Development of a Design for the Environment Workbench Software Tool

In One Volume

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DECLARATION

I hereby declare that the work presented in this thesis is my own and that it has not been used to obtain a degree in this university or elsewhere.

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Elena Man

DEDICATION

To my beloved parents…

PROLOGUE

The research described in this thesis was developed as part of the Green Advisor for Concurrent Engineering (GACE) Project. The GACE Project was founded under the Applied Research Grants Scheme administered by Enterprise Ireland. The GACE project was a partnership project between Regional Technical College Galway and CIMRU University College Galway, AST Computers Ltd. in Limerick and CEL Ltd. in Tuam. The project aimed to develop an advisor framework for a computer aided design tool to aid designers make informed decisions regarding the environmental superiority of a product at its design stage.

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Continuing with the "GACE people", Patri I want to thank you for your friendship and for guiding my first steps on the unstable ground of the GACE project.

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Chapter 1

Introduction

1.1. Thesis Motivation

Interest in the environmental qualities of products has been increasing over the last ten years. From an earlier focus on only few economic areas such as food and packaging, environmental interest has been expressed in almost all economic sectors. There are two main driving forces for the increasing environmental interest:

- Government driven forces i.e. legislation, Eco-taxes.
- Market driven forces i.e. customer pressure and Eco-labels.

Government Driven Forces

The authorities have been working on environmental legislation and environmental labelling regulations that are applied in the entire public sector. For example, in Ireland, The Environmental Protection Act 1990 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 refers to 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 Protection Agency (EPA).

It is essential to impose penalties on companies or individuals that break the law. This in itself drives industry to take environmental considerations into account. 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.*' An example of this type of legislation is the European Union (EU): The Waste from Electrical and Electronic Equipment (WEEE) directive introduced in 1998. [Lei97]

Market Driven Forces

Consumers have become more aware of the importance of environmental issues. It has been proved that the products carrying an Eco label such as Blue Angel[1] or Nordic Swan[2], are preferred to the other products with no environmental qualities [Wen97]. Because of this trend in consumer's opinion, companies are working on environmental management system and cleaner technology programmes to ensure the products they make comply with consumer's environment expectations. Many companies impose requirements on their subcontractors in order to ensure the environmental qualities of products throughout the product's life cycle.

Design for Environment

As a result of the increasing environmental interest a new concept has emerged as a key methodology in developing environmentally superior products. The concept is generally known as *Green Design* or *Environmental Design.* The concept has been defined at the Eco2-Irn Conference 1994 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"* [Eco94].

Until recently only specific areas within the Design for Environment domain have been considered as being of importance to the development of new products and have been introduced in the design process. These areas have been defined under the generic name of Design for X (DFX) and include techniques such as Design for Assembly/Disassembly (DFA/DFD), Design for Manufacture and Service (DFM/DFS). Over time, practice has proved that an early consideration in the design process of the *entire life cycle* of products saves money and time and enhances quality in the long run [Roc99].

Industry is maturing beyond these simple considerations and is taking a more holistic view as the companies begin to consider issues such as reductions of materials, reuse of

[1] Blue Angel Ecolabel has been developed in Germany and is the most widely recognised labelling system.
[2] Nordic Swan Ecolabel is an environmental labelling scheme developed for Finland, Iceland, Norway and Sweden.

components over multiple product life cycles and energy efficiency. This means that the designer can no longer be expected to consider environmental issues in a simple step manner, but as an integral part of every stage in the design process [Hol96].

The introduction of the environmental aspects in the design process may seem to generate two possibilities: firstly, to create a design team consisting of designers, suppliers, manufacturers, marketers, service engineers, distributors and end of life handlers; secondly, to make the designer an environmental expert. Unfortunately, implementing either of these solutions creates huge difficulties for management as follows: [Hol96]

- The first option involves the gathering of a vast amount of information that could create confusion in the development of the design process (not to mention the difficulties implied by the creation of such a team);
- The second option is difficult to apply because of existing pressure on the designers to develop high quality products in shorter time.

To overcome these difficulties a good solution seems to be the development of an environmentally conscious design tool, fully integrated in a Computer Aided Design[3] (CAD) environment that will help the designer to create environmentally superior products without being an environmental expert. The tool should be based on a powerful Design for Life Cycle framework and it should be supported by strong, up to date, information databases. This thesis tries to prove that the development of such a tool is possible.

1.2. Objectives of the Thesis

The research, which this Masters thesis is based on, is embedded into an industrial research project entitled GACE[4]. The main objective of the GACE project is to develop a environmental analysis tool to be used concurrently with engineering analysis tools to provide a design framework for environmentally superior products and process design. A prototype of this software tool, called *DFE Workbench*, is presented in the thesis. The DFE Workbench tool provides a framework that supports designers in taking environmentally superior decisions. The main goal of the DFE Workbench is to help the designer to implement the DFE techniques as early as possible in the design process.

The objective of the thesis is to prove the importance of integrating the design for life cycle principles in the design process in the early stages of the detailed design. This thesis also

[3] In order to create prototypes of products a designer uses a CAD environment such as AutoCAD, SolidWorks or ProEngineer tools. Details about CAD environment will be presented in Chapter 2.

[4] Green Advisor For Concurrent Engineering is funded by Industry and Forbairt (The Irish Science & Technology Board)

aims to prove that it is possible to integrate LCA and DFE processes in a virtual prototyping environment.

The *DFE Workbench* software application has been developed in order to attain these objectives. The *DFE Workbench* software is integrated in a virtual prototyping environment called SolidWorks 98Plus and provides a set of tools that enable the designer to perform environmental analysis on emergent designs. It also supports the designer with a prioritisation module and advice in order to create environmentally superior products.

1.3. Approach to Work

The research started with a study on the design process area followed by a study on the design for life cycle area. During the research it has become clear the two domains are closely related. It has been proved that the environmental issues are becoming very important for every sector of the industry and environmental analysis have to be considered in the design stage of the life cycle of any product. The combination of design process with environment area resulted in a study of the existent methodologies for designing environmental superior products within the Design for Environment (DFE) area.

A relevant DFE methodology has been selected based on a close study on existing DFE methodologies as the basis for developing a Design for Environment (DFE) Workbench Software Application. Also, a relevant virtual prototyping environment has been selected for the integration of the DFE Workbench software. The CAD Tool is called Solid Works 98 Plus and it has been selected because of its user friendly interface and the API[5] feature that permitted the integration. Solid Works came with a strong library of classes and objects that enabled the DFE Workbench integration. The DFE Workbench application has been tested throughout its development stages. Firstly it has been tested in CIMRU, a research unit of National University of Galway, and in Motorola. These preliminary tests resulted in significant changes that improved the performance of the tool. Secondly, the tool has been tested during a project developed in collaboration with a company called Jacobsen. The tests are detailed in chapter six of the thesis.

[5] Application Programming Interface

1.4. Thesis Structure

Figure 1.1. summarises the approach to work described in the previous section.

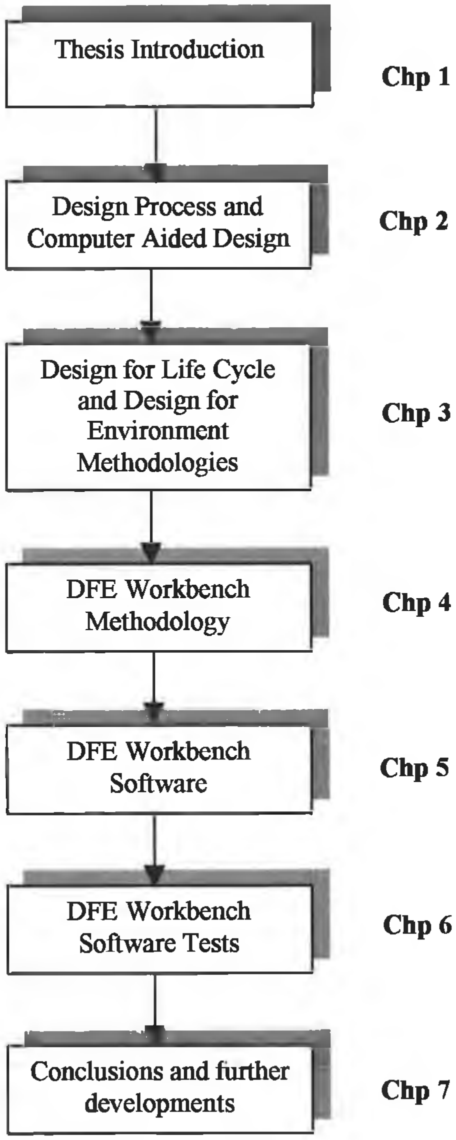

Figure 1.1. Thesis Structure

The thesis structure is as follows:

Chapter One presents the motivation, the objectives, the approach to work and the layout of the thesis.

Chapter Two contains a review of the design process and the CAD systems techniques for modelling product prototypes.

Chapter Three contains a detailed review of the Design for Environment concepts.

Chapter Four contains detailed information about the DFE Workbench framework developed within the GACE project presented in section 1.1. The DFE Workbench framework is the methodology used as a basis for developing the proposed software tool.

Chapter Five introduces the new software tool entitled DFE Workbench. The functional specification of the tool carried out using Data Flow Diagrams (DFD's) is presented in this chapter. The idea behind the DFE Workbench tool is the co-ordinated use of the modules, i.e. a 3D Solid Modeller, an Impact Assessment System (IAS) module, a Structure Assessment Method (SAM) module, a Prioritisation Module and an Advisor module.

Chapter Six presents a set of tests of the DFE Workbench tool, i.e. the preliminary tests carried out in Motorola and the design of an office chair developed in collaboration with Jacobsen, and that has been analysed using the DFE Workbench Software Application.

Chapter Seven concludes the thesis and presents recommendations for future work.

Chapter 2

Design Theory

He who loves practice without theory is like the sailor who boards ship without a rudder and compass and never knows where he may cast.

Leonardo Da Vinci

2.0. Introduction

Design theory is a vast domain that has been explored by many researchers from early centuries to present. In early days, philosophers like Leonardo Da Vinci, known not only for his art and for the man and nature studies but also for his creative designs, has designed the first flying machine, the first submarine and many other machines. Today's researchers are modelling artificial intelligent design systems and the future research will continue to reveal new aspects, techniques and models of designing.

This chapter reviews design theory with the aim of establishing criteria for the development of design tools. Initially several definitions of design are reviewed as they have been presented in time. Next the study continues with a review of the traditional design models broadly categorised as descriptive, prescriptive and computational models. A new category called *life cycle design* is introduced, which offers a more holistic view of the design process. It introduces early consideration in the design process of the entire life cycle of the candidate design from the raw material selection stage towards the end of life stage. The study particularly focuses on the computational models. Computer Aided Design (CAD) Systems fundamentals are also reviewed, with the aim of matching Design Process Models with CAD tool design.

Further on the design theory study will continue with a discussion on the importance of visualisation in the design process and it's impact on creativity. The chapter will conclude by outlining the importance of developing new design models as frameworks that stimulates the creation and introduction of new methodologies for life cycle analysis of product's prototypes, as early in the design process as possible. The structure of the chapter is illustrated in figure 2.1.

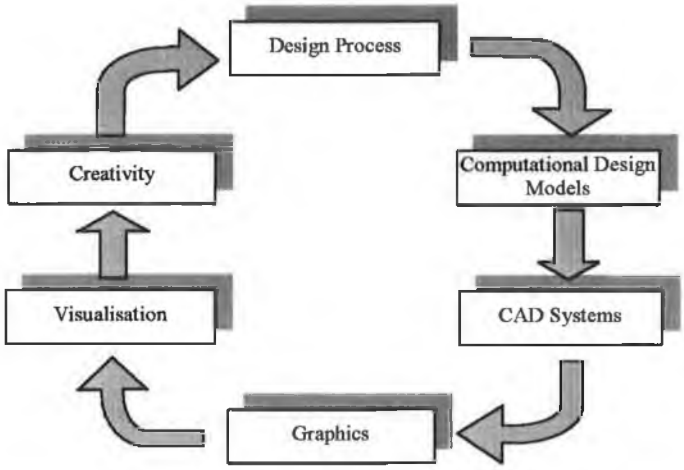

Figure 2.1. Design theory structure

The structure identified in figure 2.1 presents the author's view of the relationship between the design process, design models, cad systems, graphics, visualisation and creativity. This approach of the design theory is based on the definition of design theory proposed by Rabins et al: *"...design theory refers to systematic statements of principles and experientially verified relationships that explain the design process and provide the fundamental understanding necessary to create a useful methodology for design"* [Rab86].

2.1. Design Process

The study of the design process has been a preoccupation for engineers, designers and researchers over time. The research carried out by both industry and academia has resulted in various design philosophies, models and methodologies. Over time there have been many varied definitions given for design. For example:

In 1963 Feilden stated that: *"Engineering Design is the use of scientific principles, technical information and imagination in the definition of mechanical structure, machine or system to perform prespecified function with the maximum economy and efficiency"* [Fei63].

In the same year Caldecote stated that the function of design is *"... to design a product which will meet the specification, to design it so that it will last and be both reliable and* *easy to maintain, to design it so that it can be economically manufactured and will be pleasing to the eye"* [Cal63].

In 1983 Finkelstain defines design as *"...the creative process which starts from a requirement and défines a contrivance or system and the methods of its realisation or implementation, so as to satisfy the requirement. It is primary human activity and is central to engineering and the applied arts"* [Fin83].

In 1984 Luckman states that *"the process of design is the translation of information in the form of requirements, constraints, and experience into potential solutions which are considered by the designer to meet required performance characteristics ...some creativity must enter into the process for it to be called design"* [Luck84].

Based on the above definitions, in 1996 Evbuomwan describes design as *" The process of establishing requirements based on human needs, transforming them into performance specification and functions, which are then mapped and converted (subject to constraints) into design solutions (using creativity, scientific principles and technical knowledge) that can be economically manufactured and produced"* [Ebv96].

In 1999, after an in-depth research carried out in the design process area, Roche concludes that a more holistic definition is required, i.e.: *"design is a systematic problem solving process that uses the creativity, knowledge, experience, imagination and originality of humans to transform customer requirements into design specifications, from design specifications into functional requirements, from functional requirements to concepts and therefrom into detailed design representations of a product whilst optimising aggregate life cycle properties throughout all design phases and across many specialist domains"* [Roc99]

The definitions reviewed reflect the evolution of the design concept in time. While in 60s the focus was on designing reliable, long lasting and pleasing to eye products. The focus of the 90s is on early considerations of the product's life cycle. This includes the introduction of various specialist domains in the design process at various stages e.g. the introduction of finite element analysis in the detailed design phase. Considering the above definitions there have been various attempts to develop models of the design process. Some of these models simply describe the sequences of activities that typically occur in designing; others attempt to prescribe a better or a more appropriate pattern of activities. Some of the representative models are discussed in the following section.

2.2. Design Models

Design models are used to represent the design process and are important in the context of understanding the critical decision points and the types of decisions that a designer is confronted with, whilst in the design process [Roc99]. Design models have been traditionally divided into two types, i.e. descriptive models and prescriptive models [Pah96, Hub96, Evb96, and Fin89]. Another two categories are still evolving and these can be generally classified as life cycle design and computational models [Fin89, Evb96, Tom87, Yos81 and Roc99].

Descriptive Models

As the title suggests, the descriptive models attempt to *describe* the design process and to define it by identifying the sequences of activities that are generally performed during design activity. These models derives from the experience of individual designers and from studies carried out on how designs were created, i.e. what processes, strategies and problem solving methods designers used at various stages in the design process [Evb96]. Descriptive models are usually based on the protocol study methodology, i.e. a method to study the design process. Descriptive models emphasise the importance of generating a solution concept early in the design process. This solution is subjected to analysis, evaluation, refinement and development. Sometimes the analysis and evaluations show fundamental flaws and the initial solution has to be abandoned a new concept generated and the cycle starts again [Evb96].

One of the simplest descriptive models has been developed by Cross and it consists of four stages: exploration, generation, evaluation and communication. *Exploration* refers to the initial understanding of the problem space. *Generation* represents in fact the definition of a concept design resulted from the prior analysis of the problem space. Next, *evaluation* refers to the critique of the design proposal against goals and various constraints and criteria. The end point of the model is the *communication* of the design to the manufacture engineers.

French has developed a more detailed model of the design process. It consists of four core activities: analysis of the problem, conceptual design, embodiment of schemes and detailing (see figure 2.2).

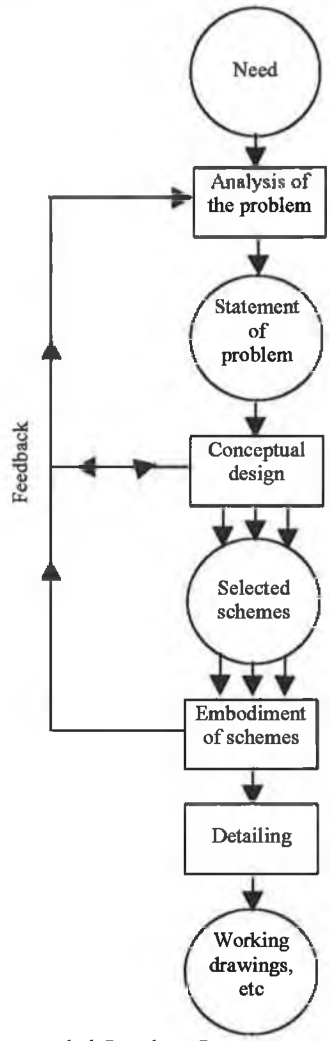

Figure 2.2. French's design model [Evb96].

In figure 2.2 the rectangles represents the activities and the circles represents the outputs. French's design model begins with the definition of *needs* and the first activity to be carried out is the *analysis of the problem*. This activity consists of identifying the design problem and the refinement of this problem after its confrontation with the limitations imposed by code of practice, statutory requirements, standards and time limitations. The output of this activity is a *statement of the problem*. The next activity in the design process model is *conceptual design*. This is the most important activity of the design process because the most important decisions are made here as the engineering knowledge, practical experience, production methods and commercial aspects come together in order to generate a design solution. The output of the conceptual design activity is a set of schemes of the generated solution. The conceptual design activity is followed by the *embodiment of schemes* activity. At this stage, the schemes previously generated are highly detailed and if there are more than one solutions proposed, a final choice is made. There is a feedback loop between this stage and the conceptual design stage as the solution is defined. The last activity identified by French is *detailing*. This phase is particularly intricate quality work because it deals with details of the solution such as transcription of the drawings and diagrams for manufacture. The introduction of Computer Aided Design[1] (CAD) systems has reduced this laborious work.

Jakobsen has developed a descriptive model based on the interrelations existent between function, material, production method and shape (see figure 2.4).

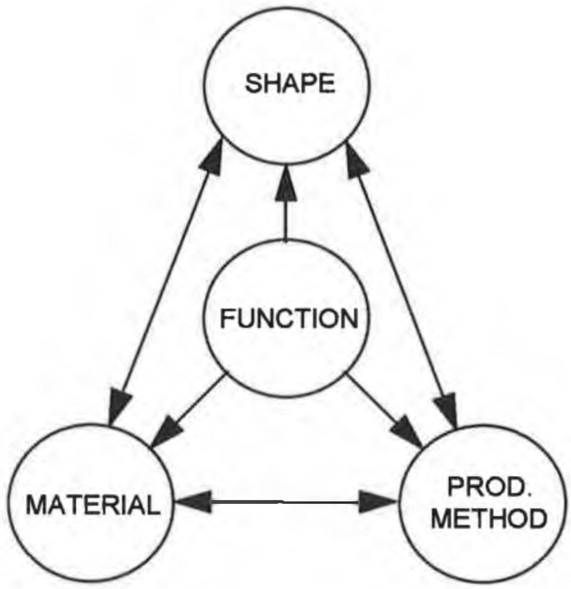

Figure 2.3. Jakobsen's model of interrelation [Hol97]

Figure 2.3. presents the Jakobsen's matrix of relationships among the components mentioned earlier. Each of the four components is directly related to the remaining three. For example, if the designer is at the point of deciding the shape of the product, the choice is restricted by the function that the product will perform the material that will be used and finally by the production method that will be used. The process is cyclic and all the elements are constrained by each other until a satisfactory solution is achieved. In summary, the model is a typical traditional problem-solving model consisting of *analysis*, *synthesis* and *evaluation* of the matrix of the different relationships among the four elements resulted from the design model [Hol97].

March has developed a new descriptive design process model based on three modes of reasoning, i.e. deduction, induction and abduction. He also identifies three steps in the design process i.e. *creation* of a novel composition (via productive reasoning, abduction), *prediction of* performance characteristics (via deductive reasoning) and *accumulation* of experiences (via induction). In summary, abduction is the creative process, deduction predicts and induction evaluates. These activities model a continuous improvement loop as the design is re-specified and the design goes through another evolution cycle [Evb96].

[1] CAD systems will be discussed later in this chapter.

The last descriptive model reviewed in the present study is the model developed by Matchett. It consists of five thinking patterns:

1. *Thinking with outline strategies.* Matchett states that the designer using this pattern has to be able to decide in advance what strategy should be adopted in the design process. During the design process, the designer should compare what has been achieved with what has been planned to achieve and he also needs to be able to create strategies for producing strategies.
2. *Thinking in parallel plans.* Designers using this pattern have to detach themselves from the design process and have to identify a pattern of thoughts while designing. Designers will identify the pattern of thoughts by observing their thoughts and their designer colleagues' thoughts during the design activity.
3. *Thinking from several viewpoints.* Designers using this pattern focus on the solution of the design problem instead of the process of finding it.
4. *Thinking with concepts.* Designers using this pattern imagine or draw geometric patterns that enable themselves to relate the design method to their memories and thoughts. This pattern enables the identification the memorisation of the relationships between the design problem, the design process and the solution.
5. *Thinking with basic elements.* This thinking pattern uses basic elements that make the designer aware of the large amount of the alternatives existent at each point of decision. The basic elements mentioned above can be categorised as: decision options, judgement options, strategic options, tactical options, relational options and concept options. First the designer needs to generate a variety of design alternatives. This involves analysing how each part of the design can be eliminated, standardised or simplified. If any changes are made, the designer needs to ensure that they are compatible with each other and with all the needs [Evb96].

Prescriptive Models

As the title suggests, the prescriptive design models tend to *prescribe* an algorithmic model to be followed for carrying out the design process. Many of the prescriptive models have been derived from the descriptive models analysed in the previous section [Fin89].

Jones has developed one of the simplest prescriptive design models. It consists of three stages [Cro94]:

1. *Analysis* is the stage where all the design requirements are identified along with the factors that affect the design solution. The output of this stage is a list of logically related performance specifications.

2. *Synthesis* stage consists of gathering all the possible solutions for each of the performance specification identified in the analysis stage. The output of this stage consists of full design proposals.
3. *Evaluation* stage consists of a detailed analysis of the design proposals in order to identify the best unique design solution.

Asimow has developed a similar three-phase design model as follows:

1. *Feasibility study phase.* This phase consists of a set of activities, firstly the needs are specified, secondly the design parameters, the constraints and the criteria need to be identified, finally several viable solutions are generated and analysed from manufacturing and financial perspectives.
2. *Preliminary design phase.* Similar to the previous stage, the preliminary design phase consists of a sequence of activities. Firstly, the best design solution will be selected from the solutions proposed at the previous stage. Next, solution algorithms are prepared and then analysed in order to establish the design parameter tolerances, the external and internal perturbation factors and the stability of the system proposed. Finally, the solution is optimised and the output of this phase is an experimental design solution.
3. *Detailed design phase.* This represents the last stage of the model proposed. It consists of a sequence of activities, firstly, the budget and the time constraints are established, secondly the detailed designs of the components, the sub-assemblies and the assembly are prepared, thirdly a prototype of the product is developed following the designs previously prepared and finally the prototype is tested in various environments and the final solution is generated.

In summary, Asimow's model consists of six generic activities: analysis, synthesis, evaluation, decision, optimisation and revision. These steps are then continuously repeated through each phase of the design process until a final solution is achieved [Evb96].

Hubka has developed a more detailed prescriptive model. It consists of four distinct stages that are summarised in Table 2.1. Hubka states that "*Each design process can be fundamentally structured with the help of a general procedural model into more or less complex partial processes, phases down to design operations and steps. The elements of the procedure that emerge are also processes within which the state of information is changed. Each of these elements is therefore directed towards a precisely formulated goal, which is evident from the procedural model. In order that these processes can proceed methodically and according to plan, directed towards the goal and under the given boundary conditions corresponding rules of behaviour and methodical advice must be* *available. These are contained in the methods or working principles, which can regulate the work as reference points*" [Hub96].

Stage	Sub-Stage	Description	Output
Elaborating Assigned Task	Elaborate the assigned specifications	Analyse and quantify the assigned problem. Complete requirements and set priorities	Design specification
Conceptual Design	Establish functions structure.	Establish the transformation process, technologies and function structure.	Function structure
	Establish organ structure	Establish inputs to TS and classes of function carriers, combine function carriers and examine relationships, establish organ structure, (an organ is a function performer).	Organ structure
Laying Out	Establish Component Structure – Preliminary Layout	Arrangement, rough dimensioning. Layout preliminary component structure.	Preliminary layout
	Establish Component Structure – Dimensional Layout	Deliver substantiation for design characteristics, form determination dimensional layout.	Component structure dimensional layout.
Detailing	Investigate alternatives.		

Table 2.1. Hubka's design model [Hub96]

Cross proposes a model of design with a number of different levels of abstraction (see figure 2.4). The higher level is a problem solving approach with an 'Overall Problem' and an associated 'Overall Solution'. Sub elements of these are sub problems and sub solutions respectively. Cross presents a set of stages for each of the sub problems and sub solutions. In turn, each of the sub-stages has a set of methodologies to perform the tasks. The model also generically represents a cyclical problem solving approach [Cro94].

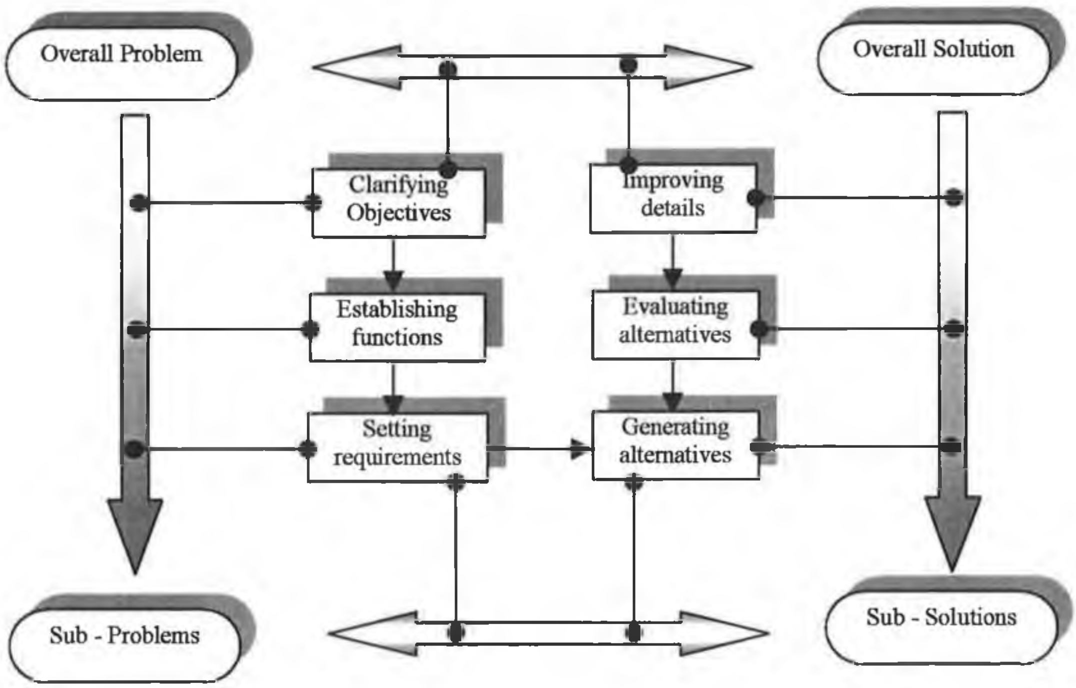

Figure 2.4. The design model by Cross [Evb96]

Pugh proposes a design model that encompasses product, process, people and organisation as performing a systematic activity that starts with the identification of needs and ends with selling a product that fulfil those needs (see figure 2.5). Pugh has called his model the Total Design Activity Model. It consists of the following central processes: market or identification of user needs, product design specifications, conceptual design, detail design, manufacturing and sales. The model shows that there are interactive movements between the proposed processes as the final design solution evolves. Recourse can be made to any of the earlier processes as new ideas and information emerge. The model also supports the use of various techniques that enables the designer's team to operate. These techniques include tools for performing analysis, synthesis, decision making and modelling and also includes more specific techniques such as stress analysis, hydraulics, thermodynamic or electronics analysis [Roc99].

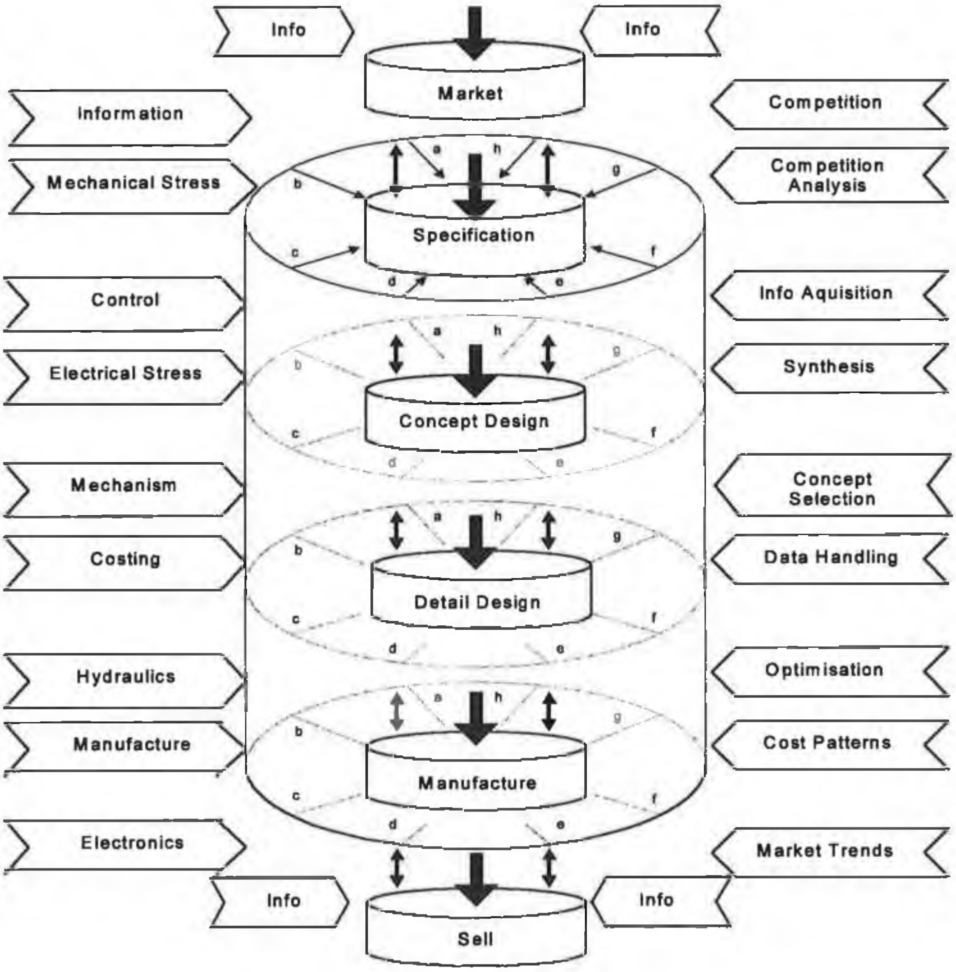

Figure 2.5. Total Design Model [Pug91]

Prescriptive models assume that a design can be decomposed into levels of abstraction and the design proceeds in a sequence through various phases. This assumption forms the main criticism of the prescriptive models as it is not always possible to draw a clear line between each of the phases [Pah96, Evb96, Bay96]. However these models are useful for describing a generic model of design in order to develop tools to support each of the phases [Roc99].

Life Cycle Design Models

The last decade has brought a new perspective to the design process. As people has become aware of the present environment problems that humans experience such as ozone layer depletion, water and soil pollution, acid rain, the researchers involved in the design domain have been trying to develop new design models to incorporate environmental considerations. For example environmental goals can be integrated with other design goals, the use of fewer materials, optimised design and appropriate fasteners meet both environmental and traditional design criteria. The incorporation of environmental designs during the early stages of product development is becoming critical for reducing long-term product management costs [APC90].

Life Cycle Design Models present two generic characteristics:

1. They attempt to integrate environmental considerations as early as possible into the design process.
2. They are generally developed to act as frameworks to support the development of new methodologies, techniques and tools to assist the designers to create environmentally superior products.

In 1997, Holloway has developed a simple Design for Environment (DFE) Framework on the basis of a modified version of the Jakobsen model reviewed earlier in the chapter.

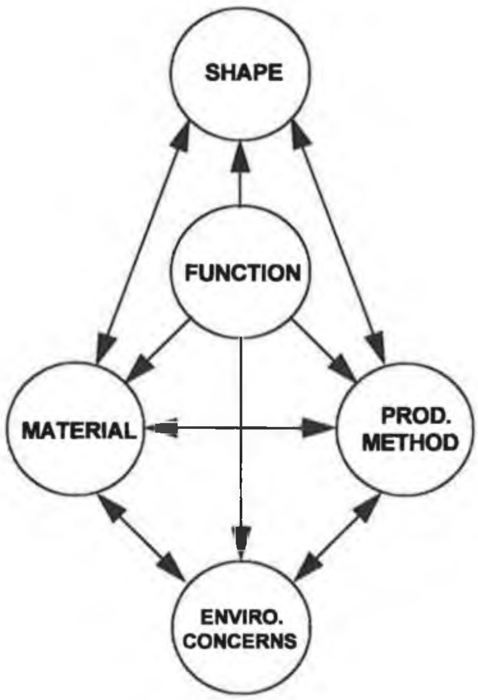

Figure 2.6. Environmental Adaptation of Jakobsen's Model [Hol97]

Using Jakobsen's Model as a basis, Holloway has developed an adapted model by including environmental concerns (see Figure 2.6). In the same way as the four components presented in figure 2.6. i.e. shape, function, production method and material are dependent on each other, they influence and are influenced by environmental concerns. The diagram also shows that there are direct relationships between environmental concerns and function, material and production method and only an indirect relationship between environmental concerns and shape.

Holloway has developed the model further onto a DFE Framework consisting of nine steps:

1. *Recognition.* Represents the first stage of the process and it consists of recognising the existence of environmental problems that can be solved or at least reduced trough design.
2. *Analysis.* This is the stage where the designer uses environment tools such as life cycle assessment, for identifying the causes of the environmental problems and for developing strategies to overcome these problems.
3. *Definition.* At this stage the designer defines the characteristics that the product must present in order to overcome the environmental problems identified at the previous stage.
4. *Exploration.* After the product characteristics have been identified, the designer needs to explore as many solutions as can be found for achieving the design objectives.
5. *Selection.* At this stage the designer needs to select the best solution that meet the environmental and economical criteria.
6. *Refinement.* After the solution has been selected, it needs to be refined and perfected by a detail analysis and by exploring any additional environmental design strategy that may be applied.
7. *Specification.* This is the stage where the manufacturing parameters are specified and their environmental advantages are presented.
8. *Implementation.* At this stage, the product is manufactured taking into account the environmental concerns.
9. *Bringing the product to market.* This represents the final stage and consists of packaging, distribution and if applicable after sales service all taking into account the environmental concerns. It also consists of communicating to the customer the environmental problems and opportunities.

Holloway admits that the model proposed is very limited as she states that the model "*is a simple straight forward, environmentally based product development framework*" but she highlights that "*as more of these exercises are carried out the experience gained will help in the refinement of the DFE frameworks*" [Hol97].

In 1999, Roche has developed a more complex model of the design process that supports the introduction of existing or the creation of new methodologies, techniques and tools to support design for environment[2]. The basis of Roche's model is represented by the design information loops presented in figure 2.7.

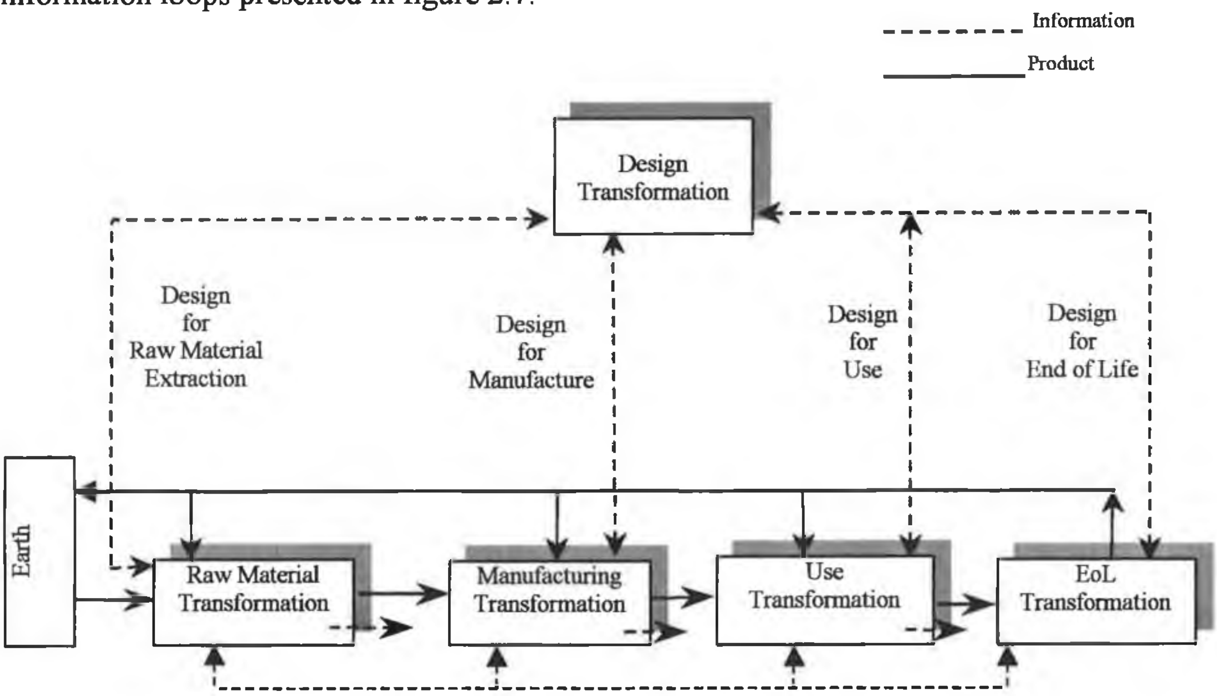

Figure 2.7. Design information loops [Roc99]

The information loops are as follows:

1. *Design for end of life.* This loop includes design information relating to the end of life options for the product, e.g. the product characteristics that promotes recycling.
2. *Design for use.* This loop takes into account design information that enhances the environmental superiority during the use phase, e.g. user profile or serviceability criteria.
3. *Design for manufacture.* This information loop enhances the environmental superiority of the manufacturing stage, e.g. production waste streams.
4. *Design for raw material extraction.* In this loop, the design engineer must evaluate the consumption of unsustainable raw materials. The design engineer must have a clear indication of the materials that are unsustainable and to implement design measures for reducing or removing the consumption of these materials.

[2] Design for environment has developed from a simple approach of the environmental concerns to a complex science that represents the core subject of the next chapter.

All the information acquired through these loops are transformed into design requirements for the product. Developing the information transformation loops model, Roche proposes a representation of life cycle design process as an tri-axial information transformation space (see figure 2.8).

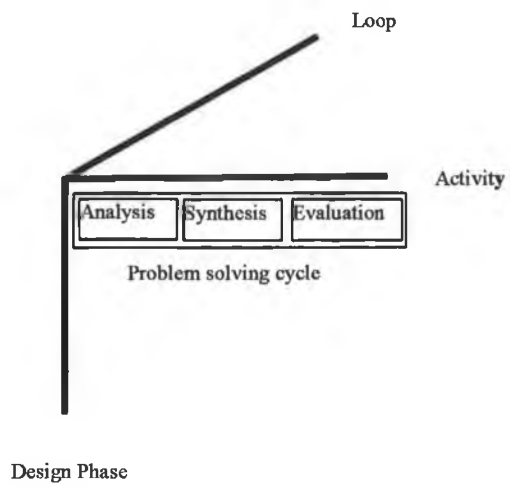

Figure 2.8. Tri-axial information transformation space [Roc99]

The axes proposed are as follows: the horizontal axis is the design activity phase, the vertical axis is represented by the degree of embodiment of the candidate design and the third axis is represented by the life cycle information loops.

Design Activity Axis

Roche describes the activity axis as a generic problem solving cycle consisting of the analysis, synthesis and evaluation steps. Consider for example the requirements specifications stage. It can be defined as an analysis, synthesis and evaluation of the design requirements.

Design Phase Axis

The axis represents the decomposition of the design process into four generic phases as follows:

1. *Requirements definitions,* is the stage where the requirements of the customer are translated into design specifications. The information in this stage is converted from general statements to design specification statements.
2. *Functional definitions,* is the stage where the design specifications of the product defined in the previous stage are converted into functional details.
3. *General design,* is the stage where the architecture of the system to be designed is defined. There is no detailed information associated with the data in this stage. The result of this stage is architecture of components to satisfy the functional requirements defined in the previous stage.

4. The final stage, *detail design* is the stage where the component's interactions are hierarchically related and detailed design information is supplied.

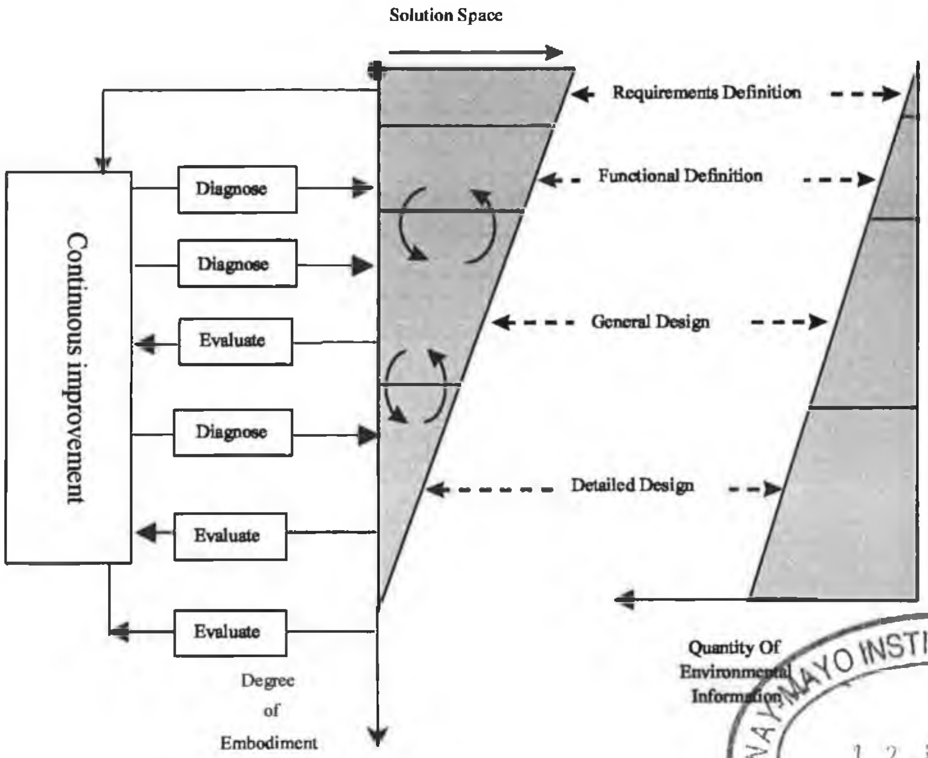

Figure 2.9. Generic evolution of design [Roc99]

Figure 2.9 is a representation of the relationship between phases and the solution space. It shows that the solution space decreases with each phase until, in the detailed design, one single solution is selected. In the same time, the amount of environmental information increases with the detailing of the design architecture. The phase and activity axes define the bounds of a design process plane where the problem solving cycle occurs explicitly at different levels of abstractions. While, for example, in the requirements definition stage the information is processed in the problem solving cycle at a general level, in the detailed phase the problem solving may be highly specific e.g. thermodynamic analysis of a specific sub-assembly. The design process plane defined by Roche acts as a useful framework that supports the development of new methodologies applicable at any stage in the design process.

Design Information Loops Axis

Roche describe this axis on the basis of the information transformation loops model described earlier in the chapter. The information loop axis combined with the activity axis bounds another plane called life cycle problem solving plane that ensures the analysis, synthesis and evaluation of life cycle information throughout each phase of the design process.

Roche has called the resulting model derived from the tri-axial information transformation space the Phase, Activity, and Loop (PAL) framework for life cycle design (see figure 2.10).

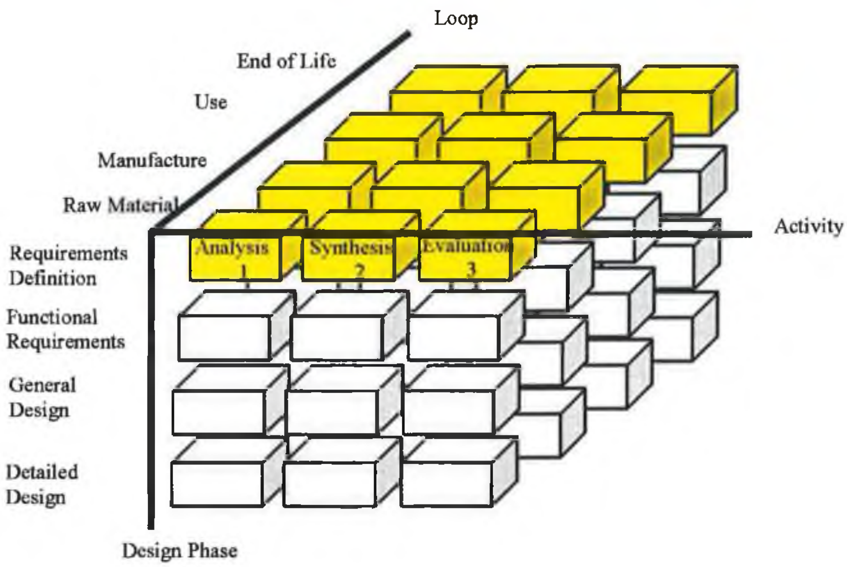

Figure 2.10. PAL life cycle design framework [Roc99]

In summary, each block within the model represents a transformation of information from one state to another. The information comes from many areas. For example, the requirements definition phase consists of the analysis, synthesis and evaluation of life cycle loops (see shaded portion in Figure 2.10). Block one represents the analysis of requirements for the raw material extraction phase, block two represents the synthesis of these requirements and block three describes the evaluation of resulting requirements. Each block in the framework can be considered to represent a partial or a full method or a set of methods (a methodology). The utilisation of the steps: analysis, synthesis and evaluation encourage the continuous improvement of a design proposal at any stage in the design process [Roc97]. Some methodologies have already been developed to support problem solving in each of the design phases e.g. The Quality Function Deployment (QFD) methodology. This methodology can be viewed as a problem solving process. For example the first phase provides for the *analysis* of customer requirements (analysis phase), the second caters to the creation of a list of those requirements (i.e. *synthesis* of '*what's* and *how's*'). Finally, there is the correlation of 'how's' and prioritisation of requirements for the candidate design (*evaluation phase).* Similar methodologies must be developed for each of the design cycle stages, particularly facilitating environmental problem solving.

The PAL framework is designed to support the development of methods, methodologies and tools to support life cycle design [Roc99].

Computational Models

Design problem solving frequently incorporates computation as part of the problem solving process and computational techniques have been available since early times. The computational design models have started to develop at least since Napier's work on logarithmic tables and also since the later work of both Newton and Leibniz who in the 1670s developed *Calculus*. It represents the mathematical theory of differentiation and integration of infinitesimal that revolutionised the application of mathematics to a wide range of practical computational problems of particular importance to design. Techniques such as these helped to develop the notion that computational methods could be capable of generating problem solving algorithms with general applications [Lid98].

The computational models describe the methods by which the computer themselves can perform the task of designing. A computational model of design views design as a problem-solving domain. Baharami cites two approaches to computational models:

- *Optimisation* can provide a vital solution in cases where a design problem can be formulated based on the function and the functional requirements.
- *Simulation* is a model-based approach to problem solving. Simulation allows us to study the design performance given a set of functional variables. However simulation does not optimise the result.

Computational models of design are important from the point of view of developing new CAD tools and they support the research into design theory and methodologies. In computer based models the information about the design process is entirely in the computer program. These models do not necessarily have to be derived from human behaviour [Wal196].

Computational Design Models and CAD

The access to computers has increased over the last number of decades and the range of applicability of computer analysis to the design process has been also extended. The fields which CAD systems are required to support are very wide. In one of his papers [Iaw92] Iawata identifies three areas of work in the various design phases: creative, innovative and routine work.

Most practical CAD systems support only routine work that appears in the detailed design phase. Such CAD systems termed Computer Aided Drafting systems, contribute to automating and improving existing design techniques and provide semi-automated functions such as annotation of the drawings with dimensions and labels. They facilitate the repetitive use of drawing geometry and perform simple calculations.

On the other hand, the conceptual design phase is far from being computerised because it includes a large amount of creative work. This creative work however includes much simple routine work that it is combined in a complex manner. Present computer science and CAD technologies are able to provide powerful supporting tools for this complex but routine work. In the recent years there was a significant amount of research carried out in the field of Artificial Intelligence (AI) in order to extend the capabilities of CAD to cover the area of innovative work. These systems are sometimes termed Computer Aided Drafting and Design (CADD) and they encompass optimisation, engineering analysis such as Finite Element Analysis used for stress calculation on virtual components, or data retrieval from vast databases. This however is more specific to the aerospace industry where the tradeoffs between performance, cost and weight are always critical.

One of the problems faced by the designers is that there are many candidate designs to be analysed in the preliminary design stage and the analysis need to be carried out as quick as possible. For this reason, rigorous analytical techniques are too computationally intense too be practical. It has been proved that approximate analyses based on simplifying assumptions, rules of the thumb and historical data are more useful at this stage. On this basis the software developed for preliminary design tends to be very special-purpose and it is usually developed 'in house' rather than purchased from a commercial vendor [Kol93].

Because of the significant impact of the preliminary design on the final result of the design process, preliminary design is more effective when performed using a multidisciplinary approach. Also, because the design evolves over time, the software developed to support preliminary design must be able to adapt to new design concepts. On this basis a computer system for multidisciplinary preliminary design must be able to incorporate new analysis codes as new design tasks are encountered and support the replacement of the old codes as their domains are superseded. It also must be able to perform mixed levels of analysis as in the preliminary design there may be a need for a more detailed analysis of a critical component while the rest of the components can be adequately analysed with the use of a more generic analysis tool [Kol93].

