concept may be scored from 0 to 100 in environmental terms.

Design Phase Tool Tier	Concept Development	Detail Design	Prototype Manufacture
Tier 1	Life Cycle Matrix for Product Systems. Circuit board design		
Tier 2		Circuit Board Design Housing Design EM Shielding	
Tier 3			De Manufacturability Life-cycle Impact

Figure 5.3 Conceptual Framework for Environmental Design - **Hoffmann** (1995)

The concept with the highest score being the best. This in theory is a clear, structured method but a number of questions need to be answered when considering the validity of the system. The concepts and approaches adopted by the designer need expert opinion to be determined. In many cases designers are not environmental experts, thus they will need to liaise with others who are. The framework would be much easier to use if it attempted to embody some of the expertise in itself. As Hoffmann points out these criteria will change but if the framework is flexible these concerns may be altered and updated as necessary. Grouping of environmental problems could be presented along with design strategies which may address them. The scoring system may also present problems. It is very common in engineering to try and rate design concepts with scores, but in the case of environmental design this is not yet a reliable method. Little is known about environmental effects and comparisons of different types of pollution to allow a score design rating, although there are many ranking and subjective scoring systems in use and under development.

The framework offered by **Oelsen & Keldmann** (1993) again presents a very structured, all be it broad based approach as shown in figure 5.1. As Oelsen points out the approach adopted is similar to the Design for Quality Approach of **Andreasen & Hein** (1987) and has four main activities:

1. Know your product and systems - understand fully the life-cycle and associated environmental effects.
2. Establish theses - based on analysis, theses are made on how the environmental performance can be raised from the existing level.
3. Create sub-solutions - based on the theses it is examined if new solutions exist in the problematic sub-systems.
4. Create system-solutions - incorporate sub-system solutions into parts of the life-systems which are not changed.

The result will point out a possible basis for a project which will satisfy the environmental specification. The designer must also know legislation and standards, analyse and verify data and decisions, weight all the different properties of the design in accordance with their importance and exploit as many opportunities as possible.

Although this is a very structured system there are again some problems. Designers have to cope with a large amount of data which may increase product development times. Oelsen does point out the need for tools but makes no great attempt to discuss the real problems or needs of such tools. The framework identified is clear and well though out but there is a lack of support for the designer in trying to work within the framework.

5.3.1 An Integrated Systems Approach to Environmental Design

Fiskel (1993) looks at an integrated systems approach. As he says 'effective implementation of

Design for the Environment requires the development of design metrics, guidelines and verification methods. These must be deployed within an integrated system framework in order to provide useful guidance for decision making during fast cycle product development. As others have, **Fiskel** (1993) recognises the links between DFE frameworks and concurrent engineering. He also points out that the current state of practice within DFE can be characterised as mainly opportunistic and project specific. However Fiskel shows that a DFE framework can be spit into four main elements:

- Design *metrics* to support objective assessments (preferably quantitative) of environmental Quality
- *Design* guidelines or rules to assure that environmental concerns are introduced early in the design process.
- Design *verification methods* to review and assess proposed designs with respect to the above metrics.
- Design *decision frameworks* to support system-level trade-offs between environmental quality and the many other inter-related quality metrics.

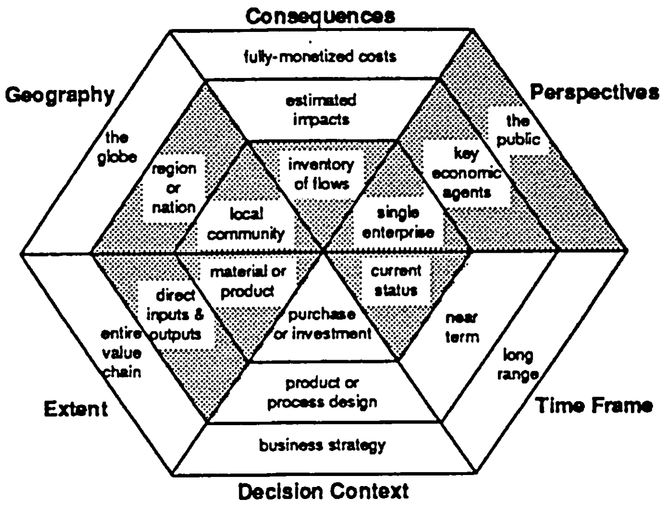


Figure 5.4 Current Boundaries of LCA Methods

Of these four key elements only two, guidelines and frameworks are in place. The guidelines are well documented and so are the structures of the frameworks, but actual data and methods to support the frameworks as a whole are still lacking. Fiskel summarises this as shown in figure 5.4. The shaded areas show where our current knowledge lies. As can be seen from the diagram it is again the decision context of design and the environment which leaves the biggest hurdle to be overcome.

5.3.2 Environomics

Frangopoulos (1991) presented a method called environomics, in which a mathematical approach is employed in determining the effect of pollution and energy usage. Areas such as measures of chemical pollution and thermal pollution as well as methods of environomic optimisation are offered. This method involves complex mathematics and relies heavily on such concepts as harmfulness of a pollutant. These measurements of harmfulness can be difficult to assess and quantify, although more reliable data is now becoming available. Also the mathematics alone in this method would discourage most designers from using it.

5.3.3 Environmental Design Matrices

Matrices are used in many different design methods but lend themselves to environmental design particularly well. Environmental effects are related to different stages of the product life-cycle and characteristics of the product. This interrelation can be clearly and easily shown on a matrix.

There have been a number of environmental design matrices developed to assist designers in considering environmental concerns during the design process. These range from matrices which give general details on environmental impact throughout a products life and simple design guidelines, figure 5.5 **Dewberry & Goggin** (1995), to environmental matrices which explore the environmental strategies which might be adopted in a particular product design, figure 5.6 **Kortman et al.** (1995). Both these and others such as those developed by **Eagan & Hawk** (1995), **Rydberg** (1993) and **Hoffman** (1995) have their merits but do very little towards giving designers advice on actual environmental design strategy development as they use no form of product classification or description. **Kortman et al.** (1995) does give some environmental strategy advice but it is difficult to see, from his work, how this is actually done. In his work he claims that 'Although this preliminary analysis does not result in a comprehensive understanding of the environmental impacts of a product, it illustrates the most likely and visible environmental problems of a product.'

Graedel & Allenby (1995) produced one of the better know matrices in DFE and has been adopted by AT&T (America's largest telecommunication company). This particular matrix, shown in figure 5.7, is constructed of 25 cells each representing a particular environmental concern at a particular life-cycle stage.

		Life Cycle of Product		
		Production	**Use**	**Disposal**
Environmental Impact	**Energy** *eg. efficiency, alternative*	More efficient production processes, reducing distribution transport.	Reducing energy consumption of products. Alternative power supplies	Non- energy intensive disassembly Appropriate disposal.
	Material *eg. virgin, recycled, minimisation*	Minimising use of raw material. Eliminating deleterious materials.	Design for quality, reducing need for new material for repair	Design for disassembly. Cascading material cycles acknowledged.
	Pollution *eg. solid waste, air emissions, water emissions.*	Reducing production waste. Eliminating toxic's	Eliminate hazardous emissions and the need for 'throw away', short term additions.	Appropriate disposal regarding grade of waste. Landfill last option!

Figure 5.5 Eco-Design Matrix

For example cell (2,3) represents solid residues from manufacturing processes. It is recommended that a qualitative score is assigned to each cell from 4 for no impact to 0 for a high environmental impact. The 25 cells will therefore give a score out of a possible 100. The lower the score the

phase		input				output				environmental strategy
		resources	(kg)	energy	GJ	waste	(kg)	emissions	UPA * E6	
1a	extraction and production of materials for the machine	metals, plastics, components	630	process energy and transport	7	ore	432	heavy metals, PAH's, phenol, oil, etc.	9	use less harmful materials
1b/2	extraction and production of ingredients	milk powder, sugar, coffee, plastics, filters	6000	process energy and transport	85		18	ash, NH3, SO2, NO3, PO4, oil, chlorine	134	reduce the consumption of ingredients and cups
3	production process			process energy and transport	8	metal scrap	Fe 35, stainl. steel 12,4	acid, oil, chlorine, dust	1	reduce the amount of materials for the coffee machine
4	use				125	cups, filters, coffee	3900	energy emissions	37	
5	operating system	detergents	?	boiler, lighting, motors, ventilation	125	energy waste	5	energy emission, detergents	190	optimise transport
6	service	components	13	transport	22	components, energy waste	14	energy emissions	33	optimise life span of components
7	disposal			transport	4	apparatus	194	energy emissions	12	stimulate high-quality reuse of machine components and materials

Figure 5.6 Environmental Matrix of a Hot Drinks Machine

	Environmental Concern				
Life Stage	Materials Choice	Energy Use	Solid Residues	Liquid Residues	Gaseous Residues
Resource Extraction	1,1	1,2	1,3	1,4	1,5
Product Manufacture	2,1	2,2	2,3	2,4	2,5
Product Packaging & Transport	3,1	3,2	3,3	3,4	3,5
Product Use	4,1	4,2	4,3	4,4	4,5
Refurbishment	5,1	5,2	5,3	5,4	5,5

Figure 5.7 The Environmentally Responsible Product Matrix

more environmentally friendly the product. The matrix therefore will assess a design in environmental terms and highlight the more problematic areas. As with the other matrices described it does not advise how to address these problems. To fully illustrate such problems it is necessary to look at the factors which affect them. Product classification systems which describe the specifics of a products life-cycle can be used to do this.

5.3.4 Summary of Environmental Design Frameworks

Holloway (1994) has shown that there is a very strong connection between most of the DFE frameworks developed or suggested and general 'green' design guidelines. The failings are not so much in the frameworks but the systems and methods in place to support the frameworks. Evaluation of design through established methods such as matrices and comparisons of designs on specified criteria as well as systems for identification of the correct design strategies are needed if these frameworks are to become an integral part of product and system design.

5.4 DFE Systems and Methods

As with DFE frameworks, there are a number of DFE systems and methodologies that have been developed in recent years. Most of these systems and methods deal with materials and processing selection on a life-cycle basis in terms of environmental performance. Some of the more noted systems are the EPS system - Environmental Priority Strategies in Product Design, **Ryding et al.** (1993); the system which is used by the SimaPro computer program, **Cleij et al.** (1993) and the PEMS system developed by **PIRA** (1994). These are by no means the only methods and systems which exist but they are the most widely known. All these systems operate using the same general LCA concept, as shown in figure 5.8.

They follow the same method as the first stages of an LCA. The designer supplies information about the product of system in terms of materials, processing, use characteristics and disposal operations.

These systems then carry out an inventory calculation and present the results to the designer. They differ mainly in the way in which the information is presented to the designer.

5.4.1 The EPS Environmental Design System

'The main idea of the EPS system is to make environmental loads and environmental impacts of products 'visible' through a transparent eco-calculation procedure to provide a holistic approach offering a synthesis and integration of environmental concerns', **Ryding et al.** (1993), this is shown in figure 5.9.

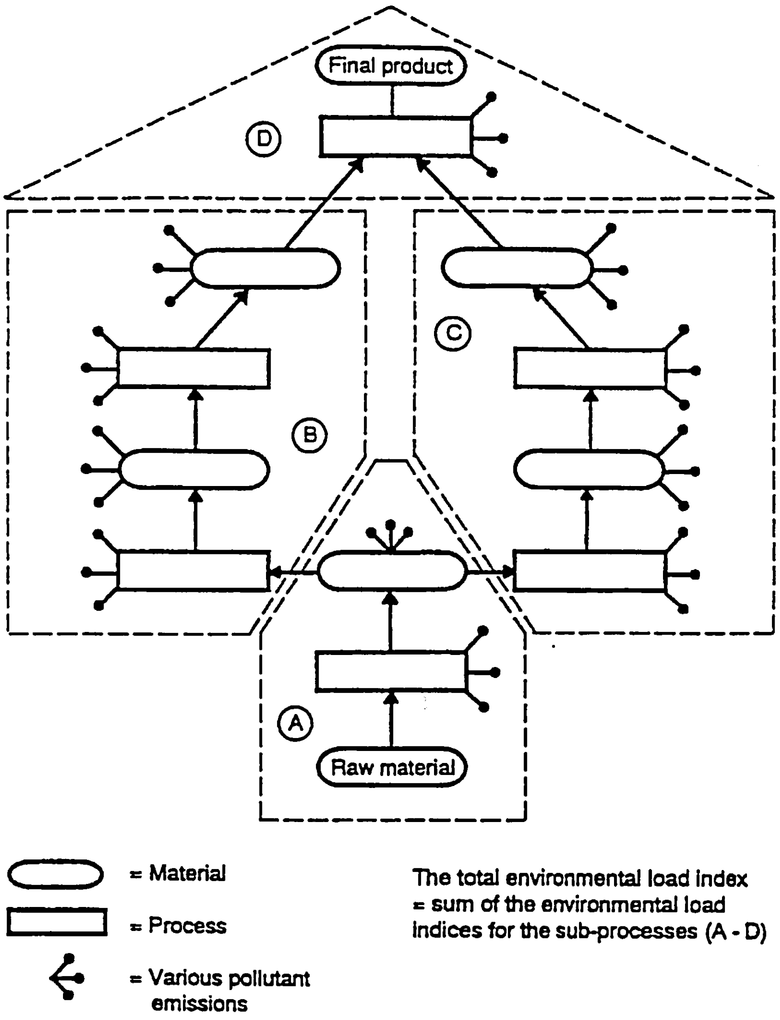


Figure 5.8 Outline of Calculation Procedure for Environmental Design System (EPS)

There are 3 main purposes of the EPS system:

- Describe the environmental impacts of the consumption of energy and raw materials, and pollutant emissions, during the different phases of the life cycle of a product,
- Systematically provide information useful for an integrated EIA of products - from cradle to grave,
- Evaluate the environmental consequences of alternative processes and construction in relative terms, to enable comparisons between different process approaches and product designs.

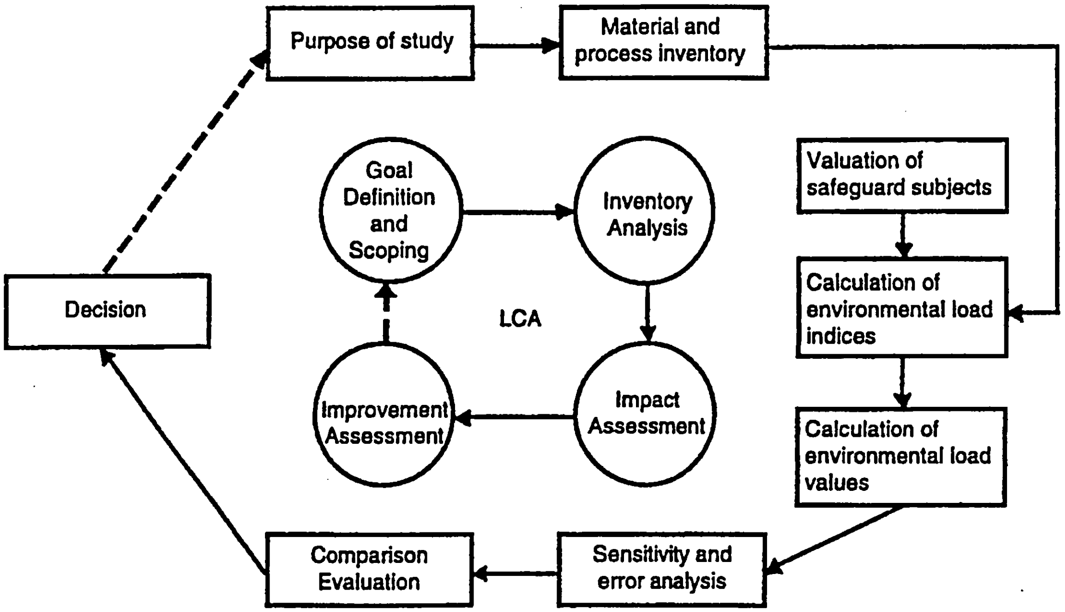


Figure 5.9 The Stepwise Calculation and Assessment Elements of the EPS System

As with most environmental design systems it is the evaluation stage which is the most important as it puts the results into context.

The system calculates in the way discussed earlier and follows the standard LCA approach.

5.4.1.1. Environmental Load Units

The way the system attempts to help designers in making their decisions is presenting the overall environmental impact as a single figure in Environmental Load Units (ELUs). An example of this is given in table 5.1 where the system is used to assess the environmental effect of a GMT composite component for a car.

The ELU is derived from an environmental load index which represents a valuation and weighting of how important use of a selected resource or emission of a certain pollutant is. As can be seen the system uses a sign convention where emissions to the environment are positive figures and the use of waste materials etc. are seen as reducing the burden on the environment and presented as negative figures.

There are advantages and disadvantages to presenting data in this way. A single figure makes comparison very easy but may hide valuable detail about the overall system, **Holloway** (1994). There are also a number of issues surrounding 'exchange rates' in ELUs. Exchange rates are used to compare pollution in different media, for example how do we compare ELUs for water with ELUs for air. The use of a sign convention is also advantageous for an overall rating system, however the main problem with this system is the lack of support for the designer in looking for alternative materials, processes or designs.

PRODUCTION				
Material/ Product	Process/ Activity	Environmental Load Index	Quantity	Environmental load value
GMT - composite	Manufactured material	0.58 ELU/kg	4.0 kg	2.32 ELU
GMT - composite	Reused production scrap	-0.58 ELU/kg	0.3 kg	-0.17 ELU
	Pressing	0.03 ELU/kg	4.0 kg	0.12 ELU
			Sum:	2.27 ELU

Table 5.1 Example Calculation using the EPS System

There is no question that the system allows the designer a structured approach to assessing environmental impact but it lacks the sophisticated comparison facilities that are needed within DFE methods and systems. Although in many cases the final decisions will be in the hands of the designer a more 'developed' comparison and evaluation stage is needed.

5.4.2 The SimaPro Environmental Design System

SimaPro is an environmental design method which is embodied in a computer tool. The specifics of which will be dealt with in a later section of this chapter. SimaPro was developed to allow designers to 'analyse and compare products.' **Cleij & Goedkoop** (1995).

For the designer who wants to use environmental data in their designs SimaPro is an easy to use, well structured system. It is one of the oldest and most used environmental design systems. SimaPro works on the main principles of LCA. The user inputs information about materials, processing, disposal etc. and the system performs a full LCA. The results are presented graphically and in tabular form.

The system presents a breakdown of all inputs, air emissions, water emissions and waste produced in a tabular form to allow the designer full access to important information. It is in the way the system presents results that the anomalies of this system show.

To allow the designer to compare products and processes in environmental terms SimaPro uses three systems of results presentation.

1. Normalisation
2. Classification
3. Eco indicators

Figures 5.10 - 5.12 show examples of these.

5.4.2.1 Normalisation

Normalisation is a qualitative method used to represent the average European load of a citizen during each year. The units for these are not specified in the documentation. The graph shown in figure 5.10 is multiplied by a weighting factor for each effect, (acidification, smog, energy etc.) to give an overall effect. These weighting factors used are MAC values for air and O.v.D values for water. The factors used for calculation of acidification and smog etc. are not made apparent by the system. This will allow designers to predict the actual effect on the population of producing, using and disposing of the design in question.

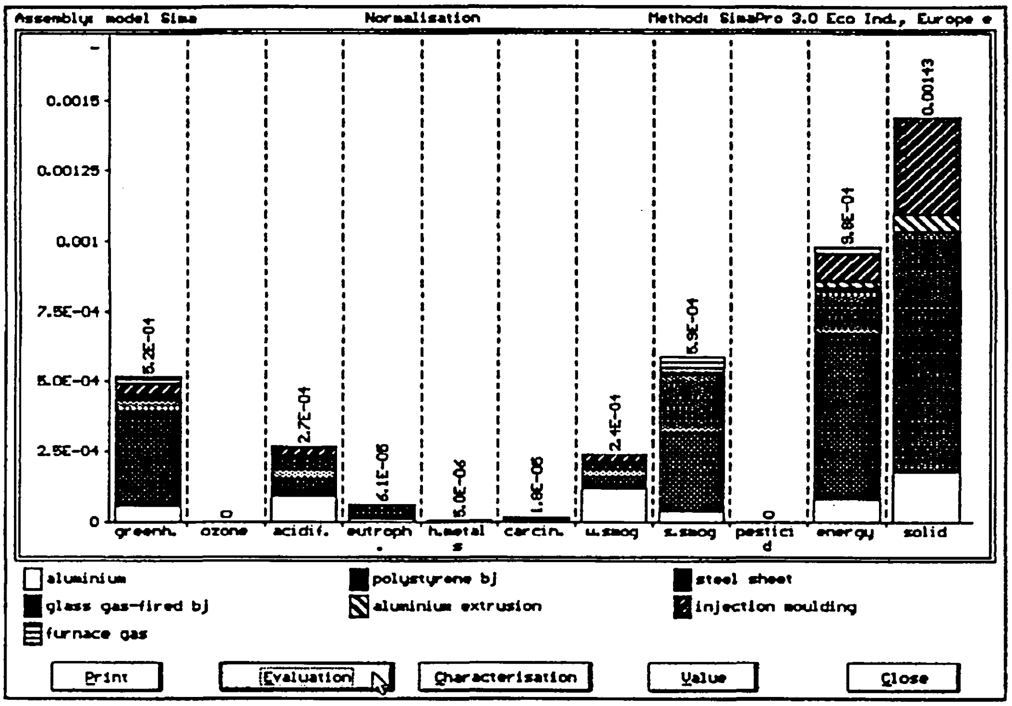


Figure 5.10 SimaPro Normalisation Graph

5.4.2.2 Characterisation

Characterisation, shown in figure 5.11, is the system of grouping emissions together into environmental effects. Emissions such as sulphur dioxides and nitrogen oxide will be added together under the classification of acidification as they are a major cause of acid rain. Emissions such as carbon dioxide and methane will be added together under the classification of greenhouse effect and so on. The contribution of each component of the LCA (i.e. material or process etc.) to the particular environmental effect is shown on the graph. This is another very good aspect of the SimaPro system. It allows designers to predict tangible environmental effects of their actions.

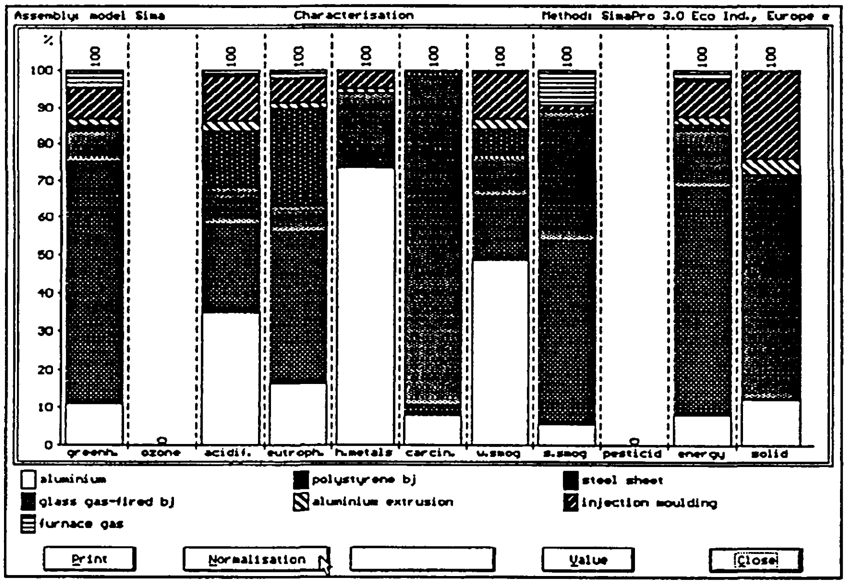


Figure 5.11 SimaPro Characterisation Graph

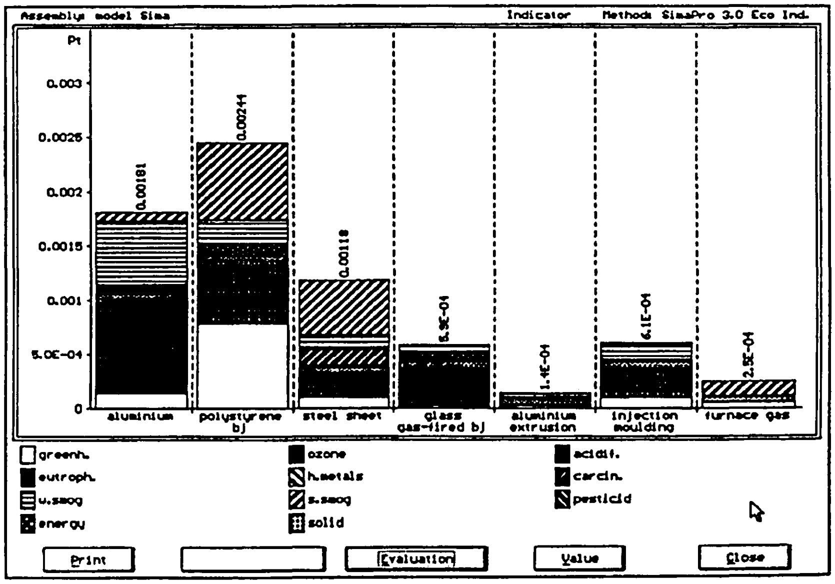


Figure 5.12 SimaPro Eco indicators Graph

5.4.2.3 Eco-Indicators

The eco indicators system which is shown in figure 5.12 is very similar to the ELU system used in the EPS Method. It is a method which has been developed by Pre-Consultants in collaboration with Phillips, Volvo and several Dutch Universities. The eco-indicator of a material or process indicates its environmental impact based on data from a life-cycle assessment. The higher the indicator the greater the impact. By presenting the results as shown in figure 5.12 SimaPro gives an immediate view of which element of the design dominates the eco-behaviour.

5.4.2.4 Comparison of Alternative Designs

SimaPro does contain a competent comparison system for evaluating more than one design concept. One product is taken as the reference point and others are compared to that. e.g. Product 1 energy usage is 25 MJ and is classed as 100%. Product 2 has an overall energy requirement of 22.6 MJ and is therefore calculated as 90.4%. This type of system is very useful to designers when making comparisons as it allows objective decisions to be made in an area where this is usually very difficult.

Because of the features used by the SimaPro system, and the comprehensive databases which support it, it is easy to see why it is the most popular system in use. It does however have some shortcomings. The main problem is that of decision support for the designer. It can compare different products or systems presented by the designer but makes no attempt to try and offer advice as to changes which could be made to improve the overall environmental performance. Once again there is complete responsibility on the designer to try and formulate different designs, the DFE system used does not offer any help in this area.

5.4.3 The PEMS Environmental Design System

The PEMS system or model was developed by PIRA International and has four major uses: **(Kirkpatrick et al.**(1994))

- benchmarking environmental performance
- identifying opportunities to realise environmental improvements
- assisting in the design of new products and processes
- setting targets for environmental management systems

The main framework of the model again relies on the process of LCA and example is shown in figure 5.13. The overall operation of the system is similar to the others discussed previously.

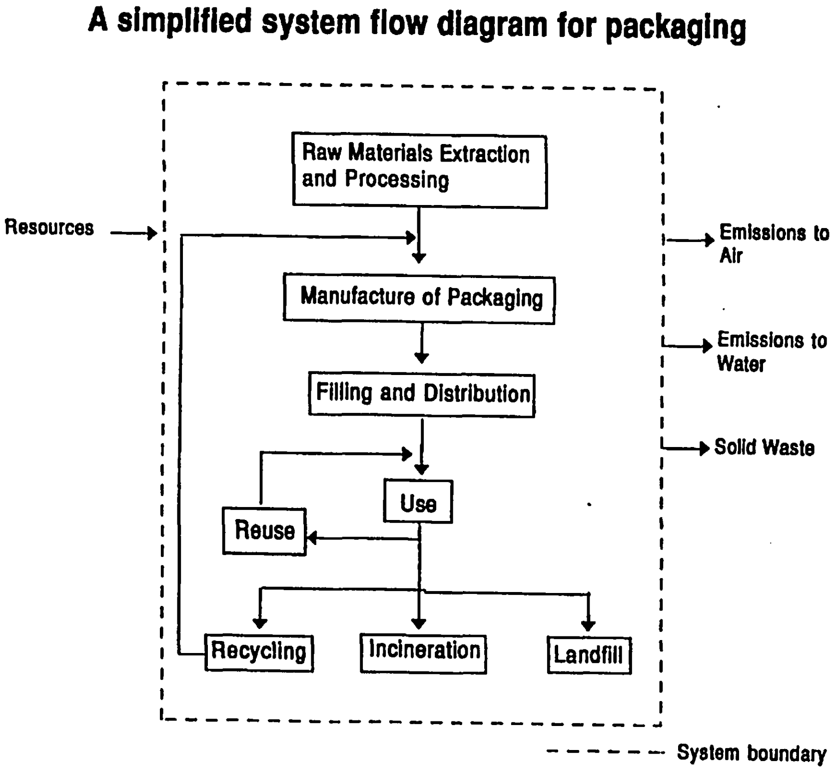


Figure 5.13 Example of the PEMS LCA System

5.4.3.1 Impact Analysis & Ranking

The PEMS system incorporates a useful system of impact analysis similar to that used in the SimaPro model. Each of the emissions present as a result of the product or system being investigated are classified , characterised and then given a value. Classification falls into one of 4 categories as shown in figure 5.14

One of the potential shortcomings of this system is the practice of ranking of environmental effects and impacts. For example it is claimed that methane is 20 times more damaging as a greenhouse gas than is carbon dioxide. This particular example is well founded and research suggests that it is the case. However in many cases the ranking of environmental impacts is not a safe practice as too little is known at this stage to be able to effectively use such a ranking system.

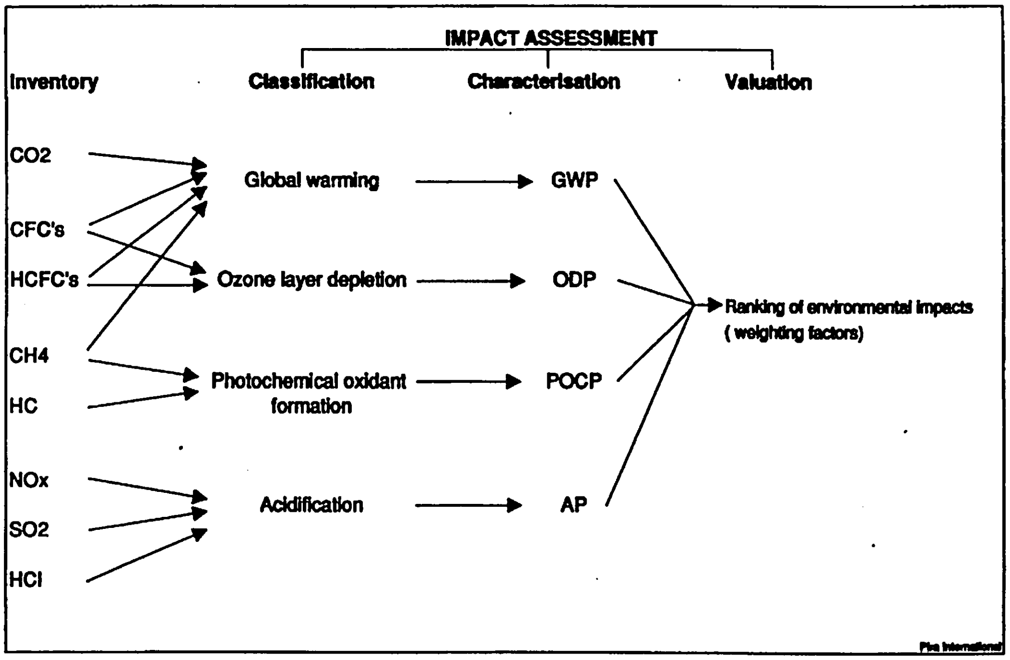


Figure 5.14 PEMS Emission Classifications System

5.4.3.2 Comparison of Alternative Designs

Figure 5.15 shows a 'credited energy graph' comparing plastic bottles with different percentages of recycled plastic content. The total inherent energy within the product is represented as a whole and also as a breakdown of process energy and energy that is recoverable from the product. This gives an overall net energy requirement of the product, or system, in question.

The problem with this graph is that it does not show any data as to the emissions created when recovering the energy from the product. In certain cases the incineration of particular substances in order to recover energy will result in harmful emissions, sometimes emissions which are more harmful than if the energy was generated from another source. Such information needs to be made available to the designer in they are to make informed decisions about the comparisons being made.

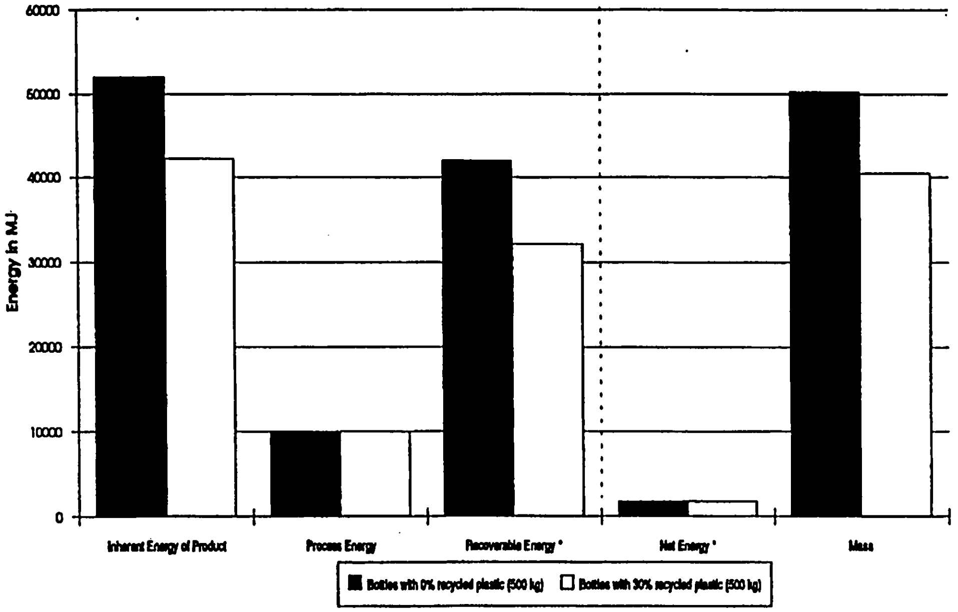


Figure 5.15 PEMS Credited Energy Graph

5.4.3.3 Sensitivity, Problem Oriented & Critical Volume Data

Figure 5.16 shows the PEMS system 'sensitivity graph'. This compares the difference in environmental damage between a number of design options showing the change in percentage figures. The example shown highlights such areas as oil consumption and water consumption as being areas of definite improvement when using 30% recycled plastic in the manufacture of bottles. The way of presenting results allows the designer much more tangible information for use in decision making.

The PEMS system also presents its LCA results in terms of 'problem oriented graphs', figure 5.17, which gives a visual representation of the classification system discussed earlier and 'critical volume' graphs, figure 5.18, which use a ranking system similar to that used in both the SimaPro and EPS systems.

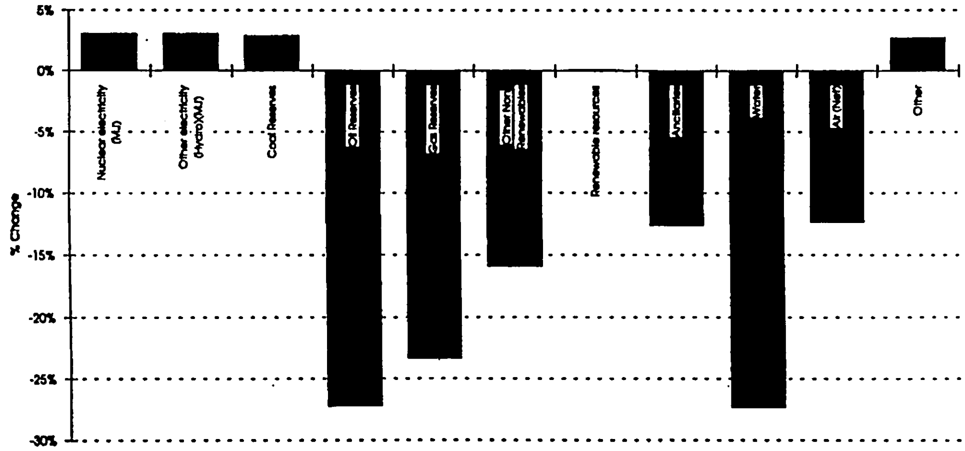


Figure 5.16 PEMS Sensitivity Graph

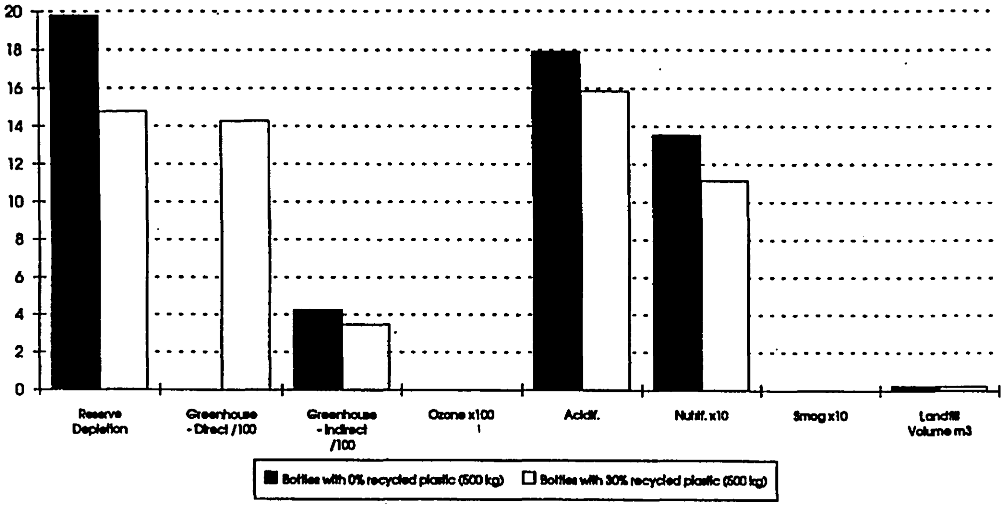


Figure 5.17 PEMS Problem Oriented Graph

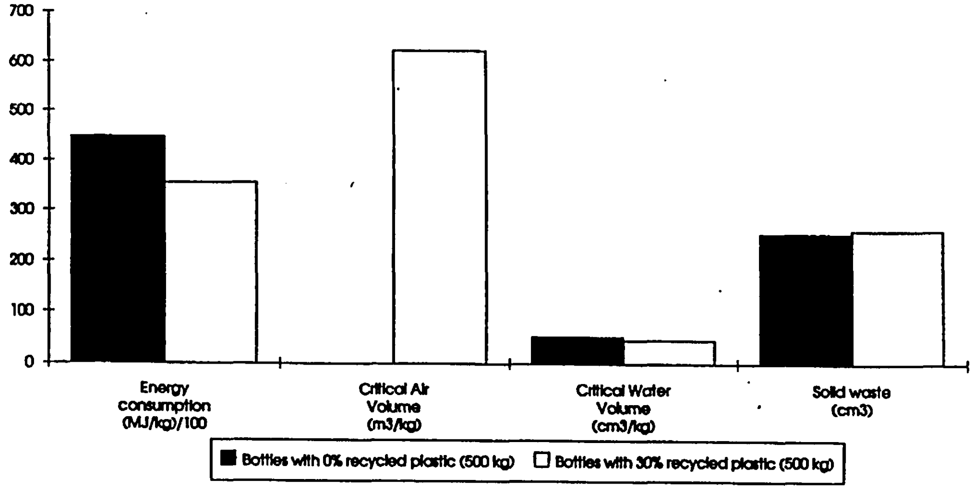


Figure 5.18 PEMS Critical Volumes Graph

5.4.3.4 Summary of PEMS System

In summary PEMS is very similar to the other environmental design systems looked at in this chapter in that it performs LCA studies and presents the data to the designer in a which attempt to help in the decision making process and comparison of design alternatives. In many ways the system does just this but again there are no mechanisms in place within this system which actually attempt to give the designer a explicit advice on the choice of materials or processing for a particular design which may reduce environmental impact.

5.5 Information and Databases

One of the most important components of any LCA study or environmental design system is the information and data sources that are used. This is still the biggest problem area in most studies and as a result of this many studies are now using the same data. **Habersatter & Widmer** (1990) **and Steinhage & Dam** (1990) are the two data sources which are most commonly used in European environmental design. The two studies are usually referred to as Buwal and Van den Burgh & Jurgens respectively and are based on lengthy studies carried out within Europe over a number of years.

Goedkoop & Volman (1992) is another general source of data. These studies give inputs required and emissions data for material extraction, refining and processing as well as recycling and other disposal practices such as incineration. Studies by the APME cited in earlier chapters are now also becoming the standard for use in European environmental design exercises. Accurate data of a high quality is critical to the success of environmental design exercises. Most of the data available is averaged from hundreds of separate studies. There will obviously be large differences in specific practices as far as energy usage and emissions is concerned, but at this stage in the development of environmental design systems the data available is sufficient. As long as the data used in comparative studies is either actual data recorded for the operations in question or average data taken form the same study, such a those cited above, then a meaningful comparison may be made between different products or systems. Caution should be exercised in using the data as absolute.

5.6 Materials Selection Methods

There are many 'traditional' materials selection methods which exist in engineering. By traditional it is meant methods which select material to a given set of mechanical, or other, criteria. Environmental criteria in materials selection is becoming increasingly important and is the mainstay of many of the environmental design methods discussed earlier in this chapter.

5.6.1 Ashby's Material Selection Method

Ashby (1992) points out that 'There is a growing interest in reducing and reversing this environmental damage. This 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' In engineering most materials selection has been carried out using approaches similar to the **ASM Handbook** (1991) or Materials Selection Charts, **Ashby** (1993).

There are very few materials selection systems which deal with environmental data. This is because of a number of factors, not least that many environmental effects are difficult to quantify.

Ashby (1992) has made some progress in terms of selecting materials on an environmental basis by further developing his materials selection charts to include energy as a design parameter. Of all the environmental concerns, energy usage or requirement is one of the easiest to quantify. This is shown in figure 5.19. This system allows designers to design to mechanical requirements while also taking into account environmental concerns. At this stage these 'environmentally-based' materials selection charts are confined to energy content only. If they are to be developed further and used by designers, a way of quantifying other environmental effects will be needed. The main problem with this type of materials selection is the manipulation of large amounts of data and that the decision on the 'best' material is again left solely to the designer. Ashby's charts offer much more clearly defined guidelines than other methods.

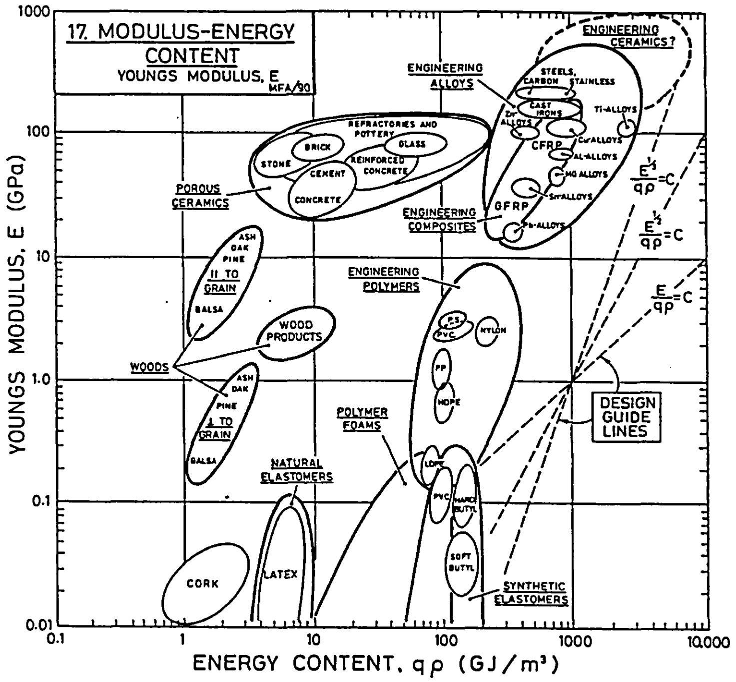


Figure 5.19 Ashby's Modulus-Energy Content Materials Selection Chart

5.6.2 The IDEMAT Materials Selection Method

One of the latest environmental materials selection methods to be developed is called IDEMAT and was developed by **Delft** (1996). 'It provides technical information about materials and processes in words, numbers and graphics, and puts emphasis on environmental information.', **Delft** (1996). The system covers standard metals and plastics and also materials like glass, wood, fabric, rubber, ceramic etc. Altogether it contains data on over 350 materials. The system provides information regarding mechanical, physical, thermal, electrical and optical properties, and also data on processabilities, and environmental information. 'The environmental properties are given in a graph showing the environmental effects normalised with the Dutch national effect scores, associated with the production of one kg of the particular material.' **Delft** (1996). Moreover, the Eco-indicator for that material is given enabling a quick impression of the environmental impact of that material.

Materials are selected by specifying all the demands in terms of minimum and/or maximum conditions. The system suggests all the materials that meet the requirements. It is apparent that the materials selection system offered by IDEMAT is a step in the right direction but it requires a high degree of detailed knowledge in terms of materials mechanical properties. In many cases designers do not know the numerical values of the strengths or stiffness required of materials for particular applications. It is this fact which may cause the biggest problems in using this system. For designers who do not have this technical knowledge a different way of describing the properties required is needed.

5.7 Summary of Environmental Materials Selection Procedures

Structured materials selection procedures exist but at the moment do not take enough environmental information into consideration. The frameworks of these systems are such that they may be adapted to include this information. There is no need to try and develop a complete new system of environmentally-based materials selection. Adoption and adaptation of existing methods may result in the structured integration of environmental concerns into the materials selection process. This may also be the case for process selection methods which are very important in DFE systems.

5.8 Computer-Based Tools

Due to the large amount of information that must be processed in DFE exercises many of the methods and systems under development are in the form of computer tools. Both the SimaPro and PEMS systems discussed earlier were developed as computer models.

In recent years much work has been carried out in this area by the likes of **Petrides et al.** (1994), **Holloway & Tranter** (1995), **Diaz-Calderon et al.** (1994) and **Chen** (1995) among others.

Poyner & Simon (1995) presented a summary of some DFE computer tools as shown in table 5.2. Many of the tools summaries here deal with end-of-life concerns and therefore are subject to the same problems discussed in the previous chapter. End-of-life measures are important but an overall environmental life-cycle picture is needed in order to fully address any apparent problems.

Those tools developed by **Navin-Chandra** (1993), **Ishii** (1994) and **Diaz-Calderon** (1994) all require very specific design details to be used and therefore are only of any real use at the detail design stage. The main problem here is that at the detail design stage it is usually too late to influence the major environmental effects of the design. Tools and systems which allow comparison of concepts in environmental terms at an earlier stage in the design process such as those developed by **Chen et al.** (1995) and **Kassahuan et al.** (1995) will be of much more benefit to designers.

5.8.1 ImSelection Computer Tool

This computer tool attempts to 'integrate the environmental life cycle impacts of materials into traditional engineering material selection processes', **Chen et al.** (1995). It does this by using design criteria, entered by the designer, that the material must match. These design criteria are in the form of both shape and mechanical properties. Designers will tell the system that the material they need requires strength, and stiffness, for example, and is flat in shape.

This is an excellent way in which to choose materials as this is how most designers work, by using 'descriptors' which describe the properties of the material.

Computer Tool	**Scope / Philosophy**	**How the tool will be used in the design process**
Design for Environment (DFE), based on DFA/DFS software. **Boothroyd & Dewhurst** (1987)	Analyses end of life options and life-cycle data for components in an assembly, including disassembly cost and recycling options.	Used during assembly analysis requires data on assembly relations of all parts and fastening methods to be entered. Links with CAD.
Materials Selection **Chen et al** (1995)	An expert system to enable suitable cost / environmental material choices to be made based upon the input of a products specification. A product can be made form the most suitable 'environmental' choice of material	Used after a product has been specified to enable the designer to arrive at a suitable choice of material based on the required attributes of the product.
Life Cycle Assessment (LCA) (E.g. Commercial systems from PIRA / Boustead)	Ecobalance tools that evaluate system inputs and outputs for each life-cycle stage. Most are limited to inventory analysis - flows of materials and energy	Can be used as soon as the processes, materials and part weights are decided, effectively the design stage. Do not directly point up design options.
ReStar **Navin-Chandra** (1993)	Performs disassembly analysis on a particular design. Optimising a design using exhaustive search of possible reuse/recycle/etc. choices at each step of disassembly.	Requires complete geometric assembly relations for the product: hence useable only at the design stage.
Design for Product Retirement **Ishii et al** (1994)	Based on Design Compatibility Analysis; provides qualitative ratings for designs and cost summaries.	Requires the product structure and fastening methods to be entered graphically.
Advisor For Component Design **Diaz-Calderon et al** (1994)	Expert system combined with geometric modeller; gives advice to designers by analysing assemblies.	Used to evaluate geometric models of parts or assemblies for material compatibility and fastening techniques; detail design stage.
Green Design Tool **Kassahun et al.** (1995)	The tool analyses a design and associated processes for their 'greenness'. By measuring the 'greenness' of certain attributes of a design, a designer can try to make improvements to their designs.	Can be used as soon as the basic embodiment of a product has been designed. The output allows the designer to analyse quickly alternative designs and manufacturing methods.

Table 5.2 A Summary of some DFE Computer Tools - **Poyner & Simon** (1995)

The methodology integrates product performance requirements, shape constraints, material properties, manufacturing processes, environmental burdens and costs.

The main aim of the tool is to help calculated overall cost including environmental cost. In this tool environmental cost is seen as two separate costs:

1. Internal Environmental Cost - which is defined as cost to the manufacturer associated with environment related activities.
2. External Environmental Cost - which is defined as the cost of environmental impact on society.

These costing systems are based on the cost in $/kg of releasing pollutants into the environment. This type of costing is very difficult to assess an is different in geographical/political location.

The tool does look at whole life-cycle costs by including processing and disposal. The results are then presented in a table to the user giving overall figures for pollution, cost etc. Although these figures are supported by discrete data it is not presented in a very transparent way. The discrete data on environmental burdens is presented in a number of sub-databases which do not seem to be able to be pulled together. This allows the user to look at the separate environmental burdens of say, processing, but it will become time consuming to work out a complete set of total discrete data for the full life-cycle of the product or system in question.

With more careful thought in the areas of data input and results presentation ImSelection may be a very useful tool for designers as it presents them with material and process selection options in order that they may attempt to reduce the environmental impact of their actions.

5.8.2 Green Design Tool

Kassahun et al. (1995) have also recognised that to 'facilitate the acceptance and eventual incorporation of DFE as part of product design criteria, both the product design and product management community need a friendly DFE tool.'

To this end Kassahun et al. have presented a framework for the development of such a computer tool. As with most of these tools and systems it uses simplified LCA theory with the user identifying the different materials used in the design along with the actual amounts of each needed. This computer tool uses a system termed 'greenness attributes' in order to assess the environmental burden of a design shown in table 5.3.

When the details of the design have been specified the system uses a number of calculations to present a single figure for the 'greenness' of the design.

Attribute Number	Attribute	Description
1	Reusability	Use of sub-assembly in its original form.
2	Label	Any marking associated with materials and means of attachment if applicable.
3	Internal Joints	Any kind of joint within in the sub-assembly.
4	Material Variety	The number of different materials used to make the sub-assembly.
5	Material Identification	Use of international or industry accepted markings.
6	Recycled Content	Recycled content of the material(s) used in the sub-assembly.
7	Chemical Usage	Chemicals used in usage (not in manufacturing processes)
8	Additives	Any material added as a stabiliser.
9	Surface finishes	Any surface treatment.
10	External Joints	Any type of joint which attaches one sub-assembly to another sub-assembly.
11	Hazard Level of Materials	A measure of the degree of hazard, toxicity, etc.

Table 5.3 'Green' Attributes used to Assess Designs - **Kassahuan et al.** (1995)

The product greenness figure merit is, $M_{product}$ is expressed as:

$$M_{product} = \sum M_{\alpha}; \quad \alpha = 1,2,3 \ldots.1$$

where $M\alpha$ is the cumulative figure of merit for attribute α and is given by:

$$M\alpha = m_{\alpha j} \; W_j$$

where W is the weighting factor for attribute α and j is the number of the sub-assembly within the product.

By calculating the total number of attributes for each sub-assembly of the design, multiplying them by the appropriate weighting factor and adding them all together a total 'greenness' figure is calculated. This allows designers to compare different design options on a single criterion.

There are problems associated with this type of assessment as discussed earlier. In this case there could be a very big problem with weighting factors. If the weighting factors are only slightly inaccurate the cumulative error by the end of the calculation could be very large.

The literature does not show if the computer tool offers actual discrete emissions data to designers. However this tool is useful for assessing attributes which are difficult to quantify, such as labelling or mixing materials.

As with most computer tools this system does not actually offer any advice to the designer and contains no 'expertise' within. The final decision is left solely on the designer, which many argue should be the case, but the designer is required to have a certain degree of knowledge about environmental problems and how to reduce them through design which may not be the case. The system does not offer any design options as part of its operation.

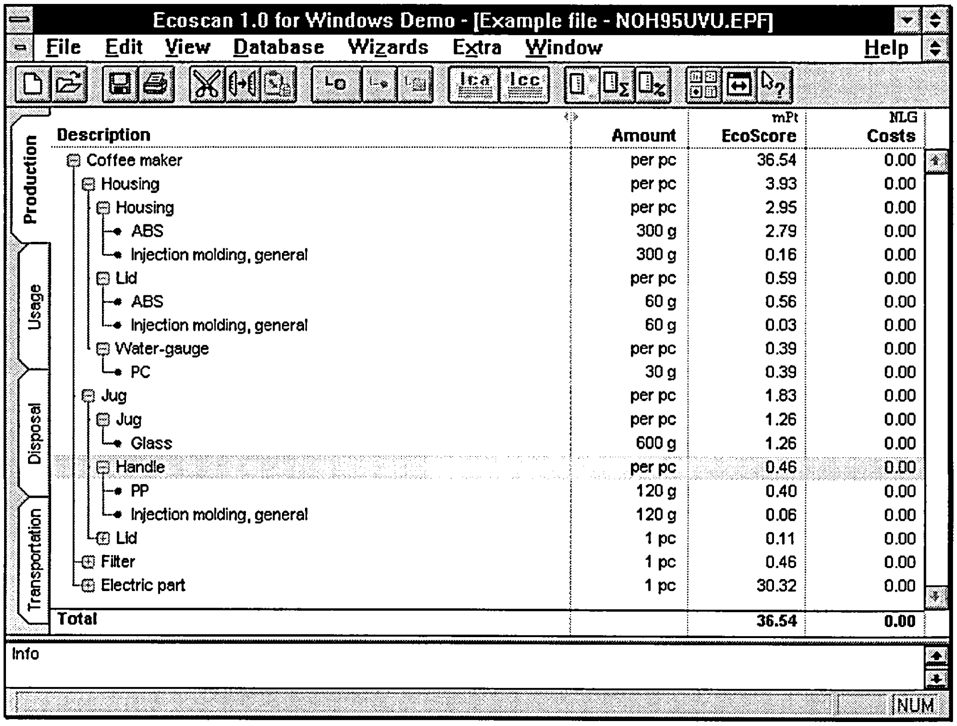
5.8.3 The Latest Computerised Environmental Design Tools

Recently two more computerised DFE tools have become available commercially. These tools are Eco-Scan and ECO-it and both are simple to use abridged LCA design tools.

5.8.3.1 Eco-Scan

Eco-scan allows the simple description of products by breaking them down into their component parts and specifying the materials, weight and processes of the part. Information on other life-cycle stages, transport, use and disposal, is also included. Figure 5.20 shows the user interface of this system.

The calculation of environmental impacts is based on the eco-indicators method discussed earlier. The software itself contains a comprehensive database of materials, processes, transportation data and disposal scenarios.



Description	Amount	mPt EcoScore	NLG Costs
Coffee maker	per pc	36.54	0.00
Housing	per pc	3.93	0.00
Housing	per pc	2.95	0.00
ABS	300 g	2.79	0.00
Injection molding, general	300 g	0.16	0.00
Lid	per pc	0.59	0.00
ABS	60 g	0.56	0.00
Injection molding, general	60 g	0.03	0.00
Water-gauge	per pc	0.39	0.00
PC	30 g	0.39	0.00
Jug	per pc	1.83	0.00
Jug	per pc	1.26	0.00
Glass	600 g	1.26	0.00
Handle	per pc	0.46	0.00
PP	120 g	0.40	0.00
Injection molding, general	120 g	0.06	0.00
Lid	1 pc	0.11	0.00
Filter	1 pc	0.46	0.00
Electric part	1 pc	30.32	0.00
Total		**36.54**	**0.00**

Figure 5.20 Eco-Scan User Interface

The results can be presented in a number of ways but all allow the designer to identify which stage of the design has the largest impact on the environment. Figure 5.21 gives an example of this.

One interesting aspect of the Eco-Scan software is the inclusion of a life cycle costing module. Although cost data must be calculated by the user it allows the parallel consideration of environmental impact and associated cost. This will show whether there is a correlation between the two costs of whether some of the cheapest phases in financial terms are the most environmentally polluting.

This system is easy to use and gives simple transparent results presentation. It can be used at the design stage as soon as the product parameters have been fixed. It is the type of tool favoured by **Billet** (1996) as it can be easily and readily used by designer who need not have extensive knowledge of factors affecting design and the environment.

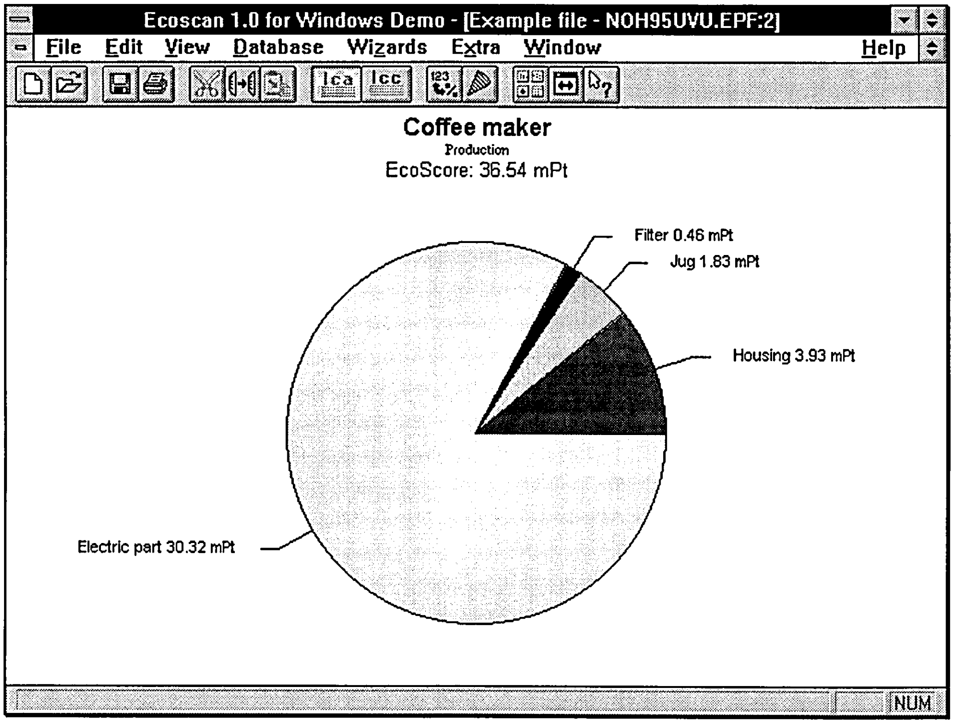


Figure 5.21 Example of Results Presentation of Eco-Scan Software

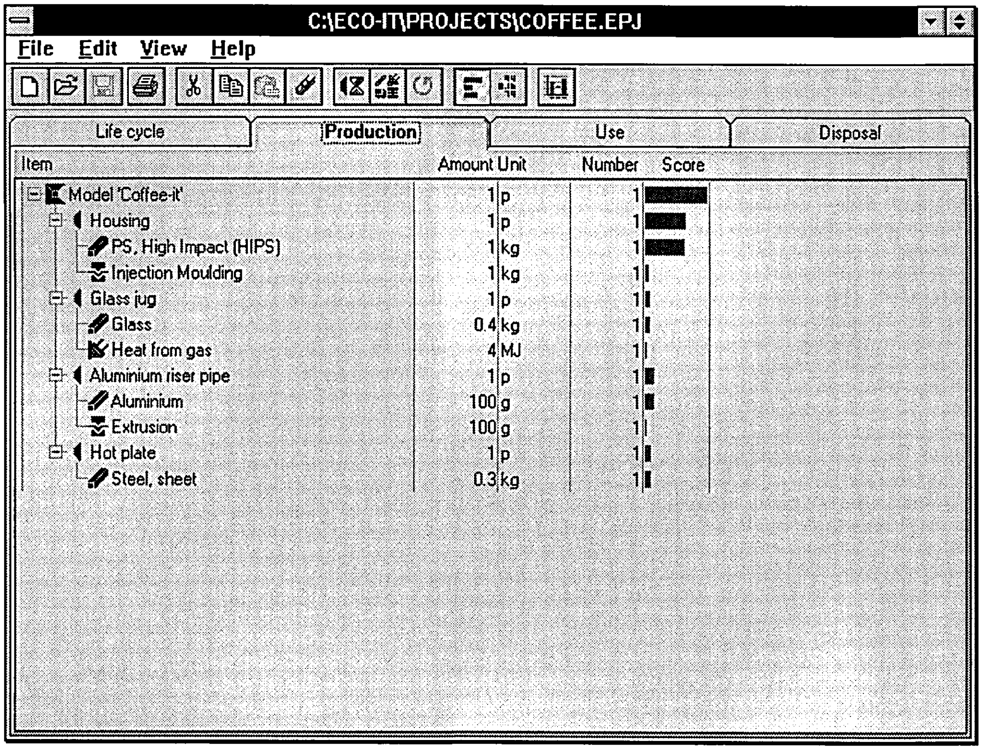
As with all the other tools discussed so far it is lacking in the facility to offer less experienced designers advice on materials and process selection and other issues such as disposal scenarios. Although life-cycle percentage impact is presented no advice on how to reduce this is given.

5.8.3.2 ECO-it

ECO-it comes from the same stable as the SimaPro software discussed earlier and is a direct competitor the Eco-Scan. It again uses the eco-indicators method of calculation and functions in a very similar way to Eco-Scan.

The similarities in user interface can be seen in Figure 5.22. The main difference in the software is the lack of a life cycle costing module in ECO-it.

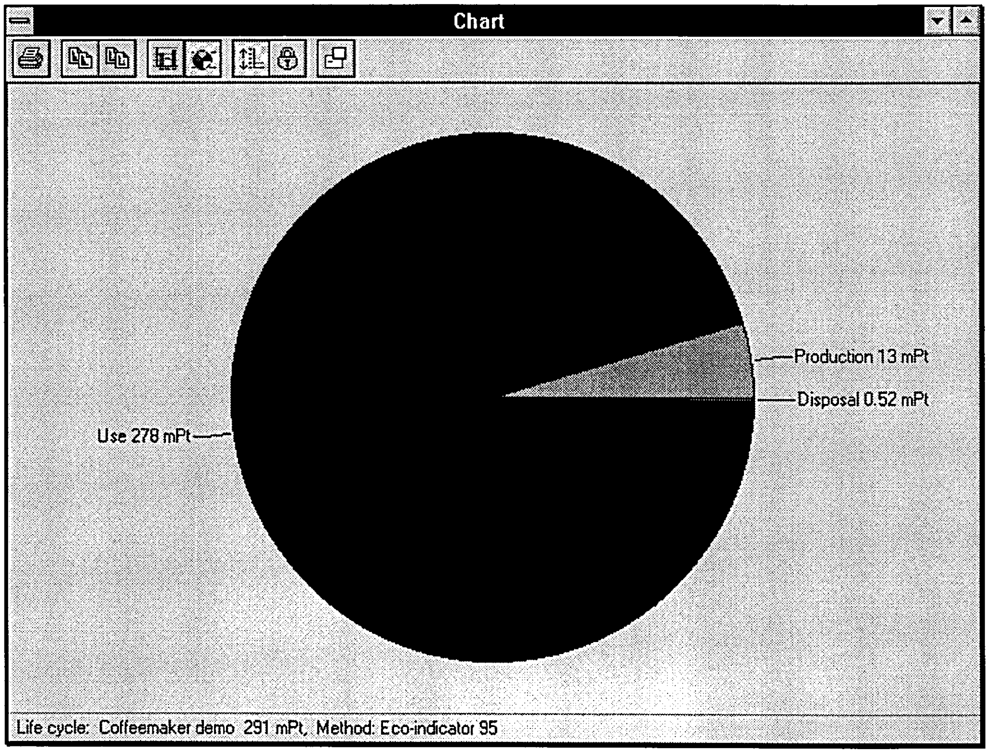
Figure 5.23 shows the way in which ECO-it presents its results. The results are in mPt from the eco-indicators method. As with Eco-Scan there are problems with presenting environmental affect as a single parameter result. This was discussed in more detail in Chapter 2.



Item	Amount	Unit	Number	Score
Model 'Coffee-it'	1	p	1	▮
Housing	1	p	1	▮
PS, High Impact (HIPS)	1	kg	1	▮
Injection Moulding	1	kg	1	▮
Glass jug	1	p	1	▮
Glass	0.4	kg	1	▮
Heat from gas	4	MJ	1	▮
Aluminium riser pipe	1	p	1	▮
Aluminium	100	g	1	▮
Extrusion	100	g	1	▮
Hot plate	1	p	1	▮
Steel, sheet	0.3	kg	1	▮

Figure 5.22 User Interface of ECO-it Software

This tool is another simple and effective way in which designers may carryout LCA exercises and use them in DFE studies. Design advice is not given by this software tool.



Life cycle: Coffeemaker demo 291 mPt, Method: Eco-indicator 95

Figure 5.23 Results Presentation of ECO-it Software Tool

5.9 Chapter Summary - Overall Needs within DFE Methods

As this chapter has shown there is much work going on in the area of DFE and particularly in developing methods and systems for designers to use. There are however some unfulfilled needs within these systems and methods.

Currently most of the methods and systems are:

- Structured
- Relatively simple to use
- accelerate the DFE process
- allow comparison of different design options in environmental terms

Only some of the systems offer:

- transparent presentation of results
- a degree of advice in terms of design options

What is needed is a DFE method or system which is easy to use and does not require the designers to have in depth knowledge of the environment and its related problems. By reviewing the systems already in use or under development the following attributes have been identified as unfulfilled requirements of a useable DFE system:

- Mechanisms which help to identify the correct environmental design strategies to adopt in order to address the environmental problems in question.
- Methods of selecting materials on a mechanical/environmental basis without the requirement of detailed data in terms of mechanical properties and geometric shape.
- Systems which present the designer with advice as to design changes, in terms of materials, processing and disposal routes, which if implemented will result in a reduction of the total life-cycle environmental impact of the system.

Due to the huge amount of data manipulation and calculations that such a system requires it is anticipated that they will be developed in the form of computer tools. As with many engineering design strategies computerisation will help structure and accelerate DFE. It has also been shown by **Ryding et al.** (1993) that 'there was a massive support for the development of practical and user friendly PC-based LCA software.'

Chapter 6

Knowledge Based Systems and their use in Environmental Design

Knowledge Based Systems and their use in Environmental Design

6.1 Introduction

There are many ways in which one may use computers as aids to the design process. This has been shown by **Colton & Dascanio** (1992) and **Diteman & Stauffer** (1992) who have reviewed the way in which users may interact with such tools as well as their framework and uses. Figure 6.1, **Dym & Levitt** (1991), shows the relationship between developments in computer science and engineering applications in general terms. The conceptually simplest form of such a tool may be a numerical manipulation package such as spreadsheets, these tools are by far the most common and widely used. Further up the hierarchy are drawing packages and CAD systems., the current generation having progressed to parametric CAD systems which automate the design process to a certain degree.

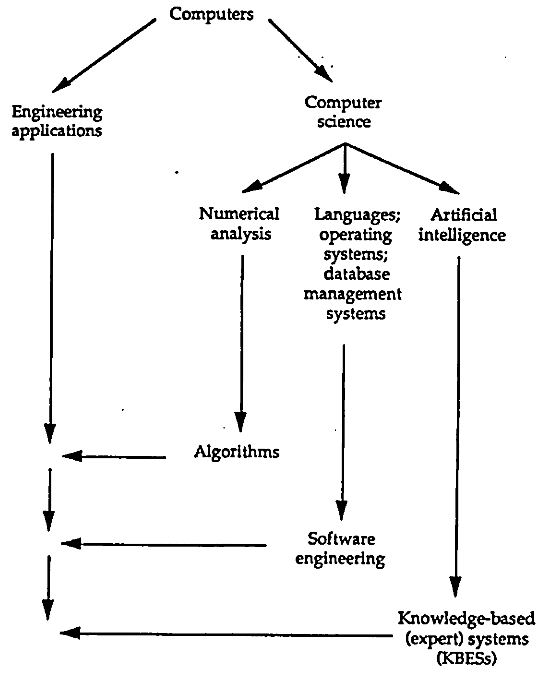


Figure 6.1 Relationship between Developments in Computer Science and Engineering Applications

When using computers to support design activities it is important to identify the levels of knowledge that are required. **Szykman & Cagan** (1992) showed that it can be separated into 3 areas:

1. knowledge about the design instance
2. knowledge about the domain of the design
3. various levels of abstraction of the knowledge.

Ryan & Harty (1990) describe a methodology for computer aided preliminary design which is based around the theory that 'successful design is one which satisfies, to an acceptable extent, a number of constraints', with these constraints rising form a number of different sources. This is what has become known as knowledge based design.

Green (199?) defined Knowledge based design as incorporating 'design rules, costing data and company expertise to produce a design solution that not only meets the needs of the design group but also satisfies the rest of the companies departmental and managerial needs.'

