Implementation of design for environment principles in product development using a case study on the design of a passenger car door

Mathur, Nehika

IMPLEMENTATION OF DESIGN FOR ENVIRONMENT PRINCIPLES IN PRODUCT DEVELOPMENT USING A CASE STUDY ON THE DESIGN OF A PASSENGER CAR DOOR

MSc (R) Dissertation by

Nehika MATHUR

School of Engineering

University of Durham

Table of Contents

Declaration

I confirm that no part of the material offered in this thesis has previously been submitted by me for a degree in this or any other university. This thesis presents the author's own work, except where appropriately acknowledged citations are given. Where material has been generated through joint work, my independent contribution has been clearly indicated.

Nehika MATHUR

School of Engineering

University of Durham

Copyright Notice

Nehika MATHUR

School of Engineering

University of Durham

Acknowledegements

I am grateful to Professor P. G. Maropoulos for introducing me to the subject of Knowledgement Management and to Dr. Peter Matthews for supervising my thesis work. I am indebted to Dr. Peter Matthews for his valuable advice, timely suggestions and encouragement during the course of this work. I am also grateful to all the staff and faculty of the School of Engineering, Durham University for providing me with an opportunity to pursue a master's degree programme. Financial support from the VRL-KCIP is gratefully acknowledged. My flatmates at Ustinov College made my stay there pleasant and exciting. Last but not least I am thankful to my parents and sister for their constant support.

Abstract

Product design is a complex process that requires design engineers taking into consideration a number of factors simultaneously. Though the primary aim is to fulfil a given function in a cost effective manner, in recent years considerable emphasis has been placed on designing products that result in minimal negative environmental impact. In the past, research has focussed on developing tools that assist designers in selecting suitable materials and manufacturing processes in the early stages of product design itself. A correct choice of materials can have a significant impact on promoting Design for Environment (DfE) and determining suitable End of Life (EoL) strategies such as recycling, reuse and remanufacture. This dissertation highlights the importance of implementing design aspects such as Design for Assembly (DfA) and Design for Disassembly (DfD). Included is a case study which illustrates the benefits of implementing DfD in the design of a passenger car door. Through a prudent selection of suitable materials, manufacturing processes and also joining and dismantling techniques, the overall sustainability of the product can been increased. It is seen that in order to incorporate DfE principles in product design, the designers must deal with vast amounts of data simultaneously. Dealing with such large quantities of data can be tricky. This dissertation proposes arranging materials, manufacturing processes and assembly and disassembly techniques in the form of an ontology so that designers can have access to design information in a systematic and precise format. The principles to construct a DfE tool that assists design engineers not only select suitable materials, manufacturing processes and assembly/disassembly methods, but also helps analyse every stage of the product's life and measure its impact on the environment during the initial stages of design itself have been provided in this dissertation.

1 Introduction

Designing products in order to minimise their impact on the environment has become increasingly important. Although in the last two decades manufacturers have focussed on production processes and environmental regulation has concentrated on pollution from industry, there is growing awareness that more can be done to reduce the overall impact on the environment. In this context, it has been recognised that the use and disposal phases, as well as the production phase of the product lifecycle are important. Moreover, as environmental regulations by governments and consumer pressure towards green design steadily increase, manufacturers are being forced to take steps that ensure the recovery of products and materials at the end of their useful lives. In order to implement safe disposal and recycling of used products, it is clear that a new approach to product design is required, one which produces a product by taking into account all the stages of its lifecycle [1].

Traditionally, issues considered in product design have related only to function, appearance and financial concerns. However, as decisions made by designers have a direct effect on the amount of raw material used, the amount of energy consumed and pollution produced by a product during its lifetime, it is important that design engineers are provided with the appropriate tools to enable the minimisation of the effect their products have on the environment. This is why the concept of Design for Environment (DfE) is increasingly gaining importance [1].

DfE is known by various other names such as green design, eco-design, sustainable design, environmentally conscious design, lifecycle design, lifecycle engineering as well as clean design. The main purpose of eco-design is to create products and services for achieving a sustainable society. This however is extremely challenging as design engineers must not just take into account environmental considerations, but also economics, technological possibilities and limitation and the needs and benefits of the customer without compromising the functionality, quality, cost and appearance of the product [2].

Although environmental issues are important and ought to be addressed, the time constraints and deadlines in the industrial design world dictate that these issues cannot consume too much of the product development design process time budget. Environmental activities simply must fit in with all the others, especially the high-priority activities relating to functionality and commercial viability. It is therefore clear that environmental issues and demands must be integrated into the early stages of product-development process itself.

The objective of this dissertation is to provide principles for a new DfE methodology that can help support concrete means to integrate environmental considerations along with other factors in the early product development phase so as to help designers minimise the overall impact of the product on the environment. The implementation of DfE principles is demonstrated through a case study designing a passenger car door. The proposed design methodology aims to provide the designer with a solution that optimises not just cost and functionality issues, but also DfE issues. The benefits of using such a design tool, namely, increase in profitability through increase in recyclability, remanufacture have been enumerated in the later part of this dissertation.

In the past, tremendous amount of work has been carried out in the area of DfE. A vast literature review of past work has been outlined in the Literature Review in Chapter 2. Problems faced by designers have been determined and the priciples to develop a design methodology in order to overcome these difficulties has been proposed in Chapter 3. The principles of DfE and the implementation of these principles in a proposed design methodology are outlined in Chapter 4. The case study in Chapter 5 illustrates the benefits and relevance of this design methodology. A detailed comparison of the design procedure with and without the use of the proposed DfE principles has been given in Chapter 5. The case study proves that environmental considerations can indeed be integrated successfully in the early stages of design. However, since DfE is a vast subject of research and a number of factors other than those discussed in this thesis are currently being examined by various other researchers. The concluding chapter examines the shortcomings of the design tool proposed and the future scope in the area of development of DfE tools.

2 Literature Review

2.1 Product Development and Design

Product development is considered to be a multi-facetted activity in industry, characterised by a large organisation, the involvement of many people, and various departments in the company such as research, design, production, marketing and management.

Many researchers have developed product development process models. The most common way of representing the product-development process is as a chain of tasks or events with milestones and decisions [3, 4, 5]. These all describe a few main steps that have to be carried out during the design process.

The product development process is characterised by analysis and synthesis in an iterative manner on different levels of detail [4]. In short, design work always starts with an analytical phase [4] where the problem is understood and the overall objective is clarified. Once the problem analysis has been completed, a requirements specification should be established and concepts are generated. This is then the synthesis phase. The next step involves evaluations conducted by the means of calculations, computer simulations or prototype testing – analysis phase. The predicted or measured product performance and properties are then compared to the specification and the synthesis and analysis is iterated until the result is satisfactory. The evaluation comprises decisions on design matters such as further analyses, modified or new concepts, production methods etc.

A total design process can be described as follows [4]:

> "All design starts, or should start with, need that, when satisfied, will fit into an existing market, or create a market of its own. From a statement of the need – often called the brief – a product design specification (PDS) must be formulated – the specification of the product to be designed. Once it is established, it acts as the mantle or cloak that envelops all the subsequent

stages in the design core. The PDS thus acts as a control for the total design activity because it places the boundaries on the subsequent designs. Conceptual design is carried out within the envelop of the PDS, and applies to all succeeding stages until the end of the core activity."

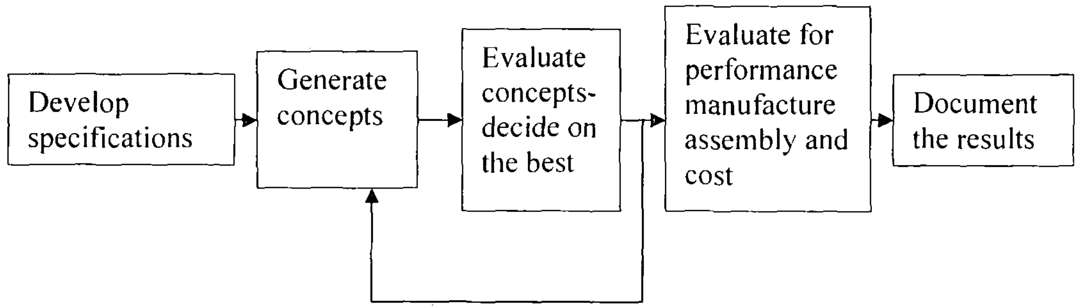

Figure 2.1: The design process can be represented as a chain of tasks [3]

Almost all models of the product development process appear in sequential flowchart (Figure 2.1) form. However, in reality it is neither so smooth nor continuous. Real-life design is executed in iterative fashion and is being continuously researched.

When designing a completely new product, the knowledge at the outset is small but there is also great amount of freedom to design the product. This is referred to as the early product design phase. The process starts with a given need to be fulfilled and the goal is to find design concepts for a product or component that satisfies these. Information about the product increases as the design develops. However this happens at the cost of design freedom. When reaching an intellectual breakeven (Figure 2.2) a concept of the new product is normally established. This phase can be called the intermediate design phase. By the end of the process the knowledge of the product is greatest but the possibilities for changing the design are small. Global design decisions are already taken and only minor changes can be made. Major changes are no longer possible, though smaller improvements such as adaptations to suit manufacturing processes and "cosmetic" changes to the shape and assembly refinements can be made. Design freedom is very limited and the principles and other global design decisions are no longer issues. These stages are called late product design phases. However, different product development projects have different starting points and most development work is actually performed in the later part of the product development phases.

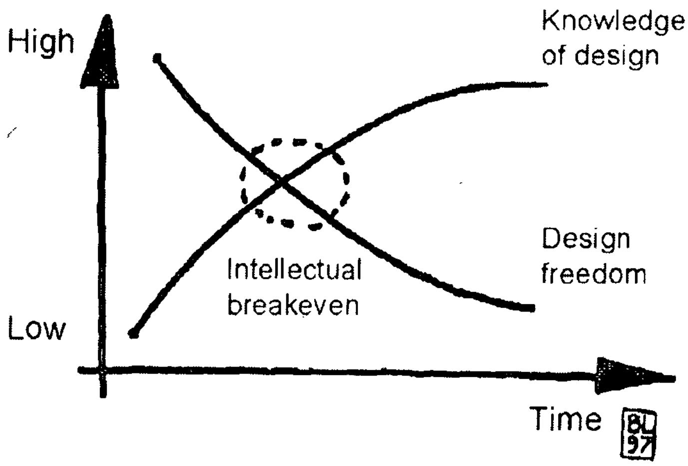

Figure 2.2: The Design Paradox [6]

Effective product development calls for decisions in early phases of product development process. Early product development phases are however challenged by poorly defined product concepts and ideas. This is because frequently important characteristics are not yet known and many options have to be evaluated. Lack of information, creative thinking and high level ambiguity are factors characterising early design phases. The design engineer should therefore learn as much about the evolving product as early as possible in the design process.

2.1.1 Product Design Requirements:

As mentioned previously, product development and design requires the consideration of a number of different aspects. Customer needs, functional requirements and technical constraints are examples of factors that must be taken into account during the early stages of product development. The seven major types of customer requirements are:

- functional-performance
- human-factor

- physical-factor
- reliability
- lifecycle
- resource
- manufacturing requirements

Therefore, even though environmental requirements are important there are a number of competing demands that also have to be taken into consideration and design solutions must seek a balance between all of these competing requirements [6].

2.2 Design for 'X'

Due to fierce competition, product developers no longer look to optimise the design with respect to just the primary functional requirements of the product. In order for their products to stay in market, product designers must ensure that the product excels in other aspects as such as cost, quality, reliability and environmental impact. Experience has demonstrated that with challenges in process (either manufacturing or assembly products); it is best to address the core problem and take efforts to improve the product rather than reacting to the symptoms.

Design for X is an integrated approach to designing products and processes for cost-effective, high quality lifecycle management [5]. Design for X, or DfX, tools help to shift the emphasis of the important design decisions to the start of the development process. In order to support the additional requirements of product designers, a variety of DfX methodologies have been developed to help achieve the diverse product requirements. These include Design for Assembly, Design for Process, Design for Serviceability, Design for Disassembly, Design for Recyclability, Design for Product Variety, Design for Supply Chain and Design for Environment.

2.2.1 The DfX's of Design for Environment:

As mentioned earlier, there are many 'Design for' topics, which can be summed up as DfX's. Two that come under DfE are Design for Disassembly (DfD) and Design for Recycling (DfR). However, another important area to study is Design for Assembly (DfA), as all manufacturing design processes investigate DfA methods. Figure 2.2 illustrates the development of DfX's over time. Until recently, designers concentrated on only developing a product without considering the end of life implications. However, in recent years, Design for Environment (DfE), Design for Disassembly (DfD) and Design for Remanufacture (DfR) have started being incorporated into the early design stages.

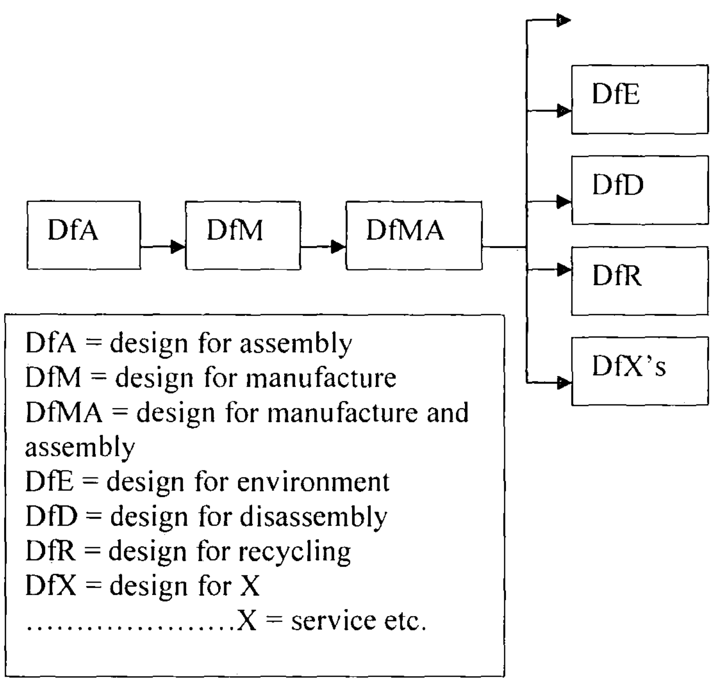

Figure 2.3: The sequence of the development of the DfX's [7]

With regard to DfA, it is useful to know criteria against which components must be examined. These are [7, 8]:

- During operation of the product, does the part move relative to all other parts already assembled? Only gross motion should be considered; small motions can be accommodated by other means such as integral elastic elements [7, 8].

- Must the part be of a different material than or isolated from all other parts already assembled? Only fundamental physical needs for material differences are acceptable [7, 8].
- Must the part be separate from all other parts already assembled? The only reason to have it separate would be that assembly or disassembly of other separate parts would be impossible [7, 8].

DfMA includes the foregoing criteria and also the following points [7]:

- Avoid unnecessary tight tolerances, and design tolerances to the middle of the range desired [7].
- Use modular constructions thereby giving building block assemblies [7].
- Design for ease of service [7].

Although DfMA seeks to optimise all the above criteria, it does not always lead to economic and easy DfD. Design for Disassembly requires that a product and its parts can be easily reused, remanufactured or recycled at the end of life. To do this the designer has to take into account product disassembly at the start of the product's design stage. DfD is part of the recycling stream and it is either a precursor or parallel to recycling and remanufacture. In addition, in order to have an efficient, cost effective disassembly system in place.

2.3 Design for Environment (DfE)

Design for Environment (DfE) is defined as the systematic consideration of design performance with respect to environmental health and safety objectives over the full product and process lifecycle [9]. Although there exist several other definitions of DfE, the scope of work of DfE includes management of the environment, product safety, occupational health and safety, pollution prevention, ecology, resource conservation, accident prevention and waste management, with a focus on product development [10, 11, 12]. As a generalisation, DfE covers any design activity, which aims at improving the environmental performance of a product [13]. There are several available tools and methods that have been developed in order to implement DfE. These range from general to specific tools, which focus on parts of the lifecycle or on certain types of products or services. Some methods are aimed at decision support early in the design process while others are aimed at use during the detailed design phase [13]. Methods and tools developed for DfE are discussed in detail in Chapter 4.

The eight aspects identified by Hill [14] that should be included in design for environment are:

- Manufacture without producing hazardous waste
- Use of clean technologies
- Reduce chemical emissions
- Reduce product energy consumption
- Use of non-hazardous recyclable materials
- Use of recycled material and reused components
- Design for ease of disassembly
- Product reuse or recycling at end of life

However, these eight aspects involve lengthy analysis and can deter designers from considering using such as technique. DfE can therefore be divided into three components for design [15]:

- Process design
- Material design
- Energy consumption design

Process design is concerned with reduction of energy consumption and minimisation of wastes and pollution processes. Material design focuses on the selection and use of raw materials to minimise hazardous wastes, amount and type of pollution emitted, and the total amount of material required. Energy consumption design is the selection of materials and processes, which result in a reduction of the product's energy requirement when being manufactured or used [16].

DfE encompasses many issues including Design for Disassembly and Design for Recycling. An important DfE strategy aimed at minimising end-of-life impacts is remanufacturing; products need to be designed to be viable for cost-effective remanufacture, reuse and to reduce the amount of waste going to landfills. With the right remanufacturing process in place, remanufacturing can be profitable for mass produced products provided that sufficient quantities of mass-produced products will be viable for remanufacturing [17].

In order to help designers focus on development of environmentally benign products, Lagerstedt [6] suggests a set of DfE rules, which summarize the guidance given by various DfE methods and tools. These are especially helpful with respect to mass produced products. The guidelines are as follows:

- Do not use toxic substances, and use closed loops when possible i.e. making sure product components are reused even after fulfilling their primary functions.
- Minimise energy and material consumption in production and transportation by striving for efficiencies.
- Minimise energy and resource consumption in the use stage, especially for products with their most significant environmental aspects in the use stage.
- Promote maintenance, especially for system dependent products.
- Promote long life, especially for products with their most significant environmental impacts outside the use stage.
- Use structural features and high quality materials, to minimise weight; these should not interfere with flexibility, impact strength or functional properties.
- Use better materials, surface treatments or structural arrangements to protect products from dirt, corrosion and wear.
- Arrange in advance for upgrading, repair and recycling, through good access, labelling, modules and breakpoints, and provide good manuals.
- Promote upgrading, repair and recycling, by using few, simple, recycled, unblended materials, and do not use alloys.
- Use the minimum joining elements possible, using screws, adhesives, welding, snap fits, geometric locking, etc. according to Life Cycle guidelines.