Over the entire design process, it is typical for a designer to use various forms of pictorial representations such as sketches. The use of the relatively unstructured forms of pictorial representations in the preliminary design and the use of more structured pictorial representations as the design evolves has been considered for a long time to be an essential part of the design process. The structured pictorial representations have been associated with the routine work while the unstructured forms of pictorial representations have been associated with the innovative and creative work. As stated above, most of the CAD systems rely on the structured pictorial representation covering the routine area of work. The very basis of any CAD system consists of geometrical representations. The most generic representation types are discussed in the following sections.

2.3.1. Two Dimensional Representations

An object representation consists of two components. Firstly is the representation of *form*, which means the representations of the object's shape. It can be done with the use of geometric entities like lines, circles and rectangles as presented in Figure 2.11.

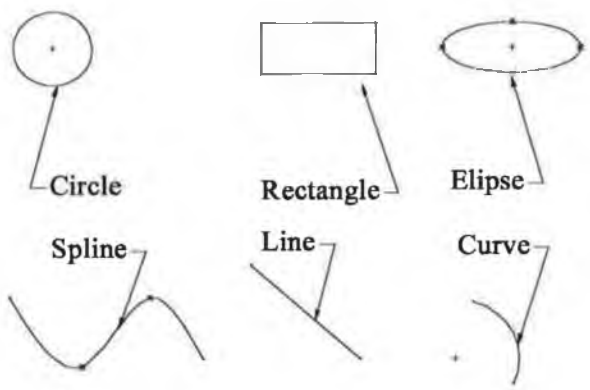

Figure 2.11. Geometric entities used in any CAD system

Secondly the representation of *structure* is made with the use of diagrams, which is a symbolic representation to support design management.

Form Representations

Engineering drawings are used for representing the shape of an object. There is a science, known as *'Descriptive Geometry'*, which studies the different ways of representing a three dimensional model in a two dimensional space. The Descriptive Geometry science has been developed on the basis of the Gaspard Monge's[2] principles [Bro98]. For an object to be considered fully defined there is a need for three representations in two-dimensional space. It has been considered that three views will reveal all the features of a particular object. However for more complex shapes, more representations may be required. There are two principal conventions to specify how the views should be related to each other in a drawing:

[2] Gaspard Monge (1746-1818) was a French military engineer. He formalised a method of representing shape by projecting views of an object on two perpendicular planes. In Monge's model the horizontal plane represents the planes used in drawings whilst the elevations are depicted in the vertical plane.

- Third Angle Projection that is used in North America with a certain acceptance in the United Kingdom. In this case the projection plane is between object and viewer.
- First Angle Projection that is used mainly in Europe, results from the positioning of the projection plane behind the part.

Figure 2.12 shows an object using the first angle projection convention. The view labelled A is the front view of the object. The view labelled B is the lateral view representing the object. The view labelled C is the upper view representing the projection of the object in the horizontal plane.

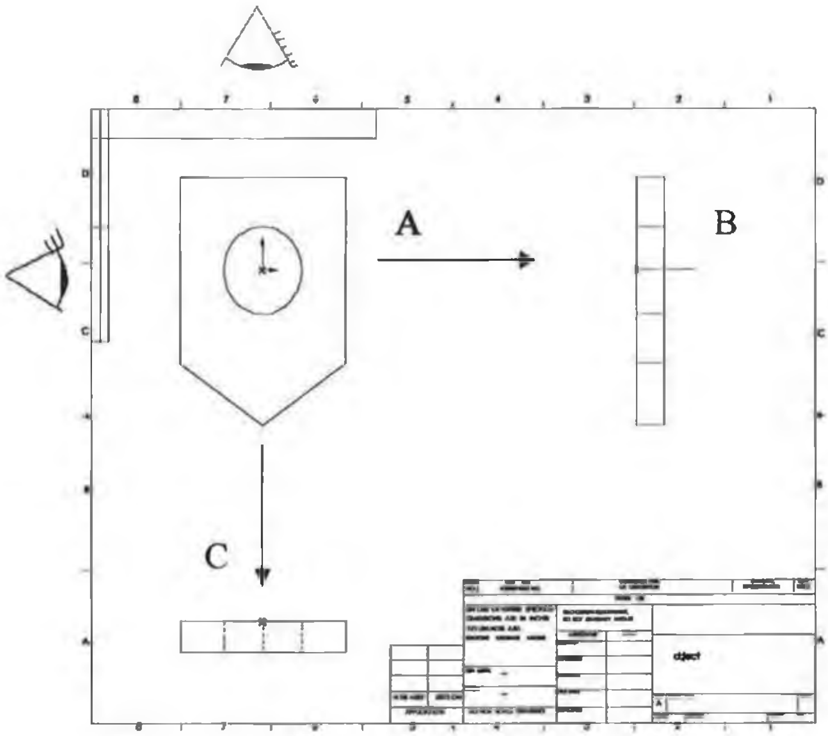

Figure 2.12. The representation of a model using 3 projections

Design conventions have been created and adopted in the form of design standards. Examples of such standards include American National Standards Institution Y14 Series or British Standard Institution BS308 series (adopted in 1980). The development of these standards is based on the need for a "common language" between designers and manufacturers. Some of the conventions presented in these standards include the types of lines and their meaning e.g. dashed lines are used for representing hidden edges, others refer to symbols to be used in the representation of surfaces such as tolerances or aspect of the surface. Without these conventions the possibility of occurrence of errors is very high because of the large number of drawings required for the manufacturing stage and because of the skills required for interpreting drawings. Computer Aided Drafting address this needs by assisting the designer to obtain more accurate representations in shorter time.

Structure Representations

Structure representation refers to the representation of the object's functionality. It is a symbolic representation using diagrams, which are a collection of symbols joined by connections. The symbols represent components of the system whilst the connections represent the relationships among components. A very common structure representation method is called the '*top down*' [Bro98]. Figure 2.13 represents a structure diagram using this approach.

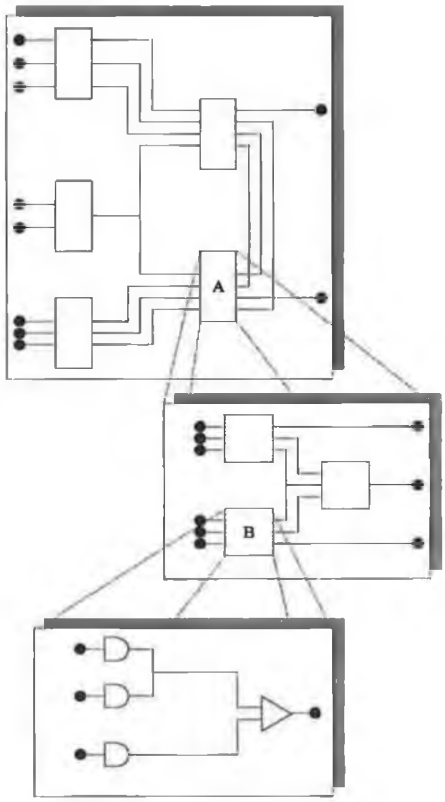

Figure 2.13. Structure Diagram

The top-down technique allows the designer to use a diagram symbol to represent another diagram at a different level. At the beginning a block diagram is developed. It represents the overall relationships among the system components. Then using the block diagram, the design is divided by components, which are analysed separately. In this way a hierarchical decomposition of a diagram is obtained.

Diagrams can be easily built by computer aided schematic systems. These representations are known as '*netlists*' and they help designers to identify unused connection points on symbols or uncompleted connections [Bro98]. Diagrams also help the designer to save time and to reduce the occurrence of transcription errors that usually appear in complex diagrams.

2.3.2. Three Dimensional Representations

Two-dimensional representations have great strengths and have served engineers very well over the years. However they can accentuate the number of errors particularly when complex product drawings are to be created. Sometimes complexity in the product may stretch 2D representations to their limits. For example there are some geometric entities that are very hard to represent, e.g. doubly curved surfaces on automobile or aircraft bodies. Another weakness of conventional representations is that the drawings can be easily misinterpreted.

Two-dimensional drawings contain valuable information for interpretation. However with increasing complexity of artefacts the probability of misinterpretations is very high. As a consequence of these limitations three-dimensional methods of representing design have been developed. Three-dimensional models contain more information in a single view that can replace multiple views, reducing misinterpretations of complex models and avoiding the transcription errors. There are different methods in three-dimensional representation as follows:

- Wire-frame representations
- Surface Modelling
- Solid Modelling

Wire-frame Representations

Wire-frame representation is the first three-dimensioning method developed. Its name derives from the wire-like appearance of the models. The entities used in this method are the same entities from computer aided drafting but the data stored to define the entities is extended. The objects represented in wire-frame method have no hidden lines and the surfaces are not pictorially represented (see Figure 2.14).

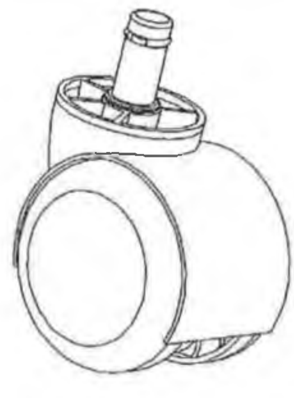

Figure 2.14. Wire-frame representation of a chair's wheel [Man00]

The advantages of the wire-frame representations include: [Bro98]

- They are easy to use.
- They are economical in terms of computer time and memory.
- They are particularly useful in the preliminary work, in solving geometric problems or for establishing the overall spatial relationship for a design.

The deficiencies include: [Bro98]

- The representations are ambiguous and hard to interpret.
- The ability to calculate mechanical properties or geometric intersections is limited.
- It is not valuable from manufacturing or analysis point of view.

Surface Modelling

The development of the surface modelling method has solved many of the ambiguities identified in wire frame method. In this case, the representations of models are performed by the use of surface representations. There are several different types of methods of representing a surface. Some of them are briefly described as follows:

- Tabulated cylinder, this is represented by projecting a generating curve along a vector (see Figure 2.15.).

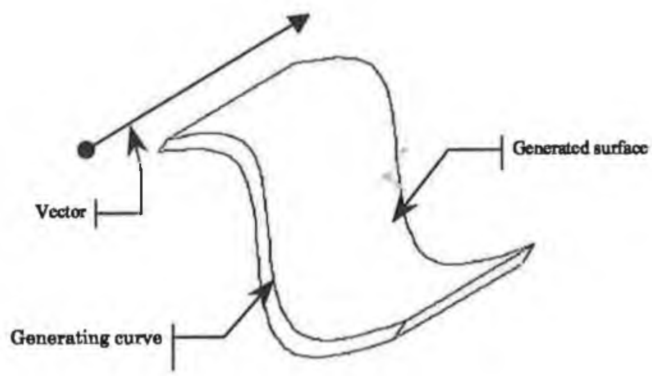

Figure 2.15. Surface representation

- Ruled surface, this is represented using linear interpolation between two generating or edge curves.
- Surface of revolution, this is represented by revolving a generating curve about a centreline or a vector (see Figure 2.16.).

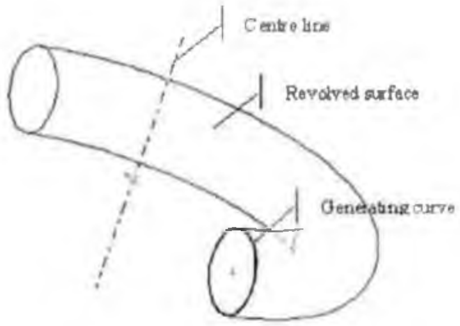

Figure 2.16. Surface of revolution

- Swept surface, this is represented using a defining curve that is swept along an arbitrary spine curve.
- Sculptured surface, this is defined by a grid of generating curves that intersect to form a patchwork of surface patches (see figure 2.17.).

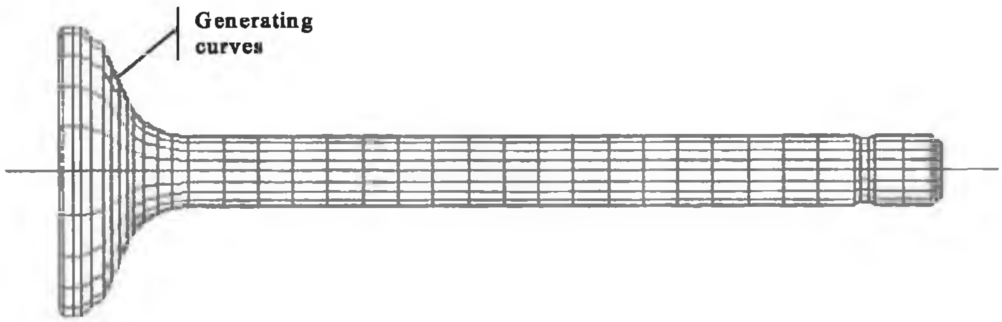

Figure 2.17. Sculptured surface [CAD97]

Surface modelling is widely used in sectors such as the automobile and aircraft industry where complex shapes are usually represented. For example surface modelling is used in the automobile industry for styling purposes in designing body shapes.

The advantages of Surface Modelling systems are as follows: [Bro98]

- Ambiguities from wire frame models are eliminated.
- The surface model provides an excellent basis for the generation of manufacturing information.
- Complex forms can be precisely modelled.

The disadvantages include: [Bro98]

- It is more computationally demanding than wire frame.
- It requires more skill for construction and use.
- Models of any complexity are difficult to interpret unless viewed with hidden surfaces removed.
- Visual inspection of the model is required to identify impossible geometry.
- There is no connectivity between surfaces, if a surface is changed the designer will have to change the adjacent surfaces.
- The model designed with Surface Modelling method will be a collection of surfaces without any information about the solid object.

Solid Modelling

Researchers in computer graphics have been constantly looking for tools for modelling real objects. Such tools must provide:

- A representation scheme based on a mathematical model adequate for objects realisable in 2 and 3 dimensions.
- A data structure to store the representation of a valid object
- A practical manner for creating a model on a computer from scratch.

Two different strategies has been proposed for solid modelling:

1. Constructive solid geometry (CSG), also known as the set-theoretic or Boolean method.
2. Boundary representation (B-rep), this is a graph-based method and represents the most frequently used method in today applications.

Constructive solid geometry is a method, which uses combinations of simple solid primitives such as cubes, cylinders, spheres, etc. The models built with the CSG method have the advantage that they are very compact, and are guaranteed to represent solids unambiguously. The disadvantage is that the range of geometric primitives is limited to those with planar or quadratic surfaces, and the geometric complexity causes performance degradation.

Boundary representation is the most frequently used method in today's solid modelling tools. The models built with this method contain no information about connections between surfaces. Surfaces are called 'faces' in this method. Systems using this method incorporate methods for checking the topology consistency of the models that is in part achieved by using data structures in which the faces are linked. The system will ensure that: [Bro98]

- The faces of the model do not intersect each other except at common vertices and edges.
- The boundaries of the faces are simple loops of edges that do not intersect with each other.
- The faces of the model close to form the shape of the object with no missing parts.

Boundary representation (see figure 2.18.) is widely used in visualisation packages e.g. games and flight simulators. It has the advantage that stores information about faces and edges in an evaluated form allowing the extraction of information directly from the data structure. For example it permits the calculations of the area of a surface, simply by adding the area of the faces involved. The disadvantage is that the boundary representation method requires large data files because of the amount of data stored

Figure 2.18. Solid model of a chair mechanism [Man00]

Both B-rep and CSG techniques apply when one just needs to look at an object as inducing 3-part space decomposition: its interior, its exterior and its boundary. For many applications this space decomposition is not enough. For instance, sometimes it is necessary to represents objects made from several materials with different properties (e.g. semiconductor circuits) or objects possessing many regions (e.g. finite element meshes). Traditional modelling systems are deficient in modelling contact relationships between solids. A significant amount of research is carried out in this field and there are several methodologies developed to cover the deficiencies highlighted above. The weakness of these methodologies, although very powerful, is that they are very specific and cannot be used as generic techniques. For example Discrete Element Method is a numerical method that geo-technical engineers use to analyse the interactions and the movement of rock blocks originated from natural fractures in a rock mass [Cav97]. However these methodologies are not further detailed as they are out of the purpose of the present thesis. The next section will focus on the importance of visualisation in design.

2.4. Visualisation and Creativity

Designing is considered to be one of the most significant intellectual activities because of its complexity and its effects on society. Design activity is the basis of almost any domain of human society starting from industrial, architectural or software design to the simplistic designing of one person's garden. All design activities, regardless the domain in which they are performed, have a similar pattern at an abstract level that starts to differentiate as the designing process is becoming more specific.

A significant research activity has been performed in the design field by both design theoreticians and psychologists as the design field is strongly related with cognitive psychology. There is a large number of design theories developed in time, some of them complementary others contradictory. However there is a generally accepted view of the design activity that considers that design can be classified under three broad categories:

1. Routine design
2. Redesign
3. Non-routine or creative design.

Routine design is a design type that has been deeply and systematically studied. Its main characteristic is that it works in known space in the means that it is performed on the basis of a predefined plan and involves no creative activity. Computer Aided Design (CAD) systems have been developed mostly to replace this type of design.

Redesign is very similar with the routine design and involves the modification of an existing design to meet new requirements and to increase the performance of the product. The work involved in the redesign process has been also automated by the existing CAD systems.

Creative design has been a challenge for the researchers in the design field. It refers to the creative work that the designer performs usually in the early stages of the design process. Purcell identifies two types of transformations into the design process. There is a *lateral transformation* identified in the preliminary design that consists of idea siftings in the creative process. Given the unstructured forms of pictorial representations, the designer can easily move from one idea to another until a plan is generated. Next by the use of *vertical transformations*, the generated plan is analysed, the main components are redrawn moving subsequently towards details. Vertical transformation is typical for the refinement and detailed design phase [Pur98].

The focus of the current section is on the creative design as it is the basis of any design study for the development of design models, methodologies and tools to support design process. The goal of any creative design study is twofold:

1. The development of new computer tools to support as much as possible of creative activities involved in the design process.
2. The creation of new design models in order to enhance design expertise and therefore supports the learning process

Innovation and creativity has been long considered to be associated with the unstructured and ambiguous forms of pictorial representation in the early design. The researchers have been involved in the dissemination and analysis of the creative process characteristic for design by conducting protocol analysis also known as empirical studies. A common subject of debate among researchers has been upon the role of imagery on the creative design and on how sketches influence lateral transformations into the creative process. There have been pro and contra theories enunciated and the following section will attempt to address them.

The Role of Imagery in Creative Design

The research carried out in the cognitive psychology has provided valuable insights on the use of pictorial representation for problem solving in the design area. Newell and Simon have disseminated this structure and they proposed a model of problem solving the creative process. The model consists of: *long-term memory* used for storing knowledge from various domains (a pool of a variety of knowledge types); *short term memory*, where the knowledge and procedures relevant for solving the problem are retrieved from long term memory, and where the cognitive activities are performed. This model of working memory has been developed largely on the basis of research and audition. Later on, Miller demonstrated that the capacity of the short-term memory is limited to seven plus/minus two chunks of information [Pur98]. Given this limitation, the majority of cognitive activities and problem solving are too complex to be processed and held in the short time memory. For this reason, Baddley completed the above model by suggesting that there are another two components involved identified as being firstly a *central executive* that performs all the cognitive activities directly involved in thinking and problem solving. And secondly a *cache* used for storing the partial results and needed material from long term memory [Pur98].

Detailing the model, it has been identified through experiments that complex thinking and problem solving involve the manipulation of two types of information: *verbal information* and *image information*. Image information consists of two important elements i.e. spatiality and visual properties such as colours. In summary, Baddley's model implies that the information is stored and then separately processed. In contradiction, Shah and Miyake performed some experiments that proved that processing and storage are performed simultaneously [Pur98]. The logic behind their model is: *"if measures of spatial and verbal working memory predict performance on spatial visualisation and language test, equally well, this would provide evidence for a single pool of general resources."* In order to prove this idea, Shah and Miyake have performed some protocol studies consisting of verbal and spatial memory span tests. The results of the tests were consistent with a model where both processing and storage occur together but there are different pools of cognitive resources allocated to visual respectively verbal information [Pur98].

In the context of the above models, the psychological literature on creativity in mental imagery has studied several different mental imagery processes. Because some of these processes are easy and frequent and others are difficult and rare the role of sketching in the creativity models is perceived differently. One group represented mainly by Finke and Slayton argue that the sketches are just a memory aid that do not enhance creativity while another group represented mainly by Chambers, Reisberg and Reed, argue that sketches promote restructuring in the idea generation process and therefore they enhance creativity [Ver98]. In this context, Finke prepared a set of tests in order to prove its beliefs. One of the tests consisted on asking a number of subjects to synthesise simple elements like several capital letters into existing object solely by the use of mental representations. For example, by combining the letter 'J' with 'D' the subjects were able to recognise an umbrella. Next, the subjects were allowed to use sketches. The results obtained in the last set of tests were not significantly better therefore Finke concluded that sketches may aid the memory but do not enhance creativity. On the other hand, Chambers and Reisberg also prepared a set of tests consisting on dual figures. A dual figure is a figure presenting an object or animal. If this figure is reversed it change its first interpretation and represent a different object or animal without any particular relation with the first interpretation. An example of a dual figure is presented in Figure 2.19.

Figure 2.19. Bird/rabbit dual figure [Pur98]

When the figure was presented to the subjects as representing a rabbit they were unable to discover the alternative interpretation solely by a mental projection of a rabbit. The discovery was easily made when the subjects were allowed to visually inspect the figure. The results proved the limitation on discovery in mental imagery as compared with visualisation (visual perception) and therefore the major role of sketching on creativity. Both views are strongly supported by a number of other protocol studies that will not be discussed in the present study [Ver98]. Analysing both arguments, Verstijnen observes that both views are correct as they are elements of a unitary concept that creativity consists of two main components: *Restructuring* and *Combining*.

Considering the experiments presented above, Verstijnen observes that Finke experiments are carried out in the combining area of creativity. The tests have been easily performed in mental imagery as they imply *combining* simple structures. Finke's tests differ essentially from Chambers and Reisberg's experiments where the subjects had to identify a new structure in a previously known figure. This operation involves *restructuring* the given figure. The experiments performed by Reed, support Chamber and Reisberg's point of view. He showed that "*the extraction of unanticipated novel component is difficult in imagery as compared with visual perception.*" One of the experiments proposed by Reed consists of presenting a composite figure to the subjects followed by another one. The subjects must decide if the second figure is contained as part of the first. The experiment proved that alternative composition was not recognised in mental imagery [Ver98].

Verstijnen has concluded his observations stating that: "*if the processes of combining and restructuring impose different loads on mental imagery, different effects of paper-and-pencil support can be expected. If the mental imagery task is easy, as in the Figural Combination task (Finke), minor effects are expected. If the mental imagery task is difficult because of the restructuring, sketching is expected to enhance performance in the*

Component detection task (Reed)" [Ver98]. Also, he shows that the inability to perform restructuring in mental imagery proves the importance of sketching in creativity.

Based on the research on the creative process, Verstijnen has identified several requirements that a computer aided design system must fulfil in order to be considered as tools supporting idea generation sketches in the creative phases of design. These requirements are:

1. These tools must be intuitive
2. Their use must not require specialised knowledge
3. They must support combining in very fast manner as combining itself is not an objective for externalisation
4. They must support restructuring by supporting unspecified forms for input. They also must allow flexible switching between different structural descriptions of the input after its creation.

A research carried out in the Computer Aided Design field by Kolli and Stuyver showed that any of the known CAD systems do not meet the above requirements and therefore they can't really help the designer in the creation phase of design. The closest models have been identified to be the Electronic Sketch Tables as they support unspecified input and leave the combining and restructuring processes to the designer. Currently they do not support restructuring therefore they need major improvements such as the implementation of a function that allows different interpretation of a given input [Ver98].

Later research in the design area regards the extension of the today's CAD systems capabilities into more visual and interactive environments. In this context, Virtual Reality (VR) emerged as a technology used in the amusements fields but it has been also experimented as human machine interface revolution in product design fields. Although carrying several unresolved problems (e.g. speed vs. reality), VR has given significant improvements in user interfaces such as stereo view according to a head movement and object manipulation according to a hand movement [Shi96]. Currently, VR systems are used only as separated visualisation tools. The most recent research in the area is carried out for enabling the integration of VR into CAD systems. This integration enables the designers to interactively visualise and modify virtual prototypes of products under development. This interactive modification of VR product models can improve the quality of evaluation and negotiation while reducing costly physical prototypes [Shi96].

2.5. Conclusions

The chapter identifies and discuses the important elements of the design theory. The study begins with a review of a number of definitions enunciates at different moments in time. On the basis of the definitions reviewed, the study continues with a discussion of the existing design models broadly categorised on descriptive, prescriptive, life cycle and computational design models. In this context a particular emphases has been made on the last category as it represents the environment that will integrate the software application being developed as a result of the research carried out in the context of the present thesis. Computer support of design analysis tasks is a key element in improving the productivity of design engineers. This undertaking is particularly difficult for preliminary design, where products are constantly evolving and therefore the required analysis change. Therefore towards the end of the chapter a more abstract level of the design process is discussed highlighting the importance of visualisation in the creativity work implied by designing.

Several conclusions have been identified throughout the research carried out in the present chapter. They are as follows:

- Presently a new category of the design models is under development. The author identified this category as life cycle design models. The design models gathered under this category attempt to integrate environmental considerations as early in the design process as possible. The models are also developed as frameworks to support the development of new methodologies for assisting the design of environmentally superior products [Roc99].
- Computational design models is another area where significant research efforts are presently focused for the development of computer design systems to support creativity in preliminary design. In this context several requirements have been identified as vital for this type of systems. They must be intuitive, they must require no specialised knowledge, they must support fast combining activities for a given structure and they must support flexible switching between the structure of a given input [Ver98].

Chapter 3

Design for Environment

The earth we abuse and the living things we kill will, in the end, take their revenge; for in exploiting their presence we are diminishing our future

Marya Mannes

3.0. Introduction

The aim of this chapter is to review the existing environmental methodologies and to demonstrate the importance of integrating the environmental analysis as early as possible in the design process. The first section will introduce the design for environment concepts, next each of the Design for Environment (DFE) components will be detailed and discussed. The chapter will conclude with a discussion reflecting the requirements that the design for environment methodology should fulfil for supporting the development of environmentally superior products.

3.1. Design for Environment

In many past situations, environmental effects were ignored during the design stage for new products and processes. Hazardous wastes were dumped in the most convenient fashion possible, ignoring potential environmental damage. Inefficient energy use resulted in high operating costs, waste was common in material production, manufacturing and distribution and consumer products were cast aside, usually with only minimal re-manufacturing or recycling [Hen99]. Designing and manufacturing environmentally superior products requires appropriate knowledge, tools and production methods. Aids for life cycle design should be easy and quick to use and understand [Roc99]. Ideally, these design tools will help identify design changes that have lower costs while improving materials use and recycling. For example, using snap fits rather than metal fasteners may have little additional cost burden at the design stage but may significantly increase recycling potential [Han98]. Life-cycle design aims to examine the environmental implications of each stage of a product life cycle, from production, through use, to product disposition at the end-of-life. Life Cycle has been defined as *"...consecutive and interlinked stages of a product or service system, from extraction of natural resources to the final disposal"* [ISO14]. In this context Life Cycle Design has been defined as: *"...a novel approach to systematically reduce or eliminate environmental impacts throughout the life cycle of a product or process by accounting for potential impacts at the outset during the continuing course of the design process..."* [Dig97]. The integration of the environmental aspects into the design process may be regarded as and extra burden on the designer's shoulders but it has been proven that early considerations of various environmental aspects in the design stage may result in significant time and costs savings. These savings are a result of a better organisation and use of the existing resources.

Traditionally environmental analysis has been performed by the use of methods that can be broadly categorised as:

- *Generic life cycle analysis tools*, which refer to what is commonly known as *Life Cycle Analysis* (LCA) methodology and is the most common methodology used for measuring the environmental impact of a product's life cycle. It consists of a set of methods that result in different types of measurement results. The results are either life cycle inventory results (measuring the inputs and outputs of a product) or life cycle impact analysis results (showing the environmental implication of the life cycle inventory e.g. CO_2 emissions results in green house effect).
- *Specific analysis tools*, which are commonly known as *Design for X* techniques where X stands for specific design focus such as assembly/disassembly, use, recycling or quality. Although some of the DFX techniques are not specifically related to the environment, taking the environment into account when applying these methods may result in environmental gains. In time it has been established that the relationships among the X techniques have a significant importance on designing environmentally superior products. An example of these relationships is for example when a reduction in the material variety is considered it results in improvements in design for assembly/disassembly and it enhances recycling. Holloway has identified some of these relationships and she ranked them using a range from 1 to 3 (1 stands for weak relationships and 3 for strong relationships). They are presented in table 3.1.

Design for	Assembly	Cost	Disassembly.	Disposal	Manufacturing	Quality	Recycling	Reliability
Assembly								
Cost	2							
Disassembly	3	2						
Disposal	2	1	3					
Manufacture	3	3	2	2				
Quality	2	2	2	1	2			
Recycling	3	1	3	3	2	1		
Reliability	1	2	1	1	2	3	1	

Table 3.1. Links between various Design for X techniques [Hol97]

One of the main differentiation among the LCA and the DFX techniques it the application time. Although it is possible to use LCA at the design stage, the majority of the LCA analyses are carried out after the product has been manufactured. In this case the LCA results are often coming late because of the duration of the analysis and the improvements resulted from the analysis are implemented only in the second or even third generation of the products that has been analysed. Figure 3.1 presents an example of the application of the DFX methods to certain design stages. It also presents the possible integration of the LCA methodology in the detailed design stage. This novel application of the LCA will be discussed in chapter four.

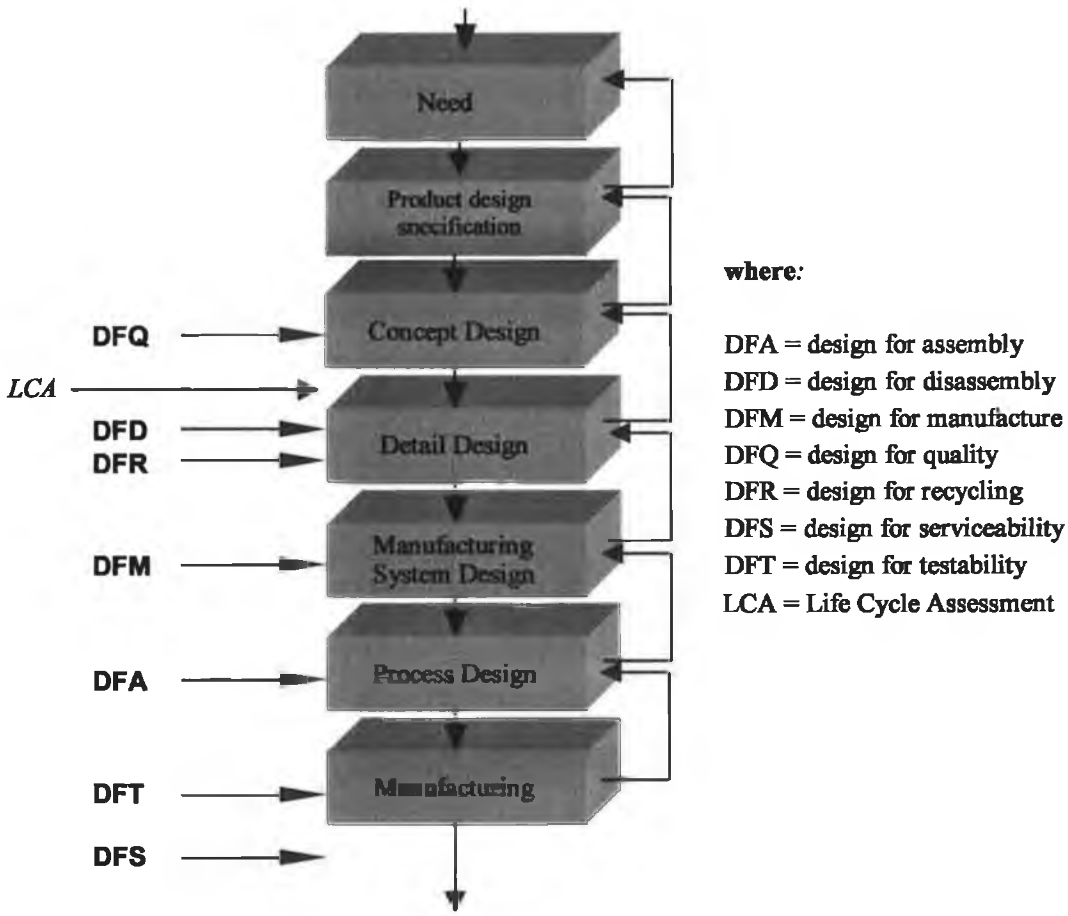

Figure 3.1. Example of DFX and LCA Application to a Design Process (after [Hol97])

There is no general agreement on the particular goals to be pursued by Design for Environment. There are arguments that life cycle assessment and pollution prevention should be pursued solely to reduce costs. In this view, any waste from a process or product is an opportunity. Other arguments refers to the importance of focusing on particular strategies, such as recycling to conserve raw materials, and develop goals specifically for these strategies, or focusing on a particular environmental problem, such as global warming. Each of these approaches is flawed. Some pollution prevention may be socially undesirable but might not be economical for the industry involved. Some recycling may have environmental burdens larger than the savings, especially if long distance transport is involved. Focusing upon a single issue, such as air pollution, may result in transfer of pollution to another media such as water. There is a need for a more general approach. For this purposes three general goals of Design for Environment has been identified: [Han98]

- Reduce or minimise the use of non-renewable resources
- Manage renewable resources to insure sustainability;
- Reduce, with the ultimate goal of eliminating, toxic and otherwise harmful emissions to the environment, including emissions contributing to global warming.

The objective of Design for Environment is to pursue these goals in the most cost-effective fashion with the use of the existing methodologies. Supporting this view, Van Hemel [DFX96] considers DFE as a strategy very similar with the DFX methodology since it involves the use of all the DFX methodologies. In addition to the DFX methodology, DFE takes into account the interrelations between the various DFX methodologies and synthesises them into a science concerned with the development of methodologies that will assist the designer in the quest of developing environmentally superior products without increasing the costs or damaging their performance. Expanding this view further, Roche considers that Design for Environment consists not only of the DFX methodologies and the existing relationship among them but also of the LCA techniques introduced as early in the design process as possible. In in other words Design for Environment consists of two generic components as follows:

Impact Assessment Evaluations consists mainly of the existing Life Cycle Assessment methodologies such as: MET Matrix, EPS Method, Eco indicator Method.

Structure Assessment Methods consist of the methodologies gathered under DFX and also of the relationship existent among these methodologies. Both components will be detailed and discussed in the following sections.

3.2. Impact Assessment Evaluation

Impact Assessment Evaluation methodology consists of the Life Cycle Assessment (LCA) techniques and it is the most widely used methodology for assessing the environmental aspects and potential impacts throughout the product's life (i.e. cradle to grave) from raw materials acquisition through production, use and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences.

There are various definitions given for LCA some of them are as follows:

ISO 14040 defines LCA as: *"... a technique for assessing the environmental aspects and potential impacts associated with a product by:*

- *compiling an inventory of relevant inputs and outputs of a product system;*
- *evaluating the potential environmental impacts associated with those inputs and outputs;*
- *Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study"* [ISO14].

The Society of Environmental Toxicology and Chemistry (SETAC) defines LCA as: *"... a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to affect 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"* [SETAC].

The quality of Life Cycle Assessment depends highly on the accuracy of the data collection associated with the system to be analysed. There is a need for a proper understanding of where each life cycle stage begins and where it ends. The generic LCA methodology defines the following life stages for a system:

- *Raw material acquisition* includes the removal of the materials and energy resources from the earth; the transportation of these materials from the acquisition point to the processing point.
- *Manufacturing* refers to the process of manufacture the product and to the all processes and transportation required to fill, pack and distribute a finished product.

- *Use, reuse and maintenance* include the energy requirements and the environmental wastes associated with the product storage and with the consumption.
- *End of Life* refers to the energy requirements and the environmental wastes associated with product disposition, it includes also the waste management options such as recycling, composting and incineration.

3.2.1. Life Cycle Assessment Structure

The generic LCA methodology is carried out following three basic steps:[Pat97]

1. Inventory analysis
2. Impact assessment
3. Improvement Assessment

Inventory Analysis

This stage represents the heart of any LCA analysis. It consists of gathering all the data associated with the system to be analysed by identifying all it's inputs and outputs.

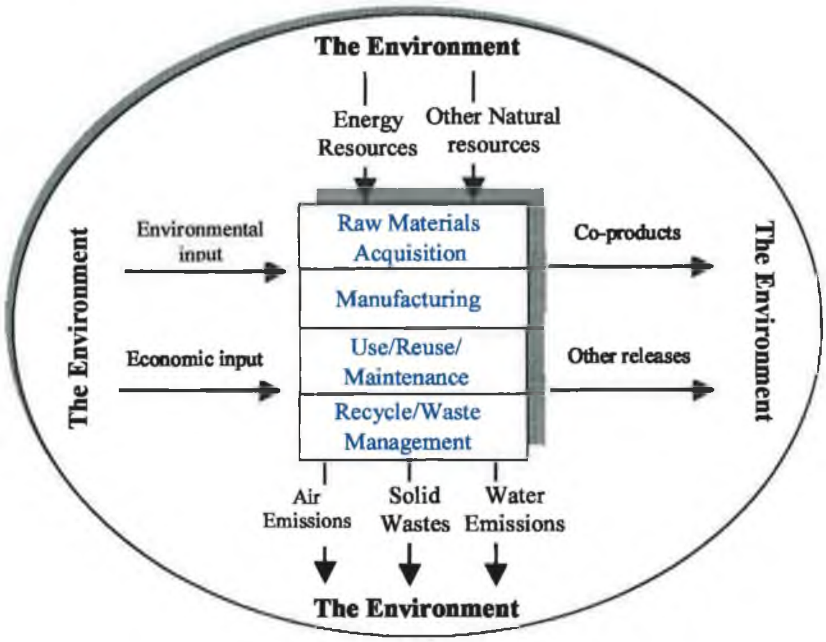

Figure 3.2. The structure of a system to be analysed with a LCA Method (after [Bog96])

Figure 3.2 presents the life cycle stages of the system to be analysed and the inputs and the outputs of the system. The inputs can be generally classified in two categories:

- *Environmental input*: Inputs of raw materials and energy resources;
- *Economic input*: Inputs of products or semi-finished products that are outputs from other processes;

The outputs of the system can be also classified in five broad categories:

- *Air Emissions* (e.g. toxic gases)
- *Solid wastes* (e.g. toxic solid substances)
- *Water Emissions* (e.g. various toxic liquid substances)
- *Co-products*: some processes in a product's life cycle may produce more than one product. In this case, the energy and the resources entering a particular process and all wastes resulting from it are allocated among the co-products. The allocation is usually based on the mass ratios of the products.

Using the data generated by each life cycle stage of the system to be analysed, it is possible to draw an inventory of system's environmental inputs and outputs. The inventory is usually called the *table of impacts*. [Pat97] Each impact is expressed as a particular quantity of a substance. For a better understanding of the table of impacts, Table 3.2 presents a part of the table of impacts associated with the *production* of 1 kg of PS.

Polystyrene

Emissions		Unit
CO2	1.60E-02	kg
HCl	4.00E-05	kg
HF	1.00E-06	kg
NOx	2.40E-02	kg
SOx	3.40E-02	kg

Table 3.2.Table of Impacts [Pat97]

Usually, Life Cycle Inventories are used internally by organisations to support decisions in implementing product, process, or activity improvements and externally to inform consumer or public policy decisions. External uses are expected to meet a higher accuracy of data associated with the system when applying the LCA methodology. It is unreasonable, however, to treat the results as absolute. There are a number of factors such as the choice of technology and systems boundaries that have to be taken into account when interpreting the results. This is why there always seems to be disagreement among experts in the comparison of the environmental superiority among products [Pat97].

Impact Analysis

The Impact Analysis stage is a qualitative and quantitative process that characterises and assesses the effects identified in the Inventory stage as the table of impacts. The impact analysis includes ecological, human health impacts and resource depletion. The analysis should also include other factors such as habitat modification, heat and noise pollution that are not easily agreeable to the quantification demanded in the inventory [Pat97].

The *stressors* represent the key link between the Inventory Analysis and the Impact Analysis phases. A stressor is a set of conditions identified in the Inventory Analysis phase that may lead to an environmental impact. The impact analysis phase will result in a set of environmental impacts and potential environmental impacts, depending on the moment when the LCA is carried out e.g. design stage or after the product is manufactured, that are identified throughout the life cycle of the system being analysed.

There are several tools that can be used to perform the Impact Analysis. These tools will be discussed later in this chapter.

Improvement Analysis

The last phase in the LCA Methodology is the Improvement Analysis Phase. It consists of identifying strategies to be used in order to reduce the environmental impacts identified in the Impact Analysis phase [Pat97].

The steps to be followed in order to carry out an Improvement Analysis are:

- Load analysis, indicating relevant processes;
- Identification of improvement options;
- Ranking and selection of the options based on their effectiveness, and on external variables such as feasibility.

3.2.2. LCA Methods

Presently there are a number of methods available for the companies to use in order to carry out a LCA analysis. The common element linking all these methods is that they all are gathering information about the system to be analysed and they all aim to obtain viable solutions for reducing the identified environmental impacts. The main differences between the methods are: [Pat97]

- The comprehensiveness of the analysis;
- The type of effect that is included;
- The degree of quantification of the result;
- The interpretation method of the environmental impacts identified;

Figure 3.3 presents the LCA methods classified on two main categories:

- Qualitative methods
- Quantitative methods

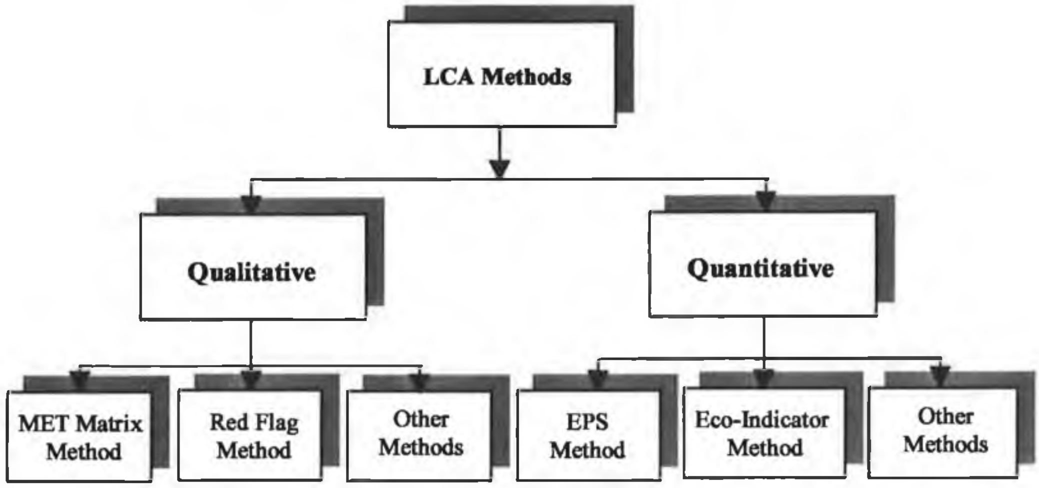

Figure 3.3. The LCA Methods Structure [Pat98]

Qualitative Methods

Qualitative methods are generally based on the expertise and sometimes the intuition of the expert carrying out the expertise. Although a lot of qualitative methods are available, only a couple of most used methods are presented in this thesis.

MET Matrix Method

MET is the acronym for Material, Energy and Toxicity. The method has been developed in a Dutch Eco-design programme [pre]. The MET matrix is used as a tool to take stock of the most important environmental impacts of a product with the minimum effort and time. The input/output model distinguishes three categories of environmental interventions; the ***materials cycle***, i.e. the nature and amount of resource consumption and waste generation, ***energy use*** for all product life phases and finally ***toxic emissions*** to water, air and soil. The information in the matrix is basically derived from the available knowledge and expertise of the project team who perform the analysis [Kor95].

The analysis consists of five steps:

1. A discussion of the social relevance of the product's functions
2. Determination of the life-cycle of the product to be analysed
3. Intuitive conclusion of the MET matrix based on existing knowledge by inexperienced people that will have to familiarise themselves with the method
4. Careful completion of the MET matrix with the aid of the environmental experts
5. Establishment and outline solutions for the environmental problems identified.

The disadvantage of the MET matrix method is it's poor reproducibility and the lack of scientific basis [Pat97].

Red Flag Method

A number of companies work with "red flags". If an emission of a priority substance, for example CFC, occurs in the impact table it is red-flagged. The product or process should not actually be used [Pat97]. The major problem is that red flags occur in almost every impact table and that a very small emission is treated in just the same way as a large one. Because of this, this approach is not very suitable for providing a qualitative evaluation.

Quantitative Methods

Quantitative methods involve weighting the environmental impact associated with a system on the basis of the impact table resulted from the Impact Analysis stage. Various methods have been developed for weighting the environmental impacts and to cumulate the result in a single environmental impact score. For the purpose of the present thesis only a couple of quantitative methods will be reviewed as follows:

Environmental Priority Strategy System (EPS)

Environmental Priority Strategy (EPS) [Eco95], is a complex method based on the premise that it is not the effect itself that has to be evaluated but the consequences of that effect (see figure 3.4). It is assumed that society places a certain value on a number of matters that are termed *safeguard subjects* such as:

- *Resources*, or the depletion of resources;
- *Human health*, or the loss of health and the number of extra deaths as a result of the environmental effects;
- *Production*, or the economic damage of the environmental effects (particularly in agriculture);
- *Biodiversity*, or the disappearance of plants or animal species;
- *Aesthetic values*, the perception of the natural beauty.

The method is using a number of correction factors such as: [Eco95]

- *Exposure*: that is the number of people who actually come into contact with the substance or phenomenon;
- *Frequency*: that is the number of times that an effect occurs or the probability that it will do so;
- *Period*: that is the time for which an effect occurs, including the speed with which a substance degrades.

Although it is right scientifically to apply this correction it substantially increases the complexity. Using the *safeguard subjects* mentioned, the damage is determined on the basis of these corrected effects. This damage is then expressed in financial terms. The evaluation is based on three different principles: [Pat97]

- Raw materials depletion is evaluated by looking at the future extraction costs for raw materials; it represents the costs that must be expended on order to extract the "last" raw materials resource;
- The production loses are measured directly from the estimated reduction in agricultural yields and industrial damage;
- The other three safeguard subjects are evaluated in terms of the willingness-to-pay principle. It represents the sum that a society is prepared to pay for ill health or the death of its citizens, the level of the extinction of plants and animals and the level of the impairment of natural beauty that can be considered acceptable are examined.

The result of the method is obtained by totalling up the financial sums calculated. The method's usability depends greatly on the availability and reliability of the large number of weighting factors.

Volvo is one of the companies, which is using this method. In the automobile industry the product development processes are characterised by rapid and extensive decision-making, so a method like EPS, which is clear and effective, is very suitable [Pat97].

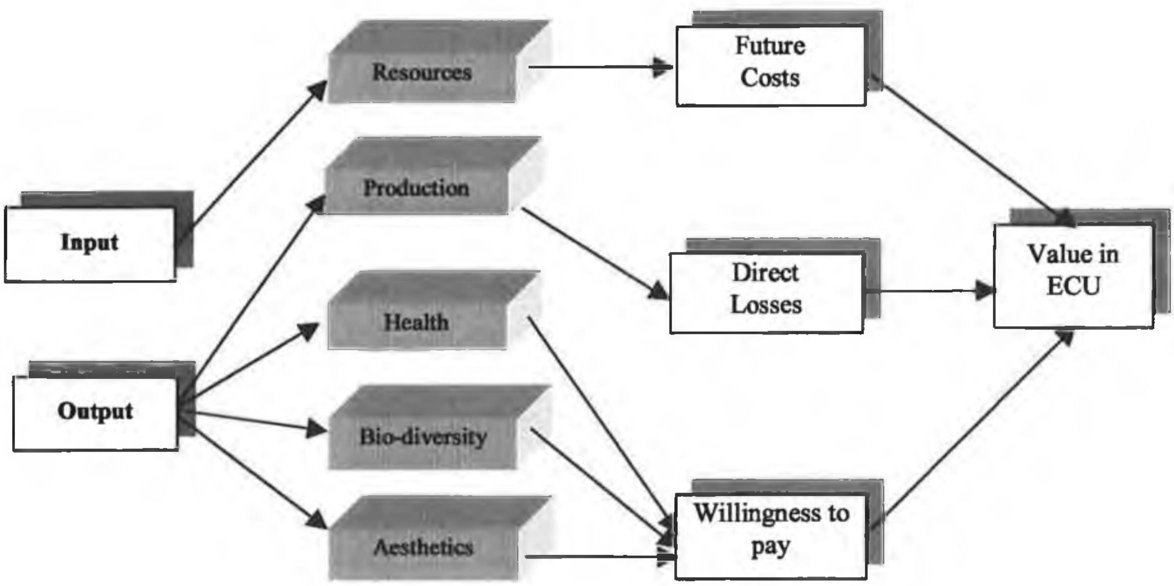

Figure 3.4. Schematic representation of the EPS system. After [Eco95]

Eco Indicator Method

The Eco-Indicator 95 method was developed by PRé Consultants in collaboration with Phillips, Volvo, Océ, Schuurink and the Universities of Amsterdam, Leiden and Delft [Pre97, Ase99]. The twofold aim of the method is as follows:

1. To analyse products or ideas looking for causes of environmental pollution and trying to find opportunities for improvement.
2. To compare the environmental impacts of two alternative product configurations.

The Eco Indicator Method is based on the Distance-to target principle. The distance between the current level of an impact and the target level is assumed to be representative of the seriousness of the emission, so the choice of the target value is crucial.

An Eco-Indicator is calculated to give a rough indication of the "absolute potential damage" on the environment caused by the product. This simplification of the LCA can be useful in communicating the results and giving indications during the design process. Indicators are never used without analysing the background of the figures, because of the many extra value judgements made during the process of their development [Pat97].

In order to achieve a weighting factor the procedure outline below has to be followed:

1. Determine the relevant effects that are caused by a process or product;
2. Determine the extent of the effect in Europe. This is carried out by the normalisation value. Divide the effect that the product or process causes by the normalisation value. This step determines the contribution of the product to the total effect. This is done because the effect itself is not so relevant but rather the degree to which the effect contributes to the total problem. An important advantage of the normalisation stage is that all the contributions are dimensionless;
3. Multiply the result by the ratio between the current effect and a target value for that effect. This ratio is called the reduction factor and can be seen as a measure of the seriousness of the effect;
4. Multiply the effect by a so-called subjective weighting factor. This factor is used because other factors in addition to the Distance-to-Target can also determine the seriousness of an effect and is entered to make corrections in the event that the Distance-to-Target principle does not sufficiently represent the seriousness of an effect.