Computer aided knowledge based design can aid the conceptual design phase and incorporate the downstream needs of the production department at this very early stage, **Green** (199?). There are many downstream activities and needs which can be addressed at the design stage and as discussed in earlier chapters, environmental considerations are growing in importance. Potentially the most comprehensive and powerful design tools are those which use the technologies of Artificial Intelligence (AI) and its subset Expert Systems (ES). Such tools can automate the process of knowledge based design and are being incorporate in the next generation of design aids as they embody expertise and aid the design process.

Computer based tools may provide valuable aids to the development of 'green' design and manufacturing practices and a powerful system to support concurrent engineering. For specific use in areas of environmental interest such tools should supply developers and designers with up-to-date information in a readily usable form. To this end a number of different tools may be suitable, such as databases and spreadsheets but as in the case of general design support the

AI and ES tools may offer the best opportunities.

'For over a decade now AI techniques have been applied to some of the hardest problems faced by business today often with stellar results and a ten-fold plus return on investment.', **Herberg** (1993). **Holloway & Tranter** (1995) have studied this area and concluded 'With environmental problems being some of the most far reaching that engineers have had to deal with it seems Expert Systems and AI could offer the answer.' As with most computer aided tools there a number of different scenarios in which AI and ES can be used. In order to assess the way in which these tools may be used in design generally and specifically in green design, and what degree of support they can offer to design teams, we need to look at expert systems and how they are developing.

6.2 Knowledge Based Systems

An expert system is 'a computer program that represents and reasons with knowledge of some specialist subject with a view to solving problems or giving advice', **Jackson** (1990). These systems may be used to fulfil functions which normally require human expertise or as advisors to decision makers. If the user is an expert in the field then the computer system must justify itself by increasing his productivity. Alternatively the system may tutor users with less experience allowing them to develop a level of expertise with assistance from the programme. Typical tasks for expert systems include data interpretation, diagnosis, structural analysis, complex configuration and planning sequences.

The term knowledge based system is often used to describe expert systems although strictly speaking the former is a much more general term. A knowledge based system contains information that will allow it to converse about a certain subject while an expert system will embody the expertise of the area allowing it to make its own decisions.

6.2.1 Basic Architectures of Knowledge-Based Systems

The basic architecture of a knowledge based system is shown in Figure 6.2, **Dym** (1985).As can bee seen in basic form it has five main parts:

- Input/output facilities allow the user to communicate with the system and to create and use a database for the specific case in hand.
- A working memory which contains the specific problem data. This includes the data from the user interface as well as the intermediate to final solutions created by the system itself.
- An inference engine that incorporates the reasoning methods. This engine uses the data from the input facility together with the data and knowledge held within the knowledge base to solve the problem and provide an explanation for the solution.
- The knowledge base contains the basic knowledge of the domain or subject. As the knowledge in most cases will come from human experts it contains facts, beliefs and rules unique to the expert or domain.

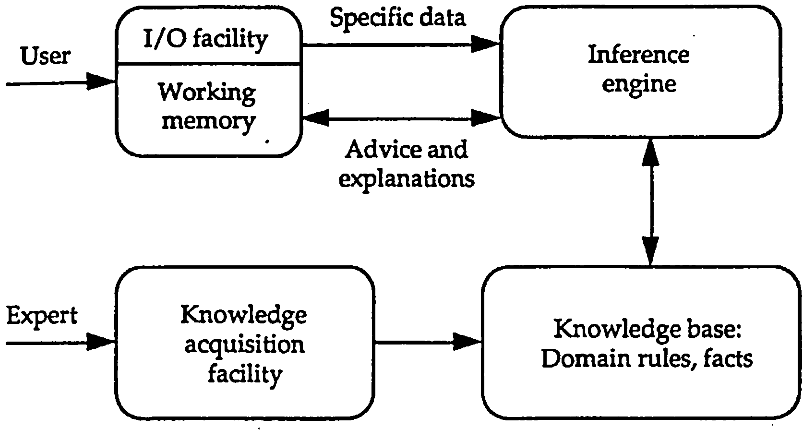


Figure 6.2 The Components of a Basic Knowledge Based System. **Dym** (1985)

The knowledge acquisition facility is not always an integral part of KBS. This facility can allow the system to acquire additional knowledge about the domain from the experts as it changes or needs to be updated. Some systems may be automated to allow the automatic acquisition of data from libraries, databases, etc.

Though definitions vary **Jackson** (1990) suggests that there are a number of features all of which should be exhibited to some degree in any expert system:

- Simulation of human reasoning. The program focuses on emulating the experts problem-solving abilities *i.*e. performing the relevant tasks as well or better than the expert.
- It performs reasoning over representations of human knowledge. The knowledge in the programme (knowledge base) and the codes that perform reasoning (inference engine)are kept separate.
- Problems are solved by heuristic or approximate methods which are not guaranteed to succeed. Heuristic methods are rules of thumb which do not require exact data to propose a solution. Such solutions derived by this system are proposed with differing degrees of certainty.
- The complexity of problems dealt with by the expert systems usually require a significant degree of human expertise. Unlike many AI programs which are purely research vehicles, expert systems, because of their relative simplicity, solve problems of genuine commercial or scientific interest.
- To be a useful tool it must exhibit high performance in terms speed and reliability. A useful expert system must propose solutions in a reasonable time and give correct solutions at least as often as a human expert.
- As an expert system may be used by a wide range of operators, who may not have the relevant knowledge of the field, the systems should be able to explain and support the decisions or recommendations it makes and justify the reasoning involved.

By looking at the basic architecture of an expert system and some of the tasks that they might perform it is apparent that this basic architecture may need to be expanded in some cases. Figure 6.3, **Maher & Allen** (1987), shows the components of a more elaborate knowledge-based (expert) system.

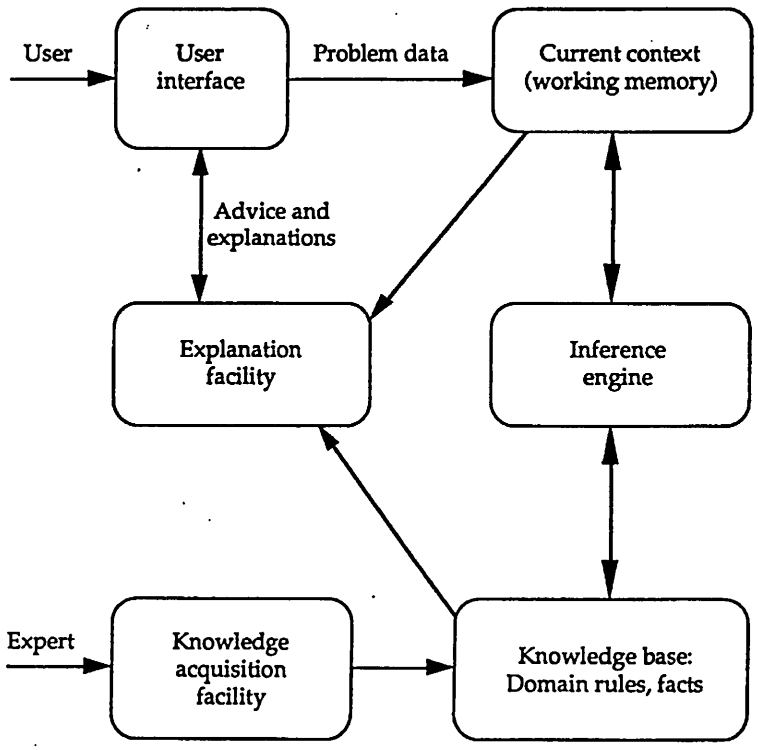


Figure 6.3 The Components of a more Elaborate Knowledge Based (Expert) System., Maher & Allen(1987).

As can be seen this structure includes an explanation facility that explains to the user the reasoning behind any particular problem solution. It is this particular feature that is important when using the ES as an advisor. In the same way as we want human experts to explain their reasoning when they make a decision or give us advise, we need expert systems to be transparent and make their chain of reasoning explicit. With the ability to explain reasoning ES become more readily accepted by their users.

There are a number of methods of knowledge representation in ES, which include:

- Objects and properties
- Classes and instances
- Rules
- Objects and relations

6.2.2 Knowledge Representation

As mentioned earlier in this chapter there are a number of ways in which knowledge may be represented in ES and each will have a possible use in supporting design. **Klein** (1992) and **Xue & Dong** (1993) have looked at the way in which differing representations may be used.

6.2.2.1 Objects and Properties

Essential parts of representations are objects. Objects may be both physical or non-physical. By defining an objects attributes properties and methods may be allocated to it. 'The values of these properties describe the object.' **Klein** (1992). Many design activities are based on the consideration of object properties, be they mechanical, financial or environmental. Objects also contain methods, pieces of programming code which are generally used to perform internal calculation or reasoning and communicate with other objects.

6.2.2.2 Classes and Instances

In many design activities it is useful to sort objects in classes. Each class can have defined properties and property values.

These classes may be formed into hierarchies and so give a structured representation of knowledge. Classes can be split into subclasses with the lowest level classes being called instances as shown in Figure 6.4. This is a simple hierarchy which could be used to represent engineering materials and their properties. Properties and their values can be brought from a super class to a class through inheritance. For example the property of high electrical conductivity may be placed in the class metals and inherited down to all the subclasses and instances. This will help in design as it can aid the search for different materials matching certain property requirements, and can provide default general characteristics in circumstances where the detailed data about an instance is not available.

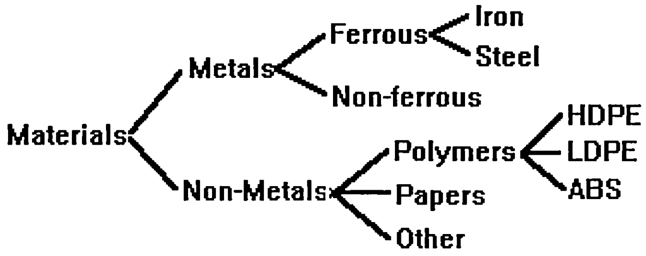


Figure 6.4 Example of an Object Hierarchy (classes and instances)

6.2.2.3 Objects and Relations

Relations are a way of creating "Object x Attribute x Value" triplets. Defining relations allows flexible handling of objects. In certain phases of the design process and specific design activities it is this flexibility which will help ES become more readily used. **Bowden & O'Grady** (1989) argue that flexibility of computer design tools at the conceptual design phase is of the utmost importance to designers.

6.2.2.4 Rules

Early knowledge based systems used a rule-based design to handle facts. Today systems often allow multiple forms of representation and 'rule-based handling of complex objects is increasing in modern systems.' **Klein** (1993). Rules can be used for a number of purposes including the definition of property values, description of relationships between objects and fixing constraints. Again many design activities are carried out using formal rules or 'rules of thumb' (heuristics), thus a rule based representation maps well. By developing systems using these architectures and structures, we may produce effective support tools for use in many aspects of engineering design.

6.3 Developing Expert Systems

As with many developing disciplines the results of developing the 'first generation' of expert systems yielded some useful results and outlined a number of limitations:

1. Many of the systems where developed using a rapid prototype approach which makes management of the system development very difficult.
2. They were very limited in their scope. Many systems would begin to perform very badly as soon as they were required to solve problems outside their very narrowly defined scope or they had to deal with incomplete knowledge.
3. Most of the systems adopted a simple rule based approach to representing the expertise. This causes different types of knowledge to become combined in the knowledge base making the system very difficult to maintain.

These results lead to the development of a methodology which structured the building of expert systems. This methodology is called KADS.

6.3.1 The KADS Methodology

The KADS methodology grew out of work being carried out by a number of people developing models of expertise including **Breuker & Wielinga** (1985), and **Steels** (1990) and has now been replaced with *Common*KADS.

KADS and *Common*KADS advocate what is essentially the same approach and it is 'intended that *Common*KADS will become the standard methodology for developing knowledge based systems.' **Barker** (1995). *Common*KADS uses a model based approach to expert system design

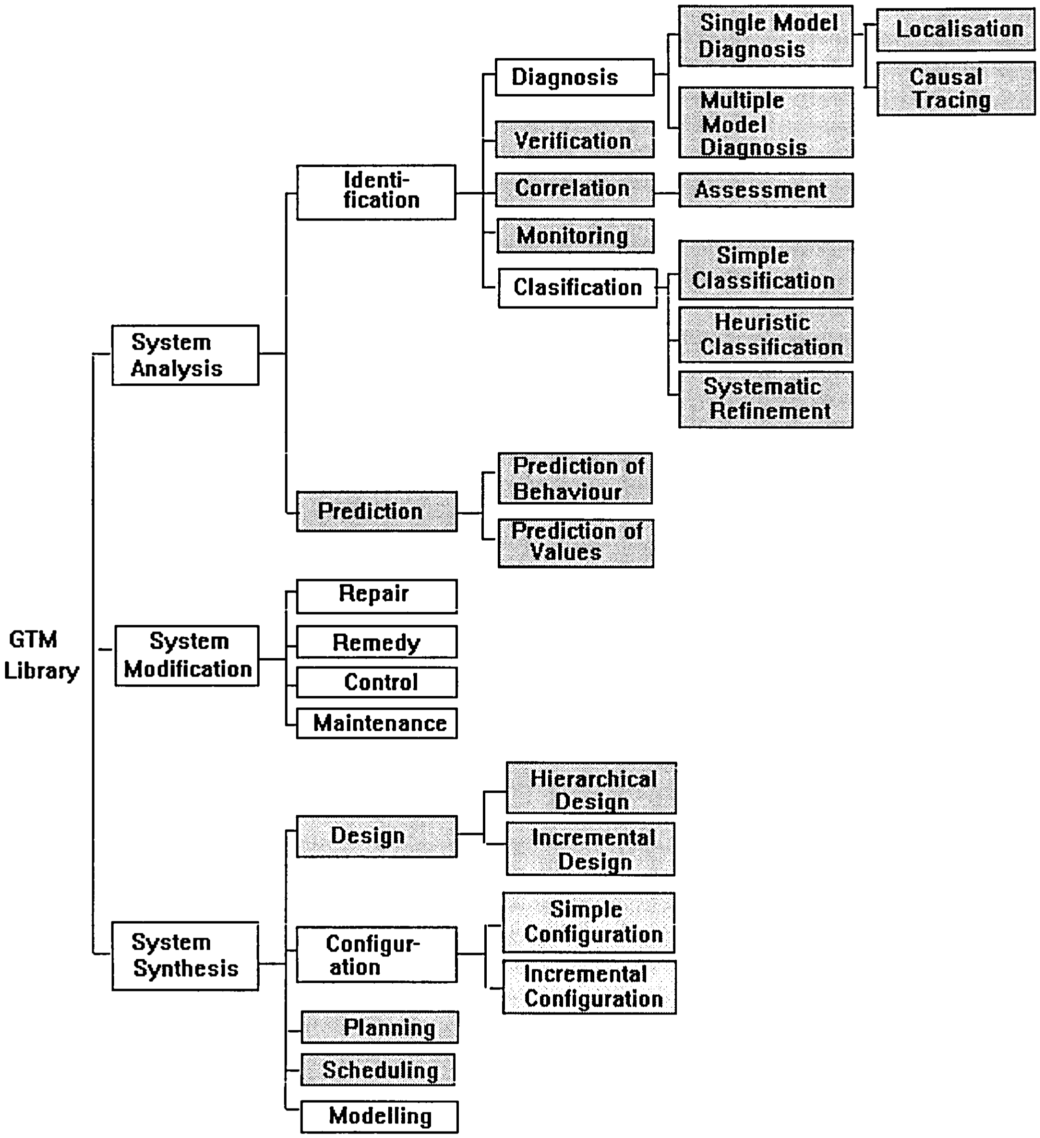


Figure 6.5 The CommonKADS Generic Task Library - **Tansley & Hayball** (1993)

and suggests that many of the tasks for which expert systems are used are indeed generic in nature. As can be seen form figure 6.5, **Tansley & Hayball** (1993), there are a large range of tasks which the *Common*KADS method sees as being generic.

Detailed description of the *Common*KADS method will not be undertaken in this work. To briefly summarise the use of the *Common*KADS methodology will allow the development of reliable, flexible, easily maintained expert systems through approaches such as evolutionary prototyping.

Hickman et al. (1992) give an overview of the KADS methodology as follows:

- it uses a modified waterfall-type life-cycle model to describe the KBS development process, based on the conventional systems development life-cycle model of analysis, design and implementation;
- it provides an additional set of supporting methods and techniques to account for areas such as expertise modelling and knowledge elicitation;
- it specifies milestone work packages and deliverables, including a full set of requirements and knowledge base documentation. The deliverable form the baseline for work in the next phase;
- it provides a set of rules and guidelines (or *normative support*) governing the traversal of the life-cycle model and the production of deliverables.

6.4 Uses of Expert Systems

Applications can be found in all the engineering disciplines but certain areas are more active than others. **DTI** (1989) showed this order of activity, table 6.1. The most active areas were those which were directly related to a function of the supporting software systems. For example design support clearly corresponds to design while testing corresponds to diagnosis.

Many of the areas of application are relatively new but there are a number of commercially available ES which are in use.

Maintex is a generic ES for fault diagnosis. It is used in the automotive industry by companies such a Renault and Peugeot.

Renault use the system for diagnosing problems in the quality of the paint used in the manufacture of its cars. It can handle 13 different types of paint faults, related to 72 basic paint components.

LINKMan is an example of a process control ES. It was developed in 1986 to control the operations of kilns used by a cement manufacturing company. It is an expert system which used the standard cement kiln instruments together with data from the analysis of the exhaust gases to optimise kiln conditions.

Most Active	Diagnosis
	Materials Design
	Design
	Process Planning
	Management Aids
	Process Control
	Scheduling
	Configuration
Least Active	Modelling / Simulation

Table 6.1 Application Areas of Expert Systems

Another example of a commercially used expert system is ACHILLES. This is a demonstration corrosion expert system that has three functional goals: materials selection, failure analysis and tutoring. 'ACHILLES can be used to get definitive advice on the selection of materials, of protective systems, of monitoring methods and of inspection techniques.' **DTI** (1989).

6.5 Knowledge Based Systems in Concurrent Engineering & Design

Design, especially concurrent design, is one of the most active areas in the use and development of expert systems. In terms of computer support for design one of the primary roles is 'to provide information in a simple and well structured form to support analysis and decision making.', **Miles & Swift** (1994). Expert systems have the ability to do this and thus may be a great aid to concurrent engineering.

When it is considered that concurrent engineering or design takes into account considerations within manufacturing, testing, redesign use etc. it can be seen that the information requirements are immense. To this end **Bowden & O'Grady** (1989) have identified the principal requirements of a computerised system to support concurrent engineering:

- It should be flexible enough to allow the design problem to be approached from a variety of viewpoints
- It should allow the designer to design despite the absence of complete information
- It should handle the large volume, variety and interdependence of life-cycle information
- It should exhibit high performance in terms of speed and reliability
- It should readily interface to database management and CAD systems
- It should have a good user interface and be able to explain itself in a manner comprehensible to humans
- It should support design and environmental audits and be easily updateable as new information becomes available.

An expert system used in concurrent engineering / design should also display these characteristics. These characteristics will be dictated to a certain extent by the way in which the knowledge is represented within the system.

6.5.2 Knowledge-Based and Expert Systems for Design Support

A considerable amount of work has been carried out in the area of ES and KBS in design. From the building of such systems, **Huang & Brandon** (1992), to their use and implementation, **Ishii & Hornberger** (1992), and their impact on technical development, **Chen** (1991), many issues have been raised. Part of this research, although taking these issues into account looks mainly at how the use of expert system may structure and accelerate a new and emerging design discipline.

Schiebeler & Ehrlenspiel (1993) define the knowledge based system for design assistance as 'a tool for the designer which supplies assistance in certain phases of the product development'. This assistance may be in one of many forms as discussed at the beginning of the chapter. There is one very important aspect of ES and KBS in design, that of flexibility. **Klein** (1993)

argues that the design engineer should have the possibility to 'extend and modify the knowledge base for special purposes' thus building in this large degree of flexibility.
In order that this flexibility be achieved there are a number of KBS approaches to engineering design as discussed by **Dym & Levitt** (1991). They present their abstraction of a taxonomy of methods for solving arrangement problems in increasing order of specificity.

- Analogy and mutation - uses case-based and analogical reasoning
- Assembly of solutions from elementary components - uses logical programming techniques, production rules or high level object oriented programming tools.
- Hierarchical generation, testing and evaluation of solutions - uses production rules, or frame-based representation as well as inferencing.
- Prototype selection and refinement - uses rules and frames.
- Pure selection - uses heuristics.

The type of approach used will depend mainly on the exact design exercise being carried out. This is supported by **Colton & Dascanio** (1991) who state 'Models of design contain information that describes the various phases of the design process and estimate the sequence of and the interaction between these phases. Models can have many forms and cover any range of the design process depending on the purpose of the study.' Both **Bascaran et al.** (1992) and **Chung et al.** (1993) have looked into the way that different design disciplines and environments will require different approaches to developing ES and KBS and decision support tools.As a result of the work carried out in this area there are a number of ES which have been developed to support all areas of engineering design.

6.5.2.1 Examples of Expert Systems in Engineering Design

Yasuda et al. (1992) developed an expert system for the material design of steel pipes. The design of material structure controls uses many related factors which can not be systematised and so is very complicated. By using ES technology Yasuda et al. have developed a computerised system which accelerates and improve the quality of materials design. The system consists of 300 rules, a large PL/M program and 50 - 100 databases. **Yasuda et al.** (1992) conclude 'As processing is made according to the expert designers thinking process, there is no difference in feeling, and it can be said to be a system that is easy to use.' A new methodology is proposed for enhancing design management and co-operation by **Guo et al.** (1992). The integration architecture, principles and implementation for Integrated Intelligent Design Environment (IIDE) are presented. The example shown, of engine design process management, consists of databases and a mixture of objects and rules linking everything together. The design results can be represented graphically as fully dimensioned engineering drawings. Using the system for mechanical design They conclude that the integrated system shows great potential to solve complex real design problems.

A KBS called REKK is a design assistance tool that supplies assistance in certain phases of product development developed by **Schiebeler & Ehrlenspiel** (1993). It consists of several task specific modules as a hybrid system rather than a pure rule based or object oriented system. The system is demonstrated using gearbox design as an example. As well as the model costs of the gearbox, the whole costs of the gearbox and the costs of the entire gearbox assembly can be calculated. The system also links to CAD and parts may be checked for manufacturability and costs through a direct link to the KBS. In this system three processes (relational database, CAD system and KBS) run simultaneously. They claim that the system supersedes those whose internal data-structure and programming interface cannot cope with highly complex elements. They go on to say that 'the results of this project help to show how future design-assisting systems may be further developed.'

Other examples of ES in engineering design are: an Integrated Circuit Design Critic, **Steele et al.** (1992); a KBS for selecting shaft-hub connections, **Klein** (1992); a KBS for engineering idealisation, **Prabhakar & Sheppard** (1992), an ES for the design of components made from powder ceramic materials, **Victor et al.** (1993) and an ES for performing techo-economic feasibility studies in the capital equipment industry, **Bate et al.** (1994)

As this chapter has shown the technologies of AI, ES and KBS have been applied to a large number of different areas one of the most active of which is design. Most of the systems and tools developed have been used in areas of design which involve complex relationships and large amounts of data processing.

Earlier sections of this work have shown how Design for Environment is becoming increasing important and that environmental concerns are very much on the agenda of every designer. The process of EIA can be integrated into the design process quite simply. The main causes of concern are the massive amounts of data this involves and the problem of unstructured methods with which to carry out the comparison of different designs, materials or processing options. It is these problems which offer the opportunity for ES and KBS technologies to be used and as a result accelerate and structure the process of environmental design.

6.6 The use of Knowledge Based Systems in Environmental Design

In order to support environmental design and manufacturing, or DFE as a concurrent engineering imperative there is a need for the development of user-friendly computer-based tools. A survey carried out has shown that 'there was a massive support for the development of practical, user-friendly PC-based LCA software', **Ryding et al.** (1993).

As shown in Chpater 5 **Poyner & Simon** (1995) have looked at the current computer based DFE tools that are available and shown that most of the tools aid the designer in analysing certain aspects of product design and advising on environmental improvements. As earlier sections of this work have shown the advisory part of the tools is limited or absent. It has been shown that the architecture and operation of expert systems closely match the requirements of these functions, **Holloway & Tranter** (1995).

There are very few KBS or ES available in the area of environmental design at the moment, but those that have been developed are very diverse in their mode of operation and area of detail.

Diaz-Calderon et al. (1994) have developed an ES that is combined with a geometric modeller. It is used to evaluate geometric models of assemblies or parts for material compatibility and fastening techniques. This type of tool is particularly useful in disassembly and recycling studies. By using such a tool the correct mix of compatible materials and non-permanent fastening techniques may be integrated into a design allowing easier recovery of materials at the end-of-life of a product.

Another expert system has been developed by **Navin-Chandra** (1993). This again looks at the end-of-life details of a product in terms of reuse/recycle choices at each stage of disassembly. The disadvantage of this system its requirement of complete geometric assembly relations. This means, that the system will only ever be of real use at the detailed design stage.

As most of the environmental effect of a product or system is made at the design stage it is essential that the right decisions are made at the very beginning of the design process.

Chen et al. (1995) have developed a ES called ImSelection which deals with environmental cost as well as financial cost of materials. The specifics of this system were discussed in an earlier chapter.

6.7 Chapter Summary

This chapter has discussed the nature and use of expert and knowledge-based systems and showed that there are a number of definitions of what constitutes a KBS and also what performance characteristics are required. Expert systems and KBS have been used in a number of fields not least design and the advent of concurrent design with its demand for ubiquitous expertise, has opened even more opportunities. With the ability to increase productivity of engineers and designers and the capacity to advise or tutor users, ES and KBS offer great opportunities in environmental design. A number of systems are already in place or under development all of which assist the designer, to a greater or lesser degree in taking environmental concerns into consideration during design. However these systems do have a number of failings as discussed earlier.

What is required is a simple KBS which will help designers to create environmentally acceptable products through careful choice of materials, processes and disposal routes. It must have a simple user interface, contain relevant environmental data, and deliver the results in a clear and concise manner. Such a system will help to integrate the consideration of environmental concerns into the design process both quickly and relatively easily.

Chapter 7

Contributions of this Research

Contributions of this Research

7.1 Introduction

The preceding chapters of this thesis have looked at many aspects of engineering and the environment and also at a number of options that are open to engineers in attempting to reduce the environmental impact of their actions.

As this work has shown, there are many problems facing engineers and designers when it comes to developing new methods and systems which allow the integration of environmental concerns into the design process. It is the development of transparent, easy to use environmental design methods which will enhance this environmental integration and make it the norm in the near future.

This chapter will summarise the state of the art at the present time, outline the apparent needs still unfulfilled and explain the approach adopted in this research to addresses these needs.

7.1 Summary of Current Practice and Developments

In recent years there has been a large increase in concern shown for the environment and as a result there has been a corresponding increase in research carried out in related areas. It is now generally accepted that prevention is better than cure and consideration of impacts in retrospect is no longer acceptable practice, **Keoleian & Menery** (1993). It has now also been accepted that if we are to adopt a preventative stance that a holistic approach is essential, **Sullivan & Young** (1995), **Fava** (1993) and **Kusz** (1991). Every stage of a product or system's life-cycle must be taken into account form raw material extraction right through to ultimate disposal. Techniques such as LCA are now generally accepted and allow engineers and designers to assess products and systems on a cradle-to-grave basis, **SETAC** (1991).

Much work has been, and is currently being, carried out in an attempt to standardise environmental design practices and frameworks. Work by **Braden & Allenby** (1993), **Ryding et al.** (1993) and **Olesen & Keldmann** (1993) amongst others, have all presented frameworks for designers and engineers to use in carrying out environmental design. These works all have a general common theme and are based around the principles of LCA but at the present time there exists no standardised method for environmental design. The methods which are in place contribute but their limitations must be understood if they are to be used correctly and yield acceptable results. It is very easy to become complacent when using such tools.

Due to the large amounts of data involved in LCA studies and environmental design a number of methods and systems have been computerised in order to accelerate the process. Examples of these such as **Ryding et al.** (1993), **Cleij et al.** (1993) and **PIRA** (1994), discussed in the preceding chapter are now in general use.

The current leading-edge of computerised LCA and environmental design systems are utilising expert system technology such as the work carried out by **Holloway & Tranter** (1995) and **Chen** (1995) amongst others. Almost all of the work to date has presented the user with information but made no attempt to guide the decision making process. There are many reasons for this, not least that environmental design and LCA systems are still not standardised.

7.2 Unfulfilled Needs Related To Current Practices

As discussed earlier, due to the complexity of environmental design current practices are by no means standardised or fully developed. Therefore there are a number of problem areas apparent within current practices which need to be addressed. In order to evaluate which needs are currently unfulfilled it may be useful to look at what engineers see as the most important aspects of environmental design systems and methods. **Ryding et al.** (1993) have shown that the top 6 most important aspects of environmental design systems to manufacturers are as follows:

1. Identifying processes, ingredients and systems that are major contributors to environmental impacts.
2. Comparing different options within a particular process with the objective of minimising environmental impacts.
3. Providing guidance in long-term strategic planning concerning trends in product design and materials.
4. Evaluating resource effects associated with particular products including new products.
5. Comparing functionally equivalent products
6. Helping to train product designers in the use of environmentally sound products and materials.

Aspects 1, 4 and 5 of the list above are all covered to a good degree in the methods and systems which currently exist. However aspects 2, 3 and 6 are lacking in the current state of the art and need to be addressed.

7.2.1 Comparison of Different Options

The comparison of different options is addressed by most of the systems available and particularly efficiently by the computer tools such as SimaPro, and PEMS. This comparison is carried with a view to reducing environmental impact. Most of the systems available, apart from ImSelection, **Chen** (1995), only compare options suggested by the user. Uniquely ImSelection will attempt to offer materials which meet user defined requirements.

If environmental impact is to be reduced to a minimum then other options may need to be explored. If the environmental design system could offer advice to designers in the form of materials or process selection then impact may be reduced further. For example if the user is comparing materials one may be more environmentally friendly than the other. However there may be another material, that the designer has not specified, which does even less damage to the environment and can perform the same required function.

The development of a system which will compare and select materials and processes, on an environmental basis, from user specified performance requirements, in addition to comparing user specified materials and processes, is a need which is currently unfulfilled.

7.2.2 Strategic Planning Guidance

A system to provide guidance in long-term strategic planning may not be possible at the present time. There is however a demand which has yet to be addressed. Much of the work carried out to date has laid down guidelines for environmental design and what it entails, see for instance **Burall** (1991) & **MacKenzie** (1991) and others, but very little work has been carried out to guide designers and engineers towards the best design strategies to adopt in an attempt address the environmental problems which are apparent in a particular case.

A system is needed which will guide designers on strategies. As strategies are dependent on key features of the product life-cycle this in turn generates a requirement for a taxonomy of product types - a product classification system. Such an approach will allow designers and engineers to describe the product or system in question in terms of life-cycle parameters and thus be guided as to which strategies to adopt. For example if a product has a very short life-cycle and consumes no energy during that life-cycle then there a certain design strategies which may be adopted to effectively reduce its environmental impact in this case mainly materials selection, processes and disposal issues, such as energy recovery or recycling. Strategies such as lightweighting and life extension are obviously not appropriate.

Such a system of guiding designers to the most effective strategies does not exist at present. It has been suggested that 'best practice' in environmental design is 'the careful consideration of the environmental problems particular to the operations in question and the adoption of appropriate strategies in order to address these problems as thoroughly as possible.' **Holloway et al.** (1995). The development of a system which supports this will help further environmental design.

7.2.3 Training Designers in Environmental Design

Training in environmental design and associated disciplines such as LCA is very much at the forefront of environmental issues for engineers and designers. Much of the groundwork is already in place and the number courses being offered is on the increase. **Devon** (1993) has pointed out the importance of education and training in design and especially in 'green' design. Education and training should start from the early stages in schools and colleges and carry through to universities and eventually in company training such as Continuing Professional Development courses. These systems are now in place and environmental concerns are becoming an everyday issue in the education of our children. The training of existing engineers and designers who are already in the work place is a more challenging task.

Many of the designers who are now required to take on board environmental considerations have little or no knowledge of the subject. **MacKenzie** (1991) has shown that environmental issues are no longer the speciality of experts and that what was once seen as a moral judgement on the part of the practitioner is now a vital design consideration.

Current education and training for industrialists is typically effected by the presentation of case studies and use of guidelines for design etc. There is an unfulfilled need for systems which actually encourage learning as part of their operation. Learning may be helped by use of expert systems and artificial intelligence techniques. As such systems contain expertise within themselves, if there are written in a way which explains the decisions made and shows the rules and expertise used they will tutor the user, **Barker** (1995).

There is a need for a system which will forward suggestions to engineers and designers of how to reduce the environmental impact of products or systems while at the same time making known the rules and heuristics used. The more the system is used the more tuition in the underlying principles the user will receive.

7.3 How this Research will Addresses the Unfulfilled Needs

As the literature survey and review of current practices has shown there are unfulfilled needs and requirements in environmental design systems and methods. This research has attempted to address some of these unfulfilled needs by the development of new methods within environmental design. The starting point of the research was to assess how environmental design fitted into the overall scope of concurrent engineering. From this a number of areas of work were defined and methods and systems for use in environmental design were developed. This research addresses the unfulfilled needs in the following ways:

7.3.1 Guidance on Design Strategies

In order that the unfulfilled need for a system of design strategy guidance is addressed this research will present a new method of environmental design. The main method is based on LCA as are all the others developed to date. The system will use a design matrix to allow designers to choose the strategy which will reap the greatest benefits in terms of the environment. By presenting a number of product attributes the method will allow designers to describe their products in terms of these attributes and so work their way through the matrix and use the information to identify appropriate design strategies. Once these strategies have been identified designers may then use the systems and methods already in place to carry out the design exercise.

The use of such a design matrix will allow environmental design to be structured and accelerated and thus more readily used in the product or system design process.

7.3.2 Comparison of Options

In order to allow comparison of a wider range of possible design options this research aims to develop a environmental design system which will not only compare user defined options but will generate options based on information given by the user.

By defining mechanical properties required from materials for a certain product or system, and allowing these properties to be characterised in a descriptive rather than numerical way, the system will propose materials not offered by the designer which may reduce the environmental impact even further. To allow this system to be developed the expertise elicited will be encapsulated in a PC based expert system prototype.

A new system of materials selection, developed by this research and based on that of Ashby's Materials and Process Selection Charts will be included in the system. This method will allow the selection of materials taking into account both mechanical and environmental requirements. The results of comparisons of different designs or materails/process selections will be presented in an easy to understand, transparent way using both tables and various graphical outputs.

7.3.3. An Expert System Based Design Advisor

The final deliverable of this research program is to encapsulate both the new method of comparing alternatives and the new method of materials selection in a piece of computer software.

Due to the large amount of data needed to perform LCAs, which are an integral part of environmental design, and the large amount of calculations needed to perform an exhaustive search of all possible alternatives, it makes sense to computerise the operation.

The software will be in the form of an expert system and will encapsulate the expertise for only a small section of the whole environmental design spectrum. Being such a large area it is not possible to develop a system, within this research program, which will cover all aspects of environmental design. It is ,therefore, the aim of this research to take a branch of the design matrix developed and encapsulate it in an expert system.

The system developed will cover environmental design of products using design strategies aimed at materials selection, process selection and disposal practices.

The system will allow users to compare alternatives, use the new method of materials selection and to ask for advice on which materials and processes to use in order to fulfil certain product or system requirements and environmental design aims.

By developing such a system this research will go some way to addressing the unfulfilled needs of environmental design and allow the use of LCA in design to become more structured and considerably accelerated. It will lay down the foundations and demonstrate the applicability of the approach to other product classes and domains.

Chapter 8

A New Method of Environmental Design

A New Method of Environmental Design

8.1 Introduction

The preceding chapters of this work have looked at the driving forces and developments in environmental design. The way in which design is adapting and the current state of the art has been studied and a critical review of these practices presented. The following chapters will present a new method of environmental design developed during this research programme and a support tool for the integration of this method into product or engineering design.

The first step in the development of an environmental design methodology that is accurate, structured and appropriate is to look at environmental design and attempt to define what is 'best practice'.

8.2 Best Practice in Environmental Design

Previous chapters have shown that there are many different design strategies to address the environmental problems present in industry today, and that application of a carefully considered number of these strategies may go some way to solving the problems. Adaptation of concurrent engineering by using a series of 'green' DFX steps seems to offer the best opportunity. As discussed earlier the application of these 'green' DFX steps at different stages of the design process will result in the implicit completion of an environmental design, or DFE exercise.

It follows, therefore, that best practice in environmental design will involve the application of the appropriate DFE strategies in a hierarchy which addresses the largest environmental problems first.

8.2.1 Defining Best Environmental Design Practices

As the whole life-cycle of a product or system has an effect on its environmental impact the whole life-cycle needs to be taken into account when attempting to define best practice in environmental design. It is this very requirement that makes defining best practice so difficult. Products and systems from different sectors of industry will have different life-cycles and life-cycle requirements, in terms of energy, resources and disposal, etc. thus necessitating different approaches in environmental design. Regardless of the particularities of a products life-cycle the main aims of 'green design' will always be applicable. It is the interpretation of these aims within the context of the particular industry which need to be addressed when defining best practice. When formulating definitions of best practice the following considerations should be taken into account:

- The environmental context within which operations are being carried out
- Environmental problems particular to a company’s operations
- Geographical position of the company and any related problems
- Technology available to the company
- The size of the company's operations

‘Best practice in environmental design should be the careful consideration of the environmental problems particular to the operations in question and the adoption of appropriate strategies in order to address these problems as thoroughly as possible.’ **Holloway et al.** (1995).

Consideration and identification of these problems and strategies is the backbone of a useable and pertinent environmental design method. To date this is lacking in the environmental design methods which have been developed. By developing a method which allows the consideration of problems and identification of appropriate strategies in a structured manner, best practice in environmental design will be achieved much more readily.

8.3 A New Method of Environmental Design

The following sections will describe a new method of environmental design developed during this research. The method allows designers to identify key areas of environmental concern, through use a product classification system and develop the appropriate environmental design strategy for specific products quickly and easily.

8.3.1 Scope of the New Environmental Design Method

Factors such as geographical position, technology and size of operations will have very complex effects on the way in which environmental design is carried out and as such require complete research programmes in their own right. They can be seen as effecting the bounds of the design solutions which come from the design method. E.g. aims to recycle are limited by available technology and infrastructure. Concerns related to environmental context and problems particular to operations or type of product produced are much more generic in nature. Also, in most cases, these factors will have a large overall environmental effect and can be addressed relatively easily. Due to this the environmental design methodology presented in this work looks only at the problems related to product type. These problems are related to the use of materials, processing options, use and disposal of products. For example automobiles are a different product type than domestic appliances and therefore will require different environmental design strategies.

The new design method will attempt to raise questions about use patterns etc. but will not attempt to address these problems explicitly or provide definite solutions.

8.3.2 Environmental Design Strategies/Considerations

If best practice in environmental design involves the consideration of problems particular to the product in question, and adoption of strategies which address those problems, then there is a need for a system of product classification. The particular life-cycle characteristics of a product system will dictate which environmental design strategies will reap the most benefits. The standard life-cycle stages which need to be used in the classification procedure are:

- Resource Consumption
- Processing / production requirements
- Distribution
- Usage
- Disposal

Another factor that must be taken into account is the duration of the whole life-cycle. Short life-cycle products have a number of particular environmental problems as do longer life-cycle products. Each of the life-cycle stages listed above will effect the choice of design strategies that should be adopted. If any of the life-cycle stages is shown to have a disproportionate effect on the overall environmental impact of the product system then it is that life-cycle stage which should be addressed with the greatest urgency.

As shown in earlier chapters of this work, decisions made during the design of a product or process can largely dictate its environmental impact throughout its life cycle. (By choosing the material content and composition as well as processing routes, component arrangement, efficiency during use and the scope for maintenance or easy recycling, the designer has fixed the main parameters of environmental effect.)

Table 8.1 shows the different strategies and considerations which need to be taken into account when considering each different life-cycle stage of a product system. The benefits of each of these strategies will depend on the type of product and its life-cycle pattern.

Life-Cycle Stage	Possible Design Considerations/Strategies
Resource Consumption	Source of material (renewable or non-renewable) Number of different materials used (compatibility etc.) Minimum energy content materials Use of recyclate Bio-degradable materials Minimise use of material Minimum pollution material (emissions from production/refining)
Processing /Production	Minimal use of energy in processing Reduction of waste Near net processing for complex shapes Reduction in processing (use pre-formed stock etc.) Testability to correct errors at each stage of assembly (reduce waste etc.)
Distribution	Mode of distribution Weight reduction Volume/size reduction Reduce / remove packaging
Usage	Type of usage Type of energy source Minimise energy consumption and related factors Minimise resource consumption Extend useful life Replaceable parts Design ‘quality’ products which are less disposable
Disposal	Material type Expected end-of-life treatment (landfill, recycle, incinerate etc.) Energy/material recovery Biodegradable materials Disassembly techniques (non permanent fixings etc.) Application of films, labels and printing which is compatible Recycling opportunities Co-location of high value recyclables within a product. Serviceable/replaceable parts

Table 8.1 Design Strategies/Considerations for each Life-Cycle Stage

8.3.3 Product Classification and Environmental Design Strategies

In the previous section the different design strategies and considerations appropriate to each stage of a products life-cycle were identified. As can be seen there is a degree of overlap and repetition in strategies applicable to different life-cycle stages with some complementing each other and others being incompatible. Not all of the strategies and considerations will be appropriate for all types of products due to different life-cycle characteristics. Through classification of products using different parameters to describe their life-cycle, identification of the appropriate design strategies and considerations may be structured and standardised.

8.3.3.1 Product Classification

It has been shown that there are 5 main stages in a products life-cycle which need to be considered and will affect the different types of environmental design strategies adopted. In developing a system of product classification it is necessary to consider what characteristics of a product will affect the impact it has on the environment at each life-cycle stage.

Although each of the characteristics will have a complex and interrelated effect with others, as a result of this research at this stage we can say that the following six can be used to describe any product:

- Life-cycle length
- Energy consumption
- Resource consumption
- Material requirement
- Configuration
- Disposal route

It can be seen that each of these six considerations will affect the design considerations for each of the life-cycle stages listed in Table 8.1.

8.3.3.1.1 Life-cycle Length

Life-cycle length will have perhaps the most profound effect on the adoption of environmental design strategies. The length of the overall life cycle will change the context of all other decisions and the emphasis on the specific environmental impact of each life-cycle stage of a product. For example in long life-cycle products the use stage may have the highest environmental impact if energy or resources are consumed as part of this use. Shorter life-cycle products may have their highest environmental impact in production or disposal.

8.3.3.1.2. Energy Consumption

Products may be classified as either energy consuming or non-energy consuming. This classification refers to whether the actual use of a product consumes any energy. For example products using electricity will be energy consuming products. Products using batteries or power cells will also be energy consuming as will products using solar power, etc. Each of these different types of energy consumption will require different considerations in environmental design as they will have widely differing environmental impacts.

8.3.3.1.3 Resource Consumption

The consumption of resources in use by a product is another classification parameter which needs to be considered in environmental design. The use of resources will affect the environment in a number of ways. It may be depletion of non-renewable resources or it may be pollution resulting from the use of resources e.g. using fossil fuels or chemicals. Either way the type and pattern of resource usage will dictate which environmental design strategies are applicable. Products may be classified as either resource consuming or non-resource consuming.

8.3.3.1.4 Material Requirement

Material requirement may result in some of the most complex environmental effects in any product or system. It can affect the environmental impact in a number of ways and many of the strategies to counter these effects will be generic to all types of products. (see section 8.3.4). In this system of classification the most important factor is the number of materials used in a product. A product can be classed a single material or multi-material. Single materials may be fixed together as separate parts (see section 8.3.1.1.5) which will dictate certain environmental design considerations and strategies being adopted. Multi-material products will have environmental effects which may result in the re-consideration of processing routes, disposal practices, assembly and disassembly and so on.

Types of materials used may also effect the overall weight or size of a product. This will have corollaries in terms of transportation and distributional effects.

8.3.1.1.5 Configuration

Products come in many different configurations but at the simplest level may be described as either single part or multi-part. This will have a number of effects on other considerations such as material requirement and processing etc. Strategies such as reducing the overall number of parts may be appropriate. Other effects may be countered by the use or serviceable of replaceable parts in multi-part products.

8.3.1.1.6 Disposal Route

Different types of products will be likely to be disposed of in different ways. Packaging, for example, will either be recycled (either consumer or municipal separation), incinerated with waste to produce power, or sent to landfill. Other products such as electrical and electronic items with either be dumped in landfill or dismantled and then disposed of through recycling, reuse or landfill. It is these different disposal characteristics which need to be taken into consideration when applying environmental design strategies.

This characteristic is one of the most difficult to define as it will, in most cases, be a prediction. Current disposal practices may change and therefore alter the characteristics of a product in terms of disposal. At this time the most appropriate way to classify products in terms of disposal is either returnable or non-returnable. Based on current disposal practices the designer must decide whether the product is likely to be returned in some form for, recycling, refurbishment etc. or whether the product will be sent into the normal waste stream. It should be remembered, however, that some waste streams are routinely separated and recycling takes place. This will be dependant on local authority practices and designers should attempt to include these factors in their decision making process.

8.3.4 Generic Concerns

Although product classification will affect environmental design strategies in a number of ways there will always be generic concerns which may be applied to all classes of products.

These generic concerns can be drawn from each of the five stages of the product life cycle and are summarised in table 8.2.

By using the classification system described, areas for application of generics may also be identified. It is a case of balancing the potential benefits of their application. It may be better to apply a specific strategy which does not allow the application of generics if the environmental gains of applying that specific strategy are higher.

Product Life-cycle Stage	**Generic environmental design Strategies**
Resource Consumption	Pollution reduction Waste reduction Consumption reduction Material substitution
Production/Processing	Minimise materials use Reduce energy consumption Minimise processing emissions and waste
Distribution	Weight reduction Size reduction Packaging design Localisation
Use	Minimise resource consumption Minimise energy use Alternative 'clean' or renewable energy and resources
Disposal	Reduce waste generated Minimise or eliminate the use of harmful substances 'Design for disposal'

Table 8.2 Generic Environmental Design Strategies

8.3.5 A New Environmental Design Matrix

This research has developed a new environmental design matrix called an Environmental Design Strategy Matrix. (EDSM), shown in table 8.3. The matrix is used to highlight areas of environmental concern and develop overall environmental design strategies in terms of a hierarchy of DFX steps or general environmental design guidelines.

The product in question is described using the product classification descriptors (PCDs) discussed in section 8.3.3. Each cell in the matrix, when completed, will contain information about the type of strategy(s) that may be adopted to allow a pertinent environmental design exercise to be carried out on the product in question. The one parameter which is not included in the matrix is life-cycle length. As discussed earlier life-cycle length will have a profound effect on the type of environmental design strategies adopted in the deign exercise.

Product Description:					
	Energy	Resource	Configuration	Materials	Disposal
Resource					
Production					
Distribution					
Use					
Disposal					

Table 8.3 Environmental Design Strategy Matrix

As a product is either long or short life-cycle it is not necessary to include it in the matrix. The effects of this characteristic will become apparent, implicitly, through the environmental design strategy generated by use of the matrix.

Design Parameter		1 - Energy				2 - Resources				3 - Confi	
Parameter Class		Energy Consuming		Non-Energy Consuming		Resource Consuming		Non-Resource Cons.		Multi-Part	
L-C Stage / Life-Cycle		SLC	LLC	SLC	LLC	SLC	LLC	SLC	LLC	SLC	LLC
A - Materials & Resources	By using different types of materials and resources the E.I. of a product may be altered. GENERIC STRATEGIES: Minimise Material consumption Minimise Pollution & Waste (Material Substitution)	Material choice in this type of product may have a lesser effect on the overall E.I If energy consumption is high Does material choice effect energy consumption? Apply generics.	Matreial choice may effect energy consumption. If so how? Is weight a factor? Mechanical or electrical efficiency? Apply generic strategies	Material choice may be a very important factor. As well as generic strategies adopt strategies linked to (4) & (5).	Material choice decisions as in SLC products should be considered. However in LLC products factors such as quality and durability could be important as they will help to increase the life-cycle.	Resource consumption over a small period of time will have smaller effect on the E.I. In most cases it will not be linked to material choice. Materials for resources?	Resource consumption should be reduced to a minimum. Questions should be asked about material choice and it's effects. May be negligable in most cases. Materials for resources?	Very little effect in the majority of cases. Apply generic strategies. Materials for resources?	Very little effect overall More important in LLC products Important to apply generics	Material choice in multi-part products will affect many other design goals and stageies. Some closely linked with (4) & (5). Increase the compatability of parts, materials etc.	Considerations as with SLC products. Again questions about durability should be asked. Durability questions will affect material choice.
B - Processing	Processing and produciton requirements can effect the E.I. of a product. GENERIC STRATEGIES: Minimise Material used Minimise Energy consumption Minimise Waste	Production and processing options will not effect the direct energy consumption of a product. Electronics processing? CLEAN UP.	Apply Generics	Very important to get the most out of generics.		The direct resource consumption of a product will not be affected by the processing or production route used. Apply generics.	Apply Generics			Some processing parameters will affect the overall E.I. in multi-part products. Design for Assembly, disassembly and also testability should be considered.	As with SLC products factors such as assembly & disassembly should be considered. This may affect material choices fixings, bonding etc.
C - Distribution	Distribution and Collection of products will effect the E.I. GENERIC STRATEGIES: Weight Reduction Size Reduction Minimise Packaging	Distribution may cause a considerable E.I. in these products. Every effort should be made to apply generic strategies, also reduce ALL non-essential packaging.	Distribution will usually be a small contributor to the overall E.I of these products. Apply generic strategies.	A large % of overall E.I. may result from distribution. Apply generics and eliminate all non-essential packaging.	Distribution may contribute a small amount to the overall E.I. Apply generic strategies. Could packaging be made more functional? E.g. a carry case for the product.	Direct resource consumption will not be affected by distribution, Secondary effects from fuel use and packaging are important Apply generics	Apply Generics Check with weight/size /packaging			The number of parts will not affect, or be effected by, distribution. Are parts being made in different locations?	Apply Ge
D - Use	Decisions made about the product in terms of energy & resource consumption. Questions may be asked about use patterns. GENERIC STRATEGIES: Minimise resource & energy use Alternative & renewable resources	Use of these types of products will contribute to the overall E.I. in differing amounts. Generic strategies should be applied giving consideration to life cycle useage pattern.	In LLC products this is usually the largest contributor to the overall E.I. Apply generics and balance them with material factors (1)A and any other specific factors.	Usually very little or no effect on E.I. in terms of energy consumption Apply generic strategies	Little or no effect to overall E.I. in terms of energy. Lengthening the life-cycle may be an appropriate strategy. Check issues such as durability with issues in (3)A and (4)A.	As with energy consumption resource use differs. Apply generic strategies taking into account the life-cyle length and pattern of use. and type of resource	Resource consumption may be the largest contributor to the E.I. Consider generic strategies but also look at alternative or renewable resources.	Little or no effect on E.I. in terms of resources Apply generic strategies	Little or no effect on E.I. Use generic considerations and considerations raised in Materials & Resource usage (1) for non-energy consuming LLC products.	Useage has little effect on the number of parts used. Servicing and replacement of parts may be considered.	Apply Replaceable/servica
E - Retirement or Disposal	Disposal options vary widely and have a profound effect on the env. impact of some products. GENERIC STRATEGIES: Waste Reduction Harmful Substance Reduction Recovery	Disposal options will have some effect on the E.I. due to energy consumption. Consider transport during disposal activities, also material choice and energy recovery.	As with SLC products but disposal will have a smaller % contribution to the overall E.I. Consider the possibility of energy recovery, recycling, material choice etc.	Apply Generics		Disposal will have little overall effect in terms of resource consumption. However strategies such as recycling, reuse and disassembly may be adopted to reduce overall consumption.	As more resources are usually consumed by LLC products, recovery is important. Balance recycling or material and energy recovery with material chocies etc.	Disposal options will have relatively little effect on this class of product. Apply Generics		Multi-part products will have specific problems in disposal. Strategies to be considered are; disassembly & recycling etc. Design for refurbishment and servicing should also be explored.	As with SLC design strategies such as disassembly, recycling and reuse should be considered. It is important to balance these strategies with those used in Materials (4) & Disposal (5).

Table 8.4 Environmental Design Strategy G

8.3.6 Completing the Environmental Design Strategy Matrix

In order to complete most environmental design matrices a degree of appreciation of environmental problems and knowledge of relevant and appropriate questions is needed. In many cases designers do not have this specialist knowledge and need a system which will highlight certain areas of concern. If such a system is developed in the correct manner it will be generic and applicable to all products. Although each product is different and will have differing environmental characteristics and associated problems, if the correct questions are asked and areas of concern highlighted then an appropriate environmental design strategy may be developed.

Table 8.4 contains this information and is called the Environmental Design Strategy Guidance Matrix.

The first step in using the Matrix is to define the product in question in terms of the PCDs discussed earlier.

8.3.6.1 Product Classification Descriptions

To illustrate the use of the system of product classification, and how designers may describe products in terms of the parameters required for the Environmental Design Strategy Matrix (EDSM), the following are example descriptions of everyday products. These are described using the product classification parameters developed in section 8.3 of this chapter.

8.3.6.1.1 Washing Machines

Washing machines have a number of specific characteristics which describe their form and function. They consume electricity, water and detergent as part of their use. They are manufactured from a number of different materials and are made up of a large number of separate parts arranged in a specific manner. They have a long life-cycle of up to ten years and are not readily disposed of. They are usually dumped at municipal waste collection sites. (This is based on current disposal practices)

EDSM Descriptor:

Long life-cycle, energy and resource consuming, multi-part, multi-material, non-returnable.

8.3.6.1.2 Chair

A chair consumes no energy or resources as a direct result of its use. Most chairs are made of more than one material or part, but in certain cases this may not be true. As with washing machines chairs do not enter the waste system on as regular basis as other waste and therefore tend not to be recycled or recovered at the present time.

EDSM Descriptor:

Long life-cycle, non energy or resource consuming, multi-part, multi-material, non-returnable.

8.3.6.1.3 Stapler

Staplers usually have a long life of a number of years and in that time consume resources in the form of staples. Energy is not consumed as a direct result of their utilisation. In most cases they are now made of a mixture of metal and plastic and are not readily collected or recycled in the current waste collection and disposal system.

EDSM Descriptor:

Long life-cycle, non energy consuming, resource consuming, multi-part, multi-material, non returnable.

8.3.6.1.4 Aluminium Can (Packaging)

Although packaging is not always seen as a product in itself it is just that. It performs a number of function including advertising and protection of the contents. An aluminium can, probably the most common form of packaging, will have a very short life-cycle. No energy or resources are consumed as a direct result of its function and it will, in the majority of cases be made form a single part and type of material. Such a product is much more likely to be returned for recycling through either the normal waste stream or through special recycling collection points situated near supermarkets and shopping centres.

EDSM Descriptor:

Short life-cycle, non energy or resource consuming, single material and part, returnable.

8.3.8 The Environmental Design Strategy Guidance Matrix

In order to complete the Environmental Design Strategy Matrix the designer must use the Guidance Matrix, table 8.4. Use of the Guidance Matrix will guide the designer through the appropriate considerations and questions which need to be raised. Each cell in the Guidance Matrix contains information relating to a specific product characteristic and the effects it may have on a specific part of the overall product life-cycle. For example the energy consumption characteristic of a product may be related to, or affected by, materials selection. The way in which it affects the materials selection depends upon whether the product is energy or non-energy consuming and whether it has a long or short life-cycle (as well as more specific effects which are detailed within the appropriate cells).

Using the EDSM descriptor, e.g. Long Life-cycle, non energy or resource consuming, multi part, single material, returnable, the designer selects the appropriate cells from the Guidance Matrix and uses the information, questions and advice within them to assess what the environmental concerns for each parameter/life-cycle stage combination are, and which strategies may be adopted to address these concerns. As the information from the guidance matrix is used, the answers, guidelines and any notes appropriate should be placed in the appropriate cells in the Strategy Matrix. For example a resource consuming short life-cycle product has specific cells within the Strategy Guidance Matrix for each of the five life-cycle stages which will be mapped onto the resources column of the smaller Strategy Matrix.

It should be noted that the Guidance Matrix was designed to be as generic as possible and therefore be applicable to any product described using the appropriate descriptors. It is essential that when completing the matrix, at all times the designer keeps in mind the actual product in question. Much of the advice given and many of the questions asked will require the designer to take into consideration product specific characteristics.

Once the matrix is complete then the designer must study each cell. If the cell contains advice to apply generic strategies only, or the answers to the questions within the cells are negative then these cells may be crossed off. If the cells contain information which says there is no environmental effect then these cells may be crossed off also.

Now the remaining cells should be studied in detail to develop the environmental design strategy for the product in question while the generics are considered in parallel.

8.3.9 Developing the Environmental Design Strategy from the EDSM

The designer should now be faced with a completed 5 x 5 matrix. Some of the cells will have been crossed off and the remaining cells contain the information, questions and advice which will be used to develop the environmental design strategy for the product in question.

The next stage is for the designer to go through the matrix and attempt to pick out important issues or common themes contained within the cells. The designer may wish to highlight the most important cells and group like cells by coloured borders or a similar system.

Once the common themes have been identified then the documentation of the strategy may begin.

The first and most important environmental design strategy will be either the one which is highlighted as this in the matrix, or the theme which occurs in the most number of cells. The environmental design strategy for the product should be documented in a 'top down' manner where the most important strategy is put at the top of the list and so on down to themes which may only occur once within the whole matrix.

As each of the cells is considered within the matrix it should be marked in some way to indicate this. This will prevent mistakes being made and the cell being considered more than once or not at all.

Finally the designer should study the environmental design strategy developed using the matrix and decide whether it is a sensible strategy for the product. If the strategy seems completely inappropriate then the matrix should be checked again. In some cases if the product has not been described correctly using the product classification descriptors then the strategy developed may be inappropriate. This in itself forms an iterative system of checking that the product description is appropriate.

If the description is shown to be incorrect or inappropriate, a new descriptor should be developed using the parameters and the matrix re-written.

8.3.10 Strategy Checklist

The strategy may now be placed in a Environmental Design Strategy Checklist as shown in table 8.5 which allows the designer to show how they aim to achieve the goals of the strategy developed. The design goal (i.e. the strategy) is listed together with information on whether it is to be addressed, how it will be achieved, whether it is realistically possible and to what level the achievement of the goal will be.

Design Goals	Method of Achievement	Possible to Achieve?	Level of Achievement in terms of reducing Env. Impact

Table 8.5 Environmental Design Strategy Checklist

8.4 Examples of Completed EDSMs

In order to demonstrate more clearly the use of the matrix this section will present some examples. Tables 8.6 and 8.8 show examples of completed environmental design matrices.

8.4.1 EDSM for Washing Machine

Table 8.6 shows a completed matrix for a washing machine. The product is described as a long life-cycle, energy and resource consuming, multi-part, multi-material, non returnable product. The product was classed as non-returnable as it is likely that it will end up in a landfill site at the end of its useful life.

The matrix contains the questions and advice from the appropriate cells in the Guidance Matrix for each product descriptor in each stage of the life-cycle.

As can be seen from table 8.6 by far the largest environmental impact of a washing machine is its consumption of resources and energy. This will be the most important issue in the environmental design strategy. Going through the rest of the matrix allows the designer to develop the following hierarchy of environmental design strategies for the washing machine:

1. Reduce the consumption of resources (Water, electricity and detergent)
2. Design for Disassembly, refurbishment, servicing etc.
3. Increase the useful life of the product (DFQ)
4. Compatibility of materials and parts with regards to disposal (encourages recycling by making it easier)
5. Address distributional effects (Localisation of production?)

The strategy may then be applied to the checklist to produce the following specific design goals shown in table 8.7.

Many of the goals are readily achievable. Distribution is an interesting point. Washing machines are very heavy and so they have a considerable distribution effect, (though the nature of resource and energy consumption during use of the machine means it is still relatively small overall).

Localisation of manufacture of the main cases and large components of the machines, such as the large weight contained inside them, would reduce environmental effects linked to distribution by a considerable amount.

It is also interesting to see that the matrix has developed a strategy which is not directly related to the actual product. The development of concentrated, low temperature effective and biodegradable detergent will reduce the impact of the use of the washing machine but it is not something that a designer of a washing machine can directly do. So the matrix may help to point out areas of concern which are not directly related to the design of a product but will affect its environmental impact.

Product: Washing Machine **Description:** *Long life-cycle, energy and resource consuming, multi-part, multi-material, non-returnable*

	Energy	Resources	Configuration	Materials	Disposal
Materials	Material choice can affect energy consumption, does it do this? Is weight a factor? Use lighter materials.	Resource consumption should be reduced to a minimum. Question the effects of material choice. Probably negligible in most cases.	Compatibility of parts? Material choice effects this. Reduce the number of parts? Can parts be made more durable? Balance with disposal issues.	Apply generic material strategies, but also consider the compatibility. Contamination? Increase quality and durability of materials? Balance with disposal.	Look at disassembly. Recycling? Balance with configuration and materials. Also balance with energy and resource consumption
Processing	Apply generic energy efficient processing strategies.	Apply generic processing strategies.	Consider design for assembly/disassembly. Also testability. Material choice and method of fixing should be considered.	Use compatible materials and balance process/assembly options with disposal options. Effects of processing appropriate to length of life?	Disassembly/recycling. Energy recovery? Consider material and configuration. Refurbishment?
Distribution	Small contribution to overall environmental impact. Apply generics.	Direct resource consumption is not directly affected. Consider the use of packaging. Is weight a factor?	No effect. Use generic strategies where appropriate.	No real effect. Balance strategies and considerations in energy/materials.	No real effect. Apply generics
Use	Largest environmental impact. Apply generic energy efficiency strategies. Does material choice play a part? Any other specifics?	Very large environmental impact. Reduce resource usage to a minimum. Apply generics Possibility of renewable/recycled resources?	Configuration will not usually effect usage strategies. Serviceable parts?	Type of material may effect usage. Apply generics. Also check mechanical requirements and working environment etc.	Delay disposal by increasing life-cycle? Balance against energy and resource consumption and material choice.
Disposal	Little effect on energy consumption. Consider energy recovery, disposal and transport.	Recovery of resources can be important in LLC products.	Parts for recycling, disassembly, refurbishment etc?	Less of an environmental impact here but a balance with material use and processing techniques.	Smaller environmental impact Energy/resource consumption more important.

Table 8.6 Completed EDSM for a Washing Machine

Design Goals	Method of Achievement	Possible to Achieve?	Level of Achievement in terms of reducing Environmental Impact
Reduce water consumption	Use shower systems Use system which weighs washload and only uses the required amount of water	Yes	High
Reduce energy consumption	Reduce energy requirement/size of motor and heater	Yes	High
Reduce detergent consumption	Develop new compact detergents which use less powder and wash at lower temperatures	Yes	Medium
Design for Disassembly/refurbishment or servicing	Use modular construction and replaceable parts with non permanent fixings etc.	Yes	Low
Increase useful life of the product	Design for quality and reliability. Improve general quality of all parts especially motors, heaters and seals.	Yes	Low
Make materials compatible	Reduce mix of materials. Apply general compatibility/recycling	Yes	Low
Distributional effects	Localisation of production of large parts. Electronics etc. may be brought in.	Possible	Medium

Table 8.7 Environmental Design Strategy Checklist for Washing Machine

8.4.2 EDSM for Cutlery

Table 8.8 shows a completed environmental design Strategy Matrix for cutlery. The cutlery defined in this example is made from steel (or a similar metal) and is cleaned after use ready to be used again. **NB.** Disposable cutlery, usually made from plastic would have a different product description and therefore result in the development of a different hierarchy of environmental design strategies.

Product: Cutlery **Description:** *Long life-cycle, energy and resource consuming, single-part, multi-material, returnable*

	Energy	Resources	Configuration	Materials	Disposal
Materials	Energy use is not directly related to materials. However energy is used as a result of cleaning the materials which is an everyday function in using cutlery New materials?	Resources are again used in the cleaning of the materials (cutlery), in the form of water and detergent.	Apply generics. Design for Quality Design for Durability	Consider compatibility of materials with regard to disposal techniques. Also use materials for quality and durability.	Products will usually end up in the domestic waste stream where they may be separated and recovered. Recycling?
Processing	Apply generics	Apply generic processing strategies.	Apply generics	Apply generics	Apply generics
Distribution	Apply generic strategies. Look at packaging and the way in which it is used in cutlery.	Apply generics	Apply generic strategies	Apply generic strategies	Apply generic strategies
Use	Large environmental impact. Energy is used as a result of cleaning the cutlery. Cleaning is an inherent past of the use of cutlery. Can materials or cleaning techniques be changed?	Large environmental impact. Reduce resource usage to a minimum. Different materials or cleaning methods?	Configuration will not usually effect usage strategies. Apply generic strategies.	Consider the effects of using different materials. Again in this case it is related to cleaning.	Design for quality. Reuse? This may be inherent in cutlery as it tends to be passed on rather than disposed of. Design for quality and durability.
Disposal	Little effect on energy consumption. Consider material recovery. Apply generics	Recovery of resources can be important in LLC products.	Parts for recycling, disassembly, refurbishment etc.? Probably not applicable in this case.	Less of an environmental impact here but a balance should be stuck with material use and processing techniques.	Apply generics. Energy/resource consumption more important.

Table 8.8 Completed EDSM for Cutlery

The cutlery is described as long life-cycle, resource and energy consuming, single part, multi-material, returnable.

When cutlery is disposed of, reuse (change of ownership) may occur a number of times before final disposal, at which point it will usually end up in the domestic waste stream. The steel in these streams may be recycled and therefore cutlery has been classified as returnable.

Looking at the matrix, table 8.8, it is apparent that there are two main areas of concern, materials and use. The materials need cleaning which results in a high environmental impact and the use involves this cleaning. Therefore the two concerns relate to a single issue, soiling of the cutlery.

Design Goals	**Method of Achievement**	**Possible to Achieve?**	**Level of Achievement in terms of reducing Environmental Impact**
Reduce resource consumption	Use materials which do not collect dirt	Not likely	High if possible
Reduce resource consumption	Different method of cleaning - ultrasonic or microwave?	Not likely	High if possible
Increase life-cycle of product	Use more durable materials Improve overall quality.	Yes	Low - medium
Encourage Recycling/Recovery	Improve collection/separation techniques	Yes	Medium
Encourage Recycling/Recovery	Make disassembly and materials separation easier - use non permanent fastening and compatible materials.	Yes	Medium

Table 8.9 Environmental Design Strategy Checklist for Cutlery

The environmental design strategy hierarchy developed from this matrix is as follows:

1. Reduce resources in cleaning (water and detergent)
2. Increase the life-cycle of the product -Design for quality and durability
3. Consider recycling/recovery options.

When this is applied to the Environmental Design Strategy Checklist, table 8.9, it is interesting to see that the issue of largest environmental impact, resource and energy consumption in this case, may not be able to be addressed.

8.5 Discussion of the New Method

The new method presents both a new system of product classification and a series of design matrices to help develop an environmental design strategy. In most cases use of both the description system and the matrices will require assumptions and simplifications of some kind, to be made.

8.5.1 Assumptions and Simplifications in Product Description

This product classification method can be used to describe any product. However certain assumptions may be made in order to simplify the description or make the description of a product more appropriate. The example of the cutlery in this chapter is a good case in point. In carrying out the design exercise originally the cutlery was described as non-energy and resource consuming. As the matrix was being completed it became apparent that the use of water and detergent in the cleaning of cutlery was an integral part of its use. Therefore it was more accurate to describe cutlery as energy and resource consuming.

Many forms of cutlery use different materials for the handles and are therefore will be classed as multi-material. However as these handles are either bonded or riveted on, and therefore difficult to separate cutlery may be classed as a single part.

Simple objects and products made of multiple parts and single or compatible materials may also be classed as single part products.

Energy consumption classification may also be open to interpretation. Many electrical goods consume energy. Those which use mains electricity may be classed as energy consuming in the description used for the Guidance Matrix but for those that use their power in the form of batteries or solar power this may not be an appropriate description. Use of batteries should be described as resource consuming, as the power comes from the batteries which are made of a mix of materials. Energy generation is carried out within the battery as a result of the chemical reaction taking place inside.

Solar powered products should be described as non-energy consuming as their energy generation is directly from the sun and therefore produces no related pollution or environmental effects.

Many assumptions may have to be made about disposal practices. These assumptions should be based , to the best of the designers knowledge, on current disposal practices. For some products current disposal practices will be dictated by the local authorities treatment of the domestic waste stream, while others may be based on consumer recycling or collection facilities.

These assumptions must be considered very carefully as they may have considerable effects on the environmental design strategies developed using the matrix. It is possible to use the matrix to develop and adopt design strategies which may influence disposal activities.

8.5.2 Interpretation of Data in the Strategy Guidance Matrix

As discussed earlier the Guidance Matrix is designed to be as generic as possible in nature. Due to this the information contained within the matrix must be open to interpretation by the user. If there was no interpretation of the information by the user then strategies developed for products which have the same Product Classification Descriptors (PCD) would be identical. This can clearly not be the case.

For example products such as an electric shaver and a washing machine will have the same PCD of :

Long life-cycle, energy and resource consuming, multi-part and material, non-returnable.

The difference between the two products is the type of resources consumed and the way in which energy is used. Washing machines consume large amounts of water and detergent in operation while the consumable resource in an electric shaver is the metal foil. This will have a dramatic effect on the choice of actual DFE strategies adopted and therefore it is important that consideration is given to the type of resource in question.

Energy consumption in these two products is on a very different scale. An electric shaver will have a motor of only a few watts in size and will probably be used once a day for approximately 5 minutes or less. However washing machines have a power requirement of up to 3 KW and although they may not be used every day a single washing cycle may take over an hour. This comparison shows that the scale of energy usage should be considered. It will be a much more important consideration in the washing machine than it is in the shaver and as a result the environmental design strategies developed using the matrix should differ.