On the whole, these guidelines focus mainly on disposal of products, the use and selection of materials in the product life cycle and on longer product life. The disposal of products and use of materials have their background in the waste generation. Apart from that, exploitation of limited and non-renewable resources also plays a role. In this context, it can be concluded that biomaterials are good as they are renewable and we can harvest them without jeopardizing their availability to future generations. On the other hand, composites cannot be separated into their original materials and the potential for recycling is therefore low. The waste hierarchy adopted for reducing waste problems recommends giving the highest priority to reuse and then to recycle or recover before land filling the waste. By closing the circle one can turn the used products into new products and reduce the generation of waste.

The focus on longer product life through design for durability, maintenance or remanufacture and extension of life is also rooted on the material content of the products. The longer the life of the product, the fewer the materials used for producing a new product and lower is the environmental impact [13].

In order to achieve environmental-product improvements, DFE must adapt to and become a natural part of the product-development process. This should be done as early as possible as early product development phases are believed to have the most influence in defining environmental aspects of products [6]. This however is difficult as conceptual design creates challenges for incorporating a life cycle design approach that combines functional and environmental assessment. Detailed information is not often available, high level decisions must be made quickly and product designers generally lack the environmental expertise or the necessary time to meaningfully address environmental issues along with other traditional design considerations. Figure 2.2 represents the design paradox that designers hope to overcome.

At the end of the design process the design freedom is very limited. This means that only small changes can be made.

For successful direction of DfE, product designers have to be provided with environmental support through various tools or results of environmental assessments and guidelines. Communication of these results is usually done by presenting charts and diagrams containing highly aggregated data. This information has to be treated together with the information on all the other product demands. In order to achieve benefits for the environment, environmental information has to be carefully selected and clearly communicated. Information should be kept as simple as possible [6]. Hauschild [13] therefore suggests guidelines that would help design engineers get the focus right for product development in order to successfully implement DfE.

2.4 Implementation of DfE

In order to successfully implement the principles of DfE eco-design methods such as Life Cycle Assessment (LCA) and Environmental Effect Analysis (EEA) have been developed. These are essentially detailed reports of the overall environmental effects of a given product. However, LCA and EEA methodologies do differ to an extent. These are discussed in further detail below.

2.4.1 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is one of the most commonly used eco-design methods. LCA is a process whereby environmental impacts from the inventory are assessed, and the overall environmental performance of the product is determined. The primary objective of LCA as stated by The Society of Environmental Toxicology and Chemistry (SETAC) 1993 is "to provide decision-makers with information which defines environmental effects of industrial activities and identifies opportunities for environmental improvement [18]."

Life cycle assessment is also known as the cradle-to-grave approach. Cradle-to-grave approach involves the gathering of raw materials from the earth to create the product and end at the point where all the materials are returned to earth. LCA evaluates all stages of the product's life from the perspective that they are interdependent i.e. one operation leads to the next. LCA enables the estimation of the cumulative environmental impacts results from all the stages in the product life cycle, often including impacts not considered in a more traditional analyses (e.g. raw material extraction, material transportation, ultimate product disposal etc.). The term 'life cycle' refers to the major activities in the course of the product's lifespan from its manufacture, use, maintenance and final disposal; including raw material acquisition required to manufacture of the product.

Therefore, with LCA, it is possible to compare [18]:

- various end of life processes for a product,
- various materials and their measure of reusability/ remanufacturability,
- various systems of products distribution, and
- various manufacturing processes.

This is done in the course of the three stages described below [6]:

- Goal-setting: This is regarded as the most important stage as the whole assessment is based on the outcomes determined at this step. Goal setting presents a qualitative description of the issue and the purpose behind LCA. This description must declare where and how the study will be performed and the results will be used for. An important part of goal setting is to define system boundaries and a functional unit (FU). A FU expresses how the new product benefits the customer [17]. The FU is derived from the main function of the product.
- Life-cycle Inventory (LCI): This is an objective process, which identifies and quantifies energy and material flows within the system boundaries. This data provides an overview of the information concerning the impact on the environment. This data, however, does not detail the effects caused by these impacts.
- Life-cycle assessment: This stage is also called Impact Analysis and involves undertaking a systematic evaluation of the inventory. The results of the inventory are translated into readily understandable figures, diagrams or indices, mirroring the effects of the environmental impacts identified in the inventory.

LCAs might be conducted by an industry sector to enable it to identify areas where improvements can be made, in environmental terms. Alternatively the LCA may be intended to provide environmental data for the public or government. In recent years, a number of major companies have cited LCAs in their marketing and advertising, to support claims that their products are environmentally friendly to those of their rival. However, many environmentalists have challenged these claims made by companies. By standardising a particular methodology, the standards of 'green design' will be kept more or less uniform, thus giving not just industry, but also consumers a better idea of the measure of environmental friendliness of a given product in comparison to one that is being sold by a rival company [19, 20].

All products have some impact on the environment. Since some products use more resources, cause more pollution or generate more waste than others, the aim is to identify those which are most harmful and use only less polluting substances.

Even for those products whose environmental burdens are relatively low, the LCA helps identify those stages in production processes and in use, which cause or have the potential to cause pollution, and those which have heavy material or energy demand.

Breaking down the manufacturing process into fine detail can also aid to identifying the use of scarce resources, showing where a more sustainable product could be submitted.

Although incorporating life cycle thinking into a new product makes sense, many of the life cycle tools developed are for a specific category of products with a predetermined list of issues to consider. The tools currently available are applicable to existing products with well-defined compositions and known characteristics. Quite often there is detailed information available on at least one manufacturing process actually in operation when lifecycle analysis is applied to products, which have been commercialised.

The process for new product development is often described in stages, which typically include concept, feasibility, development, commercialisation and established business stages. Companies may have more or less stages and define the boundaries between stages differently. Typically it is during the development stage that the company begins significant investment. The investment may peak during the development stage or later stages depending on the product. As one proceeds to commercialisation, more information relevant to lifecycle analysis and risk becomes available. More of the information is quantified and less uncertainty exists in the quantified information.

The aim of performing an LCA is to help designers select the product or process that result in the least impact to the environment. Factors such as cost and performance can also be incorporated with the LCA while selecting a product or process. LCA data can identify the transfer of environmental impacts from one media to another (e.g. eliminating air emissions by creating a wastewater effluent instead) and/or from one lifecycle to another (e.g. from use and reuse of the product to the raw material acquisition phase). If an LCA is not performed, the transfer may not be recognised and properly included in the analysis as it might be outside the typical scope or focus of product selection processes.

Performing an LCA helps designers:

- Develop a systematic evaluation of the environmental consequences associated with a given product.
- Analyse the environmental trade-offs associated with one or more specific products/processes to help gain acceptance for a planned action.
- Quantify environmental releases to air, water, and land in relation to each life cycle stage and/or major contributing process.
- Assist in identifying significant shifts in environmental impacts between life cycle stages and environmental media.
- Assess the human and ecological effects of material consumption and environmental releases to the local community, region and world.

- Compare the health and ecological impacts between the two or more rival products/processes or identify the impacts of a specific product or process.

- Identify impacts to one or more specific areas of environmental concern.

LCA reveals materials and energy flows upstream and downstream that could have been unseen by other methods. It also gives decision support for new, effective ways to fulfil the desired product specifications with less total environmental impact. An LCA can serve as a basis for making checklists/guidelines for use in Design for Environment efforts. It can also be used as a basis for learning and dialogue about the relative importance of different environmental aspects. LCA makes it possible to compare the environmental performance for different forms of solutions [20].

On the other hand, however, performing an LCA on a new product/process is costly and difficult. Data are often missing or have low quality and therefore much of the LCA activities must be based on short series of measures, theoretical calculations and estimations. In order to make a complete LCA, there is a large need for data and specialist knowledge. There is often lack of comparable and reliable LCA data making it difficult to define the product system boundaries in a consistent way [20].

Therefore, although many industrialists feel LCA is a relevant tool, it is cost ineffective as large quantities of data need to be computed and there is a need for specialised knowledge, which may be expensive to procure. This apart from its other advantages and disadvantages mentioned above has led to it receiving mixed responses from many.

LCA is under continuous development. One of the biggest challenges in performing an LCA is that a product must be completely defined prior to assessment. Consequently it is very difficult to compare a completed product with one that is still under development. Similarly, LCA is completely unsuitable for the environmental comparison between two products that have different functions, even if this difference is between one or two specifications of the product. Due to these drawbacks, LCA has been combined with other tools. One such tool is the Environmental Effect Analysis (EEA) [21].

2.4.2 Environmental Effect Analysis (EEA) [21]:

The EEA method was developed to assist product development teams in quick and effective assessment of environmental issues, clarifying their goals and objectives [21], and toward fulfilling them in real product development efforts. EEA utilises dialogue within a team, with the objective of making effective use of available knowledge and building upon the environmental laws, regulations and inputs from stakeholders. The basic principle is to list all activities considered to have significant environmental influence, and for each activity to judge the quantity and seriousness of each aspect as well as to suggest ways for making improvements that will reduce the impacts of the proposed product. EEA can be used early in the development process since it does not require detailed quantitative data.

Environmental Effect Analysis (EEA) was developed with Failure Mode and Effects Analysis (FMEA) as a prototype. This was seen as a less complicated tool than the Life Cycle Assessment methods for procuring information related to the early stages of product design and was initially called Environmental-FMEA (E-FMEA). This name was however later changed to Environmental Effect Analysis (EEA).

The objectives of EEA are to identify and evaluate significant environmental impacts of a product in an early stage of a development project. This is in order to evaluate alternative materials and processes as early as possible.

In an EEA, available competence of the design team along with experience is used to decrease the environmental impact from a tentative design in every step of the life-cycle. It is important to emphasise that the EEA focuses on the environmental requirements of the product and that the environmental examination is teamwork between different functions in a company. One of the biggest advantages of the method is that it can be used in the early phases of a product development project.

When performing an EEA, the aim is to find so called 'hot spots', that is the environmental effects that are particularly important to work with in order to decrease the environmental influence of the product.

Another aim of the method is to function as a pedagogical tool. Everybody involved learns about the environmental effects and the environmental competence increases automatically.

In short, EEA can be characterised by the following:

- It is a systematic study of the environmental effects of a product system, from extraction of raw material to the final disposal.
- It is based on environmental requirements.
- The level of detail as well as the time frame for the EEA can be varied depending on the chosen definitions of goal and system boundaries, i.e. it is a flexible method.
- It is a qualitative method.
- Assumptions and sources of data are accounted for in a transparent and understandable way.
- It is intended for internal use and especially for product development.
- It is not possible to compare two different technical functions with each other.
- It can be part of an environmental management system.

EEA is a systematic process carried out by a multifunctional team. The analysis contains a number of activities that should be coordinated with other activities in the product development work. The different activities, preparations, inventory, analysis, implementation and follow-up are integrated in the project plan, which is established before the start of the project.

The preparation work includes the collection of relevant information regarding the current product, its life-cycle and the environmental impact. It is important to know the present and expected environmentally related requirements of the product. These requirements can be divided into three categories: authority demands, market demands and internal demands (controlling documents, internal environmental aims etc.). Apart from having knowledge in the environmental requirements, designers must be aware of the materials and the manufacturing processes used, the way in which they are used and the means of final disposal of the product. If earlier life-cycle assessments have been made, they can give valuable input data for an EEA. It is important to emphasise that EEA data collection should cover all phases of the life-cycle but not necessarily in detail.

The analysis is made on the basis of the product's life-cycle, which can be divided into different phases, namely, Purchase/Procurement, Production, Use and End-of-life treatment. The composition of the EEA-team can vary as long as the design, market, purchase and management divisions are sufficiently represented. The examination should be led by somebody who has thorough knowledge of the environment in addition to being very well informed about the products and product development of the company. The result of the environment analysis is that a number of considerable environmental impacts, caused by the product are pointed out. Based on the result, different corrective and preventive actions are suggested, for instance, suggesting altering types of materials used.

When the suggested actions are carried out, a follow-up analysis is done. The environmental impacts are re-evaluated in order to check that actions introduced have resulted in positive results, i.e. that they have achieved lowering total environmental impact. The follow-up is carried out by the same EEA team that has been used from the start.

The last step is the process documentation. The documentation is important in order to be able to communicate the results and to simplify the EEA work in the next product development project.

EEA is most effective when carried out in the early stages of product development. In fact, EEA is usually carried out right after the product specifications have been defined. This allows for the EEA to have an influence even on detailed technical specifications.

An EEA is performed according to the principal structure seen in Figure 2.4. It is important to note that the flowchart should not be interpreted too literally since EEA is essentially an iterative process and therefore there will always be feedback.

The EEA methodology flowchart (Figure 2.4) is divided into five distinct stages: Preparations, Inventory, Analysis, Implementation and Follow-up. The Preparation stage is when goals and the scope of design is clarified. The EEA team determines the environmental demands the product requires. The inventory stage is a single step stage where the inventory information is gathered. This is followed by the Analysis stage, where the inventory is analysed. Depending on the analysis, it is possible that further effects on the environment are determined. At this stage, the goal and scope of the product definition can be changed. Once the design goal and inventory has been decided upon, the EEA team determined methods to implement the design. Lastly, the entire design process with regard to environmental effect as carried out by the EEA team is continuously followed-up on. Thus, an EEA team successively, considers the effect the product will have on the environment at every stage of design.

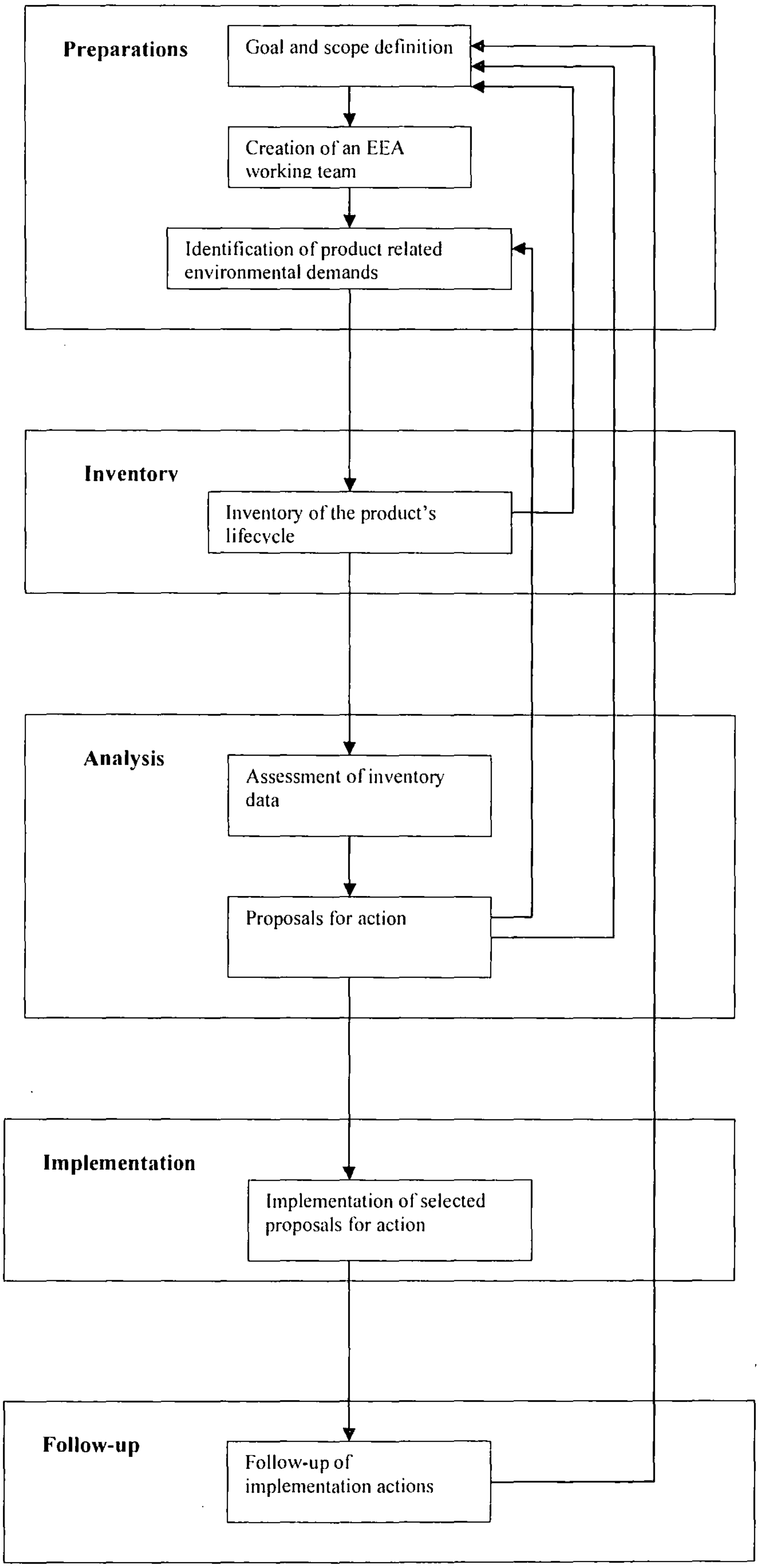

Figure 2.4: The EEA methodology flowchart [21]

In the research carried out by Mattias Lindahl [21], it was noted that the EEA methodology is still in its infancy. It is often compared with LCA, especially with regard to usefulness, time consumption and output. This is for the following reasons:

- LCA has a life-cycle perspective,
- It is regarded as the most prominent of DfE tools,
- It is the most widely used DfE tool, and
- It has been standardised over the years

Mattias Lindahl carried out case studies on four different products in order to accurately distinguish between EEA and LCA. These case studies illustrate that the LCA and EEA focus on different aspects. The LCA analyses the product environment but does not indicate if it is feasible to reduce the impact. An EEA on the other hand focuses on whether it is possible to reduce environmental effects and their relative importance.