The procedure is also presented in figure 3.5.

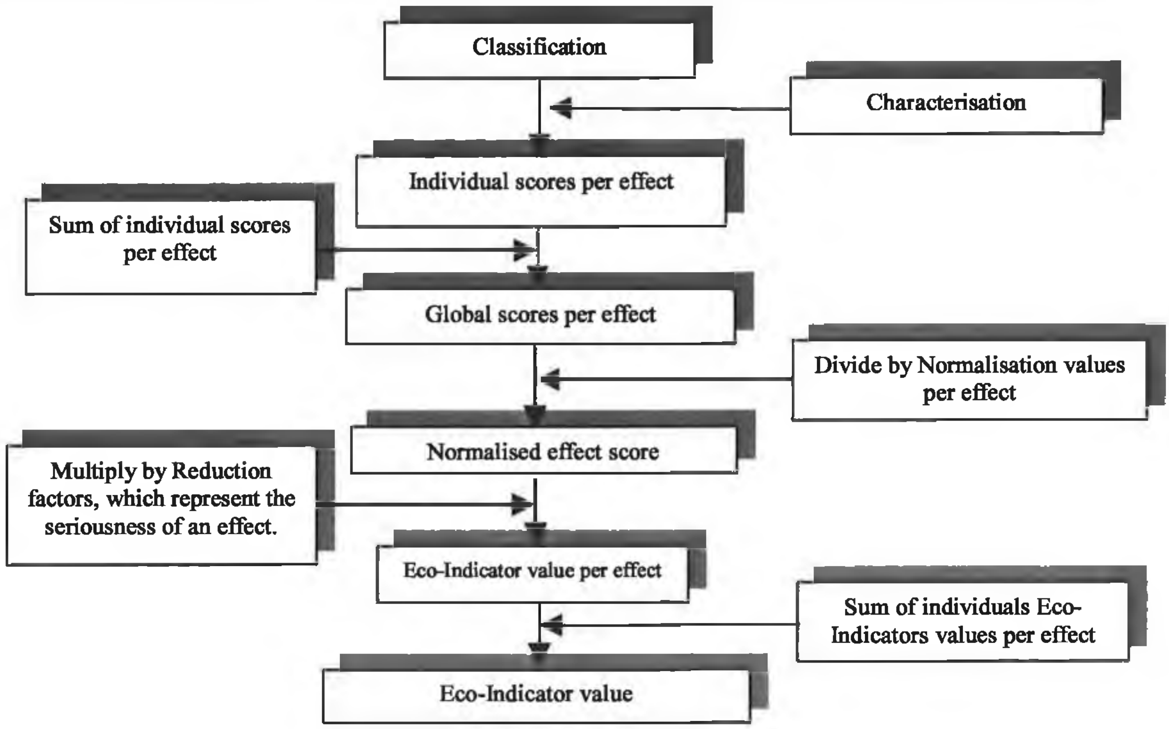

Figure 3.5. The Eco Indicator 95 procedure

The first stage of the Eco-Indicator methodology includes two sub-stages, i.e. classification and characterisation. *Classification* is the stage in which the environmental interventions listed in the inventory table, e.g. amount of CO_2, NO_x, HCl emitted, are attributed to a number of selected impact categories, e.g. greenhouse effect, ozone layer depletion, eutrophication, etc [ISO97]. Loadings are aggregated within each category to produce an effect score. It is not sufficient to add the quantities of the substances involved without applying any kind of correction factor since not all the substances have the same effect on the environment, e.g. HF has more effect into the acidification than NO_x. This problem is solved applying factors called *characterisation* factors. The emissions are multiplied by these weighting factors obtaining the individual scores per effect. After, these scores are added and the global scores per effect are obtained. Table 3.3 illustrates the stages of classification and characterisation and the scores obtained in the production of 1Kg of PS.

Emission	Quantity (Kg)	Greenhouse	Acidification	Eutrophication	Winter smog	Summer Smog
CO2	1,6	1	-	-	-	-
HCl	4,00E-05	-	8,80E-01	-	-	-
HF	1,00E-06	-	1,60	-	-	-
NOx	2,40E-02	-	7,00E-01	1,30E-01	-	-
SOx	3,40E-02	-	1,00	-	-	-
NH4	1,00E-05	-	-	3,30E-01	-	-
Dust	3,10E-03	-	-	-	1,00	-
CxHy	2,60E-02	-	-	-	-	3,98E-01
Global Effect score		1,6	5,08E-02	3,16E-03	3,10E-03	1,03E-02

Table 3.3. Global effect scores in the production of 1Kg of PS [PWMI]

These global effect scores are absolute values, difficult to interpret and not useful when a comparison between products is performed. The interpretation of the effect scores *"...depends on the relative size of an effect compared to the size of the other effects..."* [Eco95]. The relative size of an effect is obtained after the normalisation stage, in which the global effects are divided by a normal effect. Table 3.4 illustrates the normalised effect scores obtained in the production of 1Kg of PS.

Effect	Global Effect Scores	Normalisation value	Normalised Effect Score
Greenhouse	1.6	1.31E+04	1.22E-04
Acidification	5.08E-02	1.13E+02	4.50E-04
Eutrophication	3.16E-03	3.82E+01	8.28E-05
Winter Smog	3.10E-03	9.46E+01	3.28E-05
Summer Smog	1.03E-02	1.79E+01	5.78E-04

Table 3.4. Normalised value obtained in the production of 1Kg of PS [PWMI]

All the environmental effects do not have the same importance. A completed evaluation of the ecological effects can not be carried out without considering the relative importance of these effects. Thus, the normalised effect scores are multiplied by a weighting factor, called reduction factor, which represents the relative importance of an effect. In order to determine the reduction factors for each effect, a target level for the emissions of the different substances, which produce a particular effect, are established. Once these levels are known, the reduction factor will represent the factor by which an emission of a substance must be reduced to reach an acceptable level. All the normalised effect scores are multiplied by the correspondent reduction factor before they are added. The final score is the Eco-Indicator value associated with the product or component under study. Table 3.5 illustrates Eco-Indicator values for some materials, processes and means of disposal.

	Production	Extrusion	Injection moulding	Municipal waste	Recycling
HDPE	2.90 mPts/Kg	2.00 mPts/Kg	0.53 mPts/Kg	0.69 mPts/Kg	-6.20 mPts/Kg
LDPE	3.80 mPts/Kg	2.00 mPts/Kg	0.53 mPts/Kg	0.69 mPts/Kg	-6.20 mPts/Kg
ABS	9.30 mPts/Kg	2.00 mPts/Kg	0.53 mPts/Kg	0.69 mPts/Kg	-6.20 mPts/Kg
PC	13.00 mPts/Kg	2.00 mPts/Kg	1.10 mPts/Kg	0.69 mPts/Kg	-6.20 mPts/Kg
PVC	4.20 mPts/Kg	2.00 mPts/Kg	1.10 mPts/Kg	0.69 mPts/Kg	-6.20 mPts/Kg

Table 3.5. Eco-Indicator values

These pre-calculated values can be used to establish the environmental impact of a product. Software tools such as 'ECO-SCAN'[12] and others facilitate the synthesis of these values for a proposed product. However these tools are not integrated with a virtual prototyping system nor is there an advisor available to support product improvement process. The procedure can be expressed by the following equation: [Eco95]

$$I = \sum_i W_i * \frac{E_i}{N_i} * \frac{N_i}{T_i} = \sum_i W_i * \frac{E_i}{T_i}$$

(Equation 1)

where:

I Indicator value.

N_i Current extent of the European effect i, or the normalisation value.

T_i Target value for the effect i.

E_i Contribution of a product life cycle to an effect i.

W_i Subjective weighting factor.

$\frac{N_i}{T_i}$ is called the reduction factor F_i.

From the last formula can be seen that the development of the target values is very important, so now the question about how these target values are determined is formulated.

There are different approaches to selecting target levels:

- Following the objectives for environmental pollution reductions that each Government in each country has; then the target value is based in a conformity with policy decisions more than in environmental reasons;
- Following a scientific base; then three alternatives are possible: [Pat97]
    1. Considering zero as the target value for the effect, but then there is a problem when the Equation 1 is used, because the division over zero is done.
    2. Considering a target value so low that no damage occurs at this level; the problem is that this low level is difficult to determine;
    3. Considering a level in which a limited damage occurs; this is normally the option chosen for practical reasons.

The effects, which are considered in the Eco-Indicator method, are: Greenhouse effect, Ozone layer depletion, Acidification, Eutrophication, Summer smog, Winter smog, Pesticides, Heavy metals, Carcinogenic substances [Eco95]. The Eco-Indicator 95 method is

[12] Eco-Scan is a tool developed by Turtle Bay Ltd. (P.O. Box 84, 3000 AB, Rotterdam. The Netherlands) for the synthesis of environmental impact measures for a product.

very easy to use. It simply consists of filling some tables with information related to the different life cycle stages for the product, i.e. materials type and mass, manufacturing process, transport process, use and end of life strategy. Examples of these tables are presented in table 3.6.

PRODUCTION
Materials, processing, transport and extra energy

Material or process	Amount	Indicator	Result
Total			

USE
Transport, energy and any auxiliary materials

Process	Amount	Indicator	Result
Total			

DISPOSAL
Disposal processes per type of material

Material and type of processing	Amount	Indicator	Result
Total			

Table 3.6. Extract of tables used in the Eco-Indicator 95 method.

3.2.3. Advantages and Disadvantages

The main advantages of the LCA methodology are:

- LCA is an effective tool for bench marking environmental performance and can be used in comparative studies to determine the relative environmental advantages and disadvantages of products that perform equal functions.
- LCA can assist and it is already used to assist companies in quantifying and assessing their impacts on the environment. It also helps the companies in identifying the opportunities to minimise these impacts and significantly to realise cost savings by making more effective use of the available resources.

The main disadvantages identified in LCA methodology are:

- Defining system boundaries (the input and output system and the system's life stages) is controversial
- LCA is time consuming and needs to be carried out by environmental experts

- The results are very complex and difficult to interpret
- LCA cannot capture the dynamics of changing markets and technologies

3.3. Structure Assessment Evaluation

DFX is a generic title for specific mindsets, procedures, models and tools. Because of this, elements such as knowledge, development process and information system, education, training and managerial considerations are required to support DFX. Van Hemel states that DFX can be defined by: *"...its aim and result of its application: optimising the fit between the product design and the specific systems it will meet in all phases of it's 'product life'. DFX can be deployed at different stages of the product development process to facilitate continuous improvements of the engineering solution."* [DFX96]

During design, the focus is on the final product, and not its manufacture. The Design For X (DFX) philosophy suggests that a design should be continually reviewed from the start to the end to find ways to improve production and other non-functional aspects (see figure 3.6). These rules are nothing new, they are just common sense items written down that can be a good guide through the design process.

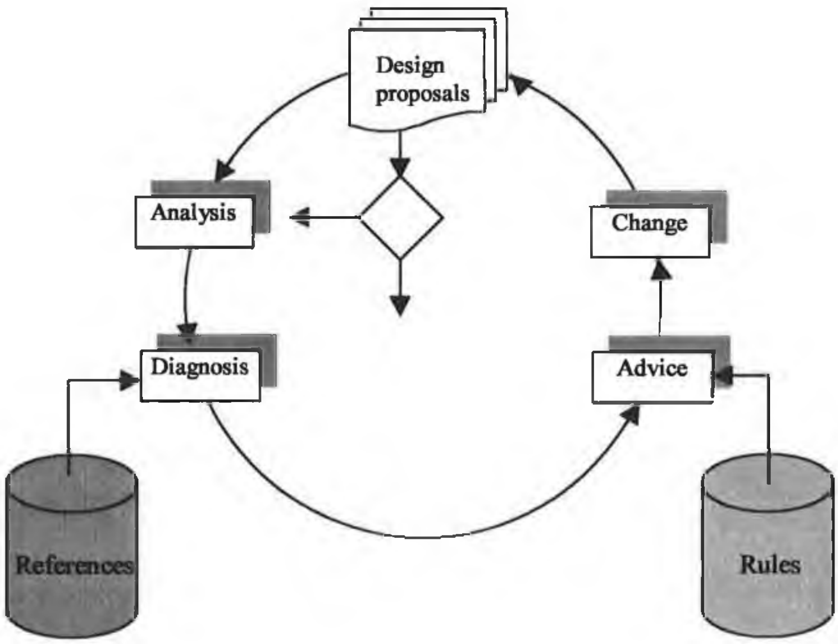

Figure 3.6. The loops within the DFX philosophy [DFX96]

According with *Van Hemel* [DFX96] there are two groups of DFX methodologies:

1. *Specific DFX methodologies* focused on a specific desired characteristic of the product to be designed such as recyclability (DFR) or disassembly (DFD)
2. *General DFX methodologies* that are a holistic approach of the product's life cycle such as DFCost or DFQuality.

Specific DFX methodologies seem to be more common than the *general DFX* methodologies, and this is because many companies are yet not aware of the importance of the life cycle thinking. Also the difficulty of implementing *general DFX* methodologies is rising from their complexity. While using the specific DFX methodologies is clear on which topic time and money will be concentrated, with the general DFX all life phases are simultaneously taken into account and this leads to many trade-offs, complex decisions process and more people involved.

Some of the DFX Methodologies that are reviewed in this thesis are:

- Design for Modularity
- Design for Manufacture and Assembly
- Design for Disassembly
- Design for Reuse
- Design for Recycling
- Design for Quality
- Material variety
- Labelling

Design for Modularity

A module is defined as a separable component, frequently one that is interchangeable with others, for assembly into units of differing size, complexity, or function [Web92]. Modular design, i.e. implies that the structure of the product should be arranged to allow simple exchange and easy refurbishment. One of the techniques used for Design for Modularity is Modular Function Deployment. Figure 3.7 presents a schematic representation of the method.

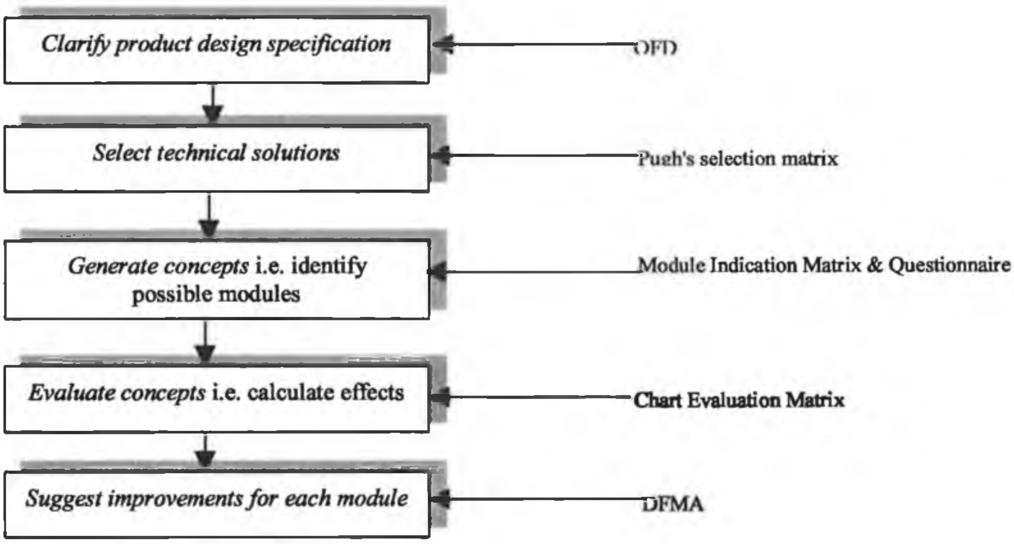

Figure 3.7. Modular Function Deployment after [DFX96]

Modular Function deployment (MFD[1]) consists of:

- A QFD[2] analysis is carried out in order to establish the customer requirements.
- From experience, the Pugh's selection matrix [Pugh91] is very efficient in helping the design team to identify the technical solutions for the defined requirements. The technical solution's selection will have an emphasis on the modularity.
- Next a Matrix called Module Indicator matrix (MIM) is created using a questionnaire, to evaluate the interrelationships between module drivers and technical solutions. MIM is used as a mechanism for investigating opportunities to integrate multiple functions within a single module. This mechanism is specific for the sub-functions level.
- The modular concepts resulted from the MIM are next evaluated with the use of the Modularity Evaluation Chart (MEC). The evaluations will cover multiple areas such as costs, quality, efficiency, flexibility and so on. MEC is specific for the product level. MIM and MEC complement each other.
- Last improvements are suggested usually by the use of the DFMA method.

Gunnar Erixon enumerates several advantages resulting from the use of design for modularity: "

1. *Structures the product development leading to rational product assessments.*
2. *Provides feedback to the synthesis phase*
3. *Provides learning feedback*
4. *Enables creative thinking and encourages team work*
5. *Modular products are more competitive...*
6. *Guides the design iterations where the results of changes are measured, obsolete ideas are scrapped, promising ideas are revised and new ideas are born."* [DFX96]

Design for Manufacture and Assembly

In the last years has been recognised that it is important to consider the manufacturing and assembly issues in the early stages of the design process. One way of achieving that is to consolidate a concurrent engineering design team including manufacturing engineers. It is important that the team has access to design for manufacture and assembly (DFMA) tools in order to provide a focal point that helps identify problems from both manufacturing and design perspectives.

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[1] Design for modularity has been successfully applied in industry. A relevant example is SCANIA AB in Oskarshamn, Sweden (see [DFX96]).

[2] QFD is an acronym for Quality Function Deployment. QFD is a customer-orientated approach to product innovation. It guides product managers and design teams trough the conceptualisation, creation and realisation process of new products [Aka90].

Boothroyd has defined DFMA as"*...a systematic procedure that aims to make companies make the fullest use of the manufacturing processes that exist and keep the number of parts in an assembly to the minimum*" [DFX96].

Figure 3.8 shows the steps required for DFMA when carried out at the design stage. First the design for assembly is carried out resulting into a simplification of the product structure. Early costs are estimated for the designs variants enabling trade-off decisions. During this process the best materials and processes to be used for various parts are considered. Next the design for manufacture is carried out for the detailed design of the parts [DFX96].

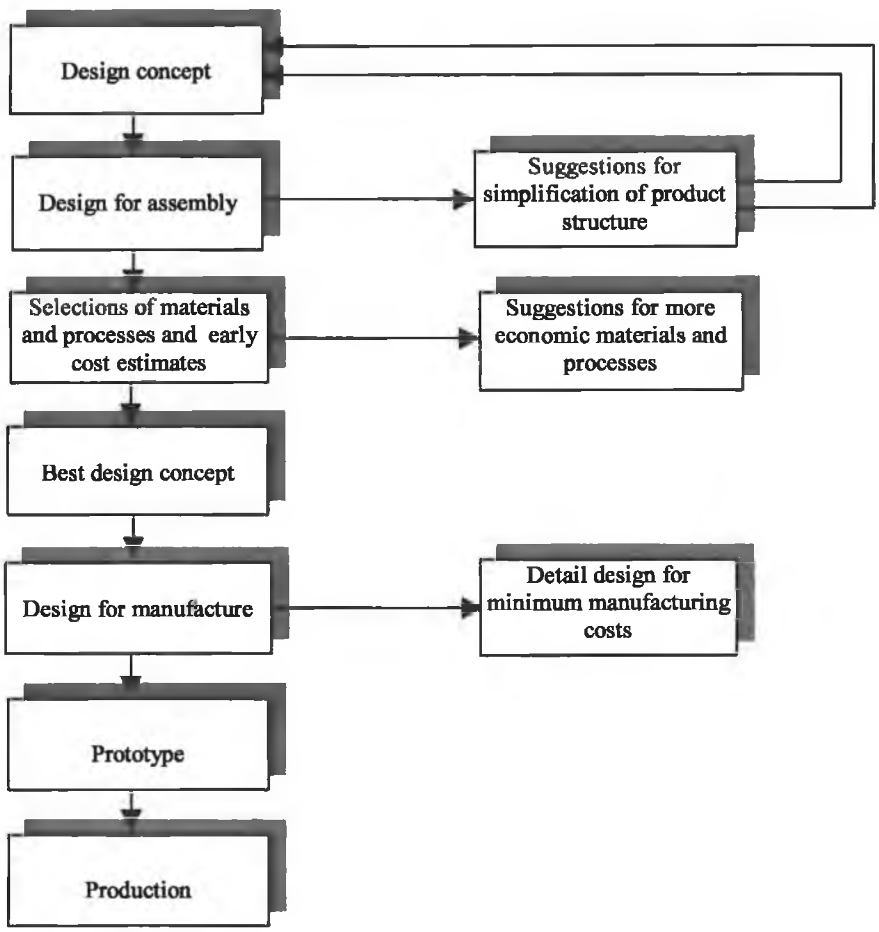

Figure 3.8. Schematic representation of DFMA [DFX96].

DFMA procedure results in simpler and more reliable products that are less expensive to assemble and manufacture. Also, any reduction in the number of parts in an assembly produces a reduction to the costs because of the drawings and specifications no longer needed and the inventory that is eliminated.

Design for Disassembly

Design for Disassembly (DFD) is the practice of using assembly methods and configurations that allow cost effective separation and recovery of reusable components and materials [Cal97]. The driving factors for implementing DFD in industry are the new emerging legislation and ecolabelling policies and penalties associated with the breaking of those laws. The manufacture will have to take back their products and to dispose them. To easy this process the DFD method is best used with Design for Assembly and Design for Recyclability effectively contributing to high environmental end economical performance.

Hanft and Kroll [DFX96] propose a technique based on a *disassembly evaluation chart* similar with FMEA[3] that gives an indicator for the difficulty of certain disassembly operations. This method takes into account the number of the parts to disassembly, directions of the operations, tools required, force and positioning for disassembly. The indicator can be also used for calculating the design efficiency from the disassembly point of view.

Some of the DFD guidelines are:

- Reduce the number of plastic parts, especially in the car products
- Allow parts consolidating by using plastic instead of metal with joints
- Snap fit fasteners are preferred over other fasteners
- Implement identification coding, material labels.
- Use compatible materials from the recycling point of view
- Use common parts for different products.

Design for Reuse

Reuse is the additional use of an item after it is retired from a clearly defined duty. Generic product characteristics that facilitate reusability have been synthesised from the literature as follows: [Roc99]

- Minimum number of components
- Serviceable
- Modular design
- Easy to disassemble
- Considers reduction of wear to components

[3] Failure Modes and Effects Analysis is a systematic and analytical quality planning tool or technique, used to define, identify and eliminate known or potential failures from the system, design, process, or service before they reach the end user [Pri95].

- Considers corrosion protection
- Minimum use of hazardous materials and facilitates their easy removal.

Design for Recycling

Recycling is the series of activities, including collection, separation and processing, by which products or other materials are recovered from the solid waste stream for use in the form of raw materials in the manufacture of new product other than fuel [Roc99].

Generic product characteristics that enhance recyclablility include:

- Minimise the variety of materials
- Minimise the number of components
- Maximise material compatibility
- Minimise the use of hazardous materials
- Choose recyclable materials
- Specify recycled content
- Label materials
- Ease of disassembly

Design for Quality

Biggioggero defines quality as " *...compliance with requirements, that is the degree to which the specific range of characteristics of a machine conform to the requirements. If they match well, the quality is high; otherwise quality is considered poor.* " [DFX96]

Design for Quality (DFQ) is a general DFX method since it takes into account the quality of the product associated with the product's entire life cycle. The *lack of quality* lead to a dissatisfied customer and it can be calculated using Taguchi's *quality loss function* [Fow95]. Most of the quality principles and methodologies are standardized in ISO14000 [ISOnet]. A typical methodology consists of the following steps: [DFX96]

- Determine the product's functions.
- Identify all physical principles according to which the product will be developed.
- Determine quality concepts respectively elaborate quality solutions for the functions identified.
- Evaluate the determined concepts and select the best option for developing the specified product.

Material Variety

Material variety is an important aspect that must be considered at the design stage. It reefers to the use of less material wherever is possible. This will reduce both the use of material resources and the material that needs to be recycled or disposed at the end of product's life. It also facilitates the efficient disassembly of the product and enhances product's recycling. Also, the amount of material should be reduced whenever possible, for example, stiffening ribs, a double wall with tack off ribs can be used for increasing plastic stiffness instead of an increased amount of material [EPA93].

Labelling

Labelling is another very important aspect of designing that has been usually neglected. Marking the materials used in a product can provide critical information to recycling facilities. This include not only the material used for manufacturing de parts but also the additives used as their use may necessitate changes in the recycling process. There are already standard marking specified by International Organisation for Standardisation (ISO). For example, ISO11469 gives the marking for plastic enclosures and significant sized[4] parts. The labels must be compatible with the material used for the part that has been marked as they may introduce dissimilar, contaminating materials into the recycling steam [EPA93].

Advantages of DFX Methodologies

Advantages of the DFX methodologies are:

1. shorter production times
2. fewer production steps
3. smaller parts inventory
4. more standardised parts
5. simpler designs that are more likely to be robust
6. they can help when expertise is not available, or as a way to re-examine traditional designs
7. they have been proven to be successful over decades of application

3.4. A Review of the Existent Software Tools to Support DFE

Presently a number of software tools have been developed based on LCA and/or DFX techniques. This section is reviewing some of them in an attempt to identify the characteristics of these tools and the requirements for a new software application to support Design for Environment (DFE).

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[4] In Europe, parts exceeding 25 grams are recommended for marking.

The existing software tools can be divided in two broad categories:

1. LCA tools
2. DFX tools

Life Cycle Assessment (LCA) Tools

This category consists of tools developed to support either part or the entire LCA methodology. Some of these applications are:

- Boustead Model (UK) is a software application supporting life cycle inventory modelling. The application is based on a large database consisting of 3000 unit operations covering the fuel producing industries and most of the major commodity products. The data supplied in the database has been collected from industry via questionnaires [Swe96].
- LCA Inventory Tool (Sweden) has been developed to aid the LCA specialists to perform inventory modelling [Swe96].
- REPAQ (SUA) is a software application that performs inventory modelling for products, processes and packaging. The application examine energy and environmental emissions for the entire life cycle of a product, beginning with raw material extraction, and continuing through refining and processing, material manufacture, product fabrication, and disposal. The user can update the REPAQ database trough the custom Materials feature [Bad99].
- Simapro 3.0 (Netherlands) is focused on analysis and comparison of the product. It allows the user to describe complex products and the analysis results in environmental scores associated with each of the life cycle sages [Swe96].
- TEAM (UK) is a LCA software tool that allows calculations of life cycle inventories, environmental assessments and associated costs. It is based on a database manager [Swe96].
- ECO-it is an LCA software tool developed to support product and packaging designers. It calculates the environmental impacts associated with each of the parts of the product analysed as well as the environmental impacts associated with each of the product's life cycle stages. The tool is based on a database of over 100 indicator values for materials, production, transport and end of life strategies such as incineration, recycling or disposal [Bad99].

- EcoScan (Netherlands) is an application based on Eco-indicator 95, IDEMAT[5] database. It also calculates environmental scores per life cycle stages associated with each component of the product being analysed. It allows the comparison of different products in a single graph, sharing data on a network, data interchange with other applications and calculations for transport distances and product mass [Swe96].
- GABI (Germany) is a LCA software application developed to assist the designers, consultants or scientists by allowing weak point analysis of inventories and balances. Some of the features of the tool refer to management of processes, construction of process chains and networks, calculation of inventories, impact assessment and balances, weak point analysis of process chains on different levels, extensive database with data from Eco indicator [Bad99].
- Umberto (Germany) is a powerful LCA tool that supports methods such as Eco Indicators 95 and Ecopoint methods. The tool uses Material Flow Analysis as a technique for representing the system being analysed. It consists of input/output balance of all mass and energy flow networks about 300 library modules and the user has the possibility to modify the data for materials, energy and processes [Bad99].

DFX Tools

This category consists of focused analysis tools that are based on indexing systems that measure product based features that contribute to the environmental impact of a product.

- Green design advisor (USA) is a computer Aided Engineering tool to assist the manufacturers to minimise the environmental impacts of electromechanical products. It is based on a ranking system that allows the designer to minimise the environmental impacts associated with manufacturing, use and disposition of the product [Swe96].
- ReStar (USA) is a software application developed to support end of life analysis of electromechanical and electronic products such as automobiles, computers and other consumer electronics. It focuses on easy to disassembly strategies for reuse, re-manufacturing and recycling [Swe96].
- Design for Environment (DFE) software tool (USA) combines cost and environmental issues in a single tool. It allows the optimisation of the product being analysed by identifying the disassembly sequence and performing two analyses. Firstly the financial return assessment of disassembly, disposal, reuse and recycling. The result of this analysis shows the financial impact at each stage of disassembly. Secondly the environmental impact assessment analysis from initial product manufacture to disposal,

[5] IDEMAT is an application developed in Netherlands to assist the product engineers in material selection process by ranking the materials in term of their environmental impacts, cost and their mechanical properties.

reuse and recycling is performed using the MET technique discussed earlier in the chapter. The results are represented in a common graph as costs and MET points [Dew00].

- Design for Assembly, DFA, (SUA) assist cost estimations of manually assembling products. The user selects the simplest product structure and minimises the assembly cost by selecting different design strategies offered by the tool [Dew00].
- Design for Manufacture, DFM (SUA) works together with design for assembly. After the analysis performed by DFA, DFM provides cost estimates for the manufacture of the individual parts. The DFM cost estimating analysis assist designers to quantify manufacturing costs and to make the necessary trade-offs decisions between parts consolidation and material/manufacturing costs [Dew00].
- Design for Service, DFS, (SUA) allows the designers to evaluate the serviceability of a product early in the design process. The tool assist the designer by prioritising the areas in the service task that must be examined for service improvement [Dew00]

The software tools reviewed presents a number of limitations that must be eliminated in order to develop effective DFE software tools. Some of these limitations are:

- Most of the LCA tools require environmental expertise.
- The results are often difficult to be interpreted and the use of the tools is laborious and time consuming.
- Most of these techniques provide specialised analysis by either addressing specific issues such as manufacturing, disassembly and costing or they are characteristic to a specific stage of the life cycle such as end of life or they address only to specific products such as electronics.
- They usually perform analysis very late, after the product has been designed.
- They have data limitations, as it is very difficult to obtain accurate information relating materials, processes, use, transport or end of life.

3.5. Conclusions

The current study has reviewed the design for Environment concepts and it has discussed its components in great detail. It also has reviewed the existent software tools that supports design for environment and has identified some of their limitations. As a result of the current study several requirements have been identified as needs for the development of a powerful design for environment application. They are as follows:

- The application must encompass both LCA and DFX techniques and they should be integrated as early in the design process as possible without disrupting the design activity.
- It must be fully integrated in the Computer Aided Design system used for the development of the product prototype.
- The application must be intuitive and user friendly and must require no expert knowledge in the environment area.
- The calculations performed must be based on standardised factors where possible.
- It must include a data interpreter and a prioritisation tool for prioritising the environmental issues to be addressed.
- The application must be supported by an advisor to guide the designer trough the efforts of designing environmental superior products without constraining the designer in any way.
- The application must also be supported by a powerful updateable database that should provide the necessary information to the designer.
- The application must also have a feature enabling an easy integration with an existing product data Management system.
- The tool must also provide clear documentation of all the activities performed by the tool.
- The tool must provide reports and graphical displays of all the environmental scores and the other metrics calculated by the tool

Design for Environment has wide reaching consequences, as the environmental decisions will determine the conditions for environmental considerations and performance through the life cycle of the product. This means that the requirements and decisions with respect to the environmental issues will affect the relations with suppliers and other business partners. DFE reaches beyond the company both upstream and downstream from production by addressing both internal and external relations and performance [DFX96].

Chapter 4

Review of the DFE Workbench Methodology

Creativity, as has been said, consists largely of rearranging what we know in order to find out what we do not know. Hence, to think creatively, we must be able to look afresh at what we normally take for granted.

George Kneller

4.0. Introduction

This chapter is a review of the DFE Workbench methodology proposed by Roche in 1999. The review starts with a brief description of a set of requirements for new Design for Environment (DFE) methodologies and continues with a description of the methodology proposed by Roche divided on its components i.e. Impact Assessment Structure (IAS) and Structure Assessment Method (SAM). The chapter will conclude with the needs for software support of the methodology.

4.1. DFE Workbench Development Needs

After a detailed analysis of the existing LCA and DFE methodologies Roche established that Life Cycle Analysis (LCA) is an essential tool to support the designer for developing environmentally superior products but the existing LCA tools tend to be time consuming and difficult for the design engineers to use. Roche proposes that the designer should use a quantitative form of comparative LCA integrated in the design process and that is Eco Indicator 95 that has been detailed in chapter three. Roche observed that most of the existing DFE Methodologies are carried out after the design was completed and generally post manufacture of the first prototype. He proposed that the DFE methodologies should be integrated much earlier in the design process and this integration should not disrupt the design activity. He established that the designer needs methodologies to support the synthesis and evaluation of the diverse information sets integrated in a DFE approach. He also, proposed a design advisor to be integrated in the DFE approach to aid the identification of environmental problems in a candidate design and to provide environmentally superior alternatives. A DFE knowledge agent that would provide passive advice and information to the designer should support the advisor. A summary of the requirements for the new DFE methodology that have been identified by Roche is presented in Table 4.1.

Criteria	Description
Integrated DFE evaluation	The methodology should take a holistic view of the product and should take cognisance of the interrelationships between design objectives, e.g. between disassembly and material compatibility.
Design process integration.	Integrated in the design process and supports continuos analysis, synthesis, evaluation and improvement of the environmental characteristics of a product structure. This activity should not be carried out post the detailed design stage.
Information management	The methodology should support the management of the diverse set of information associated with a product structure.
Identification of environmental problems	The methodology should support the search and identification of environmental problems in a design.
Continuous Improvement	The methodology should support continuous improvement of a design from an environmental perspective, i.e. design refinement.
Structural characteristics	The tool should be able to support the evaluation and improvement of product structural characteristics that enhance its reuse, remanufacture, recycling and disposal options.
Impact evaluation	The methodology should integrate a quantitative and comparative form of LCA into the product evaluation process.
Product strategy	The methodology should link product strategy with advice, e.g. product characteristics that facilitate reuse should be identifiable.
Quantitative evaluation	The methodology should preferably support quantitative evaluation of all environmentally superior characteristics of the proposed design.
Knowledge agent	A knowledge agent needs to be included in the design methodology that allows the designer to search and improve a design process, i.e. general consultative advice.
Advisor agent	The methodology should actively advise the designer on environmentally superior alternatives for a specific part of the design. This represents specific consultative advice.
Support learning	The methodology must support learning for the designer.
Virtual prototyping	There may be benefits of integrating the methodology into virtual prototyping environments.
Checklist	The methodology should act as a checklist for the structured evaluation of a design.
Documentation	The system should produce documents to aid decision-making at all stages of the life cycle.
Reporting	The methodology should support the reporting of information.

Table 4.1. Criteria for the development of a DFE methodology [Roc99]

4.2. DFE Workbench Methodology

The PAL framework as described in chapter two provides a useful basis on which the DFE methodology is both integrated in, and aligned with the design process. The goal of the DFE Workbench methodology focuses on the analysis, synthesis, evaluation and improvement of environmentally superior structural characteristics of a product in the detailed design stage, considering the DFE needs and using standardised evaluation criteria where possible.

The DFE Workbench is based on the problem solving cycle identified in the PAL framework. The methodology will be described by addressing each of the stages in this cycle showing how the methods support that process. Because of the diverse set of DFE requirements identified in table 4.1 Roche decided that the DFE Workbench would consist of a set of integrated methodologies to support the execution of the DFE process. These are as follows:

- Impact Assessment System (IAS)
- The Structure Assessment Methodology (SAM)

Impact Assessment System (IAS) is based on the Eco-indicator 95 methodology described in chapter three. It is an abridged, comparative and quantitative form of life cycle analysis. IAS focuses on the analysis, synthesis, evaluation and improvement of life-cycle environmental impacts created as a result of the product's structure, i.e. as a result of product characteristics such as material type, mass and processing system.

Structure Assessment Methodology (SAM) supports the analysis, synthesis, evaluation and improvement of structural characteristics that enhance the environmental superiority of products. This includes for example the evaluation and improvement of criteria such as; material intensity, material variety, material compatibility and disassembly time of the product. The SAM methodology consists of a nine-step procedure. A chart called the SAM chart forms the basis of data synthesis and evaluation. Improvement is based on a set of algorithms that guide the designer to identify and improve structural characteristics that enhance the environmental superiority of the product. The data synthesis and the continuous improvement process using both IAS and SAM are supported by a set of tables presented in appendix 1. SAM and IAS are integrated so that changes in SAM result in changes in the IAS.

The DFE Workbench has been designed to act as a platform to facilitate the operation of the methodologies and to manage all the interrelationships between the environmental information in the product. Roche proposed the DFE Workbench to be used in four cases as follows: [Roc99]

1. *"Analysis, synthesis, evaluation and improvement of environmental characteristics of the product structure whilst in the design process.*
2. *As a report for product users, for example recyclers can extract disassembly times, material content, disassembly instructions and disassembly tools required, or maintenance people can extract part removal time and tools required for maintenance. Reports can be generated from the Workbench after product optimisation and can be included in the delivery of the product.*
3. *Evaluation of competitors products for disassembly and general environmental performance.*
4. *Training designers how to develop environmentally superior products."*

The data synthesis and evaluation of the IAS methodology is based on a set of tables that have been created by the designers of the method. However, since the method does not cater for the impact improvement strategies, additional tables have been created to support this activity in the DFE Workbench. The improvement tables coupled with the improvement algorithms created for both SAM and IAS form the basis of the advisor agent shown in Figure 4.1.

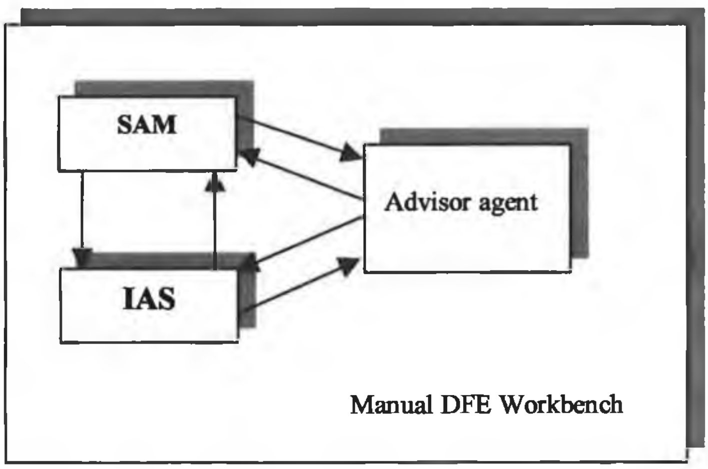


Figure 4.1. The DFE Workbench

4.3. Impact Assessment Structure

As stated earlier in the chapter, Roche has integrated an abridged quantitative LCA tool into the design process that is assisted by a design advisor to help the designer explore environmentally superior design options. Life cycle analysis of products is very closely allied to the structural analysis of the product, however from a different viewpoint. LCA can support the analysis, synthesis and evaluation of the life cycle environmental impact of the proposed structure. Structural issues that effect the environmental impact include the material type and mass. Other issues that are included in the LCA that are not included in SAM are the processing type, end of life strategy and life cycle energy consumption. Roche has proposed to include the Eco-indicator 95 method into the design tool and to support the designer by providing design advice on the environmental impacts of the proposed solution. The method has been adapted for integration (though none of the underlying principles are changed) into the DFE Workbench.

The first stage of the IAS methodology is *synthesis.* At this stage, the designer has to divide the product into its components and to identify the materials, processes, transport and End of Life strategies to be used for each of the component of the candidate design. The next stage, *evaluation* consists of the calculations of the Eco-Indicator value for each component through its life cycle. These values are then added in order to calculate the total environmental impact of the components. At the end, the final value of the environmental impact is calculated adding the values associated with the components. This value represents the total environmental impact of the product.

The last stage is the *improvement* stage. A value for improvement is identified by the largest mPt value in the component list. The primary contributor to the largest mPt value can be identified, i.e. material or process at whatever life stage. Tables that can aid the improvement process include, Table 7 for alternative materials with similar tensile strengths and with less environmental impacts. When the designer is selecting a material he must ensure that if a recycling strategy is recorded at the end of life then the material selected must be recyclable, i.e. the material type codes chart should be consulted when selecting a material. The final stage represents in fact a continuos improvement loop that ends when there are no viable alternatives left.

4.4. Structure Assessment Method

The analysis of a product using the Structure Assessment Method (SAM) provides the designer with valuable information of several different types. Figure 4.2 presents a schematic representation of the Structure Assessment Method (SAM) chart. The notation A_i with i=1...18 labels areas of the chart where different data is recorded. The areas are as follows:

- A_1 is the area where the components and subassemblies are recorded.
- A_2 records the labelling status for recycling.
- A_3 records if the component or subassembly is shared by more than one product.
- A_4 is the area where the name of the different materials used is recorded.

- A_5 records materials codes that describe materials characteristics. Each material may be described by more than one material code.
- A_6 is the area where the mass of each component is inserted. Information about the particular material that makes up each component is also recorded in this area.
- A_7 records the total mass of a particular material used in the product.
- A_8 is the area where the compatibility between different materials is recorded.
- A_9 records the variety of materials used.

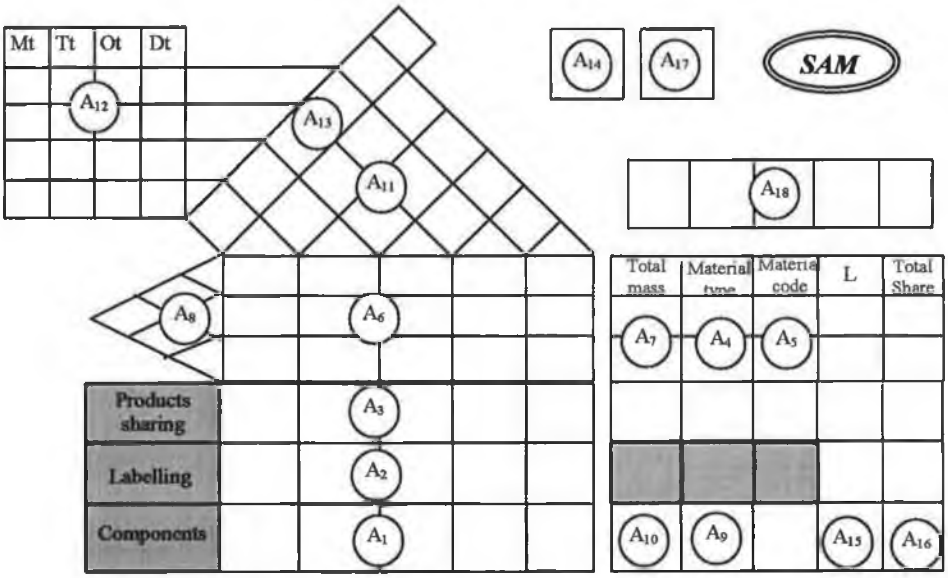


Figure 4.2 SAM Chart (after [Roc99])

- A_{10} records the total mass of the product.
- A_{11} is the area where the number and the types of joints existing between components and/or subassemblies in the product are stored.
- A_{12} presents the times associated with the disassembly process of each component. This time is broken down into three columns: D_t refers to the base time for removal; O_t refers to the obstruction time; and T_t refers to the total time needed to remove a component including the obstruction time.
- A_{13} records the number of joints used in each component.
- A_{14} represents the value of the parameter *number of joints per component*, which indicates structure complexity.
- A_{15} represents the percentage of components appropriately labelled in a product by mass.
- A_{16} records the total proportion of shared subassemblies in the product.
- A_{17} records the total number of joints used per component in the product.

- A_{18} records the total percentage of material of type i.e. recyclable, hazardous, biodegradable, recycled and sustainable.

There are nine steps to be followed in order to develop the DFE Workbench manual analysis:

1. Fill in Components and Subassemblies into A_1 Mark the serviceable/consumable components
2. Indicate shared components in area A_3. Calculate proportion of shared components in area A_{16} (the proportion of shared components is calculated as Total number of shared components/ Total number of components)
3. Fill in materials for each component in area A_4. Classify with material code in A_5. Fill A_9 with the number of different materials used in the product. Mark components made of hazardous materials
4. Fill in material mass for each component in A_6. Eliminate other materials with X. Sum masses in area A_7 and total mass in area A_{10}.
5. Mark labelled components in A_2 as per the following:

   ✓ - Labelled

   ⊗- Not applicable

   ✕ - Not labelled

   Insert value of percentage of components appropriately labelled in area A_{15}
6. Fill materials compatibility relationship in area A_8
7. Build Structural Relationship by identifying and coding connections between components in area A_{11}. Fill in A_{13} with number of fasteners presented in each component. Fill in A_{12} with disassembly times associated to each fastener.
8. Carry out evaluations of product.
9. Make modifications to structure based on evaluations and advisor

SAM method consists of three stages as follows:

1. *Synthesis*. Consists of the steps 1, 2, 3 to 7. All these steps guide the designer to fill out the SAM chart represented in Figure 4.2.
2. *Evaluation*. This stage is represented by step 8. SAM provides the designer with a set of algorithms that will prioritise the important issues for developing the desired product.
3. *Improvements*. This stage is represented by step 9. SAM contain a set of tables that will help the designer to select alternative strategies that will lead the designer to the desired design solution.

Once the structure assessment chart is filled out the data needs to be evaluated and interpreted and improvements proposed. SAM is designed to support the continuous improvement of a design solution hence the method is based on the comparison between a current and a previous state of a design. Prioritisation of improvements within each area is attempted where possible and advice is given in the form of flow charts and verbal descriptions for alternative solutions. However, there are situations where prioritisation is not possible and the designer is supported in an informative way using the advisor. Evaluations and interpretation will be discussed under a number of different headings as follows:

- Theoretical minimum number of components
- Percentage by mass of components labelled
- Material intensity
- Material variety
- Material compatibility
- Disassembly time
- Serviceability and maintainability
- Product structure
- Modularity
- Mass of material by type
- Variety of fasteners
- Number of fasteners per component in the product
- Proportion of shared components
- Removal of hazardous materials

Theoretical Minimum Number of Components

Positive impacts of component minimisation in the product structure are the *minimisation of material variety* as well as *the minimisation of the number of joints* required in the product and hence the overall reduction in disassembly time. The need for an additional component is established based on a positive response to any of the following questions:

- Does the part move relative to another?
- Must the part be made of a different material?
- Must the part be removable from the other part so as to allow disassembly of the product?

Percentage by Mass of Labelled Components

The value for the proportion of material labelled for recycling 'L' is an indication of the recyclability of the product. The designer should try to achieve a ratio of one for this index.

Material Intensity

Large masses of material should be minimised where possible particularly for components that are made of unsustainable materials (identified by material type code). The user should find the largest mass for material in area six and attempt to minimise component sizes associated with these materials. Positive impacts of material minimisation include an increase in resource sustainment, reduction in environmental impacts (in the impact assessment system), reduction in processing energy, reduction in material waste streams (as waste streams are a proportion of product material), reduction in volume and mass of product which reduces transportation costs and associated environmental impacts and finally the reduction of waste at the end of life.

Material Variety

Reduction in material variety is crucial for recycling activities. Increased material variety requires more disassembly activities as well as an increased variety of recycling processes. As a guideline components that perform the same function should be made from the same materials, e.g. casings. Criteria for reducing material variety are as follows:

- Does the component need to be made from a material with different mechanical properties, e.g. tensile strength?
- Does the component need to be made from a material with different constituent properties, e.g. pigment?

Material Compatibility

Most materials cannot be combined for material recycling because of their different structural and chemical make up. The cross contamination of two or more materials even in the smallest levels can result in significant deterioration of the mechanical properties of the resulting material. The designer should make two components separable if the materials they are made up of are incompatible so as to facilitate recycling.

Disassembly Time

The total time to disassemble is composed of the default task time and the obstruction time. The default task time is associated with the tool used to dismantle a joint. The obstruction time refers to the components that need to be removed previously to the removal of a particular component. The value of the total time to disassembly should be kept as low as possible by the means of reducing the obstruction or using joints with less default task time associated. The time needed to disassemble a full product is calculated as the sum of the default task times associated with each component. In order to minimise this value the designer should try to reduce the total number of joints used, to use easier disassembly joints where possible or even to reduce the overall number of components in the product.

Serviceability and Maintainability

Components that need to be regularly serviced or exchanged should be easily accessible hence these category of components should be marked when filling in area A_1. Serviceable components should have no obstruction relationships and the disassembly time Dt_i should be minimised. Fastening elements for these components should be standard and reusable, e.g. adhesives should not be used, as well as disassembly damage to the component should be minimised. The principles for disassembly time minimisation should be applied.

Product Structure

Product structure has enormous impacts on the disassemblability and modularity of the product. A good product structure is characterised by low number of joints per component. The structure of a product can follow one of the three patterns shown in figure 4.3.

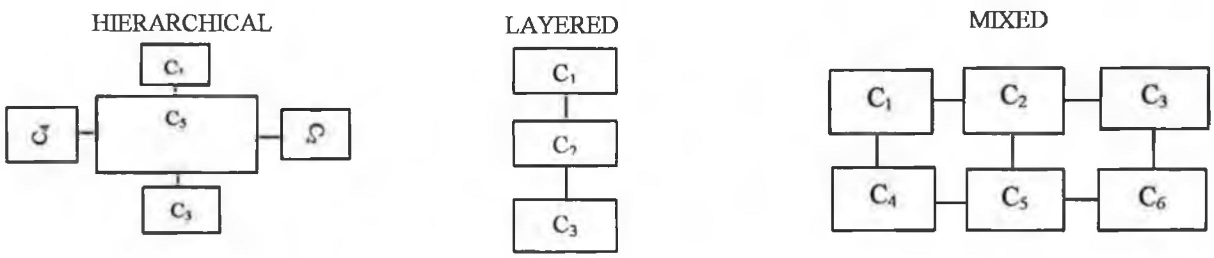


Figure 4.3. Types of product structure

Observing the number and distribution of joints used to assemble the product can indicate the type of structure. For example, a component in a layered structure tends to have two joint interfaces, whereas a hierarchical structure tends to have one joint per component with one single component having many joint interfaces. Clearly the hierarchical and layered structures are easy to disassemble whilst the mixed structure is not.

Modularity

Modular structures allow simple exchange or easy refurbishment upgrade and adaptability for life extension. Modularity of the product can be established from a number of sources in the SAM method as follows:

1. Percentage of subassemblies used in at least one other product

2. Structural relationship of components as outlined in the previous category
3. Disassembly time of modules or subassemblies.

Mass of Material by Types

According to their characteristics, the materials used in a product are classified by codes such as recyclable (R), hazardous (H), biodegradable (B), sustainable/renewable (S) or recycled (Rd). The codes for the materials are inserted in area A_5 of the SAM matrix. Analysing the information presented in A_5, the designer should try to:

- Maximise the proportion of recyclable, sustainable, biodegradable and/or recycled materials.
- Minimise the use of hazardous materials.