Data and guidelines concerning materials, parts and disposal will also be open to such interpretation.

8.5.3 Completing the Environmental Design Strategy Checklist

Completion of the Strategy Checklist is the final stage in the development of the environmental design strategy for a product. As it is the final stage, completing this checklist is very product specific. When finally trying to decide on how the strategy objectives may be achieved a brainstorming approach is needed. As many ideas as possible should be formulated and documented at this stage.

The example of the checklist for cutlery shown in Table 8.8 is, again, a good example. The highest priority objective developed by using the matrix, was to reduce the amount of resources used. As resources are used to clean the cutlery, lateral thinking produced the most obvious answers, materials that don't need cleaning and cleaning without using water or detergent. As strange as they seem these ideas should be documented. Although the checklist shows that it is very unlikely that they will be achieved it shows that the environmental impact related to those strategies has been considered.

Solutions to implement the strategies are very product specific and as such the environmental design method cannot offer advice. It is in the hands of the designer to complete the final stage.

8.5.4 Use and Implications of the New Environmental Design Method

It is apparent that the new method described in this chapter may be used at different stages in the design process. The implications of using the method will be different if it is used at different stages of the design process. The method may be used at both the detailed design stage and the conceptual design stage.

Using the method at the detailed design stage means that the type and performance of the product has been set and the environmental implications will be related to materials, process etc.

If used at the conceptual stage of design the implication may be much wider ranging. The design strategies developed may be used to reconsider design concepts. For example in the case of an environmental design exercise for an electric shaver, reducing energy consumption may lead to the concept of clockwork powered or even a non-powered shaver, thus changing the whole scope and implication of the design exercise.

This design method may be used at any stage of the design process due to its generic nature. At the conceptual stage it may bring about the most wide ranging changes to the design as altering design concepts needs many other factors such as marketing strategy etc. to be taken into account. It may also be used at the detailed design stage to address some of the technicalities which may be used to reduce environmental problems.

8.6 Advantages and Summary of the New Environmental Design Method

The new environmental design method exhibits a number of advantages over others. Most of these advantages are due to its generic nature and inherent guidance offered. By using the method the following advantages are apparent:

- Any product can be described using the method of Product Classification Descriptors (although a degree of interpretation is required).
- The Strategy Guidance Matrix allows the quick and efficient extraction of relevant data and information relating to the product in question.
- Completion of the Strategy Matrix using the information and data from the Guidance Matrix develops a simple and clear picture of the environmental issues which need to be considered in the design of the product in question.
- Starting from a very generic description, use of the Matrices in correct order of succession will develop a environmental design strategy which is specific to the product in question.
- In using the matrix, design strategies which affect the overall environmental impact but are not related directly related to the design of the product may be identified.
- Having developed the strategy it is much easier for the designer to see how the environmental impact of the product in question may be reduced. The strategy will assist the designer in developing a checklist of specific goals.

Best practice in environmental design was defined at the beginning of this chapter as '...the careful consideration of the environmental problems particular to the operations in question and the adoption of appropriate strategies in order to address these problems as thoroughly as possible.' **Holloway et al.** (1995).

The use of this method allows best practice in environmental design to be achieved by developing appropriate design strategies through the use of generic product classification descriptors and design matrices. The method both structures and accelerates the development of such strategies and so will help to make environmental design exercises much easier to carryout, particularly for designers with little knowledge of environmental concerns.

Chapter 9

A New Method of Materials Selection in Environmental Design

A New Method of Materials Selection in Environmental Design

9.1 Introduction

One of the aims of this research is to develop a new method of materials selection which takes environmental concerns into account. Having studied current design practices and concluded that they are suitable to be adapted rather than re-developed from scratch, the same is true of materials selection practices.

This chapter looks at materials selection in engineering. It explains one of the well known methods of materials selection, Ashby's Material Selection Charts, and shows how this method may be adapted to include environmental concerns. The limitations of the method are discussed.

9.2 Materials Selection for Mechanical Design

Materials properties and selection are very important areas and there are many publications and data sources available such as books by **Ashby** (1992), **Chong** (1981), **Crane & Charles** (1984) and computer programmes such as PLASCMAS, **RAPRA** (1995), CAMPUS, **Bayer UK Ltd.** (1988) and Cambridge Materials Selector (CMS) amongst many others.

When selecting materials, designers and engineers have to take into account a large number of factors. These factors range from mechanical and electrical properties to corrosion resistance and surface finish. In mechanical design it is the mechanical properties which are of greatest importance. There are a wide range of material properties which can be considered in mechanical design some of which are shown in Figure 9.1.

The relative importance of each of these properties will be dependent on the application in question. It can be seen that different classes of materials exhibit specific mechanical properties. Metals tend to be of a high stiffness, strength and ductility while having a high density. Polymers are lower in density with generally lower strength and stiffness. Because properties are grouped in this way certain classes of materials tend to be suitable for particular applications.

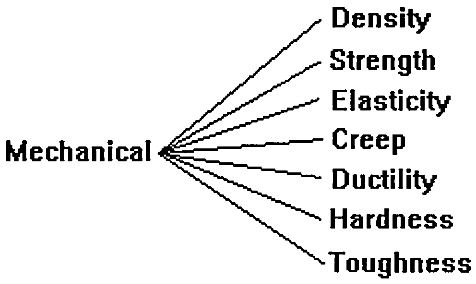


Figure 9.1 Some Material Properties Important in Mechanical Design

There are of course exceptions to these general properties in most material groups. Alloys and composite materials may exhibit properties which are considerably different from those of their pure counterparts.

Appropriate combinations of these properties will dictate the suitability of a material for a specific application. For example, values of density and Young's Modulus or modulus of rigidity will be used to select materials which are light and stiff; density and strength will be used to select materials that are light and strong and so on. It is the ratio of these properties which will change for different applications. These ratios of properties are referred to by **Ashby & Cebon** (1995) as material indices. Ashby goes on to define a material index as 'a grouping of mechanical properties which, if maximised, maximises some aspect of the performance of an engineering component'.

9.2.1 Material Indices and Design Criteria

When designers and engineers have decided on the important design criteria, the combination of parameters which best describes it (or needs to be optimised) may be derived as the material index. For example minimum weight design of stiff ties, beams, shafts, columns and plates relies on values of density and young's modulus but in differing proportions:

The material index for minimum weight design of stiff ties is E/ρ

The material index for minimum weight design of stiff beams, shaft and columns will be based on $E^{\frac{1}{2}}/\rho$ for bending loads with the shape of the section specified.

The design of stiff plates loaded in bending will rely on a material index of $E^{\frac{1}{3}}/\rho$

Where E = Young's modulus and ρ = density

In most cases it is the maximisation of these indices which is the design goal.

Other combinations of properties may be used to optimise materials selection based on such criteria as, strength limited design, vibration limited design and even cost limited design.

9.2.2 Design Goals and Material Indices

Design is dictated by a number of factors, but they can be classified very simply into two areas:

1. Objectives
2. Constraints

Objectives are aims or targets to be achieved by the designer such as reducing mass or size, or energy content. The degree to which these objectives are achieved will be dictated by the constraints. Constraints can be related to main factors such as cost or mechanical function. If the constraints are related to mechanical function then parameters such as strength or stiffness become important. It is these objectives and constraints which may be used to decide on which material indices need to be used.

Ashby & Cebon (1995) identify 3 main steps in compiling material indices:

a) Function

b) Objective

c) Constraint

These three stages can be developed in more details to what Ashby and Cebon refer to as a 'recipe' for deriving material indices shown in table 9.1.

Stage	Requirement
a)	Identify the aspect of PERFORMANCE **P** (mass energy content etc.) to be maximised or minimised.
b)	Develop an EQUATION for **P** (*the objective function*).
c)	Identify the FREE (unspecified) VARIABLES.
d)	Identify the CONSTRAINTS; rank them in order of importance.
e)	Develop EQUATIONS for the constraints (no yield; no buckling etc.)
f)	SUBSTITUTE for the free variables from the constraints into the objective function.
g)	GROUP THE VARIABLES into three groups: functional requirements, **F**, geometry, **G**, and material properties, **M**, (and possibly shape, **S**) thus Performance $\mathbf{P} \leq \mathbf{f(F, G, M, (S))}$
h)	Read off the performance index, **M**, to be maximised

Table 9.1 Deriving Material Indices - **Ashby & Cebon** (1995)

Many examples of these material indices and their applications are given in *A Compilation of Material Indices* by Ashby and Cebon.

The properties used in the material indices will usually be grouped in ranges by material types. As this is the case it is possible to plot charts to give a graphical representation of material groups in terms of properties. By doing this the appropriate material indices may also be plotted on the charts and used to select groups of materials which meet the requirements of the objectives and constraints.

9.3 Ashby's Material Selection Charts

'The Materials Charts are most effectively used by plotting performance indices onto them, isolating a subset of materials which optimally meet design goals'. **Ashby**(1993). Ashby's work has given us the material selection chart in the form shown below. Designers may choose from over 18 material selection charts and process selection charts which cover most areas of mechanical design. Plotting design requirements onto them and using a number of charts sequentially allows the simultaneous consideration of several design goals. Figure 9.2 shows Ashby's Modulus - Density chart which can be used for the design of stiff lightweight components.

As can be seen the chart encompasses a large range of engineering materials and allows the designer to use the appropriate indices as design guidelines. The guidelines are plotted on the chart as lines of constant slope, the value of the slope depending on the particular application. For example the design guideline slope for beams in bending of material index $E^{1/2}/\rho$ will have a gradient of 2.

As the lines are moved towards the top left hand side of the chart the constant C increases. Therefore the materials with the best stiffness to weight ratio lie towards the upper left hand corner of the chart.

Further design constraints may be dealt with by successive use of different charts. For example a cost constraint may be added to the design. A further materials selection chart which considers unit cost would be the next filter in the selection process. Examples of these multiple stage selections are given in Ashby & Cebon's publications and guides.

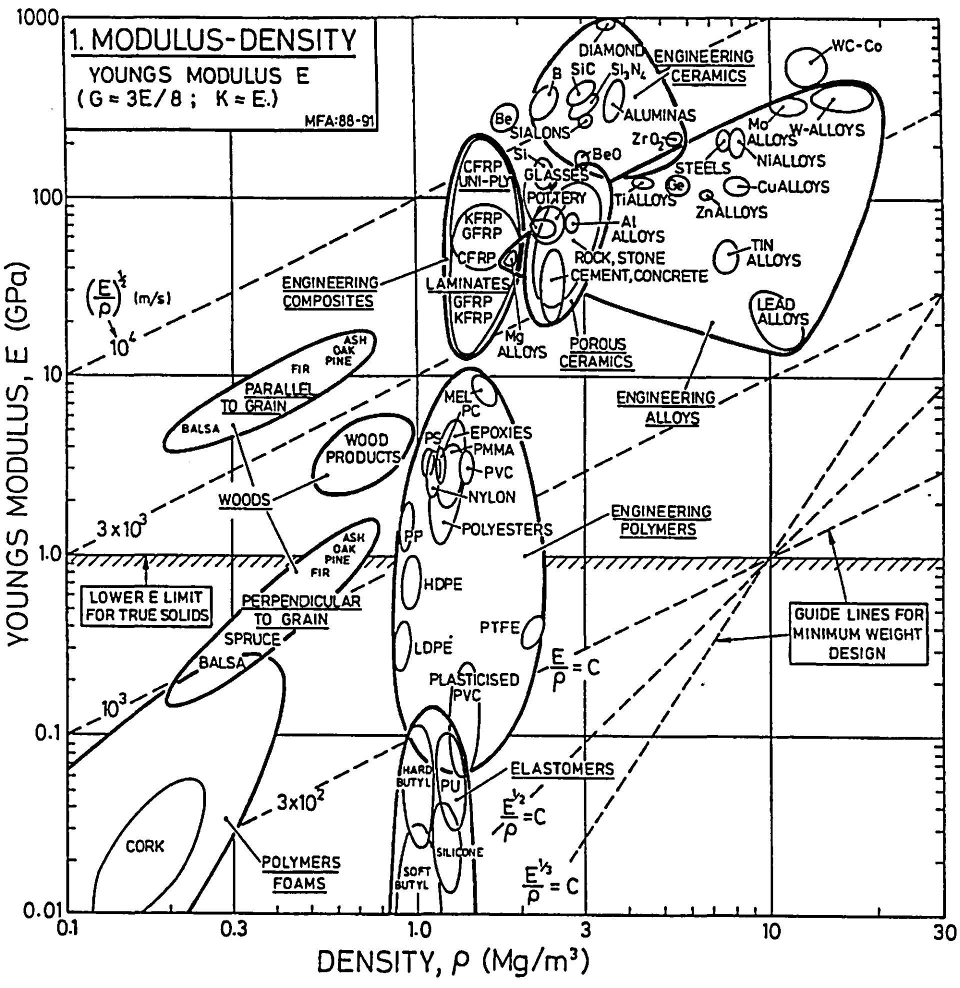


Figure 9.2 Ashby's Modulus-Density Materials Selection Chart

9.3.1 Ashby's Materials Selection Charts and the Environment

Ashby's work deals with many material properties that are classed as environmental. In most cases these are properties concerning the reaction of the material to certain environmental conditions such as heat, moisture, chemicals and so on.

When environmental concerns in materials selection are taken as meaning the effect the material has on the environment, e.g. emissions, waste etc., only one small, though very important, area is covered by Ashby's work; energy content.

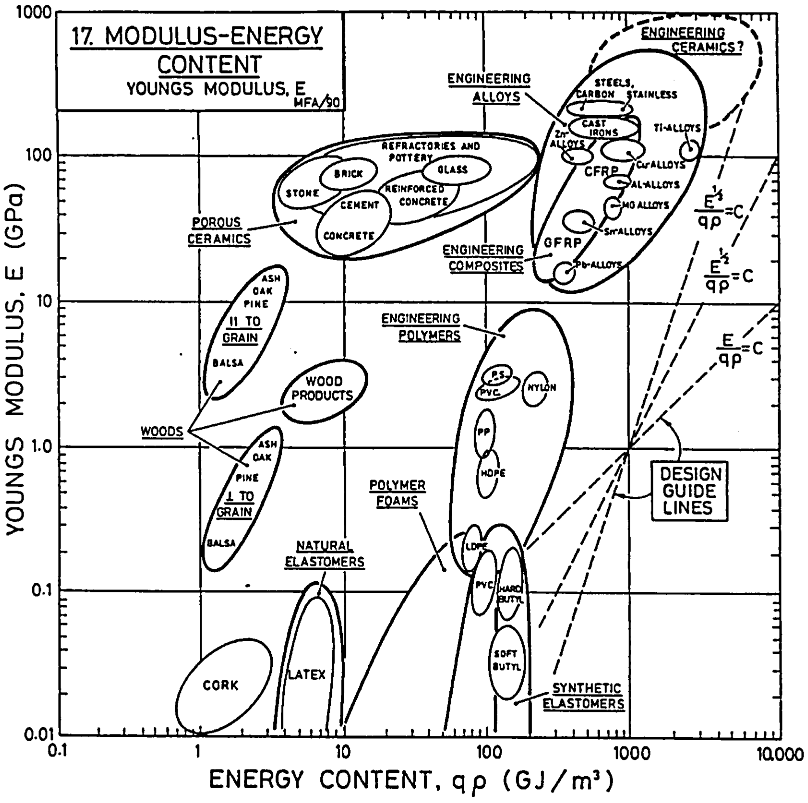


Fig. 9.3 Ashby's Modulus-Energy Content Materials Selection Chart

In Ashby's method energy content may be used just as any other material property, in composing material indices for different applications. By plotting a chart of energy content per unit volume of material against failure strength on a chart, materials for 'strong, energy-efficient ties may be selected. Figure 9.3. shows an example of one of Ashby's energy content material selection charts.

In terms of environmental design this particular chart can be very useful. One of the main aims of environmental design may be to reduce the energy requirement of a product or system. In some cases the energy content of the material is by far the greatest contributor to the overall energy requirement of a product or system.

Using this chart allows the selection of energy efficient materials for specific mechanical requirements.

9.4 Environmentally-Based Materials Selection

In the past energy use and content has been one of the few quantifiable aspects of environmental performance and could therefore be used in materials selection exercises. However with increased environmental awareness in all sectors of industry, environmental data on the effect of material production and processing is becoming more readily available. Although quantifying the amount of a single pollutant, such as for example CO_2, emitted through production of a material,is a complex task, it is relatively simple when compared to the problems which can arise when trying to assess the overall environmental effect.

Most designers and engineers, when designing for the environment, want to assess the overall environmental effect of both production and processing of a single material or a combination of materials. The production of a single material can result in over 100 inputs and outputs, emissions and waste products. Plotting charts for each of these emissions would be very time consuming and more importantly, would overwhelm the designer with massive amounts of data. By utilising concisely presented agglomeration schemes such as MAC and O.v.D, however, normalised overall environmental effects of materials may be calculated and plotted on the appropriate materials selection charts.

9.4.1 Environmental Data for Material Selection

In order to generate environmentally oriented materials selection charts, environmental indices need to be calculated. Other materials selection charts contain discreet data, giving actual values of properties such as tensile strength, density or energy content per unit volume. In environmental terms, discreet data is easily produced for single emissions, but not for a combination of different emissions. For example we can say that production of 1 kg of ABS polymer will result in a total emission of 1.98 kg of carbon dioxide gas (on average). If we then go on to consider other emissions as the result of this production, we see that there are over 10 separate emissions to atmosphere and almost as many to water. This could cause major difficulties in representing this as discreet overall data. Although in some cases providing individual representations such as amount of CO_2 or SO_2 will be necessary, figures aggregating airborne and waterborne emissions are needed to reduce the amount of data being processed. In order to compare emissions on an agglomerated basis we must be able to say which emissions are more 'serious' than others and attach a weighting as necessary. In certain cases, for example, we may need to compare the seriousness of the emission of 1 kg of CO and the emission of 1.2 kg of NO_2. This may be done effectively using MAC values and O.v.D norms discussed earlier in chapter 2.

In our sample case of comparing CO to NO_2 we can decide which is the worst case as follows:

MAC value of CO = 29 mg/m^3

MAC value of NO_2 = 4 mg/m^3

$$\text{'Seriousness' of emission} = \frac{\text{Actual Emission Value (mg)}}{\text{MAC Value }(\text{mg}/\text{m}^3)}$$

$$\text{for CO} = \frac{1000000}{29} = 34482.76(\text{m}^3)$$

$$\text{for NO}_2 = \frac{1200000}{4} = 300000(\text{m}^3)$$

Therefore it can be seen in this case that the emission of CO will pollute 34482.76 m^3 of air and the emission of NO_2 will pollute 300000 m^3 of air. A problem arises here in that although we can calculate the theoretical amount of air which is polluted by an emission we cannot say, with certainty, into what volume of air this polluted air is being released and how polluted that air is already. This system of calculation is therefore more useful for comparison or qualitative assessment than in absolute terms. To this end we can use the values as indices; ignoring the units. In this case the total air pollution index of both the emissions above will be 334482.76.

(300000 + 34482.76)

Calculations for emissions to water are carried out in the same way using O.v.D values in place of MAC values. Any number of these emissions may be added together to give an overall index to a system. The lower the value of the indices the less polluting the system. Theoretically, as the indices have no units, the air and water indices could be added together to give an overall index, but an exchange rate between air and water would be required and at this time there is no such rate.

Valuable data can also be lost by grouping them together so in order that informed decisions can be made by designers and engineers the air and water indices are best left separate.

Table 9.2 shows an example of what is an apparently simple system, the manufacture of 1 kg of HDPE. With 13 different emissions to air and eleven to water the system could become very complex when trying to express its overall effect on the environment without the use of an aggregation system.

Atmospheric Emission	**(mg)**	**MAC (mg/m^3)**	**Waterborne Emission**	**(mg)**	**O.v.D (mg/m^3)**
Acidic Ions	100	4	BOD	100	7000
Ammonium Ions	10	10	COD	200	30000
Carbon Dioxide	9.4×10^5	-	Dissolved	20	50000
Carbon Monoxide	600	29	Organics	500	50000
Chloride Ions	800	3	Dissolved Solids	150	0.2
Dust	2×10^3	10	Hydrocarbons	300	500
Hydrocarbons	2.1×10^4	500	Metals	10	5000
Hydrogen Chloride	50	7	Nitrates	30	0.2
Hydrogen Fluoride	1	2.5	Oil	5	50000
Metals	1	0.1	Other Nitrogen	1	200
Nitrogen Oxides	10×10^3	4	Phosphates	200	50000
Other Organics	5	1			
Sulphur Oxides	6×10^3	5			
Total API		**4277.5**	**Total WPI**		**915**

Table 9.2 Emissions due to the Manufacture of 1 kg of HDPE

By dividing each separate emission by its weighting factor and summing the results from emissions to like mediums we can arrive at an overall Air Pollution Index (API) and an overall Water Pollution Index (WPI) for the material. API and WPI indices can be calculated for any system whose emissions are known.

It should be noted that the effect of CO_2 emissions is not included in these calculations as a MAC value is not yet available.

If we compare HDPE to another similar polymer such as PET, Table 9.3, we see the following in terms of pollution indices:

	API	WPI
HDPE	4277.5	915
PET	20646	2106.3

Table 9.3 Comparison of Pollution Indices of HDPE and PET

The much higher WPI value of the PET results from a ten fold increase in the amount of oil released to water, which has a very low O.v.D value. What seem very similar materials in mechanical terms perform very differently in environmental terms.

9.4.2 Environmentally Based Material Indices

If we are to plot environmentally based materials selection charts we need environmentally based design criteria and material indices. If we look at Ashby's energy content materials selection chart we can see that examples of material indices are::

$E/q\rho$ (Minimum energy design of stiff ties) $E^{\frac{1}{2}}/q\rho$ (Minimum energy design of stiff beams shaft and columns)

Energy content is directly related to the mass of a material, and when multiplied by density it becomes a function of volume in Joules/m^3. API and WPI values are also related directly to the mass of the material as all emissions data is in mg/kg of material produced. Therefore in multiplying density by API or WPI they also become a function of volume and can be plotted on materials selection charts in the same way as energy.

By considering the environmental factors in question we can produce the following material indices:

$E/API\rho = C$ (Minimum air pollution design of stiff ties)

$E/WPI\rho = C$ (Minimum water pollution design of stiff ties)

$E/X\rho = C$ Where X = specific emission (Minimum emission design of stiff ties)

Design criteria for beams, shafts and plates will follow the same lines as above using $E^{1/2}$ etc.

Criteria for design of strong and brittle components will follow the same lines as follows:

$\sigma_f/API\rho = C$ (Minimum air pollution design of strong ties)

$\sigma_f^{2/3}/WPI\rho = C$ (Minimum water pollution design of strong beams and shafts)

$K_{ic}^{4/3}/API\rho = C$ (Minimum air pollution design of brittle ties)

$K_{ic}^{2/3}/WPI\rho = C$ (Minimum water pollution design of brittle plates)

As can be seen most of the standard design criteria guidelines may be adapted to take environmental concerns into account and typically air and water could be used sequentially to select materials.

Now we have 'pollution' or 'environmental' indices for different materials we can plot materials selection charts in terms of environmental concerns, giving engineers and designers easy to use comprehensive data for considering environmental design criteria. These charts will be plotted along the same lines as Ashby's energy content charts.

9.4.3 Environmental Material Selection Charts

By using the same methods as Ashby and plotting environmental properties against mechanical properties a range of environmentally conscious material selection charts may be developed. Figures 9.4 - 9.6 show three such charts.

Figure 9.4 shows an 'emission specific materials selection chart'. The X axis plots values of the amount of a particular pollutant released per unit volume of a material produced multiplied by density (in this case NO_x x ρ), while the Y axis plots the mechanical properties of the materials. (in this case Young's Modulus). This particular chart will allow engineers and designers to choose materials for a range of mechanical operations in which the emission of NO_x gas is optimised or reduced to a minimum.

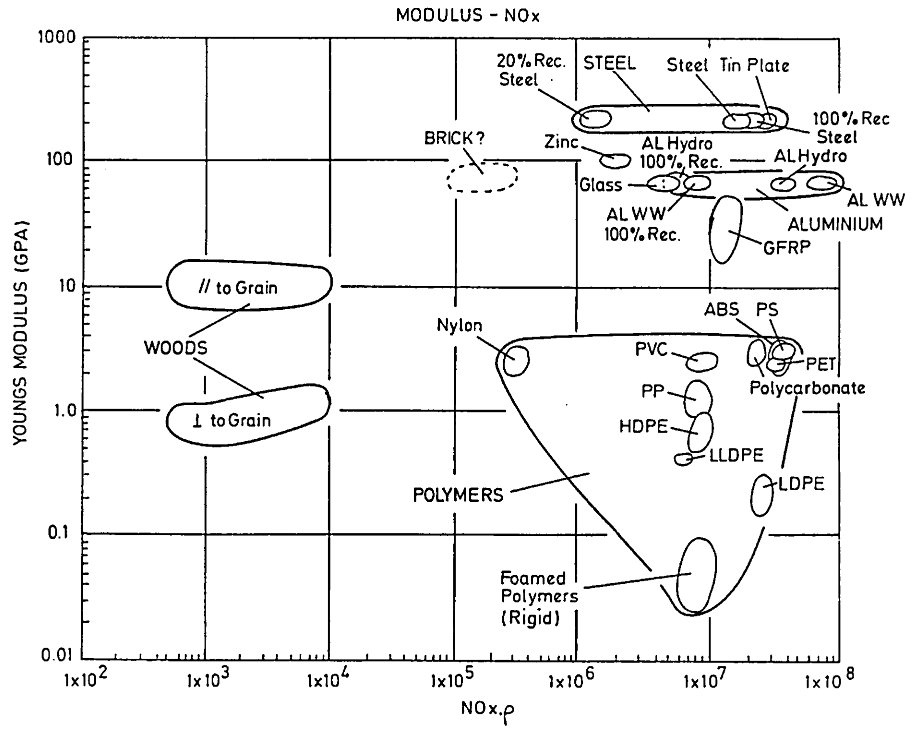


Figure 9.4 Young's Modulus - NOx Emissions Materials Selection Chart

Figure 9.5 shows a 'total air pollution materials selection chart'. In this case the X axis plots the overall API values per unit volume of a material produced multiplied by density and, again, the Y axis plots the mechanical property. This chart may be used to select materials which will fulfil mechanical requirements while reducing air pollution, as a result of material production, to a minimum.

Figure 9.6 is another materials selection chart, this time covering overall WPI and strength. This chart is plotted and used in the same way as the others and allows the design of strong minimum water polluting components.

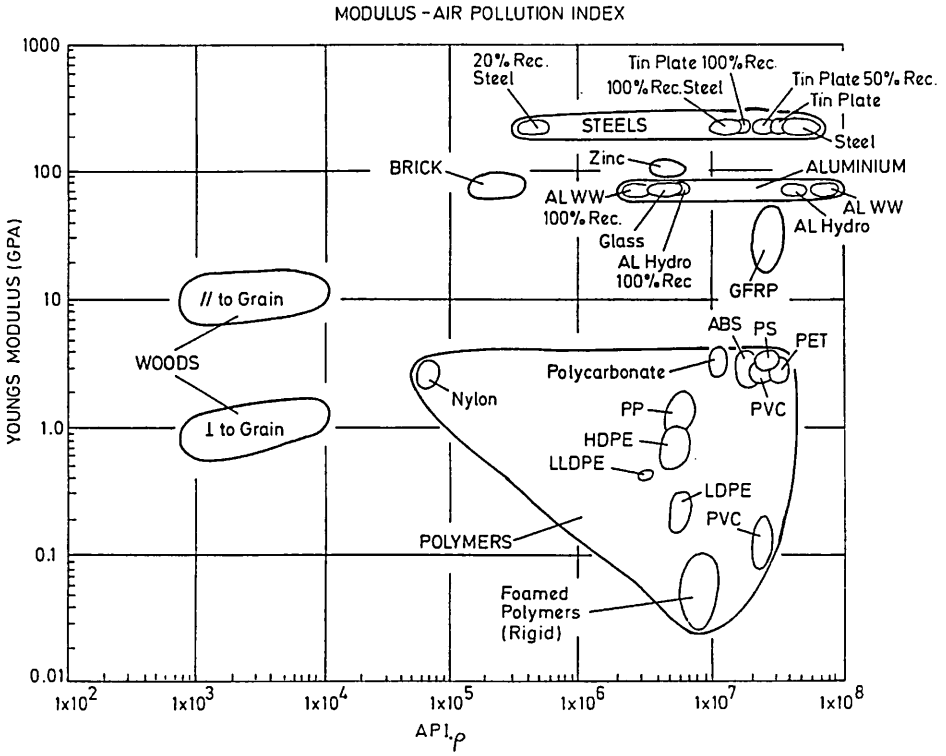


Figure 9.5 Young's Modulus - Air Pollution Index Materials Selection Chart

The design criteria guidelines plotted on these graphs are those discussed earlier. However in the case of environmental design determining a value for the constant C may be difficult. As design for the environment is a relatively new concern optimal values for C have not been calculated. As with other design criteria the higher the value of C the better the material is for the specified application. Design for the environment is set to become a very important part of mechanical design and as it becomes more common place the constant values for design criteria will develop. At this stage designers should consider the overall range of API and WPI values for all the materials on the charts and make decisions based on relative comparison.

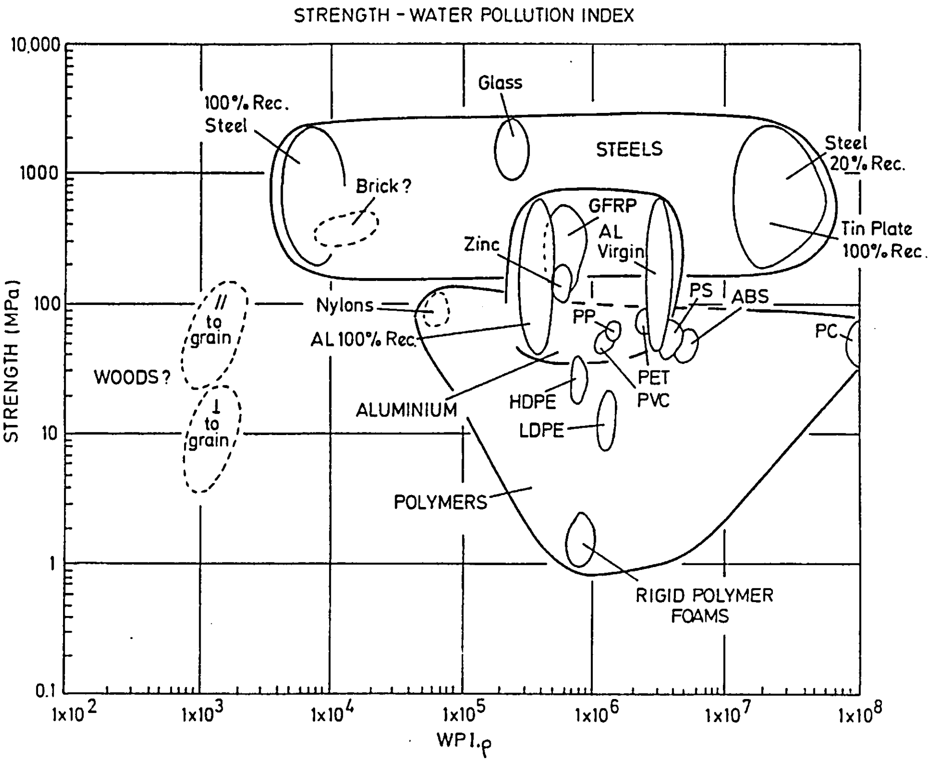


Figure 9.6 Strength - Water Pollution Index Materials Selection Chart

The materials close to the bottom right hand corner of the charts will offer the worst environmental/mechanical performance with those at the top left hand side of the charts offering the best.

If a particular material is already in use for a specified application the charts will be useful in optimising material choice. A value of C may be calculated for the material which is already used and using the charts materials with a higher value of C may be selected.

9.5 Limitations of Charts and Future Work

The environmental materials selection charts presented in this chapter have a number of limitations and it is important that these limitations are understood in order that the charts may be used properly.

The emissions data for the materials in the charts is taken from a number of different sources: **Boustead**(1992), **Steinhage & Dam Van** (1990) and **Habersatter & Widmer**(1991) amongst others. The data contained with these studies are averages of many different practices. It should be understood therefore that the data these charts present may not be representative of particular operations used to produce the specific materials. The data is however an average of extensive studies carried out upon a large number of industrial operations and can therefore be used as a guideline.

None of the overall air pollution indices include the effect of carbon dioxide gas. There is, at this time, no accepted way of defining the MAC value of CO_2 .

The number of materials in these charts is limited. The overall environmentally relevant inputs and outputs of a system are calculated using life-cycle analysis. As discussed in earlier chapters LCA studies are very long and complicated operations and as it is a relatively new science not all materials have been the subject of such studies. The material groups contained within the charts presented in this chapter are, however, among the more commonly used materials in engineering design.

As LCA studies become more common place and the data will become more accurate, more emissions will be identified and more materials will be able to be added to the charts, making them more comprehensive and more useful. The use of the Eco-Indicators methods discussed earlier in this work is now becoming much more commonplace and data is available for a large number of materials. Aside from the problems of quantifying environmental impact with a single figure use of this system would allow much more comprehensive materials selection charts.

By using the method presented in this chapter environmental concerns may also be mapped onto process selection charts and extend Ashby's work further still. Charts such as surface finish versus API may be plotted allowing engineers and designers to select processes which also optimise pollution.

9.6 Chapter Summary

Unfortunately the integration of environmental concerns into the design process threaten to complicate it further still. In order that this does not happen there is a need for tools to support designers and help them to achieve their environmental goals. Rather than attempting to develop new design methods and aids, the adaptation of existing methods may afford the best opportunities. Ashby's materials and process selection charts are a tried and tested materials selection method. In the field of mechanical design these charts are a simple and quick way of assessing whether a material is suitable for the case in hand. By taking these charts and extending their range to include environmental concerns, designers may consider them in exactly the same way they consider other material and process properties.

Although these charts have a number of limitations they are still an important addition to a designers tool kit. Limited environmental information is better than none at all and by developing such methods and approaches now when environmental information becomes readily available the tools with which to manipulate this data will already be in place. Environmentally conscious material selection charts structure and accelerate the environmental impact assessment of design decisions and readily integrate them into existing mechanical design procedures.

Chapter 10

A Support Tool for Environmental Design & Manufacture

A Support Tool for Environmental Design & Manufacture

10.1 Introduction

The need for tools to support environmental design practices was identified in the critical review carried out earlier in this work. A number of the different tools available were analysed and the future needs in this area discussed. The use of the technology of expert systems has been identified as a good way forward in the field of environmental design support tools, **Holloway & Tranter** (1995) and **Holloway et al.** (1995). This chapter describes such a prototype expert system developed during this research.

10.2 Development of the Support Tool

The support tool was developed using a prototyping system. As mentioned in Chapter 9 rapid prototyping has a number of pitfalls as far as the development of software is concerned and it should not be adopted by developers of Expert systems. Because of this the system developed here used a system of prototyping and KADS shown in figure 10.1, **Hickmen et al.** (1992).

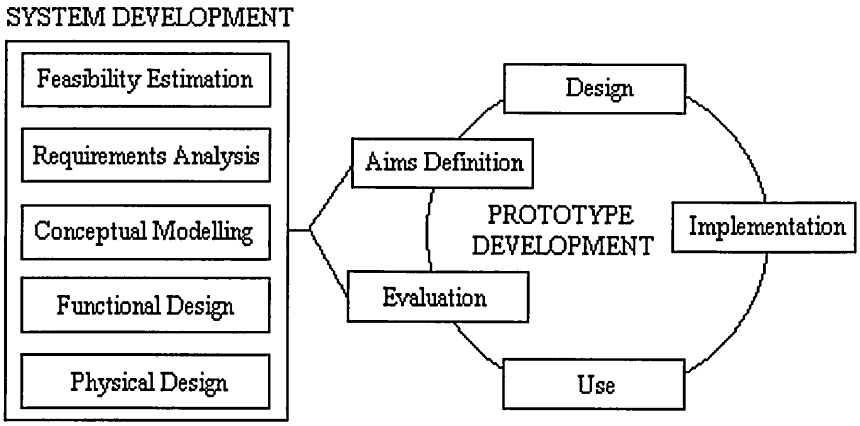


Figure 10.1 Integration of Prototyping within the KADS Life-Cycle Model

Prototyping can be seen as having a separate life-cycle consisting of 5 stages shown in Figure 10.1, and this cycle can be easily integrated into the normal *Common*KADS linear development life-cycle. By planning the prototyping in such a way many of the downsides of prototyping are almost completely removed.

Throughout its development this system has used such a method of development. Planning the activities, outlining the aims, using participation and feedback/involvement with the audience and evaluating feedback from the audience has resulted in a system which is easily used, and flexible.

10.3 System Overview

The environmental design expert system embodies part of the new environmental design method developed in this research. As discussed earlier the most difficult stage of a product or system life-cycle to model and analyse is its use because of this inclusion of user derived data for this phase is a possibility. The use stage of the life-cycle is only addressed in the LCA part of the system and not in the optimisation procedures as it is too complex to try and model usage patterns and optimise them using this tool. The system can be used to carry out LCA studies on all products but will therefore be most useful in optimising the design of short-life cycle products where energy and resource consumption contribute little or nothing to the overall environmental effect.

The following parts of this section give an overview of the operation of the expert system. The specifics of the programme will be discussed in detail later on in this chapter.

The system has four main stages to its operation:

1. Preliminary Materials Selection
2. LCA
3. Optimisation
4. Design Advice

and follows a flowchart of operation as shown in figure 10.2.

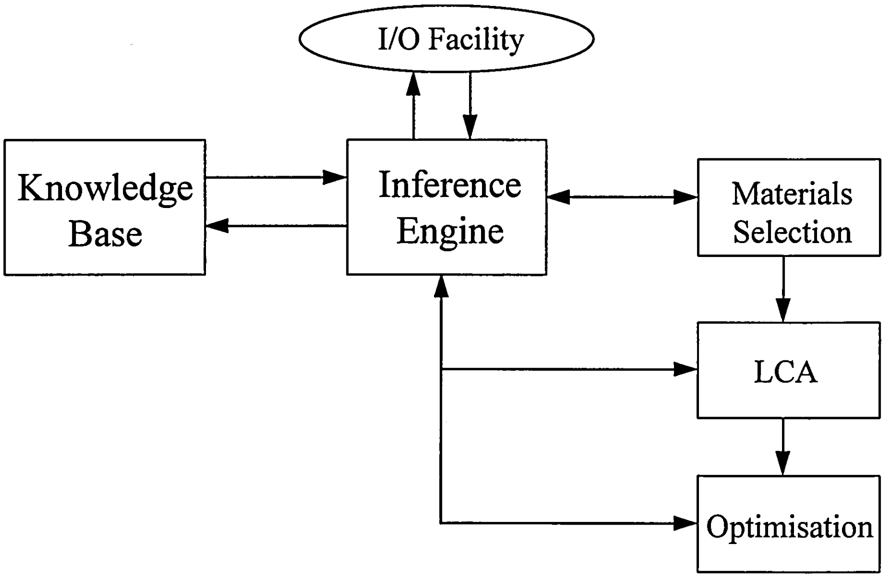
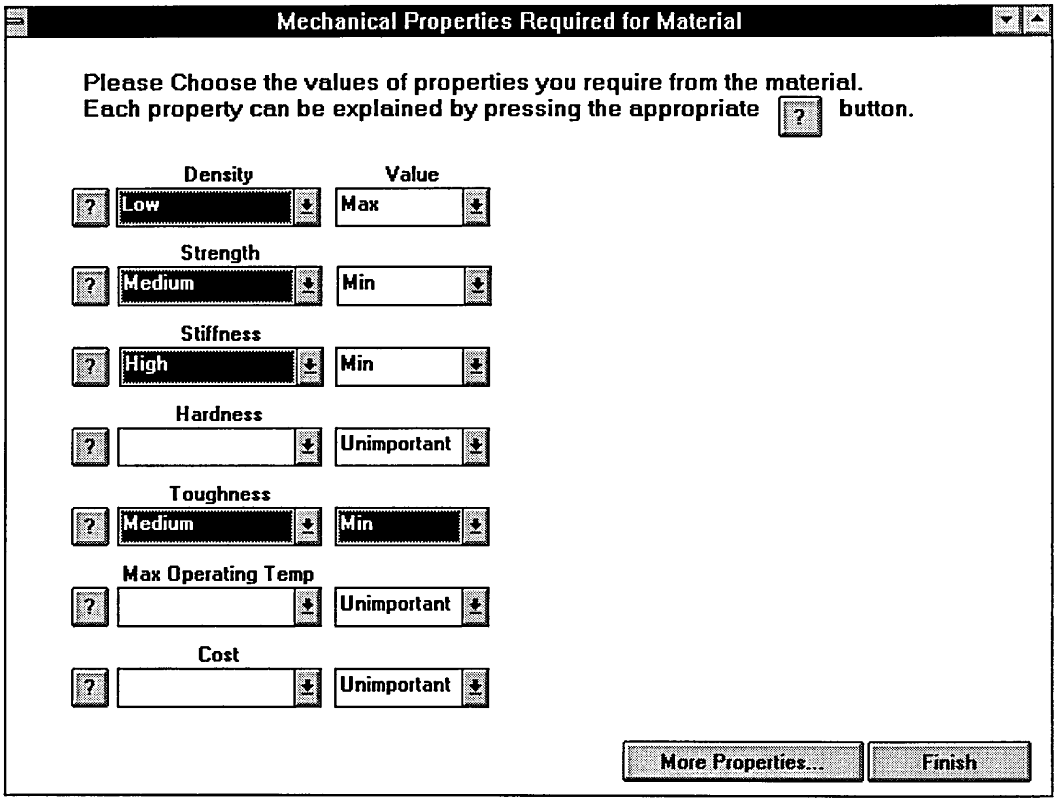


Figure 10.2 Operation of Expert System

10.3.1 Preliminary Materials Selection

The first part of the system allows the user to select materials on a descriptive basis. Required properties are described in terms of relative performance rather than quantitative figures. For example a designer may require a lightweight, stiff and tough material. The interface is shown in figure 10.3a. Once the description of properties is defined groups of materials which meet those requirements are presented to the designer. They can then choose the groups which they see as suitable (see figure 10.3b) and the system presents all the possible materials contained within the database along with their respective energy requirements, API and WPI per Kg as shown in figure 10.3c.



Mechanical Properties Required for Material

Please Choose the values of properties you require from the material.
Each property can be explained by pressing the appropriate ? button.

Density — Value
Low — Max

Strength
Medium — Min

Stiffness
High — Min

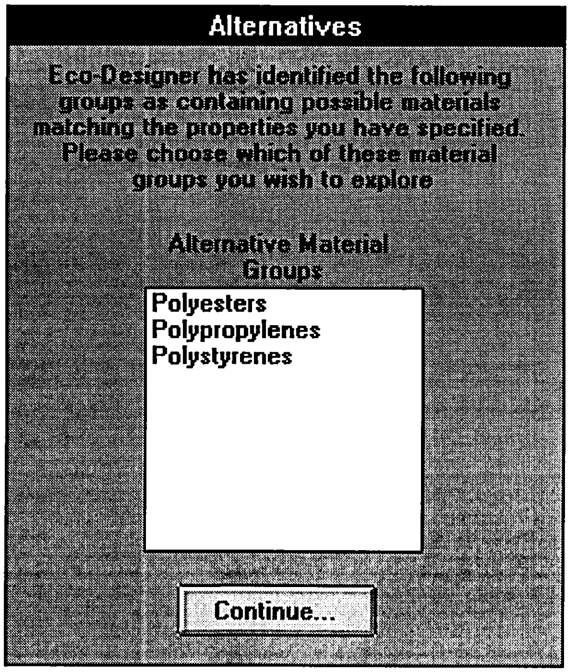
Hardness
Unimportant

Toughness
Medium — Min

Max Operating Temp
Unimportant

Cost
Unimportant

Figure 10.3a Materials Selection User Interface



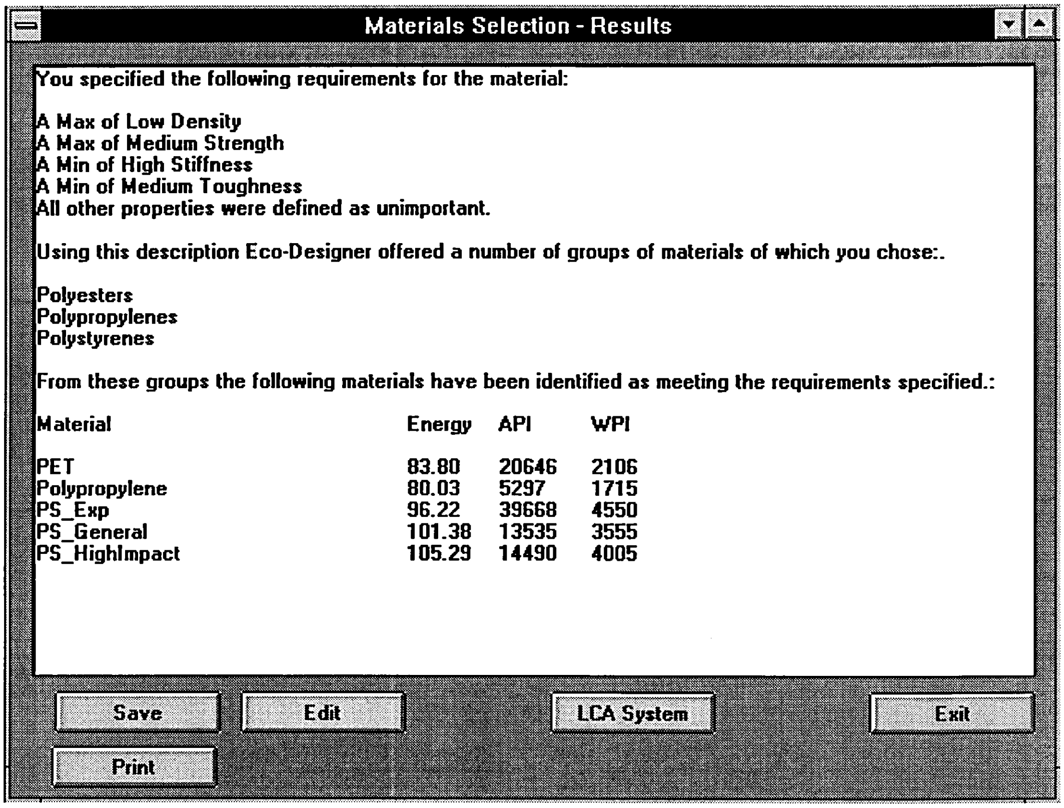
Alternatives

Eco-Designer has identified the following groups as containing possible materials matching the properties you have specified. Please choose which of these material groups you wish to explore

Alternative Material Groups

Polyesters
Polypropylenes
Polystyrenes

Figure 10.3b Possible Material Groups



```
You specified the following requirements for the material:

A Max of Low Density
A Max of Medium Strength
A Min of High Stiffness
A Min of Medium Toughness
All other properties were defined as unimportant.

Using this description Eco-Designer offered a number of groups of materials of which you chose:.

Polyesters
Polypropylenes
Polystyrenes

From these groups the following materials have been identified as meeting the requirements specified.:

Material                              Energy   API     WPI

PET                                   83.80    20646   2106
Polypropylene                         80.03    5297    1715
PS_Exp                                96.22    39668   4550
PS_General                            101.38   13535   3555
PS_HighImpact                         105.29   14490   4005
```

Figure 10.3c Materials Selection Results

This system allows the user to select materials on a purely descriptive basis. The results show the user which materials are contained within the expert system and therefore may be used in LCA studies. At this stage it also allows a preliminary judgement of the environmental impact of materials.

10.3.2 LCA

At the user input stage the designer communicates the specification of the life-cycle of the design in terms of materials used, processing routes, distribution activities and disposal practices. The system contains a database of materials, processes, distribution and disposal When all the information has been entered the system calculates the life-cycle environmental profile of the design. The results are presented in terms of inputs and raw materials used and outputs/emissions to the environment. Both tables of emissions and graphical environmental profiles are presented.

10.3.3 Optimisation

In order that the design may be optimised in terms of environmental performance the system then goes through each of the materials, processes, distribution stages and disposal practices specified by the user and attempts to find alternatives. For materials and processing optimisation the designer is asked to describe the requirement in terms of the specific parameters used by the system for optimisation and selection.

10.3.4 Design Advice

Finally the expert system will present the user with advice relating to materials, processing, distribution and disposal which may result in a design which is less environmentally damaging.

10.4 System Architecture

The architecture of the system contains the main components suggested by **Muher & Allen** (1987) and is shown in figure 6.3 in chapter 6. The knowledge base contains information on materials (mechanical and environmental properties), processing (including environmental data), distribution (environmental data) and disposal techniques (environmental data). Although the user input allows definition of the design, only materials, processes etc. which are contained within the knowledge base may be used. Other user inputs include weights of materials, specific processing information, distances of distribution and amounts of material going to different disposal routes.

The inference engine contains the methods which are used in the optimisation of the design. The user may also contribute to the inference engine by asking the system to optimise the design in terms of specific requirements.

As the system is only a prototype, and not a fully functioning piece of commercial software, the knowledge acquisition facility has not been developed.

10.4.1 Knowledge Representation

Due to the nature and type of the information used in the system an object-oriented approach was adopted. Many of the parameters used to describe the information being used are the same. For example over 90% of the environmental parameters for all materials within the system will be identical. The processing information contained within the system is structured in a similar manner. A small group of parameters may be used to describe any of the processes within the system.

It therefore makes sense to split the information into an object hierarchy. Figure 10.4 shows the general object hierarchy of the system. As can be seen it is made up of a number of subclasses, which deal with all aspects of the systems operation, but the most important are those containing the information for each of the life-cycle stages. As these form the main part of the information within the system they may be classed as the main 4 main branches of the object hierarchy.

10.4.1.1 Object Hierarchy

The object hierarchy is split into 4 main branches of:

- Materials
- Processing
- Distribution
- Disposal

which represent the life-cycle of a product or system. (Use is included within the calculations but is not represented by a specific branch in the hierarchy).

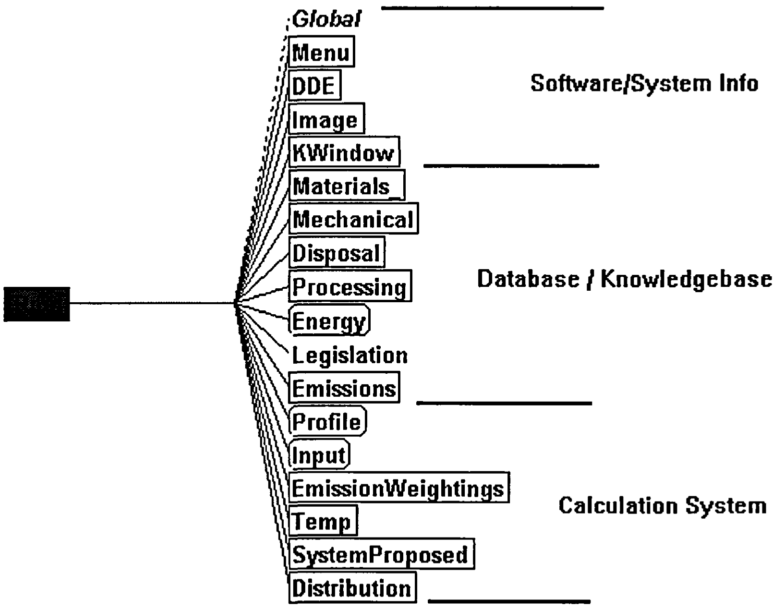


Figure 10.4 The Main Object Hierarchy of the Expert System

The hierarchy of materials is shown in figure 10.5. As can be seen the classification is congruent with that of many designers and engineers.

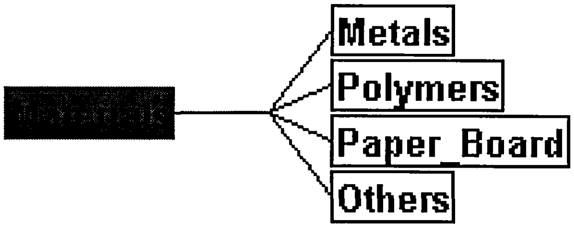


Figure 10.5 Materials Hierarchy in the Expert System

The parent class of materials is split into 4 subclasses of Metals, Polymers, Paper and Board and Others. Figure 10.6 Shows the Metals hierarchy and figure 10.7 shows the Polymers hierarchy. Each of these classes is then split further into actual materials. These are called the instances and each one is a specific object containing specific information relating to that object. These instances can be seen in figure 10.6 and 10.7 as the third level of the hierarchy. The object hierarchies for processing and disposal are shown in figures 10.8 and 10.9.

The processing class is split into subclasses dependent on the type of material to be processed. The polymer processing is split into two subclasses for different types of processing, mass processing and batch processing.

The disposal hierarchy is split into classes which represent different disposal routes, i.e. landfill, incineration and recycling. Reuse is now a disposal option which is commonly considered but the environmental effects are too complex to integrate into this hierarchy at this time. Each of these contains information on that particular disposal route for all the materials within the materials hierarchy.

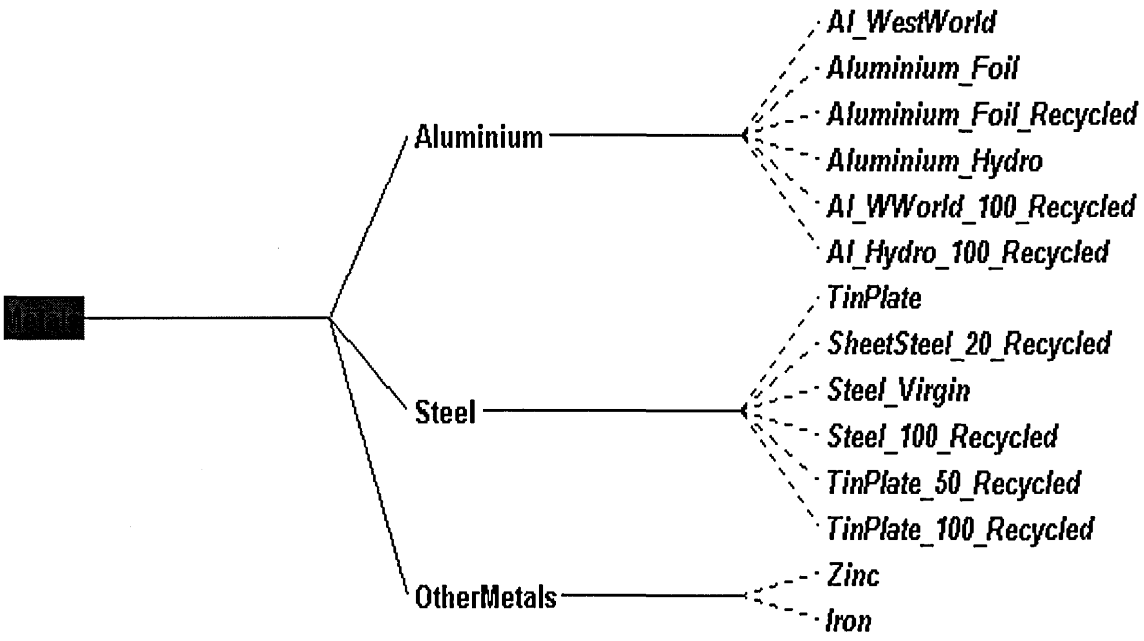


Figure 10.6 Metals Hierarchy in the Expert System

The complete object hierarchy for the system is contained in Appendix A.

This object hierarchy forms the framework of the expert system. All the information and methods used are contained within this framework. It is this information which is used to conduct LCA studies, present the results, optimise the design and give environmentally based design advice

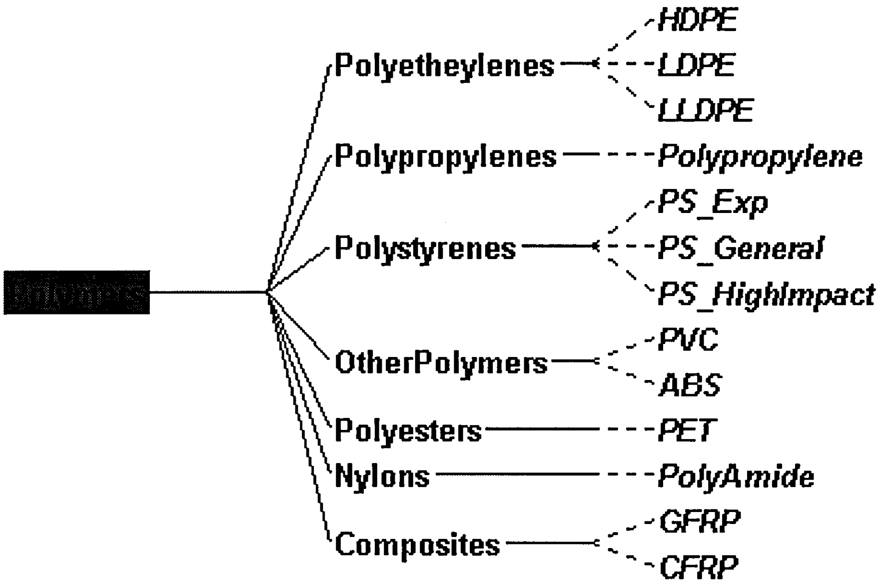


Figure 10.7 Polymers Hierarchy in the Expert System

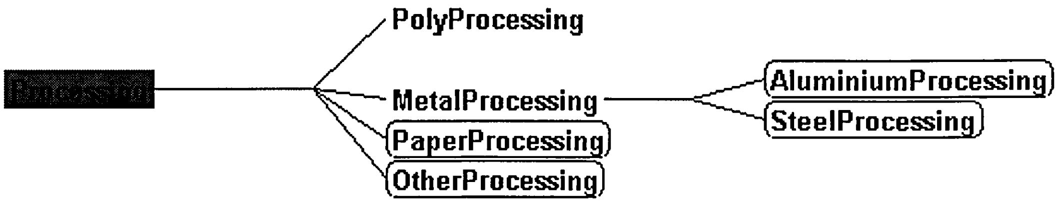


Figure 10.8 Processing Hierarchy in the Expert System

10.4.1.2 Information Contained within Classes and Instances

Stored within the classes and instances of the object hierarchy there is a large amount of information. The system itself contains information on 50 materials, 10 different energy generation sources, 35 processes, and a total of 150 specific disposal activities. (i.e. 3 different disposal options for each of the 50 materials)

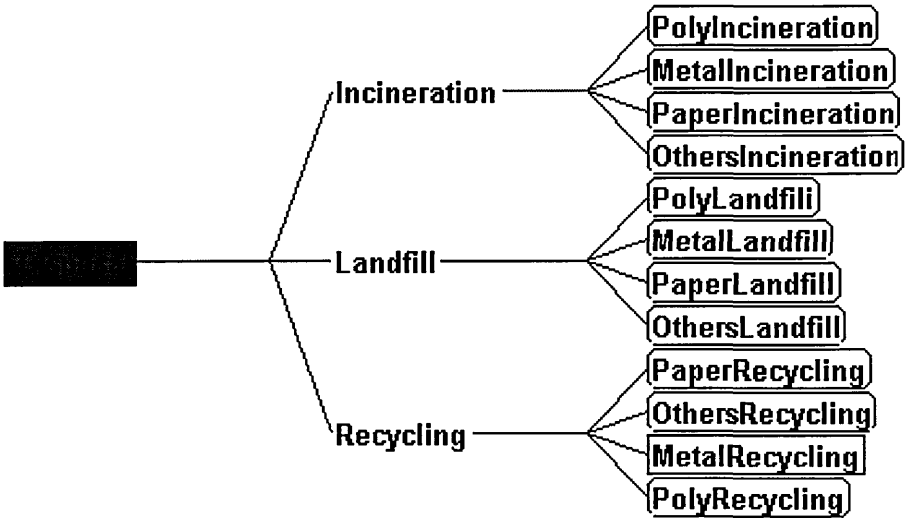


Figure 10.9 Disposal Hierarchy in the Expert System

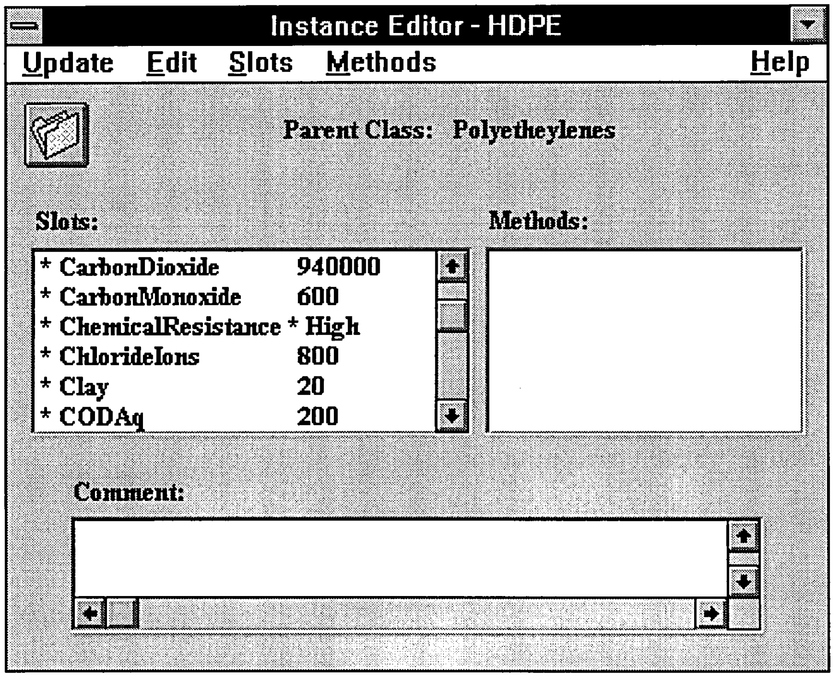
Allied to this is a large amount of environmental data. The system contains information on over 150 inputs, emissions, waste etc. related to each of the materials, processes, energy generation and disposal options.

This information is stored in the classes in 'slots'. These slots contain information about environmental, mechanical and other properties. Figure 10.10 shows an example of the slots contained within the material instance HDPE.

Each of the slots is given a value which is either numerical or descriptive, depending on what that slot is representing. For example in the case of HDPE the CarbonDioxide slot has a value of 940,000 mg/kg of HDPE produced. ChemicalResistance, which is the resistance of the material to exposure to chemicals is described as 'High', as a numerical value cannot be given.

All the information within the system is held in this way.

Some information is specific and is therefore entered at instance level, other information is inherited from higher classes.



Parent Class: Polyetheylenes

* CarbonDioxide	940000
* CarbonMonoxide	600
* ChemicalResistance	* High
* ChlorideIons	800
* Clay	20
* CODAq	200

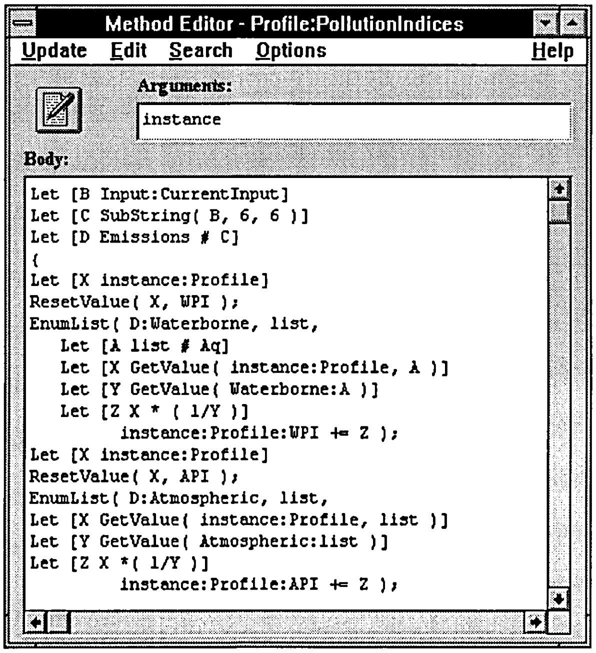
Figure 10.10 Slots within the HDPE Instance

In the case of HDPE the asterisk preceding the value High of ChemicalResistance indicates that it has been inherited from the parent class. All types of polyethylene have a high resistance to chemicals and therefore this value is entered at the Polyethylene class level (see figure 10.7). The values of emissions such as CarbonDioxide are specific to the material and therefore entered at instance level.

This type of inheritance is common throughout the system and one of the advantages of using an object oriented system. All this information forms the knowledge base of the system as shown in figure 10.2.

10.4.1.3 Methods

As well as inherited and specific information about emissions and mechanical properties etc. classes and instances also contain methods. Methods are an 'approach to representing processes which involves enhancing objects so that they represent the behaviour of the things to which they correspond.' **Kappa-PC User Guide** (1992). The methods within the system are used to carry out calculations, run the user interface, present results and also contain the expertise which allows the system to offer advice. Some of the methods form the inference engine of the system while others which carry out standard calculations may be classed as part of the knowledge base. Figure 10.11 shows an example of a method used within the system. The methods use information from the objects at both class and instance level, create and use variables and can also create new information which is then stored within the framework of the object hierarchy. This new information is part of the current context/working memory of the system referred to in figure 10.2. Methods used within this system also add and delete temporary objects to the hierarchy as part of the calculation/optimisation procedures.



Arguments: instance

```
Let [B Input:CurrentInput]
Let [C SubString( B, 6, 6 )]
Let [D Emissions # C]
{
Let [X instance:Profile]
ResetValue( X, WPI );
EnumList( D:Waterborne, list,
   Let [A list # Aq]
   Let [X GetValue( instance:Profile, A )]
   Let [Y GetValue( Waterborne:A )]
   Let [Z X * ( 1/Y )]
         instance:Profile:WPI += Z );
Let [X instance:Profile]
ResetValue( X, API );
EnumList( D:Atmospheric, list,
Let [X GetValue( instance:Profile, list )]
Let [Y GetValue( Atmospheric:list )]
Let [Z X *( 1/Y )]
         instance:Profile:API += Z );
```

Figure 10.11 Example Method from the Expert System

10.4.1.4 Data Acquisition & Sources

All expert systems contain information which has to be elicited from sources of some kind. The sources of information used in expert systems range from books and technical data collections, to knowledge elicited directly from human experts.

This expert system contains knowledge from a number of different sources. The knowledge can be split into 5 areas:

1. Environmental data for materials, processing, disposal etc.
2. Mechanical and other data for materials processing etc.
3. Data relating to results presentation
4. Optimisation procedures
5. Design guidelines

10.4.1.4.1 Environmental Data

Environmental data is particularly difficult to obtain but in recent years a number of studies have been carried out which present LCA results for a range of materials and processes. Most of these studies represent average European figures and have therefore been used in this system. Many of the other computer systems available use the same sources for their data as these sources are very limited.

During the development of the system new data sources have become available. The sources were evaluated and those deemed appropriate or more up-to-date were used in the system to replace other older data. Table 10.1 summarises the main sources of environmental data.

10.4.1.4.2 Mechanical Data

Mechanical data is much better documented than environmental data. There are many sources for this type of data and it is much more reliable.

Specific mechanical data is taken from literature by **Ashby & Jones** (1992) and the CMS computer programme, **Granta** (1995).

Data relating to:	Sources used in the E.S.
Materials	BUWAL - **Habersatter & Widmer** (1992) APME Reports - **Boustead** (1993 - 1995) Van den Burgh & Jurgens - **Steinhage & Dam** (1990) SimaPro Database - **Cleij & Goedkoop** (1995) Calculation
Processes	BUWAL Van den Burgh & Jurgens SimaPro Database Direct knowledge elicitation & calculation
Distribution	BUWAL
Disposal	BUWAL SimaPro Database Calculation

Table 10.1 Sources of Data for the Expert System

Some of the mechanical data is in the form of descriptors such as ‘low density’, ‘high strength’ ‘medium toughness’. This system as used in the preliminary materials selection is based on absolute comparison of properties, for example polymers will be ‘low density’, metals will be ‘high density’. An explanation of this can be accessed by the user to allow them to use the property description correctly.

10.4.1.4.3 Data Relating to Results Presentation

Results presentation in the field of environmental design is a very inconsistent area. Through the study of other systems and methods a results presentation system for this tool has been developed which is transparent yet concise.

Data is presented in full tabular form and graphical presentation of data is also used. Agglomeration techniques using MAC and O.v.D values (discussed in an earlier chapter) are used to present aggregated figures for pollution. Examples of all these results are shown in section 10.5, Example Results and Outputs.

10.4.1.4.4 Optimisation Procedures & Design Guidelines

The knowledge contained within this part of the system makes up the system heuristics, or 'rules of thumb'. These procedures and guidelines have been developed from a number of works by **Hill** (1993), **Hendrickson et al.**(1994), **Burall** (1992) and **Fiskel & Wapman** (1994) and work carried out during this research.

10.4.1.5 Maintenance and Updating of System

The system is constructed in such a way as to be as flexible and easy to update as possible. Data on any of the main life-cycle stages may be added directly and the system will incorporate it into its operation automatically. A fully functional knowledge elicitation facility is not used in this system.

Pollution indices etc. are calculated from scratch every time the E.S. is used. Pollution indices could be pre-set by calculating them once and then saving them as they are directly linked to the emissions/Kg of material produced. By using a recalculation every time any emissions data that has been updated within the system will automatically be included and thus the pollution indices will be updated.

Other data and procedures may be added at the users request. It should be noted however that inclusion of new methods and procedures may require the existing ones to be updated.

The most transient area of data is that of emissions data relating to the production, processing distribution, use and disposal of materials and resources. As this data is updated and replaced it can be updated simply and easily in the system with no need for the rewriting of any methods or procedures.

If the calculation method used for LCA studies changes then this section of the system would have to be re-written.

10.4.2 LCA Calculation Procedures

The LCA calculations carried out by the system use the standard procedure. All the environmentally relevant information from each stage of the life cycle is gathered and similar emissions are added together to give an overall environmental profile.