Apart from this, it was seen that performing an EEA required much less time than performing an LCA. A major distinguishing factor between EEA and LCA is that LCA requires quantitative data in contrast to EEA, which needs qualitative data. It is easier to find qualitative data and industry generally imposes fewer restrictions on handing over this kind of information. Qualitative data gives an overall picture and happens to be more informative and is easier to understand that quantitative data which is mostly a lot of data compiled together.

This distinguishing characteristic is interpreted as a positive complementary characteristic by Tingstroemm et al [20]. In the studies conducted by Tingstroemm et al, the focus lies on different ways to combine the use of EEA and LCA tools in product development. The following three combinations of usages of these tools were compared:

(a) First EEA and then LCA
(b) First LCA and the EEA
(c) Both EEA and LCA used in parallel, during the product development process

Combining eco-design tools such as EEA and LCA is to provide support for 'normal' product development process. Usual design criteria for products these days are: Energy reduction in use, Product and components life extension, Materials life extension, Design for Disassembly and the environmental assessment tools help investigate and implement these criteria for product design.

(a) EEA before LCA

The purpose of combination (a) is that EEA should be utilised as soon as the product targets are set. Already during the pre-study phase, the work to define the goal and scope of EEA can be started. When certain problem areas have been identified, the EEA work is finished and the more detailed assessments are made via LCAs. The EEA team is used to define the overall framework of the product-system that is being analysed. The evaluation is then continued via an LCA inventory of energy and materials flow. To be able to influence the product design in an effective way, a preliminary result must be available early in the development process.

(b) LCA before EEA

The goal with combination (b) is to use LCA to establish a sound frame of reference and then to continue with EEA to find inventory data in an efficient way. However, it is difficult to provide a complete LCA early in the product development process, as there is very little information available. This means that an early LCA would have to be based on data from assessments of earlier product generations. In 'evolutionary' development, when the product generations are similar and much information can be re-used from earlier development processes the alternative (b)'s use of LCA is beneficial. Then the EEA could be initiated as soon as these data are compiled and the new product targets are available. However, this study only focuses on single product generation and specific data must be predicted as early as possible to avoid the LCA from becoming a bottleneck in the development process.

(c) EEA and LCA in parallel

The purpose of combination (c) is to use both methods of working during the entire product development process. The goal is to use similar paths for the information search. To some extent, the same data are utilised in both the EEA and LCA documentation, at the same time. Most of the environmental aspects are documented in different forms of measures i.e. qualitatively respectively quantitatively, in the two tools, but still those often have some kind of common foundation. When data is entered into the documentation in one of the tools, this can also often be used in the estimation of the input that is needed for the other tool. The advantage of this concept is that it facilitates the exchange of information between the two forms of work and the two types of documentation. The parallel use of tools tends to be more realistic. This is because, when performing an EEA, the different steps of each method tend to be repeated a number of times, in iteration with gradually improving accuracy.

Though each of the methods is beneficial in certain ways, it was found that most engineers prefer combination (a) as they think that the work with Eco-design fits smoothly into their product development process. By making environmental information available early on, effective measures can be taken the development stages to make useful decisions regarding product design. The combined use of EEA and LCA highlights some aspects of the interconnection between integrative cooperation and environmental analysis. This indicates that the interconnection of methods for analysis and dialogue to business-oriented motivation could provide a key to environmentally oriented transformation of design practices. The result with having EEA before LCA in a product development process is in line with usage of other tools such as in eliminating concepts. When concepts are eliminated, often two tools are used, first a screening tool that eliminates the majority and after that a scoring tool in order to make a more accurate analysis.

2.5 Role of materials and manufacturing processes selection in product design:

Selection of materials and manufacturing process is placed in an early stage of the product development procedure, i.e. in the design stage. Typically designing accounts for 7% of the whole product cost while it is responsible for 65% of its potential decrease [22]. Product characteristics can be most easily influenced at the product's inception but this precisely is when one knows the least about them [23].

The selection of a suitable manufacturing process often involves considering the coupling between characteristics of the design, the material and the process. Though most materials can be well described by a common set of properties alone, the same is only partially true for process selection. The most discriminating characteristics of processes are often specific to the class of process. For instance, very different questions arise when selecting a casting process than when selecting a welding process. Furthermore, the data needed to capture these characteristics can be strongly influenced by the class of the material being processes – there is limited scope for selecting a welding process for aluminium, or steel, or polymers from a generic welding selector that does not have material-specific data [24]. It is therefore important to develop designing aids, which would assist designers in the selection of materials and manufacturing processes.

There are several ways to approach the early stages of product design involving materials and manufacturing process selection. Lovatt and Shercliff [25, 26, 27] present a systematic approach for handling the information needed to help select the best routes for fulfilling a specified manufacturing task. Key aspects of the approach include [25]:

- Material selection is based on a combination of features of the design and of the manufacturing process.

- The focus is on the situations where the process is the dominant aspect of the selection, but it incorporates co-selection with material when it is important for making a robust decision.

- Process data are assembled at an appropriate material-specific level to provide the discrimination needed for the manufacturing task under consideration.

- Material selection uses a combination of techniques including using empirical data and physically based process models to help determine relevant processing information.

The design process for a product can be split into the conceptual (preliminary), embodiment (intermediate) and detail (final) stages [28]. During the preliminary design stages, when little design or material detail has been fixed and all the processes are open for consideration, a broad-brush approach to selection is required. To allow rapid assessment of the options, with minimal user input, all processes may be described in a common format. The Cambridge Engineering Selector software [29] takes this approach: by using a database that describes process capabilities with records which are universal to all processes, it allows processes which meet certain design needs to be quickly identified.

During the final stages of design, when almost all details of process, material and shape have been determined, it is only possible to optimise the fine details. Knowledge based software plays an increasing role at this stage – for example, by providing checklists of "Frequently asked Questions" (FAQs) to help identify and avoid common mistakes. Similarly, there are many software packages for problems such as mould design in casting or injection moulding, which help designers to ensure good mould filling.

Much of the process selection work falls into these two design contexts. In the intermediate design stages, however, when some design details have been fixed but there are still competing possibilities, these approaches have various shortcomings, such as:

- the selection tools may not be sufficiently discriminating;
- the optimisation tools may take a prohibitive length of time to assess all the possibilities;

- data may be too sparse or unreliable to give any realistic alternative to physical prototyping (in spite of the associated costs).

It is apparent therefore, that different approaches are required in successfully choosing processes in this 'middle-ground' of design, when selection is confined to a subset of processes, which are truly competing. It should be recognised that the selection of these processes implies a much wider scope than process selection, because it is often not just a matter of choosing which process, but simultaneously refining the choice of material to be used and/or refining features of the design. In summary it may be concluded that task-based selection is particularly important whenever:

(i) the performance (and hence suitability) of the processes is closely coupled to the choice of material;
(ii) the quality or functionality of the component is strongly influenced by the interaction of the process with specific design features;
(iii) the economics of the process depend on detailed aspects of the design;
(iv) the competing processes cannot be compared on the basis of a common set of process characteristics (usually because the underlying physics, which determine how the processes work, differ widely).

Lovatt and Shercliff [26] first review the selection problem in the context of manufacturing tasks, in order to set a general framework for matching the characteristics of processes, materials and design with the requirements the designer identifies. The methodology of process modelling is investigated to enhance the selection procedure when there is a strong coupling between process, material and design.

In order to define a manufacturing process, it is important to differentiate carefully between the requirements and attributes in the context of the task-based process selection. In brief:

Requirements are characteristics of the product that the designer wishes to meet, and relate to the questions that need answering for the task in hand;

Attributes are characteristics of the solutions that can be used to make the product, and relate to how the questions are answered.

Requirements determine the scope of selection and define the domain within which the designer can expect valid results. Determining the correct requirements is important for creating a clear and robust task-based selection tool. However, identifying the important requirements is rarely straightforward. For this reason, the requirements are categorised into the following three groups:

- Design-related: specifications for the function of the component (e.g. strength, mode of loading, wear resistance), or design information that might be found on the engineering drawing such as dimensions, shape or surface finish.
- Production-related: details required for the shop floor such as batch size and production rate.
- Processing-related: in-process issues that may be reduced or eliminated at the design and production planning stage. These will generally be process specific, for instance, hot-tearing for casting.

On the other hand, attributes refer to the characteristics of the process, material and design that must be combined in some way to provide the information necessary to assess whether the requirements can be met. For instance, for steel joining, possible attributes might include:

- process: process identifier, capital cost, machine power etc.
- material: material identifier, processability indices
- design: thickness, joint loading, joint geometry, etc.

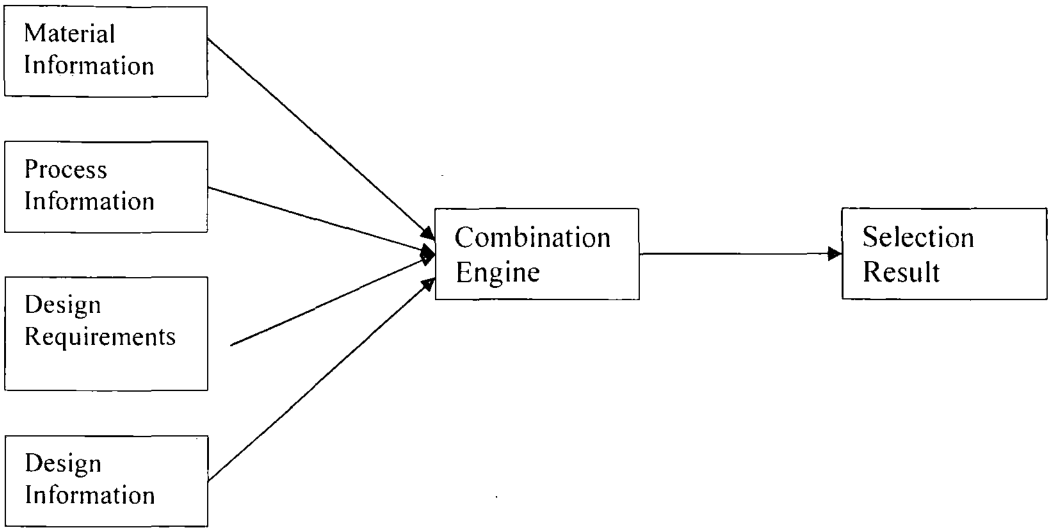

Fig. 2.5: Schematic of the way that a task-based selection tool combines attributes of the process, material and the design to determine the match to a given design requirement.

The general problem of selection within a manufacturing task may be summarised by the schematic of Fig. 2.5. Attributes of the process, material and design must be combined to address a particular requirement and output a set of selection results. There are essentially two alternative ways in which these selection results can be used – either for screening (in which options are eliminated if they do not meet the requirement) or for ranking (in which some numerical measure forms the output, allowing the options to be ranked). An important aspect of building a selection tool is considering how the results from assessing several requirements will be combined, and on what basis the options are to be screened and/or ranked.

The matching of attributes to address a requirement can take place in a number of ways. Three different ways are presented below:

One–to–one matching: In all manufacturing tasks, consideration should be given to any simple evaluation that can be conducted to screen the available options. During the preliminary design stages, this may be sufficient in itself to produce a working subset of processes, but initial screening should form the first step even if greater complexity is subsequently required. The simplest screening step is to compare a design requirement with information for each processing option on a one-to-one basis. Simple requirements to consider for each processing option could be compatibility with the chosen class of material, compatibility with the given size and upper limit on the acceptable cost of the equipment.

Paired-attribute matching: This method of matching attributes is more advanced than the one-to-one method as it incorporates a number of refinements in matching the design requirements. In a task such as metal joining, where the factors to be considered, namely, metal thickness and joint geometry and completely dependent on each other, the paired attribute matching method has been successful in capturing data, whilst maintaining discrimination.

Complex attribute coupling: The complex attribute coupling method is an extension of the paired attribute matching. The later stages of design are extremely detailed; however, considerations for the product design need to be made as early as possible. While design requirements are universal, there are often processing options for which the requirements are critical and others where the requirement is not an issue. In order to help tackle the complexity of the selection process, Lovatt and Shercliff [23] proposed a methodology to help build a selector for a chosen task and in identifying design requirements, and capturing the appropriate level of coupling needed between attributes to satisfy these requirements. The approach is summarised below.

Lovatt and Shercliff [26, 27] classified requirements into design-related, production-related and processing related, and noted that these may either be explicit (e.g. size of component) or implicit (e.g. must not crack during processing). Requirements can also be grouped into four main types of problems that the designer would be interested in solving:

-Technical Feasibility
-Avoiding in-process defects
-Product performance
-Economics

The advantage of this grouping is that it provides some sequence to the questions, for instance, there is no point in worrying about the cost before it has been established whether a process is technically viable or there is no need to wonder whether a casting alloy can meet strength requirement or will it crack on manufacture. By asking the most discriminating questions first, the viable processes are funnelled down so that fewer will remain to be assessed at the more complex assessment stages such as economic evaluation.

To guide the designer in constructing a systematic way to address these requirements, Lovatt and Shercliff summarised their methodology in a flow-chart (Fig.2.6). The preliminary Phase 1 emphasises the importance of identifying requirements and the relevant attributes. Technical evaluation proceeds in Phase 2, first by initial screening for any requirements for which useful discrimination can be obtained on the basis of one-to-one or paired-parameter matching between requirements and attributes (e.g. process compatibility with material, size, component function, etc.). The remainder of Phase 2 of the methodology deals with four categories of problems discussed above. This is when more complex coupling between attributes and requirements is generally required. Although the flowchart suggests the best sequence in which steps are considered, this does not have to be followed rigidly. Sequence is important between phases as there is often connectivity in information from one phase into a later phase. Important aspects of building a selector by following this methodology are that the selection tool is customised to the requirements of the task in hand and has a structure as to how the requirements are addressed.

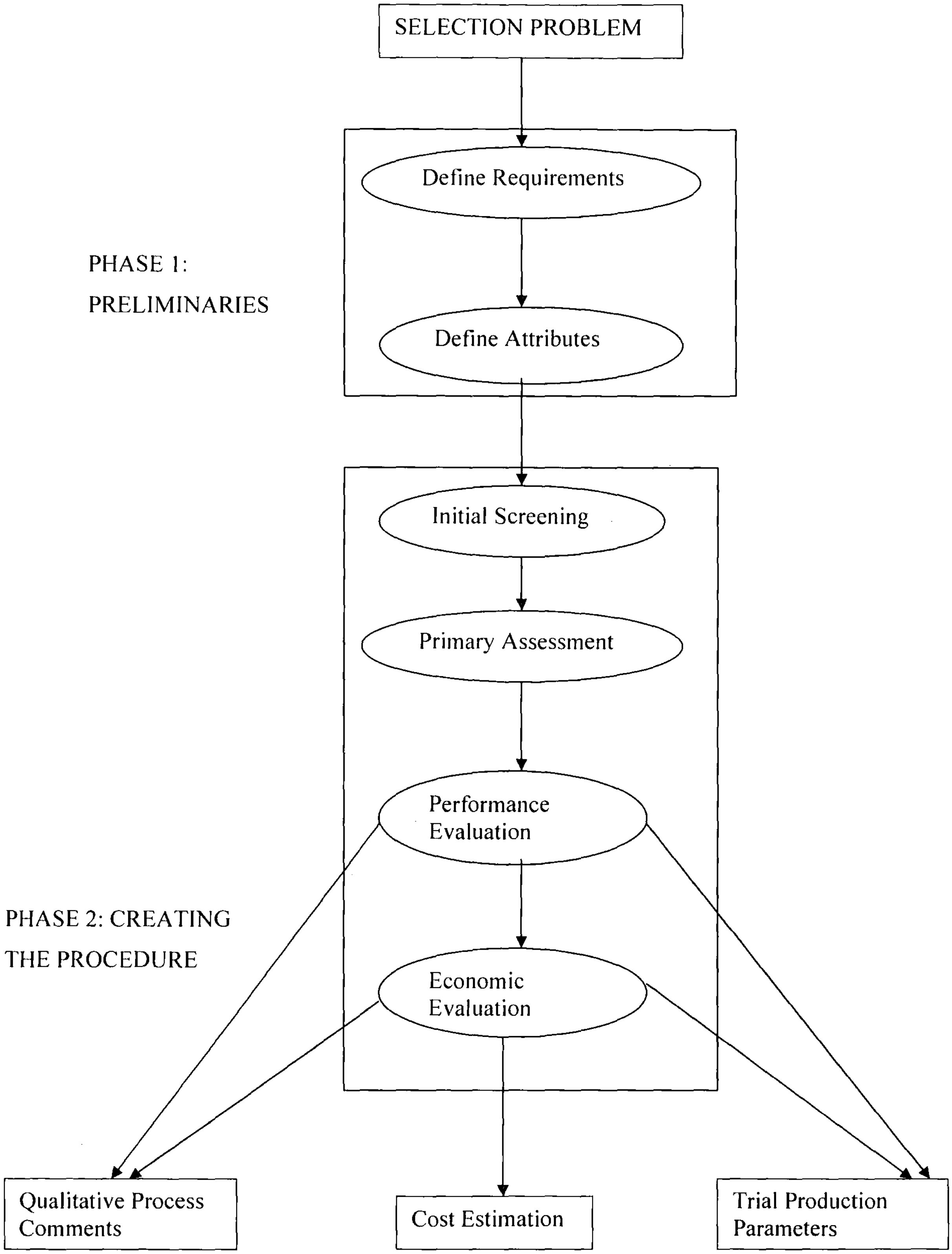

Fig.2.6: Methodology for constructing selectors for manufacturing tasks [28]

The major challenge in applying this methodology is to capture the complexity of requirements that depend on multiple attributes. The solution proposed to this challenge is to describe the relationships between the parameters by process models.

2.5.1 Cambridge Engineering Selector (CES) [29]:

Research by Ashby et al. [29] explore innovative ways of storing material attributes and comparing them with design requirements for the purpose of selecting suitable materials for a given engineering design. This resulted in the development of the Cambridge Engineering Selector (CES).