After an analysis of the SAM, it is also possible to quote the mass of materials for a particular characteristic, e.g. it is possible to extract the mass of hazardous materials used in the product.

Variety of Fasteners

The complexity of a product greatly effects the viability of disassembly. The expenditure in time and effort in disassembly depends on the number of connections made and the type used. Minimising the number of fasteners reduces the number of tools required to perform the unfastening operation. This results in a significant reduction in non-operation tool handling time in the disassembly process. Key metrics for ensuring fastener uniformity is to count the variety of fastener types 'Fn' used in the candidate design. This is recorded in the area seventeen in the SAM chart.

Number of Fasteners per Component in the Product

SAM chart is used also to record the total number of fasteners used per component in the product. The number gives an indication of the joint efficiency or joint complexity of the product. The value is calculated using the following formula:

$$Fn = \frac{\sum \text{The first digit from the joint code in all cells in the component relationship area}}{\text{Total number of components.}}$$

Proportion of Shared Components

SAM chart records the evaluation of the total proportion of shared subassemblies in the product. The index is calculated using the following formula:

$$\frac{\text{Total number of components shared with at least one other product (from Area 3)}}{\text{Total number of components in the product}}$$

A similar calculation can be carried out for subassemblies.

Removal of Hazardous Materials

The amount of hazardous materials in a product can impair its refurbishment or reuse. This is particularly the case if the hazardous materials are difficult to remove. Substances that pose a danger upon end of life should be easily identifiable in the final design and should be positioned in such a way as they can be easily removed from the product. This means that the total disassembly time 'Tt_i' for hazardous component 'i' should be minimised and there should be no obstruction relationships.

4.5. Conclusions

DFE Workbench methodology has been tested in CIMRU, a research unit within National University of Galway, and it has been also tested in the Motorola Company. The results of the tests have been positive. Some of Roche's conclusions resulted from the performed tests are as follows: [Roc99]

1. The DFE Workbench is integrated much earlier in the design process then any of the existing DFE methodologies.
2. Design is a problem solving process and designers tend to solve problems by the analysis, synthesis and evaluation of design information. The methodology is established to aid this process for DFE and deals with the large variety and volume of interrelated information associated with the environmental characteristics of a product.
3. It has been established that life cycle analysis is an essential tool to support the designer in developing environmentally superior products. An abridged quantitative LCA tool based on standardised full life cycle analysis techniques has been integrated into the model proposed. It is assisted with a design advisor to help the designer explore environmentally superior options, learn about environmental characteristics of products and therefore to be more creative in the development of environmentally superior solutions.

4. Learning influence the decision-making process for designers and for this reason learning needs to be an integral part of design methodologies and tools. The DFE Workbench methodology provides *life cycle information access* and support *interpretation and transformation* of this knowledge into product characteristics.
5. The methodology contains a design advisor that aids the identification of environmental problems in a candidate design and actively proposes environmentally superior alternatives. A DFE knowledge agent that provides passive advice and information to the designer supports the advisor. Information needs to be provided to the designer in an advisory mode rather than as a set of prescriptive rules. The prioritisation process was found to be very useful for the search and improvement activity.

There are also very distinct advantages for developing an automated version of the DFE Workbench and integrating it into virtual prototyping environment. The advantages include:

- the automation of data synthesis activity
- the availability of quantitative data directly from the model
- the manipulation of this data
- the management of data interrelationships
- the accelerated learning that takes place as a result of active experimentation
- the resulting effect of this learning
- the resulting improvement in a design before it is manufactured

Chapter 5

DFE Workbench Software

5.0. Introduction

This chapter will present a detailed review of the DFE Workbench software application. First, the schematic representation of the steps involved in the development of any software application will be presented, next the functional specification of the tool will represented using a Data Flow Diagram technique. Further on the software will be detailed using relevant screen shoots of the DFE Workbench software application.

5.1 Software Development

There are various activities performed during the software development cycle. These activities do not have clearly defined boundaries.

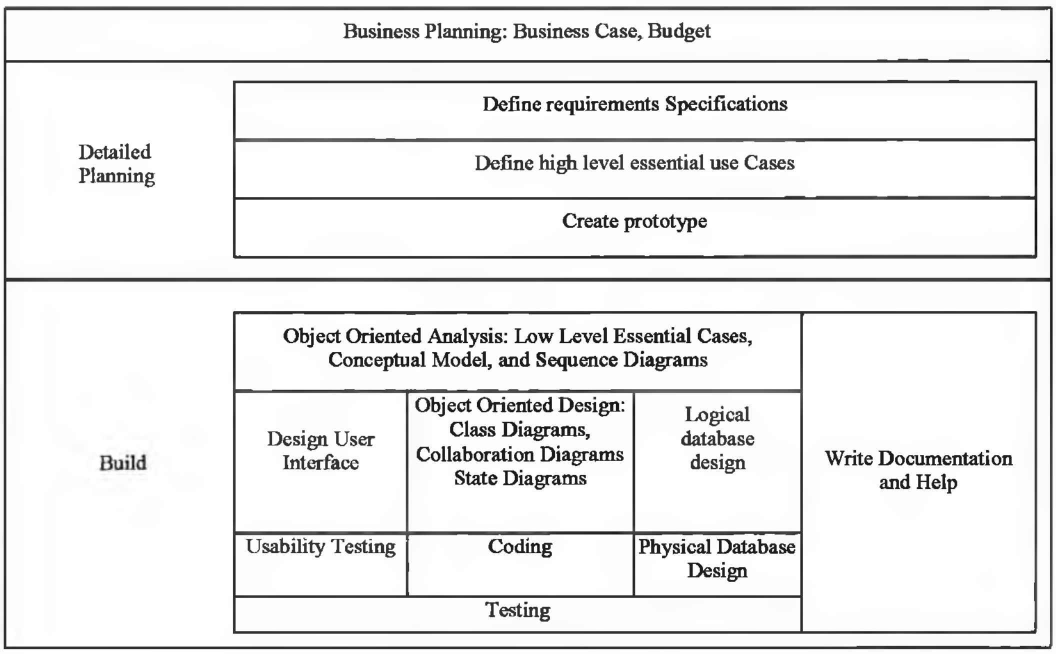


Figure 5.1. Activities of the software development [Gra98]

The activities can merge and can become iteration until the right path is identified. For example in the analysis phase, it may become apparent that there are ambiguous or conflicting requirements that need to be solved, and the process starts again. Such iterations are a normal part of the development process as long as the next iterations result in fewer and fewer problems to solve. The activities involved in the software development, presented in figure 5.1. are: [Gra98]

Business Planning: it starts with a proposal to build a software application, next a document will be written presenting the pros and cons of the software project including the estimates of the resources required to complete the project.

Requirement Definitions: At this stage, requirement definitions are being identified. It starts with identifying the goals of the software. As the requirement specification is used in subsequent activities, necessary refinements to the requirements are discovered.

Define Essential Use Case: A use case describes the events occurring between a system and other entities. Developing use cases improves the understanding of the requirements.

Create Prototype: Develop a prototype of the software application. It is useful in order to get reactions to the proposed project and also for refining the requirements.

Define High Level System Architecture: At this stage, the components of the system and their relationships are identified.

Object Oriented Analysis: the result of this activity is a conceptual model of the problem to be solved. This analysis models the situation in which the software operates from the perspective of an outsider observer.

Object Oriented Design: This activity determines the internal organisation of the software. It involves more decision taking than any other activity because it consists of identifying the classes that constitutes the internal logic of the software and determines their inter-relationships.

Coding: The purpose of this activity is to write the code that makes the software work.

Testing: This activity studies the performance of the software.

5.2. Functional Specification of the DFE Workbench Software Tool

The first activity involved in planning a software application is *Analysis Modelling.* It consists of a number of modelling tasks that result in a complete specification of the functions to be performed by the emergent software application. There are a number of methods available for performing the Analysis Modelling and the most common used one is the *Structure Analysis* method. It has been defined by Yourdoun as: *"a collection of guidelines and graphical communication tools that allows a system designer to replace the* *traditional functional specification document with a new kind of specification that users can actually read and understand"* [You86].

The tool selected for the structure analysis of the DFE Workbench Software application is Data Flow Diagram (DFD) technique that uses graphical representations of the information flows and transformations applied to data as they move from input to output [Prs87]. The DFD technique uses special graphical forms for representing the system's components as presented in table 5.1.

Description	Symbol
External entities are the elements, which provide information to or receive information from the system. They are symbolised as ovals:	
Processes are the elements, which transform or manipulate data within the system. They are represented as rectangles:	
Data stores are the elements, which store information. They are represented by rectangles with double extremes:	
Data flows are the elements, which represent packages of information flowing between objects. They are symbolised by an arrow labelled with the name or details of the information represented by the data flow	

Table 5.1. DFD's graphical representation system

The DFD technique has been selected because it allows the representation of a system by different levels of complexity ranked from 0 to n where $n-1$ is the parent of level n. The zero level is called the *fundamental system model* or the *context model* and it represents the whole system as a process with input and output data [Prs97].

The zero level of the DFE Workbench software application is presented in figure 5.2.

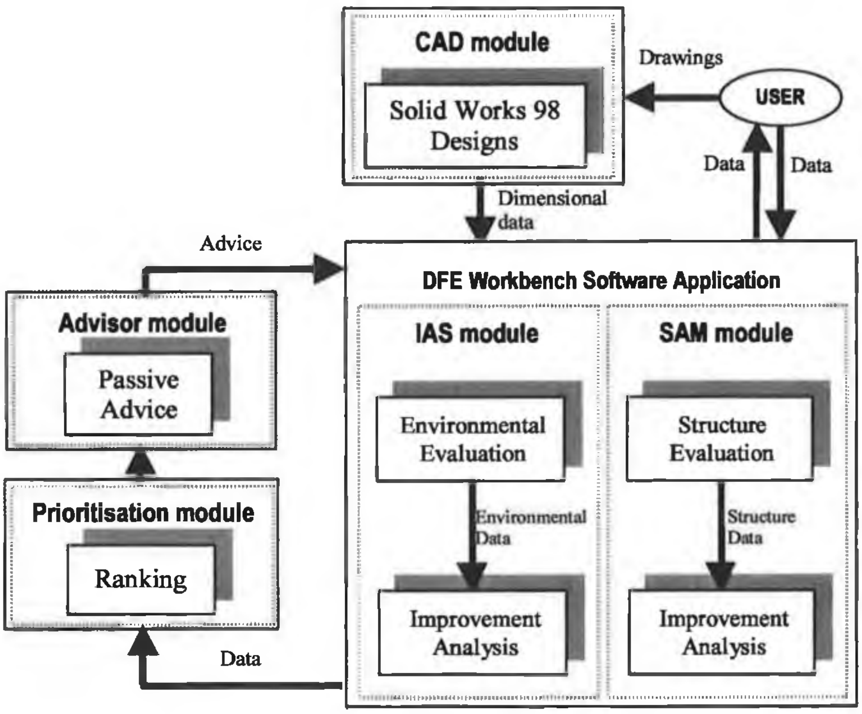
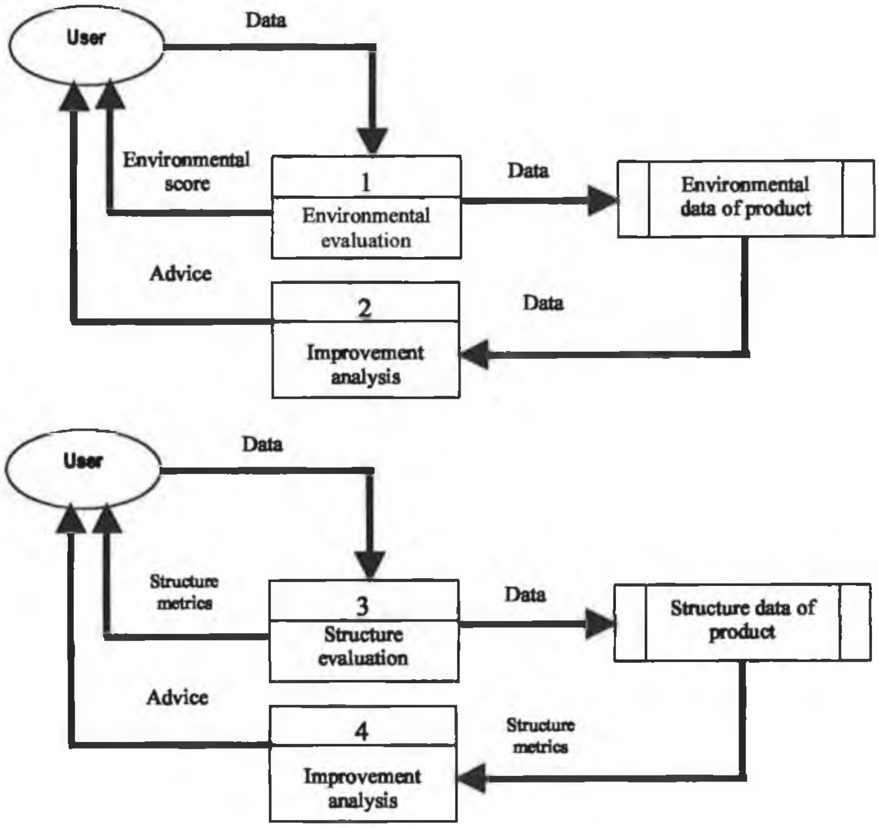


Figure 5.2. Data Flow Diagram of the DFE Workbench

The zero level of the system presents the interaction between the tool and the user. The user draws the candidate design with the help of the CAD system and defines the necessary environmental and structure data. DFE Workbench consists of two processes i.e. Impact Assessment System (IAS) and Structure Assessment System (SAM). Both modules process the stored data and the results are passed to the prioritisation module that ranks the results in terms of their environmental and structural relevance. Next the advisor provides improvement strategies that can be adopted or ignored by the user. Zero level can be exploded in two diagrams representing the level one of the system as illustrated in figure



5.3.

Figure 5.3. DFD Level 1 of the DFE Workbench software application

The two processes represented in figure 5.3 illustrate the IAS process and the SAM process of the candidate design. The software tool assesses the data obtained from the user and from the CAD system and calculates the environmental impacts and the structure metrics and saves them in databases associated with the candidate design. The results are prioritised and analysed and the advisor suggests improvements. The user may adopt or ignore the suggestions. The level one of the system may be exploded into level two. In this case a more complex representation of the system is obtained. Figure 5.4 to 5.8, presents the refinement of the four processes presented in figure 5.3 i.e. Environmental Evaluation, Improvement Evaluation of the environmental impacts, Structure Evaluation and Improvement evaluation of the structure metrics.

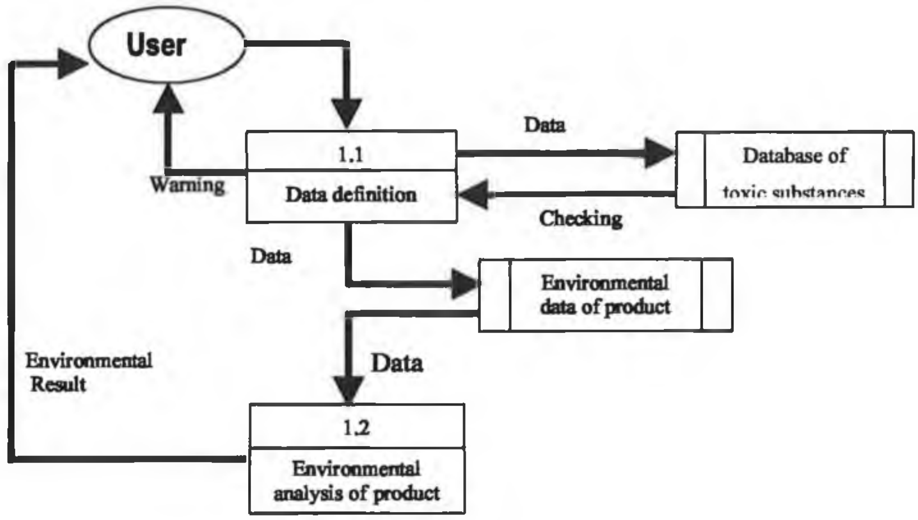


Figure 5.4 Environmental evaluation

The environmental evaluation involves the calculation of the environmental impacts associated with each component of the candidate design.

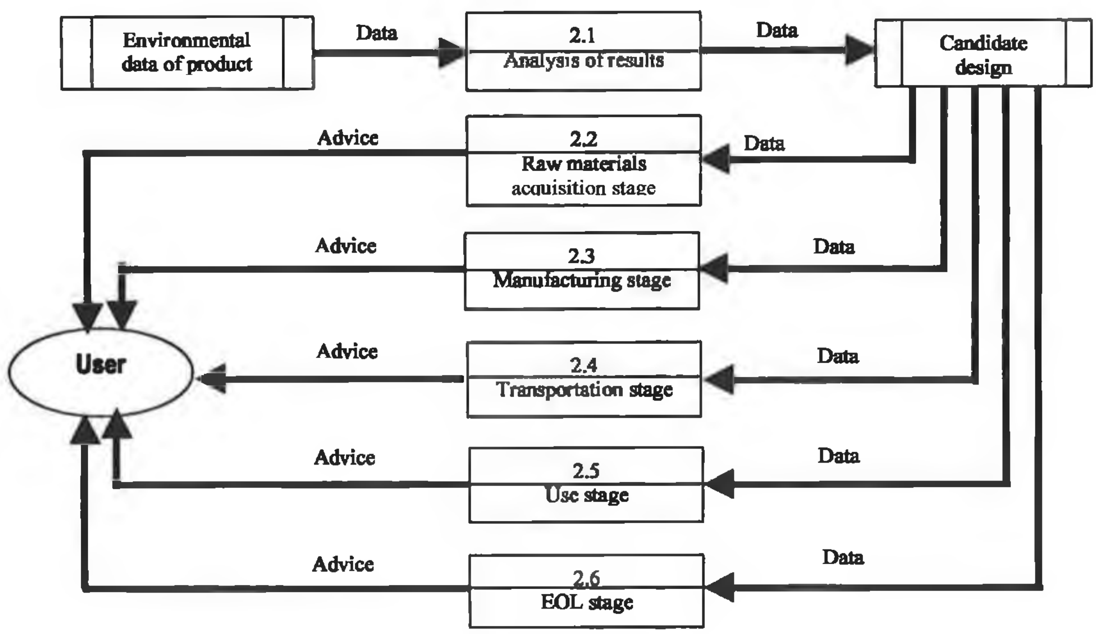


Figure 5.5. Improvement evaluation of the environmental scores

The improvement evaluation process presented in figure 5.5. involves the evaluation of the environmental scores calculated for each component at each life cycle stage i.e. raw materials, process, use, transport and end of life. The highest environmental impacts are identified and the DFE Workbench provides advice for reducing this scores.

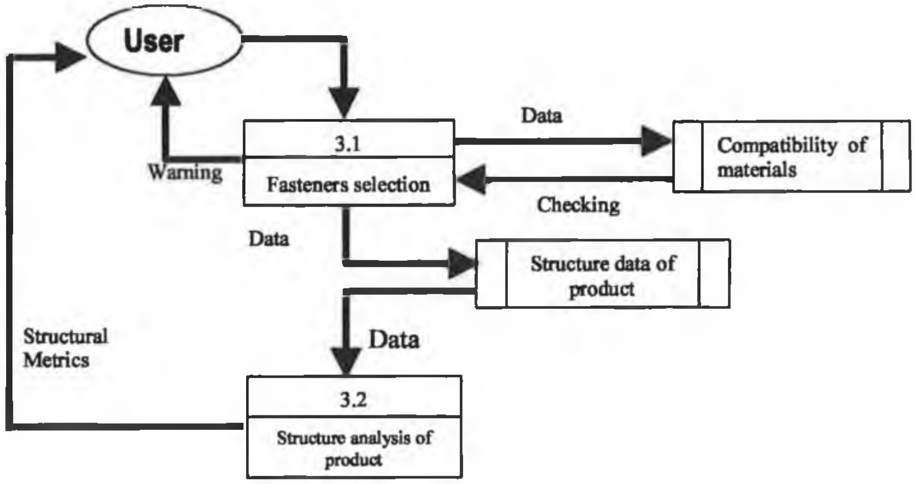


Figure 5.6. Structure Evaluation

Structure evaluation process involves the definition of the fastener's type and number associated with each of the components of the candidate design. It also involves the identification of the parts that require often service, the parts that are labelled and the existent obstructions in the assembly.

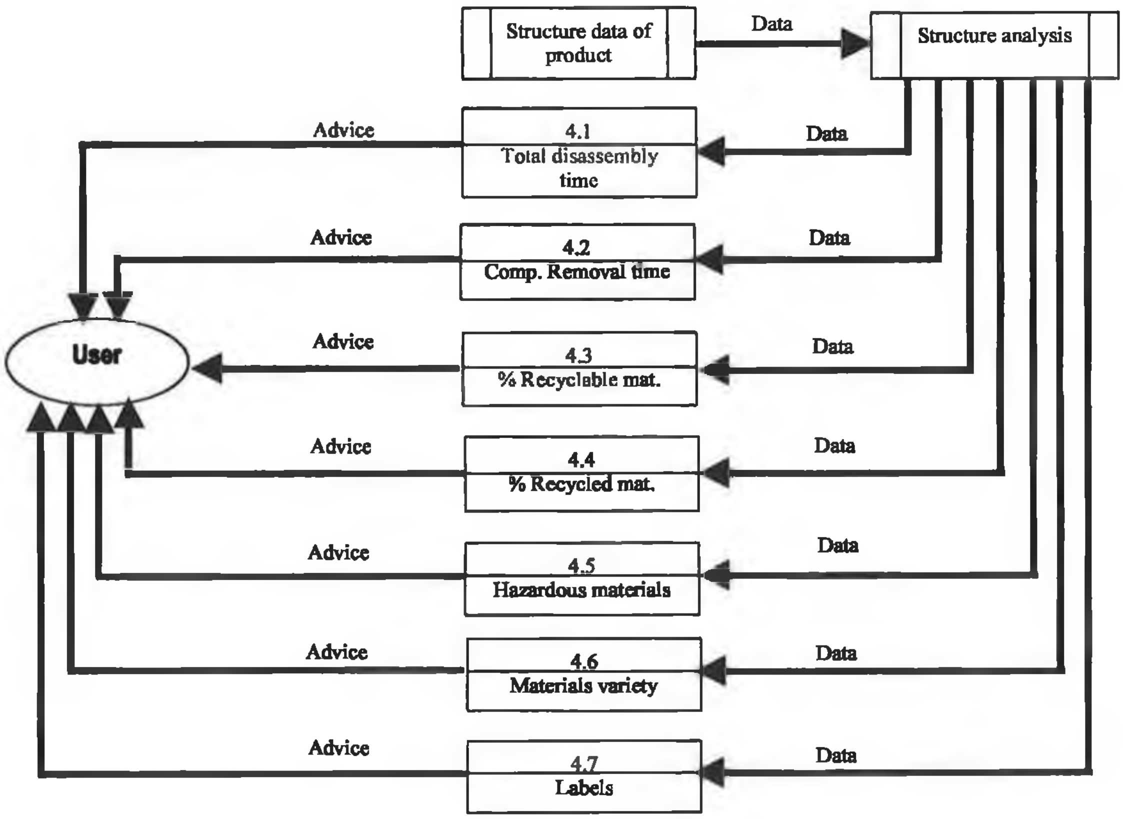


Figure 5.7. Improvement evaluation of the structure metrics

The improvement evaluation of the structure data involves the evaluation of the structure metrics i.e. total disassembly time, component removal time, percentage of the recyclable, recycled, sustainable, hazardous and biodegradable materials used in the candidate design, the material variety and the percentage of labelled parts. For each of this scores the DFE Workbench suggests alternatives for improvement.

The Environmental evaluation diagram presented in figure 5.4 consists of two processes that can be refined to the level three of DFD. The processes are as follows data definition process numbered 1.1 and environmental analysis process numbered 1.2. This processes refers to the selection of the materials, processes, use, transport and end of life strategies relevant for each of the components of the candidate design and to the calculation of the environmental scores.

The improvement evaluation of the environmental scores presented in the diagram 5.3.b. consits of 6 processes that can be refined to the level three of system's DFD as follows. The process numbered 2.1 refers to the evaluation of the data selected by the user. The advice suggested by the tool is specific for each life cycle stage of the candidate design. Figure 5.8 presents the refinement of the process 2.2 that focus on suggesting improvements for the raw material stage.

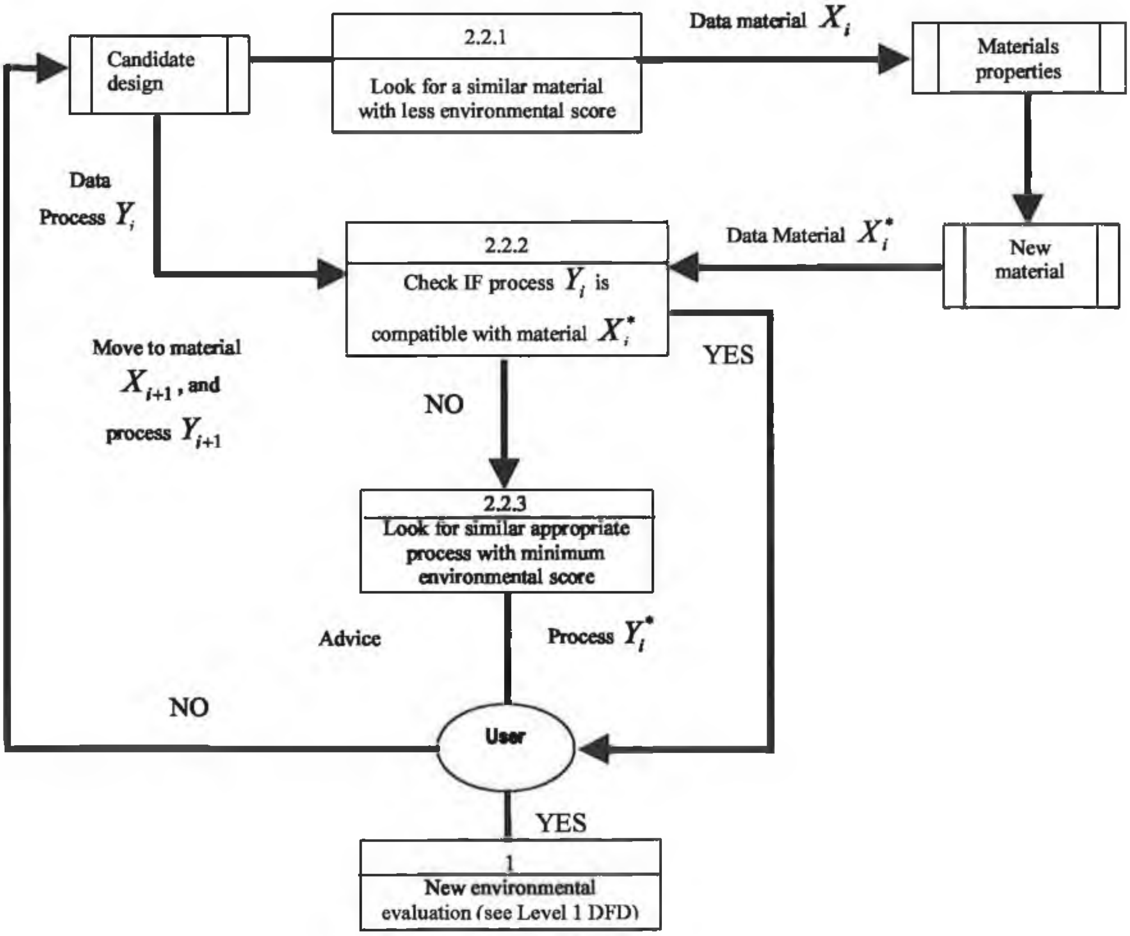


Figure 5.8. Level 3 of the system's DFD focused on the Raw Material stage.

After the data specified by the user are analysed in the process 2.1, the application evaluates the environmental impacts. If there is a high environmental impact associated with the raw material stage the advisor will suggest new materials with similar properties but a lower environmental impact. The materials are represented in the diagram by X_i and the processes are represented in the diagram by Y_i where $i = 1, 2, 3...n$. firstly the tool will look for a material X_i with lower environmental impact but similar properties and will suggest the results to the user. If the user does not accept the suggestion, the tool will search for a different material. If the user accept the material, the tool will verify if the new material is compatible with the previously selected process. If there is no compatibility the tool will search for a compatible process. The results are suggested to the user, which can accept the suggestion or refuse them. In the last case, the tool will move to material X_{i+1}, and process Y_{i+1}. The processes 2.3, 2.4, 2.5 and 2.6 refer to the advice suggestion processes associated with the remaining life cycle stages i.e. manufacturing, transport, use, and end of life. They can be refined to the level three of system's DFD in a very similar manner as the one described for the raw material stage.

The structure evaluation process presented in figure 5.6 consists of two processes i.e. Fastener selection process numbered 3.1 and the structure analysis process numbered 3.2. Both processes may be refined to the level three of system's DFD.

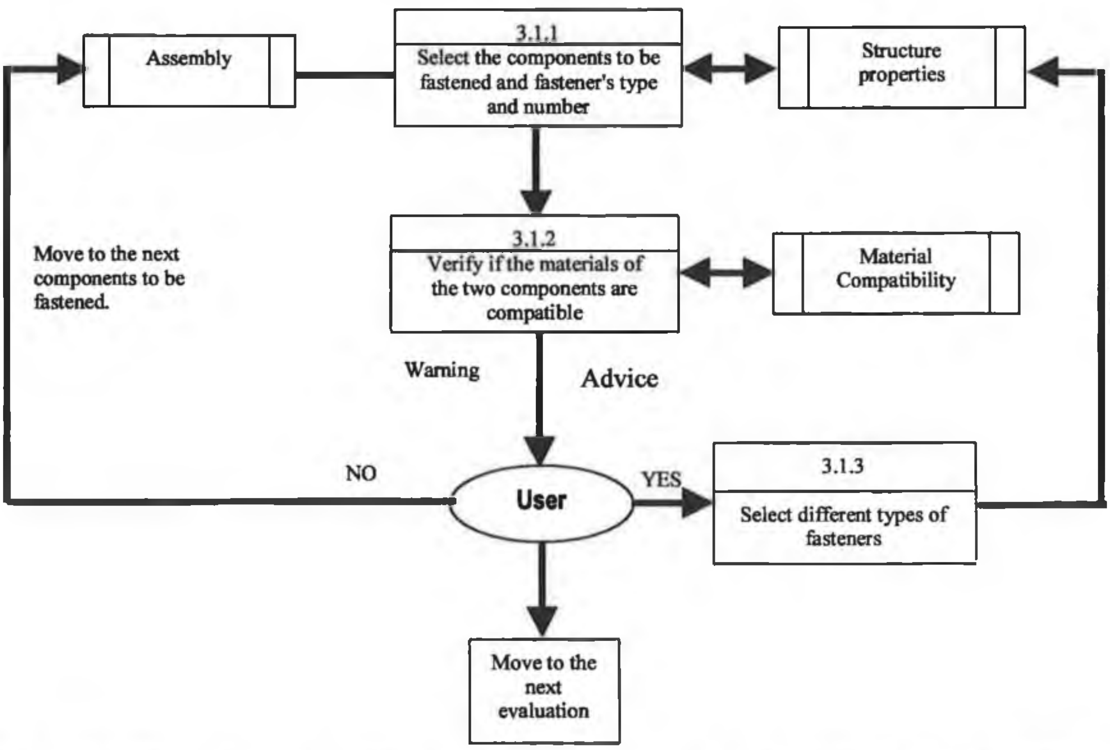


Figure 5.9. The refinement of fastener's selection process to level 3 of system's DFD.

The fastener's selection process is presented figure 5.9. Firstly, the user selects the components that are joined and the type and number of fasteners used. Next the tool will verify if the component's materials are compatible if fastener's type is adhesive or welding. If the materials are incompatible in the means of recycling, the tool will warn the user that a different type of fastener should be used. The user can ignore the warning and the advice and move further in the selection process. If the user accept the advice, a new suitable fastener will be used.

The structure analysis process will perform structure calculations i.e. total disassembly time, component removal time, the percentage of recyclable, recycled, sustainable and biodegradable materials, the number of hazardous materials used in the candidate design and the number of parts that are labelled.

The improvement evaluation of structure's metrics presented in figure 5.7 can be refined to the level three of the system's DFD by detailing the enclosed processes i.e. total disassembly time and component removal time advice process, the advice process focused on the percentage of recycled, recyclable, sustainable and biodegradable materials used in the prototype, the advice process focused on the hazardous materials used in the prototype, the material variety advisor and the labelling advisor.

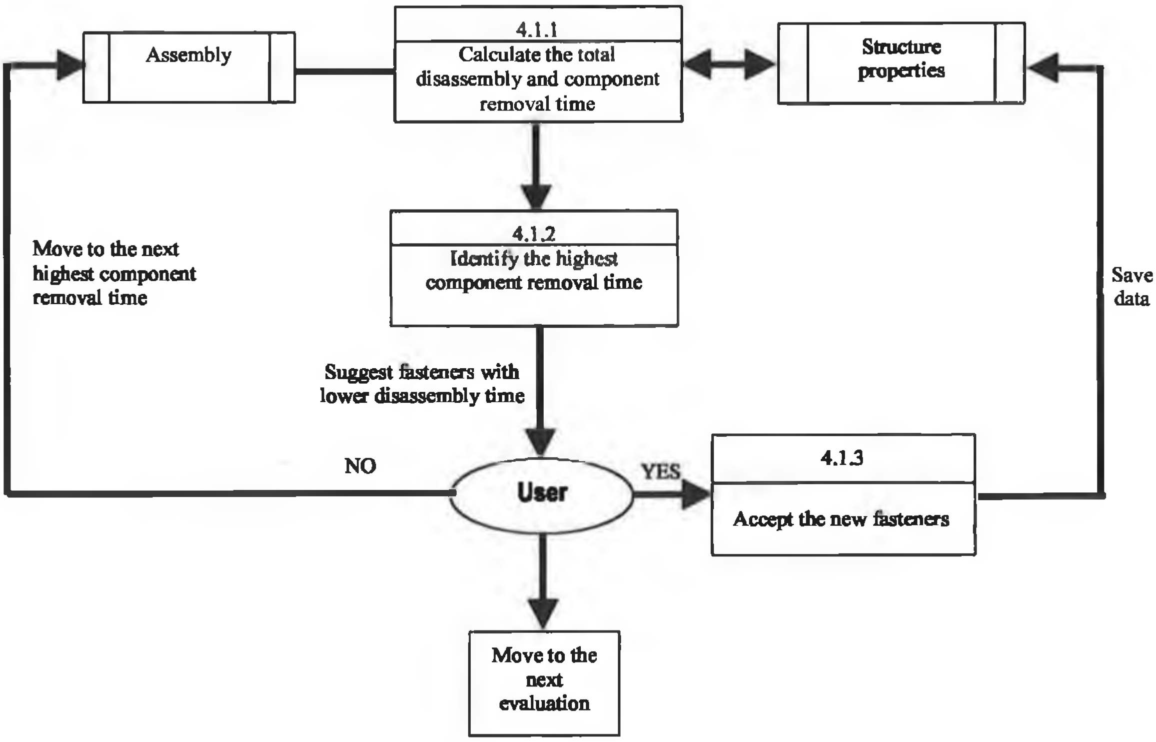


Figure 5.10. Representation of the advisor process focused on the total disassembly and component removal time.

Figure 5.10 presents the level three of system's DFD reflecting the advisor process focused on reducing the disassembly time of the prototype analysed. Firstly the total disassembly and component removal times are calculated. The tool identifies the highest disassembly time and suggests alternative fasteners with a lower disassembly time. The user can accept or refuse the suggestion. This process is a continual improvement process and it continues until there are no more alternatives left.

The next processes that may be refined to the level three of system's DFD is the advisor process focused on the percentage of recyclable materials used in the analysed prototype.

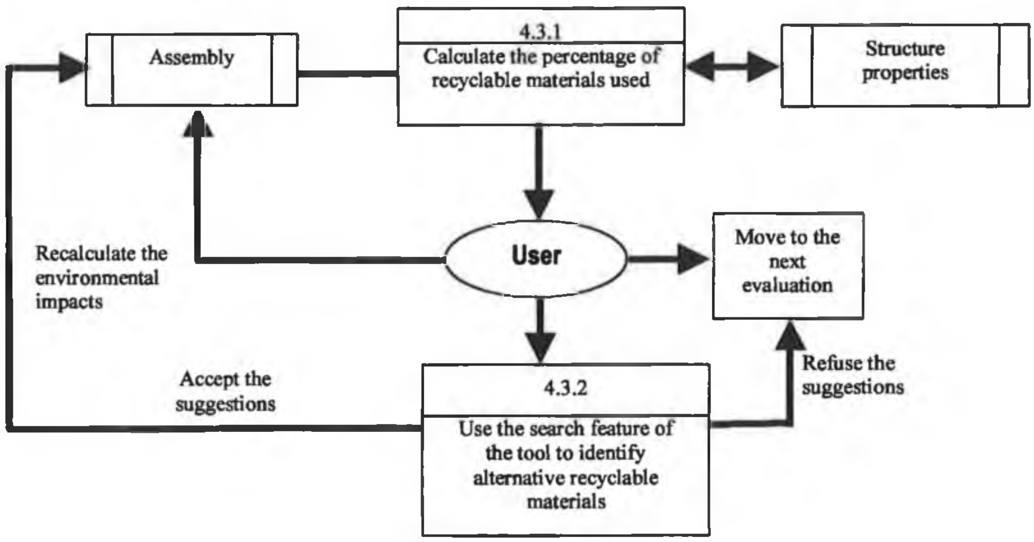


Figure 5.11. Level 3 of the system's DFD representing the advice process focused on the recyclable materials used in the prototype being analysed.

The advisor processes focused on recyclable, sustainable and biodegradable materials are very similar with the process presented in figure 5.11.

The next process to be refined to the level three of the system's DFD is the advice process focused on the hazardous materials identified in the prototype being analysed (see figure 5.12.). Firstly the tool identifies the hazardous materials used in the prototype being analysed. Next, the advisor will suggest alternative non-hazardous materials with similar properties and a lower environmental impact. The user can refuse or accept the suggestions. If the user refuse the suggestions, the advisor move to the next hazardous material identified. If the user refuse the suggestion the evaluation can continue with the next hazardous material or the user can abandon the evaluation.

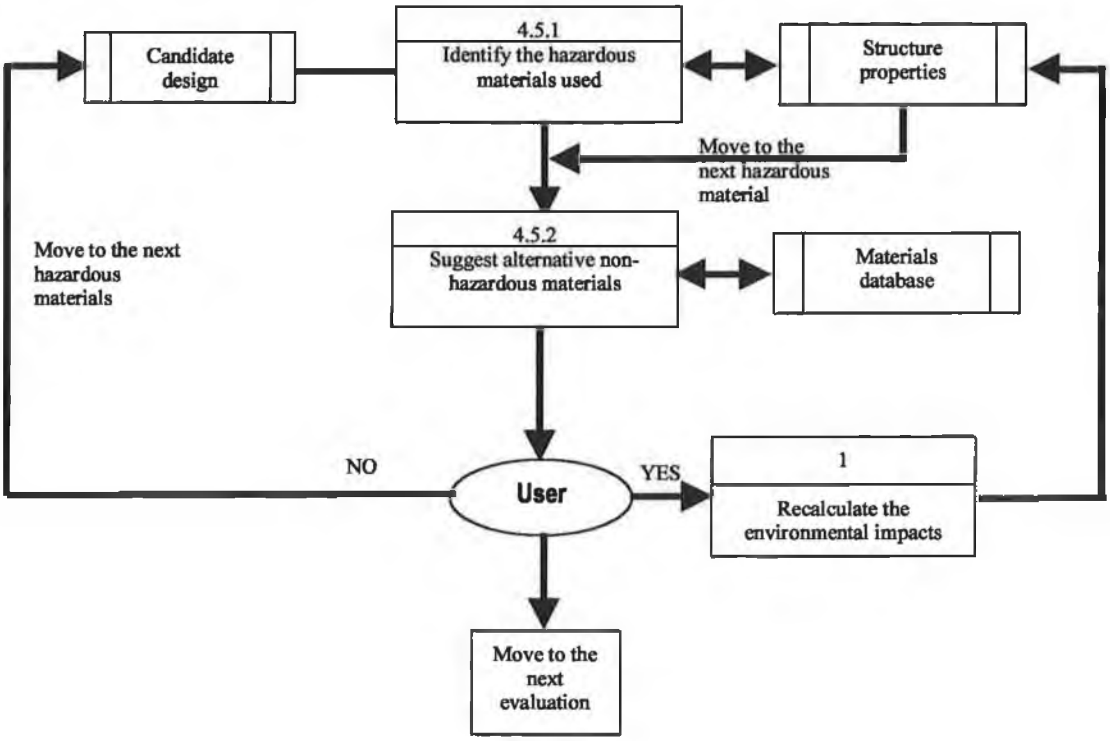


Figure 5.12. Level 3 of the system's DFD representing the advice process focused on the hazardous materials used in the prototype being analysed

The next process to be refined is the process numbered 4.6 in figure 5.7 i.e. material variety analysis.

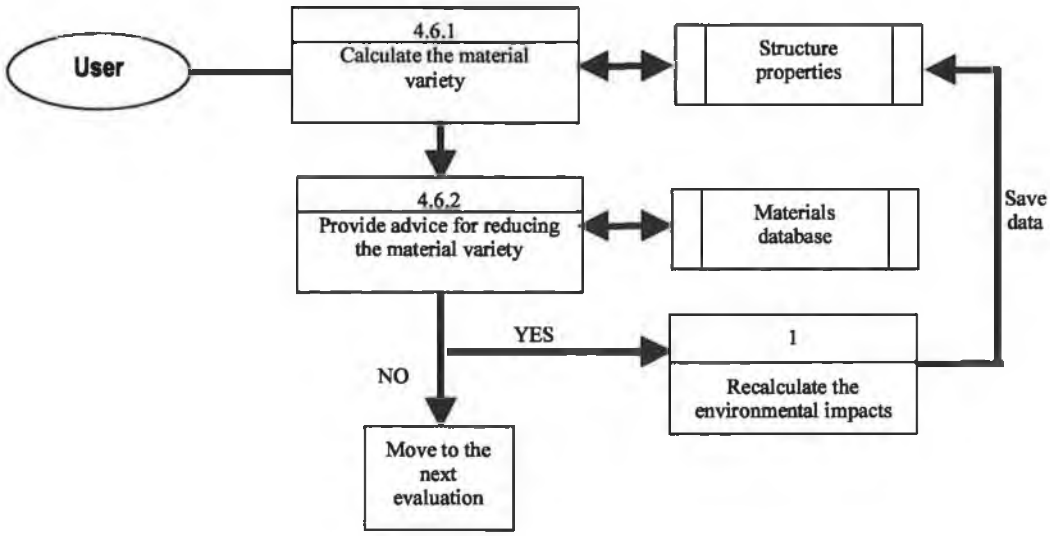


Figure 5.13. Level 3 of the system's DFD representing the advice process focused on the material variety used in the prototype being analysed

Firstly the tool identifies the material variety of the prototype being analysed and provides advice to reduce the number of different materials used in the prototype. The user can accept the advice and the tool will enter the process 1 refined in figure 5.3. The user may refuse the advice and may proceed to a different evaluation.

The last process that can be refined to the level three of the system's DFD is the advisor process focused on the labelling process. It is very important the designers label as many components as possible of the candidate design because it influences the decisions to be taken at the end of life stage of the product. Regardless the recyclable material a component is made of, at the end of life stage it may be disposed if there are no labels to identify the material used. No recycling companies will accept unlabelled components as they may contaminate the mould.

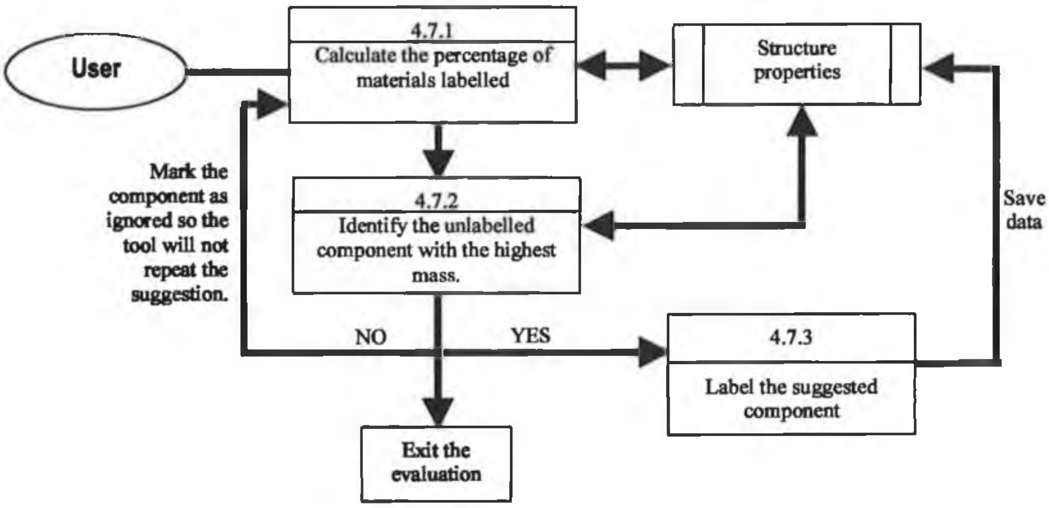


Figure 5.14. Level 3 of the system's DFD representing the advice process focused on labelling the components of the prototype being analysed

Firstly the tool calculates the percentage of the labelled components and identifies the unlabelled component with the highest mass. The user can label the suggested component or can ignore the suggestion and move to the next unlabelled component with the next highest mass. The user may also choose to abandon the evaluation.

Implementation of PAL Framework Phases

The DFE Work Bench is developed around the facility of execution of the three phases outlined in PAL Framework i.e.:

- Analysis
- Synthesis
- Evaluation and Improvements

All this phases have been described in detail for the IAS and SAM methodologies in chapter four however here will follow a brief description of how these phases have been implemented in the DFE Workbench Software.

Analysis

The Analysis phase consists in disassembling the components of the specified prototype, and analysing them separately. The analysis is performed during the design process. When a component is represented in a CAD system the DFE Workbench Software is gathering the environmental data and performs an analysis. Then, the next component will be represented in the CAD environment and analysed by the DFE Workbench Software. When all the components are defined the software will perform an evaluation of the entire assembly and will guide the designer in order to create a more environmental friendly product.

Synthesis

The synthesis phase consists of the identification of the prototype characteristics, this includes; component material, manufacturing process, transportation, use and end of life options, and joining methods. At this stage the DFE Workbench Software extracts data directly from the CAD environment, e.g. the mass of the components. First the component is designed in the CAD environment. Secondly the designer defines the component characteristics and saves them in a Microsoft Access table. There is the possibility that the designer will use a component from a supplier, e.g. an electronic component. In this case the designer will extract the characteristics from an existing file. The Synthesis Phase is completed when all the components are defined.

Evaluation and Improvements

The Evaluation and Improvements phase consists of two elements: first the DFE Workbench Software will perform the DFE calculations; secondly, a ***Prioritisation*** and an ***Advisor*** module will guide the designer in designing an environmental benign product. The Evaluation and Improvements Phase starts with the DFE calculations for the prototype, this includes environmental impact, total disassembly time, component removal time, material variety and mass intensity. Next a ***Prioritisation Module*** based on an adapted FMEA[1] analysis will highlight the environmentally related component characteristics and the ***Advisor Module*** will guide the designer to make the right decisions in order to reduce the targeted characteristics. If the designer decides to accept de improvements suggested by the ***Advisor Module***, the DFE Workbench software will save all the modifications and will restart the prioritisation. If the designer decides to ignore the advice than the ***Prioritisation***

[1] Failure Mode and Effects Analysis

Module will highlight the next relevant characteristics and will suggest improvements. The Evaluation and Improvement phase is a cycled process that ends when there are no other improvements available or the solution obtained is the desired one.

5.3. DFE Workbench Software Description

The *DFE Workbench Software* is an application that supports the execution of the steps defined by the two methodologies described in chapter four, i.e.:

- Impact Assessment System (IAS)
- Structure Assessment Method (SAM)

The *DFE Workbench Software* is developed using Visual Basic 5, which is an object-orientated programming language capable to create robust and efficient Windows applications. The data manipulated by the software are stored in databases created in Microsoft Access environment. The application is integrated with a virtual prototyping software so the designer is able to export/import DFE information to/from the model. Figure 5.15 presents the existent relationships between the virtual prototyping software (the CAD[2] System) the DFE Workbench Software and the Microsoft Access Databases.

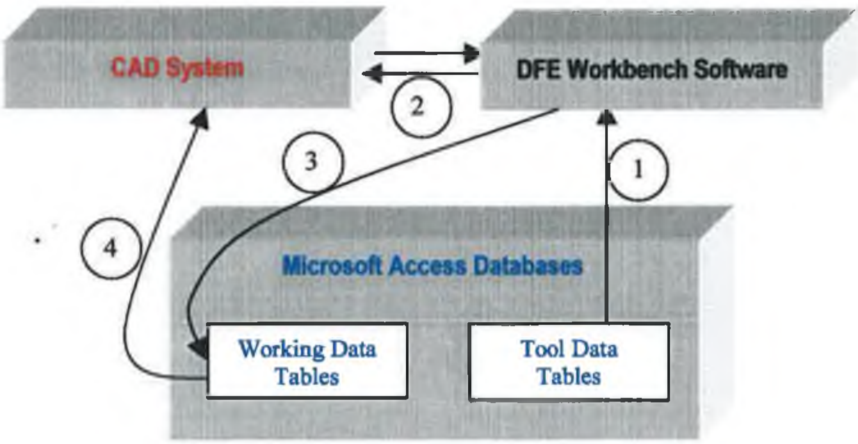


Figure 5.15. The relational diagram of the DFE Workbench Software

The *Tool Data Tables* contain the general environmental data described in chapter three, this includes Global Effects Scores (see Table 3.2, chapter three) and Eco Indicator values (see Table 3.4, chapter three).

The *Working Data Tables* contain the characteristics of the specified prototype. The relationships presented in Figure 5.15 are defined as follows:

1) First the application will communicate with Microsoft Access for extracting the specified environmental data from the *Tool Data Tables*.

[2] Computer Aided Design

2) Secondly, the Application will communicate with the CAD system by sending the material properties and extracting the mass.
3) Next the application will evaluate the environmental data defined for the prototype, will improve the results and will store the obtained data in a working data table.
4) Last the working data table will be associated with the prototype being analysed.

The DFE Workbench Software has been integrated in SolidWorks98 Plus[3] because of its user-friendly interface and its ability to communicate with different Windows based applications. The workbench currently has two integrated tools as follows:

- Impact Assessment System (IAS).
- Structure Assessment Method (SAM).

For a better understanding, the description of the DFE Workbench Software is based on a case study. The case study consists of the analysis of a domestic smoke alarm model containing the following components: base, diffuser, sensor, button and cover (see figure 5.16).