The system also calculates API and WPI values as discussed in chapter 9.

10.4.3 Optimisation Procedure

The optimisation facility of the expert system is made up of a number of different procedures relating to the different life-cycle stages of the design in question. Each stage of the life-cycle will be optimised in turn with cross referencing between procedures taking place when it is essential to do so.

10.4.3.1 Types of Optimisation

The system will optimise designs in any one of four ways:

1. General Overall Pollution
2. Airborne Pollution
3. Waterborne Pollution
4. Specific Emission

General overall pollution adds together the Air Pollution Index (API) and the Water Pollution Index (WPI) to give a single overall pollution figure. This type of assessment is often asked for by designers but can hide valuable detail. Therefore the system offers full tables of data with any optimisation method.

Airborne pollution optimisation uses API values and attempts to reduce them to a minimum.

Waterborne pollution optimisation uses WPI values and attempts to reduce them to a minimum.

Specific pollution optimisation is specified by the user. The design will then be optimised on the overall emission of a single pollutant again reducing it to a minimum.

To add extra flexibility to the system each stage of the life-cycle may be optimised on a different parameter. For example materials production could be producing a large water pollution problem and so may be optimised using WPI. While disposal procedures may be causing high air pollution and so may be optimised using API values.

10.4.3.2 Optimising Material Choice

Ashby's materials selection method shows that mechanical properties and function description are required to choose appropriate materials for an application. When searching for alternative materials which may reduce environmental impact the system uses mechanical requirements as the search parameter. If a material cannot fulfil the functional requirement then it cannot be short listed as an alternative.

Once a short list of materials which meets the specified requirements has been assembled by the system environmental optimisation may take place.

10.4.3.3 Optimising Processing

Process optimisation is carried out in the same manner as that of materials. The system uses shape as a general descriptor for processing. There are many complex factors which need to be taken into account such as cost, tolerances etc. which are too complex to include in this system. The shape required of a process is the highest level of description and thus the initial 'filter'. This allows the system to offer all the possible processing alternatives and the user can then make decisions related to other requirements.

Cross referencing should take place with materials optimisation. For example if the user defined aluminium with a process of forging, and the system optimisation of the material in terms of mechanical and environmental requirements has suggested a polymer, the process optimisation will take this into account. The current prototype system developed during this research will alert the user if materials offered in the materials optimisation are of a different class than those originally specified by the user.

10.4.3.4 Optimising Distribution

Optimisation of distribution is straight forward. The user has defined a system of distribution, and the system offers some alternatives. The environmental savings which could be made from packaging reduction (in terms of weight) and using different types of transport are outlined. Again possible cross referencing with materials optimisation is highlighted and the contribution of the distribution to the overall air pollution is shown.

10.4.3.5 Optimising Disposal

During optimisation of disposal the system assesses the current disposal practices. A hierarchy of reduce, reuse, recycle, dispose is advocated. The amount of materials/energy recovery is calculated and if it is below a certain level (set by user or legislation etc.) the system will highlight this. Possible extra gains from recycling and energy recovered are assessed. When dealing with incineration and the amount of energy recovered the system will compare the emissions of incineration with that of standard figures for electricity generation. If the emissions from incineration are greater per unit energy than standard electricity generation it is recommended that incineration is not a viable disposal option.

10.5 Using the Expert System

The following section will demonstrate how the system is used by a designer through presentation of the user interface. Screen shots are presented as they would be by the system. The system works in three parts:

1. Initial Materials Selection (explained in 10.3.1)

2. Definition and LCA of a design
3. Optimisation of the design

10.5.1 Definition and LCA of a Design

The following is the procedure for defining a design and carrying out an LCA of that design using the expert system. Figure 10.12 shows the prototype user interface of the system.

Up to three designs can be assessed or compared at any one time. Each of the designs is defined in terms of weights of materials, processing options, distribution, use and disposal. The interfaces for including this information are all shown in Appendix B(i).

The user is guided through the possibility to include each stage of the life-cycle in the LCA. For example, materials alone, or materials and disposal only or materials, processing and disposal may be included. The user may specify any number of materials and processes within any design.

Once all this information is entered into the system life-cycle inputs and emissions are calculated. A summary of these results, as indices, are presented, upon completion of the calculation, underneath the definition of the design as shown in figure 10.12.

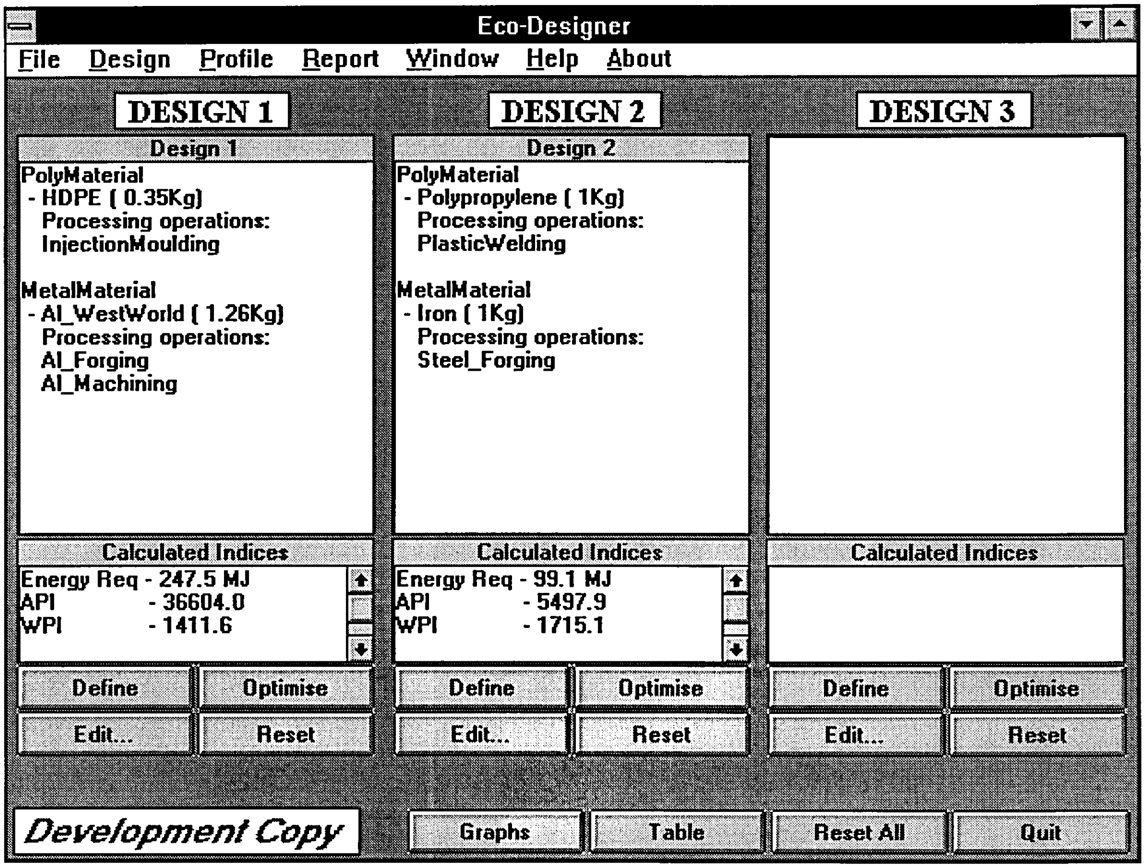
The full inventory results are displayed in a tabular form which the user can then send to a file or print off. This table is shown in 10.6 Example Results and Outputs.

10.5.3 Optimisation of Design

When the design has been defined and an LCA calculation completed the user may use the system to attempt to optimise the design as discussed in the previous sections. Using the mechanical/environmental system of optimisation each of the materials in turn can be optimised (see figure 10.13).

Each of the stages included in the LCA during the definition of the design is then optimised.

Some of the stages require user input and others do not. Again the full process is shown in Appendix B(ii).



Design 1
PolyMaterial
- HDPE (0.35Kg)
Processing operations:
InjectionMoulding

MetalMaterial
- Al_WestWorld (1.26Kg)
Processing operations:
Al_Forging
Al_Machining

Energy Req - 247.5 MJ
API - 36604.0
WPI - 1411.6

Design 2
PolyMaterial
- Polypropylene (1Kg)
Processing operations:
PlasticWelding

MetalMaterial
- Iron (1Kg)
Processing operations:
Steel_Forging

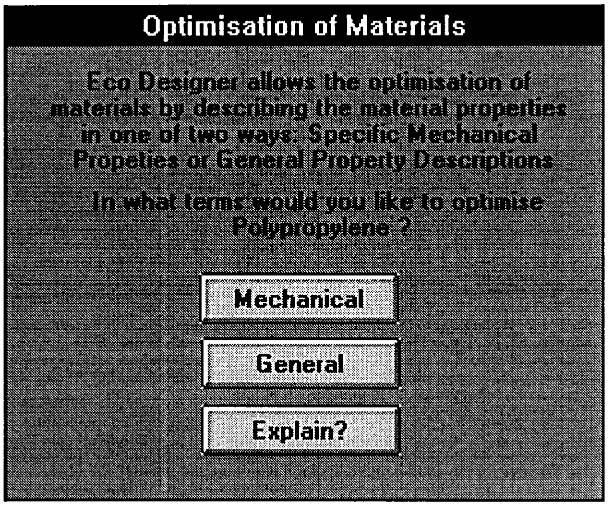
Energy Req - 99.1 MJ
API - 5497.9
WPI - 1715.1

Figure 10.12 Prototype User Interface of System

During this optimisation procedure the system uses both the materials and environmental knowledge encapsulated within it to assess all the possible alternatives and suggest design changes. The implications of these changes are also considered and presented to the user in the form of design guidelines and information.

10.6 Example Results and Outputs

The results produced by the system fall into two distinct categories as does the definition and optimisation of the design. The design definition and LCA stage presents indices, tables of data and graphs as results. The output of the optimisation stage is a number of design guidelines, suggested changes and relevant information.



Eco Designer allows the optimisation of materials by describing the material properties in one of two ways: Specific Mechanical Propeties or General Property Descriptions

In what terms would you like to optimise Polypropylene ?

Figure 10.13 Optimisation of Materials

10.6.1 LCA Results

In chapter two the different systems of presenting LCA results were identified and discussed. This system delivers the results in each of the ways suggested, agglomerated indices, full tables of data and graphical data outputs. The indices offered are:

Total Energy Required (MJ)

API (Air Pollution Index)

WPI (Water Pollution Index)

Energy Recovered (MJ)

The API and WPI indices have no units and are calculated using the system described in both chapters 2 and 9. The indices are presented to the user as shown in figure 10.12.

There is a danger of hiding relevant information by aggregation (as discussed in chapter 2) and therefore the system backs up these indices with full tables of emissions data. The tables are split into the following sections.:

Inputs

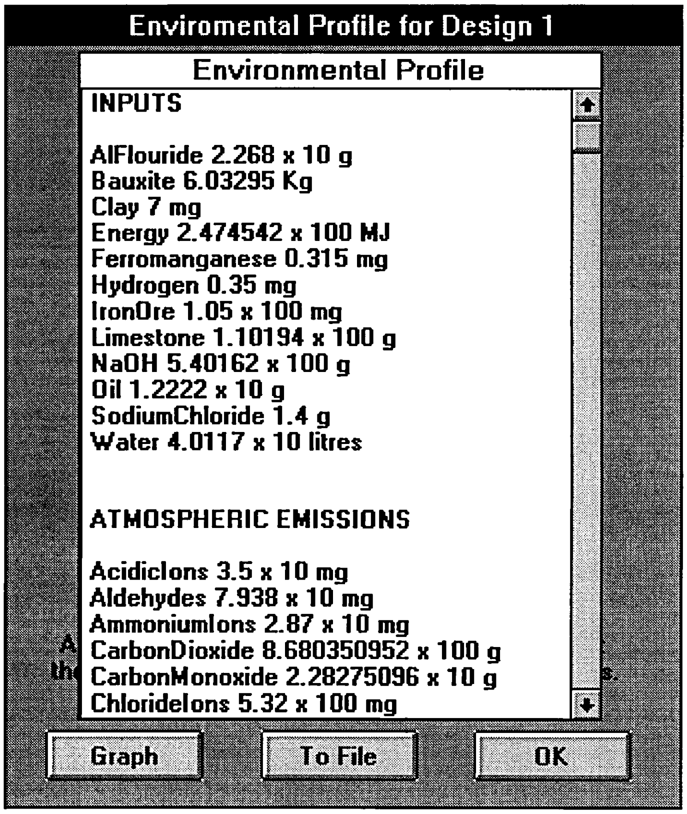
Atmospheric Emissions

Waterborne Emissions

Solid Wastes

Recovery

An example of such a table is given below in figure 10.14.



Enviromental Profile for Design 1

Environmental Profile

INPUTS

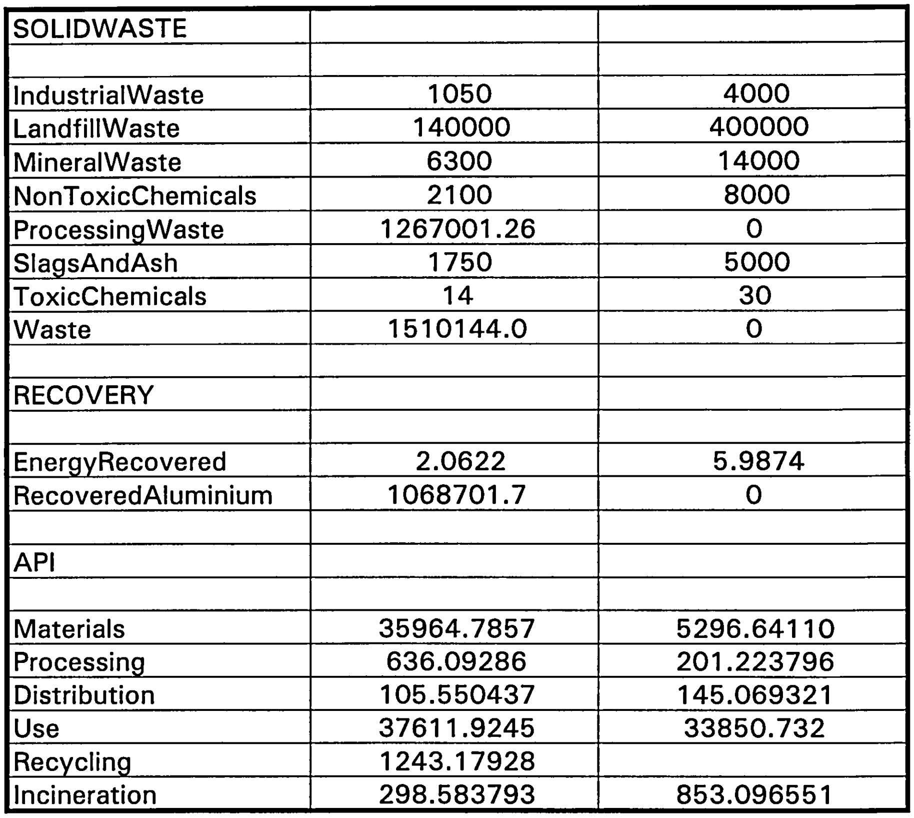
AlFlouride 2.268 x 10 g
Bauxite 6.03295 Kg
Clay 7 mg
Energy 2.474542 x 100 MJ
Ferromanganese 0.315 mg
Hydrogen 0.35 mg
IronOre 1.05 x 100 mg
Limestone 1.10194 x 100 g
NaOH 5.40162 x 100 g
Oil 1.2222 x 10 g
SodiumChloride 1.4 g
Water 4.0117 x 10 litres

ATMOSPHERIC EMISSIONS

AcidicIons 3.5 x 10 mg
Aldehydes 7.938 x 10 mg
AmmoniumIons 2.87 x 10 mg
CarbonDioxide 8.680350952 x 100 g
CarbonMonoxide 2.28275096 x 10 g
ChlorideIons 5.32 x 100 mg

Figure 10.14 Table of LCA Results

To help the user analyse this data it is useful to present the data graphically. The prototype system does this by exporting data to a spreadsheet. This allows the user to compare up to three designs at the same time and affords the versatility of spreadsheet functions in constructing the form of graphical output required. A section of the spreadsheet is shown in figure 10.15.



SOLIDWASTE		
IndustrialWaste	1050	4000
LandfillWaste	140000	400000
MineralWaste	6300	14000
NonToxicChemicals	2100	8000
ProcessingWaste	1267001.26	0
SlagsAndAsh	1750	5000
ToxicChemicals	14	30
Waste	1510144.0	0
RECOVERY		
EnergyRecovered	2.0622	5.9874
RecoveredAluminium	1068701.7	0
API		
Materials	35964.7857	5296.64110
Processing	636.09286	201.223796
Distribution	105.550437	145.069321
Use	37611.9245	33850.732
Recycling	1243.17928	
Incineration	298.583793	853.096551

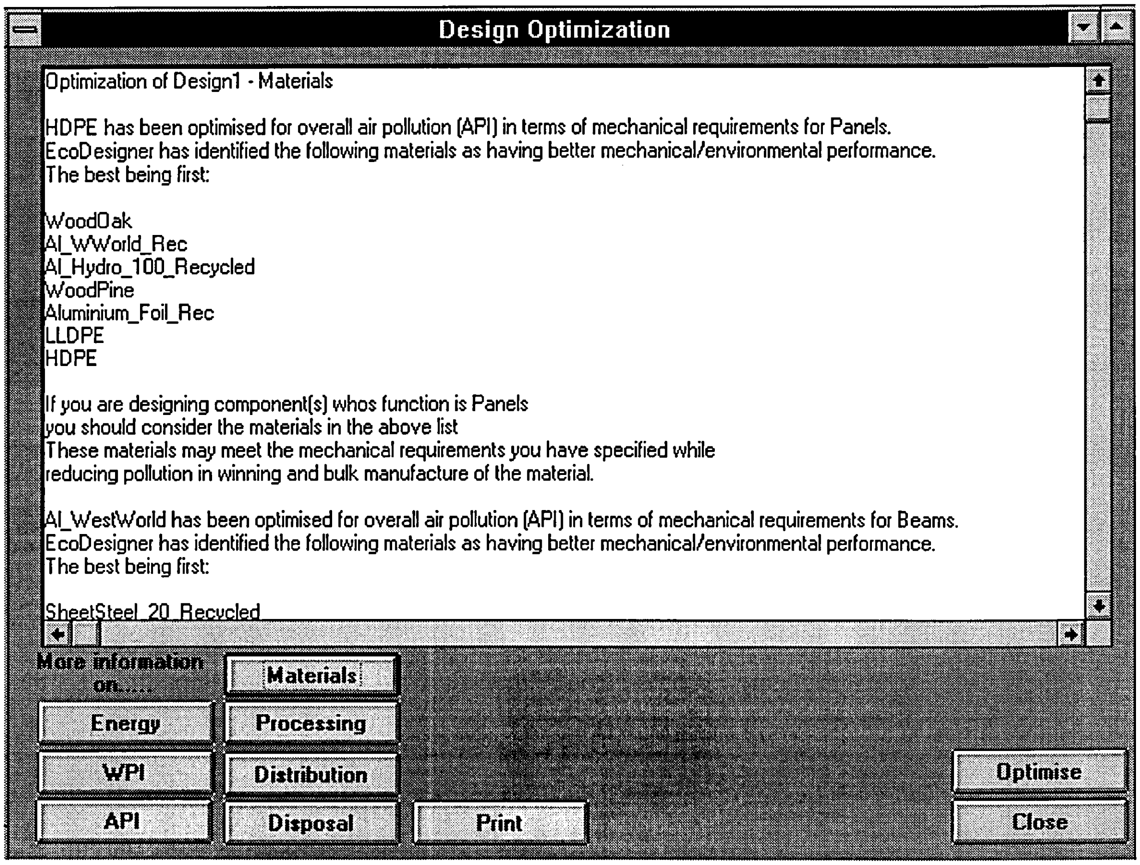
Figure 10.15 Spreadsheet Output of LCA Results

From this spreadsheet the user can generate graphical outputs for single and comparative data in the form of bar charts, pie charts, line graphs etc. Examples of these are shown in Appendix B(iii).

10.6.2 Optimisation Results

As explained in earlier sections of this chapter the optimisation procedures of the system deal with all stages of the life cycle excluding the use phase. Materials optimisation offers the user an explanation of how the optimisation took place and a list of possible alternatives generated by the system and confirmed by the user. Figure 10.16 shows an example of the material optimisation advice offered by the system.

Processing optimisation is carried out by the system using the shape of the final product and the material type as descriptors. For example HDPE material type is Polymer, and InjectionMoulding shape is 3D. If other classes of materials such as metals are possible



Optimization of Design1 - Materials

HDPE has been optimised for overall air pollution (API) in terms of mechanical requirements for Panels.
EcoDesigner has identified the following materials as having better mechanical/environmental performance.
The best being first:

WoodOak
Al_WWorld_Rec
Al_Hydro_100_Recycled
WoodPine
Aluminium_Foil_Rec
LLDPE
HDPE

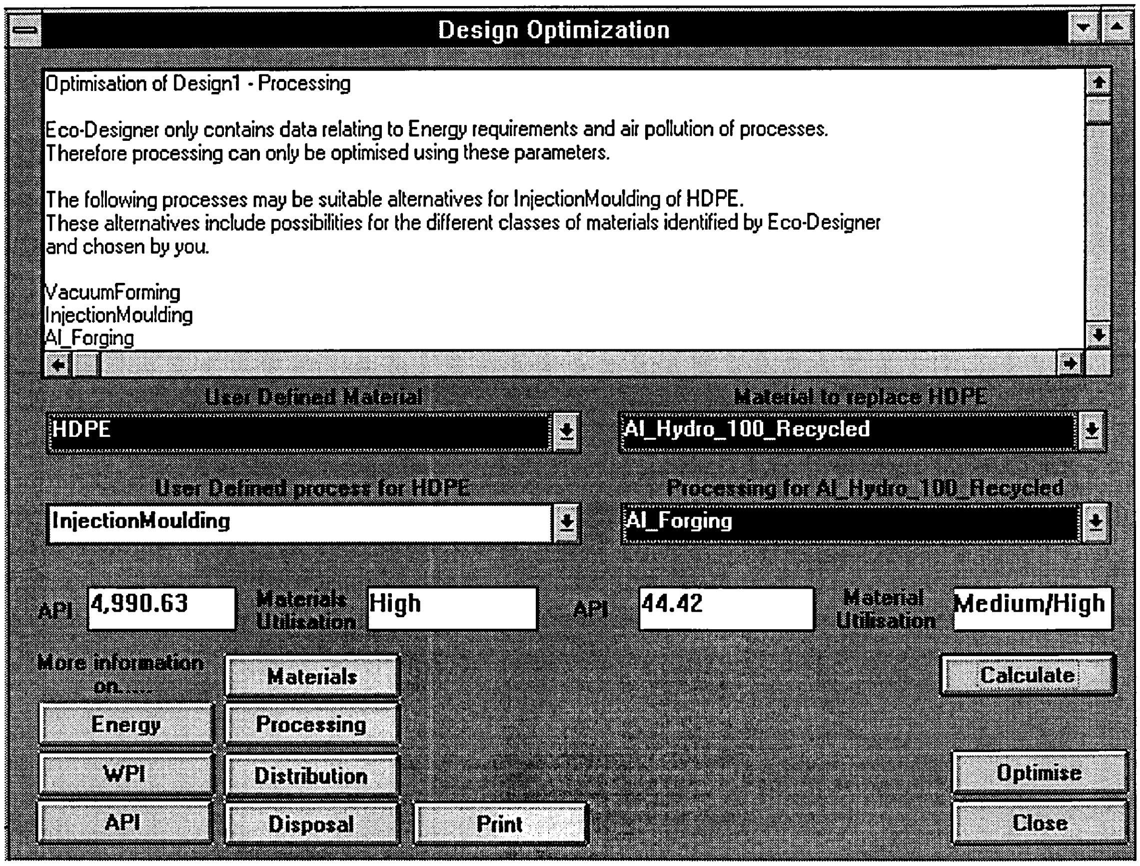
If you are designing component(s) whos function is Panels
you should consider the materials in the above list
These materials may meet the mechanical requirements you have specified while
reducing pollution in winning and bulk manufacture of the material.

Al_WestWorld has been optimised for overall air pollution (API) in terms of mechanical requirements for Beams.
EcoDesigner has identified the following materials as having better mechanical/environmental performance.
The best being first:

SheetSteel_20_Recycled

Figure 10.16 Materials Optimisation Advise

alternatives then the system will take this into account when looking for possible processing alternatives. For example if aluminium is a possible alternative for HDPE then forging will be one of the possible alternatives for injection moulding that will be offered. Figure 10.17 shows an example of the process optimisation advice offered by the system. The list of alternative materials and processes may be assessed in any possible combination and the amount of air pollution and degree of materials utilisation of that process are calculated and presented to the designer. In this way the system uses its expertise to identify possible alternative processes and gives designers all the information required to allow them to compare alternatives and make an informed decision.



Optimisation of Design1 - Processing

Eco-Designer only contains data relating to Energy requirements and air pollution of processes.
Therefore processing can only be optimised using these parameters.

The following processes may be suitable alternatives for InjectionMoulding of HDPE.
These alternatives include possibilities for the different classes of materials identified by Eco-Designer
and chosen by you.

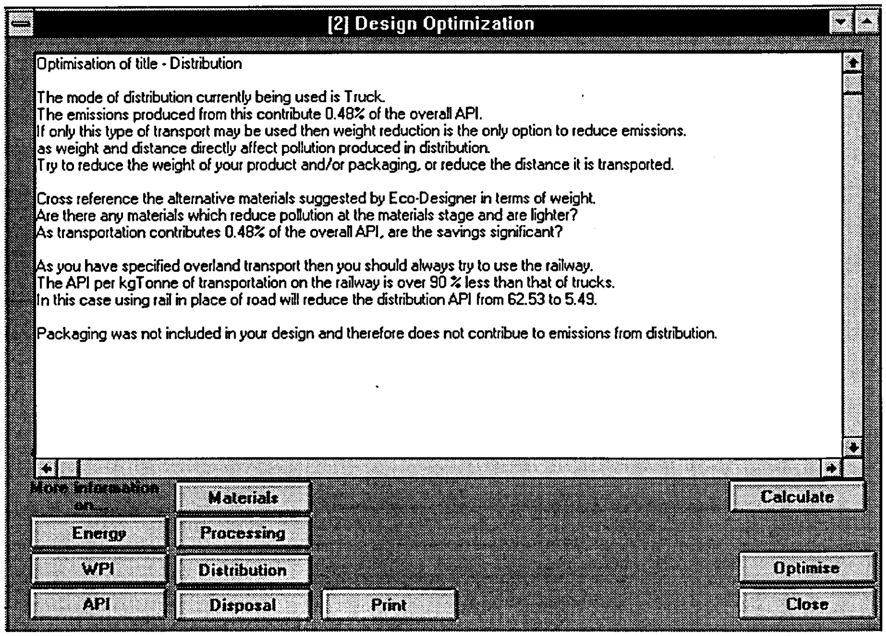
VacuumForming
InjectionMoulding
Al_Forging

User Defined Material: HDPE
Material to replace HDPE: Al_Hydro_100_Recycled
User Defined process for HDPE: InjectionMoulding
Processing for Al_Hydro_100_Recycled: Al_Forging
API: 4,990.63
Materials Utilisation: High
API: 44.42
Material Utilisation: Medium/High

Figure 10.17 Process Optimisation Advice

Advice is also given on distribution and disposal. The type of distribution is assessed and other alternatives which pollute less are offered. The contribution to overall pollution is outlined and the effect of changing materials and weights is brought to the users attention. Figure 10.18 shows an example of this.

Disposal is assessed by calculating the amount of materials recycled or incinerated. If this amount is less than targets which are either system set, or can be set by the user, the system will highlight this. Amounts of materials and/or energy recovered are highlighted. Also in the case of incineration, if the pollution caused by incineration of a particular material is greater than that which would be produced through generating the energy in the normal way (electricity) then the use of incineration is not recommended. Figure 10.19 shows an example of the type of advice given for optimisation of disposal practices.



Optimisation of title - Distribution

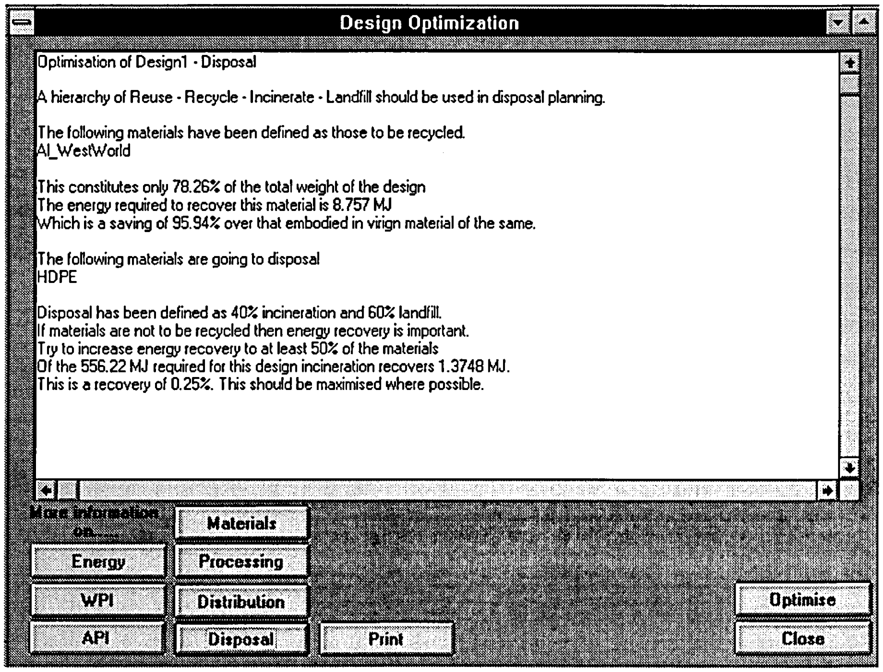
The mode of distribution currently being used is Truck.
The emissions produced from this contribute 0.48% of the overall API.
If only this type of transport may be used then weight reduction is the only option to reduce emissions.
as weight and distance directly affect pollution produced in distribution.
Try to reduce the weight of your product and/or packaging, or reduce the distance it is transported.

Cross reference the alternative materials suggested by Eco-Designer in terms of weight.
Are there any materials which reduce pollution at the materials stage and are lighter?
As transportation contributes 0.48% of the overall API, are the savings significant?

As you have specified overland transport then you should always try to use the railway.
The API per kgTonne of transportation on the railway is over 90 % less than that of trucks.
In this case using rail in place of road will reduce the distribution API from 62.53 to 5.49.

Packaging was not included in your design and therefore does not contribue to emissions from distribution.

Figure 10.18 Distribution Optimisation Advice



Optimisation of Design1 - Disposal

A hierarchy of Reuse - Recycle - Incinerate - Landfill should be used in disposal planning.

The following materials have been defined as those to be recycled.
Al_WestWorld

This constitutes only 78.26% of the total weight of the design
The energy required to recover this material is 8.757 MJ
Which is a saving of 95.94% over that embodied in virign material of the same.

The following materials are going to disposal
HDPE

Disposal has been defined as 40% incineration and 60% landfill.
If materials are not to be recycled then energy recovery is important.
Try to increase energy recovery to at least 50% of the materials
Of the 556.22 MJ required for this design incineration recovers 1.3748 MJ.
This is a recovery of 0.25%. This should be maximised where possible.

Figure 10.19 Disposal Optimisation Advice

10.7 Advantages and Implications of Using the System

There are a number of advantages of using this system when carrying out design for environment exercises.

1. The system is a central repository for information related to the environmental impact of materials, processes, distribution and disposal practices.
2. Using a structured approach to defining the design in question means that no information which is intended to be included is omitted.
3. The time taken to carryout LCA calculations is dramatically reduced and a high degree of accuracy is achievable.
4. Alternative possibilities for materials and processes are offered by the system in a structured manner and the reasoning behind these possibilities is explained.

As with most computer based systems the most obvious advantage is that of reduction in time and increased accuracy of calculations. This system, however has the added benefit of being a repository of information. Designers who do have experience in DFE exercises will be able to use the system as part of their conceptual design process. Designers who have no previous experience of DFE will also be able to benefit from using the system as it allows quick and easy calculation of LCAs and offers advice on how to improve the design in question.

The implications of all these advantages ultimately point to one main goal, the integration of environmental concern into current design practices. The way in which the system is used, and the information required, allows its introduction into the 'normal' design process with the minimum amount of disruption and reduces then need for specialist training of designers and engineers.

10.8 Chapter Summary

The preceding chapters of this thesis have explored the wide-ranging array of methods and tools to assist designers in integrating environmental concerns into the design process. Chapter 6 discussed the use of knowledge based systems in design and showed that there are a number of requirements for such tools as identified by **Bowden & O'Grady** (1989). This chapter has shown that the tool developed as part of this research programme addresses 6 of the 7 points made:

1. It is a flexible tool
2. It can be used to design despite the absence of some information
3. It can handle a very large volume and variety of life-cycle data
4. It exhibits high performance in terms of speed and reliability
5. It has a good user interface and explains advice given
6. The architecture of the system allows it to be easily updated

The only point which is not addressed by this tool is the ability to link to databases and CAD systems. This particular activity has not been undertaken during this research but the system has been constructed in such a way, and uses an appropriate language, so that it may be linked to databases and CAD systems if so desired. This would facilitate the need to programme the actual interface and data exchange procedures.

The knowledge based system presented in this chapter is an efficient, easy to use and flexible design support tool, which allows quick and easy LCA studies to be carried out and presents the user with advice which goes some way to addressing the improvement stage of the LCA.

Chapter 11

Validation of the Research

Validation of the Research

11.1 Introduction

As the preceding chapters of this thesis have shown the research carried out can be categorised into three main areas; The development of a new environmental design method, the development of a new materials selection method and finally the development of a prototype computer-based design support tool. It therefore follows that the research should be validated by consideration of each of these areas.

Validation of the design method was achieved through trials. The materials selection method has been validated by carrying out specific exercises in materials selection and the support tool has been used for a number of LCA exercises as well as specific validation exercises for the advisor component of the system.

The following sections of this chapter will explain the validation methods used for each area and discuss the implications of the results obtained.

11.2 Validation of the New Environmental Design Method

In order that the design method be validated it was important to make it available to as wide an audience as possible. As discussed in Chapter 8 the design method itself is generic in nature and ideally should be applicable to any product or system. The method was also developed to be used by designers from different backgrounds with differing experiences and varying amounts of knowledge about environmental design. Therefore selection of the validation sample was important. The overall sample of users was drawn from 6 different Universities within the UK (a number of whom are carrying out DFE work with large multi-national companies) and a major European Electronics manufacturer. The total sample of 16 users was broken down as follows:

Engineering Designers/Researchers	4
Industrial Designers/Researchers	3
Industrialists	1
Teachers of Design	2
Engineering Students	3
Industrial Design Students	2
Textile Designers	1

A pack of instructions, a worked example of the design method and a feedback form were mailed out to the designers. The product chosen was completely at the discretion of the individual. The overall results from the survey can be found in Appendix C, however the following sections will summarise and discuss the results.

11.2.1 Product Samples Chosen for Validation of Method

The following list of products were chosen by the users for use in validation of the method:

35mm Camera
Personal Electronic Organiser
Telephones
Vacuum Cleaner
Television
Cutlery
Computer Keyboard
Refrigerator
Clothes Iron
Furniture
Packaging
Electric Vehicles

As can be seen the expected class or extent of impact of the sample of products is wide ranging with some products being of only a short life-cycle and other having a long life expectancy.

The next section will look at three worked examples of the method and discuss the results.

11.2.2 Discussion of Worked Examples of the Design Method

In order to show the useful scope of the method of the examples listed in the last section the following will be discussed and analysed in detail:

Electric Vehicle

Television

Furniture (Chair)

Each of these products have a very different environmental profile and analysis of the way in which the method has been applied to these gives a good indication of the scope and applicability of the design method. Sections 11.2.2.1 - 11.2.2.3 show the examples while section 11.2.3 discusses the results obtained.

11.2.2.1 Electric Vehicle Example

Using the product classification system discussed in Chapter 8 the user described an electric vehicle (for elderly and disabled people) as, long life-cycle (LLC), energy consuming, non-resource consuming, multi part, multi material, non returnable. The assumptions made were that although the vehicle does consume batteries they are rechargeable and would not normally be replaced during the life of the vehicle. Also tyres which are a consumable on many types of vehicle will also be expected to last the whole life of the electric vehicle.

Table 11.1 shows the Environmental Design Strategy Matrix as completed by the user. The areas with dense borders are the areas of greatest environmental impact and the grey areas those which are generic considerations or not applicable to the product in question.

From this matrix the designer identified the following as being the biggest problems in terms of environmental impact of the product (in order of importance):

Energy in Use

Durability, use, servicing etc.

Reuse disassembly

Battery

Using the information and questions/pointers contained within the matrix the following design strategy was developed by the user, using the guidelines discussed in Chapter 8:

Energy Use:

- Reduce the weight of the vehicle
- Use more efficient batteries
- Recover / recycle high energy parts

Durability, Use etc.

- Share common parts (e.g. motor, gearbox, wheels)
- Use single/compatible materials
- Ease of servicing and replacement of parts.

Reuse/Disassemble

- Reclaim parts

Battery

- Address acid/lead problem
- Use more efficient batteries (less charging time)

Product: Electric Vehicle **Description:** *Long life-cycle, energy consuming non-resource consuming, multi-part, multi-material, non-returnable*

	Energy	**Resources**	**Configuration**	**Materials**	**Disposal**
Materials	Weight affects energy consumption. Lighter body / chassis, less energy used.	Apply generics.	Durability of parts. Interchangeable parts between different models. Parts should last the life of the vehicle.	Materials should be recyclable and try to use one material for many parts. Generic strategies.	Consider resources in life.
Processing	Generic	Generic	Consider generic assembly / disassembly.	Do any of the processes change the materials properties / life?	Generic
Distribution	No major part of environmental impact	Generic	N/A	N/A	N/A
Use	Most effect. Recharging of batteries, emissions etc.	Generic (Batteries)	Maintenance, interchange parts.	Are materials capable of the job?	(Batteries?)
Disposal	Recover parts that use energy in manufacture. E.g. Aluminium	Generic	Try to reuse parts. E.g. Wheels.	Try to use materials that are reclaimable	V.small effect.

Table 11.1 Completed EDSM for Electric Vehicle

11.2.2.2 Television Example

Using the product classification system discussed in Chapter 8 the user described a television as, LLC, energy consuming, non-resource consuming, multi part, multi material, returnable. The assumptions made were that at the end of the televisions life it will be collected and disassembled. (This is becoming common practice in Europe and many manufacturers will become legally responsible for the end of life treatment of their products in the future)

Table 11.2 shows the Environmental Design Strategy Matrix as completed by the user. The areas with dense borders are the areas of greatest environmental impact and the grey areas those which are generic considerations or not applicable to the product in question.

From this matrix the user developed the following environmental design strategy for designing environmentally friendly televisions (in order of importance):

Design for Disassembly / Recycling

Material choice / compatibility

Durability

Energy consumption reduction.

112.2.3 Furniture Example

One of the users chose to use the matrix to develop an environmental design strategy for a chair. Although this is not specifically an engineering design example it does illustrate the flexibility of the method in dealing with all product types. Using the product classification system the user described a chair as, LLC, non energy or resource consuming, multi-part, multi-material, non returnable.

The main assumption made was that the chair would not be returned for recycling etc. but would end up being disposed of at a municipal waste site.

Table 11.3 shows the Environmental Design Strategy Matrix as completed by the user.

Product: Televisions **Description:** *Long life-cycle, energy consuming non-resource consuming, multi-part, multi-material, returnable*

	Energy	Resources	Configuration	Materials	Disposal
Materials	Material choice may affect energy consumption.	Material choice will not affect resource consumption unless weight dependent.	Material choice will affect many other design goals and strategies. Durability!	Compatibility / contamination. DFD / DFR Quality / Durability	Reuse / Recycling May not be that important.
Processing	Generic	Generic	Consider assembly / disassembly. Consider material choice, fixings etc.	Compatibility Any processing effects appropriate to life-cycle?	Generic
Distribution	Distribution small contributor	Generic	Generic	Generic	Not as important
Use	Probably largest impact Consumption reduction	Little or no effect	Generic	N/A	No real effect Increase life cycle?
Disposal	Small contribution to overall Environmental Impact	Generic	Consider using disassembly, recycling	Less contribution to environmental impact	Smaller overall impact Generics

Table 11.2 Completed EDSM for Television

Product: Chair **Description:** *Long life-cycle, non-energy consuming, non-resource consuming, multi-part, multi-material, returnable*

	Energy	**Resources**	**Configuration**	**Materials**	**Disposal**
Materials	Material choice important Design for Quality Design for Durability Recycling, Recovery Increase life-cycle length	N/A	See 4 + 5 Compatibility Durability Replacement Parts	Quality Durability Design for Recycling Design for Disassembly	Disassembly Recycling
Processing	N/A	N/A	Design for Assembly Design for Disassembly Fixing & Materials	Design for Recycling Design for Disassembly Process/life trade-off	Generic
Distribution	Generic	Generic	Generic	Generic	Generic
Use	Increase life Durability	N/A	'Servicing' Replacement parts	N/A	Generic Durability Increase Life Cycle length
Disposal	Generic	Generic	Refurbishment Reuse of parts Disassembly	Design for Recycling Design for Disassembly	Design for Recycling

Table 11.3 Completed EDSM for Furniture (Chair)

The areas with dense borders are the areas of greatest environmental impact and the grey areas those which are generic considerations or not applicable to the product in question.

From this matrix the designer developed the following design strategy for designing environmentally friendly chairs (in order of importance):

Durability / length of life through material choice and design

Replacement Parts

Design for Recycling / Disassembly.

11.2.3 Discussion of EDSM Examples

The three examples presented in the previous sections show a cross section of not only product choice but also user experience. The electric vehicle example was completed by a student studying for a degree in Industrial Design with Applied Technology. The student had no previous experience of environmental design but had been working on the electric vehicle project for three months. Looking at the strategy developed it seems to be a pertinent environmental design strategy for electric vehicles. The matrix has allowed the user to identify the key areas of environmental concern and has assisted in the development of a design strategy which will address these concerns. The link between energy usage and weight as well as the battery efficiency / disposal problem was identified. Interestingly the issue of common parts was raised. The vehicles in question are produced in a number of forms but there is scope for standardisation. Less important issues in the life-cycle of these vehicles such as disassembly and disposability are included lower down in the design strategy hierarchy.

Interestingly, although acid / lead problems in batteries are significant in this case the matrix has allowed the user to consider the problem in context. The batteries are rechargeable and they should not need to be replaced over the life of the vehicle. Therefore in disposal the acid / lead issue is not as prominent as it might be.

The feedback from this user was favourable. The concept of a matrix was seen as a good one and easy to use. The initial amount of data was cause for concern but the user found that this issue was soon forgotten. The user thought that the matrix allowed a focused and structured approach to developing a DFE strategy and brought up considerations that had previously been omitted. For this example, the only problem the user saw was a slight difficulty in the step of developing a strategy in order of importance from the matrix. With use this becomes easier and the problem was more than likely due to lack of experience in dealing with DFE.

The television example was completed by an industrialist who works for a large electronics manufacturer in Europe. He has had direct experience of DFE and has been working in the field for some time. In this case the product was appropriately described using the system and the matrix completed in line with the instructions. Studying the matrix itself it is clear that the method has allowed the user to focus on the correct problems for this type of product. However the strategy that the user has developed does not seem to be appropriate. If the strategy is studied it can be seen that it is in exactly the opposite order to which it should be. The strategy for the design of environmentally friendly televisions should be:

Reduce energy consumption

Increase durability

Material choice / compatibility

Disassembly and recycling

Closer inspection of the matrix shows that this strategy should have been developed from the matrix as completed by the user. i.e. the matrix contains a few errors and omissions and there has been an error in developing the design strategy. Following the instructions given the user should look for any cells in the matrix which specify that the issue in question is of greatest importance. In this case (see table 11.2) the highlighted area, energy consumption, is shown as being so. Therefore the first, and most important aspect of the strategy should have been energy consumption reduction. The cell which deals with materials and use has been completed as 'no effect' by the user. If the large Environmental Design Strategy Guidance Matrix (EDSGM) is studied, it can be seen that for LLC, multi-material products, one of the guidelines is to make sure that the materials are suitable for the application, i.e. durability. If this is included in the matrix, the issue of durability is raised three times. This should then be the second aim of the overall design strategy. Compatibility of materials is an issue raised twice as is that of recycling and disassembly. These two issues should then be the last in the design strategy.

In this case it can be seen that the matrix was completed correctly (on the whole) but the guidelines for development of the design strategy were not followed thus producing an inappropriate strategy. On the feedback form the user said the matrix was very good and would be of great use to people with no DFE experience. However he did also point out that the strategy developed was the exact opposite of that which his company was adopting. Therefore if the guidelines for use of the method had been followed correctly then the environmental design strategy developed for televisions would have been identical to that being adopted by an international electronics company.

The example which looked at furniture was completed by a teacher of engineering design who has an interest in environmental design but has no practical experience of the subject. Furniture is a good example to show the diversity of application of the design method. As furniture does not consume any resources or energy as a direct result of its use many of the strategies applicable will be generic in nature. It could be argued that this may negate the need to use a method such as the matrix as the design strategy will be simple. However use of the matrix on this type of product was a useful exercise and as can be seen in section 11.2.2.3 produced a pertinent and concise environmental design strategy for chairs. The main aim is to make the product durable, which the matrix has identified. A way of achieving this has also been offered, careful material choice and design practices. While completing the matrix the user has kept in mind the type of product in question, as per the instructions, and as a result has included in the strategy a way of reducing built in obsolescence. In many cases furniture is discarded because part of it has broken. By the use of easily replaceable parts this situation can be addressed. Again issues relating to disposal are of no major concern as furniture has a very long life-cycle of many years. This is reflected in the strategy developed as design for recycling and disassembly is the last concern.

11.2.4 Survey Results

Along with all the information sent out to designers was a feedback sheet. Once they had completed the design exercise there were asked to comment on the method in terms of ease of use, method of product description, development of design strategy etc. The feedback form issued is shown in Appendix C(ii) along with the responses received. Below is a simple summary of the results.

Figure 11.1 shows that over 90% of those who used the matrix though it was a good idea.

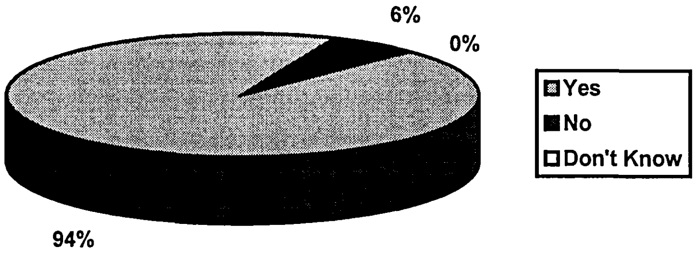


Figure 11.1 Was the Idea of a Matrix a Good One?

Over three quarters of the users said that use of the matrix either focused their ideas, accelerated the DFE study or helped their analysis in some way. (See figure 11.2) NB. Some of the users gave more than just one of the three reasons in their response.

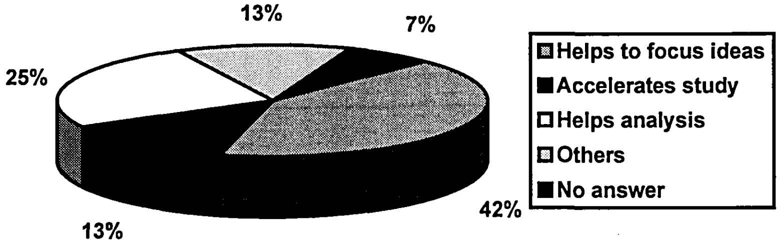


Figure 11.2 Why is the Matrix a Good Idea?

After completing the matrix and developing the design strategy as per the instructions the vast majority of users thought that the DFE strategy developed was appropriate to the product in question. (See figure 11.3)

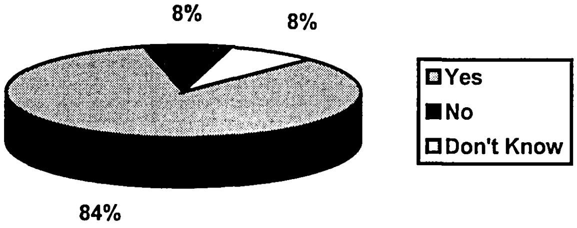


Figure 11.3 Did using the Matrix Develop an Appropriate DFE Strategy?

There were some problems encountered with the matrix as would have been expected and figure 11.4 summarises the responses of the users. These are mainly minor problems but the main point seems to be that with experience the use of the matrix will become much easier, as would be expected, and also that the layout/presentation may need changing.

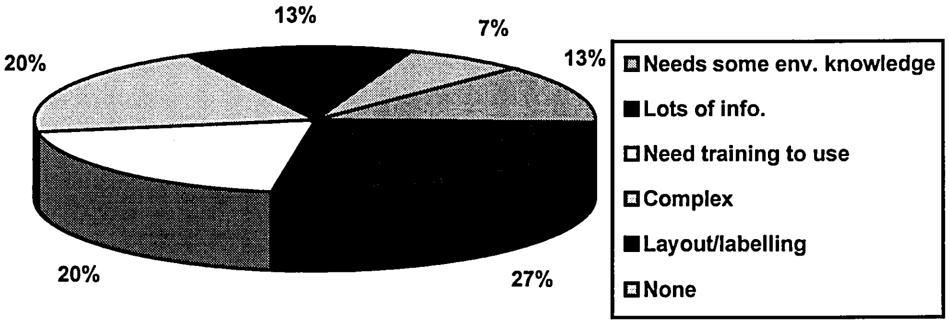


Figure 11.4 Problems with the Matrix

11.2.4.1 Discussion of Survey Results

Out of a sample of over 20 mailed out 16 were received back with only one incomplete. The base of users was a broad mix of disciplines and experience designed to show the flexibility and transferability of the design method across different industry and product sectors. The sample products chosen by the designers were wide ranging in nature and again allowed the method to be tested across the whole range of its scope.

In all but one case use of the matrix allowed the users to develop a pertinent DFE strategy. The case in which this did not happen was attributed to user error in the interpretation of the instructions. The matrix was completed correctly but the strategy developed wrongly. If the strategy was developed along the guidelines given it is interesting to note that it duplicates exactly the approach recently introduced by the manufacturer of that product, a manufacturer who has spent considerable time and effort reviewing the whole area of environmental design. In nearly 80% of cases the users saw the product classification system as useful and relevant, this being the core feature of the matrix. In retrospect after completing the exercise over 90% of the users thought that it helped them focus on relevant issues but also brought new issues to light. 15 out of the 16 users felt that the method allowed them to structure, accelerate or focus their DFE exercise.

Problems were reported but 30% of the users identified no difficulties at a general level. The majority of problems seemed to be a level of uncertainty in developing the strategy from the completed matrix. Having said this, by following the instructions and guidelines only one user failed to develop the appropriate strategy from the matrix. Those users who had no prior experience of DFE or eco-design developed sensible relevant strategies from the matrix.

With respect to suggested changes in the method 60% suggested either none or only superficial presentation alterations. Only 13% wanted to see the method simplified.

Through use of the test the methodology has been shown to be a structured, focused, accelerated way of performing DFE exercises. It has been validated as a relatively simple reliable, method which allows a pertinent DFE strategy to be developed for any product and which can be used by a wide range of designer in terms of both discipline and experience.

Billett (1996) advocates methods which 'give the designer confidence to consider environmental matters in a practical confident way at a stage in the design process where it is still possible to make major changes'. The methodology discussed in the preceding sections of this chapter does just that. By using it at the conceptual stage of design it allows the introduction of environmental concerns at the earliest possible opportunity. Many of the designers commented that use of the matrix allowed environmental problems to be viewed in a number of contexts, such as product or system concept, allowing lateral thinking and the development of relevant but not always obvious design strategies. The ability to make changes to designs is therefore achieved and the method also addresses another of the concerns which **Billett** (1996) sees as important, the prompting of explicit consideration of a number of wider eco-design issues.

11.3 Validation of the New Materials Selection Method

The materials selection method described in chapter 9 is based on that of Ashby's Materials Selection Charts and the methods employed to create and use the charts. The actual methodology of materials selection using charts is not new and therefore needs no formal validation. It is the data applied to the method and the way in which designers may use the method that is new.

Chapter 9 showed that, using Ashby's methodology for producing materials selection charts, allied to quantitative environmental data, charts can be plotted which will allow the selection of materials on a mechanical / environmental basis. Ashby's method of using consecutive charts for different design criteria is commutative and therefore the issue of at what point to use the environmental charts does not arise. The commutative nature of the charts allows the designer to introduce environmental concerns at any stage in the process.

In order to validate the environmental materials selection method it was decided to integrate it into two studies which are used as examples in the use of Ashby's materials selection software, Cambridge Materials Selector (CMS). A further validation example was carried out for the design of drinks containers.

11.3.1 Validation Example 1 - Bicycle Forks

The forks of a bicycle are loaded in bending. Table 11.4 summarises one possible design specification. This table is an adaptation of the one used by Ashby, the additions are shown in *italics*.

FUNCTION	Bicycle forks: beams loaded in bending
OBJECTIVE	Minimise the mass of the forks *Minimise the air pollution resulting from manufacture*
CONSTRAINTS	1. Must not fail in fatigue 2. Must be adequately tough, Kic > 15 MPa.m$^{1/2}$ 3. Material must not cost too much, Cm < US$ 50/kg 4. *Material must be in the top 50% of all materials in terms of air pollution*

Table 11.4 Design Specification for 'Green' Bicycle Forks

The new design specification includes the objective of minimising the air pollution caused through manufacture of the material. In life-cycle design terms the type of material could affect air pollution in later stages rather than that of manufacture only, but in the case of bicycle forks this is not the case.

There is an addition of a further design constraint in the new specification which requires the material to be in the top 50% of all materials in terms of air pollution created. In terms of using a chart for this requirement, it must be remembered that the air pollution produced by a material is a direct function of its weight.

Stage 1 in this selection exercise is to find materials which are acceptable in terms of both fatigue and density. Using Ashby's method of deriving the appropriate materials indices the relationship to be maximised is:

$$\frac{\sigma_e^{2/3}}{\rho}$$

Where σe is the endurance limit of the material and ρ is the density

Therefore a chart of endurance limit against density is plotted and materials selected by including a line of slope 1.5. This is shown in figure 11.5 (This chart was created using the CMS software).

The second stage is to minimise the air pollution resulting from manufacture of the material. In this case the relationship to be maximised is:

$$\frac{\sigma_e^{2/3}}{API\rho}$$

Where σe is the endurance limit of the material, API is the air pollution index of the material and ρ is the density.

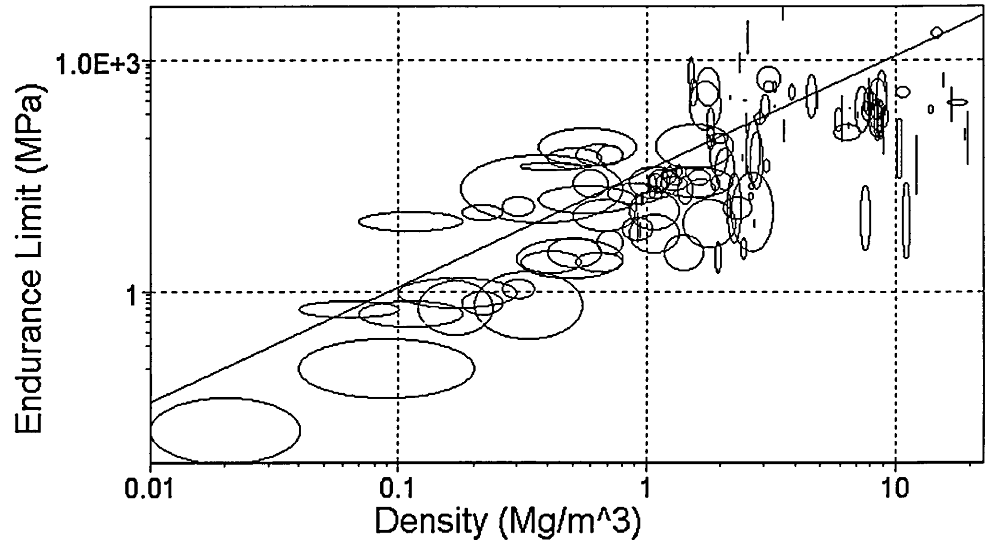


Figure 11.5 Endurance Limit v Density Materials Selection Chart

The values for API are calculated using the method outlined in Chapter 2, section 2.3.3.5.1. The chart plotted (figure 11.6) is of endurance limit versus API x density. As mentioned earlier the API of a material is directly related to the mass of material in question. Just as with the energy content charts used in Ashby's work the environmental charts developed by this research allow the combined consideration of mechanical and environmental parameters. Energy content in materials may be minimised by following the guidelines in Ashby's work of replacing ρ in the material indices with qρ (where q is energy content per kg). In the case of figure 11.6 the chart plots API as API per m^3 of material thus allowing designers to minimise air pollution. Again a line of slope 1.5 is plotted on this chart to assist selection of appropriate materials.

The third stage in this materials selection exercise is to find materials which are of the required fracture toughness and price. Another chart (figure 11.7) of fracture toughness against price is plotted and using the limits specified in the design specification a box isolates the area in which suitable materials may be found.

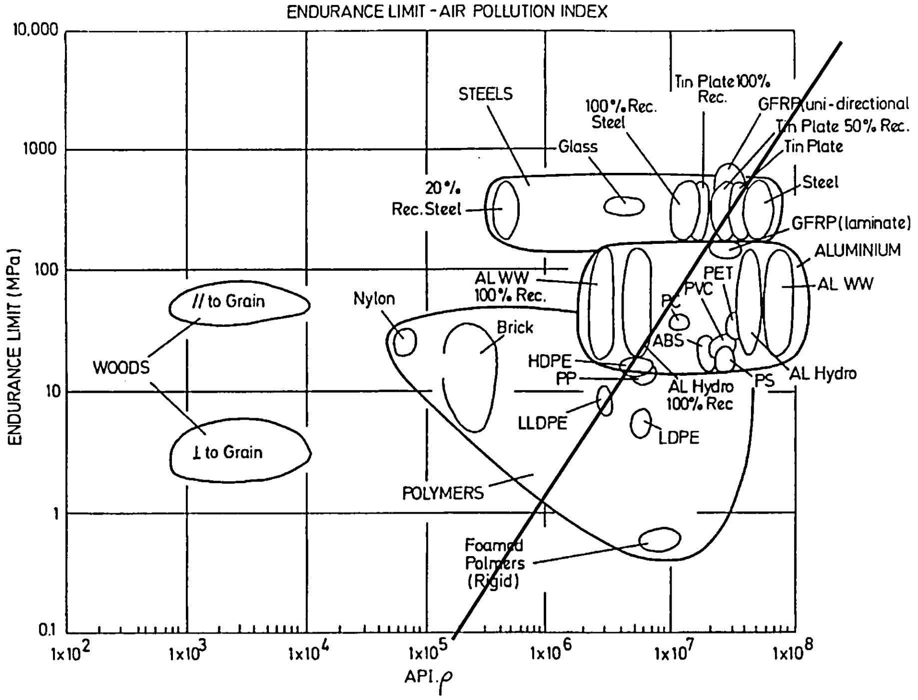


Figure 11.6 Endurance Limit v API.Density Materials Selection Chart

Appendix D contains all the data for this material selection exercise. It shows which materials passed which stages of selection and so explains how the final list of suitable materials was obtained. In this case the suitable materials for use in 'green' bicycle forks are:

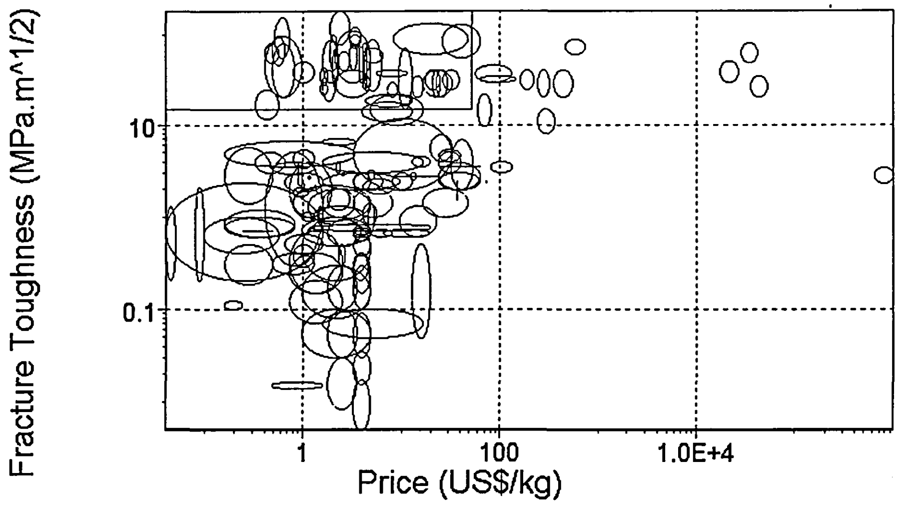


Figure 11.7 Fracture Toughness v Price Materials Selection Chart

Aluminium Alloys (wrought) *Recycled*

Glass fibre/polymer (GFRP) laminate

Glass fibre/polymer (GFRP) unidirectional

11.3.1.1 Discussion of Bicycle Forks Example

42 out of 149 materials contained within the database passed stage 1, 40 out of 149 materials passed stage 3. Stage 2 was the weak link in terms of data. As with most environmental selection methods, for materials or otherwise, data is the weak link. Although Ashby's generic database contains 149 materials the environmental database for materials with API values contained only 30 materials. This is why the constraint was set at the top 50% to allow a number of materials for consideration. A line of slope 1.5 was plotted on the chart allowing about 13 of the materials for consideration. As environmental costs are very difficult to assess in a purely quantitative form some degree of comparison is needed. By setting limits for environmental performance in terms of percentiles this qualitative consideration is achieved. Indeed by their very nature these charts allow comparison in terms of relative performance.

Using the fairly harsh fracture toughness selection criteria set in the example used in Ashby's booklet some of the more common materials for bicycle forks are excluded which pass the environmental stage such as steel. It is interesting to note however that the materials which did pass the second selection such as aluminium need to be 100% recycled. If they are virgin materials then they will not pass the environmental selection stage.

Aluminium has a very large energy content in its virgin form so it makes sense that the recycled material is better in terms of air pollution figures as the energy requirement is much lower. GFRP also seems a sensible choice in terms of environmental aspects. A number of polymers are within the top 50% of materials as is glass. An amalgamation of the two materials will have a better endurance limit but be no more environmentally damaging.

11.3.2 Validation Example 2 - Oars

The design of oars is another relatively simple example of mechanical design which could have environmental concerns included. Again the example used is based on one in Ashby's CMS examples booklet. In mechanical terms an oar is a beam loaded in bending. An oar must be both strong, stiff and lightweight. Table 11.5 shows the design specification that may be developed:

FUNCTION	Oars: beams loaded in bending
OBJECTIVE	Minimise the mass of the oar *Minimise the NOx pollution resulting from manufacture*
CONSTRAINTS	1. Must be sufficiently stiff 2. Must be adequately tough, Gic > 15 MPa.m$^{1/2}$ 3. Material must not cost too much, Cm < US$ 100/kg 4. *Material must be in the top 50% of all materials in terms of NOx emissions*

Table 11.5 Design Specification for 'Green' Oars

The mechanical requirements are those specified in the solution to the example with the new environmental constraints being in *italics*. The new design specification includes the objective of minimising the NOx pollution caused through manufacture of the material. In this case emissions of NOx are chosen to demonstrate the methods ability to deal with single pollutant as well as overall pollution such as API and WPI. As with the bicycle forks example, in life-cycle design terms the type of material could affect NOx pollution in later stages rather than that of manufacture only, but in the case of oars this is not the case.

There is an addition of a further design constraint in the new specification which requires the material to be in the top 50% of all materials in terms of NOx pollution. This new design constraint requires the use of charts similar to those used in the bicycle fork example.

Stage 1 in this selection exercise is to find materials which are acceptable in terms of both stiffness and density. Using Ashby's method of deriving the appropriate materials indices the relationship to be maximised is:

$$\frac{E^{\frac{1}{2}}}{\rho}$$

Where E is the Young's Modulus of the material and ρ is the density

Therefore a chart of Young's Modulus against density is plotted and materials selected by including a line of slope 2. This is shown in figure 11.8 (This chart was created using the CMS software).

The second stage is to minimise the NOx pollution resulting from manufacture of the material. In this case the relationship to be maximised is:

$$\frac{E^{\frac{1}{2}}}{NOx\,\rho}$$

Where E is the Young's Modulus limit of the material, NOx is the amount of NOx pollution related to the material and ρ is the density.

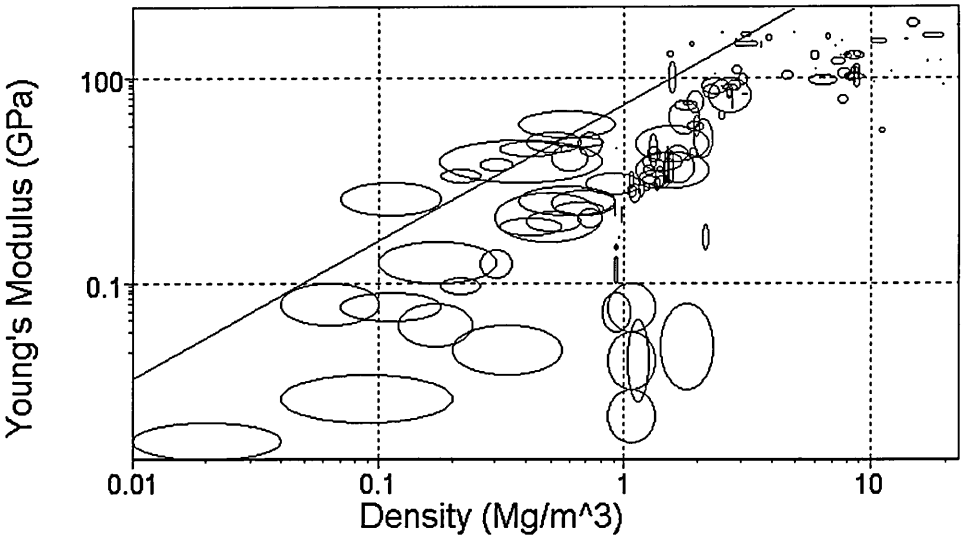


Figure 11.8 Young's Modulus v Density Materials Selection Chart

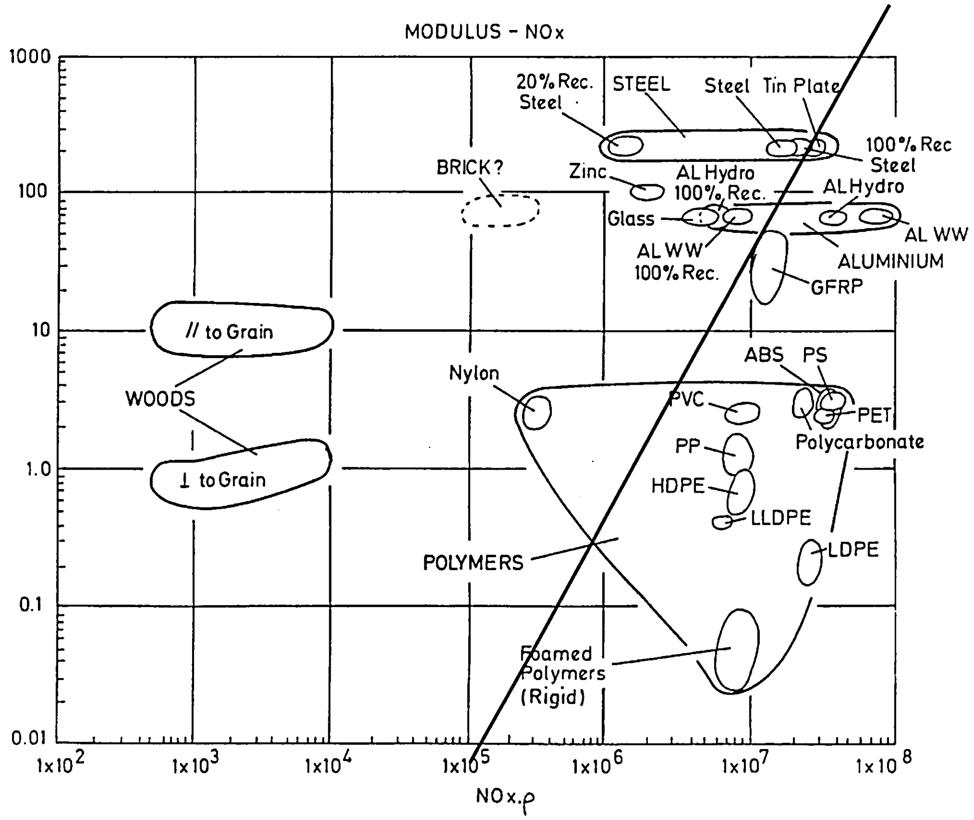


Figure 11.9 Young's Modulus v NOx Emissions Materials Selection Chart

The chart plotted (figure 11.9) is of Young's Modulus versus NOx x density. As with the API and WPI the NOx emissions of a material are directly related to the mass of material in question. In the case of figure 11.9 the chart plots NOx as NOx per kg of material thus allowing designers to minimise this form of pollution.

Again a line of slope 2 is plotted on this chart to assist selection of appropriate materials.

The third stage in this materials selection exercise is to find materials which are of the required toughness and price. Another chart (figure 11.10) of toughness against price is plotted and using the limits specified in the design specification a box isolates the area in which suitable materials may be found. In this case the toughness is a compound property as explained in the CMS examples. It is a compound of Young's Modulus and fracture toughness:

$$\frac{K_{Ic}^2}{E}$$

Where K_{Ic} is fracture toughness and E is the Young's Modulus.