The main objective of the research was to develop a systematic procedure for optimised materials selection that ensures that no promising materials are overlooked. This was implemented in a computer environment as a database of materials attributes and as a multi-objective optimisation tool for balancing performance against cost aspects of the choice. The procedure implemented in the CES program starts with an analysis of the function of the component, the constraints it must meet, and the objectives of the design itself. This identifies groups of material properties which characterise performance.

Apart from selecting the appropriate materials and manufacturing processes for a given engineering design, CES aims to promote eco-design as well. This is done by considering the four main stages of material life-cycle, namely, Material Production, Product Manufacture, Product Use and Product Disposal. All four stages of the materials life-cycle have an impact on the environment. CES aims to identify the most damaging phase and then help in the selection procedure of materials and processes to minimise this. Therefore, the method of selection depends on a targeted phase of life. The strategies used to implement CES are described in greater detail below.

Materials Selection:

Unbiased materials selection is achieved by considering all materials to be viable candidates until shown to be otherwise. Efficient selection [30] involves four steps. These are translation, screening, ranking and supporting information (Figure 2.7).

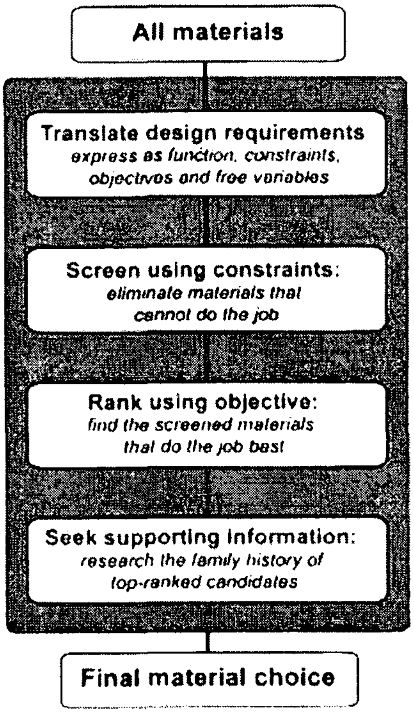

Figure 2.7: Materials selection (Granta Design) [29]

In the translation step the design requirements are reformulated as constraints on material properties and process attributes and as one or more objectives: minimisation of cost, or of weight, or of environmental impact, for instance. In screening these constraints are used to eliminate materials that cannot meet the requirements. Ideally, screening is done using a computer database containing material attributes: values of physical, thermal, mechanical and electrical properties; and in a database for eco-selection – attributes relating to the environmental impact of the production of the material itself: its energy content, the greenhouse and acidification gases created by its production, its toxicity, and so forth. Ranking is achieved by the use of material indices. There are many material indices, each measuring some aspect of efficiency for a given function. Indices are used with material selection charts where there are plots of one material property or a combination of material properties against another. Material indices can be plotted on a materials selection chart, identifying materials that have attractive values of the index. The procedure allows ranking materials according to their cost per unit of function, mass per unit of function or environmental impact per unit of function.

The output of the screening and ranking steps is a ranked short-list of materials that satisfy the quantifiable requirements of the design. The next step is to analyse supporting information such as examples of use of materials, design guidelines, failure analyses, processing information or details of availability and pricing. Supporting information helps narrow the short-list to a final choice that allows a definitive match to be made between design requirements and material attributes.

As mentioned earlier, the choice of materials and processes influences all phases of material life-cycle: production, through the drainage of resources and the undesired by-products of refinement; manufacture, through the level of efficiency and cleanness of the shaping, joining and finishing processes; use, through the ability to conserve energy through light-weight design, higher thermal efficiency and lower drainage; and disposal, through greater ability to allow disassembly and recycling. The CES tool aims to assist the designer in minimising the undesired consequences of the four phases.

The easiest way of conserving materials is to make products smaller, make them last longer and to recycle them once they reach the end of their lives. However, this idea is rather complicated as materials and energy form a part of very complex system. A number of factors play a role in estimating energy consumption of a given product. These can be energy and missions, material processing energy, toxicity, sustainability, industrial design, material wants, population etc.

The CES database can be used for retrieval – as a reference source for environmental and other information about a given material process – or it can be used for selection. Retrieval is done by browsing the database and choosing the material or interest. In the case of selecting a material, the designer must first analyse the life-cycle phases and determine which one it is that has the greatest impact. This decision then guides the designer in selecting the appropriate material and processes.

The CES database contains approximately 3000 materials. Each record has a complete list of attribute values. This is achieved by the use of estimation procedures, using correlations between attributes to approximate those that are missing. All values that are estimates are flagged so as to distinguish real form estimated values. The user can edit the database, allowing estimates to be replaced by real data as and when this becomes available [30].

2.6 Design for Assembly (DfA)

Design for Assembly is defined as 'a process for improving product design for easy and low-cost assembly focusing on functionality and on assemblability concurrently' [31]. DfA recognises the need to analyse both part design and the whole product for any assembly problems in the early stages of design itself. Not only does DfA succeed in reducing costs and in simplifying assembly, but it also results in improved quality and reliability along with a reduction in production equipment and part inventory.

Assembly methods can be divided into three major groups, namely, manual assembly, fixed or hard automation and soft automation or robotic assembly.

In manual assembly, parts are transferred to workbenches where workers manually assemble the product or components of a product. Hand tools are generally used to aid the workers. Although this is the most flexible and adaptable of assembly methods, there is usually an upper limit to the production volume, and labour costs (including benefits, compensation due to injury, overheads for maintaining a clean and healthy environment, etc.) are higher.

Fixed or hard automation is characterised by custom-built machinery that assembles one and only one specific product. This type of machinery requires large capital investment. As production volume increases, the fraction of capital investment compared to the total manufacturing cost decreases. Indexing tables, parts feeders, and automatic controls typify this inherently rigid assembly method. This kind of assembly is also called 'Detroit-type assembly'.

Soft automation or robotic assembly incorporates the use of robotic assembly systems. This can take the form of a single robot, or a multi-station robotic assembly cell with all activities simultaneously controlled and coordinated by a computer. Although this type of assembly method can also have large capital costs, its flexibility often helps offset the expense across many different products.

Assembly methods should be chosen to prevent bottlenecks in the process, as well as lower costs. It is important to quantify the improvements and goals of DfA. One such method for DfA quantification is the Boothroyd-Dewhurst method.

The Boothroyd-Dewhurst [8] method is based on two principles:

- The application of criteria to each part to determine if it should be separate from all other parts.
- Estimation of the handling and assembly costs for each part using the appropriate assembly system.

This method relies on an existing design, which is iteratively evaluated and improved. Generally, the process first selects assembly methods for each part. The parts are then analysed for the selected assembly methods. Based on the shortcomings identified during the analysis stage, the design is refined. This process continues until the design has been optimised i.e. the design shortcomings have been minimised.

The analysis is generally performed using a detailed worksheet prepared on parts, materials and assembly methods. Tables and charts are used to estimate the part handling and part insertion time. These tables are based on two-digit codes that are in turn based on a part's size, weight, and geometric characteristics.

Non-assembly operations are also included in the worksheet. For instance, extra time is allocated for each time the assembly is re-oriented.

The parts are now evaluated as to whether it is really necessary in a given assembly by asking three questions:

- Does the part move relative to another part?
- Are the material properties of the part necessary?
- Does the part need to be a separate entity for the sake of assembly?

The list of all parts is then evaluated to obtain the theoretical minimum number of theoretically needed parts.

The basic DfA guidelines are to minimise part count by incorporating multiple functions into single parts, modularise multiple parts into single subassemblies and carry out assembly in open spaces Designers must make parts such that it is easy to identify how they should be oriented for insertion. Self-locating parts are preferred. Designers must aim to standardise parts, maximise part symmetry and if non-symmetric they must design in geometric or weight polar properties. In order to prevent nesting of parts, stacked subassemblies are preferred. The design mating features for easy insertion improves assembly as does providing alignment features. For instance, designers are advised to insert new parts into assembly from above and flat surfaces ensure uniform fastening.

2.7 Product End-of-Life Stage

Reducing product environmental impact at all lifecycle stages is an important topic for manufacturers. In this context, product end-of-life strategies are gaining continuous attention in the market. More and more companies are trying to understand how to improve their products so that the environmental impact will be lower at the end-of-life, while still being economically feasible.

According to Rose [32], 'end-of-life' is defined as the point in time when the product no longer satisfies the initial purchaser or first-user. This allows for reuse or recycle of that particular product as possible end-of-life strategies. Other definitions may start from the last user, but do not include high eco-efficient end-of-life strategies such as reuse and service as strategies to improve the end-of-life performance. Others define end-of-life as the point at which the product no longer performs the intended functions due to failure or wear-out. A lot of definitions do not appropriately account for changes in customer preferences.

End-of-life strategies describe the approach associated with dealing with the product at the end of its useful life. The aim through these methods is to recover value from the product, through manual labour and/or machinery. Given below is an outline of various end-of-life strategies with their definitions [32].

- *Reuse* is the second hand trading of products for use as originally designed.

- *Servicing* the product is another way of extending the life of a durable product or component parts by repairing or rebuilding the product using service parts at the location where the product is being used.

- *Remanufacturing* is a process in which reasonably large quantities of similar products are brought into a central facility and disassembled. Parts from a specific product are not kept with the product but instead they are collected by part type, cleaned, inspected for possible repair and reuse. Remanufactured products are then reassembled on an assembly line using those recovered parts and new parts where necessary.

- *Recycling* reclaims material streams useful for application in products. Disassembly into material fractions increases the value of materials recycled by removing material contaminants, hazardous materials, or high value components. Recycling with disassembly components are separated mostly by manual disassembly methods.

- The purpose of *Shredding* is to reduce material size to facilitate sorting and disposal. The shredded material is separated using methods based on magnetic, density or other properties of the materials. This is the process of recycling without disassembly.

- *Disposal* is the end-of-life strategy where products are land filled or incinerated with or without energy recovery.

Figure 2.8 shows the end-of-life strategies defined above as part of a hierarchy. These include the closed and open strategies based on Ricoh's comet diagram [33]. Closed loops are preferable from an environmental perspective because they make use of resources and value already added to the natural resources, rather than open loops, which are landfills or the incineration of materials. Smaller loops represent a more efficient end-of-life strategy with less reprocessing of the materials for reapplication in products. The user is the focal point on the diagram. Once the products are finished being used by the consumer, there are a variety of routes the product can take – reuse, service, remanufacture, recycle with separation, or recycle without separation and disposal either in landfill or through incineration.

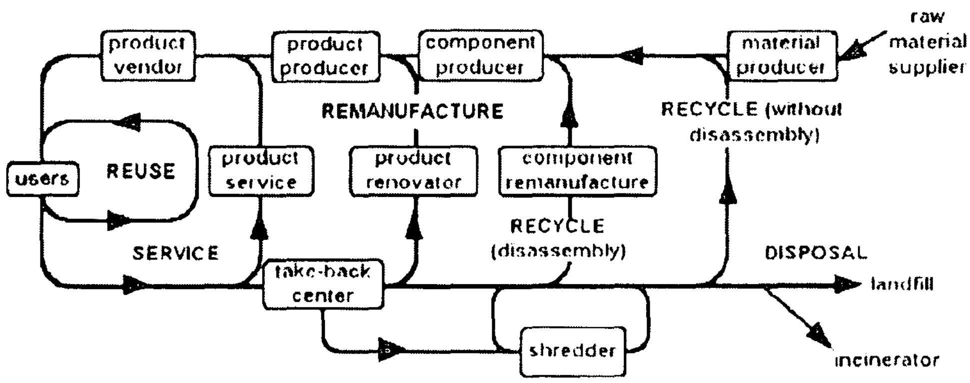

Figure 2.8: Ricoh's comet diagram [31]

Along the top line are the material producers, manufacturers, assemblers and original equipment manufacturers. The bottom line includes collection facilities and recycling companies. The middle group provides service to move the products from the recycling infrastructure back to the manufacturers and include such activities such as service, infrastructure and component remanufacturing [33].

According to Rose [32], end-of-life strategies are ranked according to the calculated environmental impact analysis. The highest on the hierarchy is reuse, then service, remanufacture, recycling and lastly disposal either through incineration or land filling. Knowledge of product characteristics allows designers to determine the end-of-life strategy early in the product design. Since, different end-of-life strategies have varying environmental impacts; design engineers aim to move to higher levels on the end-of-life hierarchy by determining product characteristics early on.

In recent times, more and more companies are taking an interest in end-of-life strategies. It is important to enable systematic integration of end-of-life concerns into all relevant phases of product development. Building a strategy for end-of-life treatment of products is necessary in order to gain market share, adhere to legislation and maintain a competitive advantage.

2.8 Design for Disassembly (DfD)

Disassembly is defined as the organised process of taking apart a systematically assembled product (assembly of components) [34]. Life cycle analyses indicate that a large chunk of the entire cost associated with the product can be attributed to the product design process. It has been proven that disassembly process optimisation accounts for a meagre 10-20% of all disassembly gains. The major chunk of disassembly related gains (80-90%) tends to be determined at the product design stage. It is therefore important to incorporate environmental considerations at the product design stage itself [34].

There are a number of benefits for achieving efficient disassembly of products as opposed to recycling a product by shredding. These include [35]:

- components which are of adequate quality can be refurbished or reused
- metallic parts can be separated easily into categories which increases their recycling value
- disassembled plastic parts can be easily removed and recycled
- parts made from other material such as glass or hazardous material can be easily separated and reprocessed.

Disassembly can be classified into [34]:

- Destructive disassembly or brute force approach, e.g. incineration, metal cutting etc.
- Non-destructive disassembly or reverse-assembly

Depending on the extent of disassembly, non-destructive disassembly can be further classified into two categories as follows [34]:

- *Total disassembly*: The entire product is disassembled into its constituent components. This is sometimes not economically feasible due to the imposition of external constraints such as time, economic factors, presence of hazardous materials etc.

- *Selective disassembly*: Selective disassembly is defined as the reverse dismantling of complex products into less complex subassemblies or single parts [36]. It involves the systematic removal of desirable constituent parts from an assembly while ensuring that there is no impairment of parts due to the process [37].

Although no single disassembly strategy works for all products, a general observation made is that the most effective method is to employ non-destructive disassembly until it is no longer effective [38]. After non-destructive disassembly reaches the point of diminishing environmental returns then destructive disassembly becomes a viable option. This general use of a non-destructive method minimises the destruction of the product and maximises the potential of not only material resources but also subcomponent reuse.

Disassemblability:

Disassemblability is defined as the degree of easy disassembly [39]. The following factors affect disassemblability:

- Use of force: Minimal use of force is recommended. This enables the disassembly process to be carried out quickly without the use of extensive manual labour.
- Mechanism of disassembly: A simple mechanism is preferable.
- Use of tools: Ideally, disassembly should take place without the use of tools. Examples of such processes would include simple push/pull processes or processes in which components become disengaged merely by the exertion of direct manual force.
- Repetition of parts: Part repetition should be minimised to enable quick and easy identification of parts at each stage of disassembly.
- Recognisability of disassembly points: Disassembly points are defined as those joints, which need to be disjointed so as to affect disassembly. Easy recognisability of these points is advisable especially in the case of products that accumulate internal dirt during their useful life.
- Product structure: The simpler a product structure, the better it is from the disassembly point of view.
- Use of toxic materials: Since most disassembly is still manual in nature it is advisable not to incorporate toxic materials in the design of parts since they may pose health hazards to the operator performing the disassembly.

The above factors assist design engineers determine easy methods of disassembly as well as in general maintenance and repair of the product. These help in the overall implementation of DfE and subsequently help promote recyclability and reusability.

2.8.1 Connection Types in DfD

Connectors play an important part in determining the disassemblability of a product. A connector or a fastener is described as a component employed between parts, which holds the mated parts together and establishes relative part location, alignment and orientation, transfers loads, and absorbs tolerances between the parts to prevent vibrations [40]. The type of fastening method used determines whether a product is to be disassembled using a destructive or a non-destructive disassembly approach. Therefore, selection of fasteners is an important issue in DfD. During disassembly of

a product, one of the main activities is unfastening the connector. Unfastening is the process of ending the role of a fastener in the product.
Connectors can be classified into several groups [40]:

- Discrete fasteners: These fasteners are independent of the parts to be merged together. They may be single unit or may consist of multiple elements. A discrete fastener can be removed from the part of the product and be reused depending on its condition after removal. Examples of discrete fasteners include screws, bolts, nuts, washers, springs, bundles etc. These connectors cause no harm to the body of the parts of the product. They are also able to join the parts with different materials.

- Integral attachments: These types of connectors are integrated into the parts of the product. They do not require the use of a supporting joining element or an assembly tool. When two parts with integral joining elements are brought together using the right motion, they lock each other and are joined. Examples include locators, locks, compliant, snap-fits etc.

- Adhesive bonding: These types of connectors join parts with different types of glues using adhesion, chemical reactions and phase transition mechanisms. There are different types of adhesives depending on the application. Although better suited aesthetically, adhesive joints may pose problems during disassembly operations.

- Energy bonding: Soldering, brazing, welding and moulding are examples of energy bonding. In this method, the joint is melted or plasticised in order to form a bond using an external energy source such as ultrasound or inductive heating. Material properties of the part to be connected determine the selection of this type of connection.

- Other connectors: These include seaming, crimping, zippers, Velcro etc.

Apart from DfD, other strategies used to implement DfE are Product Remanufacturing and Recycling.

Product Remanufacturing:

Remanufacturing involves recycling at the parts level as opposed to the scrap-material level. Value is added during the original manufacturing process in the form of energy and labour required to shape the raw material into a usable component. Recycling at the higher level of components avoids resource consumption for possibly unnecessary reprocessing of material while preserving this added value. Remanufacturing also postpones the eventual degradation of the raw material through contamination and molecular breakdown, frequently characteristic of scrap-material recycling technologies. In addition, remanufacture can divert parts made from unrecyclable materials from landfill. The production batch nature of the remanufacturing process enables it to salvage functionally failed but repairable products that are discarded due to high labour costs associated with individual repair [41].