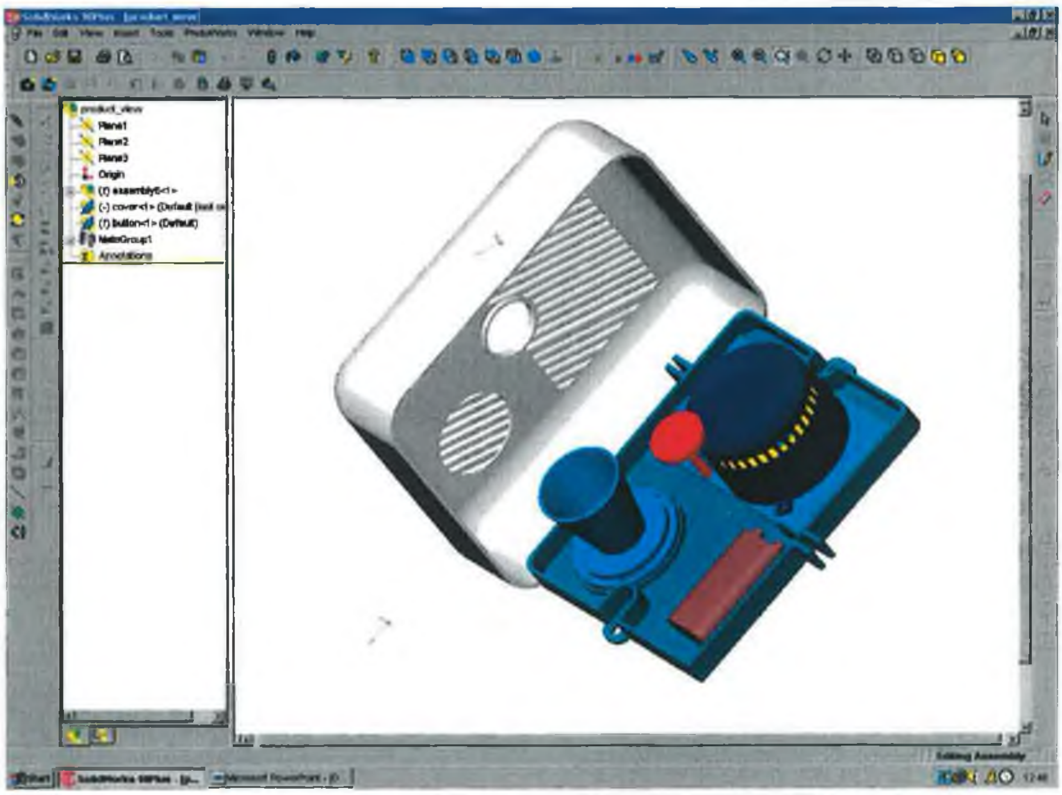


Figure 5.16. Smoke Alarm Prototype developed in the Solid Work 98Plus environment.

Both SAM and IAE tools have been integrated in single software. The starting windows are presented in figure 5.17.

[3] SolidWorks98 is a feature-based parametric solid modelling design tool that enables the creation of fully associative 3D solid models utilising automatic or user defined relations.

Figure 5.17. Starting DFE Workbench software

Impact Assessment System Tool

Impact Assessment System Tool performs a comparative Life Cycle Analysis as described in chapter three. The analysis can only begin when a component for the prototype is fully defined in the CAD environment. The designer starts by selecting the material to be used for the component. When the material is selected the IAS Tool exports the material density to SolidWorks98 and imports the mass associated with the component. The mass is used to calculate the Eco Indicators for the selected life stages options.

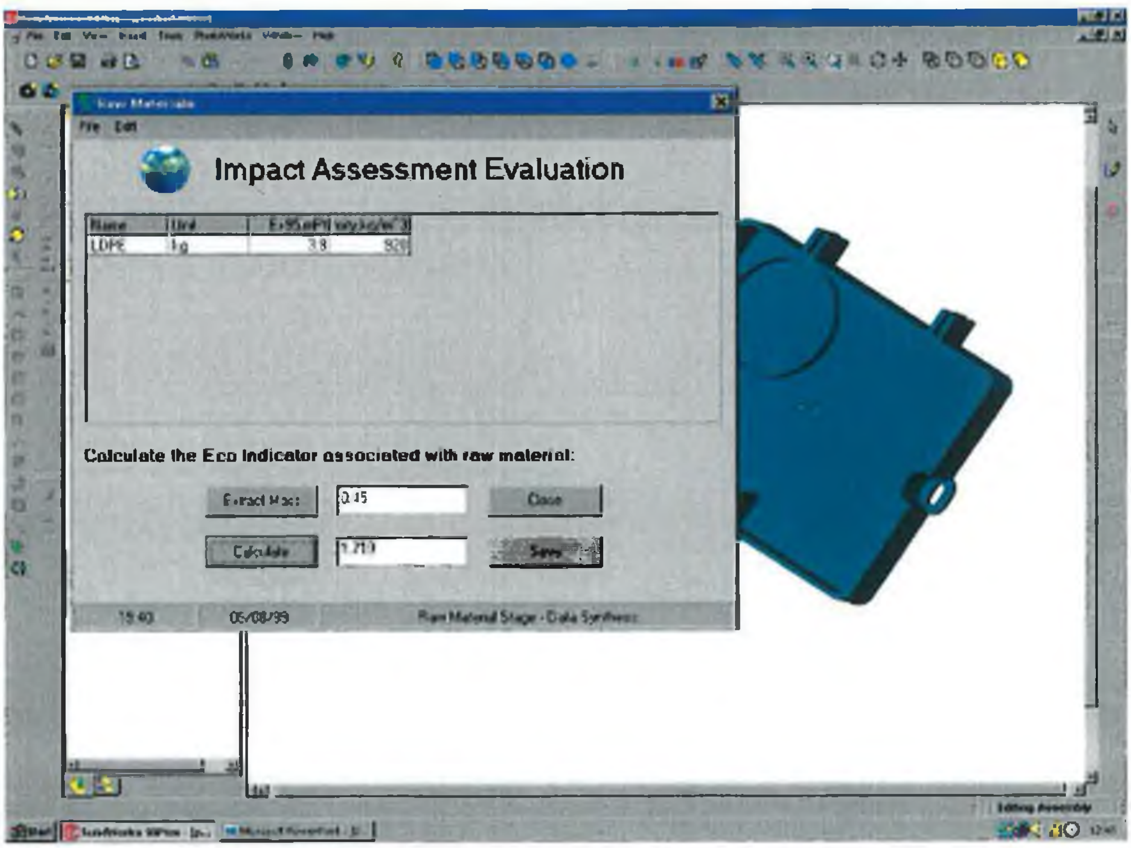


Figure 5.18. Material selection Window

Figure 5.18 presents the material selection window for the base. The material selected is LDPE. The material density is 920 kg/m^3 and the Eco Indicator calculated for 0.45 kg of LDPE is 1.710 mPt[4]. Next, the designer selects the appropriate manufacturing process, use, transportation and end of life options.

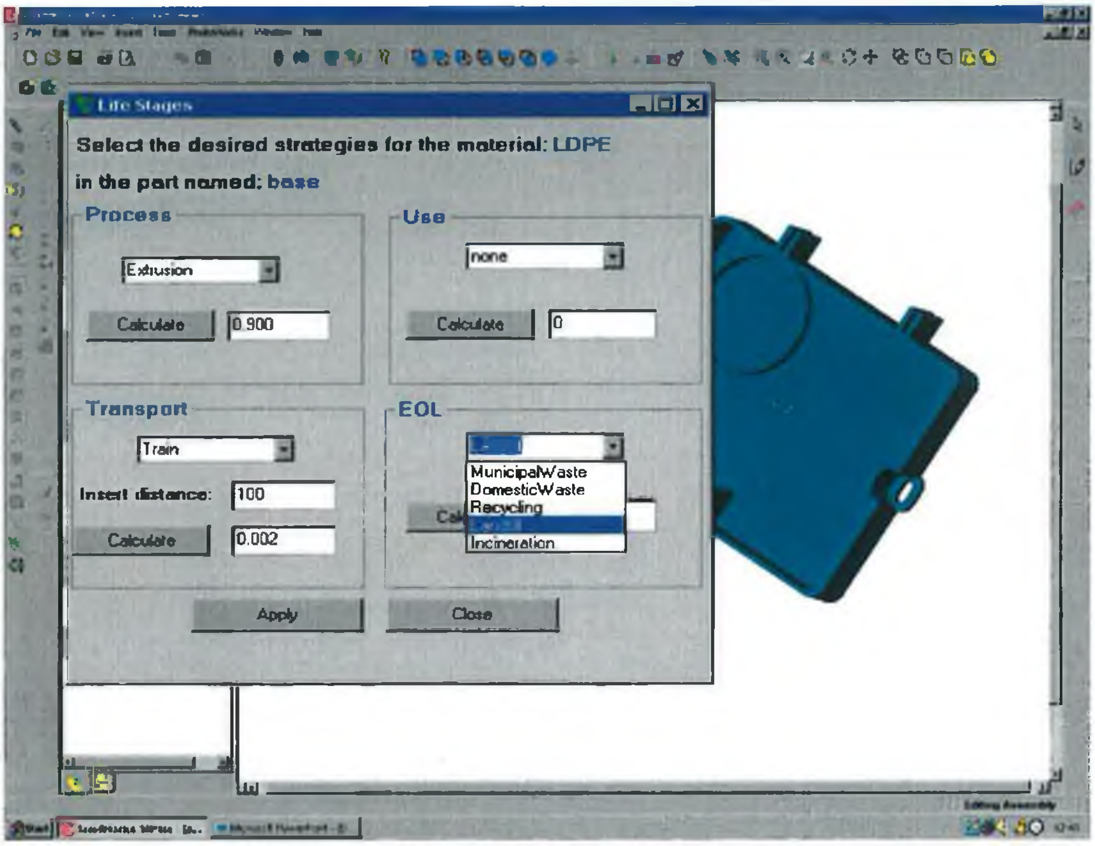


Figure 5.19. Options Window for the next Life Stages

Figure 5.19 presents the selection of the manufacturing process, use, transport and end of life options for the component named 'base'. The IAS Tool will display only the manufacturing processes and end of life options that are characteristic for the material selected. The manufacturing process for base is extrusion. The extrusion process has an Eco Indicator equal with 0.9 mPt. The component will be transported to the suppliers by train over a distance of 100Km. The Eco Indicator calculated for this option is 0.002 mPt. The options selected for the end of life stage is 'Landfill' and the Eco Indicator calculated for the disposal of 0.45 kg of LDPE is 0.018 mPt. When the Data Synthesis Phase is completed the IAE Tool will do an evaluation of the data gathered and will calculate the total environmental impact for the prototype analysed. Figure 5.20 presents the evaluation

[4] mPt is the abbreviation for millipoints, that is a measurement unit for Eco Indicator. The Eco Indicator is calculated using the Eco Indicator 95 method described in section 3.2.2.

phase for the smoke alarm case study. The total environmental impact associated with the smoke alarm is 9.119 mPt.

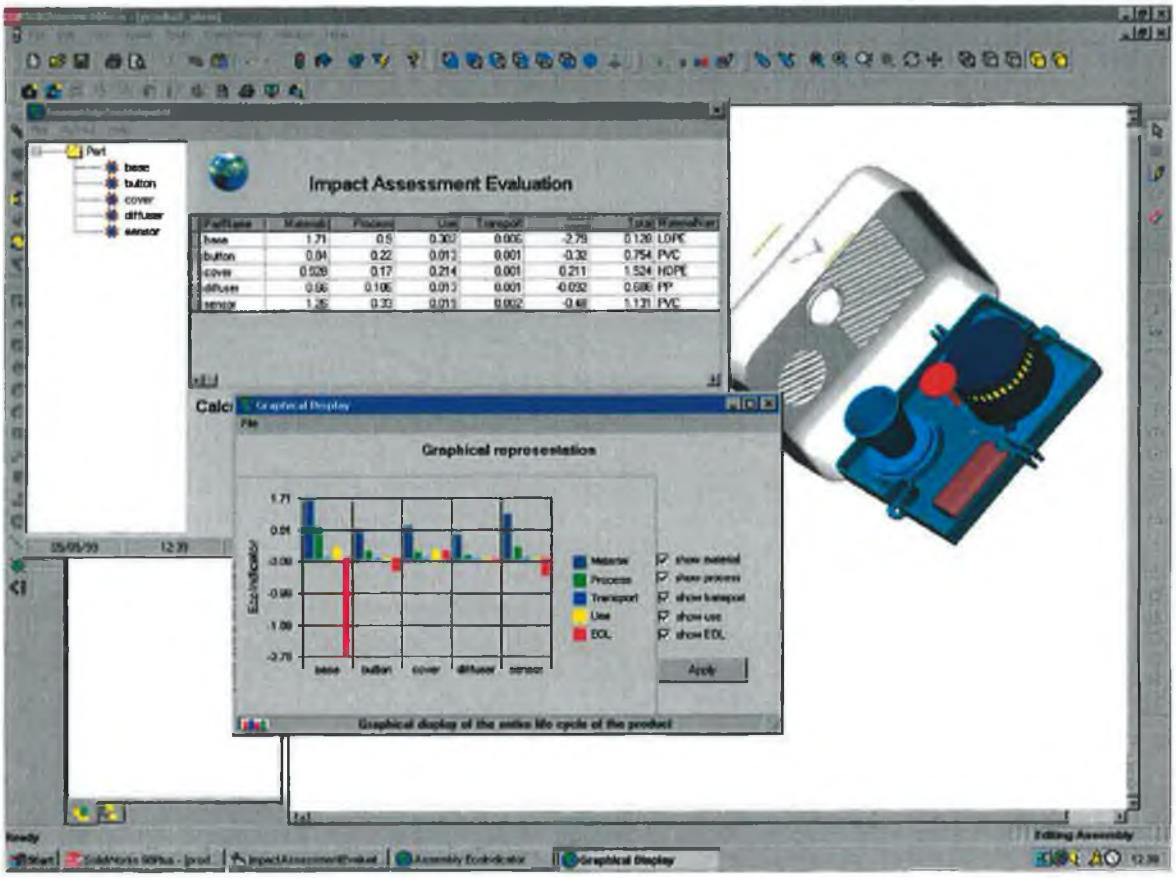


Figure 5.20. The Evaluation Phase

Next, the *Prioritisation Module* will highlight the highest environmental impact. The prioritised values are the Eco Indicators calculated for each of the component during the entire life cycle.

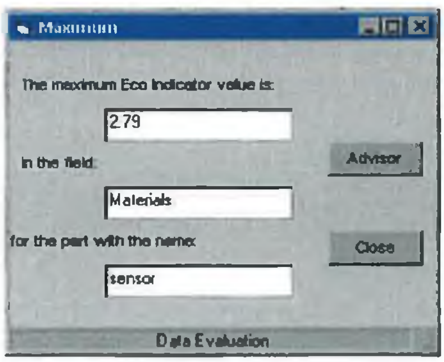


Figure 5.21. The Prioritisation Window

Figure 5.21 presents the prioritised environmental impacts. The material selected for the sensor gives the highest environmental impact, 2.79 mPt. The Advisor Module will display alternatives with similar properties and a lower environmental impact.

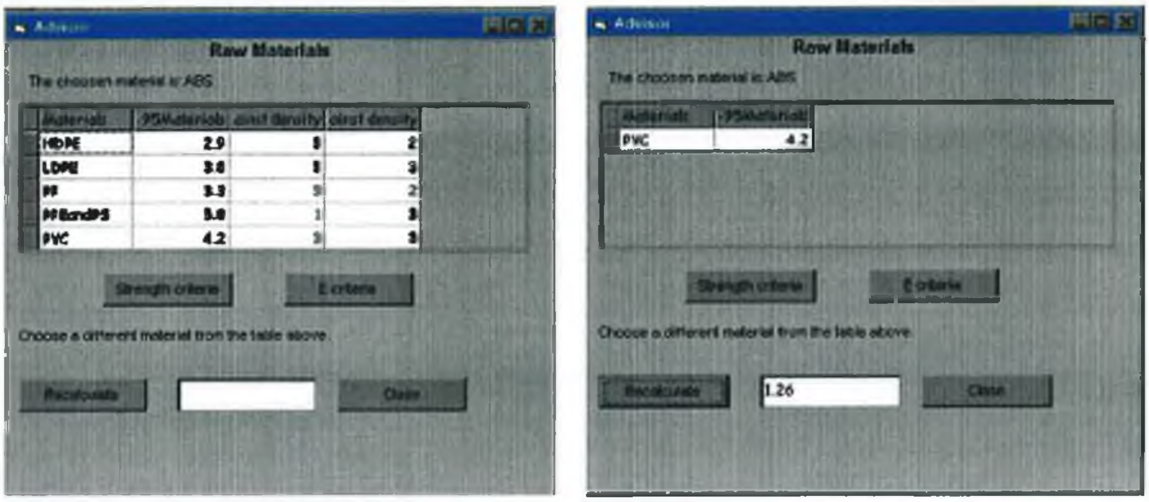


Figure 5.22. Advisor Window

In figure 5.22 the Advisor Module has displayed a window with alternative materials for ABS, the material initial selected for sensor. The alternative selected is PVC and the new Eco Indicator is 1.26 mPt. Repeating the prioritisation and the advisor steps the IAE Tool will reduce the environmental impact of the model until no other alternatives are available. The IAE Tool generates reports based on the data resulting from the procedures described above. The reports are in the form of tables and graphical displays presented in figure 5.23. They can be printed and used for comparisons between the initial data and the data resulting from the improvements.

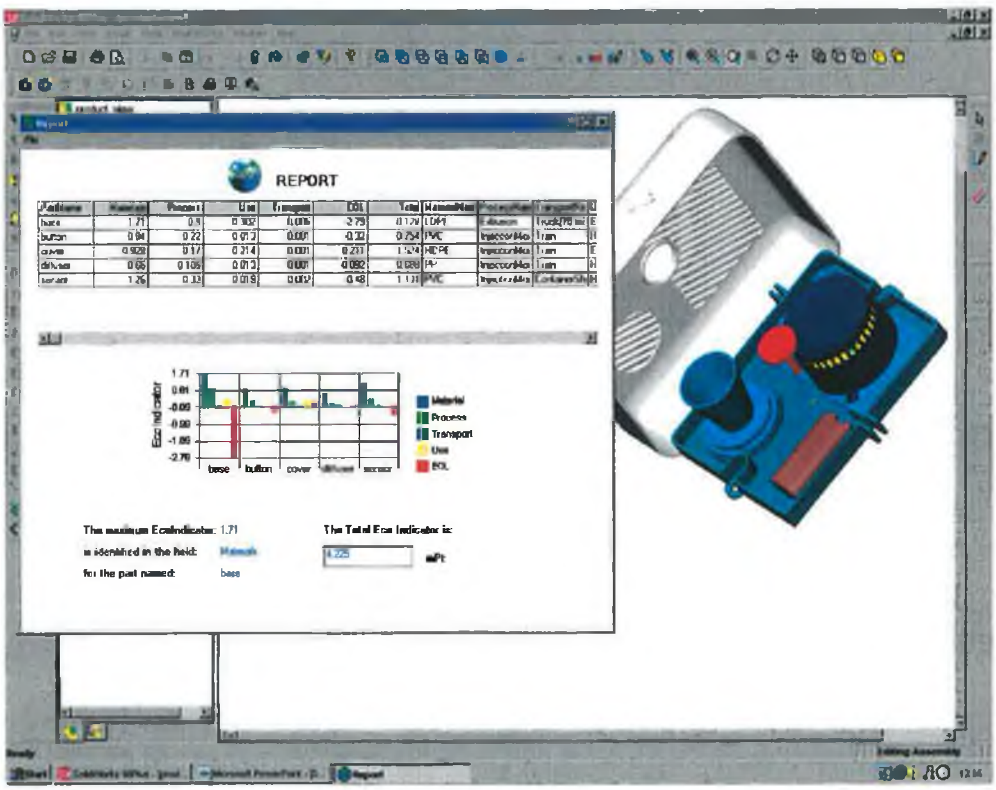


Figure 5.23. Report generated by the IAE Tool

Figure 5.23 presents a report generated by the IAE Tool. It can be seen in the table and in the graphical display that the improvement for the sensor have been saved and the new highest environmental impact is given by the material selected for the base.

Structure Assessment Method Tool

Structure Assessment Method Tool performs the SAM analysis described in chapter four. The SAM analysis is performed while the designer builds up the assembly of the prototype being analysed. The designer starts with the selection of the first set of components that will be joined together. The procedure continue with the following steps:

- Select the fasteners used to join the selected components.
- Select the tool necessary to disassembly the fasteners identified above.
- Specify the number of fasteners used.
- Define the obstruction relationships.
- Specify if the components need regular service and maintenance.
- Define the labelled components and the components that are impossible to label (e.g. the component may be too small for labelling).

When the steps are completed the designer has to identify the characteristics of the next set of components that will be joined together.

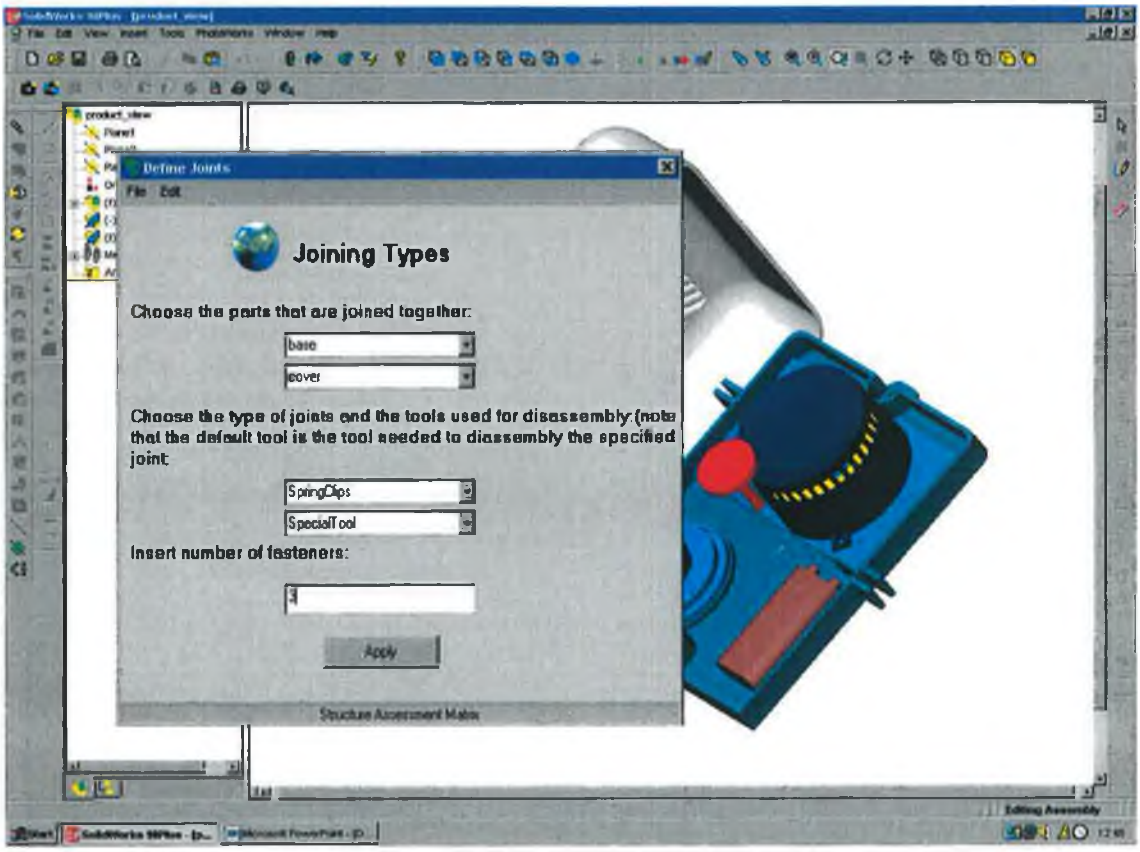


Figure 5.24. Joints Selection Window

Figure 5.24 presents the selection window of the joining methods. The designer has decided that the cover will be assembled on the base using three Spring Clips. The software will select the default tool needed for disassembly the selected Spring Clips. The designer is free to select the tool he/she considers being the appropriate one to disassembly the selected fasteners. Next, the designer will define the obstruction relationships.

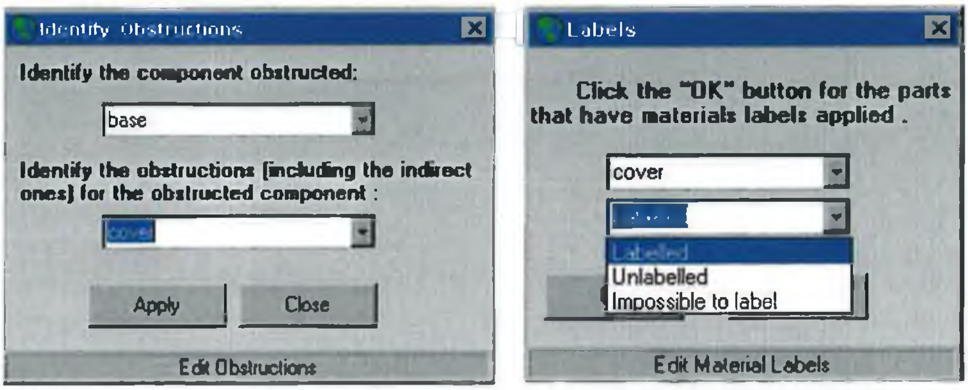


Figure 5.25. Identify Obstructions Window (left). Labels Window (right).

Figure 5.25 presents the Obstructions Window (left). The designer has specified that the cover obstructs the base. Next the designer will specify the labelled components. In figure 5.25 (right) the labels option window is presented. The designer has applied a material label on the cover.

Figure 5.26. Serviceability Window

Figure 5.26 presents the selection window for the components that need frequent service. The tool allows the designer to specify the components that need frequent service. This influences the prioritisation of the component removal time so the components that need frequent service will be evaluated first.

When the assembly is fully defined the SAM tool will perform a data evaluation. The evaluation consists of the following calculations[5]:

- Total disassembly time
- Component removal time
- Mass intensity
- Material variety
- Number of fasteners per component.
- Recycled materials content
- Recyclable materials content
- Sustainable materials content
- Biodegradable materials content
- Percentage of components labelled

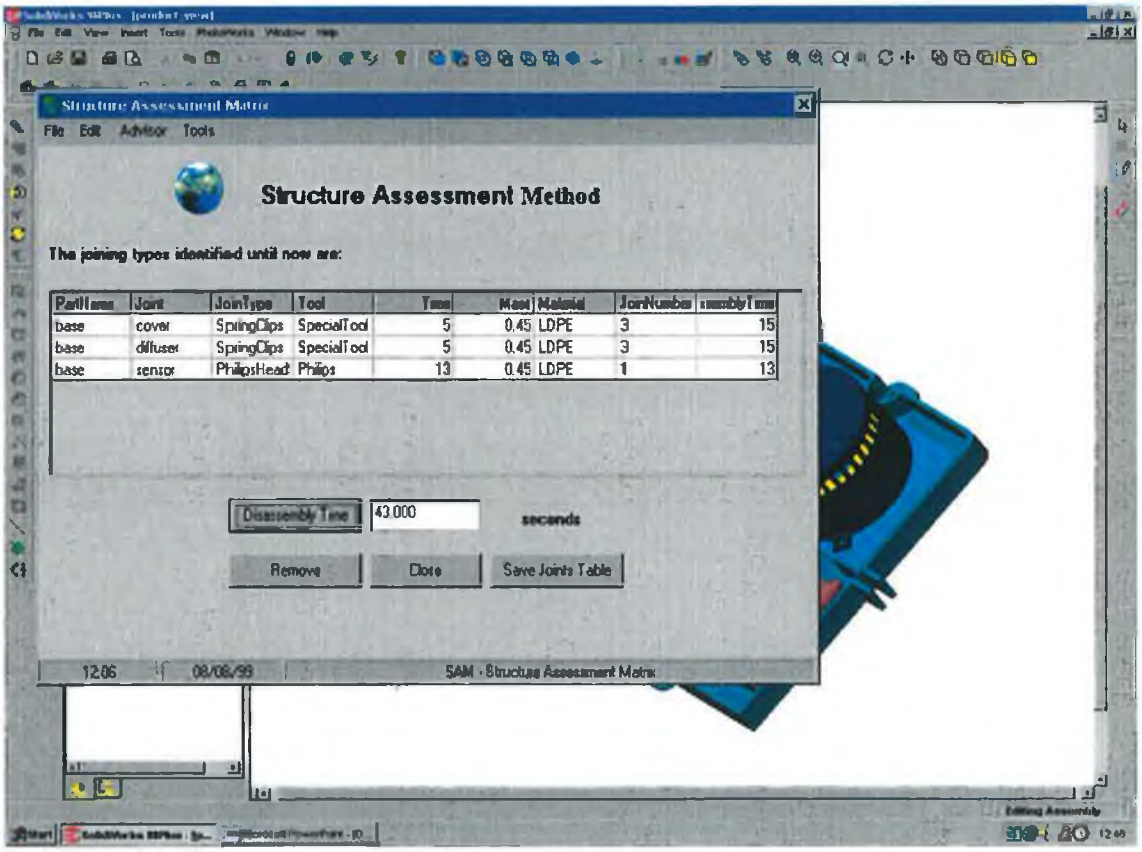


Figure 5.27. Total Disassembly Time Window

Figure 5.27 displays the total disassembly time (43 seconds) calculated for the smoke alarm model. Next the SAM Tool will calculate the components removal time.

[5] Each of the elements calculated on the structure evaluation phase is described in chapter four.

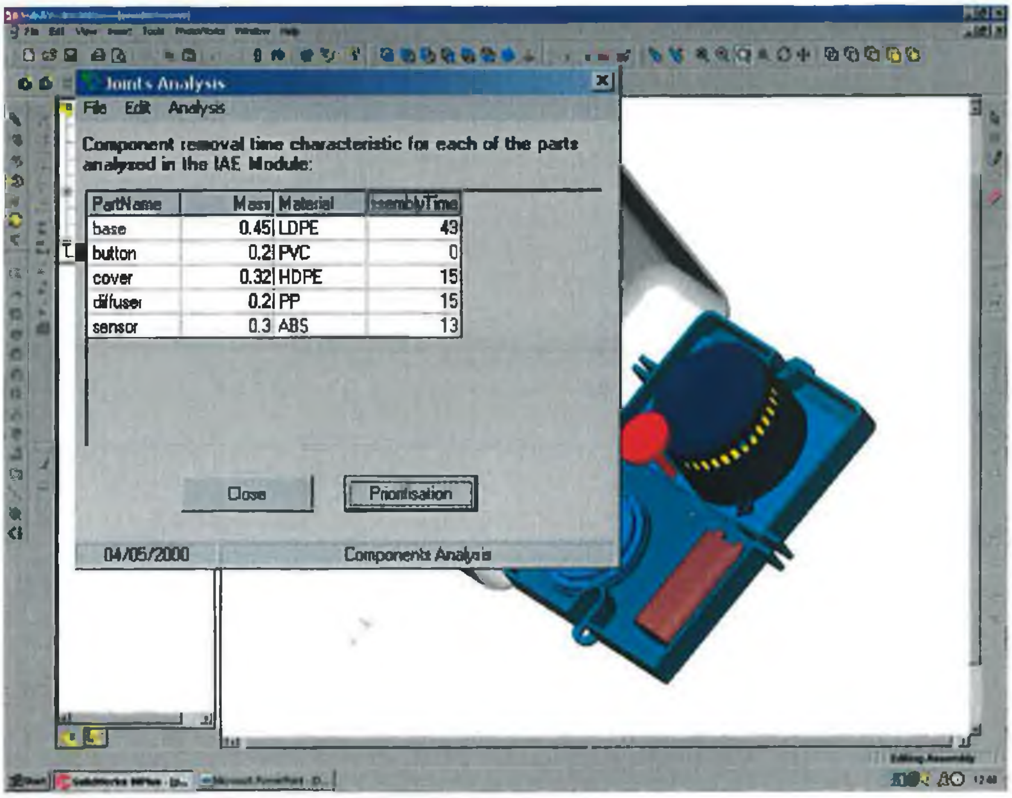


Figure 5.28. Components Analysis Window

Figure 5.28 displays the component removal time calculated for the assembly's components. For example, the diffuser removal time is 30 seconds. The cover obstructs the diffuser. For removing the diffuser the cover must be removed first.

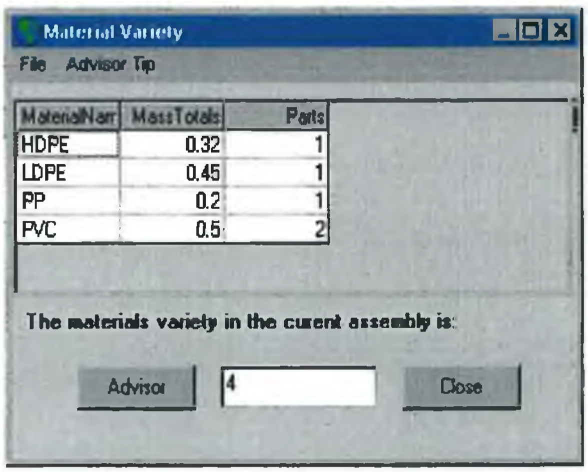


Figure 5.29. Materials Variety Window

Figure 5.29 displays the material variety, the materials used and the number of parts using these materials. There are four types of materials used in the smoke alarm model: HDPE, LDPE and PP each associated with a single component, and PVC selected for two of the components. Next the tool will calculate the percentage of recycled, recyclable, biodegradable and sustainable materials selected for the prototype being analysed.

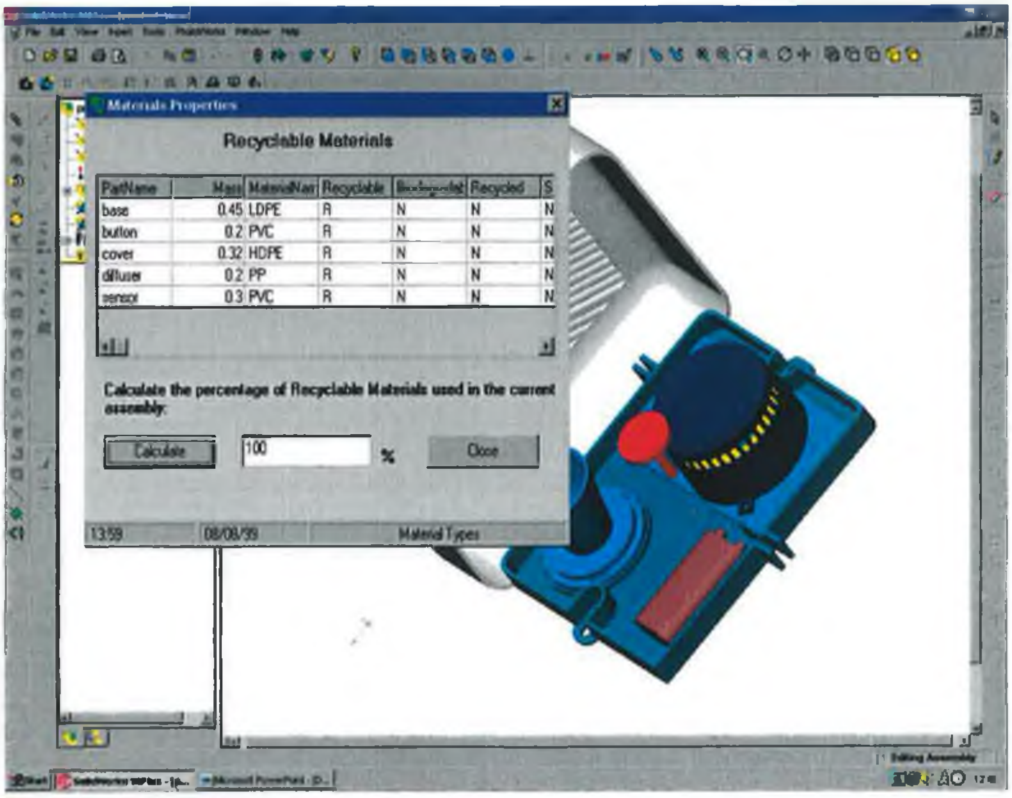


Figure 5.30. Recyclable Materials Window[6]

Figure 5.30 presents the percentage of recyclable materials selected for the prototype. In the case study all the materials selected for the smoke alarm are recyclable.

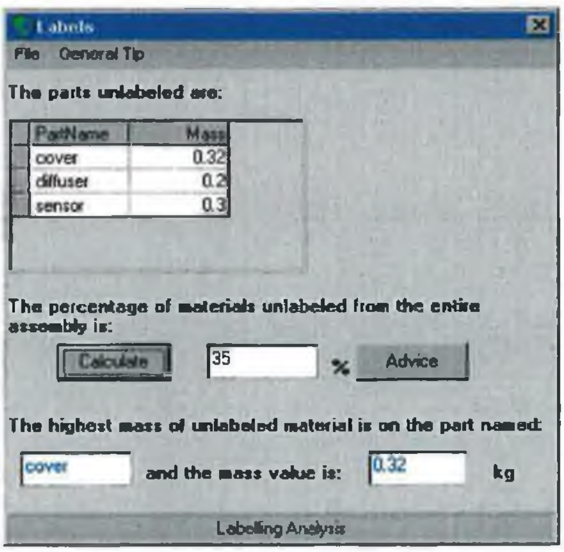


Figure 5.31. Labelling Analysis Window

[6]The windows for calculating the percentages of recycled, sustainable, and biodegradable materials are very similar with the Recyclable Materials Window.

Figure 5.31 presents the percentage of the smoke alarm components that are labelled. For the case study there, 35% of the components are labelled and the cover is the component with the highest mass that has to be labelled.

When all the calculations are completed, the *Prioritisation Module* will highlight the highest component removal time (see Figure 5.32). The components that need frequent service have the highest priority. In the smoke alarm case, the sensor has been considered as needing frequent service.

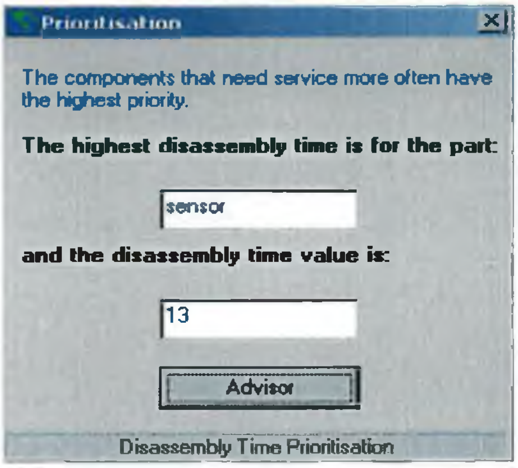


Figure 5.32. Prioritisation Window

Next, the *Advisor Module* will display alternative fasteners with a lower disassembly time.

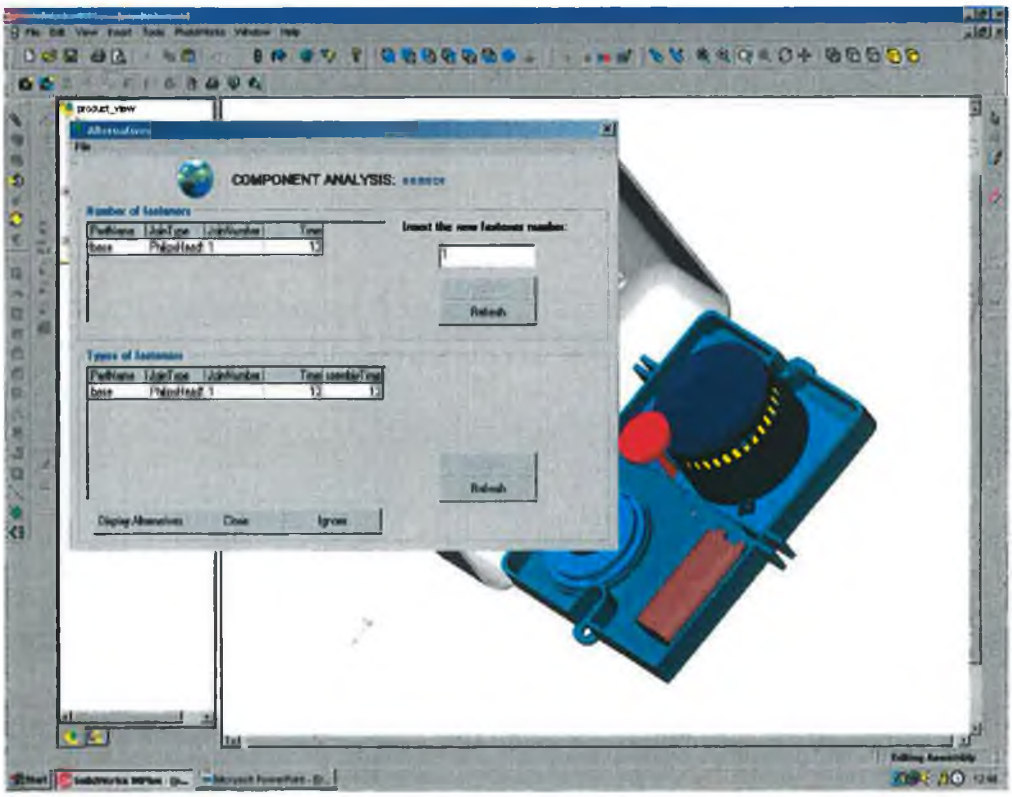


Figure 5.33. Component Analysis Window

Figure 5.31 presents the percentage of the smoke alarm components that are labelled. For the case study there, 35% of the components are labelled and the cover is the component with the highest mass that has to be labelled.

When all the calculations are completed, the *Prioritisation Module* will highlight the highest component removal time (see Figure 5.32). The components that need frequent service have the highest priority. In the smoke alarm case, the sensor has been considered as needing frequent service.

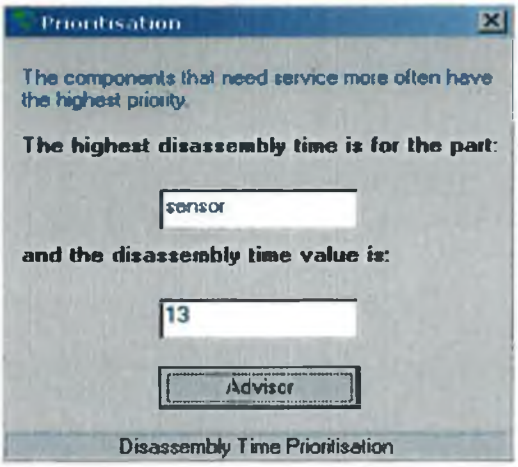


Figure 5.32. Prioritisation Window

Next, the *Advisor Module* will display alternative fasteners with a lower disassembly time.

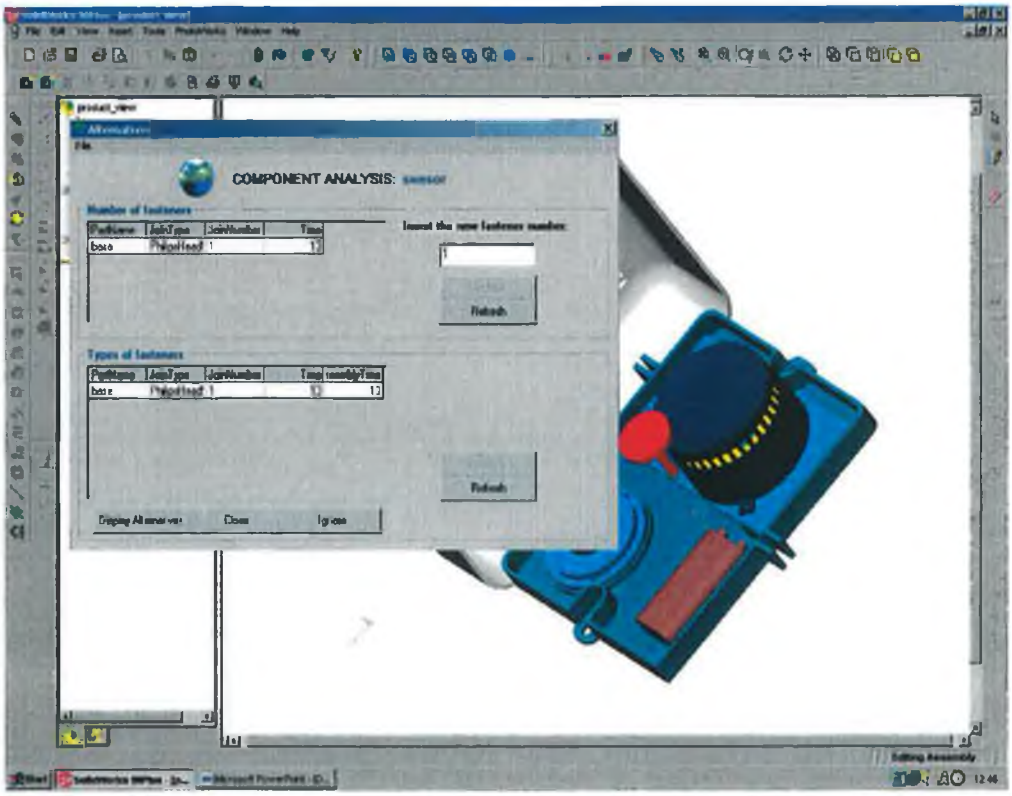


Figure 5.33. Component Analysis Window

Figure 5.33 displays the component analysis window for sensor. The designer has two possibilities:

- To change the number of fasteners used
- To change the fastener type.

For changing the number of fasteners used in the assembly, the designer has to insert the new fastener number and the replace button will became active. If the command replace will be selected, the tool will recalculate the disassembly time and will update the databases. For selecting a different type of fastener the designer has to choose the command 'Display Alternatives'. Figure 5.34 presents the Alternatives window for the Philips Head Screws used to fasten the sensor.

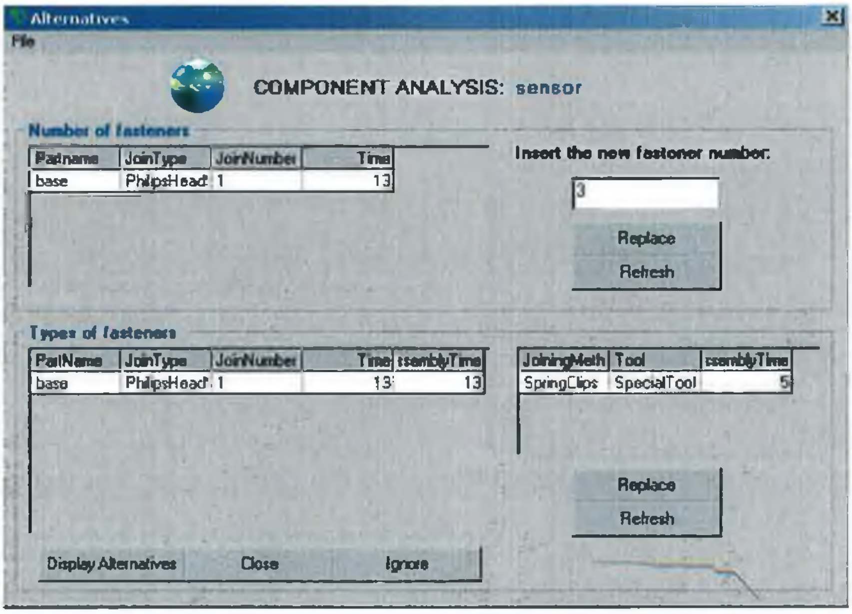


Figure 5.34 Fasteners alternatives in sensor's case

The designer can select a different fastener from the table displayed in the right-bottom corner of the window and the tool will calculate the new disassembly time and will update the database. The designer can also ignore the advisor by selecting the Ignore button. The *Prioritisation Module* will highlight the next highest component removal time. This steps will be repeated until there will be no other fasteners in the database with a lower disassembly time.

The *Advisor Module* will also inform the designer about the content of hazardous materials used in the prototype. If the designer needs an analysis of the hazardous content of the assembly, he/she needs to select from the menu Advisor and the sub-menu Material Properties the command Hazardous Materials. A window presenting alternatives for the hazardous material identified will open up.

In the smoke alarm case, a hazardous material has been used in the component called diffuser. The material used is polypropylene. The window presented in figure 5.35 is suggesting alternative materials with a lower environmental impact for polypropylene. The designer can ignore the suggestions by closing the Hazardous Materials Window.

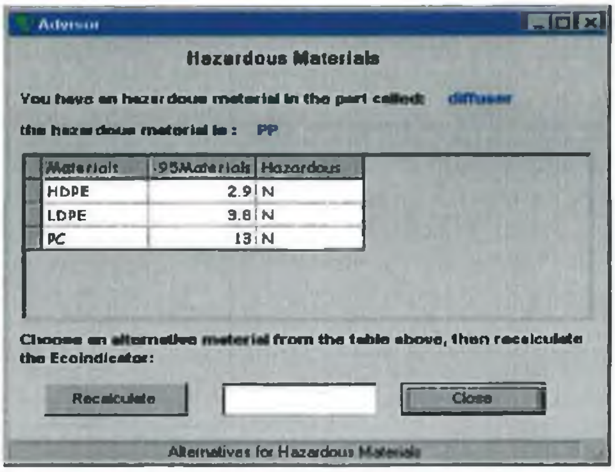


Figure 5.35. Hazardous Materials Window

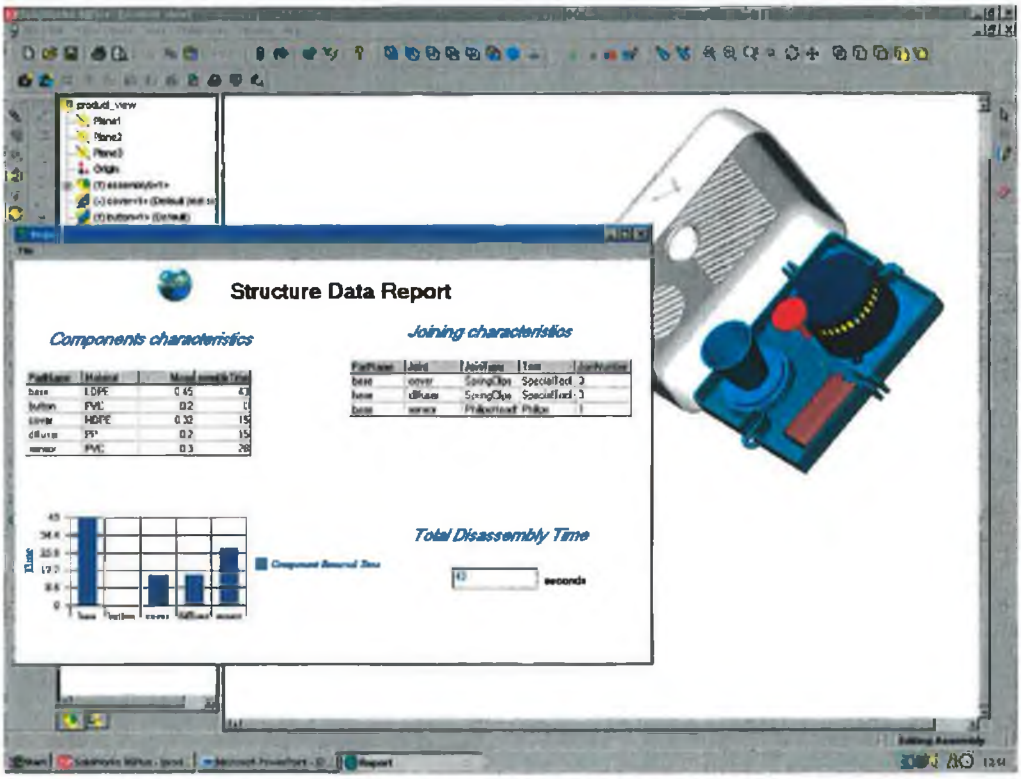


Figure 5.36. Report generated by the SAM Tool

Figure 5.36 displays a report generated by the SAM Tool for the smoke alarm model. The report contains: the materials and masses characteristic for the component, the total disassembly time, the type and the number of fasteners used in the assembly and a graphical display of the components removal times.