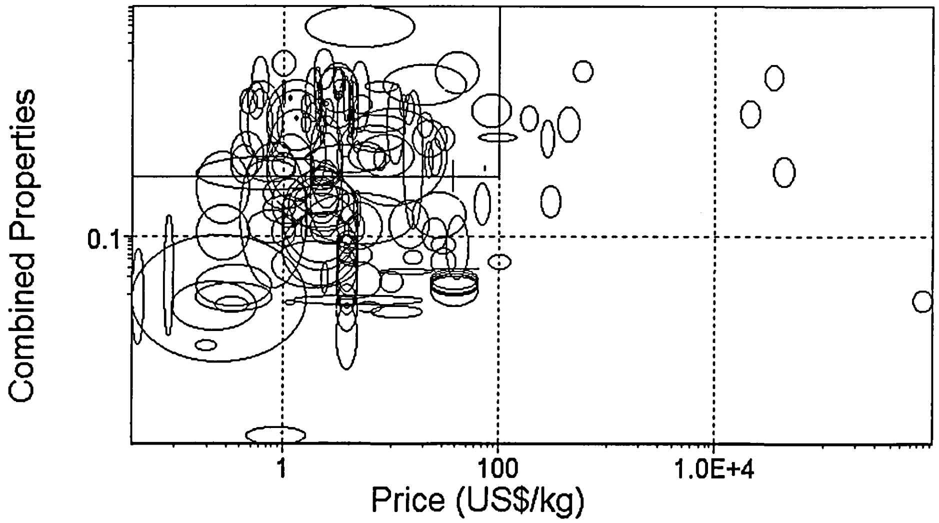


Figure 11.10 Toughness v Price Materials Selection Chart

Appendix D contains all the data for this material selection exercise. It shows which materials passed which stages of selection and so explains how the final list of suitable materials was obtained. In this case the suitable materials for use in 'green' oars are:

Palm, coconut, parallel to grain

Pine, parallel to grain

Spruce parallel to grain

Teak, parallel to grain

Possibly Carbon Fibre?

11.3.2.1 Discussion of Oars Example

As with the bicycle forks example the weak link in the 3 stages of selection was stage 2, the environmental stage. Again there were only 29 materials available for the second stage as opposed to 149 for the other two. Carbon Fibre may be a possible option but environmental information is not available. Although it can be expected to be similar to that of GFRP. Once again in this example the solutions supplied for the standard mechanical selection were used. If the stiffness requirements were less strict other materials such as GFRP and Aluminium alloys may be suitable for the application. In this case these materials would have passed the environmental stage of selection also. Once again the aluminium would have to be 100% recycled to be of the required environmental performance.

11.3.3 Validation Example 3 - Drinks Containers

Drinks containers come in a number of shapes and sizes but the most common is the standard cylindrical shaped bottle. In this example we want to consider a container for fizzy drinks which can be approximated to a pressure vessel. As the walls of the vessel are thin compared to the overall dimensions we can approximate the bottle to a thin cylinder. In this case the cylinder is loaded in plane stress.

Table 11.14 summarises one possible design specification.

FUNCTION	Bottle: cylinder - plane stress
OBJECTIVE	Minimise the mass of the bottle *Minimise the water pollution resulting from manufacture*
CONSTRAINTS	1. Must be sufficiently strong 2. Must be adequately tough, Gic > 0.04 MPa.m$^{1/2}$ 3. Material must be cheap, Cm < £1.2/kg 4. *Material must be in the top 50% of all materials in terms of WPI emissions*

Table 11.6 Design Specification for 'Green' Drinks Containers

The objectives include minimising water pollution arising from manufacture and also reducing the weight of the container. Because of the function of the container, i.e. packaging, a considerable amount of its environmental impact will result from transportation. Reducing the weight of the container will help reduce the impact in the distribution phase.

Stage 1 is the selection of materials, suitable in terms of strength and density. As the container is being loaded in plane stress the parameter to be maximised is:

$$\frac{\sigma_f}{\rho}$$

Where σ_f is the strength of the material and ρ is the density.

A chart of strength v density is plotted and a line of slope 1 used to select materials. (see figure 11.10)

The second stage is to minimise the water pollution resulting from manufacture of the material. In this case the relationship to be maximised is:

$$\frac{\sigma_f}{WPI\rho}$$

Where WPI is the water pollution index of the material.

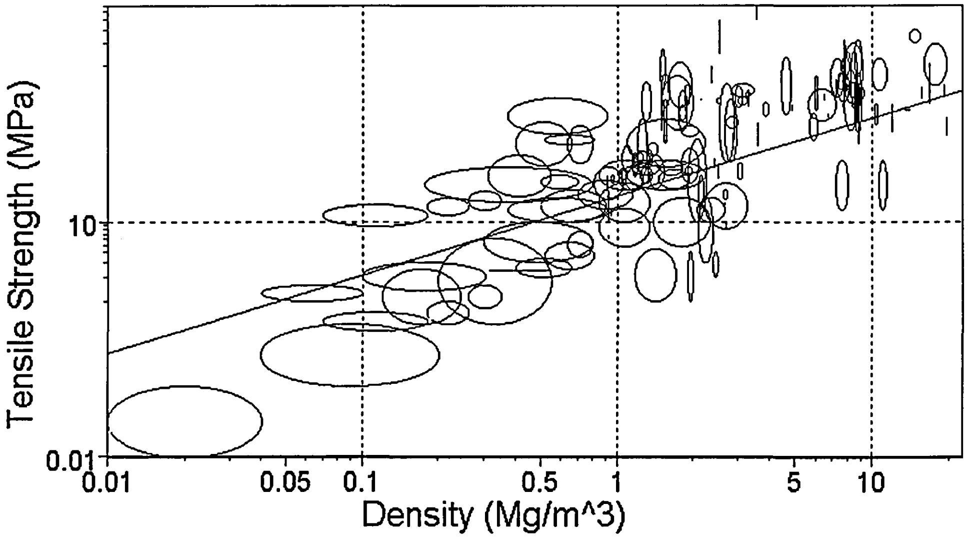


Figure 11.11 Strength v Density Materials Selection Chart

Another chart is plotted, in this case of strength v WPI x density. Once again a line of slope 1 is used to select suitable materials. This is shown in figure 11.11.

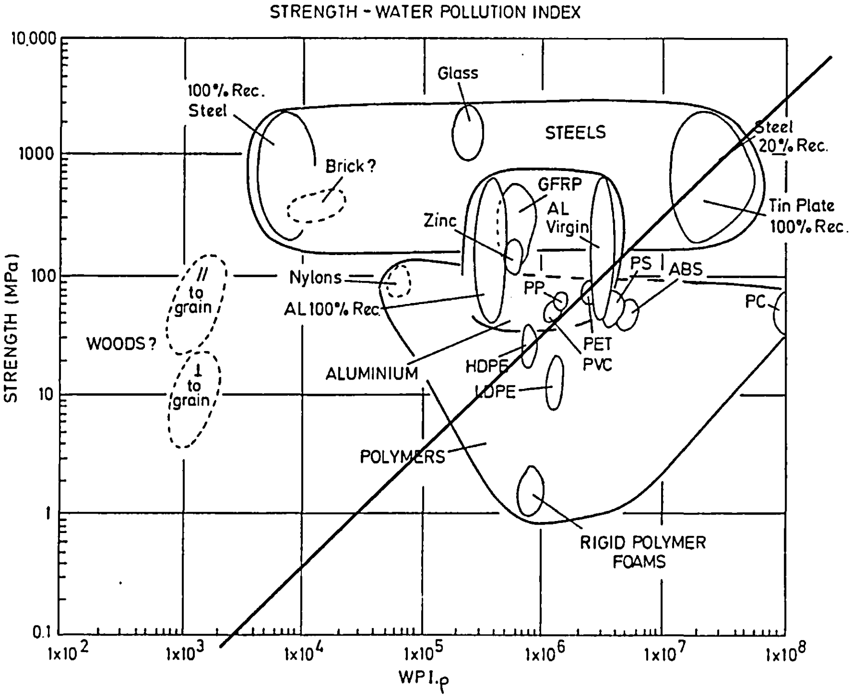


Figure 11.12 Strength v WPI.Density Materials Selection Chart

The final stage is the selection of materials within the limits of toughness and price. Figure 11.12 shows this chart.

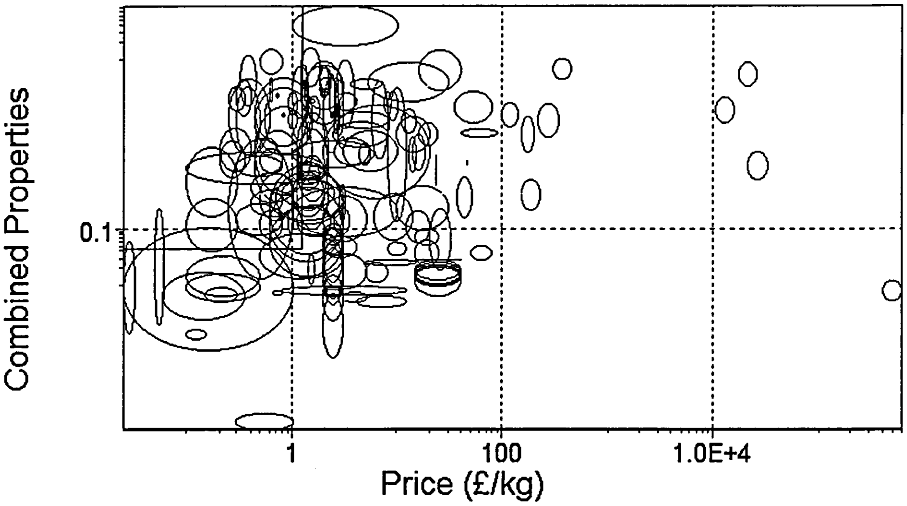


Figure 11.13 Toughness v Price Materials Selection Chart

Again appendix D shows the full results of the materials selection exercise. It shows which materials passed which stages of selection and so explains how the final list of suitable materials was obtained. In this case the suitable materials for use in 'green' drinks containers are:

Aluminium (preferably recycled)

HDPE

PET

Polypropylene

PVC (Rigid)

Soda Glass

Steel (recycled)

Zinc

11.3.3.1 Discussion of Drinks Container Example

In this example the environmental data was only available for approximately 20 materials. Fortunately many of the materials that data was available for were suitable for the required application and so the final list of materials is larger than in the other two examples.

Most of the materials that were selected are in everyday use in this type of application. However in this case we need to think about other parameters such as manufacturability and also permeability to carbon dioxide (for fizzy drinks). Glass, aluminium, steel and PET are all suitable for fizzy drinks and can be manufactured into containers relatively easily. PVC polypropylene and HDPE are not suitable for use in fizzy drinks applications but are used for packaging liquids such as milk and orange juice. These materials can also be easily manufactured using injection moulding. In these applications less strength is required due to the lack of pressure loading on the container. Once again the metals selected are better environmentally if recycled but in this case the virgin materials also fall within the constraints of the design specification.

Wood is a possible option but data is not available for the environmental selection stage. Also processing would probably rule out this material as there would be a lot of waste material generated through machining. Issues relating to health hazards are also raised.

11.3.4 Discussion of New Materials Selection Method

The basis of the materials selection method described in the previous section and in Chapter 9 of this work is that of Ashby's work. The method is accepted and practised by many designers and materials engineers as a simple and efficient way of integrating material property information into the selection process. As other parts of this work have shown integrating environmental concerns into design, specifically mechanical design, is a demanding task and requires reliable tools as an aid.

The three examples carried out in this validation, although relatively simple, show the operation and possible uses of the method. Ashby's charts are commutative, i.e. the order in which you carry out the different selection stages has no bearing on the final outcome of the exercise. This is one of the main advantages of using and adapting this method for environmental design. A major concern with materials selection is the sensitivity of the result to the point in the design process at which constraints are considered. This method allows environmental concerns to be included at any stage of the selection process as another simple step. The same materials will be selected for a given criteria no matter when the environmental concerns are included.

The charts also allow a quick and easy visual comparison of the relative environmental performance of materials. Environmental data, at this time, needs to be viewed in relative terms. Quantitative mechanical properties may be considered singularly e.g. Mild Steel has a Young's Modulus of 196 Gpa. This property value has meaning to designers and engineers who have experience in selecting and using materials. In contrast an API of 1250 will mean nothing to designers and engineers as it is an unfamiliar concept and there is still no one accepted way of quantifying air (or other types) of pollution. Using these charts allows relative comparison of materials and thus allows those inexperienced in environmental design an easy and familiar way of including it in their design and materials selection exercises.

The fact that relative performance is so important leads to another advantage of these charts. In the design exercises shown in the three previous sections the constraint in terms of environmental performance has been that the materials have to be in the top 50% of all those in the database in terms of the particular environmental concern. The way the charts have been used shows that this is easily done. However many materials selection and design exercises are used to improve on past designs. In cases such as these the charts are again an easy way of improving environmental performance at the design stage. The material which is already being used can be highlighted on the chart. A line of the required slope is then drawn on the chart passing through the lower extremity of the area representing that material. The designer then simply identifies any materials above this line as being of better environmental performance than the current material. For example figure 11.14 shows a material selection chart of Strength v Water Pollution Index (WPI). If currently a material such as LDPE was being used in a product (highlighted in grey on the chart) and its function was approximated to that of a plate we can use the chart to find better materials which satisfy the requirements of a strong plate and reduce water pollution during manufacture. The relationship between mechanical and environmental requirements that should be maximised is:

$$\frac{\sigma_f^{1/2}}{WPI.\rho}$$

A line of slope 2 is drawn on the chart passing through the lower extremity of the region representing LDPE. Any material above this line satisfies mechanical requirements while improving environmental performance.

The main failing of the charts is not method or use but in the data available to construct them. There are only 26 generic materials in the charts presented in this work. However each material may be presented in terms of API, WPI or one of many specific environmental emissions or even inputs (Such as energy or raw material requirement). There are other ways of presenting environmental performance such as the Eco-Indicators methods which gives information for over 300 materials and processes but this system has a number of disadvantages, mainly that the environmental performance is delivered as a single figure representing raw material requirements, air pollution, water pollution and waste produced.

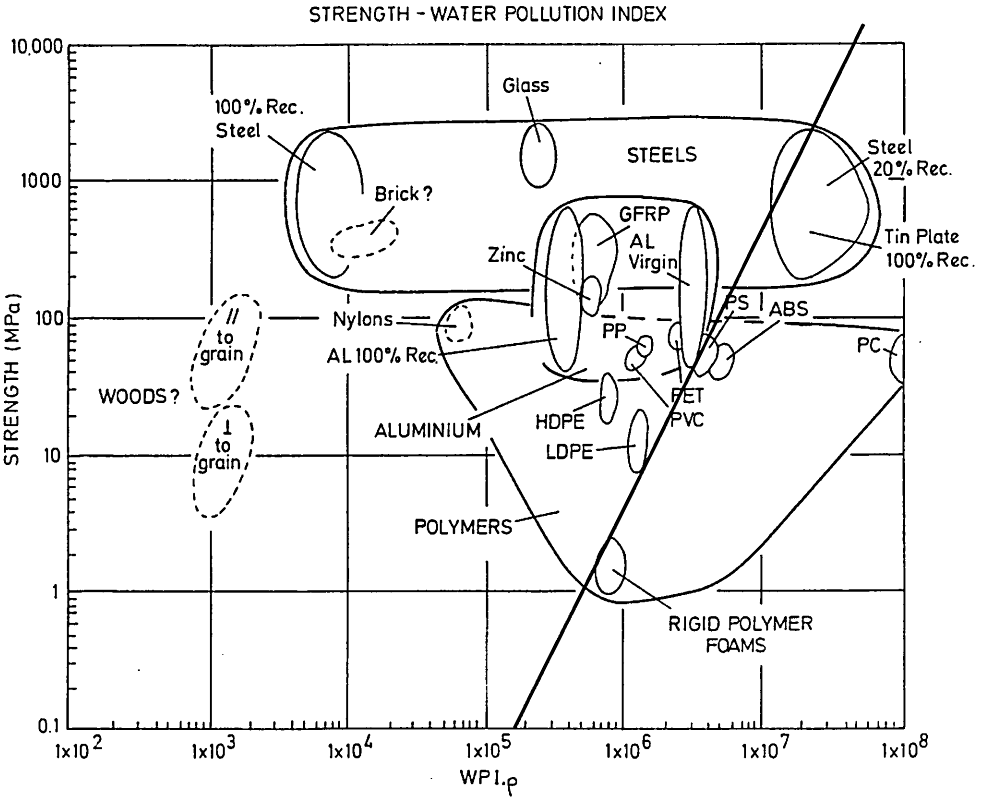


Figure 11.14 Strength v Water Pollution Index (WPI) Materials Selection Chart

There is a danger in hiding detail with these single figure systems. The system presented in this work allows more careful and thorough consideration of the issues involved by presenting environmental data in separate or agglomerated figures. However if the Eco-Indicators method was adopted then the number of materials on the charts would increase dramatically.

In summary, the method for materials selection discussed is an adaptation of a well established and accepted methodology. It allows quick and easy inclusion of environmental considerations and mechanical criteria in materials selection, gives a number of advantages in terms of time, visual representation etc. and can be used at any stage of the materials selection exercise. The only shortcoming is that of available data at the current time. However as the previous sections have shown the method is reliable and when data becomes available it may be included into the charts quickly and easily.

11.4 Validation of the Support Tool

As described in Chapter 10 the support tool functions in two specific ways, firstly as an LCA tool and secondly as an advisor for choosing alternative materials and processes etc. Because of this the validation of the support will be carried out in two distinct stages:

1. Validation of the LCA component of the system
2. Validation of the advice component of the system

The first component of the system functions as a stand alone assessment tool and the second part uses the results of the first to suggest changes. Therefore it is important that the LCA system is validated and then subsequently the advisor component can be validated knowing that the results from the first are correct.

11.4.1 Validation of the LCA Component

Validation of LCA results is a very difficult exercise to achieve. As mentioned in the earlier chapters of this thesis different LCA studies carried out on the same products or systems can deliver widely differing results. This is because of the difference in data used, the different assumptions made and sometimes because of the way the results are presented.

In order to validate the support tool developed during this research 3 example LCAs of consumer products were carried out. To allow a number of different comparisons one of the LCAs will be compared to the results generated by the ECO-it tool discussed in chapter 5 and the other two will be compared to those generated by the ECO-Scan tool, also discussed in chapter 5. Both of these tools are the latest computer based abridged LCA tools available and use the eco-indicators method, again, as discussed in chapter 5. The eco-indicators method is becoming one of the most widely used in the area of LCA and DFE.

To allow a comparison of the results of the two systems the API and WPI values calculated by the system developed during this research, were added together to give a single pollution value. Although this system hides detail it was required to give a fair comparison between systems.

Eco-indicators used by the other systems present all forms of pollution as one aggregated figure. Throughout the following sections the computer tool developed by this research will be referred to as Eco-Designer.

11.4.1.1 LCA of a Coffee Machine (ECO-it & Eco-Designer)

This product was compared using the ECO-it and the system developed during this research programme. The coffee machine is a documented example which is supplied with ECO-it and is split up into 5 main components:

1. Housing
2. Glass jug
3. Riser pipe
4. Hot Plate
5. Filter

Each of these components was then specified in terms of materials, weight, processing operations and disposal routes. The use phase of the product was also included in the LCA. The assumptions made were that the machine would be used twice a day over a period of five years. Each time coffee was brewed a new filter would be used. Filters would be included as part of the use (total of 3650 filters) and the electricity consumption over the five years was calculated to be approximately 375 KWh. Details of transportation were not included. Disposal practices assumed 100% recycling, where specified and municipal refuse treatment to be 40% landfill and 60% incineration. The inputs into each of the systems is shown in table 11.7 (over).

Eco-indicators used by the other systems present all forms of pollution as one aggregated figure. Throughout the following sections the computer tool developed by this research will be referred to as Eco-Designer.

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Component	Materials	Weight	Processing	Disposal
Housing	HIPS	1 kg	Injection Moulding	Municipal
Glass Jug	Glass (56% Rec)	0.4 kg	Glass Forming	Recycling
Riser Pipe	Aluminium	0.1 kg	Extrusion	Municipal
Hot Plate	Sheet Steel	0.3 kg	Cold Forming	Municipal
Filter	Paper (unbleached)	2g	----------------	Municipal

Table 11.7 LCA Inputs for Coffee Machine (Example 1)

The following results were obtained from each system:

	ECO-it	Eco-Designer
Materials & Production	13 mPt	50,306
Use	278 mPt	253,881
Disposal	0.52 mPt	2396

Table 11.8 LCA Results for Coffee Machine (Example 1)

As can be seen because the systems use a different way of measuring environmental impact the results delivered are very different. If however you look at the results in terms of percentage of the total impact for each of the life-cycle stages you get a different picture from the table and the results look much more similar. Figure 11.15 and 11.16 show the LCA results in these terms.

This type of results presentation is the most useful in terms of DFE exercises. We have already said that LCA is used to examine the overall environmental impact of a product or system over its complete life-cycle and then can be used to identify the areas of greatest concern and thus address these. By presenting the results in pie charts the relative impact can be compared directly between different life-cycle stages and also different LCA system results. It brings an amount of standardisation to results presentation and makes the differences in impact calculation systems almost completely if not totally negligible.

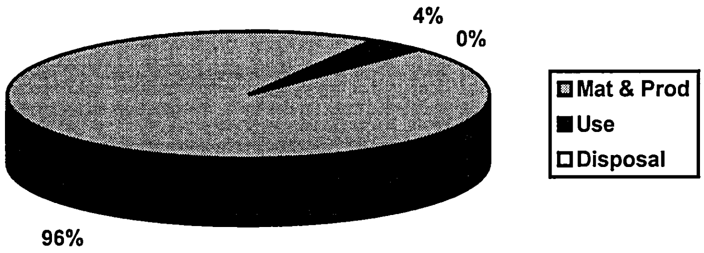


Figure 11.15 ECO-it LCA Results for Coffee Machine (Relative percentage impacts of different life-cycle stages) - Example 1

Initially although the results are not greatly different there is a considerable discrepancy between the contributions of different life-cycle stages to the overall impact between the two systems. This however, can be explained and is related to the way in which data is fed into the systems. Eco-designer only deals with electricity usage during the use stage of the life-cycle and therefore the paper filters have been considered as part of the materials and production phases. As the results are outputted to a spreadsheet it is relatively easy to revise them and include the paper filters as part of the usage stage. Having done this the two systems are much more in agreement over relative life-cycle stage impact as the new Eco-Designer results show in figure 11.17.

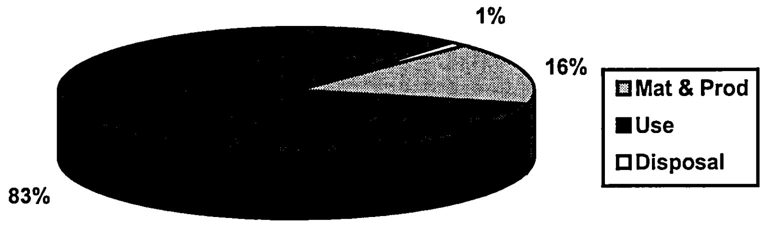


Figure 11.16 Eco-Designer LCA Results for Coffee Machine (Relative percentage impacts of different life-cycle stages) - Example 1

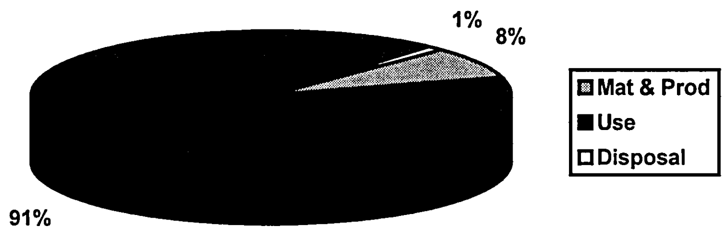


Figure 11.17 Revised Eco-Designer LCA Results for Coffee Machine(Relative percentage impacts of different life-cycle stages) - Example 1

The differences in the two systems are now very small as summarised in table 11.9.

	ECO-it	**Eco-Designer**	**Overall Difference**
Materials & Production	4 %	8 %	4 %
Use	96 %	91 %	5 %
Disposal	0 %	1 %	1 %

Table 11.9 Comparative Differences in LCA Results of the Two Systems (Coffee Machine) - Example 1

11.4.1.2 LCA of Coffee Machine (Eco-Scan & Eco-Designer)

The second LCA carried out for validation purposes was for a coffee machine again but this time used different assumptions and life-cycle data and used a different system, the Eco-Scan software developed by Turtle Bay. Again the coffee machine LCA is an example supplied with the software. As with the previous example the coffee machine was split into its main components and the data inputted as before. This time the analysis was more detailed splitting the coffee machine into nine parts. The assumptions were as follows: again the life cycle was 5 years, used 2 times per day and a new filter each time it was used. Electricity consumption in this case was much less, estimated at 91 KWh. Transportation was included in the life-cycle with 400g of cardboard packaging and 675 km travelled by truck. Disposal was assumed to include no recycling with the split between landfill and incineration being 37% / 63% respectively. The inputs into each system are shown in table 11.10.

The only assumption which had to be made when entering the data into eco-designer was to assume copper as a generic non-ferrous metal and use the data for zinc.

Component	Materials	Weight	Processing	Disposal
Housing	ABS	300 g	Injection Moulding	Municipal
Lid	ABS	60 g	Injection Moulding	Municipal
Water Gauge	Polycarbonate	30 g	----------------	Municipal
Jug Glass	Glass	600 g	----------------	Municipal
Jug Handle	Polypropylene	120 g	Injection Moulding	Municipal
Jug Lid	Polypropylene	30 g	Injection Moulding	Municipal
Filter Holder	Polypropylene	120 g	Injection Moulding	Municipal
Cord	Copper	250 g	----------------	Municipal
	PVC	150 g	Injection Moulding	Municipal

Table 11.10 LCA Inputs for Coffee Machine - Example 2

(This is similar to the way in which Eco-Scan works). In this case the adjustments for the use of paper filters and also consideration of cardboard packaging as part of distribution was included in the initial results by manipulating the spreadsheet output. Table 11.11 shows the results from the two systems.

	ECO-Scan	**Eco-Designer**
Materials & Production	36.54 mPt	18328.5
Distribution	0.96 mPt	434.7
Use	115.89 mPt	61608
Disposal	0.41 mPt	644.3

Table 11.11 LCA results of Coffee Machine - Example 2

Once again the actual figures delivered by the systems are very different and the results need to be viewed in a life-cycle stage percentage contribution to allow a comparison to be made. Figure 11.18 and 11.19 show the results from Eco-Scan and Eco-Designer respectively.

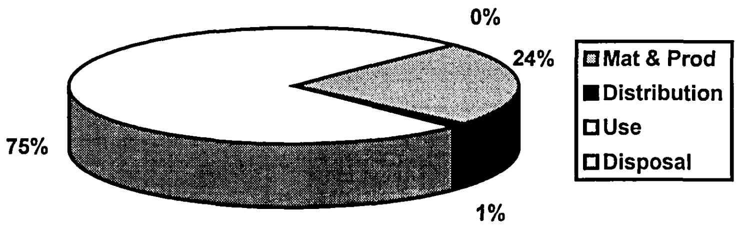


Figure 11.18 Eco-Scan LCA Results for Coffee Machine (Relative percentage impacts of different life-cycle stages) - Example 2

Once again the results from the two systems compare very favourably showing no real differences. In fact in this case the results are much closer together even though extra data has been included and some of the assumptions which have been made are different in each system due to the data contained within their respective databases. Table 11.12 shows the comparative difference (in overall terms) of each of the two system's LCA results.

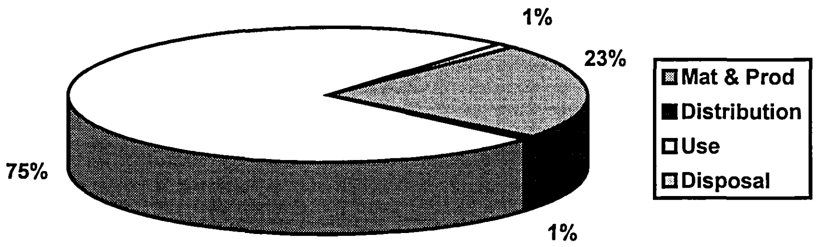


Figure 11.19 Eco-Designer LCA Results of Coffee Machine (Relative percentage impacts of different life-cycle stages) - Example 2

	ECO-Scan	Eco-Designer	Overall Difference
Materials & Production	24 %	23 %	1 %
Distribution	1 %	1 %	0 %
Use	75 %	75 %	0 %
Disposal	0 %	1 %	1 %

Table 11.12 Comparative Differences in LCA Results of the Two Systems (Coffee Machine) - Example 2

11.4.1.3 LCA of Toaster (Eco-Scan & Eco-Designer)

The toaster example is one which is not supplied with any of the software packages available.

A toaster was analysed for the purposes of this exercise. The energy consumption was measured, assumptions made about its usage pattern and then it was dismantled to assess the number of parts and materials etc. which constitute the product. The product consists of over 40 parts containing approximately 15 different materials. Appendix E shows he breakdown of inputs for the LCA along with discrete emissions data and other results.

A number of assumptions were made for the LCA of the toaster and were as follows:

It was assumed that the toaster would be used 3 times a day to toast 2 slices of bread and have a life expectancy of 5 years. Disposal would include no recycling except for the packaging materials and the remainder would constitute standard municipal practices (40% / 60% landfill/incineration split). Energy consumption over its life would be 153.98 KWh. The toaster is made in Taiwan and would be transported by container ship to England. Data for some materials was not available, so the following assumptions were made. Mica Coated paper was treated as virgin paper. Brass and tungsten were, as with the other examples, treated as generic non-ferrous materials. The small amount of printed circuitry was neglected as was the small amount of urea formaldehyde and bakelite. Table 11.13 shows the LCA results for the toaster from the two systems.

	ECO-Scan	**Eco-Designer**
Materials & Production	16.79 mPt	27394
Distribution	1.15 mPt	4736.9
Use	103.2 mPt	104373
Disposal	1.04 mPt	1199.3

Table 11.13 LCA results of Toaster

Even though the product in question is made from over 30 parts and more than 10 different materials and a number of assumptions were made, the results are clearly very similar with both systems identifying usage to be the most environmentally damaging life-cycle stage of the toaster. Figure 11.20 and 11.21 show the graphical representation of the results from Eco-Scan and Eco-Designer respectively.

Table 11.14 shows the comparative differences in the LCA results from the two systems.

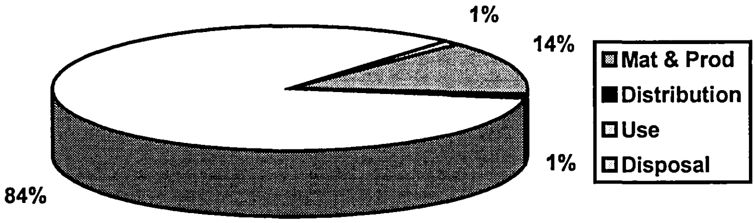


Figure 11.20 Eco-Scan LCA Results for Toaster (Relative percentage impacts of different life-cycle stages)

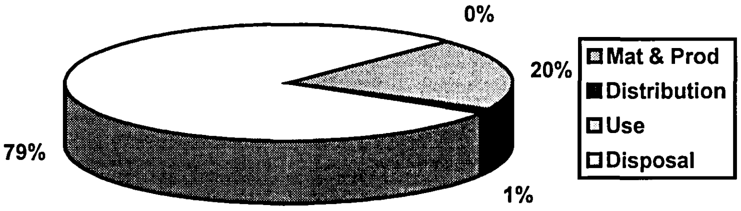


Figure 11.21 Eco-Designer LCA Results for Toaster (Relative percentage impacts of different life-cycle stages)

	ECO-Scan	Eco-Designer	Overall Difference
Materials & Production	14 %	20 %	6 %
Distribution	1 %	1 %	0 %
Use	84 %	79 %	5 %
Disposal	1 %	0 %	1 %

Table 11.14 Comparative Differences in LCA Results of the Two Systems (Toaster)

11.4.2 Validation of the Advice Component

Validation of the advice component of the system is not as straight forward as that for the LCA component. Other LCA systems exist which may be used as comparisons but in the case of design advice this is not so. As the system is new a number of ways have been adopted to validate it.

The materials optimisation is based on the method discussed in chapter 9 and so by comparing the system to the hand drawn charts presented in that chapter the calculation method of the system can be validated. Validation may also be achieved by carrying out sample exercises and assessing the results to see whether they are appropriate.

The process optimisation procedure offers alternative process routes to those selected by the user. In this case the validity of these alternatives need to be assessed. Will the alternative processes be capable of producing the required shape of component and is the calculation of pollution and material utilisation correct?

Distribution and disposal optimisation gives general advice and calculates a number of parameters. Once again the calculation of parameters needs to be assessed and discussed.

11.4.2.1 Validation of Materials Optimisation Procedures

Figure 11.22 shows an environmental materials selection chart plotting Strength against WPI. If we were currently making a component which functioned as a tie out of HDPE and we wanted to make it less environmentally damaging then we would plot a line of slope 1 through the lower extremity of the area representing HDPE. Any materials which fall to the left of this line would represent those which had better mechanical / environmental characteristics.

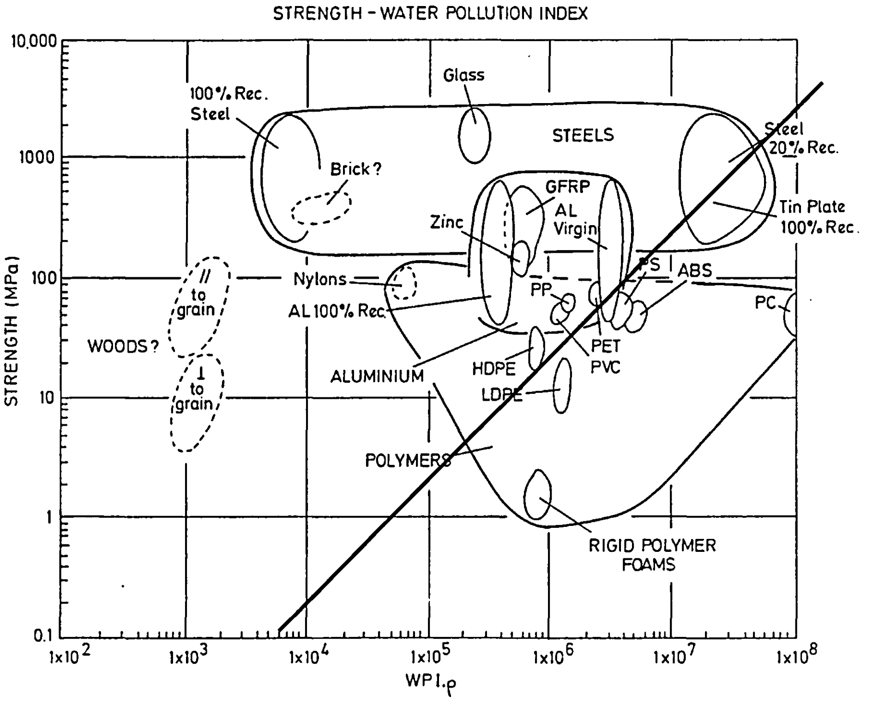
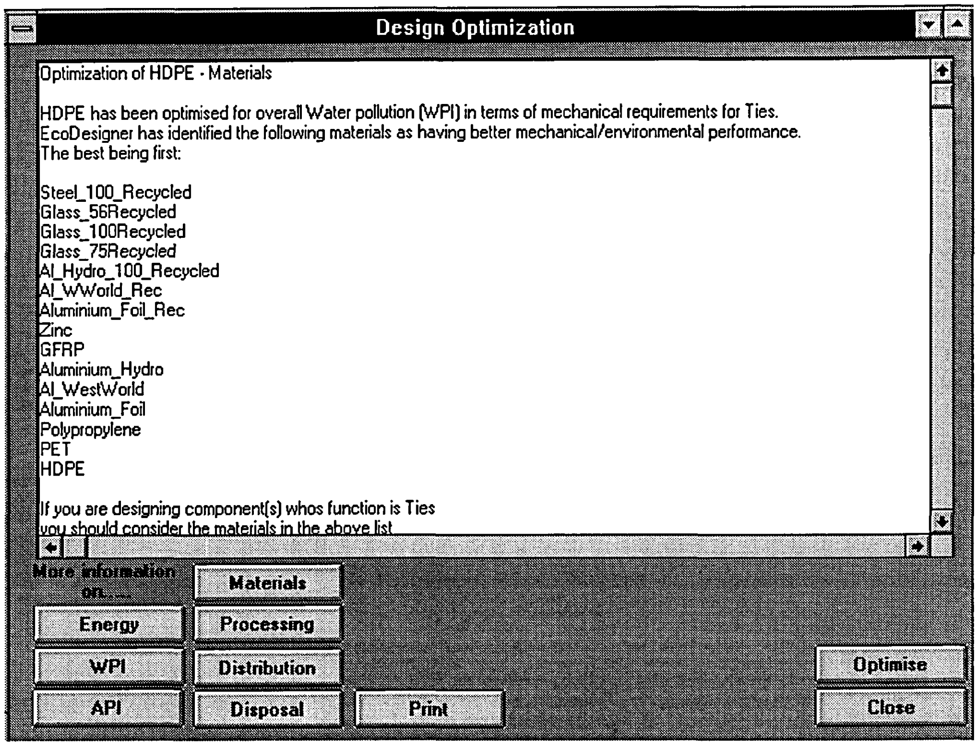


Figure 11.22 Environmental Materials Optimisation - Strong Ties

When optimising HDPE as a material for strong ties the computer tool offers a list of alternatives as shown in figure 11.23.

Comparing this list to the chart shows that the computer offers alternatives in the same order as would be generated from using the chart manually.

There is a small difference in the order of materials at the zinc/GFRP point. This will be due to the very similar performance of these materials and small errors during the construction of the chart.



Optimization of HDPE - Materials

HDPE has been optimised for overall Water pollution (WPI) in terms of mechanical requirements for Ties.
EcoDesigner has identified the following materials as having better mechanical/environmental performance.
The best being first:

Steel_100_Recycled
Glass_56Recycled
Glass_100Recycled
Glass_75Recycled
Al_Hydro_100_Recycled
Al_WWorld_Rec
Aluminium_Foil_Rec
Zinc
GFRP
Aluminium_Hydro
Al_WestWorld
Aluminium_Foil
Polypropylene
PET
HDPE

If you are designing component(s) whos function is Ties
you should consider the materials in the above list

Figure 11.23 Computer Based Material Optimisation for Strong Ties

Figure 11.24 Shows a materials selection chart of Young's Modulus and API. In this case, as an example, the original material chosen was 100% Recycled Aluminium (WesternWorld) and the application chosen was stiff plates. A line of slope 3 was plotted on the chart passing through the lower extremity of the area representing 100% recycled Aluminium. All materials falling to the left of the line offer better mechanical/environmental performance in terms of stiff plates and air pollution.

The same information was put into the computer tool, figure 11.25 shows the results of this exercise. As can be seen the manually drawn chart and the computer generated list agree. Again some of the materials are very close in their performance and there is a small overlap between glass and aluminium.

These two examples have validated the calculation method of the computer tool by showing the

the results delivered match those which are generated by carrying out the exercise manually.

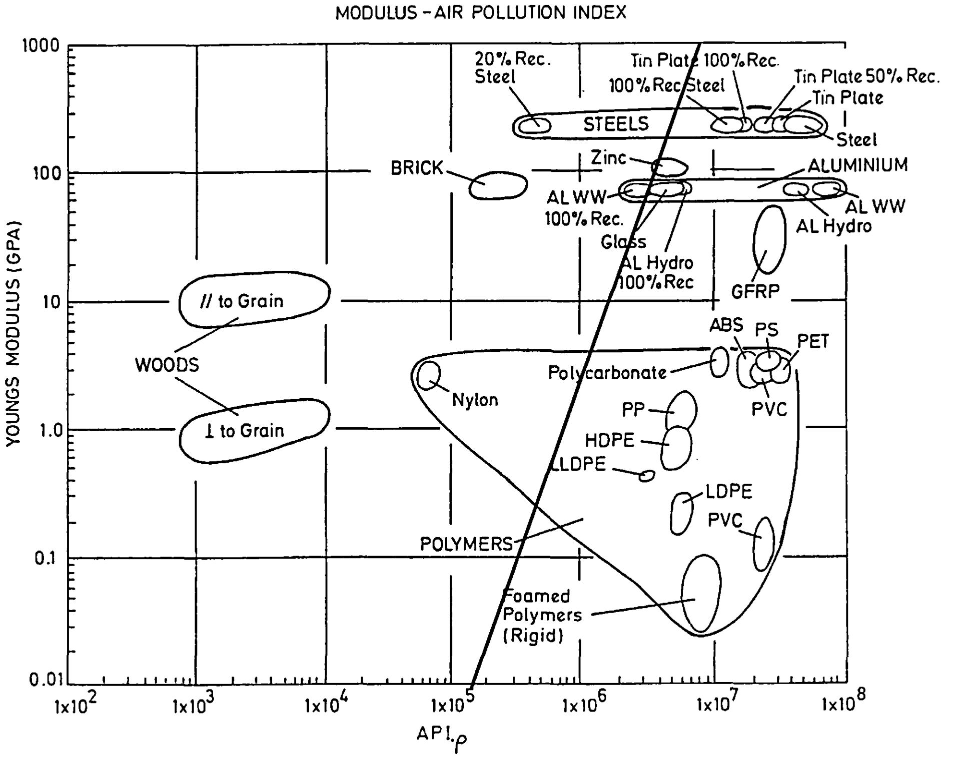
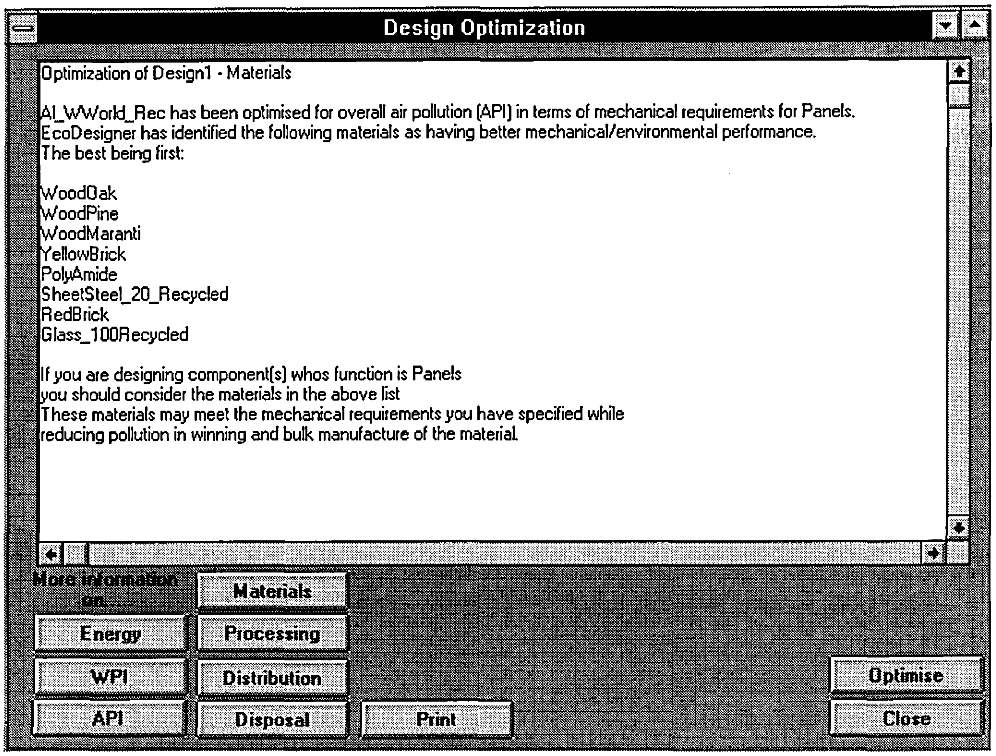


Figure 11.24 Environmental Materials Optimisation - Stiff Plates

11.4.2.2 Discussion of Materials Optimisation Procedures

Studying the results of the two previous exercises allows us to ask whether the results generated are 'sensible'. In the first case we are looking for strong materials which give least water pollution. Data for wood and water pollution is not given but it can be estimated that a material such as wood which has excellent mechanical properties, is relatively light and is not manufactured but grows in a state which requires very little processing to produce the useable raw material, would be the best. In the second example data is available for wood and as expected it is seen as the best material in terms of mechanical requirements for stiff plates (high Young's Modulus) and overall air pollution.



Optimization of Design1 - Materials

Al_WWorld_Rec has been optimised for overall air pollution (API) in terms of mechanical requirements for Panels.
EcoDesigner has identified the following materials as having better mechanical/environmental performance.
The best being first:

WoodOak
WoodPine
WoodMaranti
YellowBrick
PolyAmide
SheetSteel_20_Recycled
RedBrick
Glass_100Recycled

If you are designing component(s) whos function is Panels
you should consider the materials in the above list
These materials may meet the mechanical requirements you have specified while
reducing pollution in winning and bulk manufacture of the material.

Figure 11.25 Computer Based Material Optimisation for Stiff Plates

During the time it grows wood actually reduces the amount of some pollutants in the atmosphere e.g. carbon dioxide through photosynthesis.

In both exercises recycled materials are shown as being good candidates for the applications specified. Again this seems a sensible result as a large amount of the air and water pollution attributed to materials manufacture is a result of primary processing of the ore or raw material. When recycling, similar, if not identical mechanical properties can be achieved while energy requirements are much lower, especially in the case of aluminium. When aluminium is offered as a alternative in the first example, Al Hydro is shown as performing better than AL WestWorld. This is to be expected as the materials are the same in mechanical structure and properties but are refined from ore using different sources of energy. Al WestWorld is defined as aluminium produced in countries which use coal, oil and nuclear power stations to create electricity, whereas Al Hydro is aluminium which is refined using electricity generated from hydro-electric sources.

As energy content of materials is linked to their refining and manufacture it would be sensible to assume that there would be a similarity in energy content and air pollution figures. Looking at the results the computer tool has delivered and comparing them to Ashby's energy content charts shows some similarities. The most energy efficient materials for stiff plates are woods followed by ceramics and glass and then by steels, zinc alloys and some polymers. The results delivered by the computer tool are similar but not identical. However the comparison here is made between two systems which have used different data and there is a comparison being drawn between two different parameters which are loosely linked.

Overall the results delivered by the system compare well with other studies and with what may be expected when considering the environmental performance and mechanical properties of the materials in question.

11.4.2.3 Validation of Process Optimisation Procedures

The process optimisation procedures within the computer tool are based on the type of shape required from the process and the class of material which can be used in certain processes. For every user defined material and its associated processing operations the tool offers alternatives for the material and process. Alternative materials are taken from the list of those generated in the materials optimisation procedure. It is possible that the materials offered by the system may be of a different class than that defined by the user e.g. aluminium offered instead of polypropylene. In cases such as this the system recognised the change in class of material and offers processes which can be used for that class.

For example a user has defined Al WestWorld as the material currently being used and forging as the current process. The material is optimised in terms of air pollution and the mechanical requirements for strong beams. Of the groups of materials offered by the computer during the materials optimisation the user accepted steels and aluminium as possible alternatives. The shape required by the user was classed as 3D. Figure 11.26 shows the process optimisation screen from the computer system.

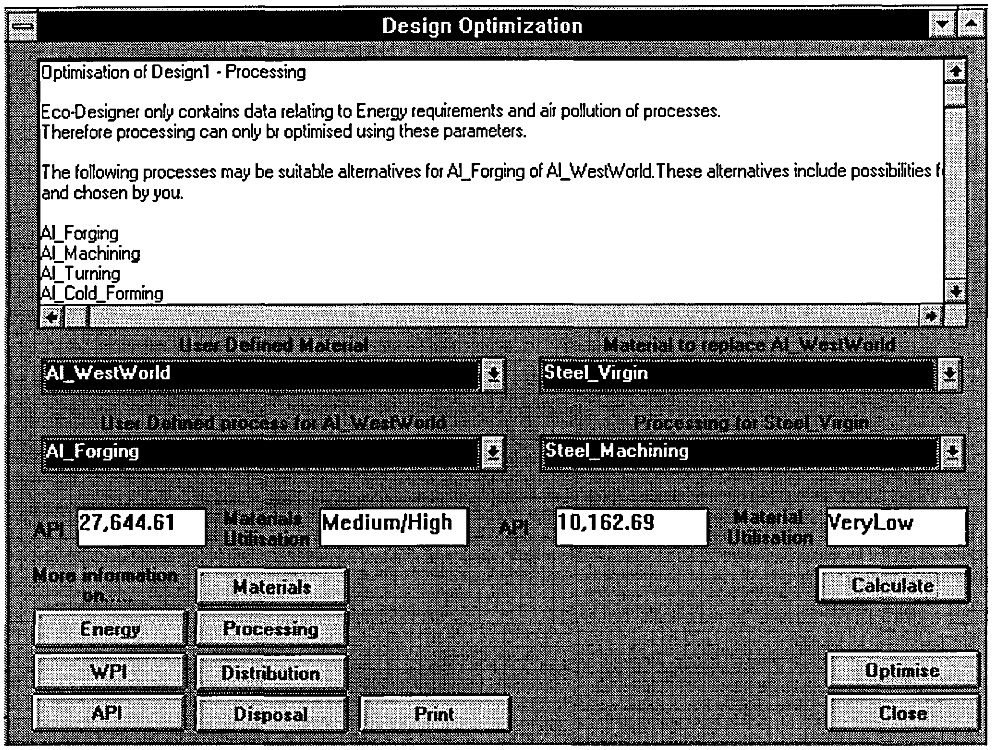
Of the materials and processing operations offered as alternatives, figure 11.26 shows the example of Steel_Virgin and machining to make the component. As can be seen the overall air pollution is more than halved but the materials utilisation is much lower also. Other processing options offered by the system for steel were casting, cold forming and forging.

Figure 11.27 shows another process optimisation exercise. Originally the material chosen was PVC, with processing of injection moulding and the shape was classed as 3D hollow. Optimisation was carried out for overall air pollution and requirements for tensile strain as in stiff ties. Of all the alternative groups of materials offered by the computer the user chose aluminium as well as the polymers identified. As can be seen from figure 11.27 the computer tools have offered a valid process option for aluminium. Casting can be used to form complex hollow shapes in metals. In this case it can be seen that the air pollution caused by using aluminium is far less. This is due to the much higher Young's Modulus to density ratio in plane strain which means you can use a lower mass of aluminium to make the same component while keeping the required stiffness.

Other processing options offered by the system for Aluminium were machining and cold forming.

11.4.2.4 Discussion of Process Optimisation Procedures

The process optimisation procedures embodied in the computer tool, examples of which were given in the previous section, are relatively simple in nature. When choosing processes there are a large number of complex factors which need to be taken into account. Issues such as cost, tolerances, tooling, shape etc. need to be balanced against each other. In many cases manufacturers of components will be tied to processes by the existing machinery they have.



Optimisation of Design1 - Processing

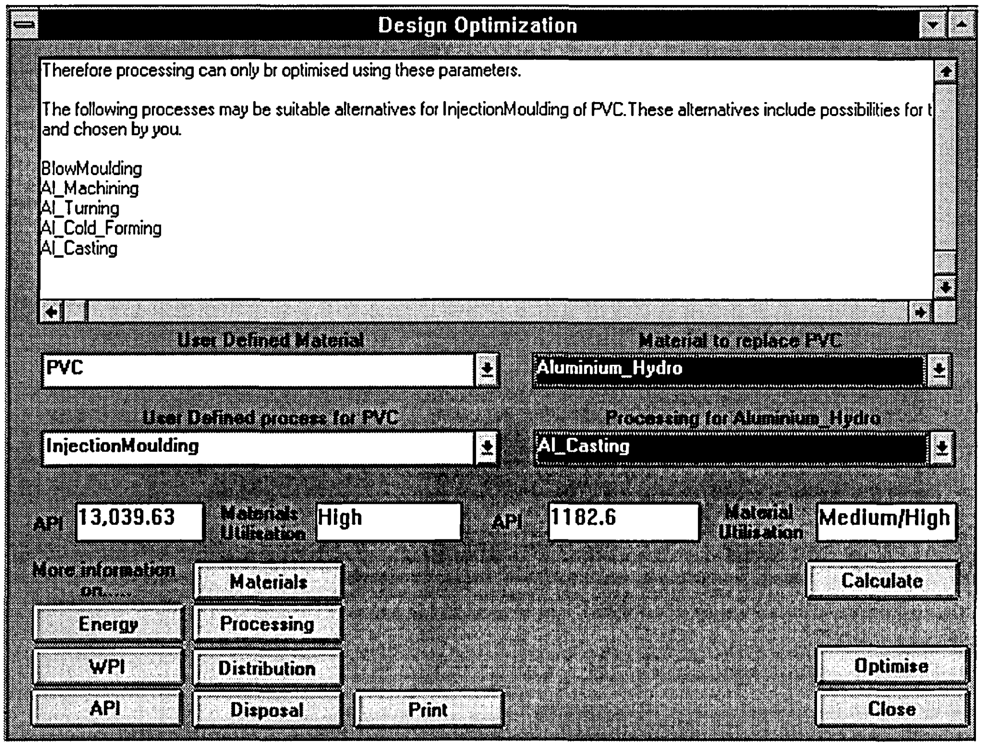
Eco-Designer only contains data relating to Energy requirements and air pollution of processes.
Therefore processing can only br optimised using these parameters.

The following processes may be suitable alternatives for Al_Forging of Al_WestWorld.These alternatives include possibilities f
and chosen by you.

Al_Forging
Al_Machining
Al_Turning
Al_Cold_Forming

User Defined Material: Al_WestWorld
Material to replace Al_WestWorld: Steel_Virgin
User Defined process for Al_WestWorld: Al_Forging
Processing for Steel_Virgin: Steel_Machining
API: 27,644.61
Materials Utilisation: Medium/High
API: 10,162.69
Material Utilisation: VeryLow

Figure 11.26 Computer Based Process Optimisation - Example 1



Therefore processing can only br optimised using these parameters.

The following processes may be suitable alternatives for InjectionMoulding of PVC.These alternatives include possibilities for t
and chosen by you.

BlowMoulding
Al_Machining
Al_Turning
Al_Cold_Forming
Al_Casting

User Defined Material: PVC
Material to replace PVC: Aluminium_Hydro
User Defined process for PVC: InjectionMoulding
Processing for Aluminium_Hydro: Al_Casting
API: 13,039.63
Materials Utilisation: High
API: 1182.6
Material Utilisation: Medium/High

Figure 11.27 Computer Based Process Optimisation -Example 2

Full consideration of all these factors would require a complex process selection tool which cannot be included in this work.

However what the procedures in this work achieve is to review possible options for processing by using a very high level of abstraction. By using only material type and required shape of the finished component the tool offers every suitable type of process. As there is relatively little environmental information about processes this high level of abstraction is needed. By presenting the designer with possible alternatives and outlining their air pollution and material utilisation the computer tool allows consideration of these alternatives but does not narrow down the choices too far. This allows the user to make the complex decisions concerning other parameters which are not included in the tool.

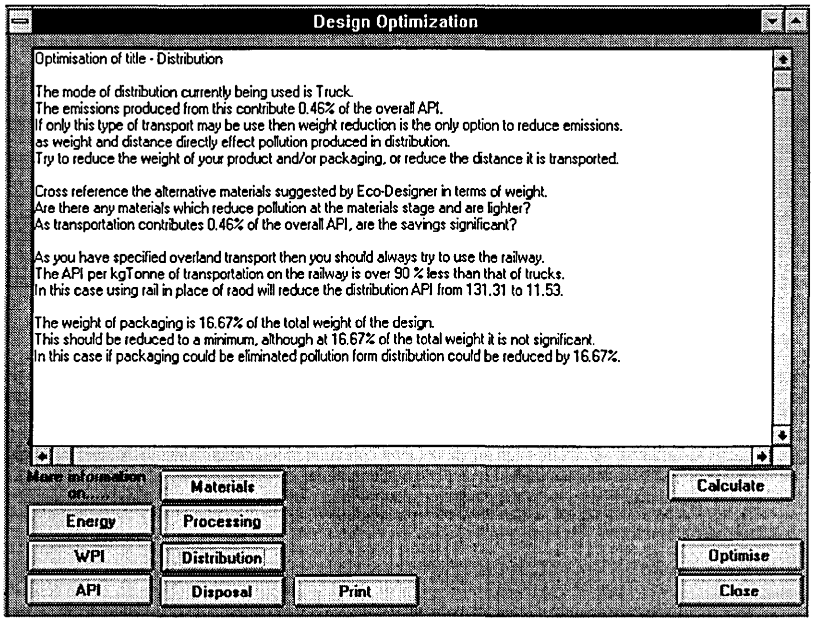
As shown in the two cases presented in the previous section the tool provides valid processing options which take into account the shape specified by the user and also automatically detects if the alternative materials are of a different class. The tool only suggests processes which are suitable for the class of material which has been proposed.

11.4.2.5 Discussion of Optimisation of Distribution and Disposal Advice

The advice given on both the distribution and disposal options highlights areas of improvement for the user to consider. Figures 11.28 and 11.29 show examples of the distribution and disposal advice respectively.

In this example the mode of distribution was to truck over 300 km. The total weight of the component is 1.2 kg and packing weighs 200g. The disposal practices defined were recycling the aluminium and 80% / 20% landfill / incineration of the remainder of the material. The information given by the system is generic advice. As can be seen the distribution advice covers a number of issues. The fact that weight affects distribution emissions is identified and possible changes in weight due to different material usage is highlighted. The percentage of overall pollution contributed by the distribution is presented and also the percentage contributed by the packaging is calculated. Possibilities for reduction of pollution are presented in terms of changing mode of transport and eliminating packaging, two of the main themes in the environmental impact of distribution.

Disposal advice highlights the main environmental aims for disposal. If you have to dispose of material the hierarchy should be reuse-recycle-incinerate. Issues surrounding reuse of materials are far too complex to include in this tool. The amount of materials going to recycling is calculated and the amount of energy this saves is presented. This allows the user not only to appreciate how many resources are saved but also the energy embodied within those resources. If the amount of the remainder of the material going to landfill is more than a specified amount (50% in this case) the advice given to the user highlights this and presents how much energy is recovered by the remainder being incinerated as a percentage of the overall energy required during the life-cycle of the design. Overall the advice given for these two life-cycle stages covers many of the generic aims of environmental design. It promotes the lightweighting of products, reduction or elimination of packaging, increase in recycling and reduction of material to landfill and an increase in energy recovery if material must be disposed of.



Optimisation of title - Distribution

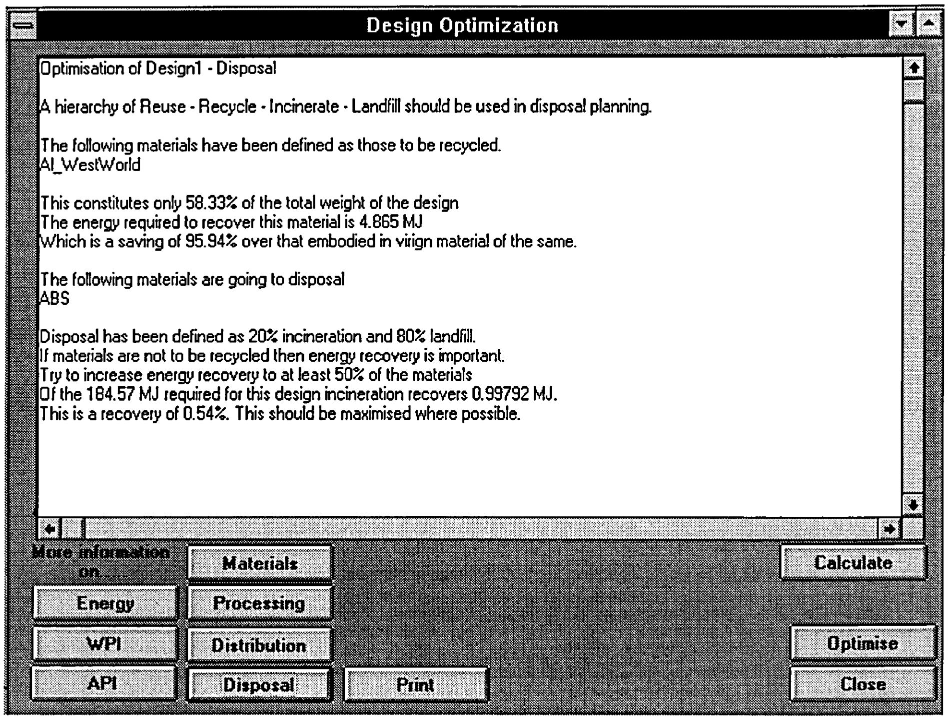
The mode of distribution currently being used is Truck.
The emissions produced from this contribute 0.46% of the overall API.
If only this type of transport may be use then weight reduction is the only option to reduce emissions.
as weight and distance directly effect pollution produced in distribution.
Try to reduce the weight of your product and/or packaging, or reduce the distance it is transported.

Cross reference the alternative materials suggested by Eco-Designer in terms of weight.
Are there any materials which reduce pollution at the materials stage and are lighter?
As transportation contributes 0.46% of the overall API, are the savings significant?

As you have specified overland transport then you should always try to use the railway.
The API per kgTonne of transportation on the railway is over 90 % less than that of trucks.
In this case using rail in place of raod will reduce the distribution API from 131.31 to 11.53.

The weight of packaging is 16.67% of the total weight of the design.
This should be reduced to a minimum, although at 16.67% of the total weight it is not significant.
In this case if packaging could be eliminated pollution form distribution could be reduced by 16.67%.

Figure 11.28 Computer Tool Distribution Advice



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Optimisation of Design1 - Disposal

A hierarchy of Reuse - Recycle - Incinerate - Landfill should be used in disposal planning.

The following materials have been defined as those to be recycled.
Al_WestWorld

This constitutes only 58.33% of the total weight of the design
The energy required to recover this material is 4.865 MJ
Which is a saving of 95.94% over that embodied in viirgn material of the same.