Design for Recycling:

Product recycling can be used to obtain a dramatic reduction in environmental impact. Recycling is of two types. The first in which the geometrical form of the product is retained and the product is reused for the same purpose as during its original lifecycle (e.g. refillable drink bottles) or for secondary purposes (e.g. reuse of automotive tyres as mooring cushions in a harbour). Recycling is advantageous because every time a part is reused, all the energy and emissions that were produced in its original manufacturing and the processing of its materials are salvaged. Also, utilisation of existing components reduces an enterprise's monetary expenditure of producing or acquiring new components. Apart from saving costs, when a company takes back its product for recycling of components after the end of its use, this company will be among the first to know that the customer needs a new product, which places the company in a favourable position compared to its competitors [42].

It is the aim of designers that products that reach the end of their lives should be dealt in such a way that much of them can be used again in some form [43]. Designing using the following methods would ensure that the products could be used again to their full potential [44]:

- Designing for ease of disassembly, to enable the removal of parts without damage.
- Designing for ease of purifying, to ensure that the purifying process does not damage the environment.
- Designing for ease of testing and classifying, to make it clear as to the condition of parts, which can be reused, and to enable easy classification of parts through proper markings.
- Designing for ease of reconditioning, supporting the reprocessing of parts by providing additional material as well as gripping and adjusting features.
- Designing for ease of re-assembly, to provide easy assembly for reconditioned and new parts.

Thus, the process of recycling a product at the end of its life can be determined in the design stages itself by taking into consideration the above-mentioned methods.

2.9 Remarks

From the literature reviewed, it is clear that Design for Environment is a subject on which a lot of research has been done over the last few years. DfE is a vast subject that covers design aspects ranging from assembly, disassembly, materials and manufacturing process selection to end-of-life strategies. LCA and EEA are some of the tools that are currently being used by industry. However, these tools have shortcomings that still must be overcome. On the one hand performing an LCA is too qualitative while on the other hand an EEA is too quantitative. On the basis of the literature reviewed, this study aims to help develop a methodology that provides vital information in the early stages of product development so as to help engineers determine the overall impact the product will have on the environment and then determine ways in which to minimise the products impact. There are a number of aspects that must be taken into account to achieve this goal. The literature reviewed covers the important stages of product development that the designer must follow and the challenges faced by product designers in incorporating DfE principles. These include materials selection and manufacturing processes selection. Over the years, numerous methodologies and tools such as the CES have been developed to simplify the materials and manufacturing processes selection for designers [26, 27, 28, 29].

These have been reviewed in this chapter. Although materials and manufacturing processes play an important role in enhancing the reusability of products, it has been recognised, through the literature reviewed, that suitable assembly and disassembly methods can further increase product sustainability. Design for Disassembly (DfD) is an area of DfE that must be further researched. DfD stresses on the importance of determining suitable joining processes in order to promote End of Life solutions such as recycling and remanufacturing. The following chapters aim to devise a way so as to incorporate suitable disassembly methods for a product soon after materials and manufacturing processes selections have been made.

3 Theoretical Proposal

This chapter defines the problems that engineers face with regard to implementing Design for Environment strategies in product design. Although there is a vast resource of information and guidelines that helps designers in developing a product, a number of problems must still be addressed with regard to minimising the effects a product has on the environment. The aim of this chapter is to outline the various shortcomings that must be overcome by designers, and to propose principles for the development of a methodology that would enable more efficient product design.

3.1 Introduction

The area of Design for Environment (DfE) is continuously being researched and developed. It is important to not only develop new DfE tools, but also to make improvements in existing ones. Many governments are becoming more stringent in their efforts to promote environmental consciousness. This has been carried out by implementing various laws after studying relationships between products and the environment. Thus, more and more companies are now realising that environmental issues may soon become a competitive issue, just as quality issues once were.

In spite of the rapidly growing significance of DfE, many enterprises are still reluctant to incorporate DfE into the design procedure [45]. Even though many companies are under pressure on implementing norms and guidelines, there are still no real DfE changes in their way of developing new products. The most common change when designing according to DfE norms is usually an improved material separation of paper, glass, metals etc. Other than that, the environmental improvements are generally marginal.

In order to make environmental-product improvements, it is necessary that DfE becomes a natural part of the product development process. This is not a simple procedure. DfE covers many aspects of product design such as materials selection, process selection, assembly and disassembly design and end-of-life strategies.

In order to determine adequate data to determine product life cycle impact, researchers have developed various DfE tools, such as The Cambridge Eco-Selector (CES) developed by Ashby et al. [29]. This tool has been quite successful in helping designers determine eco-friendly materials. However, from a life-cycle perspective tools such as LCA and EEA are being incorporated along with materials selection tools such as the CES. These have already been discussed in detail in the previous chapter where it has been seen, that although, many companies use these tools, there are severe shortcomings that must be addressed in order to make these tools more effective. For this reason design engineers must have access to a tool that can not only assess environmental impact of a product, but also, on the basis of the assessment, determine appropriate end-of-life strategies so that product components can be recycled. This would not only help save the environment, but also reduce costs in the long run. Thus, the aim of researchers is to develop a standardised and effective DfE tool that can be used in the early stages of the product development phase.

For design engineers, the environmental issue is only one of the many issues that need to be addressed [1]. It is important to be able to integrate environmental concerns along with the work that makes up the actual part of the product development process. If environmental issues are treated as an isolated issue, it will lead to fewer environmental improvements being built into the products. De Araujo [46] has listed a number of different reasons for the low utilisation of design methods in practice:

1. Lack of reasons and/or interest for design methods in order to facilitate the product development.
2. Lack of understanding of the nature of the design method – the practitioners are not sure how they can benefit from the available design methods.
3. Lack of 'appeal' – the design method is not adjusted to the needs of the practitioners.
4. Poor design of the design method – some design methods are unnecessarily complicated in relation to the practitioners needs.
5. Poor promotion (marketing) of the different design methods.
6. Negative attitude to introduction of new design methods – in many cases based on previous bad experience of design method introductions.

The general points related above are also valid for the DfE methods. Developers of DfE methods have failed to address the points listed above and have therefore been unsuccessful in meeting the requirements or wishes of numerous industrial enterprises. Methods have been developed to become stand-alone packages, focusing on a single objective, in this case, minimising environmental impact. This narrow focus on environmental issues along with method developers has sometimes resulted in overcomplicated methods with a descriptive ambition to give a detailed and precise answer.

3.2 Design for Environment (DfE) Methodology: The Importance of Design for Disassembly (DfD) and Joining Techniques

Design for Environment (DfE) covers a wide range of aspects such as materials and process selection, assembly methods, disassembly methods and end-of-life strategies such as recycling, reuse, remanufacturing and disposal. With reference to the previous chapter on literature review, it has been noted that a lot of research has been carried out on the above-mentioned areas of DfE. However, DfE tools have been seen to have shortcomings that must be addressed. These shortcomings are due to the few gaps in information in the early stages of product development regarding design methods. Although, much of the past work deals with materials selection, manufacturing processes selection and assembly methods, substantial amount of information is still lacking on methods of determining appropriate disassembly methods.

Design for Disassembly (DfD) is an area of DfE that other researchers are looking into with increased interest. Incorporating DfD in DfE tools increases the scope for better end-of-life strategies. Joining techniques are a key factor in design for disassembly. Joining techniques can be classified as mechanical fastening, adhesive bonding and welding. Figure 3.1 [47] depicts the various joining methods in each category.

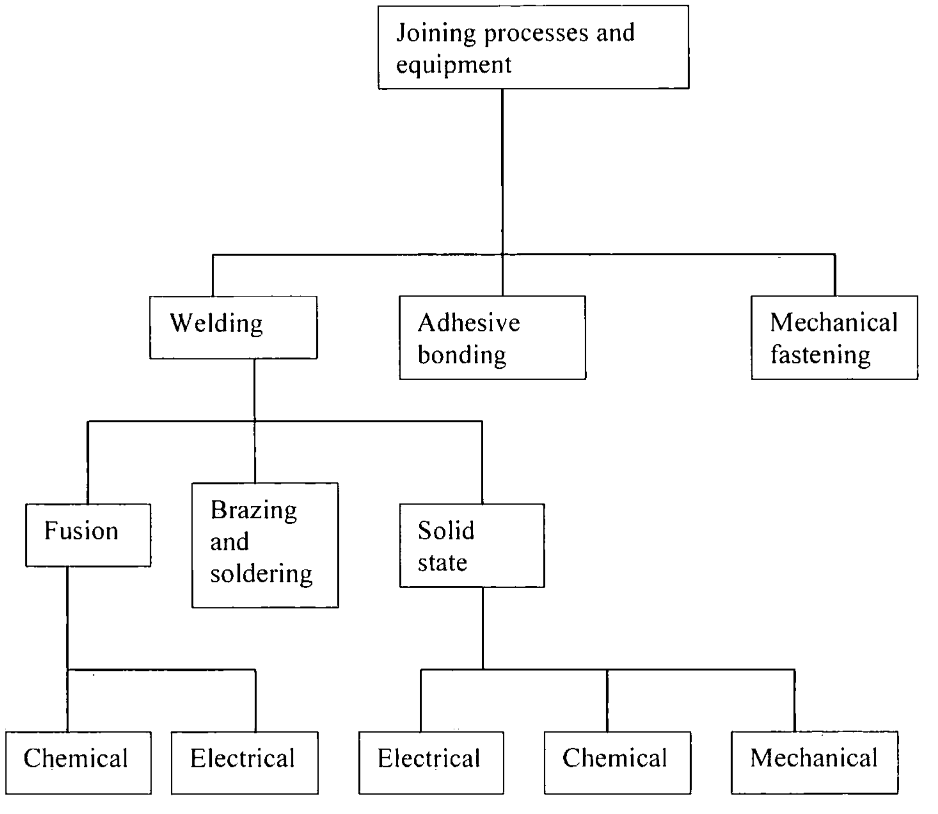

Figure 3.1: Classification on joining processes

3.3 The Significance of Process Modelling

Modelling provides a powerful tool for discriminating between processing options at the level of precision needed to answer design requirements. Process models can [42], [48]:

-connect the relevant attributes of design, material and process, while avoiding the data-explosion problem as manufacturing tasks are defined at a more refined level of detail;

-enable simultaneous selection of more than one material as well as process at a detailed level;
-offer the added value of suggesting design modifications and trial processing conditions which will satisfy the requirements;
-facilitate progress when data are sparse, by enabling interpolation based on functional inter-dependence of the design, material and process parameters;
-provide essential modularity: different models relating attributes for each process, to answer common requirements;
-link technical feasibility directly to economic evaluation.

Process models can be constructed in using various software languages. Some of the most popular ones are, Unified Modelling Language (UML), Protégé and IDEF3 [42].

The literature reviewed in Chapter 2 helps us identify challenges faced by design engineers during the early stages of product design. These include procurement of enough data so as to be able to make concrete decisions regarding product design keeping environmental issues in mind. By having adequate information on materials, processes and assembly and disassembly methods, designers will be able to determine feasibility of reuse and recycling a given product. The development of process models to simulate the design procedure would once again help designers make concrete or near-final decisions and reduce costs. The use of process models can enable design engineers to do away with experimentation, as a result of which helps economise on time and money.

3.4 Theoretical Proposal

This dissertation aims to provide principles that will enable the development of a methodology that addresses the various shortcomings faced by design engineers during product development in order to help integrate environmental factors. The methodology must aim at providing key information at the conceptualisation phase of design, thereby enabling engineers to determine the appropriate end-of-life strategies. The proposed DfE methodology must look at characterising every stage of the product's life cycle so as to determine the overall effects of the given product. Data is compiled using Life cycle assessment (LCA) and Environmental Effect Analysis

(EEA). The two environmental methodologies are often used together as they are complementary. LCA provides quantitative data while on the other hand EEA provides the design engineer with more qualitative data. Information regarding materials, manufacturing processes, assembly methods etc. are determined. Apart from these, data pertaining to environmental issues such as extent of harmful gases being emitted and hazardous wastes to be disposed are noted at every stage of the product's life. Although the knowledge LCA and EEA provide help determine the extent of environmental damage, sustainability of the product can be increased by incorporating methods of reuse and recycling. Key data on disassembly methods has been overlooked in the past. Factors such as Design for Disassembly (DfD) and joining techniques are important design aspects that design engineers must be familiar with during the early stages of product development.

In order to prevent a future DfE tool from getting unwieldy due to immense quantities of data, attention must be given to the way the information is organised. Arranging information in a standardised and systematic format can help designer engineers make quick and accurate decisions. The idea is to feed these decisions into a process model that would simulate the stages of product life. This would help determine the impact a product for given criteria. On the basis of the simulation, the designer can make changes in these criteria and run the process model again in order to implement improvements. Figure 3.2 depicts the variety of information required during the product development process and the importance of efficiently organising this information.

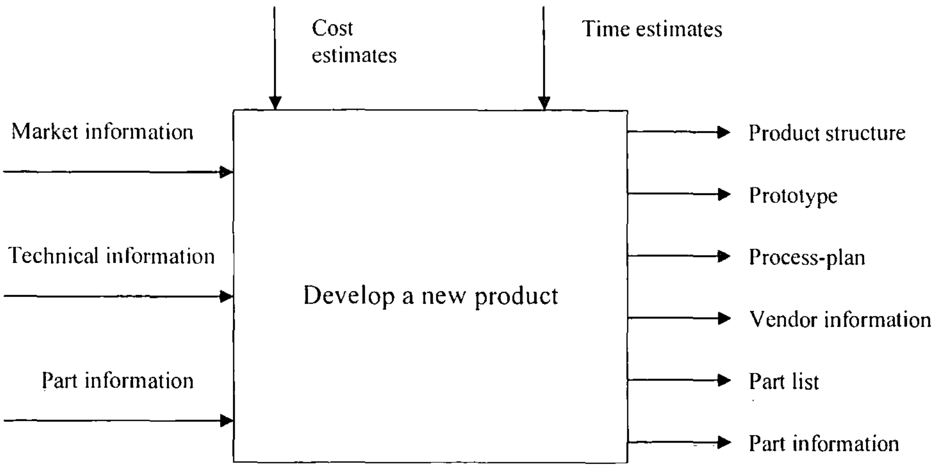

Figure 3.2: Data needed in the development of a new product

With the help of process models, designers can make quick and cost effective decisions that would enable them to determine appropriate end of life strategies for a product, thus reducing the adverse effects of product development and use on the environment. A DfE methodology of the type proposed would therefore have to address the following:

1. A method to determine both qualitative and quantitative data for a product on the basis of its product design e.g. materials, manufacturing data and estimates on emissions, hazardous wastes etc.

2. Incorporate DfD principles in the product design.

3. Assess recyclability of components and help designers determine ways of minimising overall negative impact of components that cannot be recycled.

4. Arrange data in a standardised fashion so that designers have the ability make concrete assessments of their product designs and are able to compare them to alternative designs if necessary.

3.5 Conclusion

Chapter 4 looks at ways of implementing the four key requirements enumerated previously in a design methodology in order to assist designers in the early stages of product design by providing relevant and sufficient data available in an easily interpretable form so as to enable development of process models that simulate the various stages of product development and also product life, assessing the overall impact of the product on the environment.

4 Implementation

The main challenge during product development is to be able to procure adequate amount of information for designing the product in the early stages of product design when very few product specifications have been made. Over the years, researchers have come up with various guidelines and methodologies for design engineers to follow during the early phases of product development. It has, however been seen that these guidelines and methodologies though useful in many ways, often fail to bridge gaps and essential information that ought to considered by design engineers is as a result left out. In order to overcome this problem, many researchers are now trying very hard to develop ways that enable implementing already existing guidelines and methodologies so as to help designers make decisions that are as close to the final design as possible.

Chapter 3 proposed a DfE methodology which not only recognises the importance of life cycle characterisation in order to collect relevant design information, but also the importance of incorporating Design for Disassembly (DfD) strategies. The following chapter looks at DfD aspects in greater detail and also the usefulness of ontologies in arranging design relevant data in a way that would assist designers make quick, concrete and environmentally conscious decisions. The overall aim for a DfE methodology of the type proposed is the development of process models that simulate a product's life cycle on the basis of the information received at the start of the development stage so as to determine the sustainability of the product and assess the overall environmental impact it has. This chapter looks at ways of implementing the use of design information, in particular Design for Disassembly (DfD) in ontologies that can be used in constructing process models that can successfully reduce adverse effects of a given product on our environment.

4.1 Design for Environment (DfE) Implementation: Getting the Focus Right

In order to help designers in the complicated process of product design, Hauschild et al [13] suggest ways of getting the focus of hierarchy right. The following suggestions are made in order to implement DfE:

1. Strategic considerations

At the start of this approach, functions that the product must provide are analysed [Appendix 1, Appendix 2]. The optimal ways of providing these functions are also thought of simultaneously. The considerations should include the strategic perspective that sustainability in the long run may focus the design engineers to reconsider their product strategy.

2. Focusing within the product life

Once the type of product has been decided upon, a life cycle perspective must be applied. Identifying the most important environmental impacts by performing a life cycle assessment of a product does this. For instance [Appendix 2], design considerations may include the designer to assess the reusability and recyclability of the materials and determine the extent of harmful emissions and by-products as a result of manufacturing the product components.

LCA can be performed at different stages of product the development process. During the early stages of product development the possibilities for changes and therefore for improvement of the environmental characteristics are large. However, LCA is not relevant to be performed at this stage as the product is very loosely conceptualised. Later in the product development process, it is possible to analyse consequences of small design changes. The improvement potentials are modest at this stage. The environmental issues identified by LCA have to be checked for improvement potentials by analysing potential changes in the product, before the improvement goals can be defined in the specification of the development process.

Implementing DfE:

Once product developers have identified global priorities of the product's life cycle along with requirements in legislation and standards, DfE tools can be selected to optimise the product according to the priorities set. The tools can be developed specifically for the identified priorities or they can be chosen among the many existing DfE tools which focus on optimisation stage, selection of best raw materials, manufacturing processes, assembly methods. These address the issue of designers being able to procure adequate amounts of information for product design.

The hierarchy of focusing does not require LCA be performed every time the product undergoes development. However, the approach does stress on the importance of understanding that requirements for the product development must be based on the life cycle impacts of the product.