DFE Workbench Help Support

DFE Workbench software provides the designer with a *Help Module*. The Help Module consists of two sub-modules:

- Guidance trough the steps to be followed in order obtain best results with DFE Workbench software tool
- Introduction in the DFE studies.

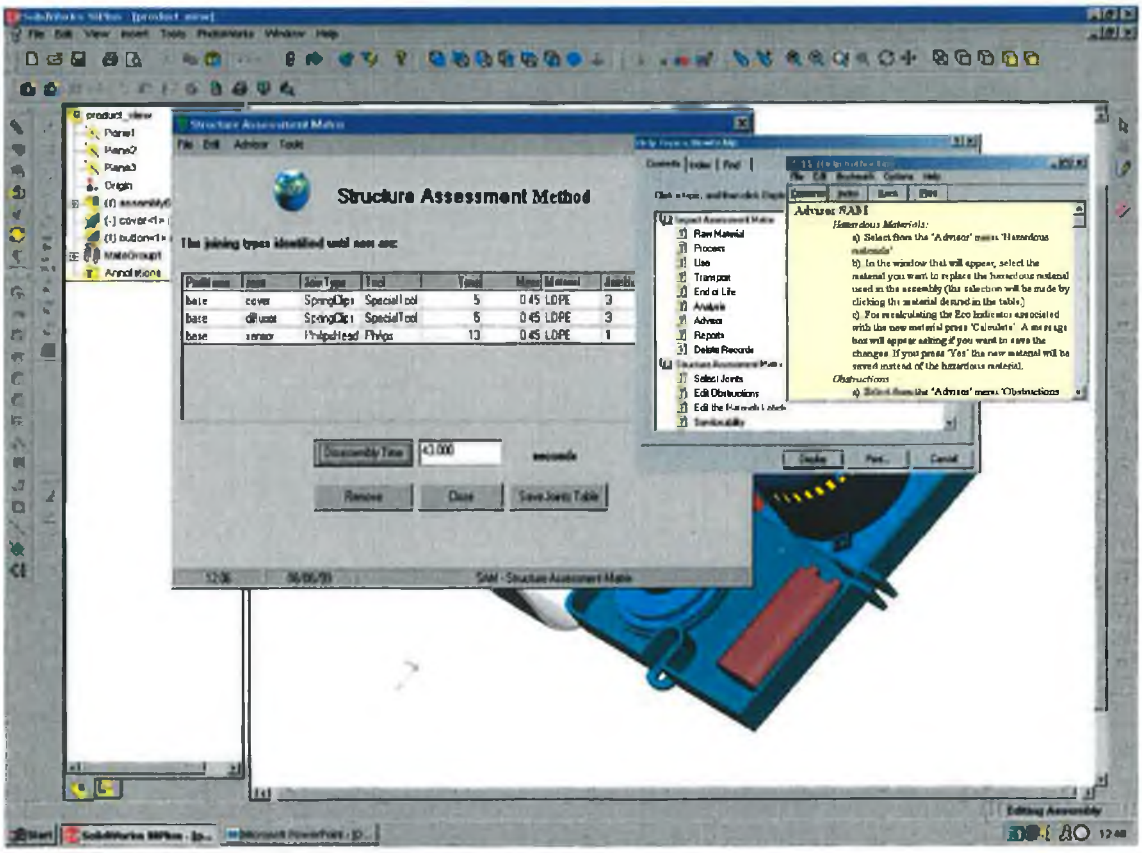


Figure 5.37. Help Window of the DFE Workbench software

Figure 5.37 shows an example of the guidance offered by the *Help Module* through the SAM Advisor issues. Help Module supports search by keywords or topics. Similar with the first type of help provided, the second sub-module provides the designer with valuable information on various topics of the Design for Environment (see figure 5.38).

The *Help Module* has been developed using Help Workshop 4.0 developed by Microsoft. Help Workshop is a program that may be used to create help files, edit project and contents files. Help Workshop helps the developer combine the topic files with bitmaps, and other sources into a single help file. After it's development the *Help Module* has been integrated in the DFE Workbench software using Visual Basic (VB) coding. Samples of codes are presented in Appendix two.

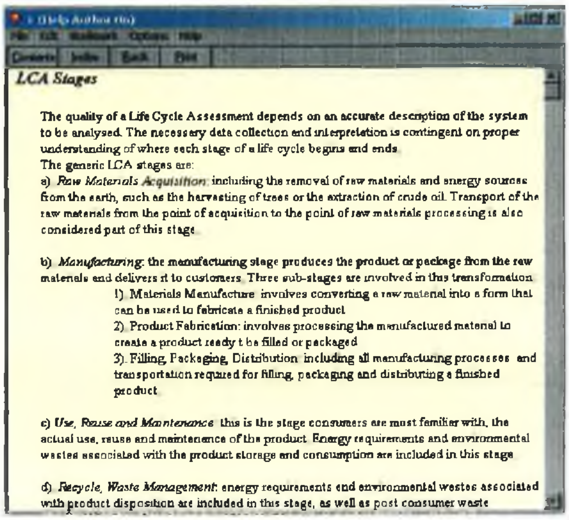
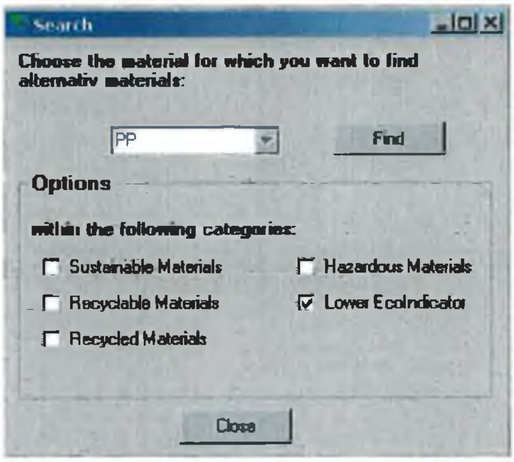


Figure 5.38. Information on Life Cycle Assessment provided by the Help Module

As an addition to the DFE workbench a search engine has been developed in order to help the designer to identify material's various alternatives for a specified material. For example if the designer wants to know the existing alternatives for PP that are not hazardous materials and have a lower environmental impact, the engine will perform a search trough the data bases and will display the findings. This example is presented in figure 5.39.



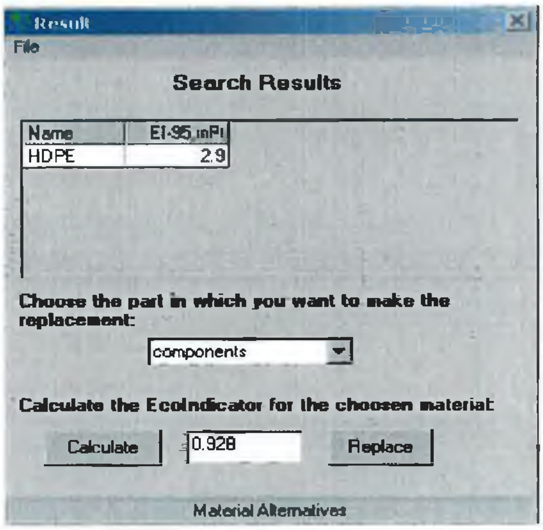


Figure 5.39. Search Engine window (left). Search Results Window (right)

Figure 5.39 left presents also the categories that can be used to refine the search. These categories are:

- *Sustainable materials*. If this category is checked the engine will look only for materials that are sustainable.
- *Recyclable materials*. If this category is checked the engine will look only for materials that are recyclable.

- *Recycled materials*. If this category is checked the engine will look only for materials that have been previously recycled.
- *Hazardous Materials*. If this category is not checked the engine will look only for materials that are not hazardous.
- *Lower environmental impact*. If this category is checked the engine will look only for materials that have a lower environmental impact that the selected material.

Figure 5.39 right presents the result window, displaying the alternatives found for polypropylene. In the search results window, the designer has the ability to replace the material in any of the components of the assembly. The components can be selected from the combo box where the blue text 'components' is displayed. By selecting the Replace button, the Eco indicator for the specified component will be recalculated and all the databases will be updated.

5.4. Conclusions

This chapter has described in detail the DFE Workbench software. The DFE Workbench has been integrated into a virtual prototyping environment called Solid Works 98 Plus. The DFE Workbench is capable of supporting the continuous improvement of an emergent virtual prototype from an environmental perspective and is supported by both an advisor and a knowledge base agent. The advisor agent automatically identifies and prioritises problems in an emergent design and suggests alternatives to improve specific environmental and structural characteristics, whilst the knowledge base agent allows the designer to consult with an information database that is not specific to any particular design characteristics. The next chapter will present a preliminary test developed in Motorola that has resulted in significant improvements. It also presents a second case study developed in collaboration with Jacobsen Ltd. The last version of DFE Workbench software has been used to analyse and improve an existing Jacobsen product.

Chapter 6

DFE Workbench Software Performance Tests

6.0. Introduction

This chapter presents the testing stage form the development of the DFE Workbench software described in the previous chapter. Firstly, some preliminary tests of the software will be presented with a particular focus on a test carried out in Motorola Company that resulted in significant improvements of the DFE Workbench software. Next, the chapter will focus on testing the last version of the software tool during a project developed in collaboration with Jacobsen Ltd. The chapter will introduce the Jacobsen Company and the goals of the Jacobsen project followed by a detailed[1] impact assessment analysis and a structure assessment analysis of a Jacobsen product carried out with DFE Workbench software. The result of the Jacobsen project consists of two virtual prototypes proposed for the Jacobsen chair under analysis, i.e. an environmentally superior chair prototype that has been developed based on purely environmental issues and an environmentally superior chair prototype developed based on design for reuse principles.

6.1. Preliminary tests of the DFE Workbench software

The DFE Workbench software has been developed during a period of 1 $^{1}/_{2}$ years. The development of the tool has been a laborious work that can be divided into four stages as follows:

1. The first stage is represented by the development of a very simplified version of the tool that consisted of a brief LCA analysis and a material compatibility function (see

[1] Note that all the graphical displays are screen shoots of the reports generated by the DFE Workbench software tool.

figure 6.1). At this stage the tool has not been yet integrated into the CAD environment.

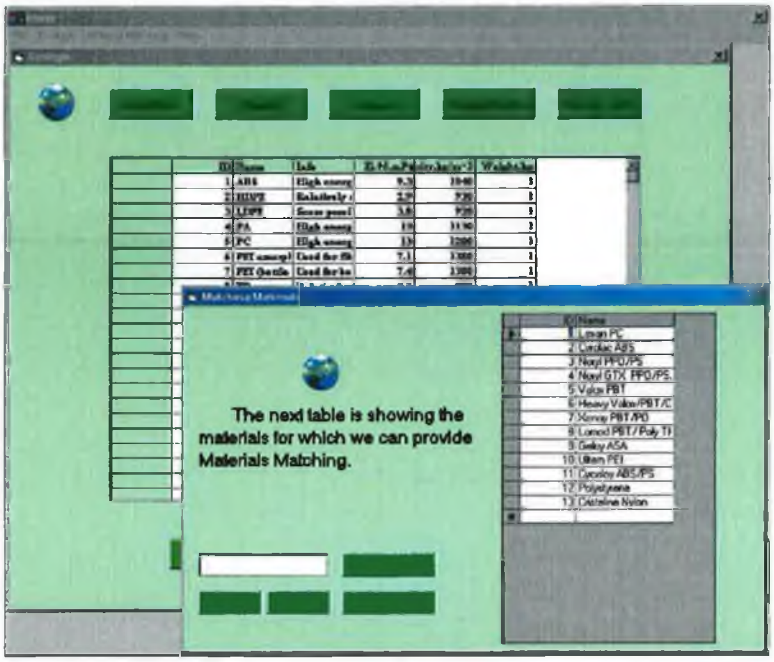


Figure 6.1 Screen shoot of the first DFE Workbench Software prototype

2. The second stage of the development of the DFE Workbench software is represented by a more complex version of the tool consisting of a more complete LCA module that included graphical displays, report generation and help functions (see figure 6.4). At this stage a first test has been carried out. It consisted of the LCA analysis of an ASCENTIA notebook provided by AST Computers, Ireland. First the notebook has been created in the Solid Works 98 Plus environment (see figure 6.2).

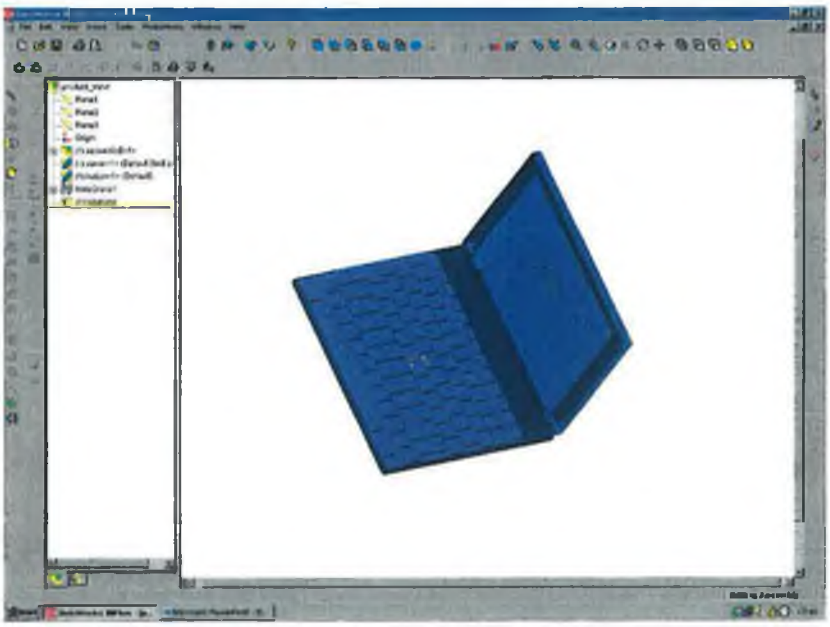


Figure 6.2. Virtual prototype of ASCENTIA Notebook

The results of the LCA analysis of the notebook are based on the data presented in table 6.1.

Part name	Part number	Material used	Processes	Mass (Kg)
Box	BA72-60722	(PC+ABS)+mild steel	Injection moulding + machining	0.202+0.01
Big trap	BA72-60733	PC+ABS	Injection moulding	0.0033
Small trap	BA72-60766	PC+ABS	Injection moulding	0.0053
Link	-	PC+ABS	Injection moulding	0.0043
Panel	-	PC+ABS	Injection moulding	0.0150
Plate	-	(PC+ABS)+Al	Injection moulding + machining	0.04+0.033
Big button	-	PC+ABS	Injection moulding	0.0010
Med button	-	(PC+ABS)+ nylon +rubber	Injection moulding	0.0001175
Small button	-	(PC+ABS)+ nylon +rubber	Injection moulding	0.00010
Cover assembly	BA72-60723A	PC+ABS	Injection moulding	0.15
Housing front	BA72-60726	PC+ABS	Injection moulding	0.025
Housing back	BA72-60724	PC+ABS	Injection moulding	0.025

Table 6.1 Data generated for the ASCENTIA Notebook

The Eco Indicator has been calculated for the two main sub-assemblies of the notebook i.e. box assembly and screen assembly. They are graphically represented in figure 6.3.

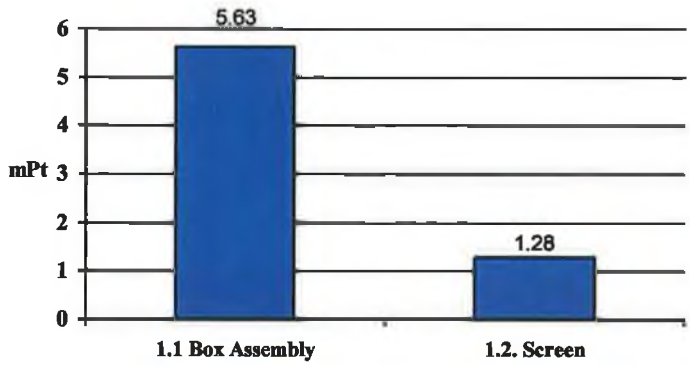


Figure 6.3. Eco Indicators calculated for ASCENTIA notebook.

The test allowed the identification of a number of limitations that should be addressed by the next version of the tool. They are as follows:

- There was no toxic emission information associated with the materials used in the prototype under analysis.
- The tool had no prioritisation facilities to identify the highest environmental impacts associated with the prototype.
- The advisor sustaining the LCA analysis was very limited and the advice generated was too generic.
- The tool could perform only LCA analysis and did not provide any structural information.

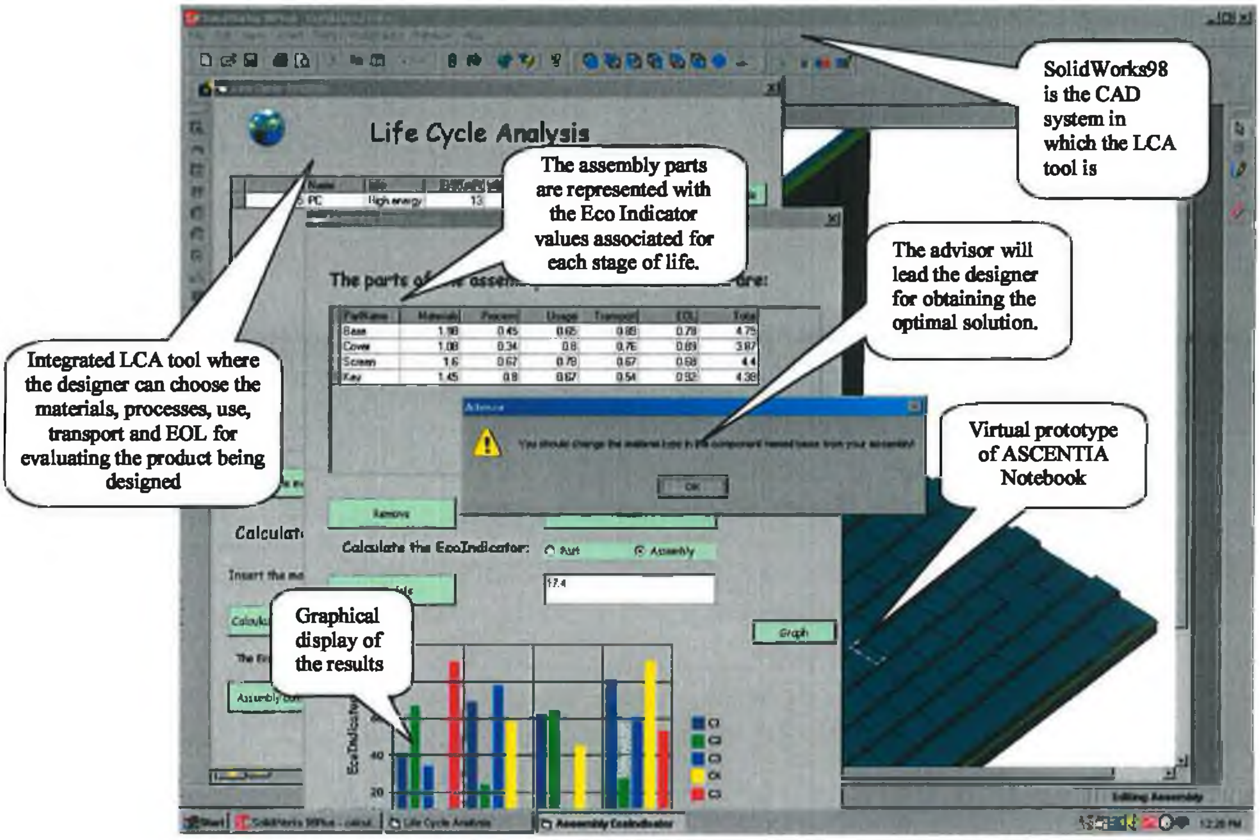


Figure 6.4. Screen shoot of the second version of the DFE Workbench software.

3. The third stage in the development of the DFE Workbench is represented by a new version of the tool that has been redesigned to meet the requirements identified at the previous stage i.e. the LCA module has been completed and optimised, a prioritisation module has been developed to support the advisor and the advisor itself has been significantly improved in terms of knowledge base and dynamics. Also a structure assessment module has been integrated with the tool that performs calculations such as component removal time, total disassembly time, material variety, percentages of recyclable, recycled, sustainable, and biodegradable materials used in the prototype being analysed. Also, prioritisation and advisor modules support the structure assessment tool. At this stage there was a second test carried out in Motorola Company based in Dublin. The test consisted of the both LCA and structure analysis of a Domestic Smoke Alarm prototype previously drawn in the Solid Works 98 Plus environment. The results of the test were positive but there were some efficiency and support limitations identified. The test is detailed in the following section.
4. The last stage in the DFE Workbench development is represented by the last version of the tool. After a number of modifications performed in order to meet the requirements identified in the previous stage, the tool was finally tested within a project developed in

collaboration with the Jacobsen Company. The Jacobsen project and the final results are detailed in section 6.2.

Motorola test

The tests carried out in Motorola Company consist of the involvement of a number of subjects in the use of the DFE Workbench software. For this purpose the prototype to be analysed, a domestic smoke alarm[2], has been previously drawn with Solid Works 98 Plus. To easy the use of the tool, the subjects were provided with a software manual, which is presented in Appendix 4 of the current thesis.

The operation of the tool during the test was different to the way it would be used in a design process because of the subject's lack of expertise in the particular CAD system and because of the time available to carry out the test. In normal conditions, the designer would extract the data from the virtual prototype after the completion of one component and before moving to the next[3], however the data evaluation and improvement occurs after the design is assembled and therefore it does not interfere with the model creation phase. The results proved that the process of data synthesis integrates well within the design process as it takes very little additional time to synthesis this data. The designer was observed interacting frequently with the virtual prototype, particularly to synthesise the masses and Eco indicator values of each individual component, and for defining the joint relationships in the case of the assembled prototype. The subjects found the visualisation of the model as extremely beneficial, particularly for defining joint relationships, however they found difficult to visualise the fasteners and how they could fit in the model. They observed that it would be beneficial to have a virtual prototype of each fastener for automatically inserting on the virtual prototype. The subjects also found the automatic extraction, manipulation and management of data directly from the model very beneficial as it facilitates the concentration in the design improvement activity. During the evaluation and improvement phase of the DFE process, all of the subjects operated with the evaluation, prioritisation and advisor elements of the tool. However their improvements were mainly limited to situations where the software automatically made the changes based on the advisor, e.g. disassembly time and environmental impact improvements. This was because of the subjects' lack of expertise on the use of the particular CAD environment. However all the subjects made valid technical improvements to the product. They stated that the

[2] The domestic smoke alarm case study has been also used in the previous chapter to describe the software tool. For this reason the focus of the current section will be solely on the development and the results of the test.

[3] The tool can support the synthesis of data after all the virtual prototypes are complete and therefore the designer is not constrained to synthesis the data after creating each individual component.

prioritisation of key issues (e.g. identification of priority disassembly time) and the coupling with an advisor were extremely beneficial, if not essential for the problem search and improvement activity.

The integration of the DFE Workbench software with a CAD environment has proved to be very important for a number of reasons. Firstly, there is quantitative data required to carry out the evaluations defined in the methodology; for example some of key elements for an impact assessment program are the mass of a component and the material type. The exact volume of the component can be extracted from the virtual prototype and combining this with density values and material types in the DFE workbench, it is possible to calculate the mass of each component, which can be subsequently used in the Impact Assessment System. Secondly, it is possible to automatically manage the many interdependencies between data within the methodology. For example there is a dependency relationship between the compatibility of materials that are used for two components that are assembled together, the fastener type and number of fasteners used.

Thirdly, because the CAD environment allows the designer to actively experiment and seek advice about the model being created, with a minimum overhead in time and cost it will result in expertise gain by the designer and reduced product cost.

There were many improvements made to operation of the software program as a result of the test. The problems identified and improved in the new version of the software are as follows:

- *Redundancy of operations.* There were many instances in the data synthesis and evaluation process where there were redundant key and mouse operations. The new software has reduced the number of mouse click operations quite significantly, e.g. in the IAS synthesis activity the number of windows used for data synthesis was reduced from five to two.
- *Absence of IAS data for supplied components*, e.g. the battery. There was no IAS data available for the battery, which effected the results. A new function was added to extract data from a supplier file for all supplied components, for direct insertion into the tool.
- There was *no context sensitive help* included in the software for the designer, e.g. images of different joint types with typical applications, unfastening tools used and time taken to disassemble this fastener and the damage to the product as a result. The new version of the software has full context sensitive help on many of the features.
- *No work flow manager* in the software. The user tended to loose their way because of the large amount of operations as the process progressed. The workflow manager has

not been covered by the present thesis but it has been mentioned in the further development section in chapter seven.

- *Lack of linkages between SAM and IAS modules*, which meant that when selecting an alternative material in SAM the new results of the IAS changed. The tools have been integrated in the new version of the software and all the data modifications are actively reflected in both modules.

6.2. Jacobsen Project

Jacobsen Ltd is an Indigenous Irish manufacturing company that was set up in Galway in 1988. The company manufactures high quality, long life customised and non-customised back support chairs for industrial and domestic use. The company hopes to promote the environmental superiority of its products whilst also enhancing life cycle cost through extended life. With the knowledge gained through this project Jacobsen Ltd. hope to define a new product and promote a new service to industry, which offers environmental superiority and the possibility of upgrade, repair, service and maintenance of the chairs.

The main goal of the Jacobsen Project is to develop a new high quality environmentally superior back support chair for the industrial market. Jacobsen see an opportunity with their product to demonstrate the long life and therefore the reduced *environmental utility index*[4] of their product over that of their competitors. Increasing the useful life of a chair without any physical changes has a positive impact on the environment, for two reasons. Firstly, a new chair does not have to be made to replace the existing chair and consequently environmental impact is decreased and secondly, disposal of the chair into landfill is reduced. A chair retains its functionality all its life, i.e. a chair never becomes functionally obsolete (like a computer), however chairs do fail in two other ways, i.e. they deteriorate due to physical wear (physical obsolescence) and also suffer from fashion obsolescence. Therefore the environmental impact of the chair can be reduced in two ways:

(a) Reducing the environmental impacts by proper material selection

(b) Extending the useful life of the product.

The *global objective* of this project therefore is to reduce the environmental utility index of the chair by reducing the environmental impacts caused by the material selection and by extending the life of the product. In summary the objectives are threefold:

[4] Environmental utility can be calculated by the following: Environmental Impact/Useful life of the product, i.e. mPt per hour of use.

1. Reduce ecological impacts derived from the product and its packaging by means of using more environmentally friendly materials and processes. This study also aims to reduce the waste associated with the manufacture of the product;
2. To optimise the structure of the product in the context of disassembly for repair, upgrading and recycling;
3. To ensure the new product complies with the requirements for an Eco-label.

6.3. Impact Assessment Analysis

In order to reduce the ecological impacts derived from the Jacobsen products and their packaging, a Life Cycle Assessment (LCA) has been carried out. A Jacobsen office chair has been analysed using a standard LCA method called Eco Indicator 95. Jacobsen aim to make the chairs highly reusable. This means that the policy of the company is to produce durable chairs that will be serviced during product's life. Any components that are damaged in any way will be replaced and if the customer decides that he/she wants a different look for the chair, Jacobsen will make the desired changes. The parts recovered from the used chairs will be stocked and reused as parts for new chairs. If the components are damaged and impossible to reuse they will be recycled. Based on these considerations, the Jacobsen chair has been analysed from two perspectives:

- The development of an environmentally superior product. This approach involves a full LCA analysis that will result in pure environmental improvements, e.g. suggesting the use of materials and processes with a very low environmental impact.
- The development of a reusable chair using recyclable materials. This approach will result in improvements that firstly considers the durability of the material suggested and than the environmental impact of that particular material.

Figure 6.5 presents the prototype of the Jacobsen chair being analysed. It has been designed using Solid Works 98 Plus. DFE Workbench software tool has been used for both impact assessment and structure assessment analysis.

Figure 6.5. Virtual prototype of a Jacobsen Office Chair

The Bill of Materials of the chair (see figure 6.6) has been extracted from the CAD system along with the dimensional properties of the chair.

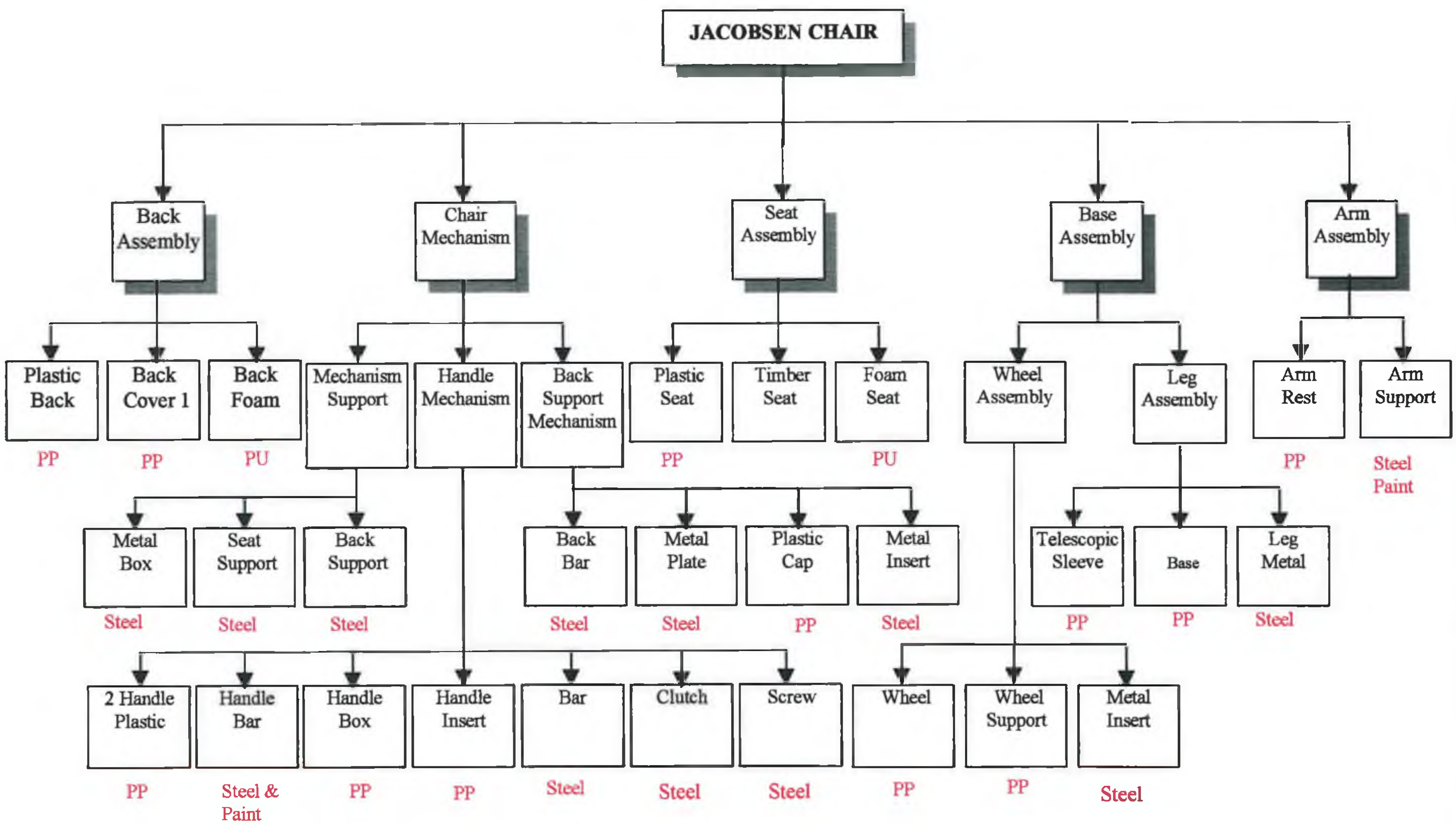


Figure 6.6. Jacobsen Chair's Bill of Materials

The LCA analysis has been divided into sub-assemblies as follows:

- Back assembly
- Chair mechanism:
- Seat Assembly
- Base Assembly:
- Arm Assembly

Back Assembly

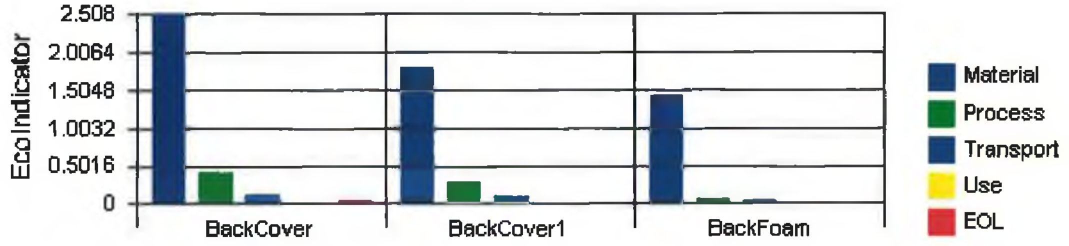
Back Assembly, represented in figure 6.6, is the first to be analysed. The LCA analysis results are represented in Table 6.2. The first five columns starting from the second column of the table presents the Eco indicators calculated for each of the life cycle stages. The Total column presents the total environmental impact of the components and next the materials, processes, mass, transport and end of life strategy associated with each of the components are presented.

Part Name	Materials	Process	Use	Transport	EOL	Total	Material Name	Process Name	Mass	Transport Name	EOL Name
Back Cover	2.508	0.403	0	0.129	0.03	3.07	PP	Injection Molding	0.76	Aircraft (continental)	Landfill
Back Cover1	1.799	0.289	0	0.093	0.022	2.203	PP	Injection Molding	0.545	Aircraft (continental)	Landfill
Back Foam	1.421	0.062	0	0.035	0.008	0.241	PUR foam	RIM pur	0.206	Aircraft (continental)	Landfill

Table 6.2. LCA results for the Back Assembly

Figure 6.6. The CAD representation of the Back Assembly

The environmental impact of the three components of the Back Assembly are graphically displayed below:



The maximum EcoIndicator: 2.508

is identified in the field: Materials

for the part named: BackCover

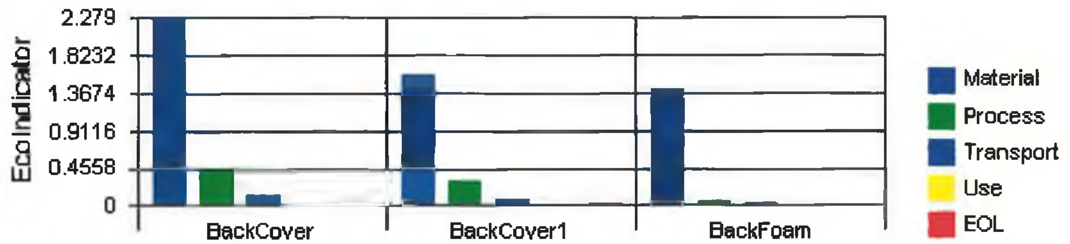
The Total Eco Indicator is: 6.799 **mPt**

The material used in both components is polypropylene (PP). The Eco Indicator calculated for the back cover material is 2.508 mPt and the total Eco Indicator calculated for the Back Assembly is 6.799. It must be specified that the present End of Life strategy for the Jacobsen chair is Landfill.

In order to reduce the environmental impact of the Back assembly two suggestion has been made:

- Material improvement
- End of Life policy suggestion

The material suggested to replace the PP used in both Back Cover and Back Cover 1 is high-density polyethylene (HDPE). It is a material with a lower environmental impact. The improvements resulted from the environmental point of view are pictured in the graph below.



The maximum EcoIndicator: 2.279

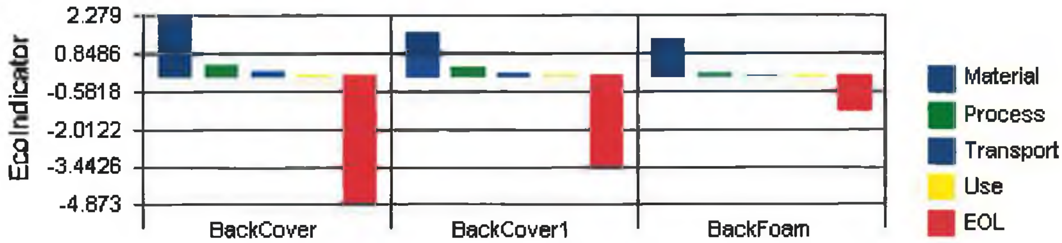
is identified in the field: Materials

for the part named: BackCover

The Total Eco Indicator is: 6.372 **mPt**

The result of the improvement suggested is that total environmental impact has decreased from 6.79 mPt to 6.37 mPt. This represents a 6% reduction in the Eco indicator.

As stated above, the end of life strategy is landfill. The policy suggested is recycling, because polyethylene is a recyclable material. The improvement in the total environmental impact of the Back assembly is pictured in the graph below:



The maximum EcoIndicator: 2.279 **The Total Eco Indicator is:**

is identified in the field: Materials -3.218 **mPt**

for the part named: BackCover

The environmental impact has decreased from 6.37 mPt to -3.21. The negative value represents a gain in terms of materials and not a loss of material as in the case of incineration or landfill.

Chair Mechanism

Figure 6.7. CAD representation of the Chair Mechanism

The next assembly analysed is the Chair Assembly, which consists of three sub-assemblies:

- Mechanism Support
- Handle Mechanism
- Back Support Mechanism

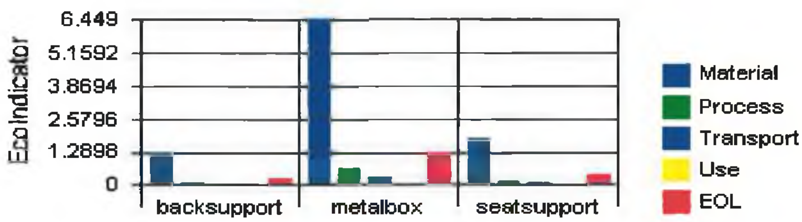
1. Mechanism Support

Figure 6.8. The CAD representation of the Mechanism Support

Part Name	Materials	Process	Use	Transport	EOL	Total	Material Name	Process Name	Mass	Transport Name	EOL Name
Back support	1.238	0.127	0	0.051	0.242	1.658	Steel	Machining	0.302	Aircraft (continental)	Landfill
Metal box	6.449	0.661	0	0.267	1.258	8.635	Steel	Machining	1.573	Aircraft (continental)	Landfill
Seat support	1.804	0.185	0	0.075	0.352	2.416	Steel	Machining	0.44	Aircraft (continental)	Landfill

Table 6.3. LCA results of the Mechanism Support analysis.

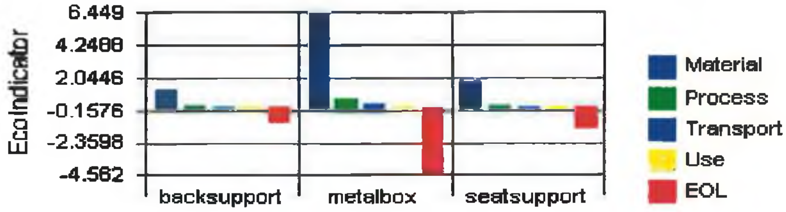
Table 6.3 presents the Eco indicators calculated for each of the life cycle stages of the Mechanism Support components. The environmental impact of Mechanism Support is pictured in the graph below.



The maximum EcoIndicator: 6.449
is identified in the field: Materials
for the part named: metalbox

The Total Eco Indicator is: 12.709 mPt

The highest environmental impact has been identified in the Metal box component in the Raw material stage. The environmental impact for this component is 6.44mPt. The total environmental impact associated with the Mechanism Support is 12.7 mPt. The material use in all the components of Mechanism Support is steel. There is not much of the material improvements that can be done in this case except the case in which second steel would be used. The material suggestion is not significant in terms of environmental improvement. A significant improvement to be made is to change the landfill policy with a recycling policy. As it can be seen in Table 6.3, the end of life strategy is landfill. Considering that steel is recyclable material, the recycling policy would significantly improve the total environmental impact of the Mechanism Support. The result of this improvement is pictured in the following graph.



The maximum EcoIndicator: 6.449

is identified in the field: Materials

for the part named: metalbox

The Total Eco Indicator is: 4.143 mPt

It can be observed that using the recycling policy the total environmental impact has decreased from 12.7 mPt to 4.14 mPt. That means that the environmental impact decreased by 67.4%.

2. Handle Mechanism

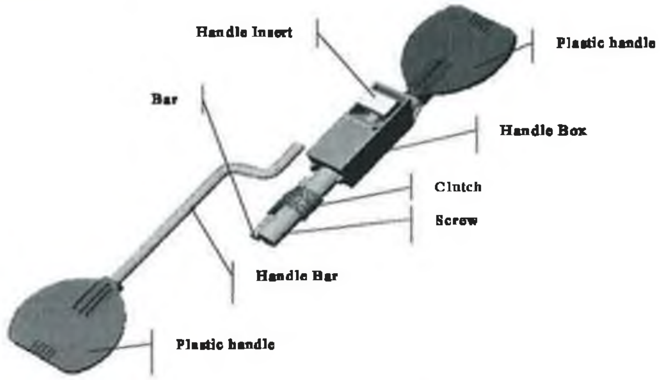
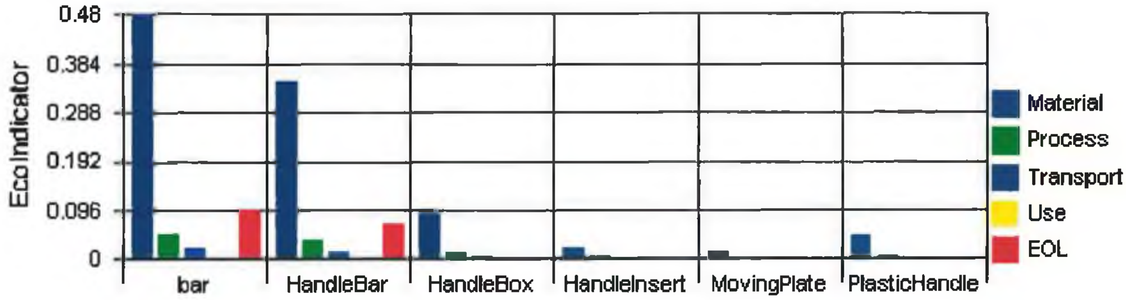


Figure 6.9. CAD representation of the Handle Mechanism

Part Name	Materials	Process	Use	Transport	EOL	Total	Material Name	Process Name	Mass	Transport Name	EOL Name
Bar	0.48	0.049	0	0.02	0.094	0.643	Steel	Machining	0.117	Aircraft (continental)	Landfill
Handle Bar	0.349	0.036	0	0.014	0.068	0.467	Steel	Machining	0.085	Aircraft (continental)	Landfill
Handle Box	0.086	0.014	0	0.004	0.001	0.105	PP	Injection Molding	0.026	Aircraft (continental)	Landfill
Handle Insert	0.023	0.004	0	0.001	0	0.028	PP	Injection Molding	0.007	Aircraft (continental)	Landfill
Clutch	0.012	0.001	0	0.001	0.002	0.016	Steel	Machining	0.003	Aircraft (continental)	Landfill
Plastic Handle	0.043	0.007	0	0.002	0.001	0.053	PP	Injection Molding	0.013	Aircraft (continental)	Landfill
Screw	0.107	0.011	0	0.004	0.021	0.143	Steel	Machining	0.026	Aircraft (continental)	Landfill

Table 6.4. LCA results form the Handle Mechanism analysis.

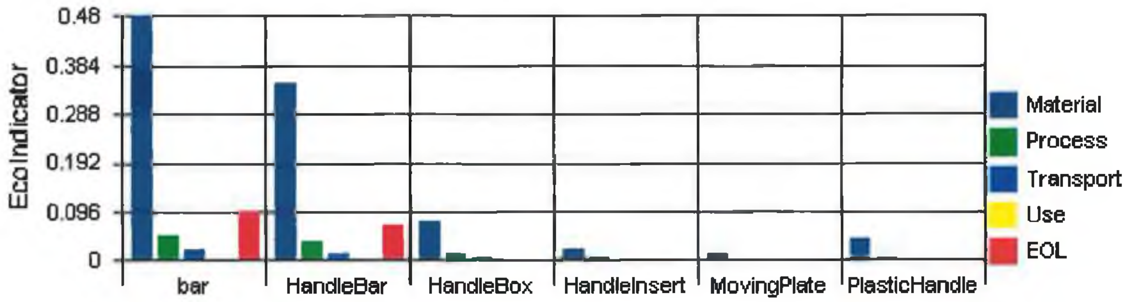
Next the Handle Mechanism has been analysed. It consists of seven components and three components out of seven are made from PP. The rest is made out of steel. The LCA results for the Handle mechanism are pictured in the graph below.



The maximum EcoIndicator: 0.48
is identified in the field: Materials
for the part named: bar

The Total Eco Indicator is: 1.312 **mPt**

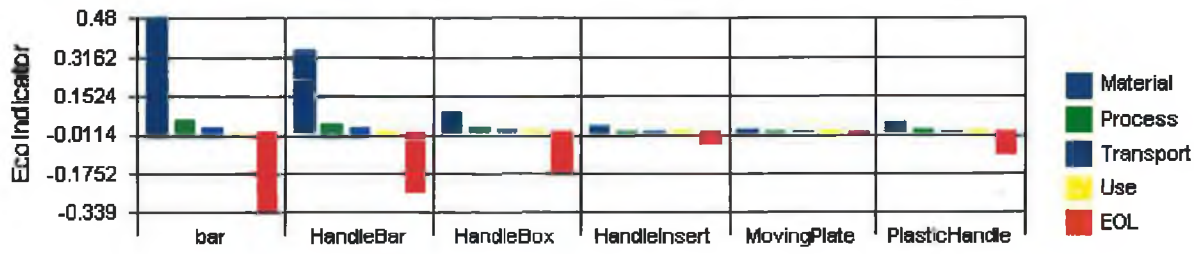
The highest environmental impact is for the bar and the component is made out of steel. As stated before there is no significant improvement that can be suggested for reducing this particular value because there is no alternative to steel with a lower environmental impact. However there are some improvement suggestions made for the three components made out of polypropylene. The material suggested is high-density polyethylene (HDPE).
The results obtained after the material has been changed are pictured in the graph below.



The maximum EcoIndicator: 0.48
is identified in the field: Materials
for the part named: bar

The Total Eco Indicator is: 1.303 **mPt**

The total environmental impact has been decreased from 1.312 mPt to 1.3 mPt. The next improvement proposed is to change the end of life strategy from landfill to recycling. The results obtained after the landfill strategy has been changed with the recycling strategy are pictured in the graph below.



The maximum EcoIndicator: 0.48

is identified in the field: Materials

for the part named: bar

The Total Eco Indicator is: 0.238 mPt

The total environmental impact has been decreased from 1.3mPt to 0.23mPt. This represents a decrease of 82.3% of the environmental impact.

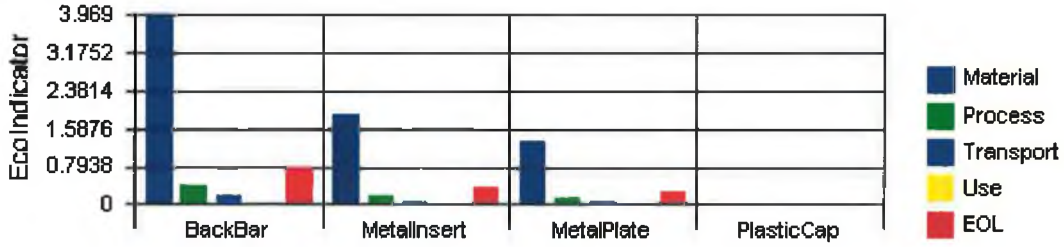
3. Back Support mechanism

Figure 6.10. CAD representation of the Back Support Mechanism

Part Name	Materials	Process	Use	Transport	EOL	Total	Material Name	Process Name	Mass	Transport Name	EOL Name
Back Bar	3.969	0.407	0	0.165	0.774	5.315	Steel	Machining	0.968	Aircraft continental)	Landfill
Metal Insert	1.866	0.191	0	0.077	0.364	2.498	Steel	Machining	0.455	Aircraft (continental)	Landfill
Metal Plate	1.312	0.134	0	0.054	0.256	1.756	Steel	Machining	0.32	Aircraft (continental)	Landfill
Plastic Cap	0.01	0.002	0	0.001	0	0.013	PP	Injection Molding	0.003	Aircraft (continental)	Landfill

Table 6.5. LCA results from the Back Support Mechanism analysis.

Next the Back Support Mechanism presented in figure 6.11 has been analysed. The LCA results are presented in table 6.5 and they are also pictured in the following graph.



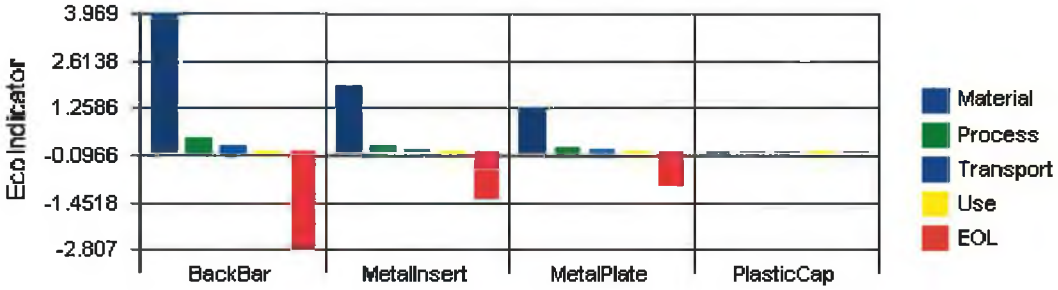
The maximum EcoIndicator: 3.969

is identified in the field: Materials

for the part named: BackBar

The Total Eco Indicator is: 9.582 **mPt**

The mechanism consists of four components and three of them are made from steel. The fourth component, Plastic Cap has a very small mass that means the environmental impact associated with it is very low. The improvement suggested for the Back Support Mechanism is changing the landfill end of life strategy with the recycling strategy. The results of this improvement are presented in the graph below.