The following materials are going to disposal
ABS

Disposal has been defined as 20% incineration and 80% landfill.
If materials are not to be recycled then energy recovery is important.
Try to increase energy recovery to at least 50% of the materials
Of the 184.57 MJ required for this design incineration recovers 0.99792 MJ.
This is a recovery of 0.54%. This should be maximised where possible.
```

Figure 11.29 Computer Tool Disposal Advice

In each case the computer calculates the specific contribution or effect of each material or life-cycle stage, allowing the user to asses the design fully and identify areas of greatest concern. All the calculations carried out in the above exercise were found to be correct when checked manually.

11. 5 Chapter Summary

This chapter has reviewed the three main areas of work carried out in this research, the development of a new environmental design methodology, a new environmental materials selection method and a computer based support tool for environmentally conscious design and manufacture.

The design method was validated through use of examples carried out by a number of users. Three of the examples were discussed and the results obtained shown to be legitimate. The problems encountered with one of the examples were discussed and the source of the problem identified.

The materials selection method, based on that of Ashby, was validated through use of three examples. It showed that the method lent itself to the integration of environmental data and that because of the commutative nature of the charts, introduction of environmental concerns into the natural flow of the materials selection process is made much easier.

Finally elements of the computer support tool were discussed and validated. The materials optimisation procedures were compared to those carried out manually using the materials selection charts and shown to be accurate. The process optimisation procedures were tested by use of two different examples and the results obtained shown to be accurate and sensible.

The distribution and disposal advice given by the system was then discussed and the validity of the advice questioned. The advice was shown to follow the general aims of environmental design discussed in earlier chapters.

The three components validated show how this research has contributed to the integration of environmental concerns into the design process.

Chapter 12

Conclusions and Further Work

Conclusions and Further Work

12.1 Introduction

This work has shown that there are a number of reasons why engineers and designers now need to include environmental concerns in their work. To date this task remains difficult due to the following :

- A holistic approach to environmental design is needed which facilitates new approaches to the design of products and systems.
- Inclusion of environmental concerns may further complicate the design process through introduction of extra data and consideration of a new agenda
- The use of life cycle analysis remains a complex exercise, requiring considerable time and resources. The practicality of these exercises is questionable as the accuracy of the results cannot be guaranteed.
- Many of the environmental design methods developed are simple frameworks which aid designers to assess the impact of their design decisions at either a very general level or extremely specific level. No method currently exists which gives tailored design advice on a wide range of product types.
- Integration of environmental factors into materials selection is difficult and currently no method exists which allows the simultaneous consideration of mechanical and environmental properties. For most engineering design a method of this type is essential.
- The computerised DFE design tools which are currently available, like the DFE frameworks, carry out LCA studies but give very limited design advice. Those which do present a degree of advice are very specialised, e.g. design for disassembly.

- Very few designers appreciate fully the complex environmental consequences of their actions. Training and education are needed to develop an awareness of the problems facing practitioners.

Many of these problems are widely recognised and were recently documented by **Otto** (1996) in the Design Council Environmental Scoping Study. The Design Council and EPSRC have also concluded that generic clean /ecodesign tools and methods are needed to provide the basis for the development of specific tools related to particular industry sectors or organisations.

12.2 Conclusions

This research has identified the need for an integrated DFE method which is simple, reliable and widely applicable. This need has been addressed in three stages, the development of a new design method, the integration of environmental concerns into materials selection procedures and the development of a computer based support tool for use in design.

12.2.1 Design Method Conclusions

The following conclusions can be drawn from the work carried out to develop and validate the new design method:

- A matrix based approach is particularly advantageous when used in environmental design as it allows the complex interrelation of the different life-cycle stages to be represented in a clear and easy manner.
- Any product can be described using the method of Product Classification Descriptors (although a degree of interpretation is required).
- The Strategy Guidance Matrix allows the quick and efficient extraction of relevant data and information relating to the product in question.

- Completion of the Strategy Matrix using the information and data from the Guidance Matrix develops a simple and clear picture of the environmental issues which need to be considered in the design of the product in question.
- Starting from a very generic description, use of the Matrices in correct order of succession will develop an environmental design strategy which is specific to the product in question.
- In using the matrix, design strategies which affect the overall environmental impact but are not directly related to the design of the product may be identified.
- Having developed the strategy it is much easier for the designer to see how the environmental impact of the product in question may be reduced. The strategy will assist the designer in developing a checklist of specific goals.

The design method may be used at any stage of the design process due to its generic nature. At the conceptual stage it may bring about the most wide ranging changes to the design, as altering design concepts brings other factors into play, such as marketing strategy etc. It may also be used at the detailed design stage to address some of the technical issues which may be used to reduce environmental problems.

12.2.3 Materials Selection Method Conclusions

The following conclusions can be drawn from the development and validation of the materials selection method:

- The method is based on accepted procedures which allow the easy integration of mechanical concerns into the materials selection process.
- The nature of the materials selection charts allows a simple and accessible visual representation of a materials performance based on given mechanical and environmental criteria.

- As well as assisting materials selection the charts may also be used to optimise material choice. Comparative performance of materials may be considered. This aspect is particularly useful as the environmental performance of materials is often very difficult to appreciate in quantitative terms.
- Due to the nature of the method and the way in which the charts are used, they address one of the most important concerns in environmentally conscious design: i.e. where to include environmental concerns within the materials selection process. Ashby's materials selection method uses a number of charts in succession to assess different design and functional constraints. The order in which these charts are used is unimportant as they are commutative. The materials selection method developed by this research works in the same way as it is based on the same principles. The environmental based design constraint may be introduced through use of the appropriate chart at any stage.

The method developed both structures, and accelerates the integration of environmental concerns into material selection exercises. It allows a visual representation of hierarchies of materials in terms of both mechanical and environmental performance. Through its use it will implicitly tutor designers and engineers helping them to appreciate the different environmental performance of the materials which they use.

12.2.4 Computer Based Support Tool Conclusions

The use of computer based support tools is becoming common place in many areas. In environmental design they offer particular advantages. The following conclusions can be drawn from the work carried out during this research programme to develop a prototype of such a tool:

- The system is a central repository for information related to the environmental impact of materials, processes, distribution and disposal practices.

- Using a structured approach to define the life-cycle in question means that no information which is intended to be included is omitted.
- The time taken to carry out LCA calculations is dramatically reduced and a higher degree of validity is achievable.
- Alternative possibilities for materials and processes are offered by the system in a structured manner and the reasoning behind these possibilities is explained.
- The system eases the burden on the user by automatically generating reports which contain LCA data, graphs, optimisation possibilities and general design advice.
- Use of the system results in implicit tutoring taking place. Users will gain a degree of understanding and appreciation of the different environmental performance of materials, processes, distribution modes and disposal practices.
- The architecture of the system allows it to be easily updated.

The system benefits designers who are both experienced and inexperienced in environmental concerns. It allows the quick and easy calculation of abridged LCAs and offers advice on how the product or system in question may be improved. The expertise of the new materials selection method is embodied within the tool. The operation of the system allows it to be quickly and easily integrated into current design procedures without unduly increasing the time and information requirements of design exercises.

12.2.5 Summary of Conclusions

The overall aims of this research have been achieved. The unfulfilled needs in environmentally conscious design and manufacture identified as the difficulty in comparing different design options in environmental terms, providing guidance and long-term planning concerning trends in product design and materials and helping to train engineers and designers in the use of environmentally sound products and materials have been addressed.

A contribution to knowledge has been made in the area of environmental design and manufacture. This contribution to knowledge has been achieved by developing a novel matrix based environmental design method, making a significant development in the integration of environmental concerns into materials selection processes, especially in mechanical design, and the development of a prototype knowledge based system which embodies the materials selection method and uniquely offers design advice relating to each stage of the product or system life-cycle.

12.3 Further Work

Further work could be undertaken to extend the knowledge base and scope of this research. The following areas have been identified as offering opportunities:

- Currently the design method is generic in nature, which results in a number of advantages. The need for the development of more specific methods and tools has been identified and this generic method is the perfect base for these detailed tools. This may be achieved by the development of low level 'plug ins' which are specific to industry sectors or product types.
- Computerisation of the method may eliminate much of the repetitive work required in the use of the matrix. Use of the product descriptors to automatically generate the design strategy matrix is a possibility.
- Lack of data is the largest area for further work relating to the materials selection method and computer tool. More environmental data is required for materials, processing, energy, transportation and disposal scenarios.
- Development of more detailed selection charts is another possibility. Selection charts which include process information and also charts which include other life-cycle data could be created. Inclusion of disposal effects and in use effects could increase the usefulness of the charts.

- Development of the computer tool from prototype stage into a fully functioning piece of software would allow further testing, validation and development work to be carried out.
- The computer support tool would benefit from the inclusion of material resource consumption for the in use phase of product life-cycles.
- Linking the computer tool to CAD systems would greatly increase efficiency. Automatically generated bills of materials could be loaded into the tool removing the need for user input at the design definition stage. Suggested design improvements in terms of materials and processes could then be returned to the CAD system allowing the effects to be assessed immediately.
- Integration of the matrix, product classification descriptors and the computer tool would ultimately result in a totally integrated DFE methodology.

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Appendix A

Object Hierarchies of the Computer Support Tool

The figures contained within this appendix diagramatically represent the object hierarchy of the computer support tool. Each of the branches shown in figure A below is expanded in full or part by subsequent figures contained herein.

The five branches within the software/system group are not expanded as there are common to all applications developed in this language.

The legislation branch cannot be expanded at the moment as there is no information contianed within it.

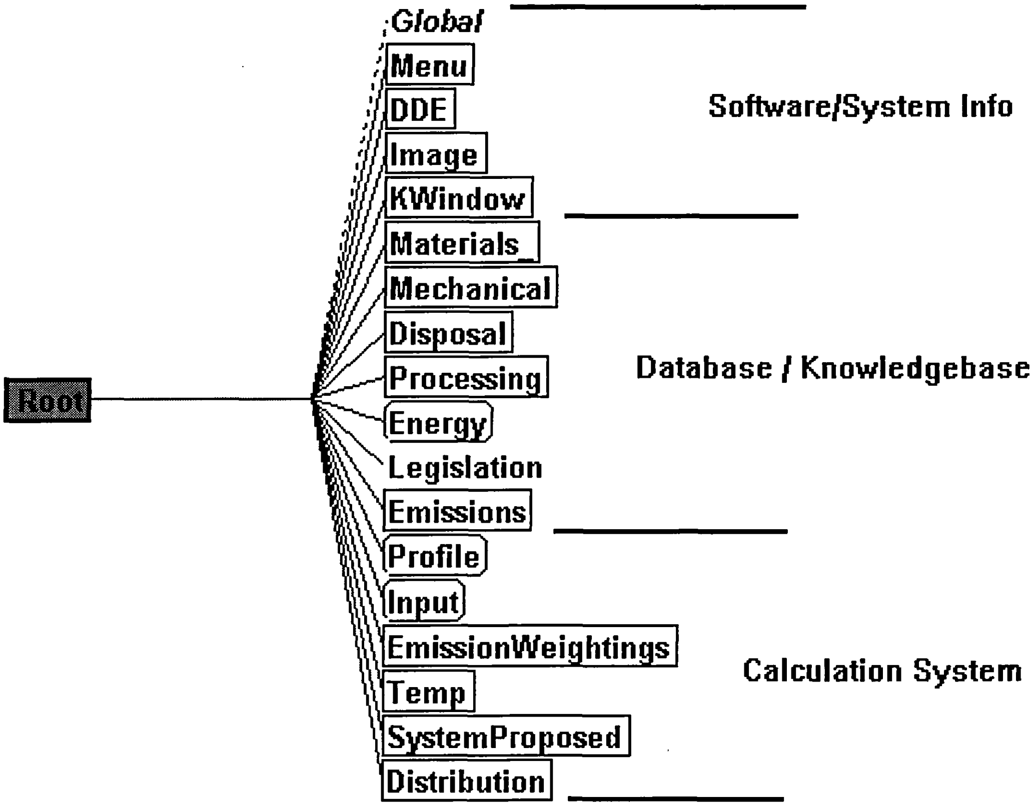


Figure A The Overall Object Hierarchy of the Computer Tool

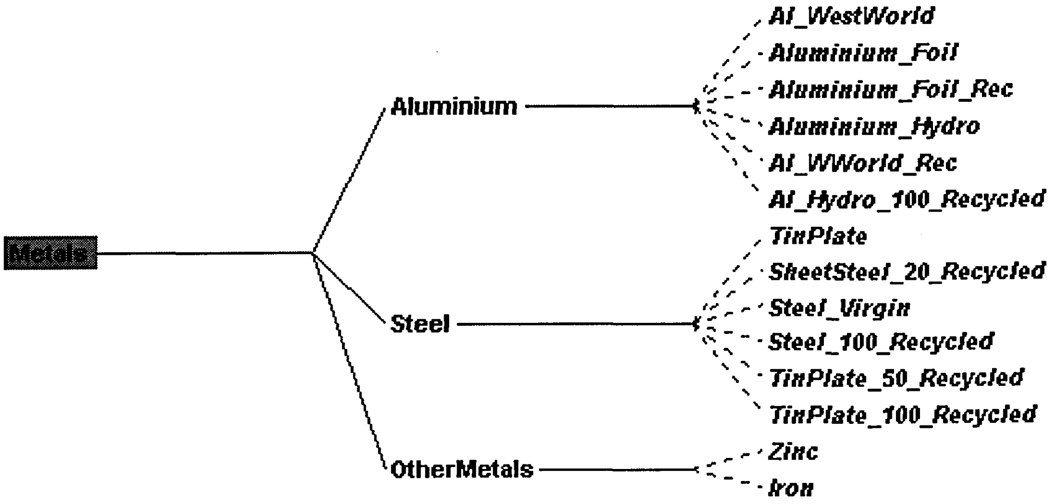


Figure A.1 Metals Object Hierarchy

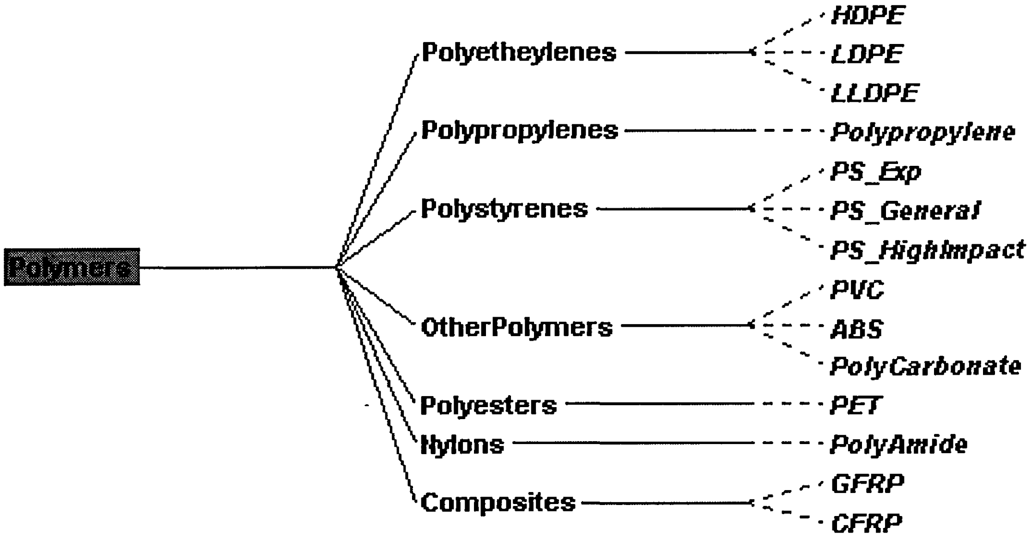


Figure A.2 Polymers Object Hierarchy

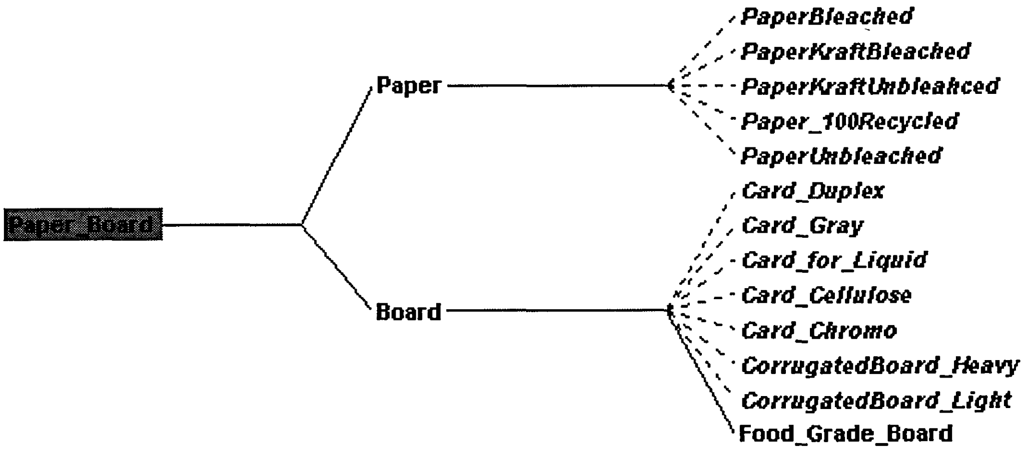


Figure A.3 Paper and Board Object Hierarchy

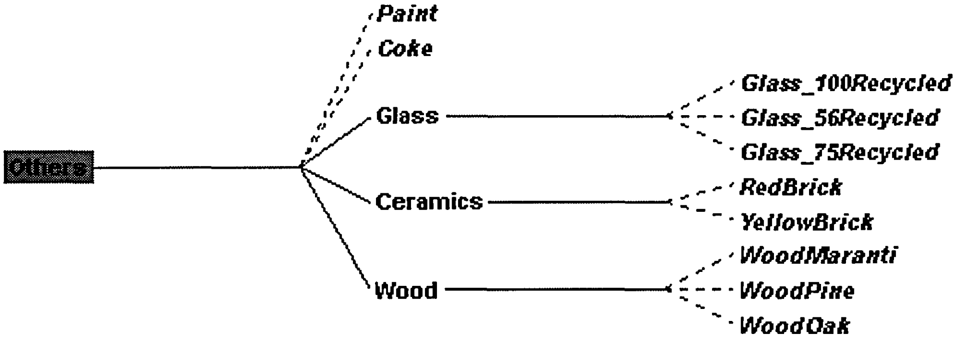


Figure A.4 Other Materials Object Hierarchy

The objects with square outlines in the following diagrams are those which are not showing all their instances. For each of the hierarchies at least one of the branches is fully expanded to allow an appreciation of what information the unexpanded branches hold.

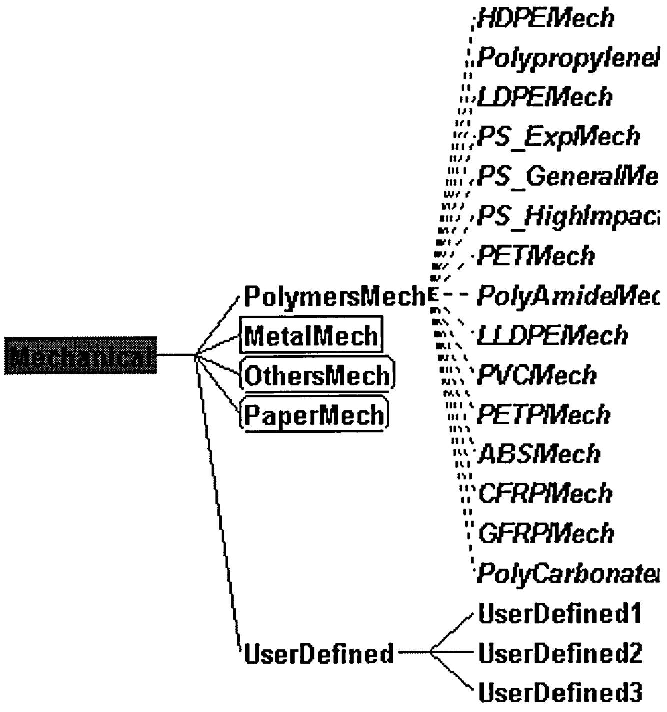


Figure A.5 Mechanical Properties Object Hierarchy

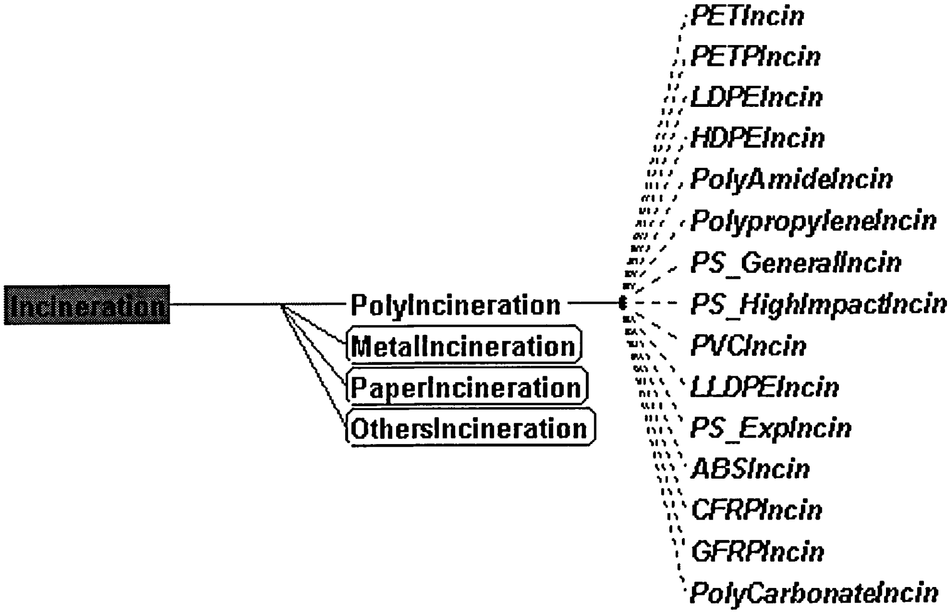


Figure A.6 Incineration Object Hierarchy

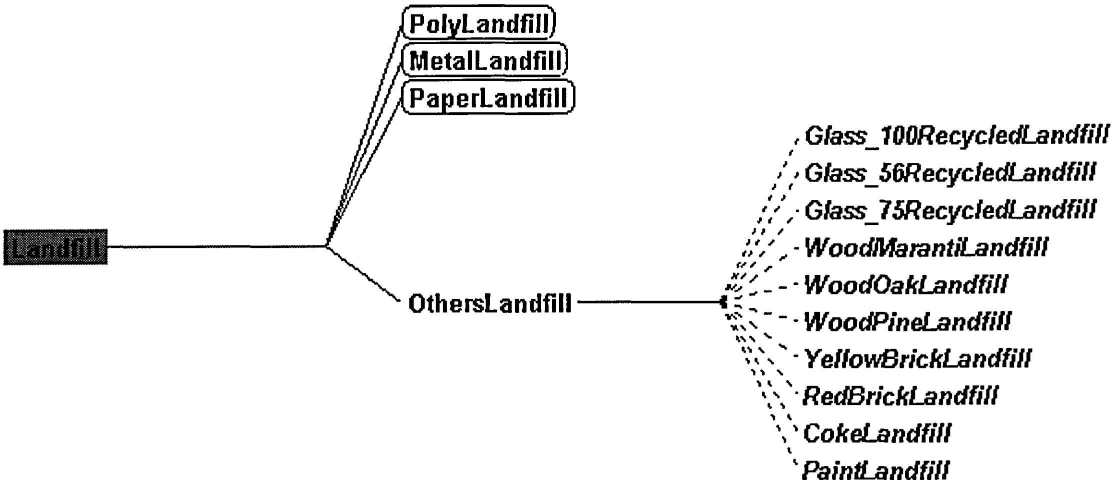


Figure A.7 Landfill Object Hierarchy

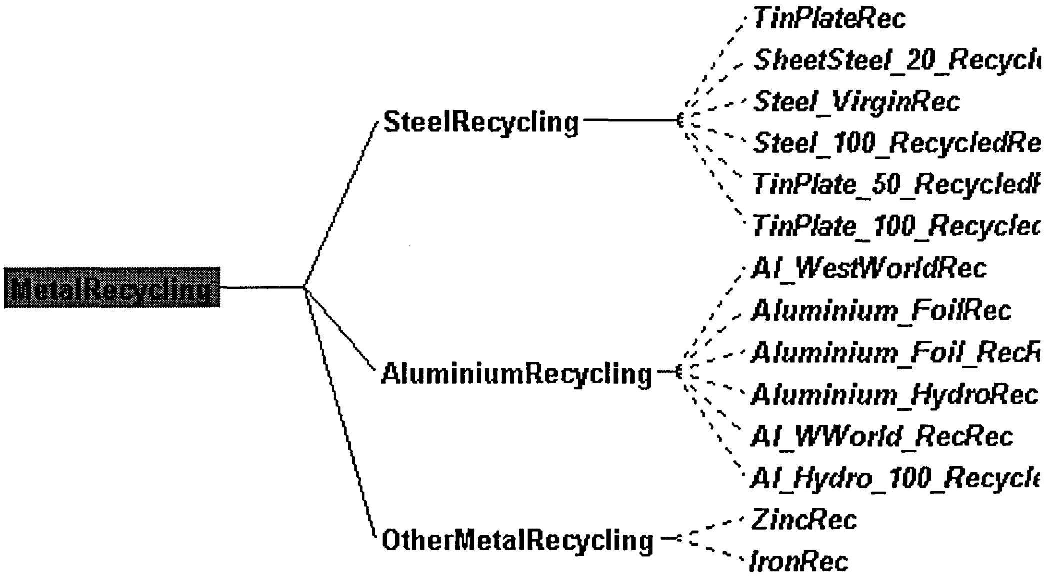


Figure A.8 Part of the Recycling Object Hierarchy

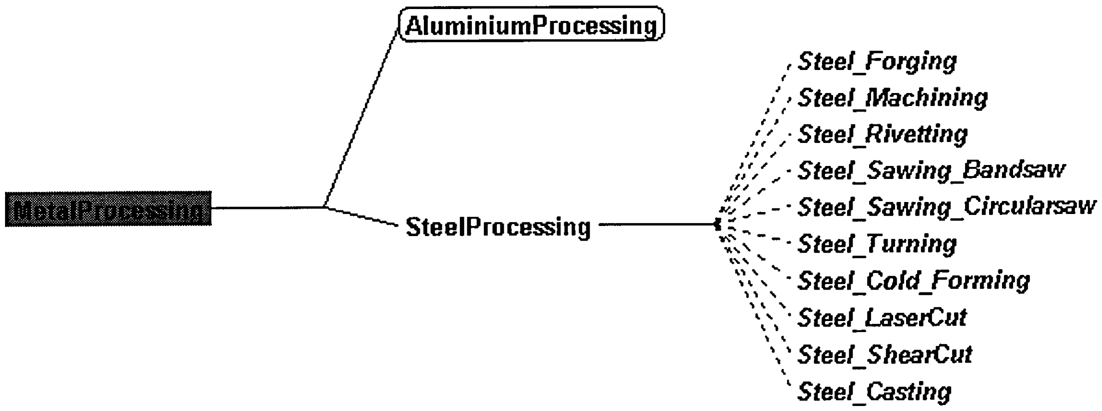


Figure A.9 Part of the Processing Object Hierarchy

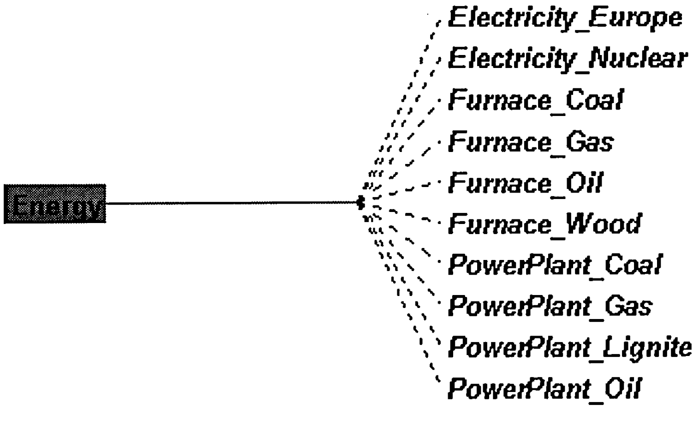


Figure A.10 Energy Generation Object Hierarchy

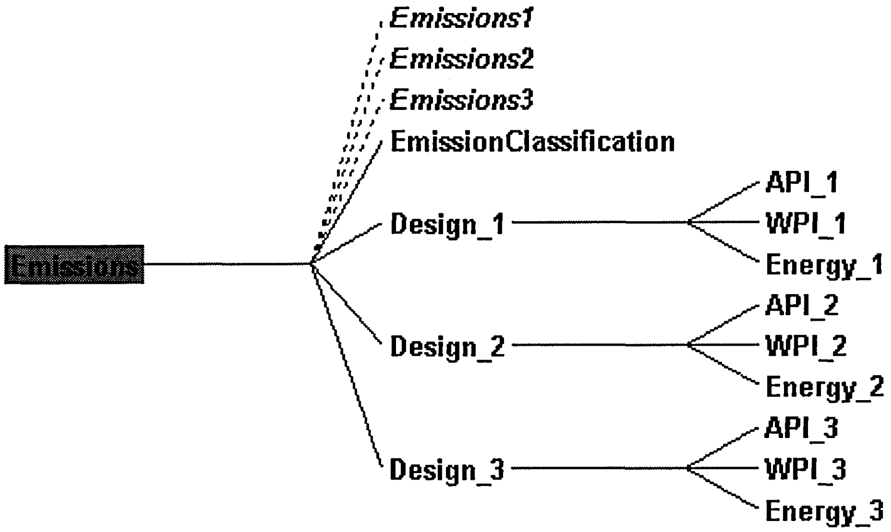


Figure A.11 Emissions Classification Object Hierarchy

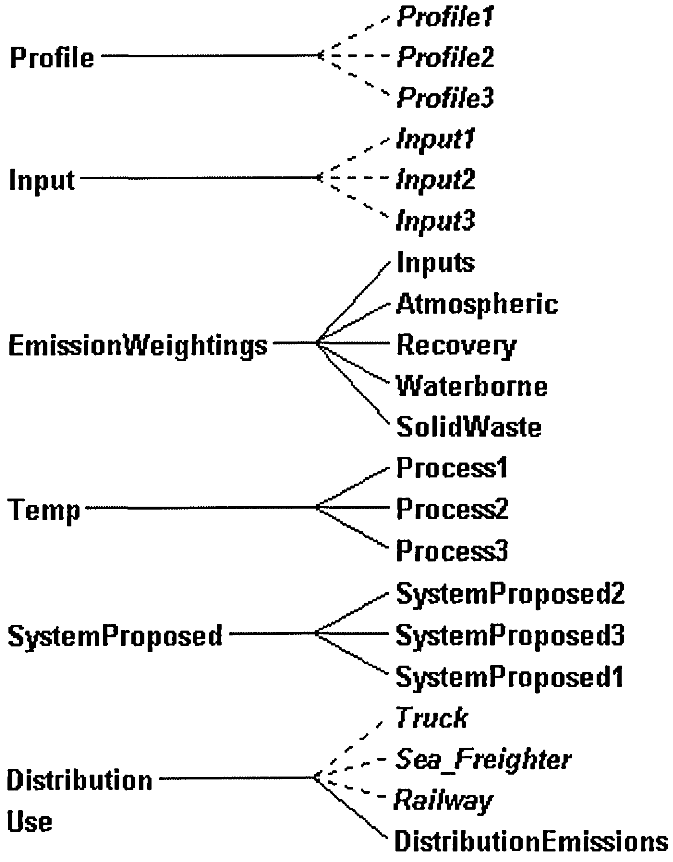


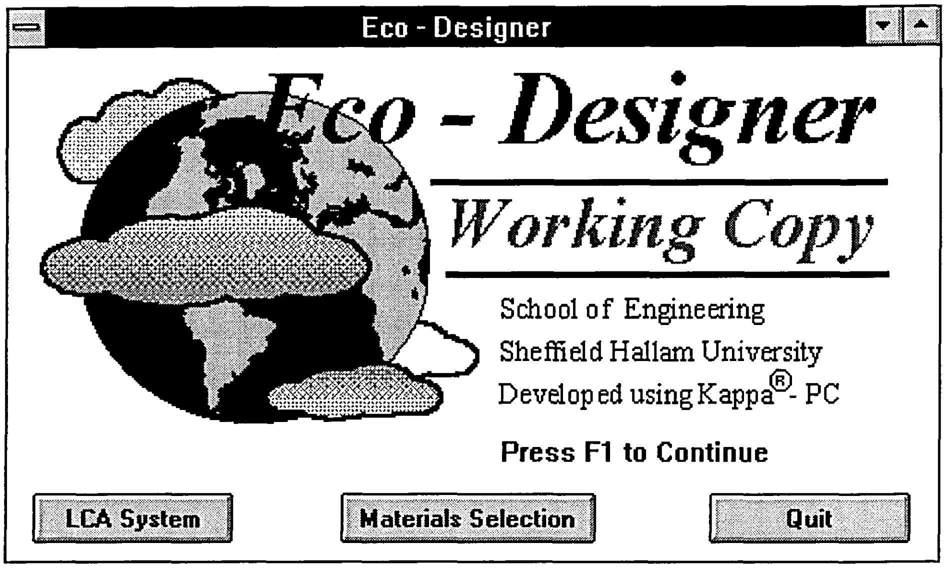
Figure A.12 All the Object Hierarchies within the Calculation System of the Tool

Appendix B

System Interfaces of the Computer Support Tool

Appendix B (i)

Computer Tool Interfaces for LCA Component



Eco - Designer

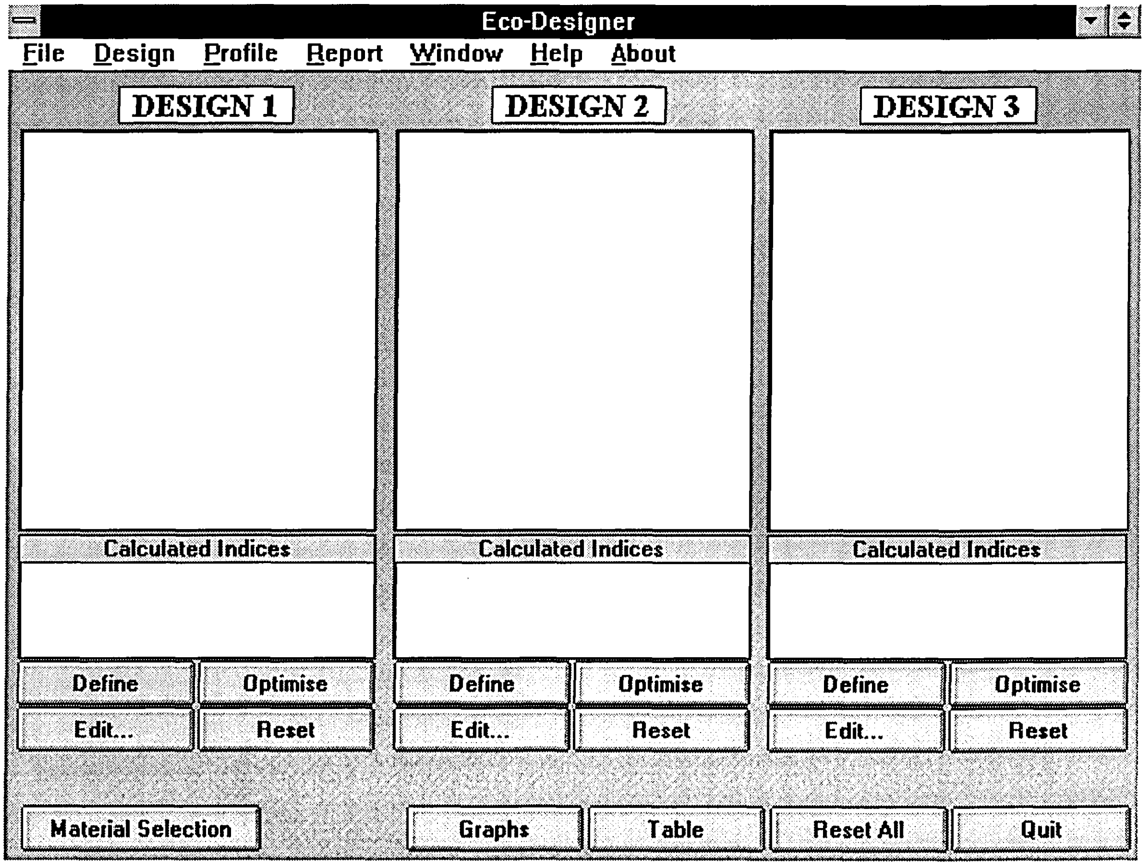
Eco - Designer

Working Copy

School of Engineering
Sheffield Hallam University
Developed using Kappa®- PC

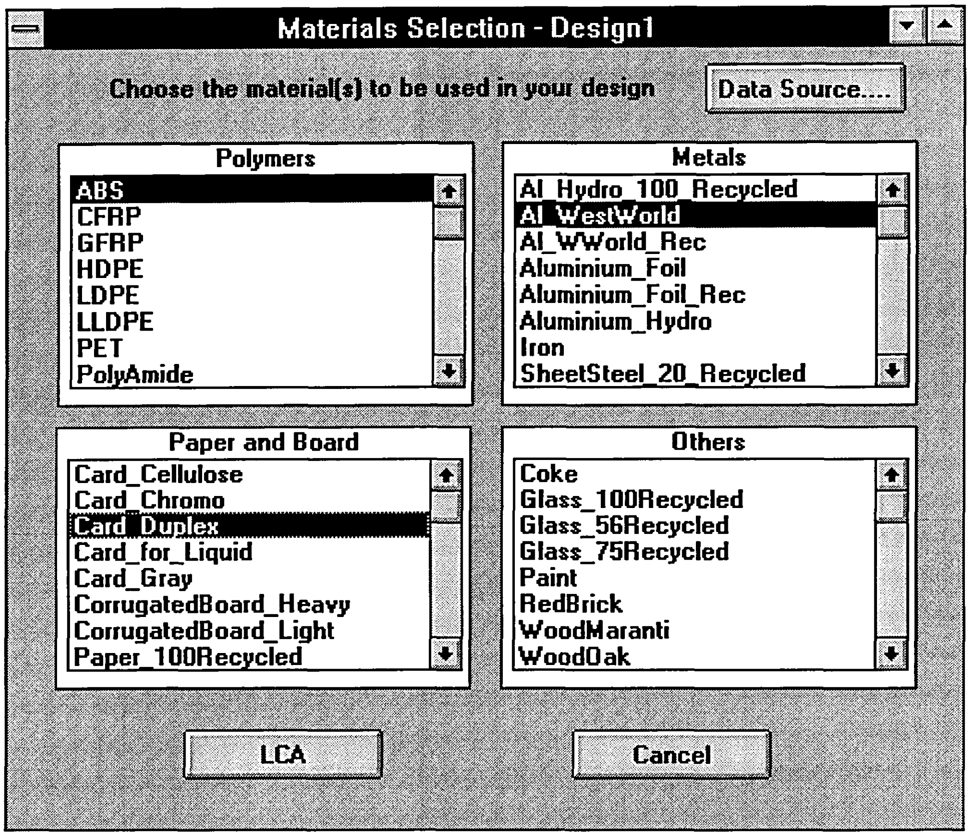
Press F1 to Continue

Figure B.1 Title Screen of Computer Support Tool



Eco-Designer

Figure B.2 User Interface of Computer Support Tool



Materials Selection - Design1

Choose the material(s) to be used in your design

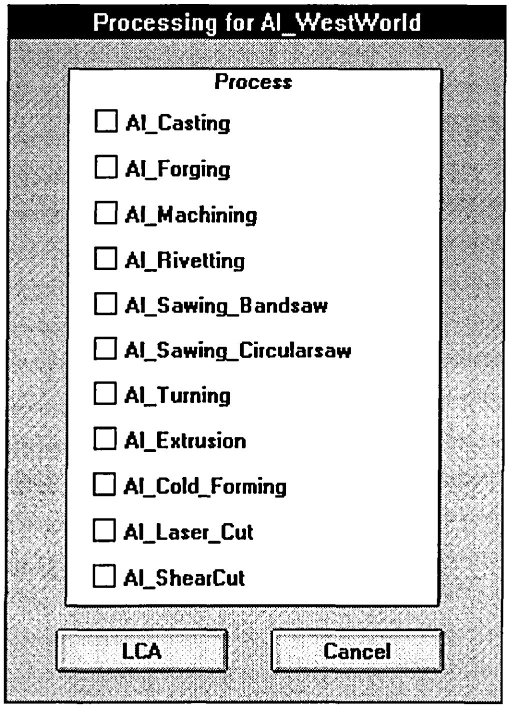
Polymers
- ABS
- CFRP
- GFRP
- HDPE
- LDPE
- LLDPE
- PET
- PolyAmide

Metals
- Al_Hydro_100_Recycled
- Al_WestWorld
- Al_WWorld_Rec
- Aluminium_Foil
- Aluminium_Foil_Rec
- Aluminium_Hydro
- Iron
- SheetSteel_20_Recycled

Paper and Board
- Card_Cellulose
- Card_Chromo
- Card_Duplex
- Card_for_Liquid
- Card_Gray
- CorrugatedBoard_Heavy
- CorrugatedBoard_Light
- Paper_100Recycled

Others
- Coke
- Glass_100Recycled
- Glass_56Recycled
- Glass_75Recycled
- Paint
- RedBrick
- WoodMaranti
- WoodOak

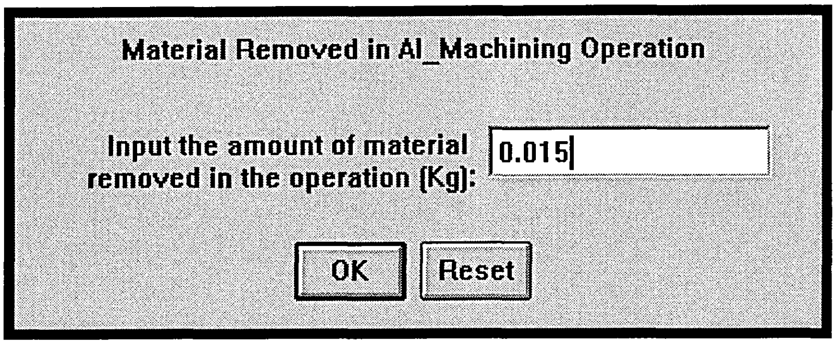
Figure B.3 Materials Selection Screen



Processing for Al_WestWorld

Process
- ☐ Al_Casting
- ☐ Al_Forging
- ☐ Al_Machining
- ☐ Al_Rivetting
- ☐ Al_Sawing_Bandsaw
- ☐ Al_Sawing_Circularsaw
- ☐ Al_Turning
- ☐ Al_Extrusion
- ☐ Al_Cold_Forming
- ☐ Al_Laser_Cut
- ☐ Al_ShearCut

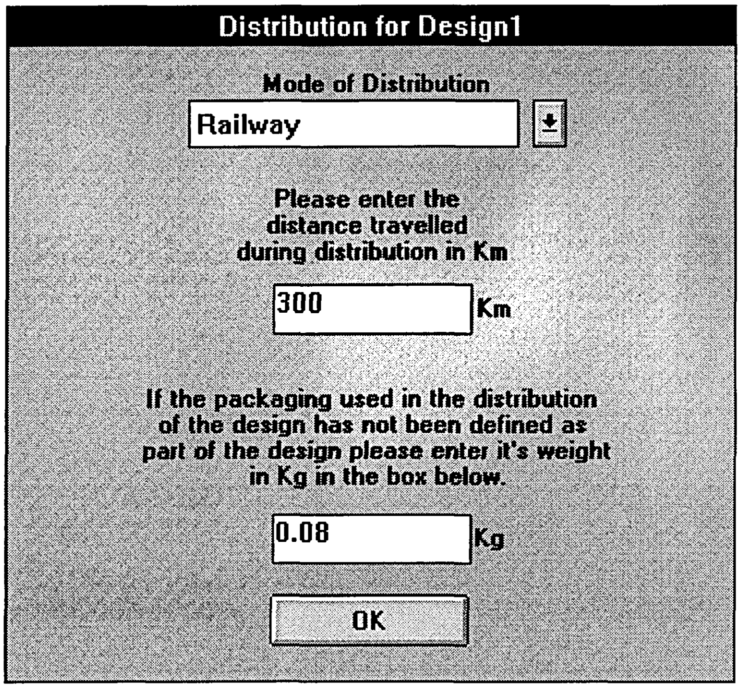
Figure B.4 Process Selection Screen



Material Removed in Al_Machining Operation

Input the amount of material removed in the operation (Kg): 0.015

Figure B.5 Process Information Input Screen



Distribution for Design1

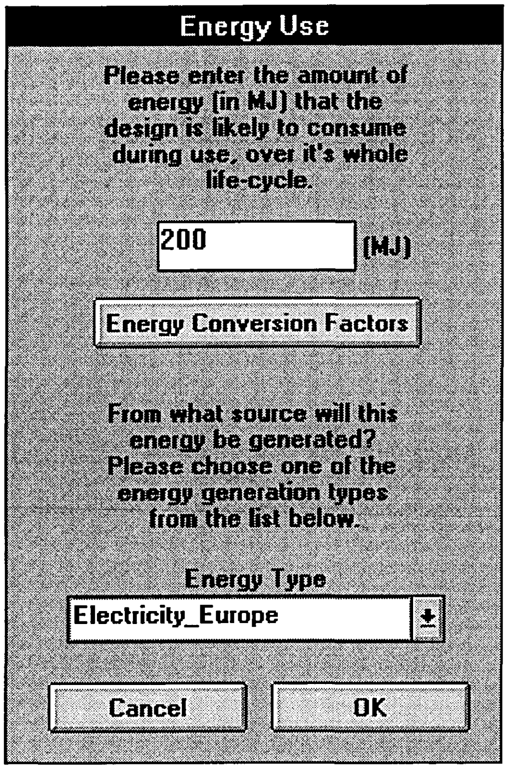
Mode of Distribution: Railway

Please enter the distance travelled during distribution in Km: 300 Km

If the packaging used in the distribution of the design has not been defined as part of the design please enter it's weight in Kg in the box below.

0.08 Kg

Figure B.6 Distribution Information Input Screen



Energy Use

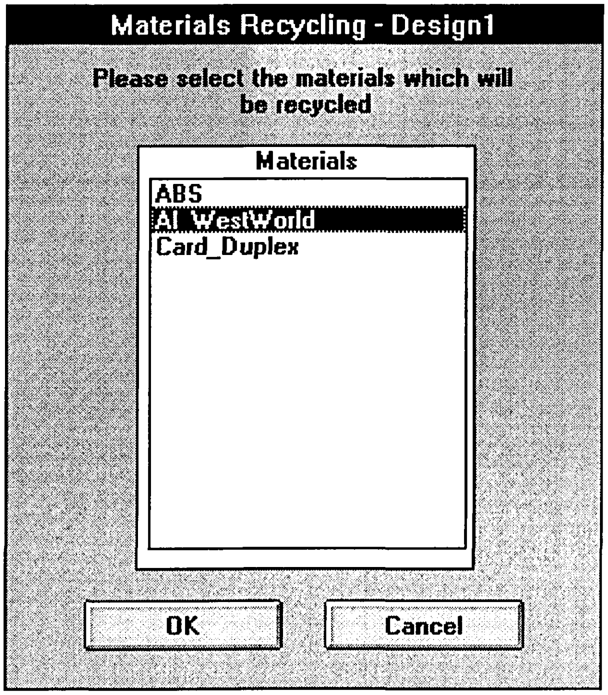
Please enter the amount of energy (in MJ) that the design is likely to consume during use, over it's whole life-cycle.

200 (MJ)

From what source will this energy be generated? Please choose one of the energy generation types from the list below.

Energy Type: Electricity_Europe

Figure B.7 Energy Consumption in Use Information Input Screen



Materials Recycling - Design1

Please select the materials which will be recycled

Materials
- ABS
- Al_WestWorld
- Card_Duplex

Figure B.8 Recycling Information Input Screen

Disposal of Materials in Design1 not being recycled (%Weight)

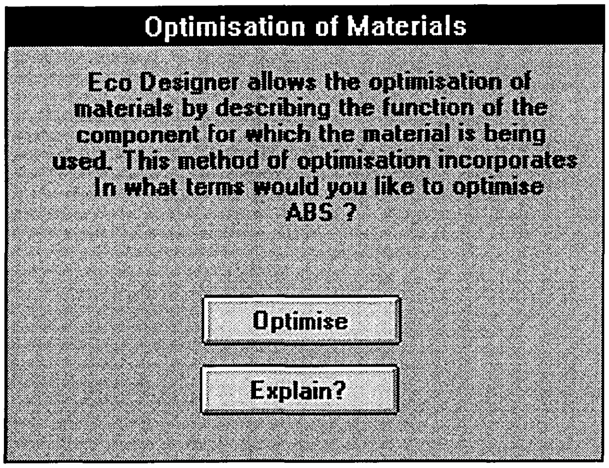
Landfill 60

Incineration 40

Figure B.9 Final Disposal Information Input Screen

Appendix B (ii)

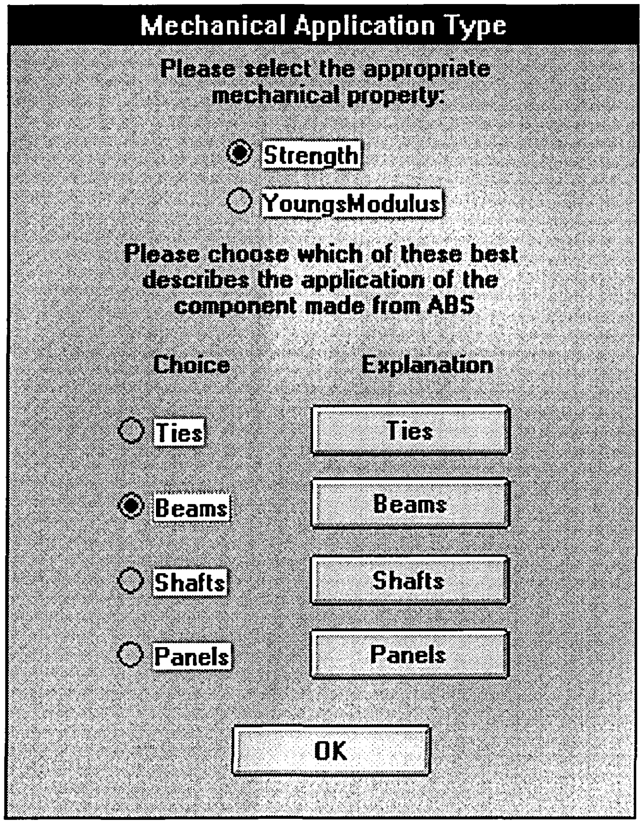
Computer Tool Interfaces for Optimisation Procedures



Optimisation of Materials

Eco Designer allows the optimisation of materials by describing the function of the component for which the material is being used. This method of optimisation incorporates In what terms would you like to optimise ABS ?

Figure B.10 Initial Optimisation Screen



Mechanical Application Type

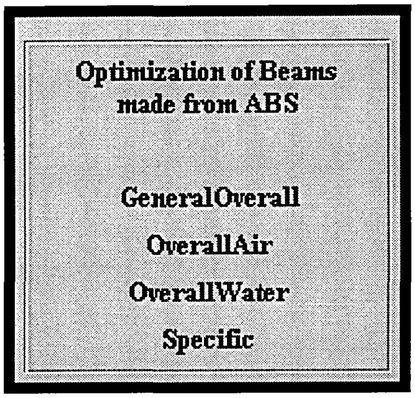
Please select the appropriate mechanical property:

● Strength
○ YoungsModulus

Please choose which of these best describes the application of the component made from ABS

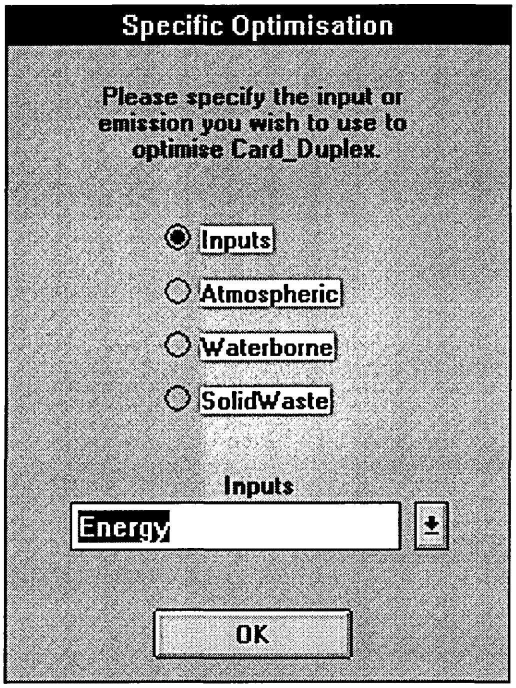
Choice	Explanation
○ Ties	Ties
● Beams	Beams
○ Shafts	Shafts
○ Panels	Panels

Figure B.11 Mechanical Application Information Input Screen



Optimization of Beams
made from ABS

Figure B.12 Environmental Optimisation Selection Screen



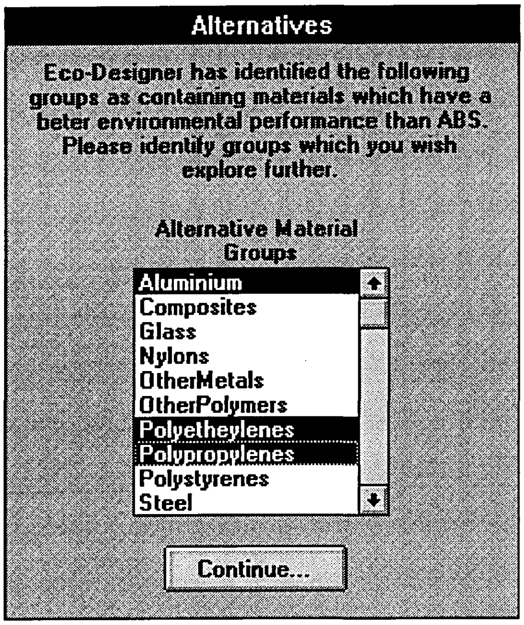
Specific Optimisation

Please specify the input or emission you wish to use to optimise Card_Duplex.

- ● Inputs
- ○ Atmospheric
- ○ Waterborne
- ○ SolidWaste

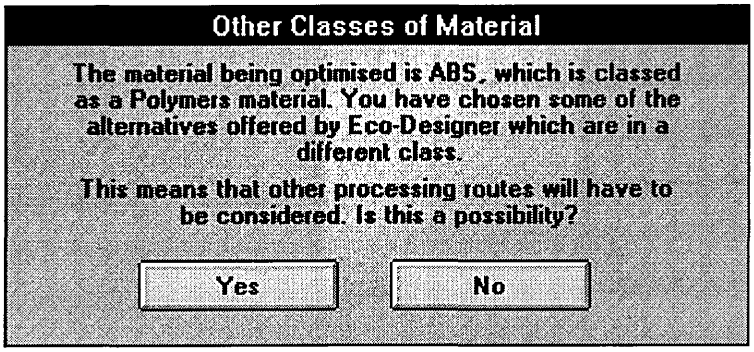
Inputs: Energy

Figure B.13 User Selection Screen of Specific Environmental Concern Used in Optimisation



Eco-Designer has identified the following groups as containing materials which have a beter environmental performance than ABS. Please identify groups which you wish explore further.

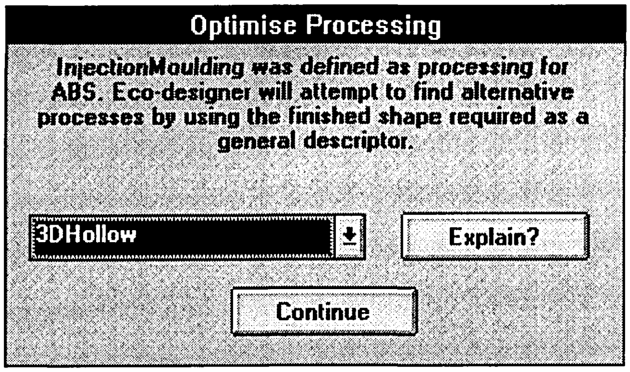
Figure B.14 User Confirmation / Selection of Possible Alternative Material Groups



The material being optimised is ABS, which is classed as a Polymers material. You have chosen some of the alternatives offered by Eco-Designer which are in a different class.

This means that other processing routes will have to be considered. Is this a possibility?

Figure B.15 Confirmation of Other Possible Processing Routes Screen



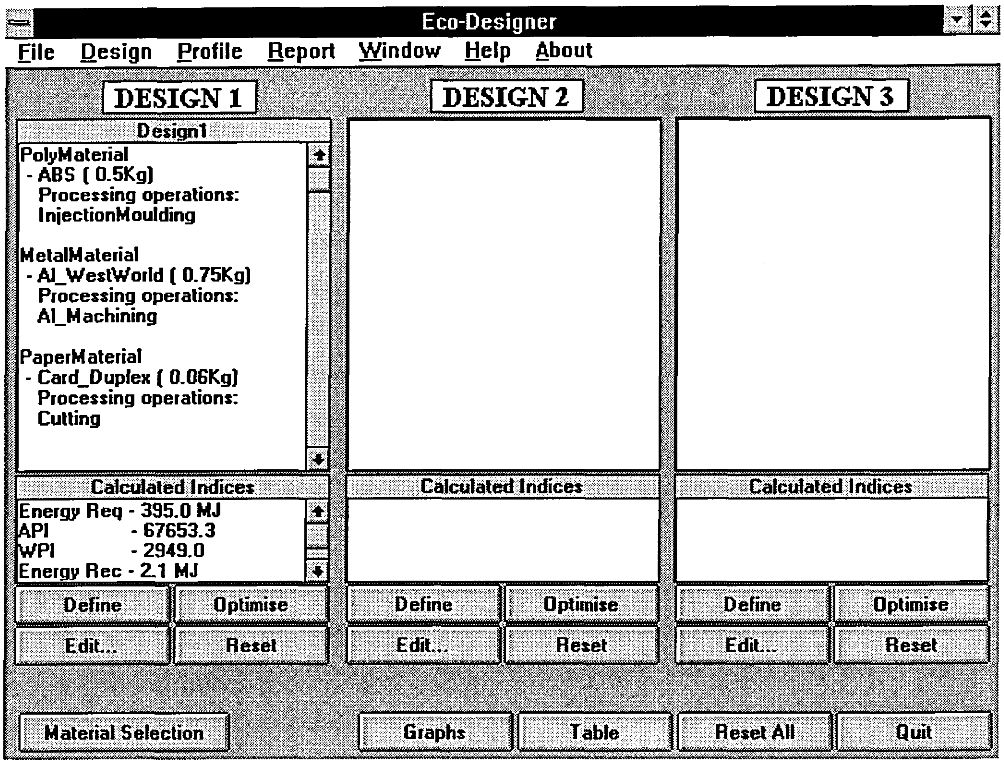
InjectionMoulding was defined as processing for ABS. Eco-designer will attempt to find alternative processes by using the finished shape required as a general descriptor.

3DHollow

Figure B.16 User Description of Finished Component Shape Input Screen

Appendix B (iii)

Example Outputs & Results from The Computer Tool



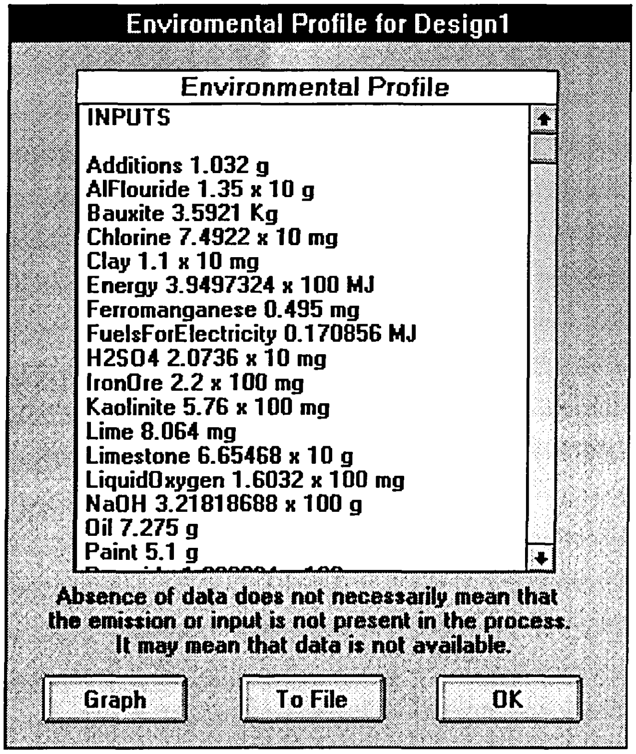
PolyMaterial
- ABS (0.5Kg)
Processing operations:
InjectionMoulding

MetalMaterial
- Al_WestWorld (0.75Kg)
Processing operations:
Al_Machining

PaperMaterial
- Card_Duplex (0.06Kg)
Processing operations:
Cutting

Energy Req - 395.0 MJ
API - 67653.3
WPI - 2949.0
Energy Rec - 2.1 MJ

Figure B.17 User Interface showing Inputs and Calculated Indices



INPUTS

Additions 1.032 g
AlFlouride 1.35 x 10 g
Bauxite 3.5921 Kg
Chlorine 7.4922 x 10 mg
Clay 1.1 x 10 mg
Energy 3.9497324 x 100 MJ
Ferromanganese 0.495 mg
FuelsForElectricity 0.170856 MJ
H2SO4 2.0736 x 10 mg
IronOre 2.2 x 100 mg
Kaolinite 5.76 x 100 mg
Lime 8.064 mg
Limestone 6.65468 x 10 g
LiquidOxygen 1.6032 x 100 mg
NaOH 3.21818688 x 100 g
Oil 7.275 g
Paint 5.1 g

Absence of data does not necessarily mean that the emission or input is not present in the process. It may mean that data is not available.

Figure B.18 Computer Generated Tabular Environmental Profile

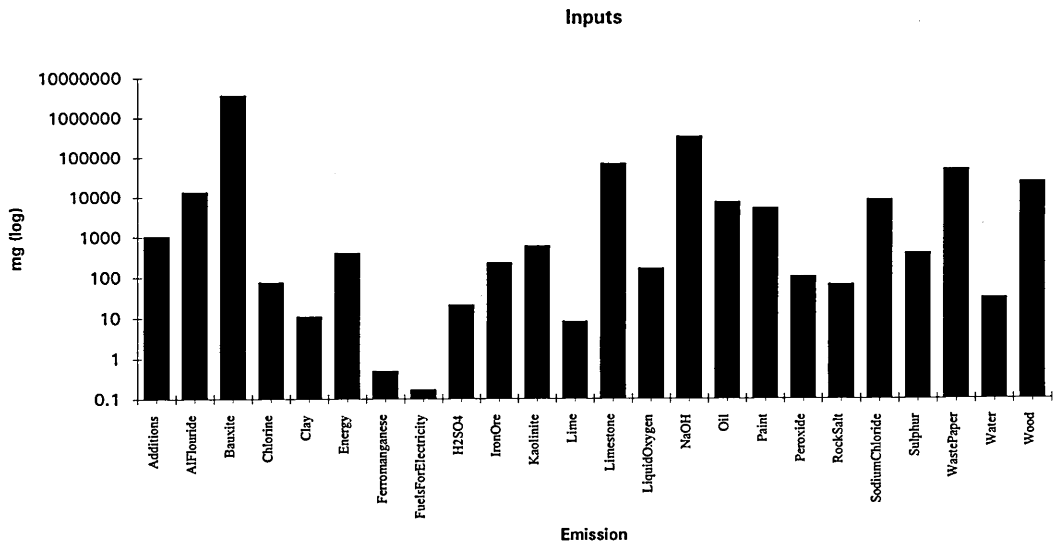


Figure B.19 Computer Generated Graph of Life-Cycle Inputs

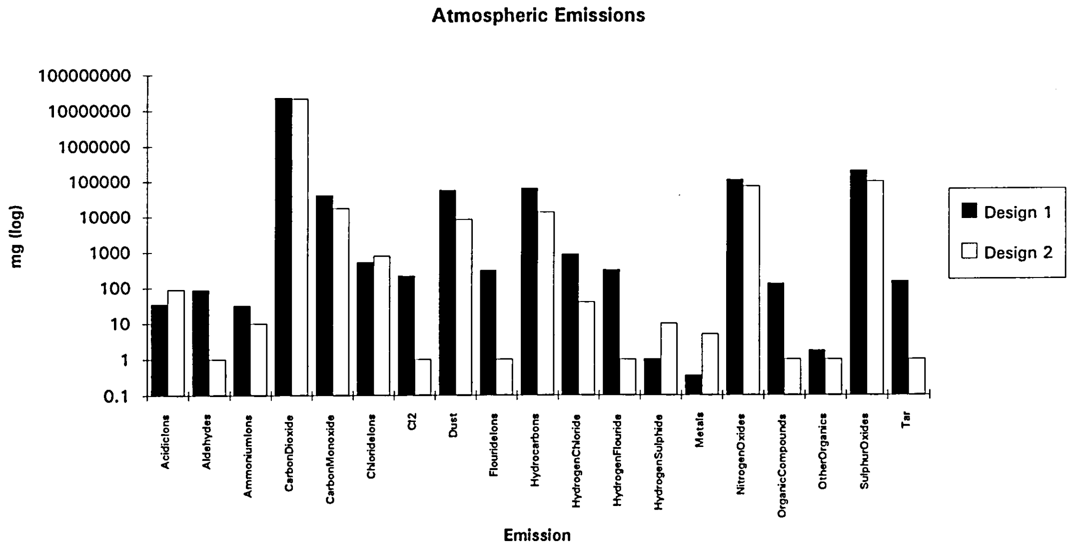


Figure B.20 Computer Generated Graphs of Life-Cycle Atmospheric Emissions (Comparative assessment of 2 designs)

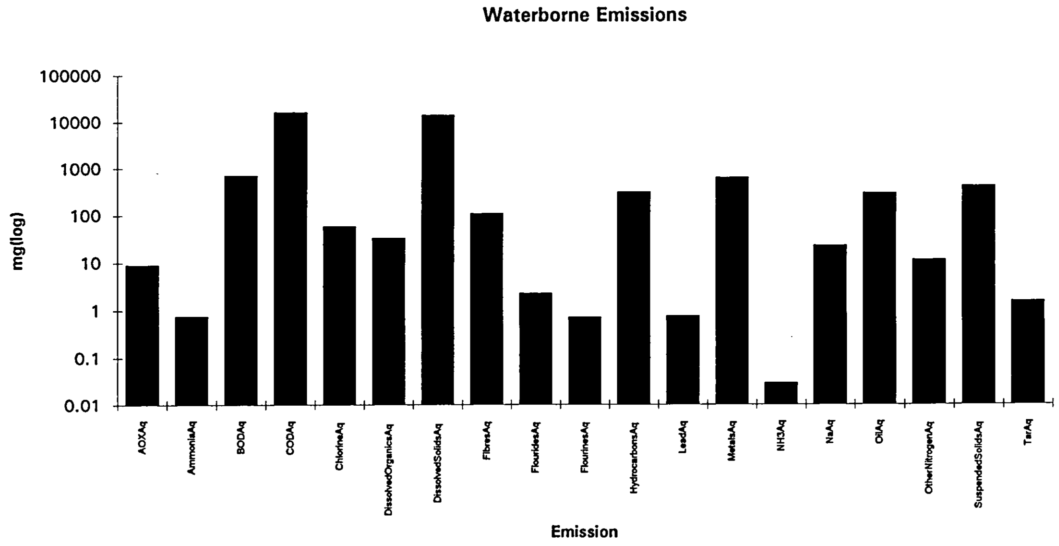


Figure B.21 Computer Generated Graph of Life-Cycle Waterborne Emissions

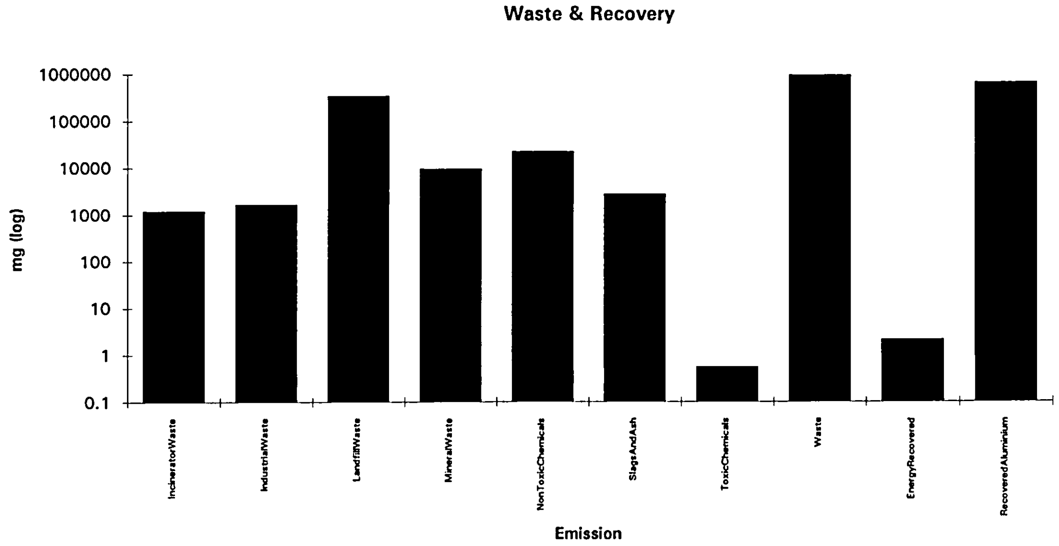


Figure B.22 Computer Generated Graph of Life-Cycle Waste and Recovery

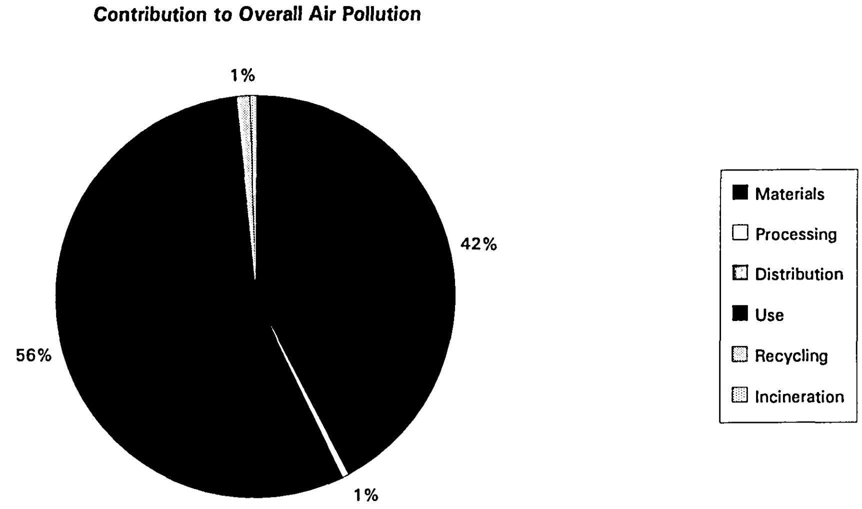


Figure B.23 Computer Generated Chart Showing Contribution of Different Life-Cycle Stages to Overall Air Pollution

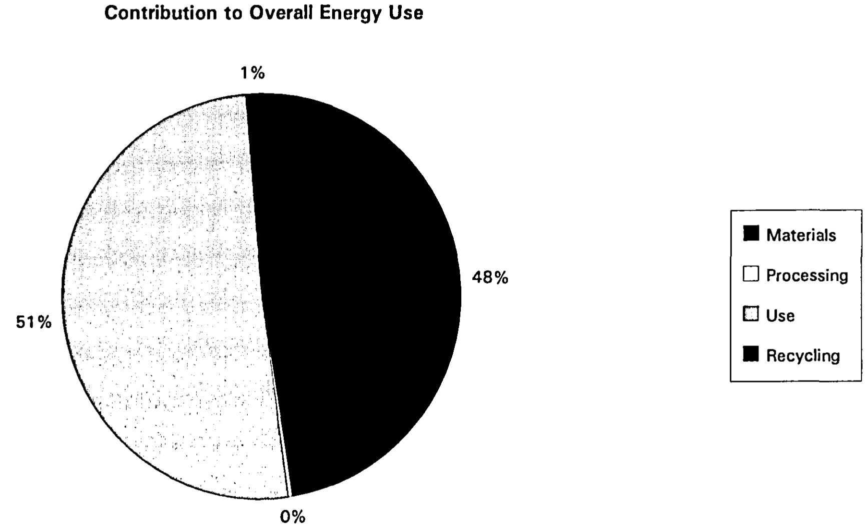
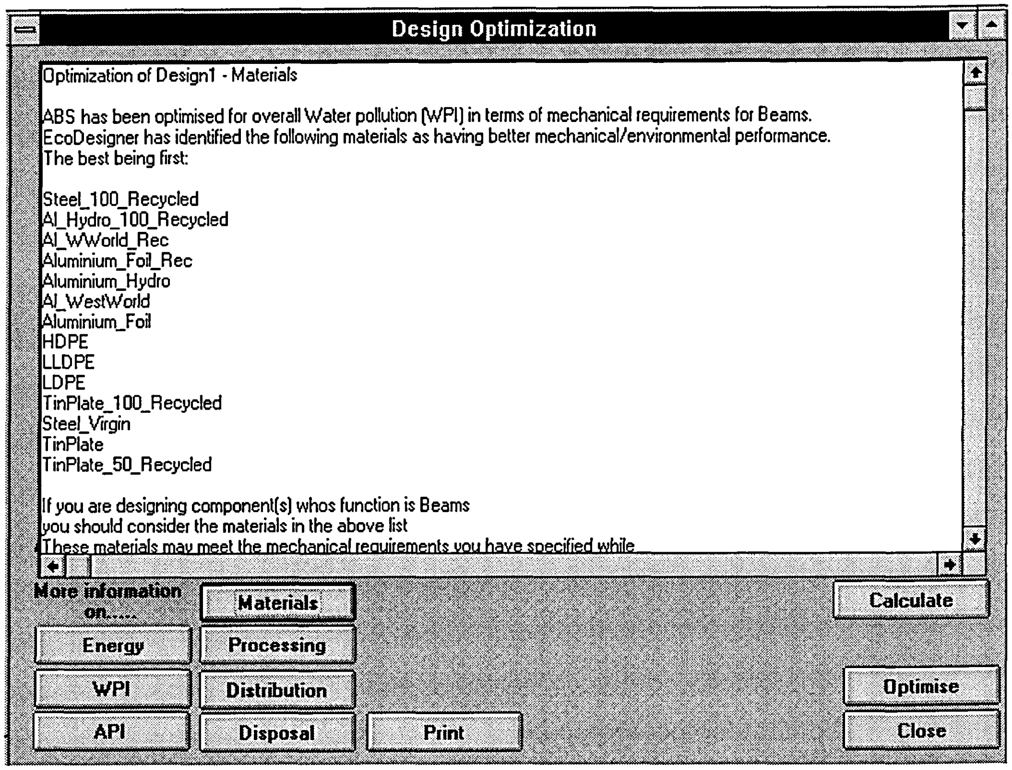


Figure B.24 Computer Generated Chart Showing Contribution of Different Life-Cycle Stages to Overall Energy Usage



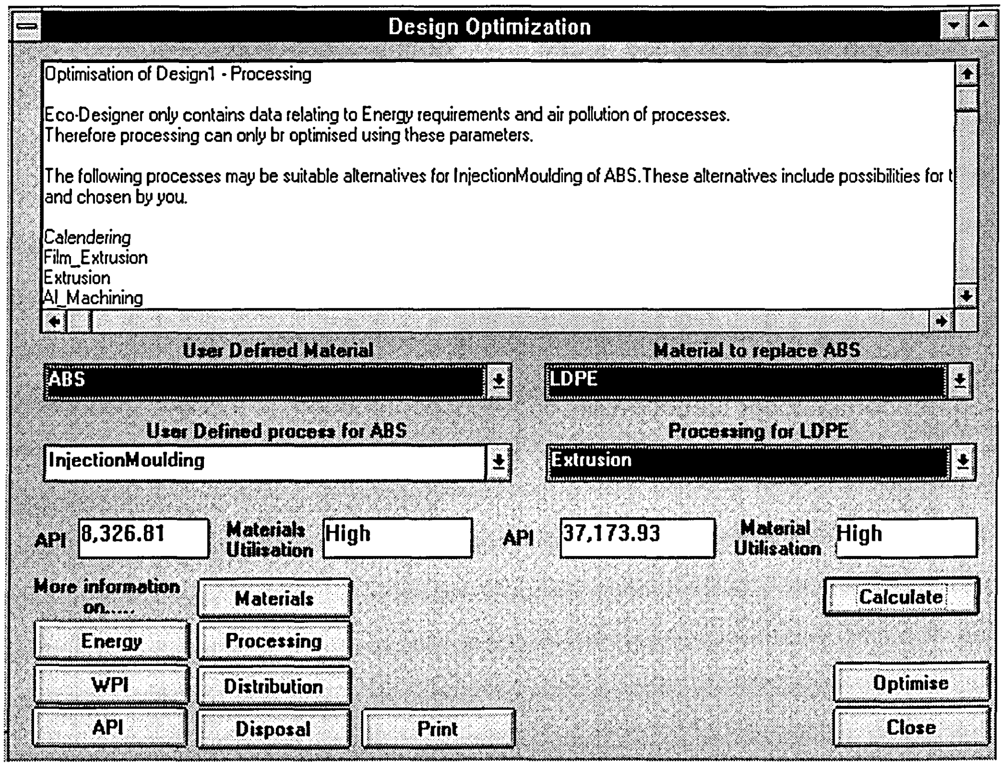
Optimization of Design1 - Materials

ABS has been optimised for overall Water pollution (WPI) in terms of mechanical requirements for Beams.
EcoDesigner has identified the following materials as having better mechanical/environmental performance.
The best being first:

Steel_100_Recycled
Al_Hydro_100_Recycled
Al_WWorld_Rec
Aluminium_Foil_Rec
Aluminium_Hydro
Al_WestWorld
Aluminium_Foil
HDPE
LLDPE
LDPE
TinPlate_100_Recycled
Steel_Virgin
TinPlate
TinPlate_50_Recycled

If you are designing component(s) whos function is Beams
you should consider the materials in the above list
These materials may meet the mechanical requirements you have specified while

Figure B.25 Computer Generated Materials Optimisation Advice



Optimisation of Design1 - Processing

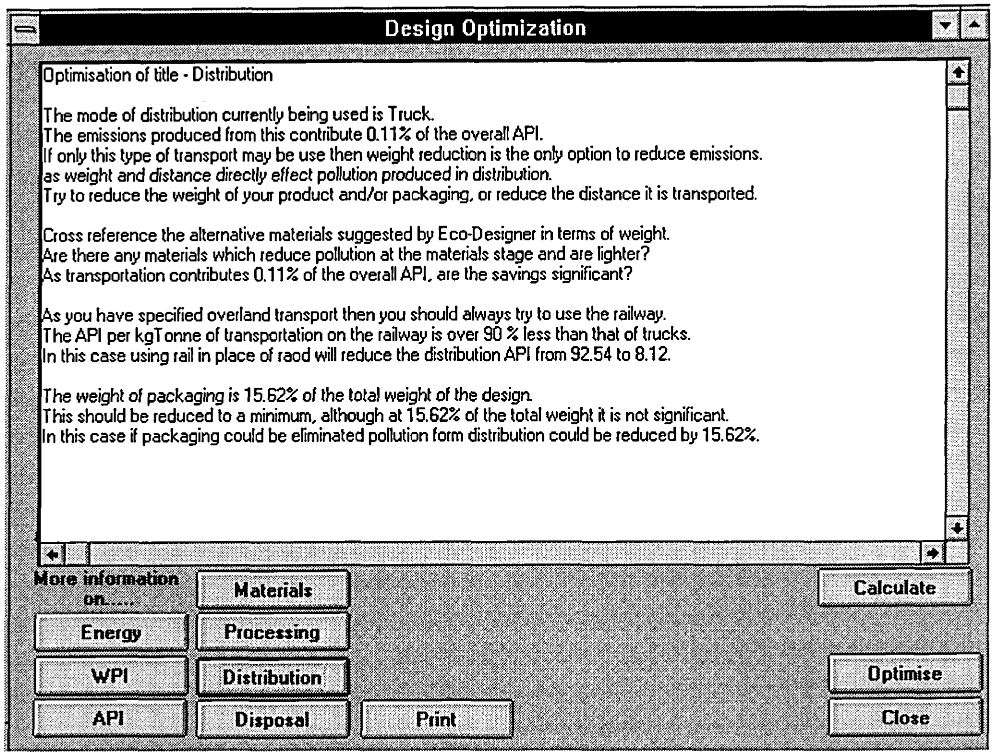
Eco-Designer only contains data relating to Energy requirements and air pollution of processes.
Therefore processing can only br optimised using these parameters.

The following processes may be suitable alternatives for InjectionMoulding of ABS.These alternatives include possibilities for t
and chosen by you.

Calendering
Film_Extrusion
Extrusion
Al_Machining

User Defined Material: ABS
Material to replace ABS: LDPE
User Defined process for ABS: InjectionMoulding
Processing for LDPE: Extrusion
API: 8,326.81
Materials Utilisation: High
API: 37,173.93
Material Utilisation: High

Figure B.26 Computer Generated Process Optimisation Advice



Optimisation of title - Distribution

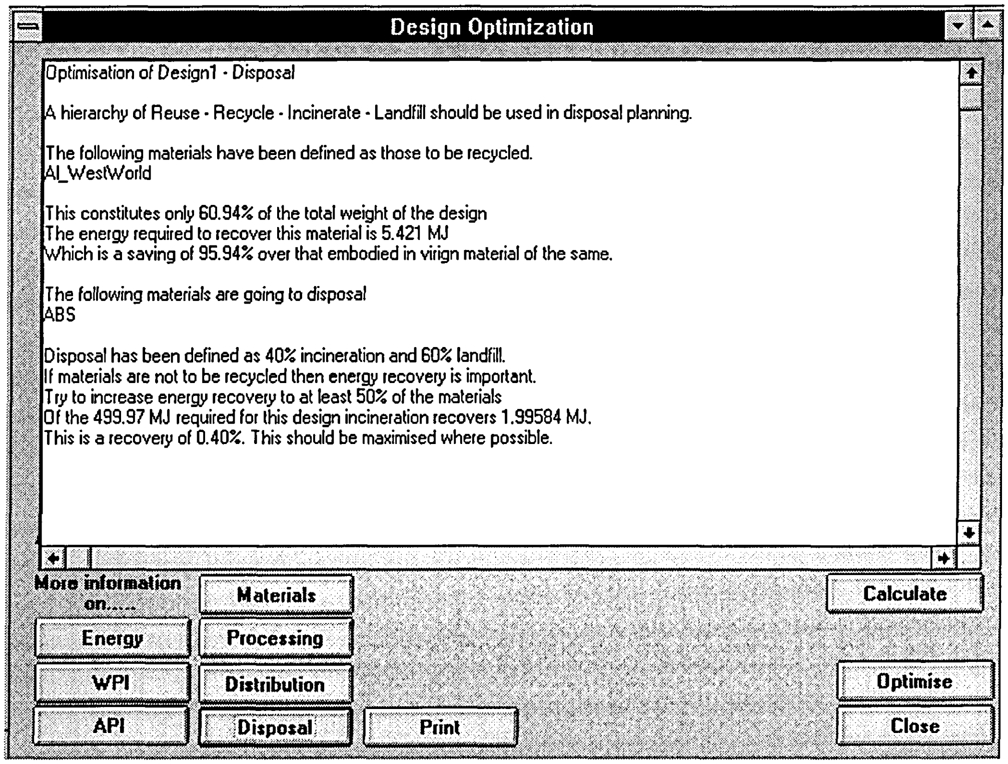
The mode of distribution currently being used is Truck.
The emissions produced from this contribute 0.11% of the overall API.
If only this type of transport may be use then weight reduction is the only option to reduce emissions.
as weight and distance directly effect pollution produced in distribution.
Try to reduce the weight of your product and/or packaging, or reduce the distance it is transported.

Cross reference the alternative materials suggested by Eco-Designer in terms of weight.
Are there any materials which reduce pollution at the materials stage and are lighter?
As transportation contributes 0.11% of the overall API, are the savings significant?

As you have specified overland transport then you should always try to use the railway.
The API per kgTonne of transportation on the railway is over 90 % less than that of trucks.
In this case using rail in place of raod will reduce the distribution API from 92.54 to 8.12.

The weight of packaging is 15.62% of the total weight of the design.
This should be reduced to a minimum, although at 15.62% of the total weight it is not significant.
In this case if packaging could be eliminated pollution form distribution could be reduced by 15.62%.

Figure B.27 Computer Generated Distribution Optimisation Advice



Optimisation of Design1 - Disposal

A hierarchy of Reuse - Recycle - Incinerate - Landfill should be used in disposal planning.

The following materials have been defined as those to be recycled.
Al_WestWorld

This constitutes only 60.94% of the total weight of the design
The energy required to recover this material is 5.421 MJ
Which is a saving of 95.94% over that embodied in virign material of the same.

The following materials are going to disposal
ABS

Disposal has been defined as 40% incineration and 60% landfill.
If materials are not to be recycled then energy recovery is important.
Try to increase energy recovery to at least 50% of the materials
Of the 499.97 MJ required for this design incineration recovers 1.99584 MJ.
This is a recovery of 0.40%. This should be maximised where possible.

Figure B.28 Computer Generated Disposal Optimisation Advice

Appendix C

Validation Survey of Design Method

Appendix C (i)

Documents Mailed out for Validation Exercise

School of Engineering
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Pond Street
Sheffield
S1 1WB

16/12/96

To whom it may concern

I am currently writing up my PhD in Design for Environment. I have developed a new methodology for helping designers develop pertinent DFE strategies for their products, and need designers to test it. I have enclosed three documents which explain how to use the methodology and would be very grateful if you could spare some time to take part in a test.

The basic procedure is to take a product of your choice and describe it in terms of the product descriptors discussed in the explanation. (see Table 4 - Washing Machinc example) Using the information in the A3 matrix (Table 3) complete the smaller A4 matrix. Then use this information to develop a DFE strategy for your product. The strategy developed for the washing machine is on the reverse of Table 4.

Please find enclosed 5 documents:

1. A piece entitled DFE Strategy Matrix
2. An A3 sheet - Table 3 (the DFE strategy guidance matrix)
3. A blank A4 DFE Strategy matrix
4. An A4 sheet - Table 4 (an example of a completed DFE Strategy Matrix)
5. A questionnaire and feedback form.

Please return the completed matrix and questionnaire to the above address.

Thank you for your time and co-operation

Leigh Holloway

DFE Strategy Matrix

Product Classification

It has been shown that there are 5 main stages in a products life-cycle which need to be considered and will effect the different types of environmental design strategies adopted. In developing a system of product classification it is necessary to consider what characteristics of a product will effect the impact it has on the environment at each life-cycle stage.
Although each of the characteristic will have a complex and interrelated effect with others, as a result of this research at this stage we can say that the following six can be used to describe any product:

- Life-cycle length
- Energy consumption
- Resource consumption
- Material requirement
- Configuration
- Disposal route

It can be seen that each of these six considerations will effect the design considerations for each of the life-cycle stages.

Life-cycle Length

Life-cycle length will have perhaps the most profound effect of the adoption of environmental design strategies. The length of the overall life cycle will change the context of all other decisions and the emphasis on the specific environmental impact of each life-cycle stage of a

product. For example in long life-cycle products the use stage may have the highest environmental impact if energy or resources are consumed as part of this use. Shorter life-cycle products may have their highest environmental impact in production or disposal.

Energy Consumption

Products may be classified as either energy consuming or non-energy consuming. This classification refers to whether the actual use of a product consumes any energy. For example products using electricity will be energy consuming products. Products using batteries or power cells will also be energy consuming as will products using solar power, etc. Each of these different types of energy consumption will require different considerations in environmental design as they will have widely differing environmental impacts.

Resource Consumption

The consumption of resources in use by a product is another classification parameter which needs to be considered in environmental design. The use of resources will affect the environment in a number of ways. It may be depletion of non-renewable resources or it may be pollution resulting from the use of resources e.g. using fossil fuels or chemicals. Either way the type and pattern of resource usage will dictate which environmental design strategies are applicable. Products may be classified as either resource consuming or non-resource consuming.

Material Requirement

Material requirement may result in some of the most complex environmental effects in any product or system. It can affect the environmental impact in a number of ways and many of the strategies to counter these effects will be generic to all types of products. In this system of classification the most important factor is the number of materials used in a product. A product can be classed a single material or multi-material. Single materials may be fixed together as separate parts which will dictate certain environmental design considerations and strategies being adopted. Multi-material products will have environmental effects which may result in the re-consideration of processing routes, disposal practices, assembly and disassembly and so on.

Types of materials used may also effect the overall weight or size of a product. This will have connotations in terms of transportation and distributional effects.

Configuration

Products come in many different configurations but at the simplest level may be described as either single part or multi-part. This will have a number of effects on other considerations such as material requirement and processing etc. Strategies such as reducing the overall number of parts may be appropriate. Other effects may be countered by the use or serviceable of replaceable parts in multi-part products.

Disposal Route

Different types of products will be likely to be disposed of in different ways. Packaging, for example, will either be recycled (either consumer or municipal separation), incinerated with waste to produce power, or sent to landfill. Other products such as electrical and electronic items with either be dumped in landfill or dismantled and then disposed of through recycling, reuse or landfill. It is these different disposal characteristics which need to be taken into consideration when applying environmental design strategies.

This characteristic is one of the most difficult to define as it will, in most cases, be a prediction. Current disposal practices may change and therefore alter the characteristics of a product in terms of disposal. At this time the most appropriate way to classify products in terms of disposal is either returnable or non-returnable. Based on current disposal practices the designer must decide whether the product is likely to be returned in some form for, recycling, refurbishment etc. or whether the product will be sent into the normal waste stream. It should be remembered, however, that some waste streams are routinely separated and recycling takes place. This will be dependant on local authority practices and designers should attempt to include these factors in their decision making process.

Generic Concerns

Although product classification will effect environmental design strategies in a number of ways there will always be generic concerns which may be applied to all classes of products.

These generic concerns can be drawn from each of the five stages of the product life cycle and are summarised in table 1.

By using the classification system described, areas for application of generics may also be identified. It is a case of balancing the potential benefits of their application. It may be better to apply a specific strategy which does not allow the application of generics if the environmental gains of applying that specific strategy are higher.

Product Life-cycle Stage	Generic environmental design Strategies
Resource Consumption	Pollution reduction Waste reduction Consumption reduction Material substitution
Production/Processing	Minimise materials use Reduce energy consumption Minimise processing emissions and waste
Distribution	Weight reduction Size reduction Packaging design Localisation
Use	Minimise resource consumption Minimise energy use Alternative 'clean' or renewable energy and resources
Disposal	Reduce waste generated Minimise or eliminate the use of harmful substances 'Design for disposal'

Table C.1 Generic environmental design Strategies

A New Environmental Design Matrix

This research has developed a new environmental design matrix called an Environmental Design Strategy Matrix. (EDSM), shown in figure 1. The matrix is used to highlight areas of environmental concern and develop overall environmental design strategies in terms of a hierarchy of DFX steps or general environmental design guidelines.

The product in question is described using the product classification descriptors (PCDs) discussed earlier. Each cell in the matrix, when completed, will contain information about the type of strategy(s) that may be adopted to allow a pertinent environmental design exercise to be carried out on the product in question. The one parameter which is not included in the matrix is life-cycle length. As discussed earlier life-cycle length will have a profound effect on the type of environmental design strategies adopted in the deign exercise.

Product Description:					
	Energy	Resource	Configuration	Materials	Disposal
Resource					
Production					
Distribution					
Use					
Disposal					

Figure C.1 Environmental Design Strategy Matrix

As a product is either long or short life-cycle it is not necessary to include it in the matrix. The effects of this characteristic will become apparent, implicitly, through the environmental design strategy generated by use of the matrix.

Completing the Environmental Design Strategy Matrix

In order to complete most environmental design matrices a degree of appreciation of environmental problems and knowledge of relevant and appropriate questions is needed. In many cases designers do not have this specialist knowledge and need a system which will highlight certain areas of concern. If such a system is developed in the correct manner it will be generic and applicable to all different products. Although each product is different and will have differing environmental characteristics and associated problems, if the correct questions are asked and areas of concern highlighted then an appropriate environmental design strategy may be developed.

Table 3 contains this information and is called the Environmental Design Strategy Guidance Matrix.

The first step in using the Matrix is to define the product in question in terms of the PCDs discussed earlier.

Product Classification Descriptions

To illustrate the use of the system of product classification, and how designers may describe products in terms of the parameters required for the Environmental Design Strategy Matrix (EDSM), the following are example descriptions of everyday products. These are described using the product classification parameters developed.

Washing Machines

Washing machines have a number of specific characteristics which describe there form and function. They consume electricity, water and detergent as part of their use. They are manufactured from a number of different materials and are made up of a large number of separate parts arranged in a specific manner. They have a long life-cycle of up to ten years and are not readily disposed of. They are usually dumped at municipal waste collection sites. (This is based on current disposal practices)

EDSM Descriptor:

Long life-cycle, energy and resource consuming, multi-part, multi-material, non-returnable.

Chair

A chair consumes no energy or resources as a direct result of its use. Most chairs are made of more than one material or part, but in certain cases this may not be true. As with washing machines chairs do not enter the waste system on as regular basis as other waste and therefore tend not to be recycled or recovered at the present time.

EDSM Descriptor:

Long life-cycle, non energy or resource consuming, multi-part, multi-material, non-returnable.

Stapler

Staplers usually have a long life of a number of years and in that time consume resources in the form of staples. Energy is not consumed as a direct result of their utilisation. In most cases they are now made of a mixture of metal and plastic and are not readily collected or recycled in the current waste collection and disposal system.
EDSM Descriptor:
Long life-cycle, non energy consuming, resource consuming, multi-part, multi-material, non returnable.

Cardboard Box (Packaging)

Although packaging is not always seen as a product in itself it is just that. It performs a number of function including advertising and protection of the contents. A cardboard box, probably the most common form of packaging, will have a very short life-cycle. No energy or resources are consumed as a direct result of its function and it will, in the majority of cases be made form a single part and type of material. Such a product is much more likely to be returned for recycling through either the normal waste stream or through special recycling collection points situated near supermarkets and shopping centres.
EDSM Descriptor:
Short life-cycle, non energy or resource consuming, single material and part, returnable.

The Environmental Design Strategy Guidance Matrix

In order to complete the Environmental Design Strategy Matrix the designer must us the Guidance Matrix. Use of the Guidance Matrix will guide the designer through the appropriate considerations and questions which need to be raised. Each cell in the Guidance Matrix contains information relating to a specific product characteristic and the effects it may have on a specific part of the overall product life-cycle. For example the energy consumption characteristic of a product may be related to, or affected by, materials selection. The way in which it effects the materials selection depends upon whether the product is energy or non-energy consuming and whether it has a long or short life-cycle (as well as more specific effects which are detailed within the appropriate cells).
Using the EDSM descriptor, e.g. Long Life-cycle, non energy or resource consuming, multi part, single material, returnable, the designer selects the appropriate cells from the Guidance Matrix and uses the information, questions and advice within them to assess what the environmental concerns for each parameter/life-cycle stage combination are, and which strategies may be adopted to address these concerns. As the information form the guidance matrix is used the answers, guidelines and any notes appropriate should be placed in the appropriate cells in the Strategy Matrix. For example a resource consuming short life-cycle product has specific cells within the Strategy Guidance Matrix for each of the five life-cycle stages which will be mapped onto the resources column of the smaller Strategy Matrix.

It should be noted that the Guidance Matrix was designed to be as generic as possible and therefore be applicable to any product described using the appropriate descriptors. It is essential that when completing the matrix, at all times the designer keeps in mind the actual product in question. Much of the advice given and many of the questions asked will require the designer to take into consideration product specific characteristics.
Once the matrix is complete then the designer must study each cell. If the cell contains advice to apply generic strategies only, or the answers to the questions within the cells are negative

then these cells may be crossed off. If the cells contains information which says there is no environmental effect then these cells may be crossed off also.
Now the remaining cells should be studied in detail to develop the environmental design strategy for the product in question.

Developing the Environmental Design Strategy form the EDSM

The designer should now be faced with a completed 5 x 5 matrix. Some of the cells will have been crossed off and the remaining cells contain the information, questions and advice which will be used to develop the environmental design strategy for the product in question.
The next stage is for the designer to go through the matrix and attempt to pick out important issues or common themes contained within the cells. The designer may wish to highlight the most important cells and group like cells by coloured borders or a similar system.
Once the common themes have been identified then the documentation of the strategy may begin.
The first and most important environmental design strategy will be either the one which is highlighted as this in the matrix, or the theme which occurs in the most number of cells. The environmental design strategy for the product should be documented in a 'top down' manner where the most important strategy is put at the top of the list and so on down to themes which may only occur once within the whole matrix.

As each of the cells is considered within the matrix it should be marked in some way to indicate this. This will prevent mistakes being made and the cell being considered more than once or not at all.
Finally the designer should study the environmental design strategy developed using the matrix and decide whether it is a sensible strategy for the product. If the strategy seems completely inappropriate then the matrix should be checked again. In some cases if the product has not been described correctly using the product classification descriptors then the strategy developed may be inappropriate. This in itself forms an iterative system of checking the product description is appropriate.
If the description is shown to be incorrect or inappropriate, a new descriptor should be developed using the parameters and the matrix re-written.

Parameter Class	L-C Stage / Life-Cycle	A - Materials & Resources	B - Processing	C - Distribution	D - Use	E - Retirement or Disposal
		By using different types of materials and resources the E.I. of a product may be altered. GENERIC STRATEGIES: Minimise Material consumption Minimise Pollution & Waste (Material Substitution)	Processing and produciton requirements can effect the E.I. of a product. GENERIC STRATEGIES: Minimise Material used Minimise Energy consumption Minimise Waste	Distribution and Collection of products will effect the E.I. GENERIC STRATEGIES: Weight Reduction Size Reduction Minimise Packaging	Decisions made about the product in terms of energy & resource consumption. Questions may be asked about use patterns. GENERIC STRATEGIES: Minimise resource & energy use Alternative & renewable resources	Disposal options vary widely and have a profound effect on the env. impact of some products. GENERIC STRATEGIES: Waste Reduction Harmful Substance Reduction Recovery
Energy Consuming	SLC	Material choice in this type of product may have a lesser effect on the overall E.I If energy consumption is high Does material choice effect energy consumption? Apply generics.	Production and processing options will not effect the direct energy consumption of a product. Electronics processing? CLEAN UP.	Distribution may cause a considerable E.I. in these products. Every effort should be made to apply generic strategies, also reduce ALL non-essential packaging.	Use of these types of products will contribute to the overall E.I. in differing amounts. Generic strategies should be applied giving consideration to life cycle useage pattern.	Disposal options will have some effect on the E.I. due to energy consumption. Consider transport during disposal activities, also material choice and energy recovery.
	LLC	Matreial choice may effect energy consumption. If so how? Is weight a factor? Mechanical or electrical efficiency? Apply generic strategies	Apply Generics	Distribution will usually be a small contributor to the overall E.I of these products. Apply generic strategies.	In LLC products this is usually the largest contributor to the overall E.I. Apply generics and balance them with material factors (1)A and any other specific factors.	As with SLC products but disposal will have a smaller % contribution to the overall E.I. Consider the possibility of energy recovery, recycling, material choice etc.
Non-Energy Consuming	SLC	Material choice may be a very important factor. As well as generic strategies adopt strategies linked to (4) & (5).	Very important to get the most out of generics.	A large % of overall E.I. may result from distribution. Apply generics and eliminate all non-essential packaging.	Usually very little or no effect on E.I. in terms of energy consumption Apply generic strategies	Apply Generics
	LLC	Material choice decisions as in SLC products should be considered. However in LLC products factors such as quality and durability could be important as they will help to increase the life-cycle.		Distribution may contribute a small amount to the overall E.I. Apply generic strategies. Could packaging be made more functional? E.g. a carry case for the product.	Little or no effect to overall E.I. in terms of energy. Lengthening the life-cycle may be an appropriate strategy. Check issues such as durability with issues in (3)A and (4)A.	