4.2 Design for Disassembly (DfD)

The design methodology proposed for development from Chapter 3 recognises the importance of incorporating DfD [Appendix2] in product design. Although numerous methodologies have been developed in order to help make the product design phase easier, it has been noted that a systematic methodology to incorporate disassembly considerations in product design and enable quantitative evaluation of the design is absent. Disassemblability [34], [49] of a product is a function of several parameters such as exertion of manual force for disassembly, degree of precision required for effective tool placement, weight, size, material and shape of components being disassembled, use of hand tools etc. Products may be disassembled to enable maintenance, enhance serviceability and/or to affect end-of-life (EOL) objectives such as reuse, remanufacture and recycling. In fact, because of increase in environmental awareness, EOL objectives such as component reuse (components from retired product being used without up gradation in a new product), remanufacture (components from a retired product being used in a new product after technological up gradation) and recycling (reuse at material level) constitute some of the most important reasons for disassembling products.

Quantitative design information is the single most important source of information available to the designer. Research efforts in addressing this issue have been few. Although performing a Life cycle assessment (LCA) helps determine quantitative design information, only a few independent researchers have been able to do a quantitative evaluation of a design from the disassembly perspective.

Most of the algorithms developed for the implementation of DfD focus on the theoretical part of the product disassembly process. For instance, optimisation algorithms based on economic analysis, CAD algorithms, etc. These have failed to consider crucial factors such as [34]:

- The magnitude of manual force required to effect disassembly.
- The need for specialised manual tools in order to facilitate disassembly.
- Accessibility issue to enhance quick and easy disassembly.
- The need for the assumption of irregular working postures for a prolonged period of time.

It is important to take into account the ergonomic aspects of the disassembly process and special provisions need to be made so as to incorporate the above factors into disassembly algorithms in order to account for these factors. One of reasons why ergonomic considerations must be made is because the disassembly process is still largely manual in nature. An effective disassembly algorithm should introduce the practical aspect into disassembly evaluation. Such considerations would facilitate the subsequent automation of the disassembly process in the future.

In the past, the various disassembly methodologies developed by researchers have been concentrated on issues such as disassembly sequence planning, disassembly evaluation and analysis and product recovery. Thierry et al. [50] developed the Product Recovery Management (PRM) approach wherein returned products could be recovered at four levels: product, module, part and material level. Krikke et al [51] considered the problem at the tactical management level so as to determine the optimal product recovery and disposal (PRD) strategy. The aim of disassembly was to make separate recovery or disposal possible for every single subassembly. In the case of a Disassembly Sequence Plan (DSP), a sequence of disassembly tasks begins with a product to be disassembled and terminates in a state where all the desired parts of the product are disconnected [49]. A DSP aims to optimise product recovery through the minimisation of cost, maximisation of material recovery, minimisation of disassembly time using mathematical techniques such as linear programming, dynamic programming and graphical tools. The disassembly methodology developed by Desai et al. [34] assigns weightage to numerous factors such as size and shape of components being disassembled, weight, frequency of disassembly tasks, requirement of manpower, postural requirements and material handling requirements. This methodology consists of the following distinct elements: A numeric disassemblability evaluation score and Systematic application of DfD methodology.

On the basis of the influence of parameters such as degree of accessibility of fasteners and components, amount of force required in disengaging fasteners, precision required, tools and design factors such as weight, shape, size of components being disassembled, numerical scores are assigned. These scores in turn help assess disassemblability and determine EoL options for each component. The EoL option assigned to each component could be Reuse, Remanufacturing and Recycling. Incineration and land filling are not considered as EoL options since this methodology was developed to enable non-destructive disassembly of all product structures.

The logic for assigning EoL options (Figure 4.1) to components early on during the evaluation process is to make sure that components destined for reuse, are considered first for design changes. Design changes are made to these components may in turn require changed to be made to other components as well.

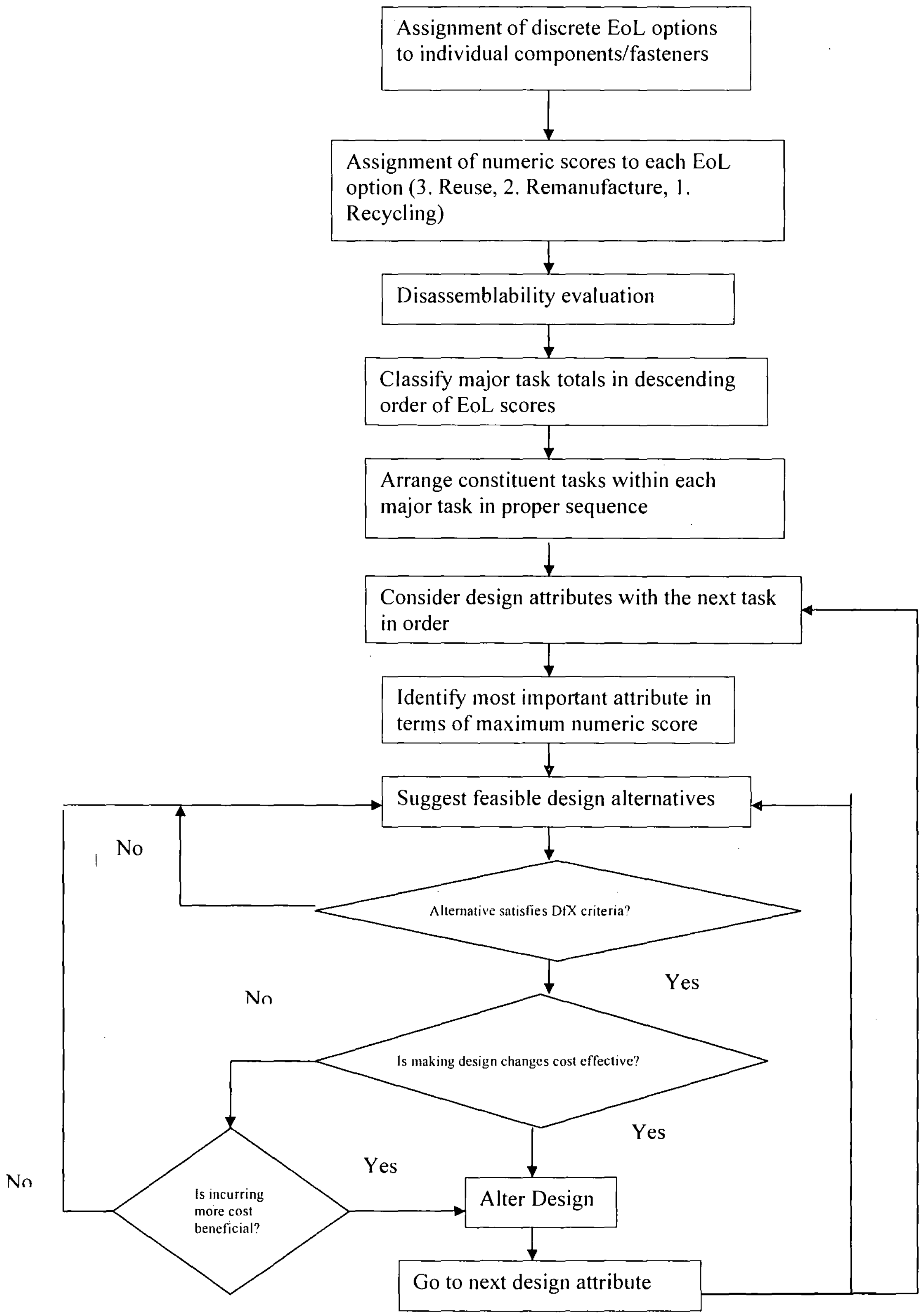

Fig 4.1 Hierarchical reasoning of the DfD algorithm [48]

4.3 Ontologies and Process Models

In order to implement Design for Disassembly (DfD) methodologies, it is important for the designers to have access to large amounts of quantitative data. Since managing large quantities of data can be extremely cumbersome, researchers have developed Ontologies using various software packages such as Unified Modelling Language (UML), Protégé and IDEF. Unlike taxonomies, which essentially only classify data, ontologies, not only classify information but also define characteristics of every attribute present in the classification. In the case of product design, this would help design engineers gather relevant data and properties associated with it.

An ontology is a vocabulary that describes all of the objects of interest in the domain and the relations between them. They allow knowledge of a domain to be shared between agents (including humans). This allows knowledge to be reused more easily and also an agent to perform inference with its current knowledge. Ontologies provide the critical semantic foundation for many rapidly expanding technologies such as software agents, e-commerce and knowledge management. For instance, the ontology Dublin Core provides a simple and standardised set of conventions for describing things online in ways that make them easier to find. Dublin Core is widely used to describe digital materials such as video, sound, image, text, and composite media like web pages [52].

Process models help define a given process in great detail by characterising every stage of the procedure. This idea can therefore be incorporated in product development, where the engineer must make numerous decisions simultaneously. Process models not only simulate the entire process, but help save costs and time as design engineers would not have to go through the trouble of creating a prototype design. All the characteristics that have been defined in the ontology would be used to simulate the process model and depending on the end results changes could be made till a desired result is reached. In this manner, ontologies and process models can be used to determine appropriate end-of-life strategies and also minimise the effects of manufacturing and using a product on the environment.

Ontologies can be implemented using various modelling languages; some of these are discussed below.

The Unified Modelling Language (UML) [52, 53]:

UML is not just a notation for drawing diagrams, but also a complete language for capturing semantics (knowledge) on a subject and expressing knowledge (syntax) regarding the subject for the purpose of communication. UML is used for specifying, visualising, constructing, and documenting systems. It is based on the object-oriented paradigm and is an evolutionary general-purpose, broadly applicable, tool-supported, industry-standardised modelling language. UML can be applied to different kinds of systems, domains, and methods or processes and enables the capturing, communicating, and leveraging of strategic, tactical, and operational knowledge to facilitate increasing value by increasing quality, reducing costs, and reducing time-to-market while managing risks and being proactive in regard to ever-increasing change and complexity. :

Though UML has been applied widely in industry, its applicability is detailed to product design of, for instance mechanical parts is unproven. This is an area where UML has still to develop. A second potential drawback of UML is that its notation may not be visually explicit. It is also hard to ensure consistent product lifecycle models with respect to constraints within the model as well as with those imposed from outside, such as by safety regulations or by the market. A possible way to enforce and maintain model consistency is by using an algorithm where many of the constraints are recognised as subjective or would depend on missing information where human intervention would be required.

Using Protégé with UML:

Protégé is a java based graphical tool for constructing ontologies. Very recently plugins for UML have also been added. Holger Knublauch has in his research tested whether Protégé can convert a given ontology into a UML representation [54].

The Protégé knowledge model, Open Knowledge Base Connectivity (OKBC) and UML allow very similar constructs:
- UML classes can be compared to OKBC classes
- UML objects are similar to OKBC instances
- UML attributes and relationships are comparable to OKBC slots

Protégé has been found to be suitable platform for interchanging models in standard languages such as UML. The wide adoption of Protégé's support for UML has demonstrated how important it is in ontology construction. On the other hand, OKBC provides a very flexible metamodelling architecture that can be easily extended to capture other languages than those natively supported by Protégé.

IDEF [55]:

The IDEF suite of modelling approaches, which comprises IDEF0, IDEF1, IDEF1x, IDEF3 and other graphically based modelling notations have been applied extensively in support of large industrial engineering projects. Individually these notations have been designed to model enterprises from a defined point of view, such as 'function viewpoint' or an 'information viewpoint'. This is both a strength and weakness of IDEF.

Since IDEF has been developed over decades, there is no overarching modelling framework and interconnects the various IDEF notations. Each can be individually applied and reapplied, in a variety of ways and its use can be supported by a selection of proprietary systems engineering tools. However, the downside of not having an overarching IDEF modelling framework is that, when carrying out multi-perspective modelling of any given complex domain, difficulties arise in communicating various domain concerns between different domain experts, because the models will not naturally be coherent with one another. Essentially, therefore the problem of achieving an integrated use of multiple IDEF notations and their supporting systems engineering tools is left to the users to solve. Generally, where large scale, complex systems require the use of IDEF notations then model integration is carried out in an ad hoc manner. This can be expected to incur significant project costs and can also inhibit model reuse and therefore is unlikely to yield solutions that can be readily reapplied.

4.4 Implementation of DfD Principles in a Proposed DfE Methodology

In order to implement Design for Disassembly (DfD) in a DfE methodology a large amount of quantitative data is required. This data can be classified in ontologies which in turn can be accessed by designers in the early stages of product design itself. As an example of the kind of data required to implement DfD, the table below enumerates some known assembly methods and their corresponding disassembly techniques.

Assembly Methods		Disassembly Methods	
I.	Permanent Methods	I.	Destructive Disassembly
(i)	Welding	(i)	Use of brute force
(ii)	Brazing	(ii)	Stripping
(iii)	Soldering	(iii)	.
(iv)	Crimping	(iv)	.
(v)	.		
(vi)	.		
II.	Non-Permanent Methods	II.	Non-Destructive Disassembly
(i)	Mechanical fasteners e.g. nuts, bolts, screws	(i)	Use of manual force
(ii)	Snap fits	(ii)	Use of robotic disassembly methods
(iii)	.	(iii)	.
(iv)	.	(iv)	.

Table 4.1: Assembly and corresponding Disassembly Methods

The disassembly methods used at the end of the product's life determines the End of Life (EOL) strategy that designers would employ for the product. For instance, non-destructively disassembly results in product components that require none or little modifications for further reuse. On the other hand, destructively disassembly results in components that are often damaged beyond repair that must be sent to the landfill for disposal. In order to determine the disassembly techniques and subsequent EOL strategy, a large amount of quantitative data is required. This data is used to decide suitable and feasible assembly methods for the product. Thus, Design for Disassembly (DfD) is incorporated in the development stages of the product itself.

In order to increase product sustainability, emphasis is being places on non-permanent assembly methods. This is because these require non-destructive disassembly which ensures reusability of product components. In case of non-destructively disassembly, it is essential for the designer to know before-hand itself various quantities such as, the amount of force required to take apart the product components, the extent of damage the component suffers if any, the method of disassembly of hazardous parts if any, the overall costs etc. These quantities are compared against those of other disassembly methods and the method that is the most feasible and that ensures least environmental impact is chosen.

4.5 Conclusion

The design considerations in order to implement DfE [Appendix 2] vary greatly with conventional design considerations [Appendix 1]. The principles for the development of a design methodology are enumerated in Chapter 3. These aim at addressing four key issues. The first, procurement of qualitative and quantitative data is achieved through the use of current DfE tools such as LCA. Design for Disassembly (DfD) is one of the several aspects designers must consider during product development. DfD can be incorporated in product design by taking into consideration various joining processes. The use of ontologies can help designers deal with cumbersome data. Ontologies can help designers share and reuse relevant information. Unlike taxonomies, ontologies not only define and characterise given attributes, but also describe the relations between the various attributes. For instance, through ontologies designers can implement Design for Environment (DfE) by using data such as the kind illustrated in table 4.1 i.e. various disassembly and assembly techniques, to develop process models that can eventually help simulate the overall product design and thereby establish the methods of dismantling and reusability of the product components at the end of the product's useful life. Process models can help address the issue of determining recyclability of product components. They help save time, costs and increase overall efficiency of product development. The main challenge lies in procuring adequate amounts of data so as to construct these ontologies and process models that can help design engineers use the required data quickly and effectively at the earliest possible stages during product design.

The aim of this study is to minimise the influence of the Design Paradox, where designers lack concrete information in the conceptualisation phase of product development. A case study demonstrating product design from a life cycle perspective is carried in Chapter 5. The case study also aims to emphasise the importance of a standardised tool that would help designers procure design relevant data when required. Two design scenarios, one using Design for Disassembly (DfD) and the other not, are compared and the results are discussed. The benefits of a Design for Environment (DfE) methodology based on the principles previously discussed are clearly demonstrated through its implementation in the case study given in the following chapter.

5 Case Study

5.1 Introduction

In order to illustrate methods of improving product sustainability using design principles, the following case study has been carried out using the example of designing a passenger car door. Two design scenarios are being presented, the first where the product design forgoes any environmental considerations and the second where design considerations are integrated in the initial stages of the design process itself. The difference in design approaches has been highlighted along with the importance of access to key design information at the start of the design procedure.

By looking at the product design process from a life-cycle point of view, a tool that can define in detail every stage of the product's life has been proposed in this dissertation. Every sub-process that takes place in the product's life, right from the manufacturing stage to the use and disposal stage is carried out on the basis of certain criteria, which determine the final outcome. Making changes in the criteria and considerations for a process would result in different outcomes. Subsequently, a tool that can simulate each sub-process on the basis of known criteria to which changes can be made by the user has been proposed. Such a tool would ideally help the designer choose process criteria that would enable designers to construct a product that has minimum impact on the environment.

5.2 Case Study Methodology

In order to construct a tool that would assist designers in making key decisions that eventually influence the environmental friendliness of the product, the following case study aims at highlighting important design aspects such as disassembly and end of life solutions. In the past, these aspects were often overlooked.

The main idea is to be able to help designers procure relevant information at the earliest possible stages of product development. This is done by looking at various aspects such as materials, manufacturing processes, assembly techniques and more recently disassembly and end-of-life management techniques. By providing the designer with data on the above-mentioned design areas from a life-cycle point of view, the overall design of a product can be made more environmentally sustainable. Assessing the impact of the product design at every stage gives designers an idea of the extent of possible environmental damage. Incorporating solutions to these end of life problems would certainly help to minimise the overall damage.

In the following chapter, two design scenarios are presented. Case 1 aims at fulfilling the various function specifications in an economic manner. On the other hand Case 2 incorporates Design for Environment (DfE) principles that enable reuse and remanufacture of product components after it has been used for its primary functions. This is done by providing the designer with all the relevant supporting data that enables determining the impact the product will have during and at the end of its life, at every stage of design [Appendix 1, Appendix 2].

The DfE tool proposed serves as an extension of EEA and LCA. These are complementary tools which when used together provide the designer with both qualitative and quantitative data. However, in order to assess End of Life (EoL) options at every stage of design and to assess the impact of the product at every stage of its life, Design for Disassembly (DfD) must be addressed.