The maximum EcoIndicator: 3.969

is identified in the field: Materials

for the part named: BackBar

The Total Eco Indicator is: 3.132 **mPt**

The total environmental impact associated with the Back Support Mechanism has been decreased from 9.5 mPt to 3.13 mPt. This means a decrease by 67%.

Seat Assembly

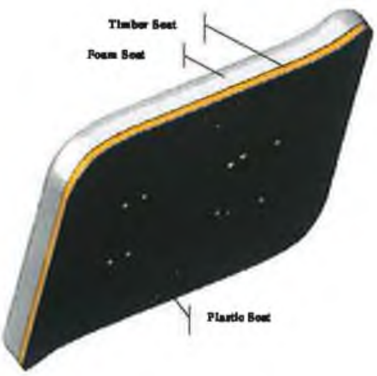
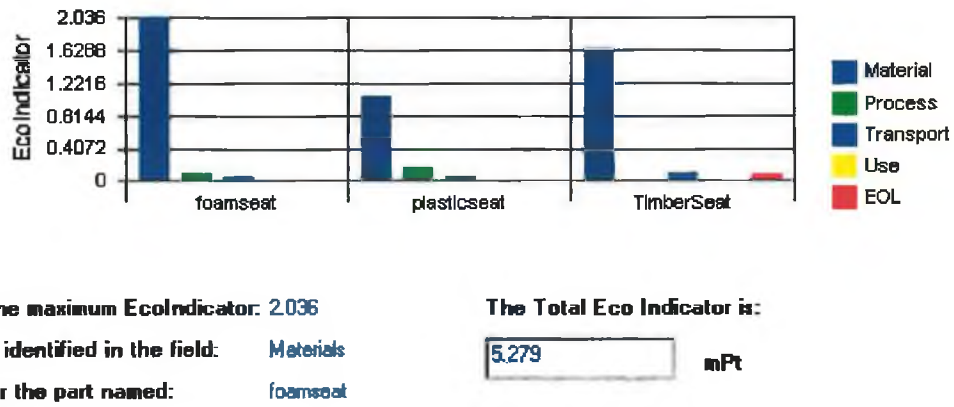


Figure 6.11. CAD representation of the Seat Assembly

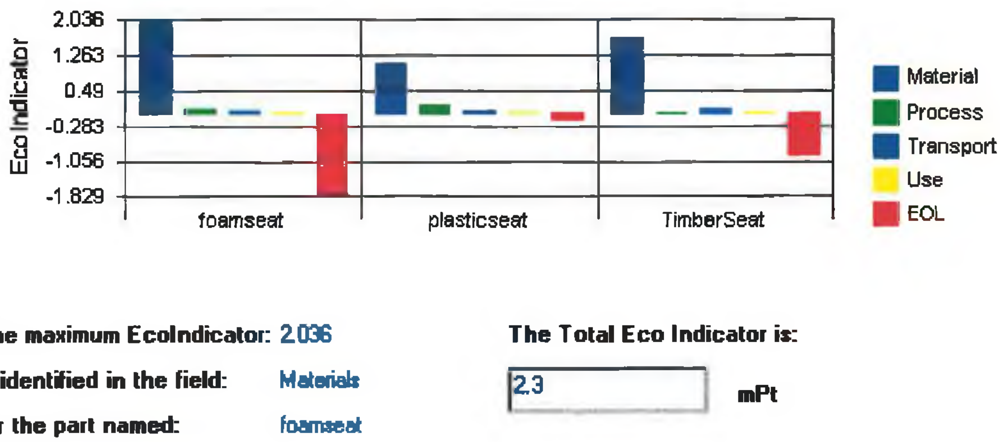
Part Name	Materials	Process	Use	Transport	EOL	Total	Material Name	Process Name	Mass	Transport Name	EOL Name
Foam Seat	2.036	0.089	0	0.05	0.012	2.187	PUR foam	RIM PUR	0.295	Aircraft (continental	Landfill
Plastic Seat	1.043	0.167	0	0.054	0.013	1.277	PP	Injection Molding	0.316	Aircraft (continental)	Landfill
Timber Seat	1.65	0	0	0.085	0.08	1.815	Timber	Hot Press	0.5	Aircraft (continental)	Landfill

Table 6.6. LCA results from the Seat Assembly analysis.

Figure 6.11 is the CCAD representation of the Seat Assembly. The LCA results of the Seat Assembly analysis are represented in table 6.6. The sub assembly consists of three components. The Foam seat is made out of polyurethane (PUR foam) and it has the highest environmental impact in the subassembly, 2.03 mPt. The improvements that could be made is to change the materials in both the foam and the plastic seat (PP) but the overall improvements would not be significant becouse of the low mass of both components, 300 grams for the plastic seat and 200 grams for the foam. The results of the LCA analysis are graphically displayed in the graph below:



A significant improvement can still be obtained by the change of the end of life strategy, which is landfill. If the end of life strategy would be recycling then the following results will be obtained:



As it can be seen from the graph above, the total environmental impact of the seat assembly will decrease from 5.279 mPt to 2.3 mPt. This represents a decrease by 56%.

Base Assembly

The next assembly to be analysed is the Base Assembly presented in figure 9. The base Assembly consists of the following subassemblies:

- Leg Sub Assembly
- Wheel Sub Assembly

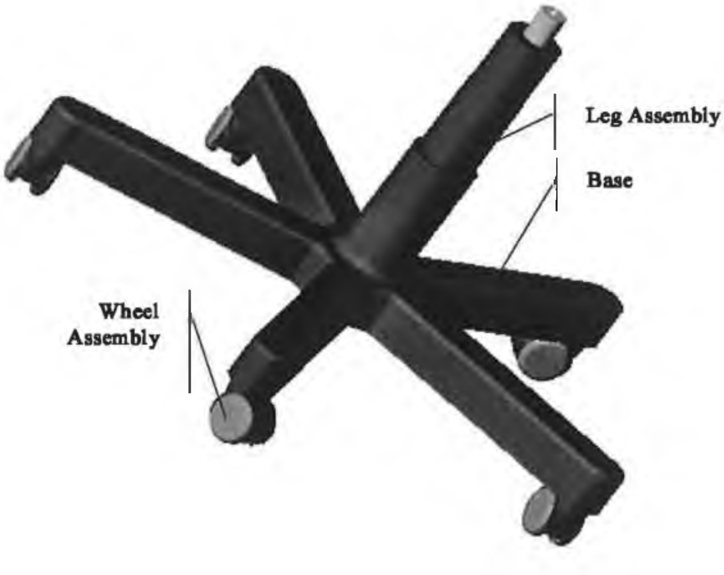


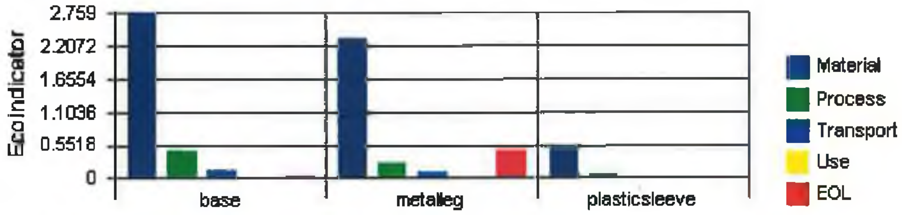
Figure 6.12. CAD representation of the Base Assembly

1. Leg Sub-Assembly

Part Name	Materials	Process	Use	Transport	EOL	Total	Material Name	Process Name	Mass	Transport Name	EOL Name
leg	2.312	0.237	0	0.096	0.451	3.096	Steel	Machining	0.564	Aircraft (continental)	Landfill
base	2.759	0.443	0	0.142	0.033	3.377	PP	Injection Molding	0.9	Aircraft (continental)	Landfill
Plastic Sleeve	0.475	0.076	0	0.024	0.006	0.581	PP	Injection Molding	0.144	Aircraft (continental)	Landfill

Table 6.7. LCA results from the Leg Sub-Assembly analysis.

Table 6.7 presents the results of the LCA analysis carried out for the Leg Sub assembly. The same results are pictured in the following graph.

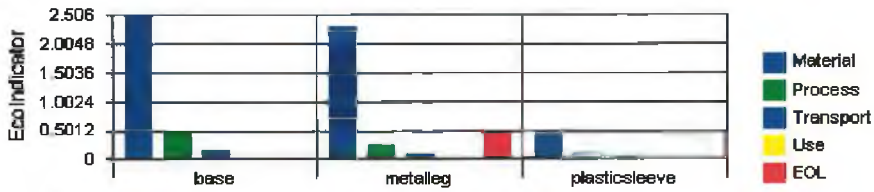


The maximum EcoIndicator: 2.759 **The Total Eco Indicator is:**

is identified in the field: Materials 7.054 **mPt**

for the part named: base

The highest environmental impact is found in the component called Base and it is 2.75 mPt. The total environmental impact of the Leg Sub Assembly is 7.054 mPt. The Sub Assembly consists of three components from which there are two components made from PP. The first suggestion is to change the PP with HDPE. The improvement is represented in the following graph.

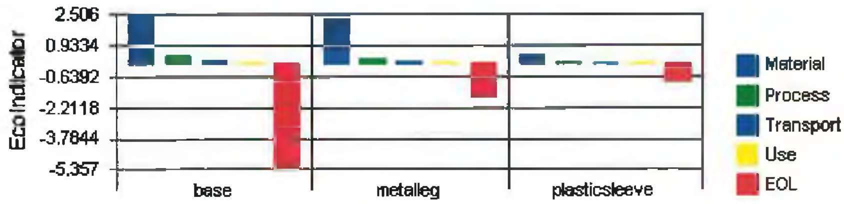


The maximum EcoIndicator: 2.506 **The Total Eco Indicator is:**

is identified in the field: Materials 6.784 **mPt**

for the part named: base

The Environmental impact for the Base has decreased from 2.75 mPt to 2.5mPt. The total environmental impact of the sub assembly has decreased from 7.05 mPt to 6.78 m.Pt. This means a decrease by 3.8%. The next improvement suggested is the change in the end of life policy from landfill to recycling. The improvement resulted is presented in the graph below:



The maximum EcoIndicator: 2.506 **The Total Eco Indicator is:**

is identified in the field: Materials -1.625 **mPt**

for the part named: base

The total environmental impact associated with the Leg Sub Assembly has decreased from 6.78 mPt to -1.62 mPt. As previously stated the minus result is possible because there is a gain in terms of materials (HDPE and Steel) and not a loss, as would be the case of incineration or landfill.

2. Wheel Sub Assembly

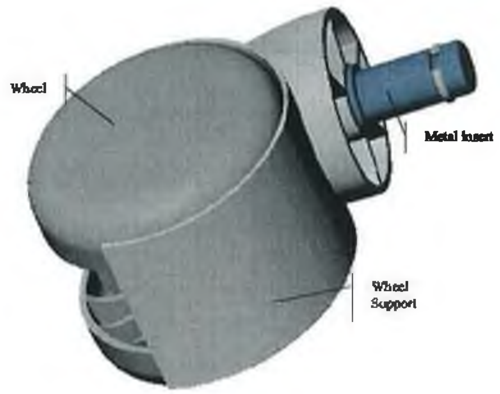
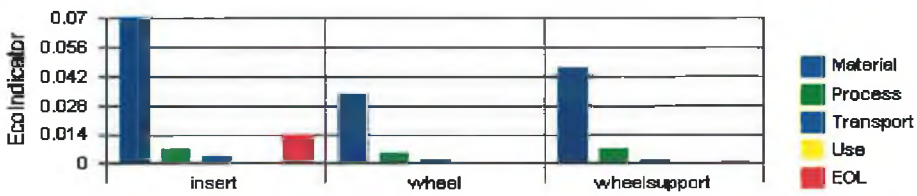


Figure 6.13. CAD representation of the Wheel Sub Assembly.

Part Name	Materials	Process	Use	Transport	EOL	Total	Material Name	Process Name	Mass	Transport Name	EOL Name
insert	0.07	0.007	0	0.003	0.014	0.094	steel	Machining	0.017	Aircraft (continental)	Landfill
Wheel support	0.046	0.007	0	0.002	0.001	0.056	PP	Injection Moulding	0.014	Aircraft (continental)	Landfill
wheel1	0.033	0.005	0	0.002	0	0.04	PP	Injection Moulding	0.01	Aircraft (continental)	Landfill
wheel2	0.033	0.005	0	0.002	0	0.04	PP	Injection Moulding	0.01	Aircraft (continental)	Landfill

Table 6.8. LCA results of the Wheel Sub Assembly analysis.

Table 6.8 presents the results of the LCA analysis carried out for the Wheel Sub Assembly presented in Figure 6.13. The sub assembly consists of four components from which three components are made from PP and one component is made from steel. The LCA results are represented as well in the following graph.



The maximum EcoIndicator: 0.07
is identified in the field: Materials
for the part named: insert

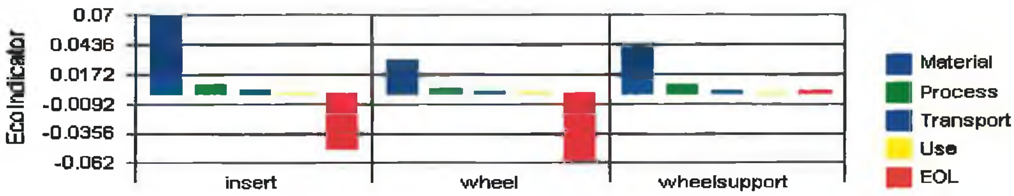
The Total Eco Indicator is: 0.19 mPt

As before, one of the improvements suggested is to change PP with HDPE, which has a lower environmental impact. The improvements are pictured in the graph below.

The maximum EcoIndicator: 0.07
is identified in the field: Materials
for the part named: insert

The Total Eco Indicator is: 0.181 **mPt**

The total environmental impact of the wheel assembly has decrease from 0.19mPt to 0.18 mPt. The next environmental improvement suggested is the end of life policy change from landfill to recycling. The policy change resulted in an environmental improvement of the Wheel Sub Assembly from 0.18 mPt to 0.05 mPt. This means a decrease of the environmental impacts of the sub assembly by 72%. This improvements has been represented in the graph below:



The maximum EcoIndicator: 0.07
is identified in the field: Materials
for the part named: insert

The Total Eco Indicator is: 0.056 **mPt**

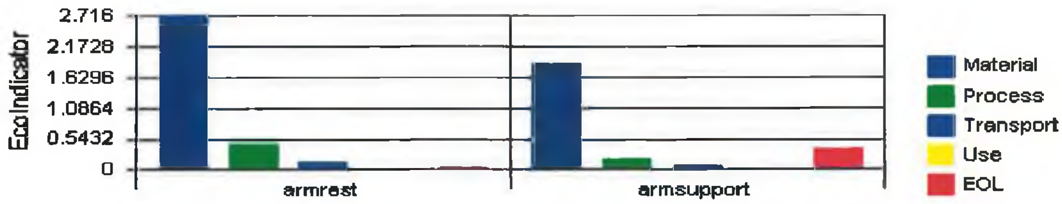
Arm Assembly

Figure 6.14. CAD representation of the Arm Assembly.

Part Name	Materials	Process	Use	Transport	EOL	Total	Material Name	Process Name	Mass	Transport Name	EOL Name
Arm Support	1.861	0.191	0	0.077	0.363	2.492	Steel	Machining	0.454	Aircraft (continental)	Landfill
Arm Rest	2.716	0.436	0	0.14	0.033	3.325	PP	Injection Molding	0.823	Aircraft (continental)	Landfill

Table 6.9. LCA results of the Arm Assembly analysis.

Figure 6.14 presents the Arm Assembly prototype represented in Solid Works 98 Plus. The LCA analysis carried out for the Arm Assembly has resulted in the environmental impact values for each of the life cycle stages of the assembly. These results are presented in Table 6.9 and graphically displayed below:

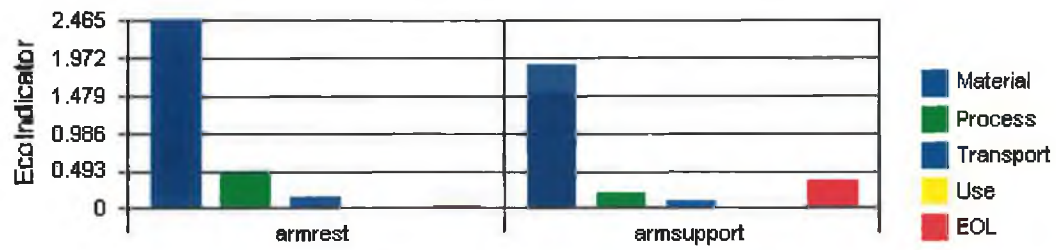


The maximum EcoIndicator: 2.716 **The Total Eco Indicator is:** 5.817 **mPt**

is identified in the field: Materials

for the part named: armrest

The assembly consists of 2 components, one made out of steel and the other made out of PP. As in the previous analysis the first improvement suggested is to change the PP with the HDPE that has a lower environmental impact. The improvement has been graphically represented below:

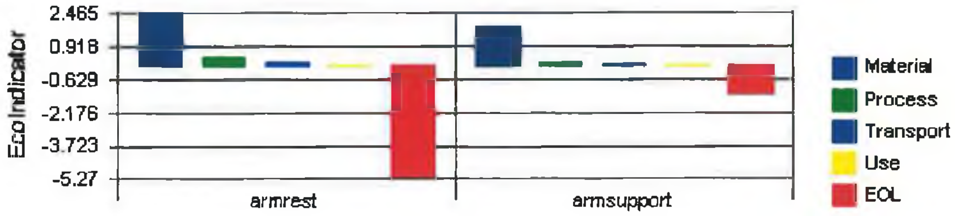


The maximum EcoIndicator: 2.465 **The Total Eco Indicator is:** 5.587 **mPt**

is identified in the field: Materials

for the part named: armrest

The total environmental impact of the assembly has decreased from 5.8 mPt to 5.5 mPt. The next environmental improvement suggested is to change the landfill end of life strategy to recycling. This improvement will reduce the total environmental impact of the Arm Assembly from 5.5 mPt to -0.39 mPt. This improvements resulted are represented in the following graph.



The maximum EcoIndicator: 2.465

is identified in the field: Materials

for the part named: armrest

The Total Eco Indicator is: -1.397 **mPt**

The Total Environmental Impact of the Jacobsen Chair

Part Name	Materials	Process	Use	Transport	EOL	Total	Material Name	Process Name	Mass	Transport Name	EOL Name
Arm Rest	2.716	0.436	0	0.14	0.033	3.325	PP	Injection Molding	0.823	Aircraft (continental)	Landfill
Arm support	1.861	0.191	0	0.077	0.363	2.492	Steel	Machining	0.454	Aircraft (continental)	Landfill
Back Bar	3.969	0.407	0	0.165	0.774	5.315	Steel	Machining	0.968	Aircraft (continental)	Landfill
Back Cover	2.508	0.403	0	0.129	0.03	3.07	PP	Injection Molding	0.76	Aircraft (continental)	Landfill
Back Cover1	1.799	0.289	0	0.093	0.022	2.203	PP	Injection Molding	0.545	Aircraft (continental)	Landfill
Back Foam	1.421	0.062	0	0.035	0.008	1.526	PUR foam	RIM PUR	0.206	Aircraft (continental)	Landfill
Back support	1.238	0.127	0	0.051	0.242	1.658	Steel	Machining	0.302	Aircraft (continental)	Landfill
Bar	0.48	0.049	0	0.02	0.094	0.643	Steel	Machining	0.117	Aircraft (continental)	Landfill
Base	2.759	0.443	0	0.142	0.033	3.377	PP	Injection Molding	0.836	Aircraft (continental)	Landfill
Foam seat	2.036	0.089	0	0.05	0.012	2.187	PUR foam	RIM PUR	0.295	Aircraft (continental)	Landfill
Handle Bar	0.349	0.036	0	0.014	0.068	0.467	Steel	Machining	0.085	Aircraft (continental)	Landfill
Handle Box	0.086	0.014	0	0.004	0.001	0.105	PP	Injection Molding	0.026	Aircraft (continental)	Landfill
Handle Insert	0.023	0.004	0	0.001	0	0.028	PP	Injection Molding	0.007	Aircraft (continental)	Landfill
Insert	0.07	0.007	0	0.003	0.014	0.094	Steel	Machining	0.017	Aircraft (continental)	Landfill
Metal box	6.449	0.661	0	0.267	1.258	8.635	Steel	Machining	1.573	Aircraft (continental)	Landfill
Metal Insert	1.866	0.191	0	0.077	0.364	2.498	Steel	Machining	0.455	Aircraft (continental)	Landfill
Metal leg	2.312	0.237	0	0.096	0.451	3.096	Steel	Machining	0.564	Aircraft (continental)	Landfill

Metal Plate	1.312	0.134	0	0.054	0.256	1.756	Steel	Machining	0.32	Aircraft (continental)	Landfill
Moving Plate	0.012	0.001	0	0.001	0.002	0.016	Steel	Machining	0.003	Aircraft (continental)	Landfill
Plastic Cap	0.01	0.002	0	0.001	0	0.013	PP	Injection Molding	0.003	Aircraft (continental)	Landfill
Plastic Handle	0.043	0.007	0	0.002	0.001	0.053	PP	Injection Molding	0.013	Aircraft (continental)	Landfill
Plastic seat	1.043	0.167	0	0.054	0.013	1.277	PP	Injection Molding	0.316	Aircraft (continental)	Landfill
Plastic Sleeve	0.475	0.076	0	0.024	0.006	0.581	PP	Injection Molding	0.144	Aircraft (continental)	Landfill
Seat support	1.804	0.185	0	0.075	0.352	2.416	Steel	Machining	0.44	Aircraft (continental)	Landfill
Timber Seat	1.65	0	0	0.085	0.08	1.815	Timber	Hot Press	0.5	Aircraft (continental)	Landfill
Wheel	0.033	0.005	0	0.002	0	0.04	PP	Injection Molding	0.01	Aircraft (continental)	Landfill
Wheel Support	0.046	0.007	0	0.002	0.001	0.056	PP	Injection Molding	0.014	Aircraft (continental)	Landfill

Table 6.10. LCA results of the whole chair analysis before any improvement has been made.

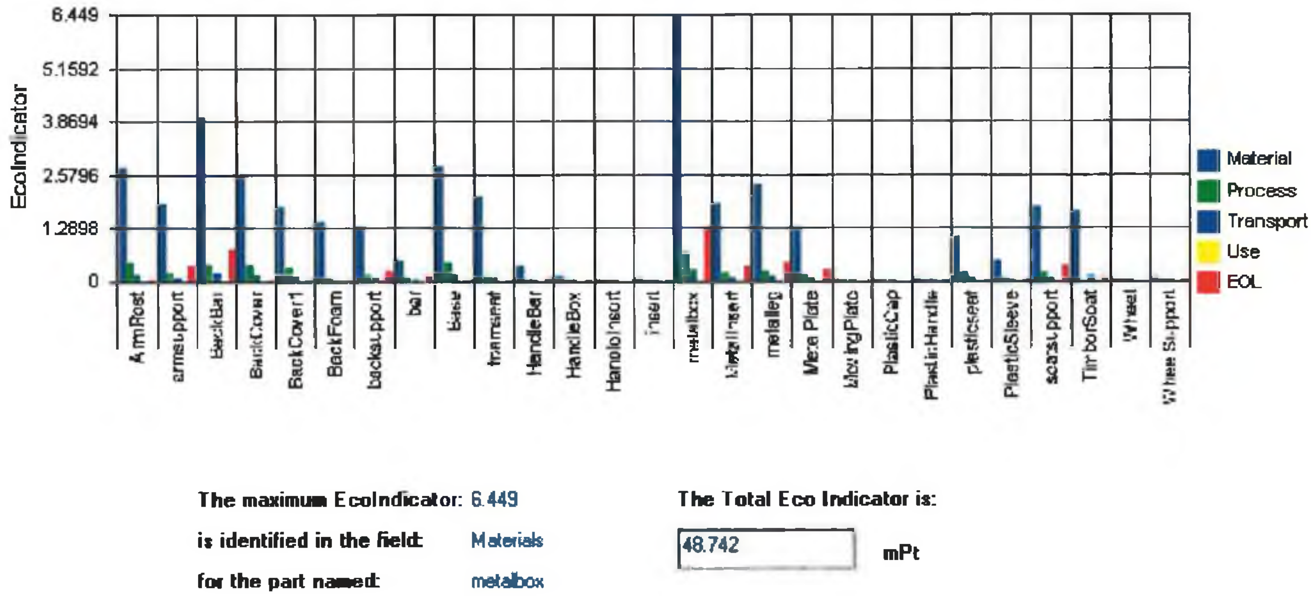
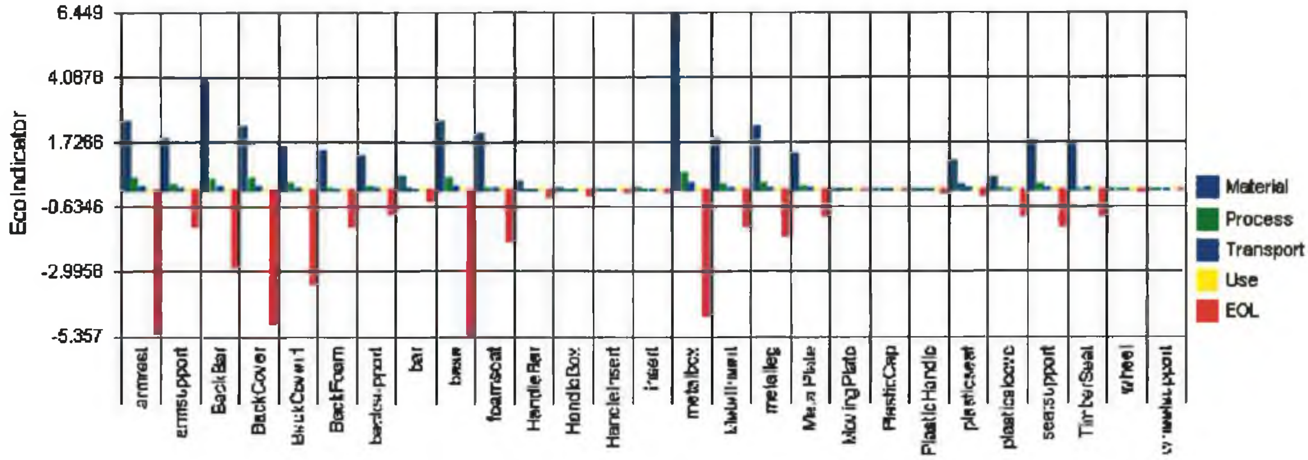


Table 6.10 presents the results of the LCA analysis carried out on the Jacobsen chair. These results have been presented in the graph above. It must be specified that this are the LCA results obtained from the very first LCA analysis. After the improvements suggested in the previous sections have been implemented another LCA analysis has been carried out. The results of this second analysis are presented in Table 6.11.

Part Name	Materials	Process	Use	Transport	EOL	Total	Material Name	Process Name	Mass	Transport Name	EOL Name
Arm Rest	2.465	0.436	0	0.14	0.033	3.325	HDPE	Injection Molding	0.85	Aircraft (continental)	Recycling
Arm support	1.861	0.191	0	0.077	0.363	2.492	Steel	Machining	0.454	Aircraft (continental)	Recycling
Back Bar	3.969	0.407	0	0.165	0.774	5.315	Steel	Machining	0.968	Aircraft (continental)	Recycling
Back Cover	2.279	0.403	0	0.129	0.03	3.07	HDPE	Injection Molding	0.786	Aircraft (continental)	Recycling
Back Cover1	1.581	0.289	0	0.093	0.022	2.203	HDPE	Injection Molding	0.545	Aircraft (continental)	Recycling
Back Foam	1.421	0.062	0	0.035	0.008	1.526	PUR foam	RIM PUR	0.206	Aircraft (continental)	Recycling
Back support	1.238	0.127	0	0.051	0.242	1.658	Steel	Machining	0.302	Aircraft (continental)	Recycling
Bar	0.48	0.049	0	0.02	0.094	0.643	Steel	Machining	0.117	Aircraft (continental)	Recycling
Base	2.506	0.443	0	0.142	0.033	3.377	HDPE	Injection Molding	0.864	Aircraft (continental)	Recycling
Foam seat	2.036	0.089	0	0.05	0.012	2.187	PUR foam	RIM PUR	0.295	Aircraft (continental)	Recycling
Handle Bar	0.349	0.036	0	0.014	0.068	0.467	Steel	Machining	0.085	Aircraft (continental)	Recycling
Handle Box	0.078	0.014	0	0.004	0.001	0.105	HDPE	Injection Molding	0.027	Aircraft (continental)	Recycling
Handle Insert	0.023	0.004	0	0.001	0	0.028	HDPE	Injection Molding	0.008	Aircraft (continental)	Recycling
Insert	0.07	0.007	0	0.003	0.014	0.094	Steel	Machining	0.017	Aircraft (continental)	Recycling
Metal box	6.449	0.661	0	0.267	1.258	8.635	Steel	Machining	1.573	Aircraft (continental)	Recycling
Metal Insert	1.866	0.191	0	0.077	0.364	2.498	Steel	Machining	0.455	Aircraft (continental)	Recycling
Metal leg	2.312	0.237	0	0.096	0.451	3.096	Steel	Machining	0.564	Aircraft (continental)	Recycling
Metal Plate	1.312	0.134	0	0.054	0.256	1.756	Steel	Machining	0.32	Aircraft (continental)	Recycling
Moving Plate	0.012	0.001	0	0.001	0.002	0.016	Steel	Machining	0.003	Aircraft (continental)	Recycling
Plastic Cap	0.01	0.002	0	0.001	0	0.013	PP	Injection Molding	0.003	Aircraft (continental)	Recycling
Plastic Handle	0.041	0.007	0	0.002	0.001	0.053	HDPE	Injection Molding	0.014	Aircraft (continental)	Recycling
Plastic seat	1.043	0.167	0	0.054	0.013	1.277	PP	Injection Molding	0.316	Aircraft (continental)	Recycling
Plastic Sleeve	0.432	0.076	0	0.024	0.006	0.581	HDPE	Injection Molding	0.149	Aircraft (continental)	Recycling
Seat support	1.804	0.185	0	0.075	0.352	2.416	Steel	Machining	0.44	Aircraft (continental)	Recycling
Timber Seat	1.65	0	0	0.085	0.08	1.815	Timber	Hot Press	0.5	Aircraft (continental)	Recycling
Wheel	0.029	0.005	0	0.002	0	0.04	HDPE	Injection Molding	0.01	Aircraft (continental)	Recycling
Wheel Support	0.041	0.007	0	0.002	0.001	0.056	HDPE	Injection Molding	0.014	Aircraft (continental)	Landfill

Table 6.11. LCA results of the Jacobsen Chair analysis after the improvements have been implemented.

The LCA results presented in Table 6.11 are graphically displayed s follows:



The maximum EcoIndicator: 6.449
is identified in the field: Materials
for the part named: metalbox

The Total Eco Indicator is: 3.629 **mPt**

After the improvements have been implemented the total environmental impact of the Jacobsen chair has decreased from 48.742 mPt to 3.629 mPt. This means a decrease by 92.5%

Improvement Suggestions in the Case of Design for Reuse

As stated in the introductory section, Jacobsen goal is to produce reusable chairs. For this reason the components of the chair must be durable as well as environmental friendly. In order to promote this goal, an analysis has been carried out. It has been established that the metallic parts are made out of steel and steel is a durable and recyclable material. The plastic parts that have been considered as being the most exposed to ware are the Armrest and the Back Cover. For this reason, these parts should be made out of a resistant material such as polyurethane.

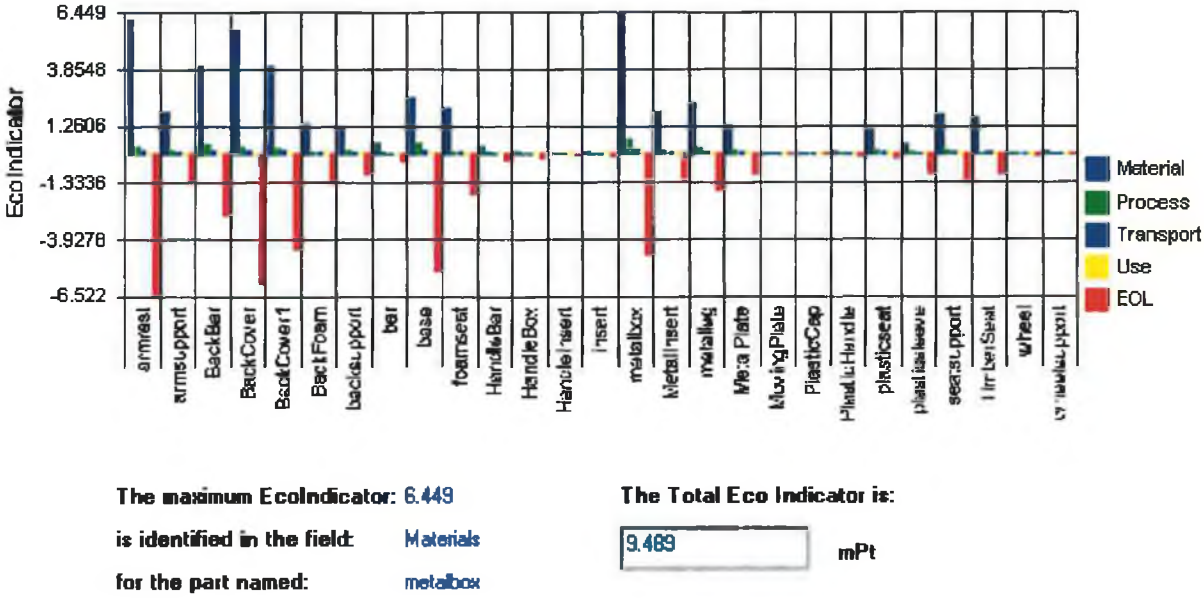
Some of the polyurethane characteristics[5] are as follows:

- Polyurethane is resistant to abrasion, typically outwears other materials such as rubber, plastics and metals by ratios of five-to-one and sometimes as high as fifty-to-one in cases of severe abrasion.
- Plastic materials tend to become brittle as they become harder; Polyurethane retain their elasticity. They resist breakage even in the hardest formulations. This toughness makes polyurethane ideal for parts subject to high impact or repeated pounding.

[5] See http://www.sunray-inc.com/polyurethane.html

- Under repeated flexing, polyurethane resist cracking as well as most other elastomers. However, since cracking in any elastomer can be reduced by making the part thinner, polyurethane offer an important advantage: they can be used in very thin sections because of their inherent strength and toughness.
- Unlike rubbers, polyurethane does not have to be made soft to make them resilient. In fact, polyurethane can be as resilient as much softer materials. For shock absorbing applications, polyurethane can be formulated with rebound values as low as 10% to 25%. For quicker recovery, or where high-frequency vibrations are a factor, rebound values of up to 40% to 70% can be formulated.
- Special formulations allow polyurethane to remain quite flexible even in frigid temperatures. In addition, they have proven remarkably resistant to thermal shock and withstand sudden and drastic temperature drops without cracking. Also, Polyurethane can be formulated to withstand continuous use at maximum temperatures of 200° to 250° F.
- Polyurethane remains stable even when immersed in water as warm as 120° F for very long periods of time. (Continuous use in water hotter than 160° F is not recommended.) They absorb practically no water...just 0.3 to 1.0 percent by weight, and show negligible swelling even after prolonged immersion.
- Polyurethane is virtually immune from attack by ozone and oxygen. This makes them the ideal for use around electrical equipment without the cracking and hardening associated with other elastomers and plastics.

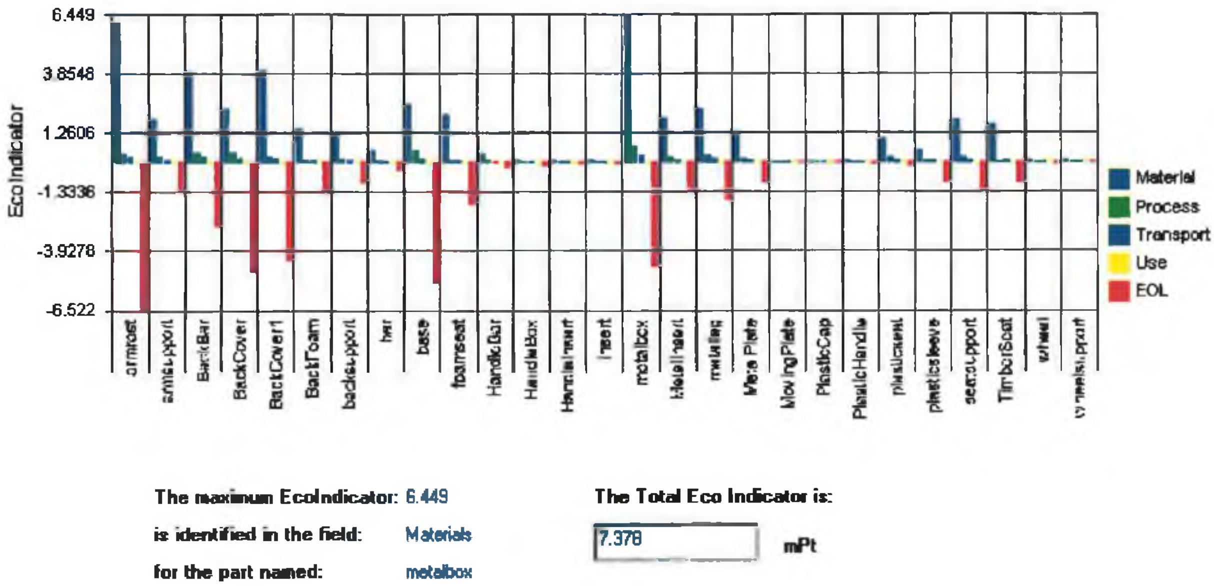
The plastic parts of the Jacobsen Chair have been made originally out of polypropylene (PP). The total environmental impact of the chair was 48.742 mPt. One of the improvements suggested for designing an environmental superior chair was the use of polyethylene in most of the plastic parts. This improvement, combined with the introduction of the recycling policy in the end of life of the chair has reduced the total environmental impact to 3.629 mPt. However, Polyurethane has a higher environmental impact than polyethylene. If the arm rest and both components of the back are made out of polyurethane the total environmental impact will be 9.489 mPt that is higher than the environmental superior chair proposed in the previous section. However, this result is significantly smaller than the original environmental impact of 48.742 mPt. The LCA results of the chair proposed for the case of design for reuse are displayed in the graph below:



The total environmental impact of the chair can be reduced if the inside component of the back will be made out of polyethylene. The reasons for not making both of the back components out of polyurethane are:

- The back components are fastened together by the use of spring clips that can be easily unfastened.
- The foam and the textile used to cover up the chair protect the back cover component.

After the implementation of the improvements suggested above the total environmental impact became 7.378 mPt. The environmental impact of the chair is presented in the graph below:



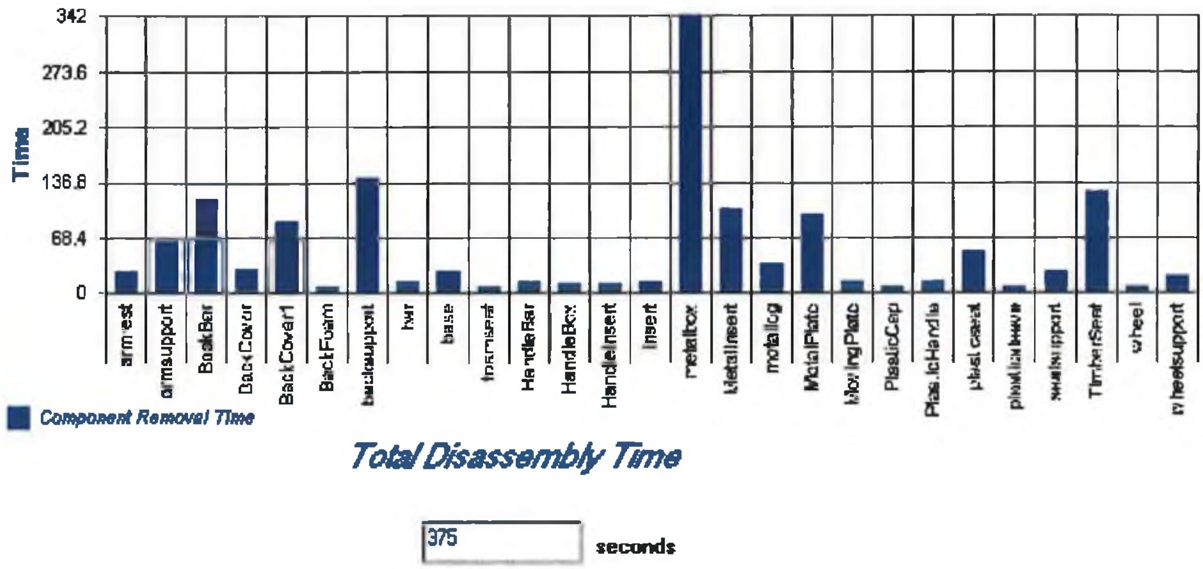
6.4. Structure Assessment Analysis

The structural analysis is carried out with the help of the Structure Assessment Module (SAM) of the DFE Workbench software tool. First the module performs basic calculations i.e. total disassembly time of the chair, components removal time, number of fasteners per component and the type of structure of the chair. The chair is layered structured. Layered structures are particularly easy to disassemble. Observing the number and distribution of joints used to assemble the product can indicate the type of structure. For example a component in a layered structure tends to have two joint interfaces, whereas a hierarchical structure tends to have one joint per component with one single component having many joint interfaces [Roc99].

Part Name	Joint	Join Type	Tool	Time	Mass	Join Number	Disassembly Time
Metal box	Metal leg	Snap Fit	Prybar	7	1.573	1	7
Metal box	Seat support	Philips Head Screw	Philips	13	1.573	2	26
Metal box	Back support	Philips Head Screw	Philips	13	1.573	2	26
Metal box	Timber Seat	Philips Head Screw With Insert	Philips	13	1.573	4	52
Metal leg	Base	Snap Fit	Prybar	7	0.564	1	7
Base	Insert	Snap Fit	Prybar	7	0.864	1	7
Wheel support	Wheel	Press Fit	Prybar	7	0.014	1	7
Wheel support	Insert	Press Fit	Prybar	7	0.014	1	7
Metal box	Handle Bar	Press Fit	Prybar	7	1.573	1	7
Arm support	Armrest	Philips Head Screw With Insert	Philips	13	0.454	2	26
Timber Seat	Arm support	Philips Head Screw	Philips	13	0.5	3	39
Back support	Back Bar	Press Fit	Prybar	7	0.302	1	7
Back Bar	Metal Insert	Press Fit	Prybar	7	0.968	1	7
Metal Insert	Metal Plate	Stud Weld	Prybar	7	0.455	1	7
Metal Plate	BackCover1	Philips Head Screw	Philips	13	0.32	4	52
Back Cover1	Back Cover	Spring Clips	Special Tool	5	0.696	6	30
Back Cover1	Back Foam	Adhesive	Prybar	7	0.696	1	7
Handle Box	Handle Insert	Screw Insert	Hammer And Chisel	12	0.027	1	12
Base	Plastic sleeve	Snap Fit	Prybar	7	0.864	1	7
Plastic Handle	Handle Bar	Snap Fit	Prybar	7	0.014	1	7
Back Bar	Plastic Cap	Snap Fit	Prybar	7	0.968	1	7
Timber Seat	Foam seat	Adhesive	Prybar	7	0.5	1	7
Bar	Moving Plate	Press Fit	Prybar	7	0.117	2	14

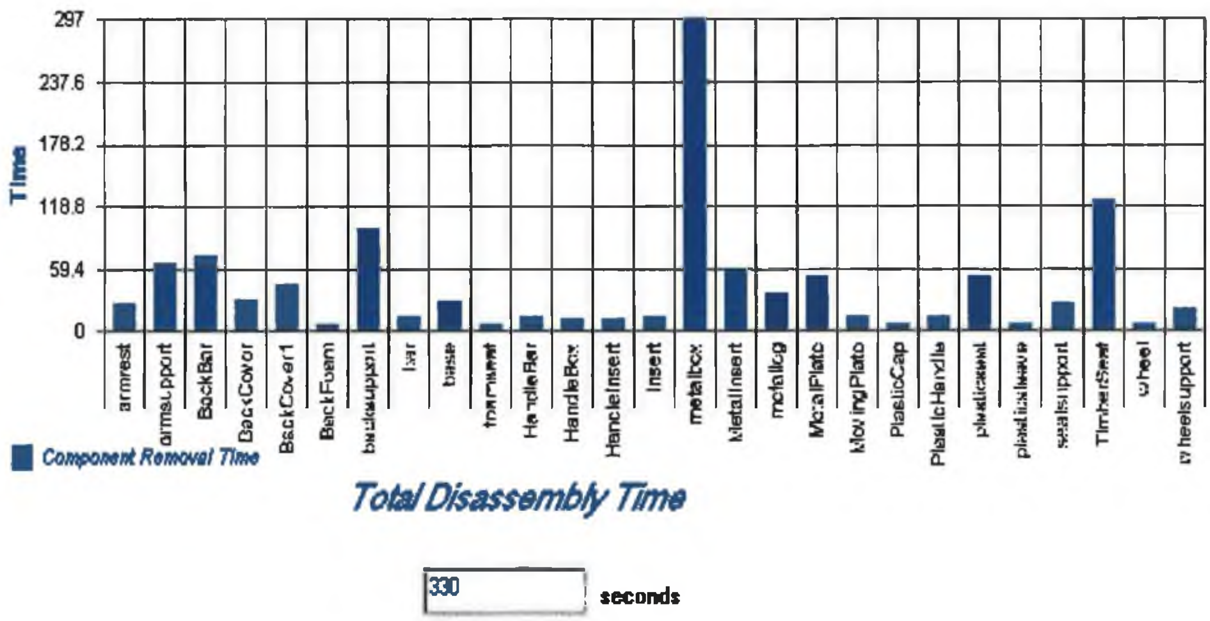
Table 6.12. The fasteners identified in the chair assembly

The component removing times associated with the components of the chair assembly are presented in Table 6.12. They are also graphically displayed below.



The total disassembly time is 375 seconds. The highest disassembly time has been identified in the component metal box that makes the link between all the other components of the chair.

The chair is very well structured however there would be an improvement suggestion to be made. It refers to the Back support mechanism and suggests that the Philips Head Screws should be replaced with a press fit built on the Back Cover 1. This will give a smaller disassembly time and will reduce the number of components. As presented in the graph below, the disassembly time will decrease from 375 seconds to 330 seconds. This represents a decrease by 12% of the total disassembly time.



6.5. Conclusions

The initial plan for developing the DFE Workbench software was the development of a prototype software application that will prove that the automation of the DFE Workbench methodology described in chapter four is possible. A first prototype of the software has been developed and has been analysed in CIMRU[6] by the GACE team. A number of iterations followed until a new, more complete, prototype has been developed. Next the prototype has been tested in Motorola, based in Dublin. The errors identified during the tests were efficiency errors. There were too many steps involved in making some calculations. For example, for calculating the Eco Indicator associated with each stage of the life cycle of a product, five windows have been built, one for each of the stages: raw materials, process, use, transport and end of life therefore the calculation process was very slow. Another error was the calculation of the component removal time in the structure analysis of a product. Initially the calculations were made for one component at the time. This resulted in slow progress of the analysis and some of the users lost track of the steps to be followed. These errors have been solved, the Eco Indicator is now calculated using only two windows, one for the raw material and another for the remaining four life cycle stages i.e. manufacturing, transport, use and end of life. In the case of the component removal time the software had to be rewritten integrally and a new module has been added. The Jacobsen project case study has been used not only for the development of new prototypes of environmentally superior chairs but also for testing the performance of the DFE Workbench software tool. The overall results are positive. The desired goals have been attained. The software prototype proves that such a DFE tool can be built and can be integrated in a virtual prototyping system for being concurrently used in the design process. The improvements suggested have a significant environmental value and also the structure changes suggested are viable. However some disadvantages have been encountered. The software prototype has some difficulties in handling a large number of components. For example, if the number of components is higher then 25, the graphical displays are almost unreadable. If the component number is higher then 30 than the graphs will not be displayed at all. Along with the calculation of components removal time the obstructions of each of the components of the product are recorded using a string[7]. If the number of components is higher than 15, the string will not be displayed or recorded in the databases because of its size. These disadvantages are somewhat normal because of the

[6] Computer Integrated Manufacturing Research Unit is a part of the National University of Galway, Ireland
[7] In programming, a string is a contiguous sequence of symbols or values, such as a character string (a sequence of characters) or a bit string (a sequence of binary values) [Int99]

limited resources used for the development of the software tool. Another disadvantage is represented by the amount of information recorded in the databases used as knowledge based agent. The information existing for the raw materials and process stages is very limited. The companies developing different types of materials and even the companies developing components for different products are very restrictive in releasing information. For this reason, the next step for the development of the DFE Workbench software tool would be its integration into a Product Data Management (PDM) System and probably the development of a web based software application that will allow easy access to the information needed.

Apart from the mentioned disadvantages, the methodology behind the software tool is a powerful DFE methodology and its automation is highly beneficial for the designers.

The next chapter will conclude the thesis and will introduce suggestions for further development of the existing DFE Workbench tool not only for the software but also for the methodology behind. These further developments have been proposed within the GACE Project, presented in the beginning of the present thesis, and they represent the collaborative work of the GACE team.

Chapter 7

Conclusions and Further Development

7.1. Thesis Summary

The research involved in the development of the current thesis has been focused on design theory, computer aided design and design for environment areas and the existent relationships among them (see figure 7.1).

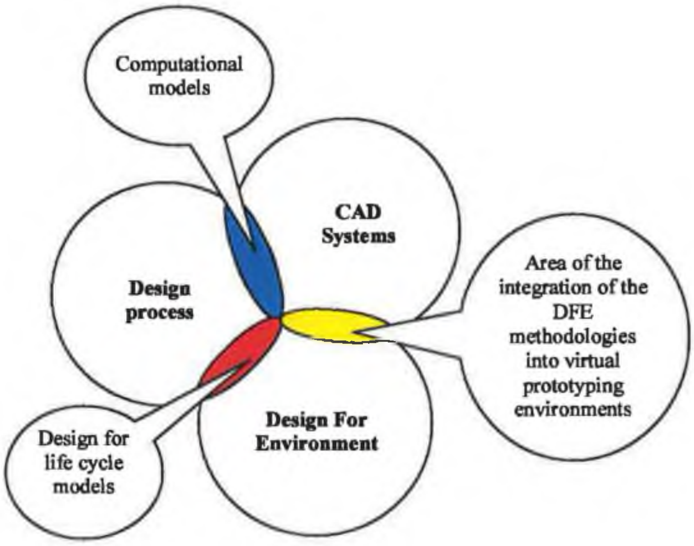


Figure 7.1. Current thesis research areas and the relationships between them.