Resource Consuming	SLC	Resource consumption over a small period of time will have smaller effect on the E.I. In most cases it will not be linked to material choice. Materials for resources?	The direct resource consumption of a product will not be affected by the processing or production route used. Apply generics.	Direct resource consumption will not be affected by distribution, Secondary effects from fuel use and packaging are important Apply generics	As with energy consumption resource use differs. Apply generic strategies taking into account the life-cyle length and pattern of use. and type of resource	Disposal will have little overall effect in terms of resource consumption. However strategies such as recycling, reuse and disassembly may be adopted to reduce overall consumption.
	LLC	Resource consumption should be reduced to a minimum. Questions should be asked about material choice and it's effects. May be negligable in most cases. Materials for resources?	Apply Generics	Apply Generics Check with weight/size /packaging	Resource consumption may be the largest contributor to the E.I. Consider generic strategies but also look at alternative or renewable resources.	As more resources are usually consumed by LLC products, recovery is important. Balance recycling or material and energy recovery with material chocies etc.
Non-Resource Cons.	SLC	Very little effect in the majority of cases. Apply generic strategies. Materials for resources?			Little or no effect on E.I. in terms of resources Apply generic strategies	Disposal options will have relatively little effect on this class of product. Apply Generics
	LLC	Very little effect overall More important in LLC products Important to apply generics			Little or no effect on E.I. Use generic considerations and considerations raised in Materials & Resource usage (1) for non-energy consuming LLC products.	
Multi-Part	SLC	Material choice in multi-part products will affect many other design goals and stategies. Some closely linked with (4) & (5). Increase the compatability of parts, materials etc.	Some processing parameters will affect the overall E.I. in multi-part products. Design for Assembly, disassembly and also testablility should be considered.	The number of parts will not affect, or be effected by, distribution. Are parts being made in different locations? Apply Generics	Useage has little effect on the number of parts used. Servicing and replacement of parts may be considered.	Multi-part products will have specific problems in disposal. Strategies to be considered are; disassembly & recycling etc. Design for refurbishment and servicing should also be explored.
	LLC	Considerations as with SLC products. Again questions about durability should be asked. Durability questions will affect material choice.	As with SLC products factors such as assembly & disassembly should be considered. This may affect material choices fixings, bonding etc.		Apply Generics Replaceable/servicable parts in Multi-part?	As with SLC design strategies such as disassembly, recycling and reuse should be considered. It is important to balance these strategies with those used in Materials (4) & Disposal (5).
Single Part	SLC	Very important to choose the correct materials. Use generic strategies and where applicable use miniturisation. Balance with decisions in (4) & (5).	Apply generic strategies. Can preformed parts be used to reduce enrgy consumptiion and waste. Near net processing for complex shapes? Balance with (4) & (5).			Single part products make the consideration of disposal options much simpler. Apply generic strategies. Biodegradability / Recovery Apply Generics
	LLC	Issues such as compatability of materials is not important. Make sure material meets general requirements and is of suitable quality and durability.	As with SLC products a balance should be achieved. Is durability an issue? The balance with (4) & (5) may not be as important as with SLC products.			
Multi-Material	SLC	Generic strategies are applicable but should be balanced with decisions on compatability, contamination etc. which effect (5). Design for recycling, disassembly etc.	Some processing operations may bond different materials together making disposal (5) difficult. Fixings? Attempt to use compatible materials & balance with (3).	The actual number of materials used will not be effected by distribution activities. Types of materials used and the amounts used may be important Volume/weight.	Multipe material choices are not affected to any great extent by use.	Multi-material products will have complex disposal effects. Many different strategies should be considered such as; material compatability, fixing and bonding, general disassembly rules etc.
	LLC	Decisions as with SLC products should be made. Also factors such as quality and durability should be taken into account.	Similar decisions to SLC products should be made, taking into the durability of the processed material/product. Are processing effects appropriate to life-cycle of product?	Sources of materials? Apply Generics	As with SLC products use does not effect choices of different materials. Balance against issues raised in Materials (1)A and ensure material meets mech. requirements.	As with SLC products but overall % contribution to E.I. may be less. Balance with choices made in Materilas/Resource Usage (4)A and Processing & Production (4)E.
Single Material	SLC	Material effects may be a large contributor to the overall E.I. The main generic strategies should be balanced against disposal facotrs in (5). Especially if non-energy consuming	Processing can have a large E.I. in this type of product. Balance generic strategies with appropriate issues in (3) & (4) Very important in energy/resource consuming products		Use of certain materials may effect use and E.I. if the product consumes energy. Balance choices with Materials (1)A and apply generics.	With single material products strategies will tend to be generic. Strategies such as energy recovery and recycling etc. should also be considered.
	LLC	Material consideration are again important as they may have a large E.I. In LLC products durability is an important consideration.	The % of the overall E.I. will usually be less in LLC products. especially if they consume energy or resources Apply generics and balance with (3) & (5).		The issues here are similar to those raised in SLC products. They may have more importance. Apply generics where possible, Check mechanical/environmental issues etc.	In non-energy consuming LLC products disposal strategies should be as SLC products. Energy consuming products may have a lower % contribution to E.I. in this stage, consider all strategies.
Returnable	SLC	Returnable SLC products such as bottles have specific E.I. linked to material choice. Decisions on reuse, recycling etc. should be balanced with generics.	Processing will have little effect unless it involves the bonding of materials If so consider disassembly recycling and refurbishment.	Distribution of returnable products includes collection at end-of-life. Generics are very important as they effect more than one journey	Some usage issues may be affected by disposal practices. Apply generics where possible and balance with issues such as material/disposal factors.	Large env. effects are possible If product is returnable then use a hierarchy of reuse, reprocess, recycle. Choice of strategies should balance with materials, parts etc.
	LLC	Althought the same factors as SLC products should be considered, they may not be as important in the case of energy consuming LLC products.	Apply Generics	Less % contribution to E.I. than in SLC products (usually). Application of generic strategies will help reduce the E.I. especially in energy or resource consuming products.	No real effect on use related design strategies. Increasing the life-cycle and therefore use period may be appropriate. Consider Material (1).	This stage will have a smaller overall % contribution to E.I. in energy/resource consuming products. Consider the hierarchy of reuse, reprocessing then recycling.
Non-Returnable	SLC	Many factors here are affected by material choice; disassembly recycling, incineration, landfill etc. Consider bio-degradabilty and energy content. Balance with (3)&(4).		Non-returnables will be collected for disposal and therefore applying generics will help in both distribution and collection.	Apply generic use related strategies. Minimisation of materials / resource / energy consumption is important	This stage will usually contribute a considerable amount to the overall E.I. of the product. Apply generics and balance them with disposal options such as landfill, incineration & recycling.
	LLC	Consider material choice with respect to disassembly, recycling, landfill etc. Consideration to energy/resource consuming LLC products (1) & (2) must be given,		The same issues as in SLC non-returnable products apply. If possible apply generic strategies.	Apply generic use related strategies. Increase life-cycle? Check against material choice as well as energy/resource consumption.	Smaller contribution to overall E.I. especially in energy/resource consuming products. Opportunity to apply strategies as in SLC products, other considerations?

Product: **Description:**

	Energy	**Resources**	**Configuration**	**Materials**	**Disposal**
Materials					
Processing					
Distribution					
Use					
Disposal					

Table C.3 Blank A4 DFE Strategy Matrix

Product: *Washing Machine* **Description:** *LLC, energy and resource consuming, multi-part/material, non-returnable*

	Energy	**Resources**	**Configuration**	**Materials**	**Disposal**
Materials	Material choice can affect energy consumption. Does it do this ? **NO**	Resource consumption should be reduced to a minimum. Reduce water, electricity and detergent consumption.	Compatability of parts? Reduce number of parts. Durability DFD, DFR?	Apply Generics	DFR, DFD? Balance with enegy and resource consumption.
Processing	Apply Generics	Apply Generics	DFA, DFD Testability Fixings?	Use compatible materials. Blance with proces, assembly, disposal options. Life-cycle requirements-durability?	DFD, DFR Energy Balance? Refurbishment?
Distribution	Apply generics Very heavy so distribution can affect EI greatly.	Weight Packaging?	No effect Apply Generics	No effect Apply Generics Balance with energy/materials	No effect Apply Generics
Use	Largest EI. Reduce enrgy consumption	Very large EI. Reduce water consumplton. Increase efficiency?	Apply Generics	Apply Generics Durability and quality forLLC products?	Increase life-cycle. Technological advances?
Disposal	Apply Generics Energy balance with use/disposal?	Recovery of resources important in LLC products.	DFD, DFR Refurbishment?	Less of an EI here but balance should be made betwwen material use and processing techniques.	Smaller EI in this stage. Apply Generics. Energy/resource consumption issues more important

Table C.4.Washing Machine Example of EDSM

DFE Matrix Feedback Form

Name (optional): **Current Position:**

Position held previously

Please elaborate where appropriate

Do you think the concept of the matrix is a good one?

Was the matrix easy to use or where there any problems?

Was the system of product description appropriate?

Did it allow you to develop a DFE strategy which seems appropriate to the product you chose?

Where there any problems in completing the matrix or developing the strategy from the matrix?

Did this method help you focus on the important DFE issues?

Did using the matrix bring up considerations you had not thought of previously?

Did the matrix help you focus or structure this form of DFE?

Are there any additions you would like to see to this method?

Please give any general comments you feel may be appropriate.

Appendix C (ii)

Completed Design Matrices and Developed Strategies

Product: *Cutlery(metal)* **Description:** *LLC, Energy Consuming, Resource Consuming, Single Part, Multi Material, Returnable*

	Energy	Resources	Configuration	Materials	Disposal
Materials	Materials use energy through cleaning. Cut down on cleaning, how? Clean Materials?	Materials use resources. Water/detergent	Generic Design for quality Design for durability	Contamination Compatibility Design for quality Design for durability	Reuse? (Inherent) Recycling?
Processing	Generics	Generics	Generics	Generics	Generics
Distribution	Generics Packaging?	Quality of packaging? Functionality	Generics	Generics	Generics
Use	Energy Same as materials and energy (above)	As materials and resources (above)	Generics	As in materials and resources and materials and energy (above)	Design for quality Reuse? Increase Lifer-cycle?
Disposal	Generic Recovery?	Recovery?	Recycling?	Generics Contamination?	Reuse? Recycle? Reprocessing?

Figure C.1 EDSM for Cutlery

Product: *Packaging for Milk* **Description:** *Short life-cycle, non- energy consuming non-resource consuming, minimal-part, single-material, returnable*

	Energy	**Resources**	**Configuration**	**Materials**	**Disposal**
Materials	Material choice doesn't effect energy consumption. Disposability?	Apply Generics	Increase compatibility of materials.	Design for separation	Reuse / Recycling Material choice
Processing	Apply Generics	Apply Generics	N/A	N/A	N/A
Distribution	Reduce weight Reduce size	Apply Generics Check weight, size and packaging	Number of parts does not effect distribution	Look at size and weight	Weight and size
Use	Apply generics	Apply generics	N/A	N/A	Minimise materials Increase disposability
Disposal	pply generics educe waste	Apply generics Reduce waste	Look at separation and recovery issues	Separation needs to be considered	Could it be reused? Could it be reprocessed? Could it be recycled?

Figure C.2 EDSM for Milk Packaging

Product: *Electric Vehicle* **Description:** *LLC, Energy Consuming, non-resource consuming, Multi-part, multi-material, non-returnable*

	Energy	Resources	Configuration	Materials	Disposal
Materials	Mass is a factor Lower mass means lower energy consumption Use light weight materials.	Non consuming so materials cannot affect consumption of resources. Apply generics	Select materials where by parts will either last or be easily replaced. Design so that parts do not need replacing often but can be replaced easily	Materials should be durable but non - contaminating. By DFD, DFR you can aid disposal. DFM can cut machining & assembly costs.	Small factor. More attention should be given to energy and resources.
Processing	Apply Generics	Apply Generics	The way the product is put together can affect whether the parts are replaceable and recycling. Disassembly	Use materials easy to manufacture. Reduce energy. Use process that enhance durability, strength.	Apply generics
Distribution	Apply Generics	Apply Generics	Apply Generics	Lightweight materials to reduce transport effect. These are low due to low volume.	Use generics. Non- returnable products may be badly disposed of.
Use	Highly important. Reduce weight Apply generics	Durable parts reduce resources consumed. But as it is essentially non-consuming this is a small factor.	Apply Generics	Material must be up to job. Materials must be light and clean.	Increase life-cycle to postpone disposal. Does this affects energy/resource consumption. As well as material choice.
Disposal	Work at recovering energy. Which designs are more energy efficient to dispose?	Apply Generics	DFR, DFD Use replaceable parts to extent life-cycle. Balance with materials and disposal	Materials need to be easily broken down, but still strong and processed.	Long life-cycle low environmental impact. Try to apply generics.

Figure C.3 EDSM for Electric Vehicle

Product: *Electric Vehicle Chassis* **Description:** *LLC, energy consuming, non-resource consuming, single part multi-material non-returnable*

	Energy	**Resources**	**Configuration**	**Materials**	**Disposal**
Materials	Weight is a factor. The lighter the chassis the energy consumed. Apply Generics	Lighter materials	Material to be repaired, durability. Must last long because effects the vehicle.	Quality Durability	Disassembly Recycling Landfill? Consideration to energy recovery.
Processing	Process and production req. minimise material used. Minimise energy consumed Minimise waste.	Apply Generics	Apply Generics	Processing. Makes durability of product?	Apply Generics
Distribution	Apply Generics	Apply Generics Weight, size, packaging	Apply Generics	Apply Generics	Apply Generics
Use	Weight of materials	Apply Generics	Apply Generics	Material meets mechanical requirements where possible?	Apply Generics
Disposal	Energy recovery Recycling Material choice	Apply Generics	Apply Generics	Apply Generics	Smaller contribution to overall environmental impact. Apply Generics Landfill, incineration, recycling.

Figure C.4 EDSM for Chassis of Electric Vehicles

Product: *Clothes Iron* **Description:** *LLC, energy consuming, non-resource consuming, multi-material, multi-part, non-returnable*

	Energy	Resources	Configuration	Materials	Disposal
Materials	Apply Generics New materials /components for better efficiency in use.	Apply Generics No major impact	Use robust construction for long life.	Strong materials for long life	Value / ease of material recovery?
Processing	Apply Generics No major impact	Apply generics No major impact	Design for disassembly. Design for recycling or replaceable components.	Assembly / disassembly considerations	Already has long life-cycle. Technical / efficiency improvements are reason for disposal usually.
Distribution	Apply Generics No major impact	Apply Generics No major impact	No major impact	Apply generics Lighter materials will minimise transportation impact.	Local distribution and servicing will minimise environmental impact.
Use	Major factor in environmental impact. Energy consumption should be reduced.	High energy consumption in use.	Design for disassembly for easy recovery/ renewing of components. Recovery of materials	Robust Construction	Apply Generics
Disposal	Recycling materials will minimise environmental impact	Apply Generics	Design for disassembly	Design for disassembly. No composites	Long life-cycle with renewable components. major advantages but low value in recovered materials.

Figure C.5 EDSM for Clothes Iron

Product: *Chair* **Description:** *LLC, non-energy/resource consuming, multi-part, multi-material, non returnable*

	Energy	Resources	Configuration	Materials	Disposal
Materials	Material choice important Design for quality & Durability DFR, DFD, Recovery Increase life-cycle length	N/A	See materials and disposal Compatibility, durability Replacement parts	Quality Durability DFR, DFD	Disassembly Recycling
Processing	N/A	N/A	DFA, DFD Fixings and materials	DFR / DFD Process / life trade off?	Apply Generics
Distribution	Apply Generics	Apply Generics	Apply Generics	Apply Generics	Apply Generics
Use	Increase life Durability	N/A	'Servicing' Replacement parts	N/A	Apply Generics Durability Increase length of life.
Disposal	Apply Generics	Apply Generics	Refurbishment Reuse of parts Disassembly	DFD DFR	DFR

Figure C.6 EDSM for Chair

Product: Televisions **Description:** *Long life-cycle, energy consuming non-resource consuming, multi-part, multi-material, returnable*

	Energy	**Resources**	**Configuration**	**Materials**	**Disposal**
Materials	Material choice may affect energy consumption.	Material choice will not affect resource consumption unless weight dependent.	Material choice will affect many other design goals and strategies. Durability!	Compatibility / contamination. DFD / DFR Quality / Durability	Reuse / Recycling May not be that important.
Processing	Generic	Generic	Consider assembly / disassembly. Consider material choice, fixings etc.	Compatibility Any processing effects appropriate to life-cycle?	Generic
Distribution	Distribution small contributor	Generic	Generic	Generic	Not as important
Use	Probably largest impact Consumption reduction	Little or no effect	Generic	N/A	No real effect Increase life cycle?
Disposal	Small contribution to overall Environmental Impact	Generic	Consider using disassembly, recycling	Less contribution to environmental impact	Smaller overall impact Generics

Figure C.7 EDSM for Television

Product: Electric Vehicle **Description:** *Long life-cycle, energy consuming non-resource consuming, multi-part, multi-material, non-returnable*

	Energy	**Resources**	**Configuration**	**Materials**	**Disposal**
Materials	Weight affects energy consumption. Lighter body / chassis, less energy used.	Apply generics.	Durability of parts. Interchangeable parts between different models. Parts should last the life of the vehicle.	Materials should be recyclable and try to use one material for many parts. Generic strategies.	Consider resources in life.
Processing	Generic	Generic	Consider generic assembly / disassembly.	Do any of the processes change the materials properties / life?	Generic
Distribution	No major part of environmental impact	Generic	N/A	N/A	N/A
Use	Most effect. Recharging of batteries, emissions etc.	Generic (Batteries)	Maintenance, interchange parts.	Are materials capable of the job?	(Batteries?)
Disposal	Recover parts that use energy in manufacture. E.g. Aluminium	Generic	Try to reuse parts. E.g. Wheels.	Try to use materials that are reclaimable	V.small effect.

Figure C.8 EDSM for Electric Vehicle

Product: *35mm Camera* **Description:** *LLC, non-energy consuming, resource consuming, multi-part, multi material, non-returnable*

	Energy	**Resources**	**Configuration**	**Materials**	**Disposal**
Materials	Material choice may effect energy consumption. Is weight an issue? Material substitution / reduction	Resource consumption should be reduced to a minimum. Type of material questioned - generally is the effect on EI.	Material choice effects other material and disposal. Main issue for LLC is durability, maintenance and repair.	Apply generic strategies. Focus on compatibility / contamination issues. Durability and quality to increase life-cycle	Address disassembly and recycling. Weigh up against configuration, energy and resource consumption
Processing	Apply Generics Minimise energy consumption within processing.	Apply generics Reduce resource consumption.	Consider design for assembly and disassembly. Especially reparability and testing	Issues re. material compatibility. Decisions balanced with the durability of the product - i.e. process effect relative to life-cycle length	Disassembly / recycling / refurbishment. Elimination of hazardous materials. Balance with generics
Distribution	Usually a small contributor to overall EI. Apply Generics	Resource consumption - minimal effect. Issue re packaging, is weight an issue.	No effect. Generics where appropriate.	Types and amounts and sources of materials may impact. Minimal	No current impact. Apply generics might be a future issue re. long life-cycle of product.
Use	Major EI contributor. Minimise energy and resource use. Encourage alternative sources / technologies. Consider life-cycle usage pattern.	Indirect major impact (re film & processing) Encourage alternative resource usage. Apply Generics	Not major impact Focus on serviceability, ease of repair. Service issues.	Appropriate materials used for appropriate life-cycle need. Material quality and durability are important.	Delay disposal by increasing life-cycle Balance against energy and resource consumption and material reclamation. (Technological advances)
Disposal	Small effect on overall EI Consider energy recovery Transport impacts and collection..	LLC = greater requirement for resource recovery (or reducing overall resource needed)	Recycling, disassembly, refurbishment, reclamation, re-use. Balance with strategies for materials and disposal.	Minimal EI. Must balance with type (quality?) Material use & processing techniques - effects on life-cycle.	Smaller impact for LLC at the moment. But apply generics - balance with materials hierarchy, energy & resource issues.

Figure C.9 EDSM for 35mm Camera

Product: *Vacuum Cleaner* **Description:** *LLC, energy & resource consuming, multi-part/material, non-returnable*

	Energy	Resources	Configuration	Materials	Disposal
Materials	Material choice may affect energy consumption. Is weight a factor? Use lighter materials	Resource consumption should be kept to a minimum. Question the effect of material choice probably negligible.	Compatibility of parts? Material choice , reduce the number of parts. Can parts be made durable. Balance with disposal	Generics Consider compatibility & contamination. Increase quality and durability of materials.	Consider materials for disassembly, recycling & landfill. Consider energy & resources.
Processing	Apply Generics	Apply Generics	Consider DFE, DFA and testability. Methods of fixing should be investigated.	Use compatible materials & balance processes, assembly with disposal options. Processing appropriate to length of life.	Apply Generics
Distribution	Distribution small EI. Apply Generics	Apply Generics Packaging Weight Size	Number of parts not effected by distribution.	Apply Generics	Non-returnable will be collected. There apply generics for disposal and distribution.
Use	Largest EI. Apply generics & consider materials. Generics - resources, energy (clean and renewable)	May be large EI. Generics Alternative or renewable resources.	No impact Serviceable parts?	Type of material not affected by use.	Apply generics Increasing life-cycle. Check against material choice & energy / resource consumption.
Disposal	Little effect on EI. Energy consumption. Consider energy recovery in disposal and transport.	Recovery of resources important.	Consider general disassembly rules	Balance with materials & resource usage and processing	Smaller EI. Apply generics and balance against disposal options.

Figure C.10 EDSM for Vacuum Cleaner

Product: *Telephone* **Description:** *SLC, non-energy/resource consuming, multi-part, multi-material, non-returnable*

	Energy	**Resources**	**Configuration**	**Materials**	**Disposal**
Materials	N/A	N/A	.Make parts form compatible materials. Reduce number of parts. Make more durable	Consider compatibility Increase durability	Look at disassembly and recycling.
Processing	N/A	N/A	Design for assembly Design for disassembly	Limit use of adhesives Follow DFD principles	Minimise waste
Distribution	Eliminate packaging	N/A	N/A	N/A	N/A
Use	N/A	N/A	N/A	N/A	N/A
Disposal	N/A	N/A	Design for disassembly Look at recycling and reuse etc.	Material compatibility Limit harmful materials Design for disassembly	DFD DRF Balance against incineration, landfill & recycling

Figure C.11 EDSM for Telephone

Product: *Computer System Keyboard* **Description:** *LLC, energy consuming, non-resource consuming, multi-part/material, returnable*

	Energy	Resources	Configuration	Materials	Disposal
Materials	Material choice Weight Apply Generics	Material choice Weight	Compatibility Durability	Compatibility Communication Design for disassembly, recycling, durability Quality	Material choice Reuse, recycling
Processing	Apply Generics (minimise materials and energy waste)	Apply Generics	Material choice Fixing Assembly / Disassembly	Durability Fixing Compatibility Processing effects	Apply Generics
Distribution	Apply Generics (weight & size reduction localisation)	Apply Generics	Apply Generics	Apply Generics	Apply Generics
Use	Apply Generics (minimise resource and energy, alternative and renewable resources)	Apply Generics	Apply Generics Replaced / Service parts	Material choice Mechanical requirements	Materials Life-cycle increase.
Disposal	Energy recovery Material recycling Material choice	Apply Generics (waste reduction, harmful substance reduction, recovery)	Disassembly Recycling Reuse	Material compatibility Fixings Bonding Disassembly	Reuse Reprocess Recycle

Figure C.12 EDSM for Computer System Keyboard

Product: *Telephone* **Description:** *SLC, low energy consuming, resource consuming multi-part/material returnable*

	Energy	**Resources**	**Configuration**	**Materials**	**Disposal**
Materials	Choice of materials could reduce EI. No energy consumption not effected by material choice.	Resource consumption should be minimised. Material choice does not really effect EI.	Material choice would not effect EI. But could effect aspects / options for disposal. Apply Generics	Multi-material - not likely to effect contamination. Could cause recycling problems though.	Material choice will effect disposal / recycling routes. Design for disassembly
Processing	Processing will not effect energy consumption. Apply Generics	Processing will not affect resources to significant extent. Apply Generics	Could effect EI. Design for assembly processes.	Could cause end-of-life difficulties. Fixings / snap fits / adhesives etc.	Bonding and joining methods will affect disposal aspects.
Distribution	Could be the greatest use of energy. Not weight and size particularly but breadth of distribution.	Only fuel and packaging	No effect	No significant effect. (unless extra packaging is required for some materials)	If units returned then this could use lots of energy.
Use	Not significant Energy consumption associated with 'line' rather than product	Not significant	Only servicing	Only cleaning perhaps	Longer use phase may reduce overall EI.
Disposal	Transport - high EI. Energy recovery could be best option.	Would have to balance EI of recycling with EI of getting new materials for new product.	Multi-part could cause problems. Depends on nature of recycling / reuse.	Multi-material could cause problems with recycling, but not with product reuse.	Design for disassembly. Takeback legislation Would need to ensure reuse rather than disposal?

Figure C.13 EDSM for Telephone

Product: *Personal Organiser* **Description:** *SLC, energy consuming, small resource consumption, multi-part/material, non-returnable*

	Energy	Resources	Configuration	Materials	Disposal
Materials	PCB impact could be reduced - smaller PCB. Reduce number and different types of materials. Durability	Battery Rechargeable option Solar best	Reduce number of materials. Too durable? Therefore out of date in 6 months.	Design for recycling and disassembly	Return to recycle
Processing	Apply Generics	Apply Generics	Design for disassembly and recycling	No adhesives Reduce number of materials Material compatibility Card necessary?	Design for disassembly / recycling.
Distribution	Reduce packing Apply Generics	Packaging Apply Generics	No effect Apply Generics	No effect Apply Generics	Collection Design for disassembly / recycling.
Use	Apply Generics	Apply Generics Minimal but product not likely to be used for long. Design for module accommodation?	Minimal Apply Generics	Reduce number of materials Apply Generics	Apply Generics
Disposal	Apply Generics Transport Disposal options Design for disassembly & recycling	Recycle Reuse Design for disassembly / recycling	Reduce number of parts Design for disassembly / recycling	Bonding Recyclability	Reuse cycle Disassembly

Figure C.14 EDSM for Electronic Personal Organiser

Product: *Refrigerator* **Description:** *LLC, energy consuming, non-resource consuming, multi-part/material, non-returnable*

	Energy	**Resources**	**Configuration**	**Materials**	**Disposal**
Materials	Generics Minimise material pollution and waste Material substitution.	Apply Generics	Increase compatibility Choose durable materials	Design for disassembly & recycling Apply Generics	Materials selected with regard to disassembly and recycling.
Processing	Apply Generics Minimise materials / energy / waste.	Apply Generics	Disassembly	Compatible materials Durable materials	Apply Generics
Distribution	Apply Generics Size & weight reduction Reduce packaging Trade offs with durability	Apply Generics	Apply Generics	Apply Generics What about returnable or recyclable packs?	Apply Generics What about returnable or recyclable packs?
Use	Apply Generics Minimise energy use - seek alternative / renewable energy resources. User behaviour?	N/A	Apply Generics	No recommendations in matrix. What about thermal conductivity, insulation etc?	Increase life-cycle! Questionable with compressor efficiency / insulation properties. Key issues subject to technological change
Disposal	Apply Generics Waste reduction Reduce or remove harmful substances.	What about use of recyclable materials?	Disassembly, recycling & reuse What about access to hazardous materials, i.e. CFC / HCFCs etc.	Disassembly considerations apply	Apply Generics Disassembly considerations apply

Figure C.15 EDSM for Refrigerator

DFE Consideration	Strategy
Materials	Cleaning in service/ Use Large EI Change materials to reduce need for cleaning? Ultrasonic / Microwave cleaning?
Life Cycle	Increase life-cycle Achieve this through increased quality Reuse issue? Is this inherent in cutlery?
Disposal	Recycling / recovery of materials?

Table C.1 Environmental Design Strategy for Cuttlery

DFE Consideration	Strategy
Disposability	Separation of lids Design for space saving at recovery stage. Minimise use of material
Materials	Recyclability Bio-degradability? Possibility of integral lids? Alternative seals?
Weight/packaging	Flexible packaging Refillable / Bulk storage at store? Pipe milk to the home!

Table C.2 Environmental Design Strategy for Milk Packaging

DFE Consideration	Strategy
Weight	Reduce weight Reduces energy consumption
Durability	Increase quality and durability Increases life cycle Reduces impact
Service/Disassembly	Ease of maintenance Refurbishment Recycling

Table C.3 Environmental Design Strategy for Electric Vehicle

DFE Consideration	Strategy
Weight	Lighter materials Higher strength to weight ratio
Durability	Mechanical strength Durability
Disposal	Recyclability Disassembly

Table C.4 Environmental Design Strategy for Electric Vehicle Chassis

DFE Consideration	Strategy
Energy consumption	More efficient heating element. Ceramics? Quick to heat up.
Components	Standard components available locally Prolongs life of iron?
Function	Remove the need for ironing in the first place. New materials Clothes that don't need ironing.

Table C.5 Environmental Design Strategy for Clothes Iron

DFE Consideration	Strategy
Durability	Increase durability and length of life Through material choice and design
Servicing	Replacement parts
Disposal	Design for recycling Design for disassembly

Table C.6 Environmental Design Strategy for Chairs

DFE Consideration	Strategy
Disposal	Design for recycling Design for disassembly
Life cycle	Overall Durability Material choice Compatibility
Energy	Reduce energy consumption

Table C.7 Environmental Design Strategy for Television

DFE Consideration	Strategy
Energy Use	Reduce weight Use more efficient batteries recover/recycle parts
Durability, Use etc.	Share common parts Use single materials Ease of servicing Changing of parts
Reuse, Disassemble	Reclaim parts
Battery	Acid / lead problem

Table C.8 Environmental Design Strategy for Electric Vehicle

DFE Consideration	Strategy
Energy /Resource Use	Alternative sources Encourage less film usage Use alternative technology to produce pictures (digital etc.)
Life length	Repair & maintenance Ease of disassembly
Disposal	Material durability compatibility
Distribution	Minimise packaging

Table C.9 Environmental Design Strategy for 35mm Camera

DFE Consideration	**Strategy**
Energy & Resources	Reduce energy and resource usage Electricity, dust bags etc.
Servicing	Design for disassembly Refurbishment Ease of maintenance Increase life-span
Disposal	Make materials compatibly Design for disassembly

Table C.10 Environmental Design Strategy for Vacuum Cleaner

DFE Consideration	**Strategy**
Disposal	Design for disassembly Refurbishment Servicing Compatibility of materials
Life-use	Design for durability (production and parts)
Distribution	Eliminate unnecessary packaging

Table C.11 Environmental Design Strategy for Telephone

DFE Consideration	**Strategy**
Life-Use	Increase useful life Increase durability
Disposal	Design for disassembly Design for recycling Reuse
Materials	Materials selection Compatibility of materials

Table C.12 Environmental Design Strategy for Computer Keyboard

DFE Consideration	Strategy
Disposal	Assembly & disassembly methods Best disposal options
Distribution	Packaging Weight / volume
Materials	Material choice

Table C.13 Environmental Design Strategy for Telephone

DFE Consideration	Strategy
Disposal	Design for disassembly Recyclability Reuse
Configuration	Reduction of number of components / materials Bonding?
Use	Increase useful life Design for module accommodation Quality of function Eliminate battery? (Solar cell)

Table C.14 Environmental Design Strategy for Electronic PersonalOrganiser

DFE Consideration	Strategy
Use	Reduce energy consumption Increase thermal efficiency of materials / design
Disposal	Reduce hazardous materials used in production. Increase recyclability.

Table C.15 Environmental Design Strategy for Refrigerator

Appendix C (iii)

Completed Questionnaires and Analysis of Responses

DFE Matrix Feedback Form - Cutlery

Name (optional):

Current Position: *Design Lecturer*

Position held previously: *Design Engineer*

Please elaborate where appropriate

Do you think the concept of the matrix is a good one?

Excellent method for specifying opportunities, choices and strategies.

Was the matrix easy to use or where there any problems?

After initial training method becomes second nature.

Was the system of product description appropriate?

The framework for product description appears to be a sensible and complete mix of all the possible variables

Did it allow you to develop a DFE strategy which seems appropriate to the product you chose?

Yes.

It produced / identified major areas for consideration which can then be taken forward by conventional design methods, brainstorming etc.

Where there any problems in completing the matrix or developing the strategy from the matrix?

Only initially due to lack of experience.

I particularly picked a problem which would be difficult, and was slightly unsure of. Surprisingly this was easily fitted into the matrix.

Did this method help you focus on the important DFE issues?

Yes

Did using the matrix bring up considerations you had not thought of previously?

It helped identify issues from other fields of engineering which may not have been apparent without the use of the matrix.

Did the matrix help you focus or structure this form of DFE?

Yes.

It produced a structured approach to DFE. Without it the integration of other fields of work may not have been considered.

Are there any additions you would like to see to this method?

I would like to see the method computerised with a good user interface and a large degree of interactivity.

A good tool for innovation.

Please give any general comments you feel may be appropriate.

A computer based system with a good 'help system' would alleviate any problems of cross referencing on the paper based system.

DFE Matrix Feedback Form - Milk Packaging

Name (optional):

Current Position: *IDAT Student (Final Year)*

Position held previously

Please elaborate where appropriate

Do you think the concept of the matrix is a good one?

Yes.
At the end of the matrix it makes you think laterally about solutions

Was the matrix easy to use or where there any problems?

Generally the matrix was easy to use although certain cases meant that it was hard to fit the product tot the recommendations.

Was the system of product description appropriate?

With time the matrix could become second nature.
It could be used a very important part of brainstorming.

Did it allow you to develop a DFE strategy which seems appropriate to the product you chose?

Yes.
Quite a few possible solutions to the use of disposable packaging were thought of.

Where there any problems in completing the matrix or developing the strategy from the matrix?

Only that certain parts of the matrix were hard to fit to the product.
This might be due to the choice of product.

Did this method help you focus on the important DFE issues?

Yes considering how something you design effects the environment.

Did using the matrix bring up considerations you had not thought of previously?

Yes.

Did the matrix help you focus or structure this form of DFE?

Yes
It made me look more at the process of distributing milk.

Are there any additions you would like to see to this method?

Presentation, ease of use.

Please give any general comments you feel may be appropriate.

The matrix is a good idea as it takes the problem out of context and allows you to think laterally about a solution

DFE Matrix Feedback Form - Electric Vehicle

Name (optional): **Current Position:** ***IEAS Student (Final Year)***

Position held previously

Please elaborate where appropriate

Do you think the concept of the matrix is a good one?

Yes
Setting out initial steps to follow and focus in the early stages.
It also avoids major areas being overlooked.

Was the matrix easy to use or where there any problems?

The matrix is definitely a fast way but it is thought provoking and if each step is considered thoroughly it makes good sense.

Was the system of product description appropriate?

It seemed to be

Did it allow you to develop a DFE strategy which seems appropriate to the product you chose?

Yes
It highlighted the areas of importance

Where there any problems in completing the matrix or developing the strategy from the matrix?

There is a lot of cross referencing between cells.
This can be confusing if rushed.

Did this method help you focus on the important DFE issues?

Did using the matrix bring up considerations you had not thought of previously?

Did the matrix help you focus or structure this form of DFE?

Are there any additions you would like to see to this method?

Please give any general comments you feel may be appropriate.

DFE Matrix Feedback Form - Chassis for Electric Vehicle

Name (optional): **Current Position:** *IEAS Student (Final Year)*

Position held previously

Please elaborate where appropriate

Do you think the concept of the matrix is a good one?

Yes
Breaks down the five areas simply
Helps you think more about the product.

Was the matrix easy to use or where there any problems?

Colour coding could make it easier

Was the system of product description appropriate?

Yes

Did it allow you to develop a DFE strategy which seems appropriate to the product you chose?

Yes

Where there any problems in completing the matrix or developing the strategy from the matrix?

No problems encountered.

Did this method help you focus on the important DFE issues?

Yes

Did using the matrix bring up considerations you had not thought of previously?

It helped me understand which areas are the most important.

Did the matrix help you focus or structure this form of DFE?

Yes

Are there any additions you would like to see to this method?

No

Please give any general comments you feel may be appropriate.

DFE Matrix Feedback Form - Clothes Iron

Name (optional): **Current Position:** *IDAT Student (Second Year)*

Position held previously

Please elaborate where appropriate

Do you think the concept of the matrix is a good one?

Yes
The matrix is a good idea. It gives a good starting point and a structure to evaluate a products environmental impact.

Was the matrix easy to use or where there any problems?

It's major drawback is its presentation.
I got a bit bogged down with what information was meant by the headings

Was the system of product description appropriate?

After a couple of tries it will probably be clearer.
Improved graphical presentation would make it more instantly accessible.

Did it allow you to develop a DFE strategy which seems appropriate to the product you chose?

Yes.
I could have gone deeper into the products analysis but even with a brief examination of the product and the matrix I was able to see the problem in a wider context.

Where there any problems in completing the matrix or developing the strategy from the matrix?

It would help to be more familiar with the topic.
The more you do it the easier it gets.

Did this method help you focus on the important DFE issues?

Yes

Did using the matrix bring up considerations you had not thought of previously?

Yes

Did the matrix help you focus or structure this form of DFE?

Yes

Are there any additions you would like to see to this method?

Better presentation.

Please give any general comments you feel may be appropriate.

DFE Matrix Feedback Form - Chairs

Name (optional):

Current Position:

Position held previously

Please elaborate where appropriate

Do you think the concept of the matrix is a good one?

Was the matrix easy to use or where there any problems?

Was the system of product description appropriate?

Did it allow you to develop a DFE strategy which seems appropriate to the product you chose?

Where there any problems in completing the matrix or developing the strategy from the matrix?

Did this method help you focus on the important DFE issues?

Did using the matrix bring up considerations you had not thought of previously?

Did the matrix help you focus or structure this form of DFE?

Are there any additions you would like to see to this method?

Please give any general comments you feel may be appropriate.

DFE Matrix Feedback Form - Television

Name (optional): **Current Position:** *Industrialist (Major Electronics)*

Position held previously

Please elaborate where appropriate

Do you think the concept of the matrix is a good one?

I think you should not use the 'apply generics' arrows. When leaving out these generics to develop the strategy, important issues are missed. When you say they will always be applied where possible, why not include them in the strategy?
The method is nice, however qualitative, which will probably not speed up industrial implementation.
You already need to be wanting to do some DFE practice to use the merits fully

Was the matrix easy to use or where there any problems?

I was a bit sceptic at first, but it was OK.
You have a tendency however to maybe not fill in all the appropriate issues in the matrix.

Was the system of product description appropriate?

Yes (no need to elaborate on that)

Did it allow you to develop a DFE strategy which seems appropriate to the product you chose?

Well, the different strategies are all important but it seems that at Philips the order of importance is somewhat reversed .I'm not sure who is right on this......
(When taking generic strategies into account this may(?) be different)

Where there any problems in completing the matrix or developing the strategy from the matrix?

You have a tendency however to maybe not fill in all the appropriate issues in the matrix

Did this method help you focus on the important DFE issues?

Well, I already knew something about DFE for televisions, so no, not really.

Did using the matrix bring up considerations you had not thought of previously?

No.
(probably to someone less experienced in DFE it would have)

Did the matrix help you focus or structure this form of DFE?

See previous answer

Are there any additions you would like to see to this method?

Figures!
But that is outside the scope I know that.

Please give any general comments you feel may be appropriate.

All in all, I feel that the method may be somewhat too generic to really get into the issues.
Of course, it is really a matter of scope/aim/objective.
To a designer without any DFE experience it's probably very useful, I mean that.

But for any incremental changes it doesn't give any further guidance where to focus on.

DFE Matrix Feedback Form - Electric Vehicle

Name (optional):

Current Position: *IEAS Student (Final Year)*

Position held previously

Please elaborate where appropriate

Do you think the concept of the matrix is a good one?

Yes
Kind of simplifies thinking

Was the matrix easy to use or where there any problems?