The design processes comprises four stages. The first is clarifying the task: The design is analysed and information is collected. Requirements and constraints are established and listed in a requirements specification. Conceptual design is the next step. Essential problems are identified, function structures are established and concept variants are elaborated and evaluated in order to determine the principal solution. After the conceptual design, Embodiment design is carried out. Preliminary layouts are established. Technical and economic considerations are taken into account in order to evaluate and reject and/or combine the preliminary layouts so as to produce a definitive layout. The final stage of the design process is the Detail design stage. Production documents are produced implying an entire specification of arrangement, dimensions, materials and tolerances of all the parts in the product [28].

The aim of the case study is to measure the overall benefits of using a DfE methodology that implements the design principles discussed earlier. Ideally, the designer would like to measure the total impact of the product on the environment before actually finalising the product design. This would involve a sum analysis of all design aspects such as materials selection, manufacturing processes selection, assembly and disassembly methods and finally reusability of components in the early stages of design. This, for instance, can be done by determining suitable manufacturing processes by implementing DfE. However, these can be determined only once the product requirements have been clarified and precise data pertaining to product development has been systematically organised for easy reference by the designer as and when required. Both case study scenarios are based on the designer "asking" design relevant questions at every stage of product development. However, in design 2 the designer is "asking" design relevant to minimise negative environmental impact. This kind of analysis is carried out at every stage of the design process and enables the designer to judge the most effective ways of developing the product from an environmental perspective whether it be selection of suitable materials or appropriate manufacturing processes.

5.3 The Car Door

This case study uses the design process methodology developed by Pahl and Beitz [28] in order to design a car door. Two cases are considered; the first where a designer designs a car door solely to fulfil the required functions without considering disassembly and end of life strategies such as reuse and recycle and the second where it is assumed that a designer is provided with enough supporting data in order to carry out an EEA and LCA so as to optimise the door design in order to include environmental considerations and increase product sustainability. The differences in design considerations for the two cases are then enumerated and analysed. This, it is hoped would illustrate the important data required by DfE tool developers and design engineers for successful optimisation of product development.

5.3.1 Case 1: Car Door Design without Environmental Considerations

This instance of product design aims to fulfil the basic functions of the passenger car door. The functions a car door must fulfil are:

- Protect passengers from the outside environment
- Protect passengers from collisions and side impacts
- Reduce noise and vibrations
- The door must open and shut

Identifying the functions of the product helps in clarifying the task at hand. The next step is the conceptualisation phase. This stage of the design process involves the designers generating different ideas for constructing the product. The main function of a passenger car door is to provide protection from collisions and side impacts. Appendix 1 provides designers with a set of "questions" that must be "answered" during the development of the passenger car door. These pertain to the kinds of materials and manufacturing products that can be used so as to develop a product that fulfils the required functions in an economical manner. Designers choose to work with metals such as steel and aluminium as these provide sufficient strength. Also, because these metals are used widely, manufacturers are well accustomed with the process methods these require. In the case of a car door, metals can be easily stamped into the desired shape. The car door consists of two components, the outer skin and the inner shell. The inner shell is where the door locking mechanism, window mechanism and other peripheral components are installed. The outer skin and the inner skin of the door are usually welded or crimped together (Figure 5.1). Once the finishing processes such as painting have taken place, the entire door assembly is mounted onto the car frame using hinges and bolts.

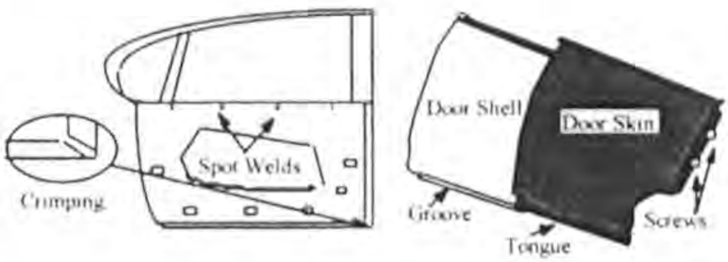

Figure 5.1: Joining and assembly of car door components

5.3.2 Case 2: Car Door Design Incorporating Environmental Considerations

The functions that must be fulfilled by the car door are:

- Protect passengers from the outside environment
- Protect passengers from collisions and side impacts
- Reduce noise and vibrations
- The door must open and shut
- Minimise overall environmental impact

Unlike Case 1, the additional function to be fulfilled for the new design is to minimise the overall environmental impact and to increase recyclability. The shortcomings of the previous design are established [Appendix 2]. The main disadvantage of the design in Case 1 was that at its end of life, destructive disassembly was required and this severely limits the reuse of the product components. The proposed DfE methodology is a combination of LCA and EEA, therefore provides the designer with both qualitative and quantitative information the short-listed materials. It also places emphasis on DfD. Therefore, the materials, namely, steel, aluminium, plastics, metal/plastic hybrids are chosen for the design [Appendix 2]. Metals provide strength required to minimise impacts while plastics and hybrids materials can be used for the interiors. These materials are also capable of being remanufactured and reused. Unlike the conventional design method discussed earlier, the new design uses the proposed DfE methodology which is more advantageous as it answers the designers' environment related questions in the early stages of design itself. Through the use of this tool, the designer is able to procure information such as material properties, the measure of recyclability, remanufacturing methods, emissions and the scale of overall damage to the environment if any in the design stage itself.

Once the materials for the product are selected, suitable manufacturing processes associated with them are short-listed. Metals are usually stamped and pressed while plastics are tailored through extrusion and thermoforming processes. Unlike the passenger door design in Case 1, the improved door design comprises three main components, namely, the outer panel, the inner panel (Figure 5.2) and the door system (Figure 5.3). The outer panel is made out of steel or aluminium and is a stamped into the required shape. The door system consists of a door carrier that is made out of either plastic or steel and has the window mechanism, latches, power closure mechanism attached to it. The inner panel can be made out of thermoplastics, metal/plastic hybrids or fibre reinforced polyurethanes using the process of thermoforming.

Figure 5.2: Inner door panel [Faurecia doors]

Figure 5.3: Door carrier [Faurecia doors]

The principles proposed for the development of a new DfE methodology encourages designers to lay greater emphasis on joining methods that will eventually influence the methods of disassembly and thus determine the extent of reusability of the product components. In order to simplify disassembly and also maintenance during the product's lifetime, it is decided that the current design will comprise three main modules and not two like in the old design. The joining methods are determined using the proposed DfE methodology. These include joining components mostly through the use of mechanical fasteners that will enable non-destructive assembly. Mechanical fasteners used can be made of metals as well as non-metals. Non-metal fasteners such as plastic screws are especially useful because they do not rust like metals do when subjected to the moisture present in the environment. However, at extremely high temperatures, plastics may have a tendency to fuse with the adjoining surfaces.

The three car modules are attached together using plastic screws and bolts and also joining techniques such as the 'tongue and groove' design where one part is mounted on to the other by sliding it over a groove built in the second component. The parts are the bolted together to minimise vibrations. In some cases, an extruded component made out of aluminium or steel called an intrusion beam is bolted across the lower part of the outer panel. The function of the intrusion beam is to provide extra protection against side impact collisions.

A proposed DfE methodology aims to provide designers with adequate information on the materials used for joining with regard to their characteristics and behaviours under various environmental conditions so that designers are able to select the most appropriate joining mechanism. Once the joining methods have been decided on, the designer must ensure ways of easy assembly and disassembly. A detailed analysis on the components of the passenger car door must be carried out so as to determine the overall extent of reusability of all the parts. Thus, once the product reaches its end of life, information regarding remanufacturing as well as disposal would be available.

Though design of a passenger car door serves as a case study in this dissertation, other product designs too may require the designer making a number of decisions simultaneously on the basis of vast amounts of data. Data arranged in ontologies would not only help simplify design decisions, but would also assist the designers in making accurate decisions. In the current case study, questions enumerated in Appendix 2 serve as guidelines in not just designing a passenger car door that fulfils its primary functions of protecting passengers for impacts and allowing an access point into the car, but also serves as a product whose components can be easily disassembled and reused when the product reaches its end of life.

5.4 Analysis of the Design Procedures Used for Case 1 and Case 2 (Appendices 1 & 2)

Appendices 1 and 2 enumerate the stepwise design considerations a designer must make during product design for each of the given cases.

With regard to materials used, it is seen that the previous design described in Case 1 relies on the use of metals such a steel and aluminium. Metals comprise about 76% of the car body. Although steel has been used traditionally, more and more car manufacturers are using non-ferrous metals such as aluminium and magnesium. Non-ferrous metals are lighter and are able to provide the required strength. Apart from this, aluminium is known to be easily recyclable. Newer designs have also been increasingly adopting plastics in their designs. A lot of new materials have been successful at replacing metal components because not only do they fit the safety standards, but also help reduce weight. In the case of an automobile, weight reductions can help lower fuel consumption thereby helping promote environmental friendliness. There are a number of different kinds of plastics available and all of these are recyclable. Therefore, using new materials provides not just better performance, but also greater environmental sustainability.

The joining techniques used in both design scenarios differ greatly. Not much thought has been given to disassembly techniques in older products designs. For instance, design Case 1 uses welding and crimping methods for joining the car door components together. These are both permanent joining methods that eventually require destructively disassembly methods to be taken apart. This results in permanent damage of components, so much so that at times parts must be disposed off in landfills because they have incurred too much damage to be remanufactured. The joining techniques in design Case 2 are mechanical joining techniques, i.e. mechanical fasteners such as screws and bolts are used to assemble the car door components together. These not only enable easy disassembly at the end of the product's life, but also help in general repair and maintenance during the life of the product. Non-destructive disassembly helps disassemble components with little or no damage. The components can therefore be easily reused and remanufactured.

Although mechanical fasteners help improve disassembly of the product, factors such as material choice and compatibility play a big role. For instance, metals in contact may corrode thus weakening the joint. On the other hand, plastics joined together may fuse, thereby making disassembly difficult. Therefore, product developers must pay close attention to material compatibility and factors such as temperature, humidity etc. of the environment so as to minimise the chances of designing a poor joint.

In order to ensure optimal design, a number of factors with regard to materials and correct manufacturing processes must be determined at the very beginning of the design phase. The car door design in Case 2 has a lower impact on the environment than the design in Case1. The design process in Case 2 looks at determining the impact of the product on the environment at every stage of product development [Appendix 2]. For instance, in Case 1, the designer chooses steel because of its strength but also because it would have traditionally been the choice given the requirements of the product in question. However, Case 2 looks at incorporating "newer" materials such as lightweight metals like aluminium and magnesium, and plastics. Using these materials resulted in a passenger car door that is lighter than the one developed in Case1 and therefore results in better vehicular performance. Case 2 requires the designer to continuously assess the environmental impact the product will have at every stage of its life including while it is being designed. This is evident by the "questions" enumerated in Appendix 2. This is also evident by the kind of joining processes used in each design. Joining processes in Case 1 are permanent and restrict maintenance and repair during the product's lifetime. They also result in the need for destructive disassembly which does not allow for the components to be reused as they usually get damaged during dismantling. On the other hand, Case 2 uses mechanical joining methods that are easy to disassemble. This is because DfD principles have been incorporated during the early design phase. The joining methods for Case 2 have been evaluated with respect to functionality as well as promoting product sustainability. This is evident by the "questions" asked by the designer in Appendix 2. Design data must be presented to designers in a systematic and precise way. This can be achieved through the use of well-constructed ontologies. This is the DfE methodology proposed in this thesis.

Although Design for Environment (DfE) is becoming increasingly important, one of the most important factors that determine the feasibility of developing a product using new design principles is the cost factor. For instance, new materials and processes can significantly improve performance and make the product environmentally friendly, however, they may require specialist knowledge and expertise apart from new machinery. These increase the overall costs of product development and design engineers may much rather continue using older design methods. It is possible that the new designs help reduce costs in the long run; however, many companies may be apprehensive of making that initial investment.

In the case of the car door design, companies such as Faurecia and Brose are already using design considerations enumerated in Appendix 2. Manufacturers and consumers (the car manufacturers) see the benefits of a 3-module door design in comparison two the traditional two-component door design. The new design is easily constructed and assembled. It allows maintenance and repair, and also easy disassembly. This not only makes it more consumer-friendly, but also reduces the impact it has on the environment as components can be dismantled from the original assembly and used again if they have not suffered damage.

5.5. Remarks

The aim of the case study presented is to demonstrate the importance of ways to promote environmental friendliness. In this case, presenting designers with design relevant data in a systematic format can help them make design decisions more quickly and effectively. Tools such as EEA and LCA can be implemented in determining the impact of the product on the environment and consequently the appropriate end of life strategy that must be employed to ensure minimal environmental damage. Design for Disassembly (DfD), it has been established, has been successful in helping designers increasing sustainability of products. However, there is scope for further improvement in other areas of design. These are discussed in further detail in the following chapter.

6 Discussion

In the past, environmental effects were ignored during the design stage for new products and processes. Consumers discarded used products, usually with only minimal remanufacturing or recycling. Although remediation and waste treatment work is being undertaken, it is clear that design changes can often be more effective at reducing environmental burdens and more efficient at reducing costs than traditional "end-of-the-pipe" clean up strategies. Therefore, the challenge of environmentally conscious design is to alter conventional design and manufacturing procedures to incorporate environmental considerations systematically and effectively.

The present study has focused on the subject of optimising the design process by incorporating life cycle thinking into the earliest stages of product development when there are still many uncertainties about the final product design. The objective is to propose a DfE support tool. This has been done by first developing a framework comprising design principles in order to enable the development of a DfE methodology in future. This methodology must characterise the stages of a given product in order to assess and minimise the overall impact of the product on the environment.

Although a number of companies are using tools such as LCA and EEA, there is a significant interest in attempts to make improvements on current DfE tools. Both LCA and EEA have shortcomings and although they are complementary tools and the DfE tool developed in this thesis is an extension of EEA and LCA. Designers require a tool that can be used in the initial stages of product design and has the ability to accurately make decisions concerning not just materials selection, manufacturing processes selection and assembly and joining methods, but also at the same time help create a sustainable product. The methodology proposed in the present study emphasises the need for incorporation of Design for Disassembly (DfD) in the design process.

6.1 Case Study

The case study in Chapter 5 compares 2 design procedures, the first where a product is developed to fulfil a given set of functions, and the second where a product is developed integrating DfE principles. The aim of the case study is to illustrate the benefits of incorporating DfE tools in product design. Case 1 of the case study looks at fulfilling the following functions:

- Protect passengers from the outside environment
- Protect passengers from collisions and side impacts
- Reduce noise and vibrations
- The door must open and shut

The passenger car door in the first design case successfully satisfies the consumers' demands. However, its recyclability is limited due to factors such as materials and joining techniques used. Case 2 on the other hand tries to promote reusability of the passenger car door. The driving factors behind carrying out the case study are to demonstrate the importance of developing a tool that helps designers derive essential design data in the early stages of product design and to apply this knowledge to implement DfE principles such as DfD and recyclability.

The materials used for the development for a two-component car door in Case 1, are metals such as steel and aluminium. Traditionally only steel was used in the construction of vehicles. However, the importance of non-ferrous metals such as aluminium and magnesium is being recognised. Non-ferrous metals such as aluminium and magnesium are lighter than steel thus lowering weight of a vehicle and improving its performance. Also, at the end of its useful life a product's aluminium content can be used again and again without loss of quality, saving energy and raw materials. The recycling process used for steel in comparison to that used for aluminium requires far more energy. Therefore, auto manufacturers are working with aluminium producing companies so as to develop components for vehicles of aluminium that can be easily dismantled and recycled.

The design in Case 2 uses not just steel and aluminium, but also plastics and plastic-metal hybrid materials. There are a number of different kinds of plastics with varying strengths and compositions. Plastics are versatile materials and can be easily recycled. In case of the three- component door design, plastics are used in the inner panel and are manufactured using the thermoforming process. Although plastics are becoming increasingly popular in industry, one major drawback of plastics producing them requires several chemical treatments that result in harmful emissions. This makes it all the more important that plastics be recycled.

Once the components have been made, they are assembled together. In Case 1, the door shell and the outer skin are joined using welding and crimping techniques. These are permanent joining procedures. In Case 2, on the other hand, the components, namely, the outer panel, the inner panel and the carrier are joined using mechanical fasteners such as screws and bolts. This enables easy disassembly of parts.

6.2 Case Study Results

The design in Case 1 is a functional design. It is an economic design that allows manufacturers to mass-produce it. The designers' aim in Case 1 has been primarily to design a product that does not require too many resources and fulfils all the required functions. The drawbacks in design Case 1 are that maintenance is extremely difficult. This is because the components have been joined using welding and crimping methods. These are permanent joining methods. Therefore, taking the parts apart results in destructively disassembly, where one or both the parts result in being damaged. A lot of times the component is damaged beyond repair and has to be disposed off altogether.

In Case 2, environmental considerations have been integrated in the design process. At every stage of the design stage, designers are provided with valuable information that helps them determine the impact of the product on the environment. The case study presents an example where only qualitative data is used, however, in reality quantitative data is also determined in order to get a clearer idea. The aim is to choose design criteria that result in minimum impact on the environment. Therefore, there is an assessment of design criteria at every stage of design. Factors such as materials, manufacturing processes and assembly methods are assessed. At every analysis stage, the product designer must take into account how the components of the product can be reused at the end of its life. The DfE methodology used in Case 2 incorporates Design for Disassembly (DfD) in the design process. For instance, the design methodology proposed in this dissertation enables designers to derive joining methods that result in non-destructive disassembly of the passenger car components which can eventually be reused. The joining methods in Case 1 allowed for only destructively disassembly, often damaging the product components thus rendering them unusable in most instances. The appropriate joining methods are determined when the product designer "asks" questions that help in not only fulfilling the product's primary function, but also help the designer assess the extent of environmental impact at that stage itself.

The joining methods used to assemble the three-component door in Case 2 are non-permanent joining methods. Mechanical fasteners such as screws and bolts are used to put the car door together. The mechanical fasteners can be made out of metal or plastic and allow non-destructive disassembly. This design allows for repair, part replacement and cleaning while the product is in use. Once the product has come to the end of its useful life, the components can be taken apart without suffering any damage and can be reused or recycled.

Companies such as Faurecia and Brose are already manufacturing car doors according to the design considerations in Case 2. Modular components with standardised interfaces and communisation of parts helps designers establish a standard that can be followed. Design 2 places emphasis not just on materials and assembly methods, but also on design for separability, cleaning, parts replacement and design for recovery and reuse. These have been implemented by incorporating Design for Disassembly (DfD) in the DfE methodology proposed in this thesis.