Firstly the thesis presents a detailed study of the design process broadly divided onto descriptive, prescriptive, design for life cycle and computational models with a particular focus on the last two preparing the introduction in chapter three of a study on the Design for Environment area. The DFE study is gradually narrowed towards the essential methodologies that need to be integrated early into the design process i.e. LCA and the Structure Analysis Methods. The DFE Workbench methodology has been identified to be one of the most effective DFE methodologies presently developed and it has been selected as the basis of the software development. The DFE Workbench software has been described in detail in chapter five. Further on the thesis focuses on testing the software application. The description and the results of the tests are discussed in chapter six. The current chapter presents the conclusions of the thesis and proposes further development of the DFE Workbench.

7.2. Conclusions

Several conclusions have been identified throughout the research carried out in the design process area. They are as follows:

- Presently a new category of the design models is under development. The author identified this category as life cycle design models. The design models gathered under this category attempt to integrate environmental considerations as early in the design process as possible. The models are also developed as frameworks to support the development of new methodologies for assisting the design of environmentally superior products.
- Significant research efforts are also focused on the development of computer aided design systems to support creativity in preliminary design. In this context several requirements have been identified as vital for this type of systems. They must be intuitive, they must require no specialised knowledge, they must support fast combining activities for a given structure and they must support flexible switching between different structures of a given input.

Further on the research has focused on the Design for Environment area and has identified several requirements for the development of a powerful design for environment application. They are as follows:

- The application must encompass both LCA and DFX techniques and they should be integrated as early in the design process as possible without disrupting the design activity.
- It must be fully integrated in the Computer Aided Design system used for the development of the product prototype.
- The application must be intuitive and user friendly and must require no expert knowledge in the environment area.
- The calculations performed must be based on standardised factors where possible.
- It must include a data interpreter and a prioritisation tool for prioritising the environmental issues to be addressed.
- The application must be supported by an advisor to guide the designer trough the efforts of designing environmental superior products without constraining the designer in any way.

- The application must also be supported by a powerful updateable database that should provide the necessary information to the designer.
- The tool must also provide clear documentation of all the activities performed by the tool.
- The tool must provide reports and graphical displays of all the environmental scores and the other metrics calculated by the tool

A new design for environment methodology has been identified to meet these requirements. Roche has developed the methodology in 1999 calling it DFE Workbench methodology. The methodology has been tested in CIMRU, a research unit within National University of Galway, and it has been also tested in the Motorola Company. The results of the tests have been positive. Some of the conclusions resulted from the performed tests are as follows: [Roc99]

- The DFE Workbench is integrated much earlier in the design process then any of the existing DFE methodologies.
- Design is a problem solving process and designers tend to solve problems by the analysis, synthesis and evaluation of design information. The methodology is established to aid this process for DFE and deals with the large variety and volume of interrelated information associated with the environmental characteristics of a product.
- It has been established that life cycle analysis is an essential tool to support the designer in developing environmentally superior products. An abridged quantitative LCA tool based on standardised full life cycle analysis techniques has been integrated into the model proposed. It is assisted with a design advisor to help the designer explore environmentally superior options, learn about environmental characteristics of products and therefore to be more creative in the development of environmentally superior solutions.
- Learning influence the decision-making process for designers and for this reason learning needs to be an integral part of design methodologies and tools. The DFE Workbench methodology provides *life cycle information access* and support *interpretation and transformation* of this knowledge into product characteristics.
- The methodology contains a design advisor that aids the identification of environmental problems in a candidate design and actively proposes environmentally superior alternatives. A DFE knowledge agent that provides passive advice and information to the designer supports the advisor. Information needs to be provided to the designer in an advisory mode rather than as a set of

prescriptive rules. The prioritisation process was found to be very useful for the search and improvement activity.

The advantages for developing an automated version of the DFE Workbench and integrating it into virtual prototyping environment are as follows:

- the automation of data synthesis activity
- the availability of quantitative data directly from the model
- the manipulation of this data
- the management of data interrelationships
- the accelerated learning that takes place as a result of active experimentation
- the beneficial effect of this learning
- the resulting improvement in a design before it is manufactured

The initial plan for developing the DFE Workbench software was the development of a prototype software application that will prove that the automation of the DFE Workbench methodology described in chapter 4 is possible. A first prototype of the software has been developed and has been analysed in CIMRU. A number of iterations followed until a new, more complete, prototype has been developed. Next the prototype has been tested in Motorola Company, based in Dublin. The errors identified during the tests were efficiency errors. There were too many steps involved in making some calculations. For example, for calculating the Eco Indicator associated with each stage of the life cycle of a product, five windows have been built, one for each of the life cycle stages i.e. raw materials, process, use, transport and end of life therefore the calculation process was very slow. Another error was the calculation of the component removal time in the structure analysis of a product. Initially the calculations were made for one component at the time. This resulted in slow progress of the analysis and some of the users lost track of the steps to be followed. These errors have been solved, the Eco Indicator is now calculated using only two windows, one for the raw material and another for the remaining four life cycle stages i.e. manufacturing, transport, use and end of life. In the case of the component removal time the software had to be rewritten integrally and a new module has been added. Further on another test has been carried on in collaboration with Jacobsen[1] to test the performance of the last version of the DFE Workbench software tool. The overall results were positive. The software prototype proves that an effective DFE tool can be built and can be integrated in a virtual prototyping system for being concurrently used in the design process. The

[1] See chapter six.

improvements suggested have a significant environmental value and also the structure changes suggested are viable. However some disadvantages have been encountered. The software prototype has some difficulties in handling a large number of components. For example, if the number of components is higher then 25, the graphical displays are almost unreadable. If the component number is higher then 30 than the graphs will not be displayed at all. Along with the calculation of component's removal time the obstructions of each of the components of the product are recorded using a string[2]. If the number of components is higher than 15, the string will not be displayed or recorded in the databases because of its size. Another disadvantage is represented by the amount of information recorded in the databases used as knowledge based agent. The information existing for the raw materials and process stages is very limited. The companies developing different types of materials and even the companies developing components for different products are very restrictive in releasing information. For this reason, the next step for the development of the DFE Workbench software tool would be its integration in a Product Data Management (PDM) System and probably the development of a web based software application that will allow easy access to the information needed. Next section will introduce suggestions for further development of the existing DFE Workbench tool not only for the software but also for the methodology behind. These developments have been proposed within the GACE Project[3] and they represent the collaborative work of the GACE team.

7.3. Further Development

This section proposes further developments for the existing DFE Workbench application. DFE Workbench should be developed to include new tools to perform life-cycle analysis and life extension methodologies. It should also consider the linkages between the methodologies and attempt to correlate the results of the life extension methods in terms of life cycle impact savings.

The first limitation identified by the majority of the subjects during the Motorola Tests was the difficulty of keeping track of the actions performed and the ones to be performed during the Impact and Structure Analysis. Therefore the DFE Workbench Software should also consist of a Workflow Manager Module. Further more the Workflow Manager should be developed after the model of the PDM systems keeping

[2] In programming, a string is a contiguous sequence of symbols or values, such as a character string (a sequence of characters) or a bit string (a sequence of binary values) [Int99]

[3] See the prologue of the thesis.

track of the changes proposed by the designers giving the designers the chance to return to previous versions. The Workflow Manager Module may also embed a tool to support the implementation of standards into companies. For example the nature of ISO 14000 implementation is that it is extremely complex set of steps, with many people across the enterprise involved from raw materials suppliers to plant maintenance to process engineers and site managers. Therefore the existence of a workflow manager that can assist the implementation of each step of the ISO 14000, would be very beneficial.

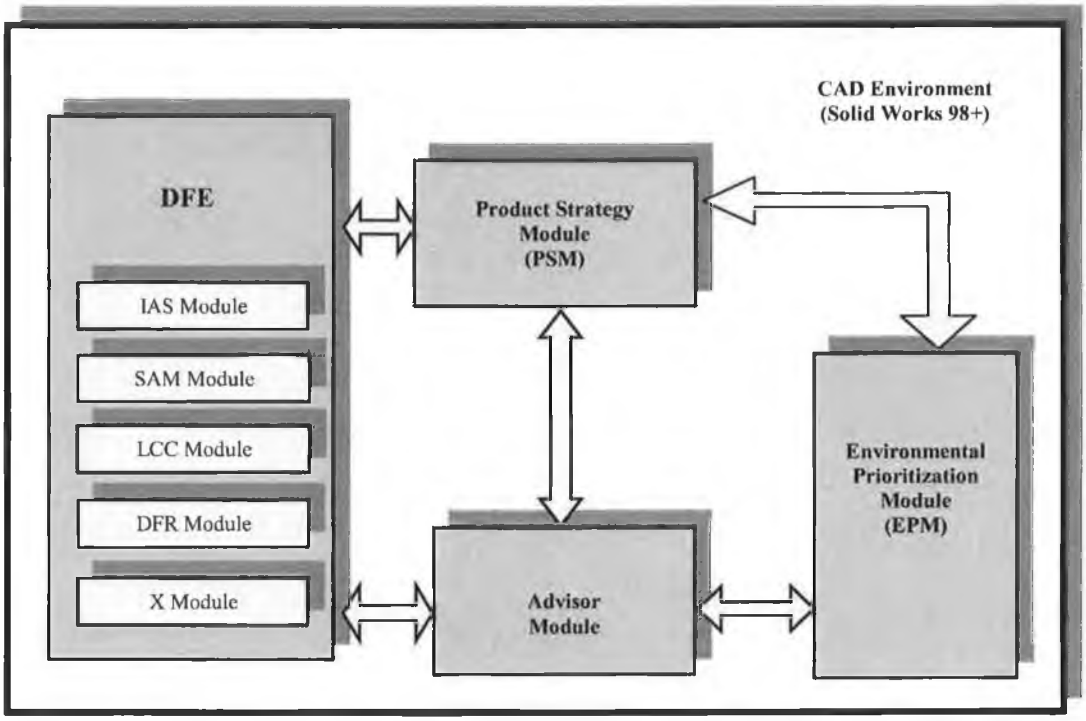


Figure 7.2. Proposed model for further development of the DFE Workbench.

Presently, the DFE Workbench consists of the prioritisation, advisor, IAS and SAM modules integrated into Solid Works 98 Plus environment. The improvements presented in figure 7.2. consist of the integration of new methodologies such as Life Cycle Cost (LCC) or Design for Re-manufacturing (DFR) methods on the existing structure of the DFE Workbench. Another development would be the integration of a Product Strategy module that would act as a constraining factor for the tool guiding the advisor with respect of the product strategy such as re-manufacturing, reuse or recycling strategies. For example, in the case of reuse product strategy, the advisor will suggest polyurethane (PU) rather than polyethylene (PE), as an alternative material for polypropylene because PU is a more resistant material to friction and use than PE even though PE has a lower environmental impact than PU. Also the product strategy module may be used to identify the appropriate end of life strategy to be used for particular products based maybe on a check list or an Analytical Hierarchical Process (AHP) system.

The next step in the development of the DFE Workbench is the integration of the tool with an information management system Figure 7.3 shows the linkages between the information management system, the DFE methodologies and the design process.

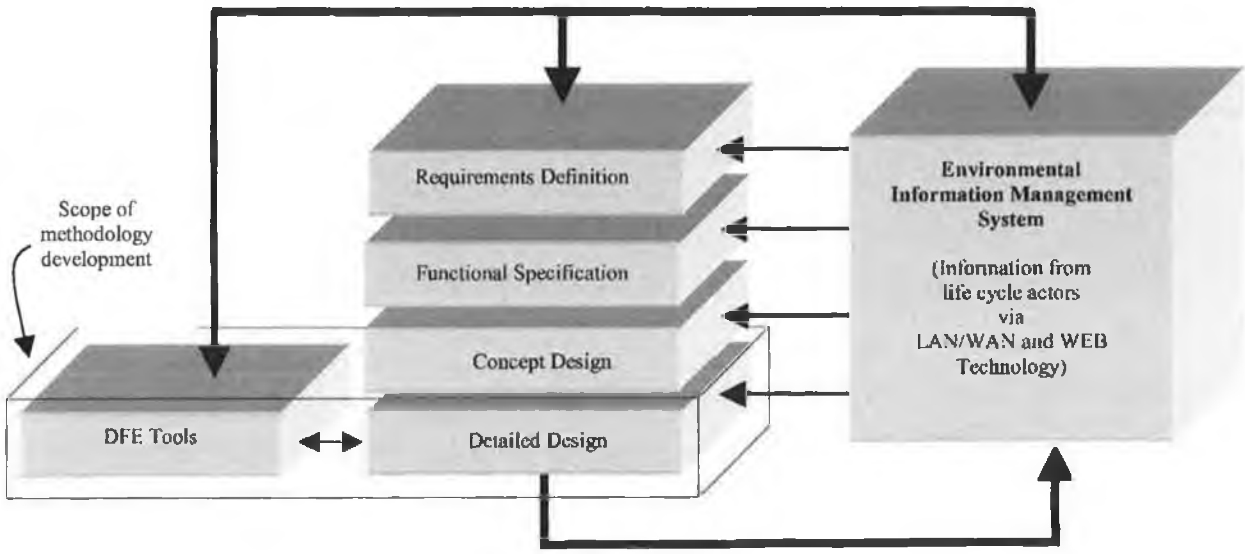


Figure 7.3.Integration of DFE Methodologies with Information Management System [Roc99]

The information management system should consist of three main elements as follows [Roc99]:

1. Database of information
2. Collaboration loops
3. Information storage and retrieval loops

The proposed database should be central to the storage and management of the environmental information. The management and acquisition of loop information in the framework may be done by a Product Data Management (PDM) system. PDM is a database framework for product data storage. PDM applications typically offer users the ability to create and update a wide variety of product data structures during a product's life cycle. The core of a PDM system is its electronic data vault, which provides for the secure, controlled storage of all data sets managed by the PDM system. The vault provides storage and checkout control of electronic files, ranging from engineering drawings governing a part's configuration to documents of interest to the entire enterprise (e.g., ISO14000 environmental management system data). The guiding principle underlying the existence of the Vault, is that the maximum number of users should be given permission to view and mark up copies of documents therein, but that 'check out' privileges should only be extended to those actually authorised to make approved changes to those documents.

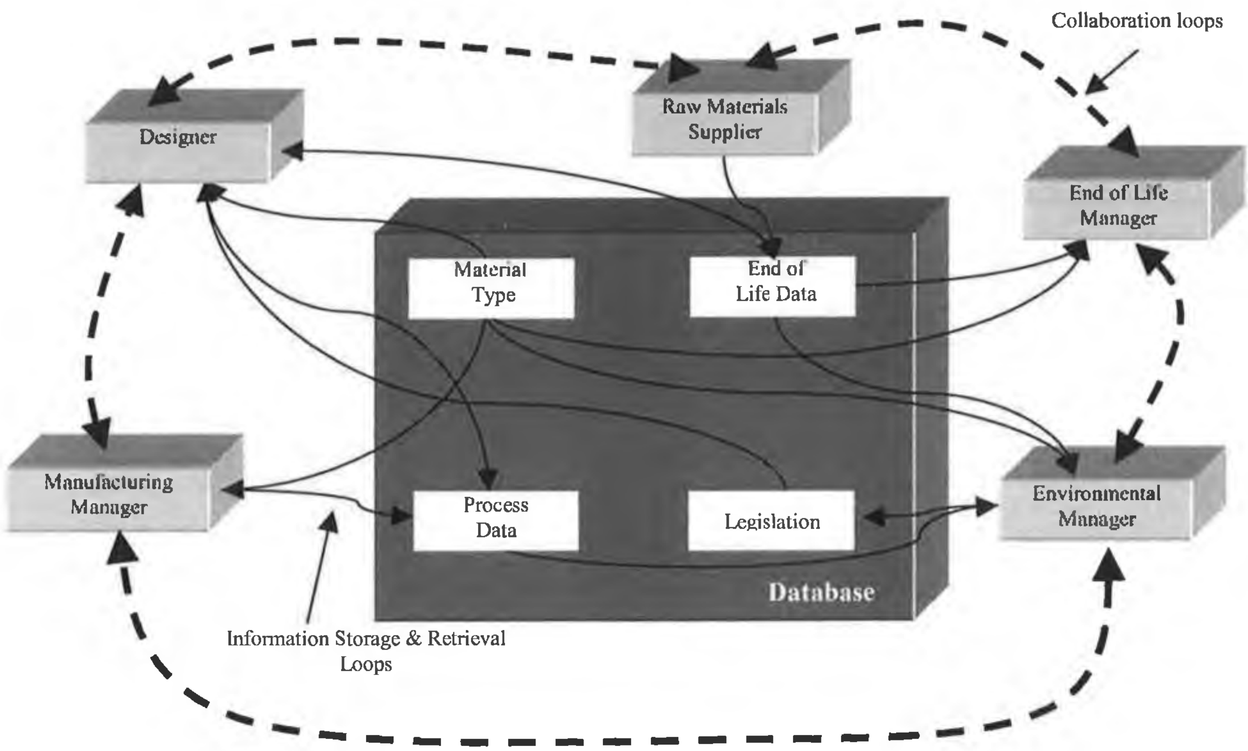


Figure 7.4. Environmental Information Management System [Roc99]

The *Collaboration loops* support the collaboration of the primary actors with the design engineer. The facilitation of these loops is an important ingredient to the environmental design process Collaboration can be facilitated through the PDM system, which offers the flexibility of client/server architecture, which allows multiple users to access data simultaneously via LAN/WAN and WEB networks.

The *information storage and retrieval loops* support the storage and management of information in a product database. Knowledge for design is available from various sources therefore data organisation is important, e.g. search, access, retrieval, update, and evolution all depend on the source and form of knowledge stored. The information storage and retrieval loops may be facilitated by the development of a web application for accessing and storing this information. This allows the designer to place information on the system and to query the database for data placed on the system by other life cycle actors. In summary product data management facilitates the streamlining of design information over the information loops defined in the PAL life cycle design framework in two ways. Firstly, it supports the storage of life cycle information from all life cycle actors on a common database that is managed and controlled i.e. information storage and retrieval loops. Secondly, it facilitates the live communication between all life cycle actors in the design process i.e. facilitates the collaboration loops [Roc99].

The DFE Workbench software needs also further improvements in terms of coding system and structure. For being able to cope with more information, the codes should be optimised and maybe a more reliable software programme should be used instead of Visual Basic 5.0. Also, the information coming from different sources may be stored in more simple to use database systems such as My SQL databases that allows easy and fast update and data retrieval even when these operations are performed with a web based application.

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Appendix 1

Tables used by the DFE Workbench
Methodology

	ABS	HDPE	LDPE	PC	PP	PPE/PS	PVC	Steel	2^{nd} Steel	Al	2^{nd} Al	Cu	Cu 60%	2^{nd}Cu	Glass	Paper	Recycled paper	Raw Rubber
ABS		2	3	-	2	1	1	1	1	-	1	-	-	-	1	3	3	1
HDPE	-		-	-	-	-	-	-	1	-	1	-	-	-	1	-	3	1
LDPE	-	1		-	1	-	-	-	1	-	1	-	-	-	1	3	3	1
PC	-	-	-		-	-	-	1	1	-	1	-	-	-	1	3	3	1
PP	-	2	-	-		-	-	-	1	-	1	-	-	-	1	3	3	1
PPE/PS	-	2	3	-	2		1	1	1	-	1	-	-	-	1	3	3	1
PVC	-	3	3	-	3	-		1	1	-	1	-	-	-	1	3	3	1
Steel	-	3	3	-	3	-	-		2	-	3	-	-	-	1	3	3	3
2^{nd} Steel	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-
Al	3	3	3	3	3	3	3	1	1		2	-	-	-	1	3	3	1
2^{nd} Al	-	-	-	-	-	-	-	-	1	-		-	-	-	-	-	-	-
Cu 1°	3	3	3	3	3	3	3	1	1	2	2		2	2	1	3	3	1
Cu 60% 2^{nd}	3	3	3	3	3	3	3	1	1	2	2	-		2	1	3	3	1
Cu 2^{nd}	3	3	3	3	3	3	3	1	1	2	2	-	-		1	3	3	1
Glass	-	-	-	-	-	-	-	-	3	-	3	-	-	-		-	3	1
Paper	-	1	-	-	1	-	-	-	1	-	1	-	-	-	1		2	1
Recycled Paper	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-		1
Raw Rubber	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	3	

Table 1. Material Compatibility Chart

	Recyclable	Hazardous	Biodegradable	Recycled	Sustainable
ABS	✔	✔	-	-	-
HDPE	✔	-	-	-	-
LDPE	✔	-	-	-	-
PC	✔	-	-	-	-
PP	✔	✔	-	-	-
PPE/PS	✔	✔	-	-	-
PVC	✔	-	-	-	-
Steel	✔	-	-	-	-
2^{nd} Steel	✔	-	-	✔	-
Al	✔	-	-	-	-
2^{nd} Al	✔	-	-	✔	-
Cu	✔	✔	-	-	-
Cu 60% 2^{nd}	✔	✔	-	✔	-
Cu 2^{nd}	✔	✔	-	✔	-
Glass	✔	-	-	-	✔
Paper	✔	-	✔	-	✔
Recycled Paper	✔	-	✔	✔	✔
Raw Rubber	-	-	-	-	-

Table 2.Material types

Fastening Relationship	Type	Joint Type Code	Permanent	Non-Permanent	Tool Code	Comment
	Metal Fastener				-	
	Philips Head Screw with Insert	PSI		R	P	Clearance must be provided for tools. Good tool/component positioning. Screw insert must be removed for recycling.
	Flat Head Screw with Insert	FSI		R	F	Clearance must be provided for tools. Difficult tool/component positioning. Screw insert must be removed for recycling.
	Philips Head Screw	PS		R	P	Clearance must be provided for tools. Good tool/component positioning.
	Flat Head Screw	FS		R	F	Clearance must be provided for tools. Poor tool/component positioning.
	Screw Insert			R	H&C	
	Rivet	R		NR	Sh, PB	Product is damaged with disassembly, fast method of assembly.
	Spring Clips	SC		R	ST, PB	Very quick and are usually placed over a plastic or steel boss – can be removed with special tools.
	Nut				N.S	
	Bolt With Nut				N,S	
	Plastic Fastener					
	Blind Plastic Rivets	BR		R	S, K	
	Hook	H		R	PB	
	Ratchet Fasteners	RF		R	PB	
	Snap-fit	SF		R	PB	
	Press Fit	PF		NR	PB	
	Adhesives	A	NR		PB	Look for adhesives that are compatible with the material being used. Incompatible materials.
	Welding/Bonding					
	Ultrasonic Welding	UW	NR		PB	Environmentally benign must be similar materials.
	Stud weld	SW	NR		PB	Non-compatible materials
	Moulded in	MW	NR		PB	Non-compatible materials
	Focused Infrared	IW	NR		PB	Compatible materials

Table 3. Joining methods with default disassembly tools used.

Operation	Tool Type	Tool Code	Base Time	Force	Positioning	Total
Screwing Unscrewing	Philips	P	8	3	2	13
	Flathead	F	8	3	6	17
	Nut Driver	N	8	7	8	23
	Socket	S	8	7	7	22
Gripping/ Fixturing	Vice	V	10	7	7	24
	Pliers	Pl	8	7	5	20
	Standard Gripper	SG	8	7	5	20
Cutting Breaking	Knife	K	5	3	1	9
	Shears	SH	5	5	1	11
	Grinder	G	3	2	1	6
	Saw	SA	5	2	1	8
Cleaning	Brush	BR	3	2	1	6
	Cloth	C	3	2	1	6
Other	Hammer & Chisel	H/C	5	2	5	12
	Prybar	PB	3	3	1	7
	De-Solder	DS	5	1	3	9
	Special Tool	ST	3	1	1	5

Table 4 Default task time[1] for each tool type, after [Kro96].

[1] Note that whilst task time is intended to be based on the MOST motion time study methodology as in Hanft and Kroll's approach these values are selected arbitrarily for demonstration purposes.

	Disassembly Time	Disassemblability	Variety of Fasteners	Removal of Hazardous Materials	Hazardous Material Content	Biodegradable Material Content	Recyclable Material Content	Recycled Material Content	Mass of Sustainable Materials	Variety of Materials	Material Compatibility	Mass of materials Labeled	Product Structure	Theoretical Minimum	Modularity
Reuse	√	√	√	√	√								√	√	√
Remanufacture	√	√	√	√	√								√	√	√
Recycling	√	√	√	√	√		√	√	√	√	√	√	√	√	
Disposal				√	√	√				√	√	√			
Environmental Impact				√	√	√	√	√	√	√	√	√		√	

Table 5. Direct relationships between product structural characteristics and end of life strategy

Fastener type	**Tool Code**	**Part Reusable after Disassembly**	**Disassembly time**
Spring clip	ST	√	5
Hook	PB	√	7
Ratchet fasteners	PB	√	7
Snap fit	PB	√	7
Press fit	PB	√	7
Adhesives	PB	x	7
Ultra-sonic welding	PB	x	7
Stud weld	PB	x	7
Moulded in	PB	x	7
Focused infrared	PB	x	7
Solvent bonding	PB	x	7
Blind plastic rivet	K	√	9
De-solder	DS	√	9
Rivet	Sh	x	11
Philips head screw with insert	P	√	13
Philips head screw	P	√	13
Flat head screw with insert	F	√	17
Flat head screw	F	√	17
Blind plastic rivet	S	√	22
Nut	N	√	23
Bolt with nut	N	√	23

Table 6. Ranked disassembly times for particular fastener types

	ABS	HDPE	LDPE	PC	PP	PPE/ PS	PVC	Steel	2^{nd} Steel	Al	2^{nd} Al	Cu	Cu 60%	2^{nd}Cu	Glass	Paper	Recycled Paper	Raw Rubber
ABS		2	3	-	2	1	1	1	1	-	1	-	-	-	1	3	3	1
HDPE	-		-	-	-	-	-	-	1	-	1	-	-	-	1	-	3	1
LDPE	-	1		-	1	-	-	-	1	-	1	-	-	-	1	3	3	1
PC	-	-	-		-	-	-	1	1	-	1	-	-	-	1	3	3	1
PP	-	2	-	-		-	-	-	1	-	1	-	-	-	1	3	3	1
PPE/PS	-	2	3	-	2		1	1	1	-	1	-	-	-	1	3	3	1
PVC	-	3	3	-	3	-		1	1	-	1	-	-	-	1	3	3	1
Steel	-	3	3	-	3	-	-		2	-	3	-	-	-	1	3	3	3
2^{nd} Steel	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-	-	-
Al	3	3	3	3	3	3	3	1	1		2	-	-	-	1	3	3	1
2^{nd} Al	-	-	-	-	-	-	-	-	1	-		-	-	-	-	-	-	-
Cu 1°	3	3	3	3	3	3	3	1	1	2	2		2	2	1	3	3	1
Cu 60% 2^{nd}	3	3	3	3	3	3	3	1	1	2	2	-		2	1	3	3	1
Cu 2^{nd}	3	3	3	3	3	3	3	1	1	2	2	-	-		1	3	3	1
Glass	-	-	-	-	-	-	-	-	3	-	3	-	-	-		-	3	1
Paper	-	1	-	-	1	-	-	-	1	-	1	-	-	-	1		2	1
Recycled Paper	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-		1
Raw Rubber	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	3	

Table 7 Materials with tensile strength compatibility and lower environmental impact, 1 stronger, 2 equal and 3 weaker tensile strength

Appendix 2

Source Codes

Samples of Coding

The sample of coding presented in the current appendix represents the code performing the function of calculating the component removal time in the SAM module.

```
Public Sub initGlobals()

    Dim d1 As Database
    Dim R1 As Recordset
    Dim r As Recordset
    Dim d, DB As Database
    Dim name As String
    Dim lista As String
    Dim timp As Double
End Sub

Public Sub ini()
    path = "D:/Visual/DFEWorkbench"
    frmstart.txtpath.Text = path
End Sub

Private Sub eli()
Module1.ini
path = frmstart.txtpath.Text
    Set d = OpenDatabase(path & "/database/new1.mdb")
    Set r = d.OpenRecordset("SELECT [Joint],[DisassemblyTime] FROM Assemblies WHERE [PartName]='" & name & "'")
    If r.RecordCount > 0 Then
        r.MoveLast
        r.MoveFirst
        lista2 = ""
        While r.EOF = False
            n = r("Joint").Value
            ss = "* " + n + " *"
            b = lista Like ss
            If Not b Then
                lista2 = lista2 + " " + n + " "
                lista = lista + " " + n + " "
                t = r("DisassemblyTime").Value
                timp = timp + t
            End If
            r.MoveNext
        Wend
        r.MoveFirst
        While r.EOF = False
            n = r("Joint").Value
            ss = "* " + n + " *"
            b = lista2 Like ss
            If b Then
                s = name
                name = n
                eli
                name = s
            End If
            r.MoveNext
        Wend
    End If
    Set r = d.OpenRecordset("SELECT [PartName],[DisassemblyTime] FROM Assemblies WHERE [Joint]='" & name & "'")
    If r.RecordCount > 0 Then
        r.MoveLast
        r.MoveFirst
```

```
        While r.EOF = False
            n = r("PartName").Value
            ss = "* " + n + " *"
            b = lista Like ss
            If Not b Then
                t = r("DisassemblyTime").Value
                timp = timp + t
            End If
            r.MoveNext
        Wend
    End If

    Set r = d.OpenRecordset("SELECT [Obstructioner],[DisassemblyTime] FROM Obstructions WHERE [PartName]='" & name & "'")
    If r.RecordCount > 0 Then
        r.MoveLast
        r.MoveFirst
        While r.EOF = False
            n = r("Obstructioner").Value
            ss = "* " + n + " *"
            b = lista Like ss
            If Not b Then
                lista = lista + " " + n + " "
                t = r("DisassemblyTime").Value
                timp = timp + t
            End If
            r.MoveNext
        Wend
    End If
    ss = "* " + name + " *"
    b = lista Like ss
    If Not b Then
        lista = lista + " " + name + " "
    End If
End Sub

Public Sub calculateTime()

    Set d1 = OpenDatabase("D:/Visual/DFEWorkbench/database/new1.mdb")
    Set R1 = d1.OpenRecordset("SELECT * FROM Assembly")
    R1.MoveLast
    R1.MoveFirst
    Do
     name = R1("PartName").Value
     lista = " " + name + " "
     timp = 0
     eli
     R1.Edit
     R1("TotalDisassemblyTime") = timp
     'R1("Obstructions") = lista
     R1.Update
     R1.MoveNext
     If R1.EOF = True Then
        Exit Do
     End If
    Loop
    d1.Close
End Sub
```

Appendix 3

Manuals

Manuals used in the Motorola tests

The current appendix presents the manuals used by the subjects performing the Motorola tests.

Impact Assessment Structure (IAS) Manual.

1. *Select the 'LCA' from the 'Tools' menu.*
2. *Row Material.*

   a). Select the material desired in the table displayed.

   b). Extract the mass of the part being analysed.

   c). Calculate the Eco Indicator for the material chosen by pressing the 'Calculate EcoIndicator' button

   d). Save the values by pressing 'Save' button.
3. *Process.*

   a). Select the process associated with the material saved.

   b). Calculate the Eco Indicator for the process chosen by pressing the 'Calculate EcoIndicator' button.

   c). Save the values by pressing 'Save' button
4. *Use.*

   a). Select the usage associated with the part analysed.

   b). Calculate the Eco Indicator by pressing the 'Calculate EcoIndicator' button.

   c). Save the values by pressing 'Save' button
5. *Transport.*

   a). Select the transport type used from the table displayed.

   b). Insert the distance (in km) on which the part will be transported.

   c). Calculate the Eco Indicator by pressing the 'Calculate EcoIndicator' button

   d). Save the values by pressing 'Save' button.
6. *End Of Life.*

   a). Select the EOL strategy associated with the part analysed.

   b). Calculate the Eco Indicator by pressing the 'Calculate EcoIndicator' button.

   c). Save the values by pressing 'Save' button
7. *Analysis.*

   a). Select 'Show Assembly Components' from the 'Edit' menu.

b). Select the first part displayed in the assembly table. Select the part option and press 'Calculate' button. It will calculate the total EcoIndicator for the part selected.

c). Repeat the step above for all the parts.

d). Select the 'Assembly Options' and press the' Calculate' button. It will calculate the EcoIndicator associated with the entire assembly.

e). For viewing a graphical display of the values press 'Graph' button or choose the desired graph display from the 'Options Menu'.

8. *Advisor.*

A. Assembly

a) In order to find the highest EcoIndicator value in the assembly, select the 'Max' button.

b) For getting advise select the 'Advisor' button.

c) Select the alternative strategies displayed in the table.

d) In order to calculate the Eco indicator associated with the new strategy chosen, press the 'Recalculate' button.

e) A message box will come up asking about saving the changes. If the 'Ok' button is pressed, then the changes will be saved.

f) Closing the Advisor Window , the user will return to the Assembly Window where the same analysis can be repeated for further improvements.

B. Parts

a) In order to find the highest EcoIndicator value in a particular part, select 'Local Maximum' from the 'Options' menu.

b) Select the part to be analysed from the table displayed.

c) For getting advise select the 'Advisor' button.

d) Select the alternative strategies displayed in the table.

e) In order to calculate the Eco indicator associated with the new strategy chosen, press the 'Recalculate' button.

f) A message box will come up asking about saving the changes. If the 'Ok' button is pressed, then the changes will be saved.

g) Closing the Advisor Window, the user will return to the Assembly Window where the same analysis can be repeated.

9. *Reports*

   a) For getting a report for the entire assembly select 'Report Display' from the 'File' menu.

   b) For getting reports for a particular part from the assembly select the part name from the Tree View in the Assembly window. (the report will be displayed by positioning the mouse on the name of the part and pressing the right button of the mouse)

10. *Deleting a particular part.*

   a). Select the part to be removed from the assembly table displayed in the Assembly window.

   b). Press the 'Remove' button. Note: After deleting, the values for that particular part will be lost.)

Structure Assessment Method (SAM) Manual

There are some steps to be followed in order to obtain the desired results with SAM as follows:

1. *Select 'SAM' from the 'Tools' menu.*
2. *Establish all the joints in the assembly*:

   a). Choose from the first Combo Box called 'Parts' the component on which a joint will be set.

   b). Choose from the second Combo Box called 'Parts' the part that will be joined to the component set in a).

   c). Choose the fastener type used for assembling the parts together.

   d). Insert the number of fasteners used for joining the parts identified above, for each fastener type.

   e). To save the settings press the 'Apply' button.

3. *For viewing the table of joints saved go to the 'File' menu, and select the 'Joins Table' instruction.*
4. *For comparing the results save the joints table by pressing the 'Save Joints Table' button.(The table will be saved in an excel format)*
5. *Calculate the disassembly time for the assembly by pressing the 'Disassembly Time' button.*
6. *Edit Obstructions:*

   a). Go to the 'Edit' menu and choose 'Obstructions'.

   b). Select the part obstructed from the first Combo Box.

c). Select from the second Combo box the part that obstructs the part selected above.

d). Save the settings by pressing the 'Apply' button.

e). Repeat the same steps for all the obstruction relationship

7. *Edit the Materials Labels:*

a). Select from the 'Edit' menu the 'Material Labels'.

b). From the first Combo Box choose the part desired.

c). From the second Combo Box choose the appropriate labeling option for the part selected above, i.e. labeled, unlabeled, impossible to label.

d). Save the settings by pressing the 'Ok' button.

8. *Define the components that need to be serviced often :*

a). Select from the 'Edit' menu the 'Serviceability'.

b). From the Combo Box choose the part desired.

c). Save the settings by pressing the 'Ok' button.

9. *Getting Advice:*

A. Hazardous Materials:

a). Select from the 'Advisor' menu 'Hazardous materials'

b). In the window that will appear, select the material you want to replace the hazardous material used in the assembly (the selection will be made by clicking the material desired in the table.)

c). For recalculating the Eco Indicator associated with the new material press 'Calculate'. A message box will appear asking if you want to save the changes. If you press 'Yes' the new material will be saved instead of the hazardous material.

B. Obstructions

a). Select from the 'Advisor' menu 'Obstructions Disassembly Time'.

b). Select the first part by clicking it in the obstruction table.

c). Calculate the disassembly time by pressing the 'Calculate' button.

d). Find the highest disassembly time in the assembly by pressing 'Prioritization' button.

e). Get advice by pressing the 'Advisor'

f). Choose an alternative fastener presented in the table, or ignore by closing the window.

g). If you choose an alternative then insert in the text box the number of the new fasteners used.

h). Calculate the disassembly time by pressing 'Calculate'.

g). Save the new settings by pressing 'Replace'.

h). Repeat the steps above for the next joint.

C. Calculate the percent of the sustainable materials used in the assembly by selecting 'Sustainable Materials' from the advisor menu.

D. Calculate the percent of the recyclable materials used in the assembly by selecting 'Recyclable Materials' from the advisor menu.

E. Calculate the percent of the biodegradable materials used in the assembly by selecting 'Biodegradable Materials' from the advisor menu.

F. Calculate the percent of the recycled materials used in the assembly by selecting 'Recycled Materials' from the advisor menu.

G. Evaluate the Materials Variety by selecting the 'Materials Variety' from the 'Advisor' menu.

H. Labels.

a). Select 'Labeling' from the Advisor menu.

b). Calculate the percentage from the total mass that is not labeled.

c). Pressing 'Calculate' the parts that are not labeled will be displayed.

d). The advisor will highlight the part with the highest mass and unlabeled

e). A window will come up and will allow the user to edit the label for the part highlighted at the step d).

10. Evaluating the components:

a) Select 'Parts Analysis' from the 'Advisor' menu.

b) Choose from the table the desired part in order to calculate the total disassembly time necessary to extract it from the disassembly. (Attention: You have to calculate these times for all the parts)

c) To calculate the disassembly time, press the 'Disassembly Time' button.

d) To choose a different component, press the 'Refresh' button.

e) To make a prioritization of the components on the disassembly time basis, choose 'Prioritization' from 'Analysis' menu.

f) A window will come up highlighting the component with the highest disassembly time. The components that need service often will have the highest priority. Then the components will be prioritized in disassembly time order.

g) Pressing the 'Advisor' button a window will come up highlighting the fasteners used in the part identified in the 'Prioritization' stage.

h) Select the fastener for which you want to find an alternative with a lower disassembly time and press 'Display Alternatives'.

i) Select a new fastener to replace the selected one in the step h). or ignore by closing the window.

11. Generate reports.

a) To generate a report select 'Generate Report' from the 'Tools' menu.

b) A window with a report will come up. To print the report select 'Print' from the 'File' menu.

12. Different types of materials can be found with the help of the 'Search Engine'.

a). Select 'Search Engine' from the 'Tools' menu.

b). Select the material for which you want to find alternatives.

c). Check the desired properties in the Options frame.

d). Press the 'Find' button.

e). From the result table pick the material you want.

f). Choose the part from the Combo Box, where you want to change the material.

g). To calculate the Eco Indicator associated with the new material press the 'Calculate' button.

h). To save the desired material press the 'Replace' button.

Appendix 4

Extract from the databases used by the DFE
Workbench Software Tool

ID	Name	Type	Unit	Info
1	ABS	1	kg	High energy input for production, therefore high emission output.
2	Aluminium	1	kg	Containing an average of 20% recycled material.
3	Cu60%Primary	1	kg	Normal proportion secondary and primary copper.
4	CuPrimary	1	kg	Primary electrolytic copper from relatively modern American factories.
5	CuSecondary	1	kg	100% sec. copper, (not easy to obtain!).
6	Glass	1	kg	57% secondary glass.
7	HDPE	1	kg	Relatively simple production process.
8	LDPE	1	kg	Score possibly flattered by lack of CFC emission.
9	NaturalRubberProduct	1	kg	Vulcanised with 28% carbon black; used for truck tyres.
10	Paper	1	kg	Chlorine-free bleaching, normal quality.
11	PC	1	kg	High energy input for production, therefore high emission output.
12	PP	1	kg	Relatively simple production process.
13	PPEandPS	1	kg	A commonly used blend, identical to PPO/PS.
14	PUR	1	kg	For furniture, bedding, clothing, leisure goods (water blown).
15	PURfoam	1	kg	Used in dashboards (pentane blown).
16	PVC	1	kg	Calculated as pure PVC, without addition of stabilisers or plasticizers.
17	RawNaturalRubber	1	kg	Dried en baled natural rubber from latex, for vulcanisation.
18	RecycledPaper	1	kg	Unbleached, 100% waste paper.
19	SecondaryAl	1	kg	Made completely from secondary material (not easy to obtain!).
20	SecondarySteel	1	kg	Block material made from 100% scrap.
21	Steel	1	kg	Block material with average 20 % scrap.

Table 1. Raw Materials Table

Ei-95,mPt	Weight,kg	Hazardous	Density,kg/m^3	Sustainable	Recyclable
9.3	1	H	1040	N	R
18	1	N	2710	N	R
60	1	H	8900	N	R
85	1	H	8900	N	R
23	1	H	8900	N	R
2.1	1	N	2600	N	R
2.9	1	N	930	N	R
3.8	1	N	920	N	R
4.3	1	N	0	S	R
3.3	1	N	950	S	R
13	1	N	1200	N	R
3.3	1	H	900	N	R
5.8	1	H	1060	N	R
5.8	1	N	1150	N	R
6.9	1	N	32.03	N	R
4.2	1	N	1380	N	R
1.5	1	N	1200	S	R
1.5	1	N	950	S	R
1.8	1	N	2710	N	R
1.3	1	N	7850	N	R
4.1	1	N	7850	N	R

ID	Name	Type	Unit
1	BlankingAndCutting	2	m
2	Bending	2	m
3	Rolling(cold)1	2	m2
4	Spot-welding1	2	pc
5	Machining1	2	kg
6	Machining2	2	cm3
7	Extrusion	2	kg
8	InjectionMouldingGgeneral	2	kg
9	InjectionMouldingPVCandPC	2	kg
10	RIM,PUR	2	kg
11	ExtrusionBlowingPE	2	kg
12	VacuumForming	2	kg
13	VacuumPressureForming	2	kg
14	CalanderingOfPVC	2	kg
15	FoilBlowingPE	2	m2
16	UltrasonicWelding	2	m
17	Machining3	2	cm3
18	BendingSteel	2	m
19	BendingStainlessSteel	2	m
20	CuttingSteel	2	m
21	CuttingStainlessSteel	2	m
22	PressingAndDeepDrawing	2	kg
23	Rolling(cold)2	2	m2
24	Spot-welding2	2	pc
25	Machining4	2	kg
26	Machining5	2	cm3
27	Hot-galvanising	2	m2
28	ElectrolyticGalvanising	2	m2
29	Electroplating(chrome)	2	m2

Table 2. Processes Data Table

Info	Ei-95,mPt	Density,kg/m^3
Length of the cut in a sheet 1 mm thick.	0.00092	0
Length of the fold of a sheet 1 mm thick. 90° folding.	0.0012	0
Per pass.	0.28	0
Per weld of 7 mm diameter, sheet thickness 2 mm.	0.068	0
Per kilo machined material ! (turning, milling, boring).	0.12	0
Per cm3 machined material ! (turning, milling, boring).	0.00033	0
	2	0
May also be used as estimate for extrusion	0.53	0
May also be used as estimate for extrusion.	1.1	0
	0.3	0
For bottles and such like.	0.72	0
	0.23	0
	0.16	0
	0.43	0
Per m2, thin foil (for bags).	0.03	0
Per metre weld length.	0.0025	0
Per cm3 machined material.	0.00016	0
Length of the fold of a sheet 1 mm thick, 90° folding.	0.0021	0
Length of the fold of a sheet 1 mm thick, 90° folding.	0.0029	0
Length of the cut in a sheet 1 mm thick.	0.0015	0
Length of the cut in a sheet 1 mm thick.	0.0022	0
Per kilo deformed steel, do not include non-deformed parts!	0.58	0
Per pass.	0.46	0
Per weld of 7 mm diameter, sheet thickness 2 mm	0.0074	0
Per kilo machined material ! (turning, milling, boring).	0.42	7800
Per cm3 machined material ! (turning, milling, boring).	0.0033	0
10 micrometres, double-sided; data fairly unreliable .	17	0
2.5 micrometres, double-sided; data fairly unreliable.	22	0
1 micrometre thick; double-sided; data fairly unreliable.	70	0

ID	Name	Type	Unit	Info	Ei-95,mPt
1	ElectricityHighVolta	3	kWh	For industrial use.	0.57
2	ElectricityLowVolta	3	kWh	For consumer use (230V).	0.67
3	HeatFromGas	3	MJ	Per MJ heat.	0.063
4	HeatFromOil	3	MJ	Per MJ heat.	0.15
5	Mechanical(diesel)	3	MJ	Per MJ mechanical energy from a diesel engine.	0.17
6	None	3	no unit	none	0

Table 3. Use Data Table

ID	Name	Type	Unit	Info	Ei-95,mPt
1	Truck(28 ton)	4	tkm	60% loading, European average.	0.34
2	Truck(75 m3)	4	m3km	60% loading, European average.	0.13
3	Train	4	tkm	European average for diesel and electric traction.	0.043
4	ContainerShip	4	tkm	Fast ship, with relatively high fuel consumption.	0.056
5	Aircraft(continental)	4	kg	Per kg ! With continental flights the distance is not relevant.	1.7
6	Aircraft(intercont.)	4	tkm		0.81

Table 4. Transport Data Table

ID	Name	Type	Unit	Info	Ei-95,mPt	Weight,kg
1	Glass1	6	kg	Processing of waste by average Dutch municipality. 37% incinerated, 63% landfilled.	0.35	1
2	Ceramics1	6	kg	Processing of waste by average Dutch municipality. 37% incinerated, 63% landfilled.	0.041	1
3	Plastics and rubber1	6	kg	Processing of waste by average Dutch municipality. 37% incinerated, 63% landfilled.	0.69	1
4	PVC1	6	kg	Processing of waste by average Dutch municipality. 37% incinerated, 63% landfilled.	2.6	1
5	Paper and cardboard1	6	kg	Processing of waste by average Dutch municipality. 37% incinerated, 63% landfilled.	0.33	1
6	Steel and iron1	6	kg	Processing of waste by average Dutch municipality. 37% incinerated, from which 70% is recovered, 63% landfilled.	1.2	1
7	Aluminium1	6	kg	Processing of waste by average Dutch municipality. 37% incinerated (30% recovery), 63% landfilled.	-3	1
8	Copper1	6	kg	Processing of waste by average Dutch municipality. 37% incinerated (30% recovery), 63% landfilled.	-2.6	1

Table 5. Extract from End of Life Data Table

Materials	EI-95 Materials	Hazardous	Density	Priority E against density	Process	Unit	EI-95 Process	EOL	EI-95 EOL	Priority strength against density	Recyclable	Bio-degradable	Recycled	Sustainable
HDPE	2.9	N	930	3	Extrusion	kg	2	Municipal Waste	0.69	2	R	N	N	N
LDPE	3.8	N	920	3	Injection Moulding	kg	0.53	Domestic Waste	0.66	3	R	N	N	N
PC	13	N	1200	2	Machining	kg	0	Recycling	-6.2	1	R	N	N	N
PP	3.3	H	900	3			0	Landfill	0.04	2	R	N	N	N
PPEandPS	5.8	H	1060	1			0	Incineration	1.8	3	R	N	N	N
PVC	4.2	N	1380	3			0			3	R	N	N	N

Table 6. Sample of Material Data Table. Properties associated with ABS.

Joining Method	Symbol	Tool	Comment	Disassembly Time
Adhesive	A	Prybar	Look for adhesives that are compatible with the material being used.	7
BlindPlasticRivets	BR	Knife		9
BoltWithNut	BN	NutDriver		23
FlatHeadScrew	FS	Flathead	Clearance must be provided for tools. Poor tool/component positioning.	17
FlatHeadScrewWithInsert	FSI	Flathead	Clearance must be provided for tools. Dificult tool/component positioning.	17
FocusedInfrared	IW	Prybar	Compatible Materials	7
Hook	H	Prybar		7
MouldedIn	MW	Prybar	Non Compatible Materials	7
Nut	N	NutDriver		23
PhilipsHeadScrew	PS	Philips	Clearance must be provided for tools. Good tool/component positioning.	13
PhilipsHeadScrewWithInsert	PSI	Philips	Clearance must be provided for tools. Good tool/component positioning.	13
PressFit	PF	Prybar	not available	7
Ratchetfasteners	RF	Prybar	not available	7
Rivet	R	Shears	Product is damaged with disassembly, fast method of assembly	11
ScrewInsert	SI	HammerAndChisel		12
SnapFit	SF	Prybar		7
SolderWeld	SO	Desolder		9
SolventBonding	SB	Prybar	Good for joining similar materials as bonding does not modify materials properties.	7
SpringClips	SC	SpecialTool	Very quick and are usually placed over a plastic or steel boss - can be removed with special tools.	5
StudWeld	SW	Prybar	Non Compatible Materials.	7
UltrasonicWelding	UW	Prybar	Environmentally acceptable must be the same materials.	7

Table 7. Fasteners Data Table

Operation	Tool	Symbol	BaseTime	Force	Positioning	Total
Cleaning	Brush	BR	3	2	1	6
Other	Desolder	DS	6	2	1	9
Screwing/Unscrewin	Flathead	F	8	3	6	17
Cutting/Breaking	Grinder	G	3	2	1	6
Other	HammerAndChisel	H&C	5	2	5	12
Cutting/Breaking	Knife	K	5	3	1	9
	Manual	M	4	1	0	5
Screwing/Unscrewin	NutDriver	N	8	7	8	23
Screwing/Unscrewin	Philips	P	8	3	2	13
Gripping/Fixturing	Pliers	Pl	8	7	5	20
Other	Prybar	PB	3	3	1	7
Cleaning	Rag	RG	3	2	1	6
Cutting/Breaking	Saw	SA	5	2	1	8
Cutting/Breaking	Shears	SH	5	5	1	11
Screwing/Unscrewin	Socket	S	8	7	7	22
Other	SpecialTool	ST	3	1	1	5
Gripping/Fixturing	StandardGripper	SG	8	7	5	20
Gripping/Fixturing	Vice	V	10	7	7	24

Table 8. Fastener's disassembly times

Joining Method	Symbol	Tool	Comment	DisassemblyTime
Adhesive	A	Prybar	Look for adhesives that are compatible with the material being used. See compatibility.	7
Ultrasonic Welding	UW	Prybar	Environmentally acceptable must be the same materials.	7
Stud Weld	SW	Prybar	Non Compatible Materials.	7
Molded In	MW	Prybar	Non Compatible Materials	7
Focused Infrared	IW	Prybar	Compatible Materials	7
Solvent Bonding	SB	Prybar	Good for joining similar materials as bonding does not modify materials properties, but is also used for joining dissimilar materials	7
Solder Weld	SO	Desolder		9

Table 9. Permanent fastening methods