Quite easy to use.
At first the volume of information is quite frightening.

Was the system of product description appropriate?

Yes

Did it allow you to develop a DFE strategy which seems appropriate to the product you chose?

Yes.
The outcome was what I would expect.

Where there any problems in completing the matrix or developing the strategy from the matrix?

No.
Could be difficult to choose the environmental impact in order (1,2,3) in some cases.

Did this method help you focus on the important DFE issues?

Yes

Did using the matrix bring up considerations you had not thought of previously?

Yes
Distribution.

Did the matrix help you focus or structure this form of DFE?

Yes

Are there any additions you would like to see to this method?

Colour coding for Long life-cycle and short life-cycle.

Please give any general comments you feel may be appropriate.

DFE Matrix Feedback Form - 35mm Camera

Name (optional):

Current Position: *Researcher (Cambridge Uni.)*

Position held previously: *Eco-design researcher*

Please elaborate where appropriate

Do you think the concept of the matrix is a good one?

Yes
It helps you to focus the task in hand by structuring it into these matrix categories.

Was the matrix easy to use or where there any problems?

Generally easy.
Labelling needs to be more obvious re. life-cycle stages and design parameters.

Was the system of product description appropriate?

Yes.
The generic application information helped focus what should be included in the product description. It is important as I can imaging designers getting carried away and rather unfocussed at this stage.

Did it allow you to develop a DFE strategy which seems appropriate to the product you chose?

I guess so.
So many products are actually quite similar I was surprised to find the camera fitting into the W.M. strategy - but than I guess 'resource in use' is a major component in the domestic product. Hard to be relative with this matrix with the information given.
Could be more complicated if designer's wished to explore further.

Where there any problems in completing the matrix or developing the strategy from the matrix?

Not at the level that indicates the major 'ball park' environmental danger areas.

Did this method help you focus on the important DFE issues?

Yes
It is a good systematic process which, with practice, designers should be able to incorporate into the day to day design process with great ease.

Did using the matrix bring up considerations you had not thought of previously?

Yes.
In the sense that it made you aware of the whole life-cycle
Minor impacts tend to get overlooked if you don't use a systematic analysis.

Did the matrix help you focus or structure this form of DFE?

Definitely.
A good visual tool, easy to cross reference and balance the different components of the matrix.

Are there any additions you would like to see to this method?

Maybe more background information on justification.
Understanding the method increases the ease of implementing the process.

Please give any general comments you feel may be appropriate.

May be a need for:

- *greater explanation (background and method)*
- *good to have guidance examples (case studies)*
- *I liked the way all the information was there on 1 page, as opposed to computer programmes that encourage a trawl through multi-layers. This didn't give you the opportunity to get lost!!*

DFE Matrix Feedback Form - Vacuum Cleaner

Name (optional):

Current Position: *Eco-design Researcher (MMU)*

Position held previously: *Researcher (RMIT)*

Please elaborate where appropriate

Do you think the concept of the matrix is a good one?

I think the matrix concept is a good one.
Implementation confusing and often repetitive.

Was the matrix easy to use or where there any problems?

Main problems:
requires too much time to rewrite all the advice & refer back to generics.

Was the system of product description appropriate?

Product description was useful.
Why not have a separate matrix for the main types?
It would save a lot of writing and as you have noted most products can be broken down into key areas.

Did it allow you to develop a DFE strategy which seems appropriate to the product you chose?

Using a vacuum cleaner I often copied the washing machine example (much easier than the A3 matrix)
I can't say it told me much more that the generics apart form prioritising energy.

Where there any problems in completing the matrix or developing the strategy from the matrix?

As mentioned earlier time was an issue it took close to 3 hours to fully understand the system. The laborious task of rewriting was annoying. The referencing to other sectors was confusing.
Also it was often noted to balance issues, without appropriate weightings this is difficult.

Did this method help you focus on the important DFE issues?

Apart from the weighting of energy I feel that most of the information was similar to the generics.

Did using the matrix bring up considerations you had not thought of previously?

No but having undertaken many LCAs I'm a bit biased.

Did the matrix help you focus or structure this form of DFE?

No.
The weightings were not clear. Perhaps if it was separated into multiple specific matrices with coloured quadrants indicate 'hot' issues it would have been clearer.

Are there any additions you would like to see to this method?

By being generic the matrix doesn't really add any more specific information.
By repeating the washing machine case study for the chair etc. a designer could choose one A4 page that best matches their product and then not have to rewrite everything.

Please give any general comments you feel may be appropriate.

As each industry or even product has it's own specific environmental problem, generic have limited use.
For example on the vacuum cleaner a key issue is copper used in the motor. A generic system may be useful to start the process but is unlikely to tell the designer this key information.
So each industry or product needs it's own matrix, with key issues defined, for example the materials/resources and processing section would have highlighted the concerns of copper.

DFE Matrix Feedback Form - Telephone

Name (optional):

Current Position: *Eco-design Researcher (CIM, Cranfield)*

Position held previously: *DFD Researcher (MMU)*

Please elaborate where appropriate

Do you think the concept of the matrix is a good one?

Yes.
Matrices are my favourite way of analysing things too.

Was the matrix easy to use or where there any problems?

Initially there was a lot of information to get to grips with, I wouldn't call it easy but with simplification it could be.
I feel that designers would need extensive training if they were going to be able to use the system as it stand now.

Was the system of product description appropriate?

Yes definitely.
This was very easy to understand and apply to almost anything.

Did it allow you to develop a DFE strategy which seems appropriate to the product you chose?

Yes.
I tried not to use too much prior experience, but the A3 matrix did give good guidance.

Where there any problems in completing the matrix or developing the strategy from the matrix?

Non at all

Did this method help you focus on the important DFE issues?

Definitely

Did using the matrix bring up considerations you had not thought of previously?

Yes.
Distribution hasn't been an area I'd previously looked at in any detail.

Did the matrix help you focus or structure this form of DFE?

Not much but that is only because I used a small, light product as an example.

Are there any additions you would like to see to this method?

No additions.
Make it more simple.

Please give any general comments you feel may be appropriate.

Although the matrix is a very good one and the principles are sound I have reservations about it's usefulness in an everyday design environment. My feeling is that is too much to do and so many designers just wouldn't bother.
If it was simplified to make it a '5 minute' tool I think it would be excellent.

As it stands it might be better suited as a training tool, getting designers aware of the principles of DFE and how to develop a DFE strategy.

I personally found it quite easy to use but I have considerable knowledge of the subject, others I have asked to look at it were not so keen as it seemed too complicated to them.

DFE Matrix Feedback Form - Computer Keyboard

Name (optional): **Current** ***Position: Researcher (Glamorgan Uni)***

Position held previously: ***R & D Engineer***

Please elaborate where appropriate

Do you think the concept of the matrix is a good one?

Yes.
Forms a nice step forward from abridged LCA techniques currently available.

Was the matrix easy to use or where there any problems?

Was easy to use.
Liked the fact that it was paper-based. Could have 4 separate sheets for analysis
<u>OR</u> make it computer based with levels.
Prefer as is.

Was the system of product description appropriate?

Found defining long life-cycle & short life-cycle products difficult.
Also disposal options (as expected)
Other than that it was very good.

Did it allow you to develop a DFE strategy which seems appropriate to the product you chose?

Yes.
Strategy options which showed up frequently in the matrix where as I would expect.

Where there any problems in completing the matrix or developing the strategy from the matrix?

No problem in matrix.
Strategy was more difficult to pick as all the options could look confusing.
More information on choosing strategy could be useful. A sheet with example on how to select from A4 matrix.

Did this method help you focus on the important DFE issues?

Yes
In comparing it with abridges LCA techniques such as Graedel et at. I found this helped (or made) me think/focus better on issues such as materials/compatibility etc.

Did using the matrix bring up considerations you had not thought of previously?

No

Did the matrix help you focus or structure this form of DFE?

Helped me to focus in terms of selecting product - categorising and than selecting strategy.

Are there any additions you would like to see to this method?

Not of the top of my head.

Please give any general comments you feel may be appropriate.

Interesting.
Personally I am very interested in abridged/qualitative LCA techniques and product categorisation as a lot of my PhD research related to these.
Interested in taking part in future exercises or getting more info. when available.

DFE Matrix Feedback Form - Telephone

Name (optional):

Current Position: *Eco-design Researcher (Brunel Uni)*

Position held previously

Please elaborate where appropriate

Do you think the concept of the matrix is a good one?

Certainly helped as a quick check.
Could be done in greater depth I guess.

Was the matrix easy to use or where there any problems?

Took a little getting to grips with it.
Would be easier with more practice.

Was the system of product description appropriate?

Yes

Did it allow you to develop a DFE strategy which seems appropriate to the product you chose?

With more time I think a useful and more detailed strategy could be developed.

Where there any problems in completing the matrix or developing the strategy from the matrix?

Found I was uncertain what to put in some boxes.
OK on the whole.

Did this method help you focus on the important DFE issues?

Some aspects come up that I may not have thought of otherwise.

Did using the matrix bring up considerations you had not thought of previously?

Yes

Did the matrix help you focus or structure this form of DFE?

Yes
As an outline.

Are there any additions you would like to see to this method?

No

Please give any general comments you feel may be appropriate.

Seems good as one of several methods or on it's own if a bit more time was spent for developing a DFE strategy.

DFE Matrix Feedback Form - Personal Organiser (Electronic)

Name (optional): **Current Position:** *Researcher (Brunel Uni.)*

Position held previously: *Product Designer*

Please elaborate where appropriate

Do you think the concept of the matrix is a good one?

Yes.
Especially for general application.

Was the matrix easy to use or where there any problems?

Didn't quite understand at first.
No problem after a trial.

Was the system of product description appropriate?

Seems reasonable and appropriate.

Did it allow you to develop a DFE strategy which seems appropriate to the product you chose?

Yes.
Would appreciate more detail however.

Where there any problems in completing the matrix or developing the strategy from the matrix?

I felt I could include more detail for a strategy.
However the matrix allowed me to see that.

Did this method help you focus on the important DFE issues?

Yes definitely!

Did using the matrix bring up considerations you had not thought of previously?

Not really but I have already looked into these issues quite deeply before.
However for the typical businessmen/designer this is an appropriate tool to consider in application of designing.

Did the matrix help you focus or structure this form of DFE?

Yes, very appropriate.

Are there any additions you would like to see to this method?

Detail - perhaps product type specivity, maybe?
General application is a great motivator for designers.

Please give any general comments you feel may be appropriate.

It would be nice to see these considerations (that the matrix brings up) introduced or used by all product development, not just in theory but in practice.
We need more of this, I like it!

DFE Matrix Feedback Form - Refrigerator

Name (optional): **Current Position:** *Eco-design Co-ordinator at Goldsmiths College*

Position held previously: *Lecturer in Product Design (Nottingham, UCE, Bristol, Sheffield)*

Please elaborate where appropriate

Do you think the concept of the matrix is a good one?

Yes
Rapid way to visualise product life-cycle and environmental fields.
Forces you to consider all stages

Was the matrix easy to use or where there any problems?

Concept is easy but need reasonable knowledge of subject for outcome to be really useful

Was the system of product description appropriate?

Yes
I thought this factor a particularly useful idea.

Did it allow you to develop a DFE strategy which seems appropriate to the product you chose?

Unfortunately no. If I follow guidelines.
Key issues with fridges are energy in use hazardous materials in production and disposal and difficulty in recycling. All of these factors are highlighted but only through generics.

Where there any problems in completing the matrix or developing the strategy from the matrix?

As a result of the above comment environmental priorities not clear.
Strategy could be mis-targeted.

Did this method help you focus on the important DFE issues?

It raised a number of issues and missed others.
But I would not say it provided focus.

Did using the matrix bring up considerations you had not thought of previously?

No
But then I would say that.

Did the matrix help you focus or structure this form of DFE?

Again focus unclear.
Difficult to develop strategy in response to matrix results.

Are there any additions you would like to see to this method?

Lacked detail to be really effective without a reasonable idea of key environmental impacts.
It is difficult to identify priorities and eco-design response.

Please give any general comments you feel may be appropriate.

In many ways this is attempting to be all thing to all people. I have become convinced that some form of simplified LCA (SimaPro et al.) is almost also required to identify key issues.
This approach cannot do that.
Therefore this work is ill-equipped to fully inform strategy.
Equally because it aims to cover all products it lacks enough detail to be really useful as a design tool. It is all one level and perhaps needs depth.

Appendix D

Materials Selection Exercises

'Green' Bicycle Forks

Materials Passing Stage 1	Materials Passing Stage 2	Materials Passing Stage 3
Aluminas (Al2O3) Aluminium Alloys (wrought) Aluminium Nitride (AlN) Balsa, high density, parallel to grain Balsa, low density, parallel to grain Balsa, medium density, parallel to grain Bamboo, parallel to grain Bamboo, perpendicular to grain Beryllia (BeO) Beryllium alloys Bone (compact) Boron carbides (B4C) Carbon fibre/polymer (CFRP) laminate Carbon fibre/polymer (CFRP) unidirectional Cermets (WC-Co) Diamond Elastomers (EL), high stiffness Foamed polymers, rigid (low density) Glass Ceramic Glass fibre/polymer (GFRP) laminate Glass fibre/polymer (GFRP) unidirectional Glass Fibres Magnesium alloys (cast) Magnesium alloys (wrought) Metal Matrix Composites, Al-SiC(p) Mullites (Al2O3-SiO2 alloys) Oak parallel to grain Palm, coconut, parallel to grain Paper Pine, parallel to grain Plywood (Canadian softwood ply) Shell Short fibre reinforced polymers Sialons (Si-Al-O-N ceramic) Silica glass (SiO2) Silicon Carbides (SiC) Silicon Nitrides (Si3N4) Silicon pure Spruce parallel to grain Teak, parallel to grain Titanium alloys Titanium carbides (TiC)	Aluminium- WW (Recycled) Aluminium - Hydro (Recycled) Brick Glass GFRP (Unidirectional) GFRP (Laminate) HDPE LLDPE Maranti,parallel to grain Maranti, perpendicular to grain Nylon Oak, parallel to grain Oak perpendicular to grain Pine, parallel to grain Pine, perpendicular to grain Polypropylene Steel (20% Recycled) Steel (100% Recycled) Tinplate Tinplate(50% Recycled) TinPlate(100% Recycled)	Aluminium alloys (cast) Aluminium Alloys (wrought) Aluminium Bronzes Brasses Bronzes Chromium pure Cobalt alloys Copper Berylliums Cupro-Nickels General Purpose Coppers Glass fibre/polymer (GFRP) laminate Glass fibre/polymer (GFRP) unidirectional Gunmetals High Conductivity Coppers Iron-based superalloys Irons, Cast Lead alloys Magnesium alloys (cast) Magnesium alloys (wrought) Metal Matrix Composites, Al-SiC(p) Molybdenum alloys Nickel Alloys Nickel Silvers Silicon Bronzes Stainless steel 302 (EN58A) Stainless steel 316 (EN58J) Stainless steels austenitic Stainless steels ferritic Steel, Low carbon (Mild) Steels, Carbon Steels, High Carbon Steels, low alloy Steels, Medium Carbon Steels, pressure vessel Tin alloys Titanium alloys Tungsten alloys Uranium pure Vanadium pure Zinc alloys
42 out of 149	18 out of 30	40 out of 149

Table D.1 Materials Selection Table for 'Green' Bicycle Forks

Materials passing 3 out of 3 stages

Material	Stage:	1	2	3
Aluminium Alloys (Recycled)		P	P	P
Glass fibre/polymer (GFRP) laminate		P	P	P
Glass fibre/polymer (GFRP) unidirectional		P	P	P

3 out of 149

TableD.2 Materials Passing all Selection Stages

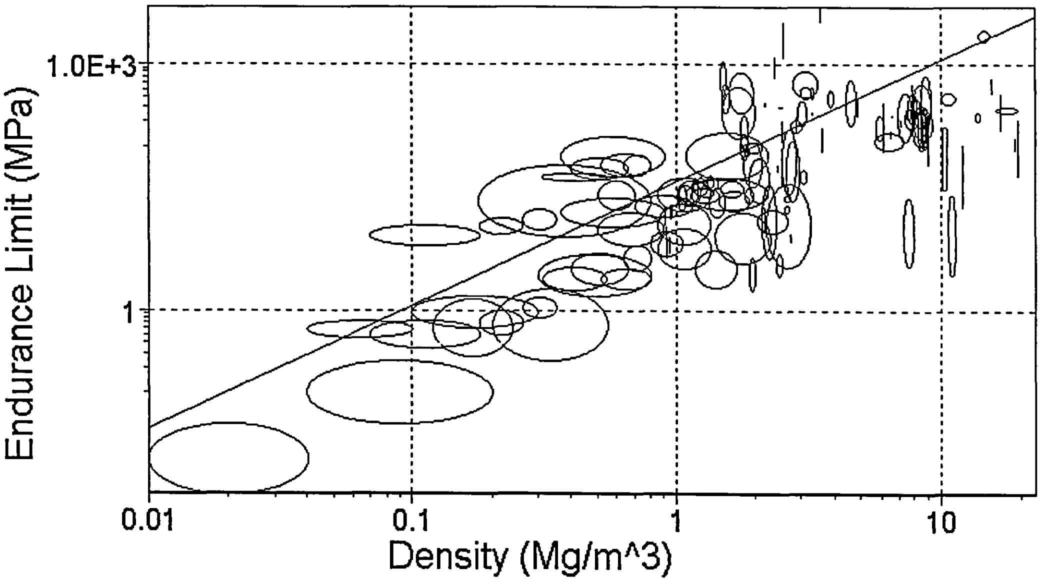


Figure D.1 Endurance Limit v Density Materials Selection Chart

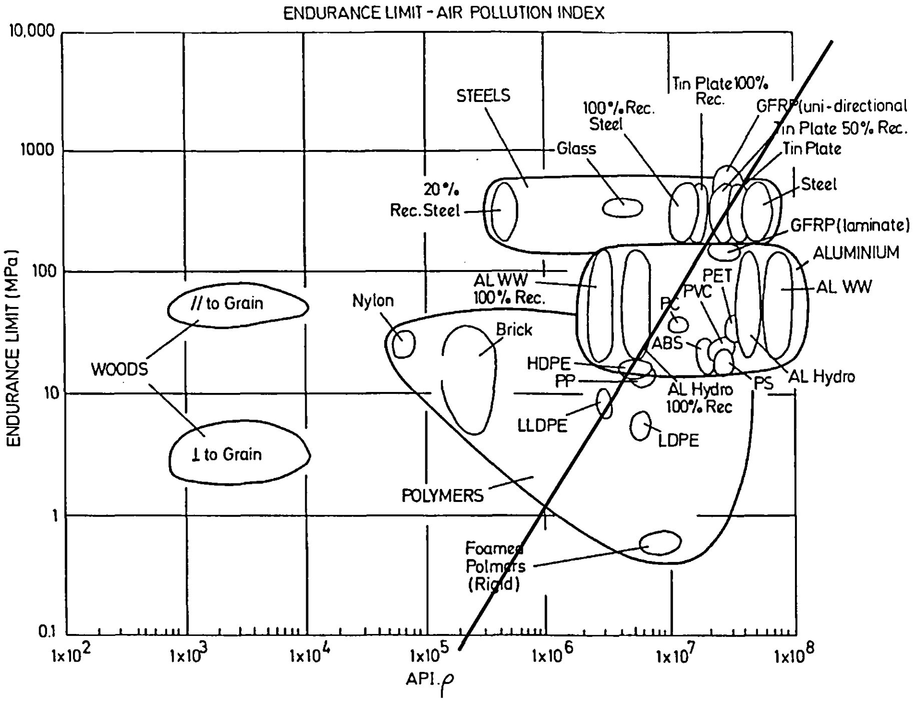


Figure D.2 Endurance Limit v API.Density Materials Selection Chart

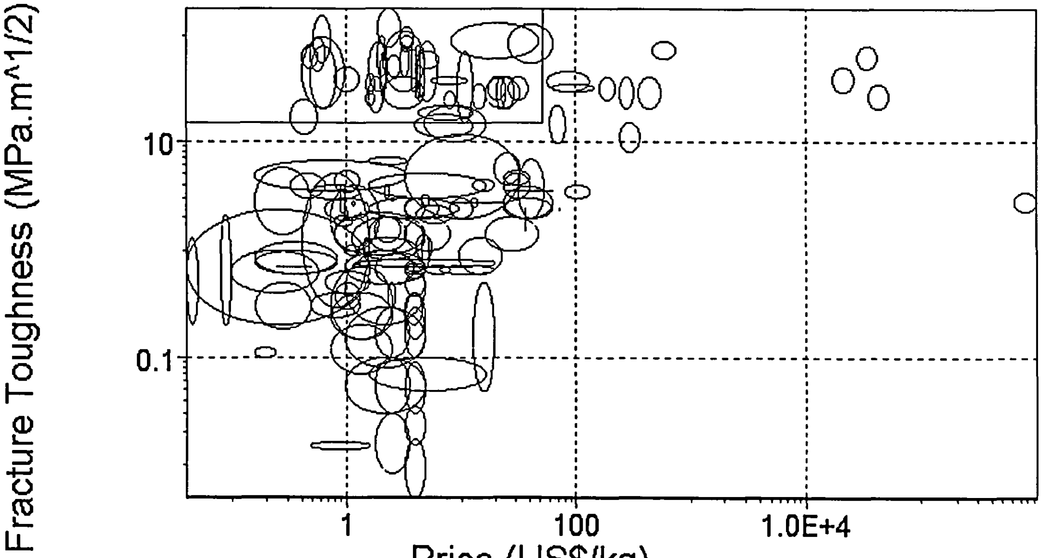


Figure D.3 Fracture Toughness v Price Materials Selection Chart

'Green' Oars

Materials Passing Stage 1

- Balsa, high density, parallel to grain
- Balsa, low density, parallel to grain
- Balsa, medium density, parallel to grain
- Bamboo, parallel to grain
- Beryllia (BeO)
- Beryllium alloys
- Boron carbides (B4C)
- Carbon fibre/polymer (CFRP) laminate
- Carbon fibre/polymer (CFRP) unidirectional
- Diamond
- Palm, coconut, parallel to grain
- Pine, parallel to grain
- Silicon Carbides (SiC)
- Spruce parallel to grain
- Teak, parallel to grain

Materials Passing Stage 2

- Aluminium WW (Recycled)
- Aluminium Hydro (Recycled)
- Glass (56% Recycled)
- Glass (75% Recycled)
- Glass (100& Recycled)
- Maranti ,parallel to grain
- Maranti, perpendicualr to grain
- Nylon
- Oak, parallel to grain
- Oak, perpendicular to grain
- Pine, parallel to grain
- Pine, perpendicular to grain
- Steel
- Steel (20% Recycled)
- Steel(100% Recycled)

Materials Passing Stage 3

- Acrylobutadienestyrene (ABS) - High Impact
- Aluminium alloys (cast)
- Aluminium Alloys (wrought)
- Aluminium Bronzes
- Bone (compact)
- Brasses
- Bronzes
- Carbon fibre/polymer (CFRP) laminate
- Carbon fibre/polymer (CFRP) unidirectional
- Chromium pure
- Cobalt alloys
- Copper Berylliums
- Cupro-Nickels
- Elastomers (EL), high stiffness
- Elastomers (EL), low stiffness
- Elastomers (EL), medium stiffness
- Foamed polymers, flexible (high density)
- Foamed polymers, flexible (low density)
- Foamed polymers, flexible (medium density)
- Foamed polymers, rigid (high density)
- General Purpose Coppers
- Glass fibre/polymer (GFRP) laminate
- Glass fibre/polymer (GFRP) unidirectional
- Gunmetals
- High Conductivity Coppers
- High density Polyethylene (HDPE)
- Iron-based superalloys
- Irons, Cast
- Lead alloys
- Leather generic
- Lin.Lo. Density Polyethylene (LLDPE)
- Low Density Polyethylene (LDPE)
- Magnesium alloys (cast)
- Magnesium alloys (wrought)
- Medium Density Polyethylene (MDPE)
- Metal Matrix Composites, Al-SiC(p)
- Molybdenum alloys
- Nickel Alloys
- Nickel Silvers

		Nylons (Polyamide, PA) Palm, coconut, parallel to grain Paper Particulate reinforced (filled) polymers Pine, parallel to grain Plywood (Canadian softwood ply) Poly TetraFluoro Ethylene (PTFE) Polycarbonates (PC) Polyether ether ketone (PEEK) Polyethylene terephthalate (PET) Polyimides (PI) Polypropylenes (PP) PolyUrethane (PU), flexible Polyvinylchlorides (PVC) - Rigid Shell Short fibre reinforced polymers Silicon Bronzes Silicone (SIL) elastomers Spruce parallel to grain Stainless steel 302 (EN58A) Stainless steel 316 (EN58J) Stainless steels austenitic Stainless steels ferritic Steel, Low carbon (Mild) Steels, Carbon Steels, High Carbon Steels, low alloy Steels, Medium Carbon Steels, pressure vessel Teak, parallel to grain Tin alloys Titanium alloys Tungsten alloys Ult.Hi.Mol.Wt Polyethylene (UHMWPE) Uranium pure Vanadium pure Zinc alloys
15 out of 149	12 out of 30	76 out of 149

Table D.3 Materials Selection Table for 'Green' Oars

Materials passing 3 out of 3 stages

Material	Stage: 1	2	3
Carbon fibre/polymer (CFRP) laminate	P	P	?
Carbon fibre/polymer (CFRP) unidirectional	P	P	?
Palm, coconut, parallel to grain	P	P	P
Pine, parallel to grain	P	P	P
Spruce parallel to grain	P	P	P
Teak, parallel to grain	P	P	P

4 (6) out of 149

Table D.4 Materials Passing all Selection Stages

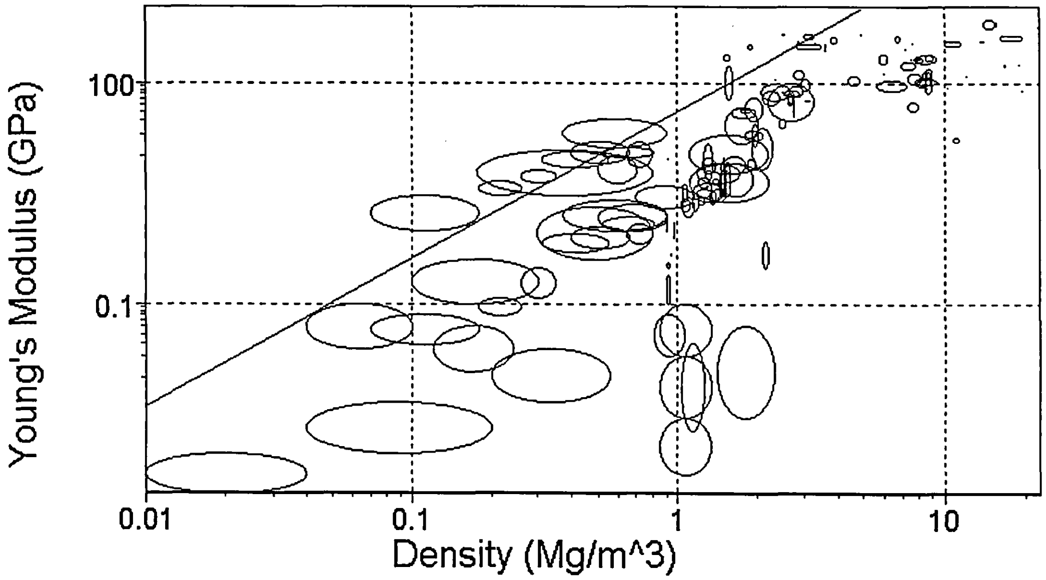


Figure D.4 Young's Modulus v Density Materials Selection Chart

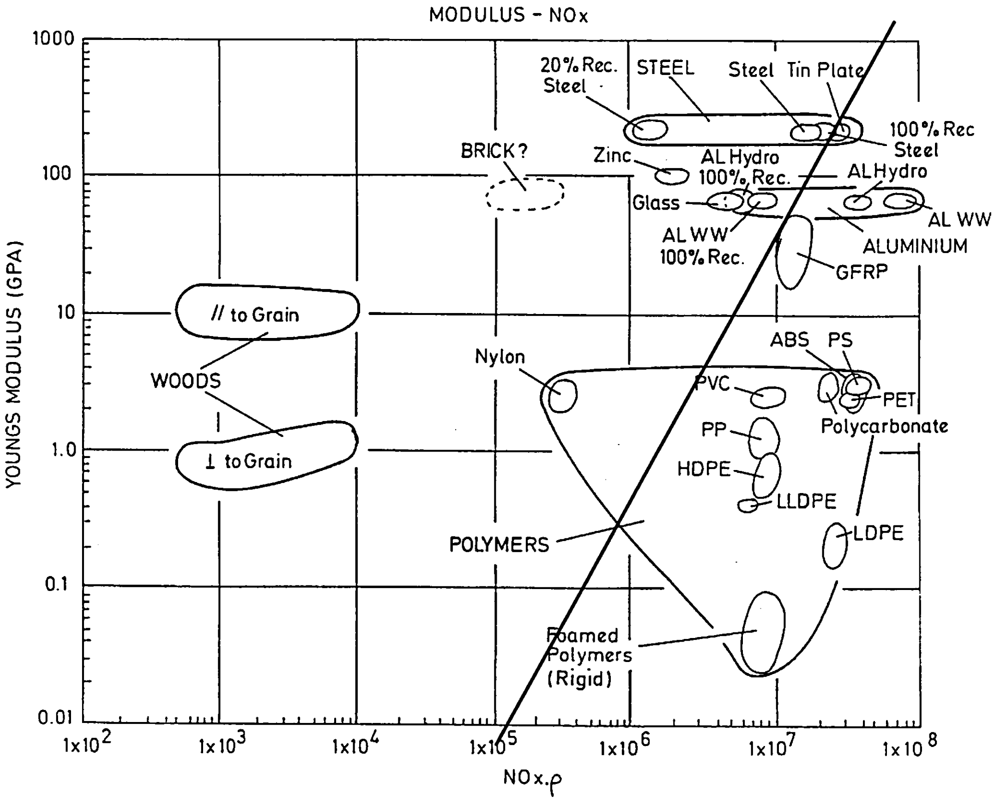


Figure D.5 Young's Modulus v NOx Emissions Materials Selection Chart

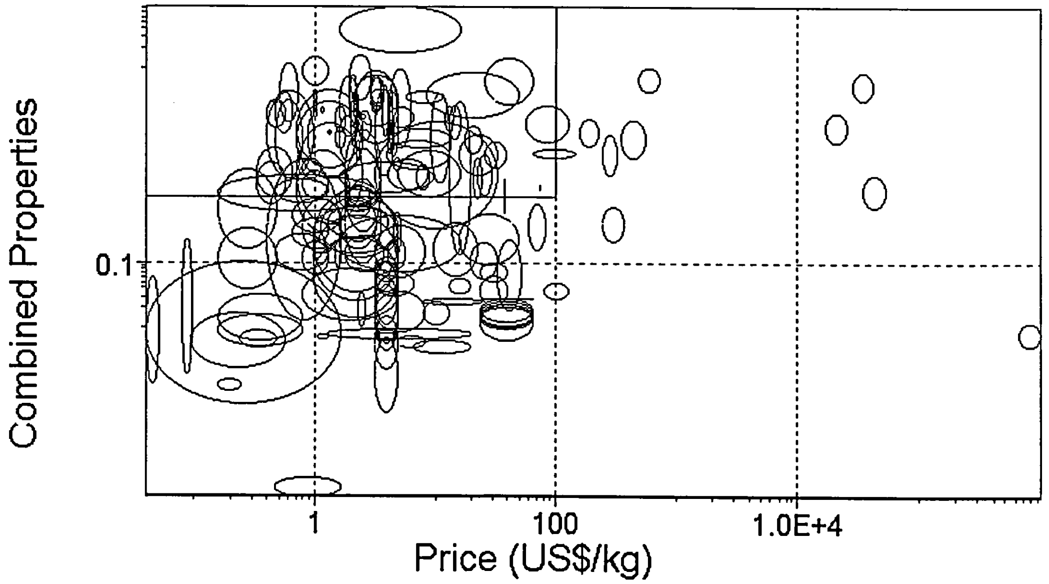


Figure D.6 Toughness v Proce Materials Selection Chart

'Green' Drinks Containers

Materials Passing Stage 1

- Acrylics (PMMA)
- ABS - High Impact
- Alkyds (ALK)
- Aluminas (Al2O3)
- Aluminium alloys (cast)
- Aluminium Alloys (wrought)
- Aluminium Bronzes
- Aluminium Nitride (AlN)
- Balsa, hd, parallel to grain
- Balsa, ld, parallel to grain
- Balsa, md, parallel to grain
- Bamboo, parallel to grain
- Bamboo, perp to grain
- Beryllia (BeO)
- Beryllium alloys
- Bone (compact)
- Boron carbides (B4C)
- Brasses
- Bronzes
- CFRP laminate
- CFRP unidirectional
- Cermets (WC-Co)
- Chromium pure
- Cobalt alloys
- Copper Berylliums
- Cotton
- Cupro-Nickels
- Diamond
- Elastomers, high stiffness
- Elastomers, medium stiffness
- Epoxies (EP), rigid
- Flax
- Foamed polymers, rigid (hd)
- Foamed polymers, rigid (ld)
- Foamed polymers, rigid (md)
- Foamed polymers, structural
- General Purpose Coppers
- Glass Ceramic
- GFRP laminate
- GFRP unidirectional
- Glass Fibres
- Graphite
- Gunmetals
- Hemp
- High Conductivity Coppers
- HDPE
- Iridium pure
- Iron-based superalloys
- Irons, Cast
- Leather generic
- LLDPE
- LDPE
- Magnesia (MgO)
- Magnesium alloys (cast)
- Magnesium alloys (wrought)

Materials Passing Stage 2

- Acrylics (PMMA)
- Aluminium alloys (cast)
- Aluminium Alloys (wrought)
- Bone (compact)
- Brasses
- Brick
- Concrete
- Cork
- Cotton
- Elastomers (EL), high stiffness
- Elastomers (EL), low stiffness
- Elastomers (EL), medium stiffness
- Flax
- Foamed polymers, rigid (high density)
- Foamed polymers, rigid (low density)
- Foamed polymers, rigid (medium density)
- Foamed polymers, structural
- Glass Fibres
- Granite
- Hemp
- High density Polyethylene (HDPE)
- Irons, Cast
- Lead alloys
- Leather generic
- Limestone
- Lin.Lo. Density Polyethylene (LLDPE)
- Low Density Polyethylene (LDPE)
- Marble
- Medium Density Polyethylene (MDPE)
- Oak parallel to grain
- Oak perpendicular to grain
- Palm, coconut, parallel to grain
- Paper
- Particulate reinforced (filled) polymers
- Phenolics (PHEN)
- Pine, parallel to grain
- Pine, perpendicular to grain
- Plywood (Canadian softwood ply)
- Polypropylenes (PP)
- Polystyrenes (PS)
- Polyvinylchlorides (PVC) - Rigid
- Portland Cement
- Sandstone
- Shell
- Soda Glasses

Materials Passing Stage 3

- Aluminium Alloys
- Glass Fibres
- HDPE
- Wood, parallel to grain (?)
- Polypropylenes
- Polyvinylchlorides - Rigid
- Soda Glasses
- Steels
- Zinc Alloys

Melamines (MEL) Metal Matrix Composites, Molybdenum alloys Mullites (Al2O3-SiO2 alloys) Nickel Alloys Nickel Silvers Niobium (Columbium) alloys Niobium Carbides (NbC) Nylons (Polyamide, PA) Oak parallel to grain Palladium pure Palm, parallel to grain Paper Particulate reinforced (filled) polymers Phenolics (PHEN) Pine, parallel to grain Plywood (softwood ply) Polycarbonates (PC) Polyesters (PES), rigid PEEK PET Polyimides (PI) Polypropylenes (PP) Polystyrenes (PS) PolyUrethane (PU), flexible PVC - Rigid Pyrex glass Shell Short fibre rein. polymers Sialons (Si-Al-O-N ceramic) Silica glass (SiO2) Silicon Bronzes Silicon Carbides (SiC) Silicon Nitrides (Si3N4) Silicon pure Silicone (SIL), rigid Silk Silver alloys Soda Glasses Spruce parallel to grain Stainless steel 302 (EN58A) Stainless steel 316 (EN58J) Stainless steels austenitic Stainless steels ferritic Steel, Low carbon (Mild) Steels, Carbon Steels, High Carbon Steels, low alloy Steels, Medium Carbon Steels, pressure vessel Tantalum alloys Teak, parallel to grain Titanium alloys Titanium carbides (TiC) Tungsten alloys Tungsten carbides (WC) (UHMWPE) Uranium pure Vanadium pure	Spruce parallel to grain Spruce perpendicular to grain Steel, Low carbon (Mild) Steels, Carbon Steels, High Carbon Steels, low alloy Steels, Medium Carbon Stone, generic Teak, parallel to grain Teak, perpendicular to grain Wool Zinc alloys	

Wool Zinc alloys Zirconia (ZrO2) Zirconium alloys Zirconium carbides (ZrC)		
119 out of 149	57 out of 149	8 (9) out of 20

Table D.5 Materials Selection Table for 'Green' Containers

Materials passing 3 out of 3 stages

Material	Stage: 1	2	3
Aluminium (preferably recycled)	P	P	P
HDPE	P	P	P
PET	P	P	P
Polypropylene	P	P	P
PVC (Rigid)	P	P	P
Soda Glass	P	P	P
Steel (recycled)	P	P	P
Zinc	P	P	P

8 out of 149

Table D.6 Materials Passing all Selection Stages

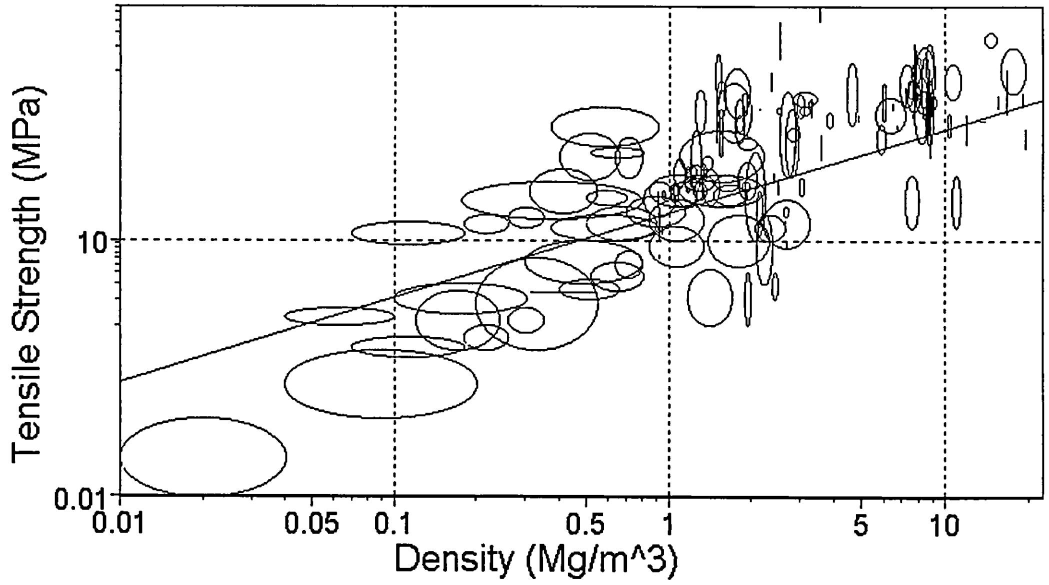


Figure D.7 Strength v Density Materials Selection Chart

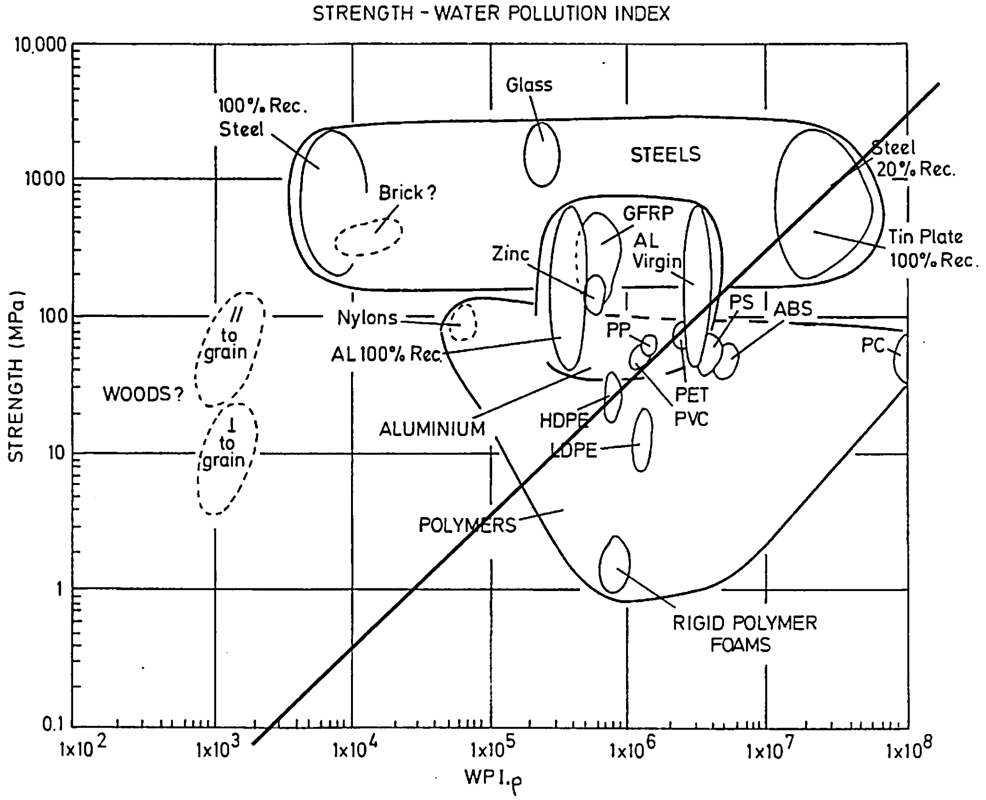


Figure D.8 Strength v WPI.Density Materials Selection Chart

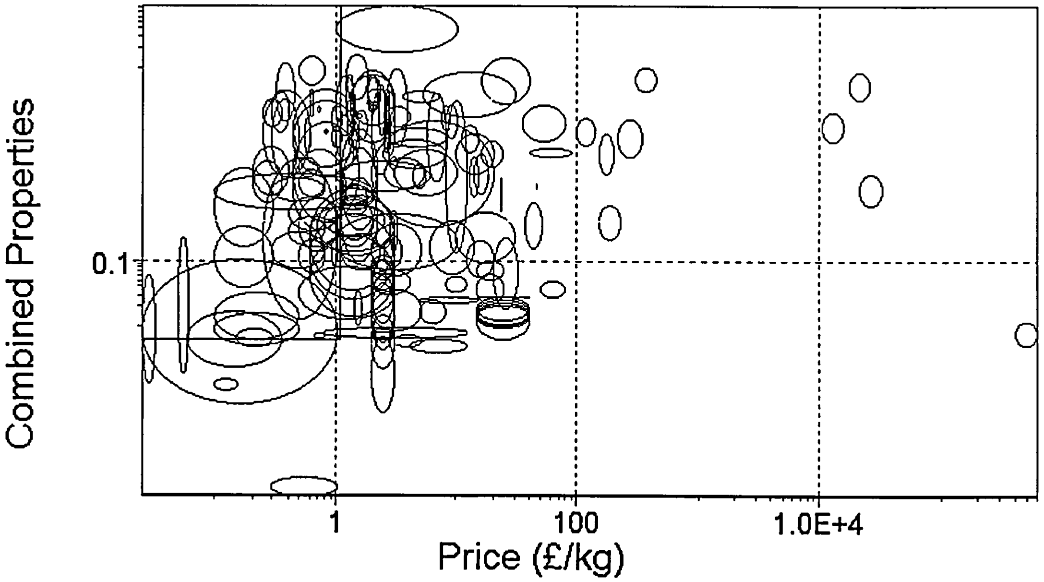
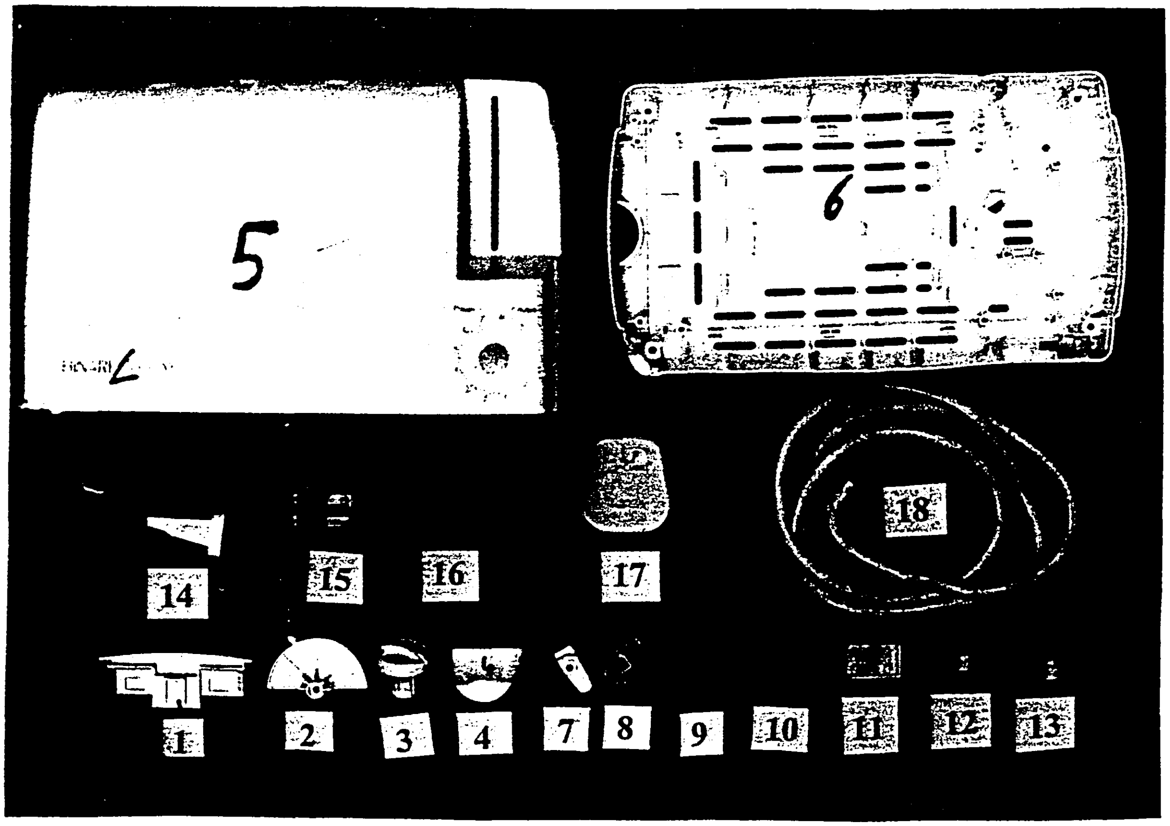


Figure D.9 Toughness v Proce Materials Selection Chart

Appendix E

LCA Exercise for Toaster


5
6
18
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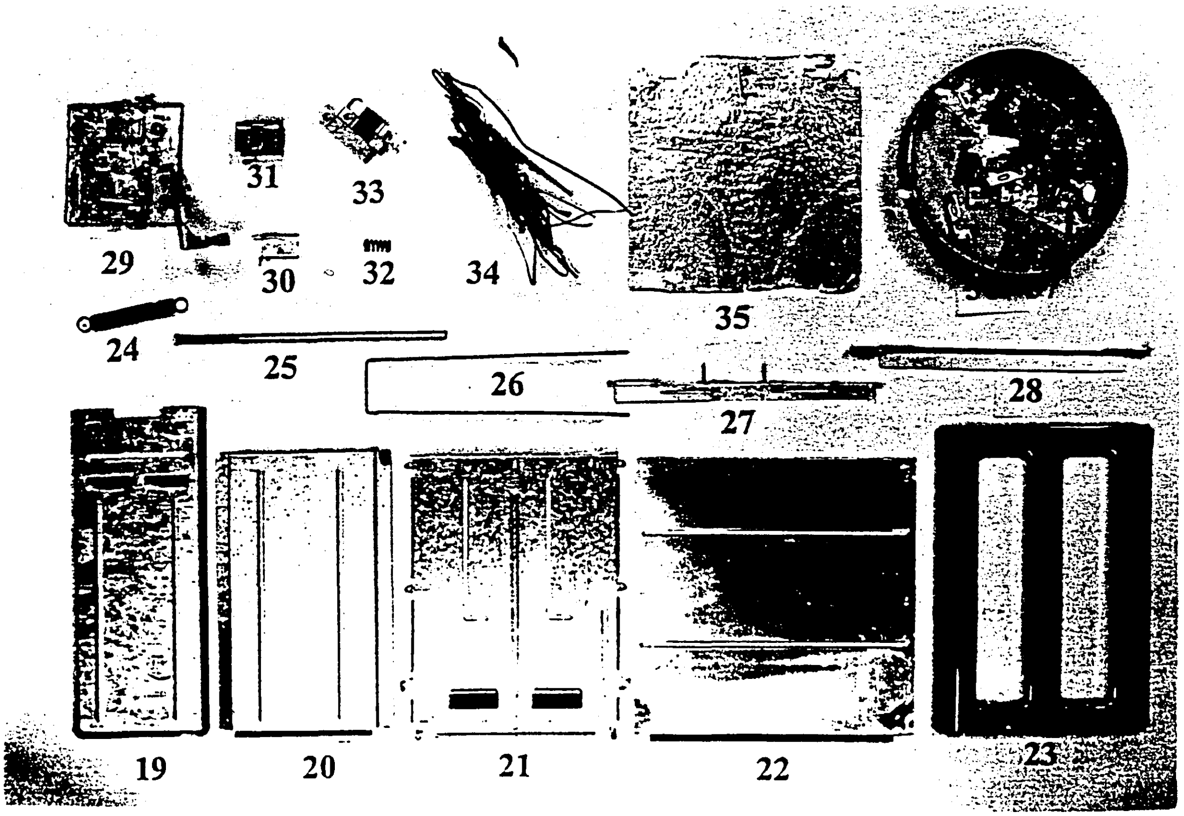
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LCA Inputs for Toaster

Polymers				
Part No	***Name***	***Material***	***Quantity (kg)***	***Process***
1	Crumb Tray Handle	Polypropylene	0.049	Injection Moulding
2	Feet	“	2 x 0.05	“
3	Toasting Control Button	“	0.024	“
4	Bread Lowering Handle	“	0.034	“
5	Outer Casing	“	0.224	“
6	Base	“	0.127	“
7		“	2 x 0.0002	“
8	Release Button	“	0.0001	“
9		Nylon	2 x 0.002	“
10		“	0.0007	“
11		ABS	2x 0.0031	“
12		“	4 x 0.0005	“
13		“	3x 0.005	“
14		Polypropylene	0.02	“
15	Contact	Bakelite	0.02	Compression Moulding
16		“	5 x 0.0007	“
17	Plug	Urea Formaldehyde	0.0338	“
18	Cord	PVC	0.00725	Extrusion

TableE.1 Polymer Materials used in Toaster

Metals & Others				
Part No	***Name***	***Material***	***Quantity (kg)***	***Process***
19	Crumb Tray	Galvanised Mild Steel	0.04	Cold Forming
20	Internal Base	“	0.045	“
21	Inner Walls	“	2 x 0.052	“
22	Outer walls	Aluminium	0.05	“
23	Top Plate	Mild Steel	0.043	Cold forming + Chrome Plating
24	Spring	Steel	0.0027	
25	Rod	“	0.0136	Chrome Plating
26	Small Rods	“	9 x 0.0028	
27		Mild Steel	8 x 0.0062	Cold Forming
28		Steel	2 x 0.006	“
29		“	0.035	“
30		“	0.001	“
31		“	0.0068	“
32	Small Spring	“	0.0003	
33	Plug Pins	Brass	0.023	Machining
34	Heating Element	Tungsten	0.0027	
35	Insulation Paper	Mica Coated Paper	0.034	
36	Screws	Steel	0.027	Machining

Table E.2 Metals Materials used in Toaster

Packaging			
Name	***Material***	***Quantity (kg)***	***Process***
Box	Cardboard	0.2317	
Manual	Paper	0.0177	
Bag	LDPE	0.01	Foil Blowing
Polystyrene	Polystyrene	0.049	Injection Moulding

Table E.3 Packaging Materials used in Toaster

Use, Transport & Disposal		
Transport	Taipei to Liverpool (Ship) Liverpool to Sheffield (Truck)	9800 miles 50 miles
Use	Total Life-Use	153.98 kWh
Disposal	Municipal Waste	Landfill Recycle Packaging

Table E.4 Other Life-Cycle Inputs

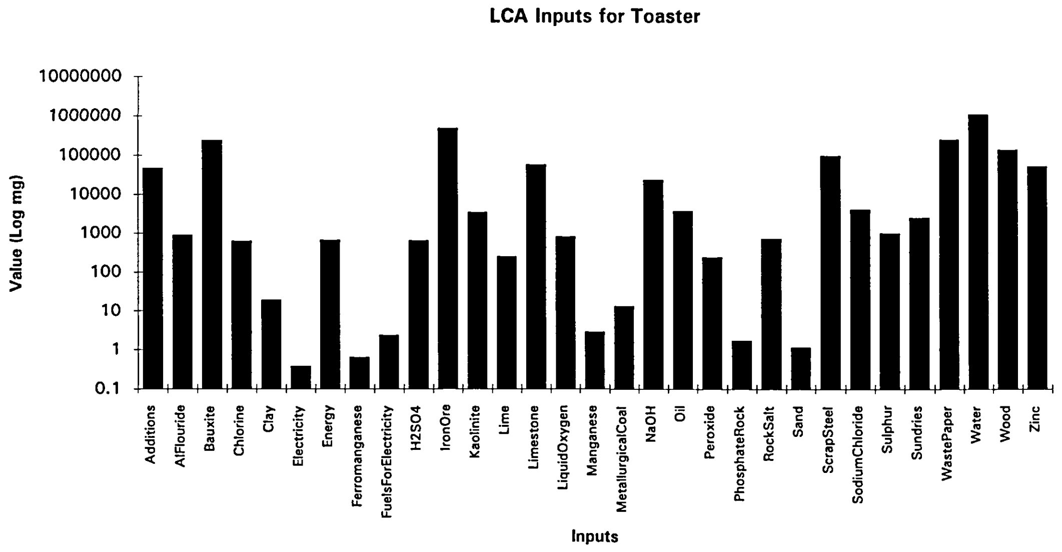

Figure E.1 Graph of LCA Inputs for Toaster

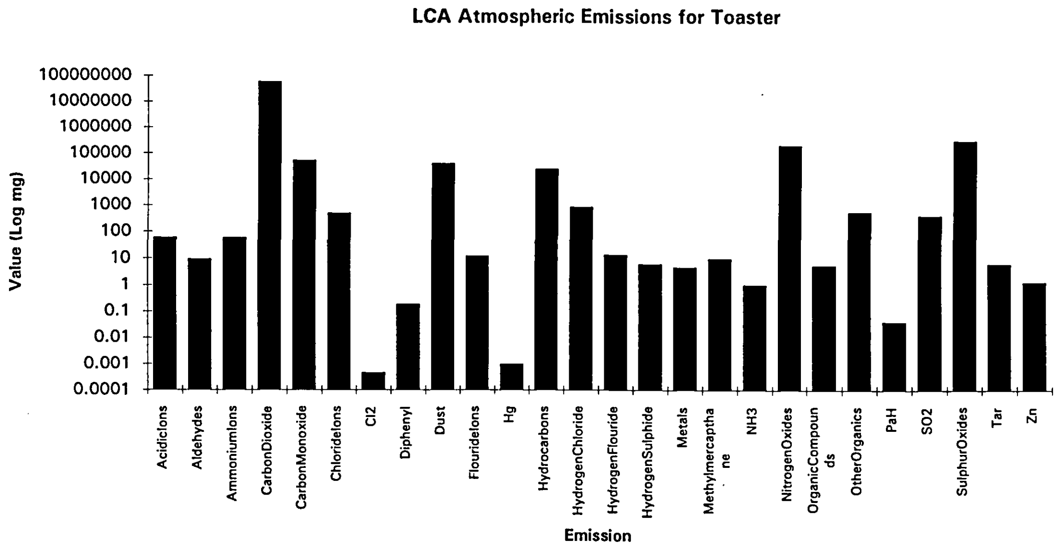

Figure E.2 Graph of LCA Atmospheric Emissions for Toaster

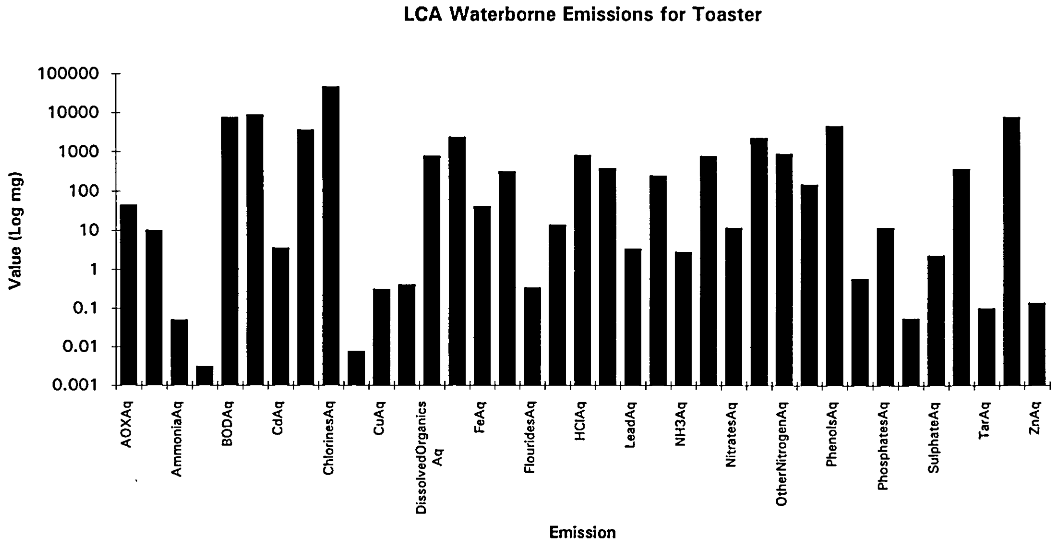

Figure E.3 LCA Waterborne Emissions for Toaster

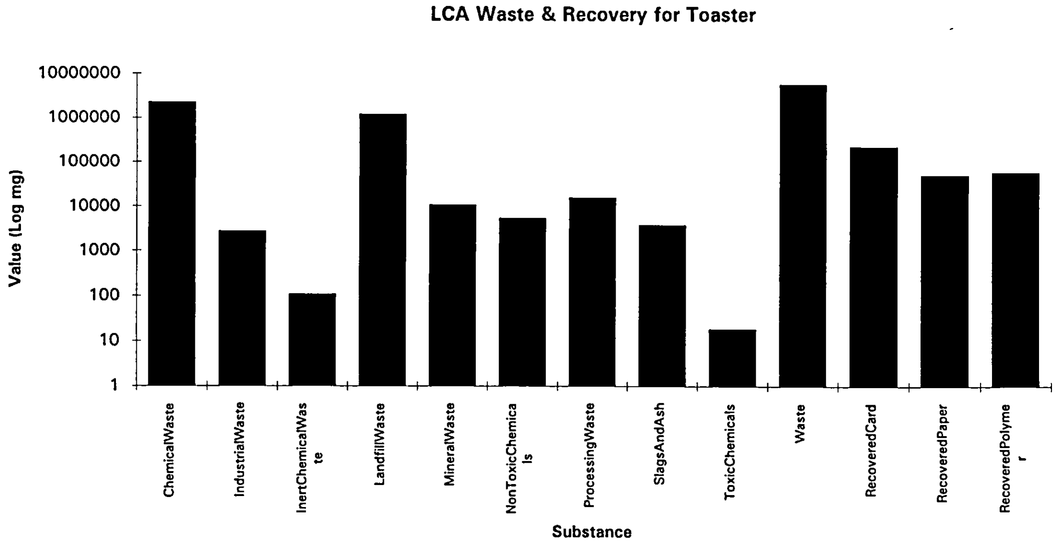

Figure E.4 LCA Waste & Recovery for Toaster

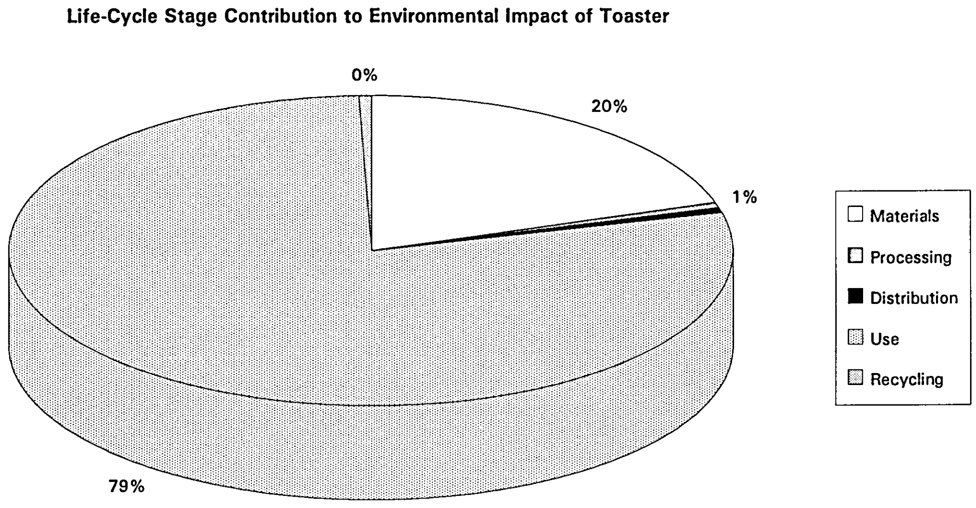

Figure E.5 Breakdown of LCA Pollution for Toaster

Complete Breakdown of LCA Inputs & Outputs

INPUTS

Additions	4.70351764 x 10 g
AlFlouride	9 x 100 mg
Bauxite	2.39751903 x 100 g
Chlorine	6.298094 x 100 mg
Clay	1.88057 x 10 mg
Electricity	0.3765564 mg
Energy	6.604696815 x 100 MJ
Ferromanganese	0.640653 mg
FuelsForElectricity	2.3584838 MJ
H2SO4	6.394949 x 100 mg
IronOre	4.74074263 x 100 g
Kaolinite	3.3605 g
Lime	2.479015 x 100 mg
Limestone	5.5421723 x 10 g
LiquidOxygen	8.02384 x 100 mg
Manganese	2.865 mg
MetallurgicalCoal	1.3179 x 10 mg
NaOH	2.2726983 x 10 g
Oil	3.60504 g
Peroxide	2.399914 x 100 mg
PhosphateRock	1.719 mg
RockSalt	7.111335 x 100 mg
Sand	1.146 mg
ScrapSteel	9.36012 x 10 g
SodiumChloride	4.00132 g
Sulphur	9.9253476 x 100 mg
Sundries	2.4415 g
WastePaper	2.3251095 x 100 g
Water	10027.541336 x 100 litres
Wood	1.2812236 x 100 g
Zinc	4.89585 x 10 g

ATMOSPHERIC EMISSIONS

AcidicIons	6.04808316 x 10 mg
Aldehydes	9.4524192 mg
AmmoniumIons	5.80024259 x 10 mg
CarbonDioxide	5.8651392498776 x 10 Kg
CarbonMonoxide	5.2872740128 x 10 g
ChlorideIons	4.86469 x 100 mg
Cl2	0.0004653 mg
Diphenyl	0.188 mg
Dust	3.96896085992 x 10 g
FlourideIons	1.215 x 10 mg
Hg	0.0009823 mg
Hydrocarbons	2.463837761372 x 10 g
HydrogenChloride	8.455365 x 100 mg
HydrogenFlouride	1.355430022 x 10 mg
HydrogenSulphide	6.05134 mg
Metals	4.6022 mg
Methylmercapthane	9.5645 mg
NH3	0.982474 mg
NitrogenOxides	1.9922090018 x 100 g

OrganicCompounds	5.25 mg
OtherOrganics	5.4170489 x 100 mg
PaH	0.04052 mg
SO2	3.895595 x 100 mg
SulphurOxides	3.0697739367 x 100 g
Tar	6 mg
Zn	1.2336 mg

WATERBORNE EMISSIONS

AOX	4.51341 x 10 mg
AcidicIons	1.0314 x 10 mg
Ammonia	0.05 mg
As	0.003084 mg
BOD	7.49178200896 g
COD	8.7490847323 g
Cd	3.6004415 mg
Chlorine	3.617221994 g
Chlorines	4.6078183 x 10 g
Cr	0.00771 mg
Cu	0.3084 mg
Cyanide	0.4052 mg
DissolvedOrganics	7.787752 x 100 mg
DissolvedSolids	2.311923 g
Fe	4.05175688 x 10 mg
Fibres	3.09008 x 100 mg
Flourides	0.3444124 mg
Flourines	1.37184071 x 10 mg
HCl	8.104 x 100 mg
Hydrocarbons	3.777385 x 100 mg
Lead	3.391 mg
Metals	2.436630517 x 100 mg
NH3	2.8014718 mg
Na	7.5381891012 x 100 mg
Nitrates	1.176004052 x 10 mg
Oil	2.20257815 g
OtherNitrogen	8.626357 x 100 mg
OtherOrganics	1.44625 x 100 mg
Phenols	4.42267886 g
Phosphate	0.573 mg
Phosphates	1.162 x 10 mg
Sb	0.05397 mg
Sulphate	2.292 mg
SuspendedSolids	3.55923212 x 100 mg
Tar	0.1 mg
Toluene	7.25 g
Zn	0.13621 mg

SOLID WASTES

ChemicalWaste	2.247507449 Kg
IndustrialWaste	2.70896 g
InertChemicalWaste	1.0887 x 100 mg
LandfillWaste	1.2036 Kg
MineralWaste	1.079839 x 10 g

NonToxicChemicals	5.4058 g
ProcessingWaste	1.56355634 x 10 g
SlagsAndAsh	3.78193 g
ToxicChemicals	1.841467 x 10 mg
Waste	5.7697592444 Kg

RECOVERY

RecoveredCard	2.271568264 x 100 g
RecoveredPaper	5.06862664 x 10 g
RecoveredPolymer	5.9 x 10 g

Environmental Principles for Design

Leigh Holloway
Sheffield Hallam University
School of Engineering

Published on the WWW: http://ie.uwinsor.ca/other_paper_01.html
Environmentally Conscious Design and Manufacturing Group Infobase
University of Windsor
Canada
1994

Abstract

The effects of our everyday actions on the environment are coming under increasing scrutiny. Every product we produce, use and dispose of, has a profound effect on the balance of the ecological systems around us. If we are to curb this ever-growing environmental problem design practices will have to change. This paper looks at the way in which designers may help reduce the environmental burden of the products they devise and the environmental problems which they face.

Existing design practices are observed and the *'extra'* environmental considerations outlined. Mechanisms of attributing environmental cost to product life-cycles are investigated and a method for conducting such studies is proposed. Sources of data for such studies are cited.

Finally a eco-checklist for designers is presented and an outline for a 'Green Design' methodology is suggested.

Domain Specific Minimum Environmental Impact Vehicles

I. Tranter, L. Holloway, P.W. Foss
School of Engineering
Sheffield Hallam University

Proceedings of the 27th International Symposium on Automotive Technology and Automation
Aachen, Germany
October 31 - November 4 1994

Abstract

The use of different vehicles in particular domains will result in specific environmental problems. One of the most extreme cases is the use of vehicles in areas of special environmental interest. By assessing the problems present in using vehicles for activities such as National Park and forestry work this paper highlights the specific areas for environmental improvement. A method for addressing these problems and carrying out environmental optimisation exercises using computer based tools is presented.

Incorporating Environmental Principles into the Design Process

Leigh Holloway, David Clegg, Ian Tranter & Graham Cockerham
School of Engineering
Sheffield Hallam University

Materials & Design
Volume 15, Number 5
Pages 259 -267
November, 1994

Abstract

The effects of our everyday actions on the environment are coming under increasing scrutiny. Every product we produce, use and dispose of, has a profound effect on the balance of the ecological systems around us. This problem is increasing at a considerable pace and something must be done soon. The practice of engineering is one of the largest contributors to the environmental problem and if something is to be done product design practices will have to adapt. This paper looks at the problems faced by designers in attempting to integrate environmental concerns into the design process.

Existing design practices along with documented principles and frameworks are observed, the environmental considerations which need to be taken into account are outlined and mechanisms for attributing environmental cost to product life-cycles are defined. By showing how traditionally independent disciplines may be integrated in concurrent engineering practices this paper attempts to demonstrate the principles of Design for the Environment

An Expert System Based Advisor for Assisting Predictive Environmental Impact Assessment

Leigh Holloway & Ian Tranter
School of Engineering
Sheffield Hallam University

Proceedings of the International Symposium on Intelligence, Knowledge and Integration for Manufacturing
Southeast University
Nanjing, China
March 28 - 31, 1995

Abstract

The criteria for good design are expanding from functionality, efficient manufacture and value for money, to include environmental considerations such as efficient use of material, minimisation of waste and reduction in pollution throughout entire manufacturing systems. The production of raw materials and in turn the manufacture of these materials into products has a direct effect on the environmental impact of a production system. Therefore, by considering overall inputs and outputs an 'environmental profile' of any manufacturing system may be drawn up.

The lack of standardised methodologies for 'green design' and the absence of environmentally relevant data has hindered the progress of promoting more 'environmentally friendly' manufacturing practices and sustainable development in many areas. As this relatively new area changes and the information needed becomes more readily available there will be a need for tools to assist designers in the manipulation of what will become massive amounts of data. Expert Systems and Artificial Intelligence techniques have been applied to some of the most complex problems in engineering, and other fields, and would seem to go some way to providing a solution to the 'green designers' problems.

This paper will look briefly at the changing face of design and manufacturing and highlight the problems which engineers now confront. In an attempt to illustrate how predictive assessment of the environmental impact of product design decisions may be standardised and accelerated, the development and future implementation of an expert system based design advisor encapsulating these new design disciplines is discussed.

Environmental Design - What is Best Practice ?

Leigh Holloway, Ian Tranter & Dr David Clegg
School of Engineering
Sheffield Hallam University

Proceedings of the Inaugural Conference of the European Academy of Design - Design Interfaces
Volume 4 - Design Management, International Issues, Eco/Environmental Design and Gender Issues
University College Salford
11 - 13 April, 1995

Abstract

Environmental considerations are becoming increasingly important in all aspects of industry. Many organisations are now turning to tools such as Life-Cycle-Analysis (LCA) and Environmental Cost Attribution (ECA) in an attempt to better their awareness and understanding of the environmental problems particular to their operations. As well as highlighting environmental problems tools such as LCA can be used as a basis for improvement analysis studies. Designers are in a central position within the product development programme and as such have the power to influence the environmental effects imposed by a product. For designers to make effective use of environmental data there is a need for design guidelines.

Currently much work is being carried out in the field of 'Eco' or 'Green' design with a view to documenting or standardising procedures. This paper asks whether best practice can be defined using such procedures or whether the environmental problems faced by different sectors of industry facilitate different approaches in design. To highlight the differing considerations present, the process of environmental design is observed and compared in the automotive and packaging industries. Finally general guidelines for eco-design are presented and the question "can best practice be defined" is addressed.

Expert Systems for Eco-Design

Leigh Holloway, Ian Tranter & David Clegg

School of Engineering
Sheffield Hallam University

Proceedings of the First International Interdisciplinary Conference on the Environment -
The Natural Environment: Interdisciplinary Views.
Boston, MA. USA
June 21 - 24, 1995

Abstract

Design has the potential to help change a world in which environmental problems are becoming increasingly apparent. Design is a vital part of the product development programme and as such designers are in the unique position to influence the environmental impact of products from initial concept to ultimate disposal.

The criteria for good design are expanding from functionality, efficient manufacture and value for money, to include environmental considerations such as efficient use of material, minimisation of waste and reduction in pollution.

The design community has a long way to go to reach the standards set by the service industries over the last few years. The lack of standardised methodologies for 'green design' and the absence of environmentally relevant data has hindered the progress of promoting sustainable development in 'green design'. As this relatively new area changes and the information needed becomes more readily available there will be a need for design tools to assist designers in achieving their environmental goals.

Expert Systems and Artificial Intelligence techniques have been applied to some of the most complex problems in engineering, and other fields, and would seem to go some way to providing a solution to the 'green designers' problems.

In this paper we will look at the changing face of design, in particular with plastics in mind, and the implementation of the new methodologies into expert systems in an attempt to standardise and accelerate the assessment of the environmental impact of product design decisions.

Green Design in the Automobile Industry

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1 - School Of Engineering, Sheffield Hallam University
2 - Faculty of Technology, Open University

Co-Design Journal
Double Issue 5 & 6
Pages 88 - 91
March, 1996

Abstract

The key to effective clean design is the identification of the main areas of environmental impact and use of appropriate design strategies. This Paper looks at some current practices within the automobile industry and attempts to analyse whether the environmental strategies are reaping the greatest environmental rewards.

Reducing the Environmental Impact of Vehicles - Replacement verses Refurbishment

L. Holloway, M. Bassett & P. W. Yates
Sheffield Hallam University
United Kingdom

Proceedings of the 29th International Symposium on Automotive Technology and Automation
Florence, Italy
June 3 - 6, 1996

Abstract

This work looks at the evolution of a typical family saloon car over recent years in terms of functional, aesthetic and environmental performance. The energy required in each stage of the vehicles life-cycle is calculated. A comparison of the environmental effects of replacing or refurbishing vehicles in terms of energy usage is carried out. It is suggested that although there are savings to be made by refurbishment or recycling the adoption design strategies which lead to a reduction in fuel consumption may result in the greatest life-cycle energy savings

Design for Optimal Environmental Impact

L. Holloway, I. Tranter & D.W. Clegg
School Of Engineering
Sheffield Hallam University

Book Chapter in:
Design for X: Concurrent Engineering Imperatives
Chapman & Hall
1996

Abstract

In the past environmental problems were seen, and dealt with, as specific problems affecting certain areas, such as waste disposal sites containing hazardous materials or certain stretches of river and waterways being polluted. Traditionally manufacturing and environmental problems were treated very much independently and little or no concern was given to the environment during the course of product development. As our understanding and awareness of these problems develops it is becoming apparent that design and manufacturing have a very immediate effect on the environment and can, to a large extent, dictate the effects which products and their related systems have on the eco-systems around us. If the environmental problem is to be addressed it appears that design practices will have to change. Design activities can dictate up to 70% of the total manufacturing cost of a product, so it would be reasonable to conceive that a large proportion of the environmental cost of a product can also be dictated at the design stage. The complexity of the product design process necessitates approaches such as concurrent engineering which utilises a number of methodologies and tools to assist designers and keep product development times low. The inclusion of further concerns, such as environmental, threaten to complicate design even further and as such the development of an environmental concurrent design methodology, Design for the Environment, is required.
The development of such a methodology facilitates the exploration of many new and existing areas of design. Consideration of the complete life cycle of the product from 'cradle-to-grave' is required if designers are to successfully address the environmental problems they are facing. The use of recyclable materials and re-using waste are some of the more obvious approaches which can be adopted, but others depend on complex relationships between, function, manufacturing and material choice. Designers must achieve a comprehensive understanding of these relationships and associated problems in order to design products which have the optimal

environmental impact. As with other concurrent engineering disciplines the development of computer based tools will go a long way in helping designers to achieve these goals.

There is a need for a holistic approach to developing solutions to the environmental problems. The whole life cycle of a product must be studied if complete decisions are to be made on it's ecological effects and it is no use making one part of the process *'green'* if the rest is unacceptably damaging. Designers must ensure that by providing one set of solutions to an environmental problem it does not create or increase others. They must grasp this concept fully to design truly *'green'* products as they have great influence over every aspect of the products life, from manufacture and ease of repair to use and final disposal.

From Product Designer to Environmentally Conscious Product Designer

T. C. McAloone[1] & L. Holloway[2]
1- CIM Institute, Cranfield University
2- School of Engineering, Sheffield Hallam University

Proceedings of the First Annual Conference on Applied Concurrent Engineering
Seattle, Washington, USA
November 5 -7, 1996

Abstract

In recent years there has been a growing interest in making products more environmentally benign. Until now public policy has focused mainly on industrial waste streams and end-of-pipe problems and paid little or no attention to the design and development stage of a products life-cycle. Product designers are in a unique position within the product development process and through design have an unrivalled opportunity to address environmental issues.
This paper examines the traditional role of the designer, the dilemma faced when considering environmentally conscious design and looks at how to progress in this field. Areas such as responsibilities of designers and design teams, frameworks for DFE and the information problem are all discussed. Finally the efficient use of environmental resources and networks is considered.

Legislation and It's Effect on Manufacturing Industry in the UK

Leigh Holloway
Sheffield Hallam University

Environmentally Conscious Design and Manufacture
IEE Colloquium
Digest No: 97/312
CIM Institute, Cranfield University
May 22, 1997

Abstract

This work looks at the ever increasing barrage of environmental legislation being brought into force in Europe and the United Kingdom. It attempts to predict some of the effects of this legislation on industry and offer outlines to solutions for manufacturers in their attempts to come into line with these regulations