The methodology proposed in this dissertation is based on the principle of better knowledge management, where designers can access relevant design data and make decisions that are more or less final in the early stages of product design itself, thus serving as not only an economical design tool but also one that enables more environmentally friendly design. The use of ontologies in recording and presenting data in a systematic manner is required in order to manage the vast quantities of data needed by a design engineer in the early stages of product design. The case study, through the use of the appendices illustrates the development of the passenger car door with and without implementing DfE. In both cases, data required by the designer is enumerated qualitatively and these serve as guidelines during the design process. However, unlike Case 1, Case 2 requires the designer to determine the influence of every design decision on the environment. For this reason, the product design in Case 2 requires a lot of qualitative and quantitative data that the designer must use to compare various design options.

6.3 Remarks

To remanufacture a product, an assessment of the current design, repair process and associated costs need to be made. A detailed assessment of the process required for assembling and disassembling the product must be carried out. In case of remanufacturing a product, since the product has already been defined, EEA and LCA become easier to carry out. However, when creating an entirely new product, as mentioned previously, both EEA and LCA demonstrate disadvantages that inhibit manufacture of a product that has minimum impact on the environment.

The aim of this work has been to provide engineers with design principles that will help them develop a design tool that incorporates Design for Environment (DfE) considerations in the design process. The awareness of environmental aspects in product development has grown over the last decade and one trend in the literature on this matter has been an increasing integration of DfE tools such as LCA and EEA in the product development process. However, environmentally conscious design is an area that is being continuously researched. Although guidelines on how to optimise design have been provided over the years, it is important to remember that product development is a creative process and cannot be limited to guidelines that are too strict. Therefore, the primary aim of this study has been to provide a framework for DfE tools to be developed that provides the design engineer a way for environmental modelling and decision-making during the product development process. However, because product designs can vary to great extents, the DfE tool developed must be flexible enough so as to not inhibit the creative ideas of engineers. The main challenge is designing an entirely new product, which has never been defined before. Integrating environmental considerations in a product that has been defined previously is less complicated and allows further modifications that can be tested quite easily from an environmental point of view before implementation. Also, conclusions with respect to processes and materials can to a large degree be transferred from the studied product to other products in the same family. DfE tools that are integrated to define a product must be quick and easy to use and understand. Ideally these tools must help identify design changes that have lower costs while improving materials and recyclability. For instance, using snap fits rather than metal fasteners may have little additional cost burden at the design stage but may significantly increase recycling potential.

6.4 Industrial Significance

Manufacturing companies are continuously striving to increase their profitability and revenues. Companies are starting to recognize the impact of incorporating "green design" as long-tern benefits. There is a growing demand for manufactured goods and decreasing availability of landfill space. This is making the implementation of DfE more of a necessity than just a good idea. Many large corporations realize that being able to recycle and re-use their own parts gives them an edge, because in sue course of time compliance of DfE, DfD and other green initiatives are going to be regulated in an extremely stringent manner.

BMW is one such organization that has been continuously studying methods of increasing re-usability of its vehicles. The 1991 Z1 Roadster had plastic side panels that came apart like the halves of a walnut shell. This car is an example of designing for disassembly. It was learned that gluing or soldering in bumpers should be replaced with fasteners so that they can be taken apart easily and materials can be recycled. BMW now uses variations of polyurethane, foam and rubber so that the panel can be recycled. From being able to recycling 80% by weight of the car, BMW is now working on ways of achieving 95% recyclability [56].

Hewlett-Packard is also designing products to be recycled. Nearly all their products are manufactured keeping in mind the advantages of modular designs and the use of snap joints over glues and adhesives that make it difficult to disassembly products. Modular designs allow components to be replaced or removed with ease. HP has also made an effort to reduce the number and typed of materials used. Using moulded in-colours and finishes instead of paints, coatings and platings helps limit contaminants. In a similar manner, GE Plastics has been instrumental in recycling old computer housings into roof tiles for restaurants [57].

There are several benefits to incorporating DfE in product design. Use of DfE demonstrates environmental responsibility. With increasing consumer awareness, “green design” provides companies with a marketing edge. From a technical point of view, product design is a point where decisions on resources and manufacturing processes are made. These decisions determine the waste streams. Therefore, the result of incorporating DfE can result in not only environmentally friendly products, but also help companies reduce cycle times and overall costs through recycling and reuse of product components.

In order to increase use of DfE, tools that are easy to use must be constructed and aggressively marketed. The DfE tool proposed in this thesis, recommends users being allowed to make design decisions through the help of process models. The use of ontologies can serve as an efficient knowledge sharing tool that ensures the designer chooses efficient design parameters e.g. materials, manufacturing processes, joining methods. The process models can help simulate the behaviour of the various design parameters over the product's life and compare them against other design parameters the designer may see appropriate to use. These would help designers estimate the total cost, quality levels, measure of environmental friendliness, recyclability, reusability and the amounts of waste products e.g. emissions, contaminants, unrecyclable components etc. that would be generated by manufacturing the product in question. Thus, the proposed tool would assist design engineers make accurate decisions that are based on minimising overall environmental effects and maximising long-term profit.

6.5 Conclusion: Recommended work

Design principles discussed in this dissertation form a framework to develop a DfE methodology that will enable design engineers meet a number of requirements with greater flexibility. The design tool must be able to evaluate environmental attributes of potential product designs and also evaluate environmental attributes of existing product designs. Design engineers must be able to compare potential product designs with existing product designs and be given the means to select design parameters that enhance environmental friendliness of the product. Future work in this area would be to practically develop such a tool. To begin with, knowledge sharing tools, i.e. Ontologies must be developed to assist designers in materials, manufacturing processes and joining processes selection. Ontologies can be constructed using software packages such as UML, Protégé or IDEF3. These have been discussed briefly in Chapter 3. The use of ontologies can help designers narrow down on a set of design parameters. Once design parameters have been selected, the proposed DfE tool must be able to simulate the behaviour of the product over its life. This can be done through the help of process models. Process models are mathematical tools and can help designer engineers make a number of estimations for a given set of parameters. A process model that uses ontologies to simulate the stages of not just the design process, but also the life-cycle of a given product can help designers determine end-of-life options and assess the impact the product has on the environment under given criteria. These could be not just cost related, but also estimations on emissions, contaminants, behaviour of materials after a certain period of time, amounts of recyclable and unrecyclable materials etc. If the end results are unsatisfactory, the designer must be able to change conditions and simulate the procedure once again in order to determine the best results, thus, optimising the design process so that the impact a product has the environment is minimised. The DfE tool must also be able to compare various design possibilities and make concrete conclusions. For instance, it is possible that there will at times be unavoidable trade-offs. The process model must help negotiate these trade-offs. It is possible that for a given manufacturer, efforts to reduce solid waste through greater use of scrap materials actually results in increased amounts of pollution. Thus, with the help of process models, designers will be able to compare mathematically drawn conclusions that will help them draw concrete conclusions.

The framework investigates several aspects of product design, such as materials, processes, assembly procedures and in particular emphasis the importance of disassembly methods. However, future work on the subject requires further work to be carried on joining techniques. New and innovative joints are being developed in order to ease disassembly and cause minimum damage to components in order to ensure recyclability. When speaking of joints, it is also important to take into account compatibility of materials that are being joined and also the material that the actual joint is made out of. Also, in order to construct process models and knowledge management systems, a lot of relevant quantified data is required. This is difficult to procure, as many companies may be unwilling to share this knowledge, thus making information available at the start of the design process a challenging task.

On the whole, potential in the area of DfE is enormous. However, further research must ensure that design methods apart from developing environmentally friendly products, must also be economically viable. DfE tools must be well marketed and industry must be shown the benefits of integrating DfE tools in their design processes.

Design of Environment is being continuously researched and it is clear that there is scope for further work in the area. In order to provide relevant data at the start of the design process, a tool that would enable to engineers to determine end-of-life options needs to be constructed. Design data is extremely vast. Therefore, ontologies can be constructed in order to facilitate better knowledge management.

7 References

[1] Dowie-Bhamra, T., 1996. Design for disassembly, Co-design: The Interdisciplinary Journal of Design and Contextual Studies, pp 28-33

[2] Lagerstedt, J., Luttropp, C., Lindfors, L.-G. 2003. Functional Priorities in LCA and Design for Environment, International Journal of Life Cycle Assessment Volume 8 pp 160-166

[3] Andreasen, M. M., Hein, L., 1987. Integrated Product Development, Springer Verlag, London

[4] Pugh, S., 1991. Total Design – Integrated Methods for Successful Product Engineering, Wokingham, England Addison – Wesley Publishing Company, Wokingham

[5] Ullman, D. G., 1997. The Mechanical Design Process, McGraw Hill, New York

[6] Lagerstedt, J., 2003. Functional and Environmental Factors in the Early Phases of Product Development – Eco Functional Matrix, PhD Thesis, KTH, Stockholm

[7] Hauschild, M., Jeswiet, J., Alting, L., 2005. From Life Cycle Assessment to Sustainable Production: Status and Perspectives, Annals of CIRP Volume 54 (2) pp 70-87

[8] Boothroyd, G., Dewhurst, P., Knight, W.A., 1992. Selection of Materials and Processes for Component Parts, Proceedings of the 1992 NSF Design and Manufacturing Systems Conference, Atlanta, GA

[9] Fiksel, J. R., 1996. Design for Environment: Creating Eco-Efficient Products and Processes, McGraw-Hill, New York

[10] Glazebrook, B., Coulon, R., Abrassat, C., 2000. Towards a Product Lifecycle design tool, Proceedings of the 2000 IEEE International Symposium on Electronics and the Environment, IEEE, pp 81-85

[11] Ufford, D.A., Ward, W. J., 1999. Next Generation Design for the Environment Paradigms. Proceedings of the 1999 IEEE International Symposium on Electronics and the Environment, IEEE, pp 268-273

[12] Zhang, H.C., Yu, S.Y., 1997. An Environmentally Conscious Evaluation/Design Support Tool for Personal Computers. Proceedings of the 1997 IEEE International Symposium on Electronics and the Environment, IEEE, pp 131-136

[13] Hauschild, M., Jeswiet, J., Alting, L., 2004. Design for Environment – Do We Get The Focus Right? Annals of CIRP Volume 53 (1) pp 1-4

[14] Hill, B., 1993. Design for the Environment: An Integrated Systems Approach, IEEE International Symposium on Electronics and the Environment, Virginia, IEEE

[15] Wang, M. H., Johnson, M. R., Dutta, S., 1993. Design for Environment: An Imperative Concept in Concurrent Engineering, CE & CALS, Washington D. C.

[16] Zussman, E., Kriwet, A., Seliger, G., 1994. Disassembly Oriented Assessment Methodology to Support Design for Recycling, Annals of CIRP, Volume 43 (1) pp 9–14

[17] Powell, J.C., Craighill, A.L., Parfitt, J.P., Turner, R.K., 1996. A Lifecycle Assessment and Economic Valuation of Recycling. Journal of Environmental Planning and Management, Volume 39 (1) pp 97 –112

[18] Wenzel, H., Hauschild, M., Alting, L., 1997. Environmental Assessment of Products: Methodology, Tools, Techniques and Case Studies, Volume 1, Kluwer Academic Publishers, Hingham, MA

[19] Srinivas, H. Information for Decision Making, URL http://www.gdrc.org/decision/info-decision.html 2007-03-03

[20] Tingstroemm, J., Karlsson, R. 2006. The Relationship between Environmental Analyses and the Dialogue Process in Product Development. Journal for Cleaner Production, Volume 14 (15-16) pp 1409-1419

[21] Lindahl, M., 2000. Environmental Effect Analysis (EEA) – An Approach to Design for Environment, PhD Thesis, Department of Chemical Engineering and Technology, Royal Institute of Technology, Stockholm

[22] Hundal, M.S., 1993. Designing to Cost, Concurrent Engineering: Contemporary Issues and Modern Design Tools, Chapman and Hall, Melbourne pp 330-351

[23] Perzyk, M., Meftah O. K., 1998. Selection of Manufacturing Process in Mechanical Design, Journal of Materials Processing Technology, Volume 76 (1-3) pp 198-202

[24] Shercliff, H. R., Lovatt, A. M., 2001. Selection of Manufacturing Processes in Design and the Role of Process Modelling, Progress in Materials Science, Volume 46 pp 429-459

[25] Lovatt, A.M., Shercliff, H. R., 1998. Manufacturing Process Selection in Engineering Design. Part 2, A Methodology for Creating Task-Based Process Selection Procedures, Materials and Design, Volume 19 pp 217-230

[26] Brechet, Y., Bassetti, D., Landru, D., Salvo, L., 2001. Challenges in Materials and Process Selection, Progress in Materials Science, Volume 46 (3-4) pp 401-428

[27] Lovatt, A. M., Shercliff, H. R., 1998. Manufacturing Process Selection in Engineering Design. Part 1, Materials and Design, Volume 19 pp 205-215

[28] Pahl, G., Beitz, W., 1977. Engineering Design: A Systematic Approach, Springer-Verlag, Berlin

[29] Abel, C.A., Edwards, K.L., Ashby, M.F., 1994 Materials, Processing and the Environment in Engineering Design, Materials and Design, Volume 15 (4) pp 179-193

[30] Ashby, M.F., Miller, A., Rutter, F. Seymour, C., Wegst, U.G.K., 2005. The CES Eco-Selector-Background Reading. A white paper, Granta Design Ltd, Cambridge

[31] Chan, V., Salustri, F. A., Design for Assembly, URL http://deed.ryerson.ca/~fil/t/dfmdfa.html 2005-12-27

[32] Rose, C. M., 2000. Design for Environment: A Method for Formulating Product Eend-of-Life Strategies, PhD Thesis, Stanford University, CA

[33] Tani T., 1999. Product Development and Recycle System for Closed Substance Cycle Society. Eco Design '99: First International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Published by IEEE Computer Society Piscataway NJ pp 294-299

[34] Desai, A., Mittal, A., 2003. Evaluation of disassemblability to enable design for disassembly in mass production. International Journal of Industrial Ergonomics, Volume 32 pp 265–281

[35] Burke, D.S., Beiter, K., Ishii, K., 1992. Lifecycle Design for Recyclability, Proceedings of ASME Design Theory and Methodology Conference, Scottsdale, AZ pp 325-332

[36] Lambert, A. J. D., 1991. Linear Programming in Disassembly/Clustering Sequence Generation, Computers and Industrial Engineering, Volume 36 pp 723 – 738

[37] Brennan, L., Gupta, S. M., Taleb, K. N., 1994. Operations Planning Issues in an Assembly/Disassembly Environment, International Journal of Operations and Production Management, Volume 14 (9) pp 57–67

[38] Shyamsundar, N., Gadh, R., 1999. Geometric Abstractions to Support Disassembly, Engineering Design - IIE Transactions on Design and Manufacturing, Volume 31 (10) pp 935-946

[39] Mok, H. S., Kim, H. J., Moon, K. S., 2001. A Multi-Objective Methodology for Evaluating Product End-of-Life Options and Disassembly. The International Journal of Advanced Manufacturing Technology, Volume 18 pp 148–156

[40] Sonnenberg, M., 2001. Force and Effort Analysis of Unfastening Actions in Disassembly Processes, PhD thesis, New Jersey Institute of Technology, NJ

[41] Shu, L. H., Flowers, W., 1999. Application of a Design-for-Remanufacture Framework to the Selection of Product Life-Cycle Fastening and Joining Methods, Robotics and Computer Integrated Manufacturing, Volume 15 pp 179-190

[42] Mazumdar, S. K., 2001. Composites Manufacturing – Materials, Product and Process Engineering. CRC Press, New York

[43] Edwards, L., Endean, M., 1990. Manufacturing with Materials, Open University Butterworths, London

[44] Harjula, T., Rapoza, B; Knight, W.A.; Boothroyd, G., 1996. Design for Disassembly and the Environment, CIRP Annals - Manufacturing Technology, Volume 45 (1) pp 109-114

[45] Lindahl, M., 2006. Designers' Utilisation of DfE methods, Design Inverse Manufacturing, Product Eco-Design, Second International Symposium

[46] De Araujo, C. S., 2001. Acquisition of Product Development Tools in Industry: A Theoretical Contribution, PhD Thesis, Technical University of Denmark, Lyngby

[47] Kalpakjian, S., Schmid, S. R., 2002. Manufacturing Processes for Engineering Materials, Prentice Hall, New York

[48] Advani, S. G., Murat Sozer, E., 2002. Process Modelling in Composites Manufacturing, Taylor and Francis, London

[49] Gungor, A., Gupta, S. M., 1999. Issues in Environmentally Conscious Manufacturing and Product Recovery: A Survey, Computers and Industrial Engineering pp 811–853

[50] Thierry, M., Salomon, M., Van Nunen, J., Van Wasserhowe, L., 1995. Strategic Issues in Product Recovery Management. California Management Review, Volume 37 (2) pp 114-135

[51] Krikke, H. R., Harten, A., Schuur, P. C., 1998. On a Medium Term Recovery and Disposal Strategy for Durable Assembly Products. International Journal of Production Research, Volume 36(1) pp 111 – 139

[52] Sinan, S. A., 1998. UML in a Nutshell, O'Reilly Publication, Cambridge, MA

[53] Thimm, G., Lee, S.G., Ma, Y. S., 2006. Towards Unified Modelling of Product Lifecycles, Computers in Industry, Volume 57 pp 331–341

[54] Knublauch, H., 2003. Case Study: Using Protégé to Convert the Travel Ontology to UML and OWL, In Proceedings of 2nd International Workshop on Evaluation of Ontology-based Tools (EON 2003) (CEUR Workshop Proceedings)

[55] Cheol-Han Kim, Weston, R. H., Hodgson, A., Kyoung-Huy Lee, 2002. The Complementary Use of IDEF and UML Modelling Approaches, Computers in Industry, Volume 50 pp 35–56

[56] Kenneth, C., Design for the Environment, 2002. DRM Associates, URL www.npd-solutions.com/dfe.html

[57] Hewlett Packard Development Company, 2007. Company Information: End of Life, URL www.hp.com/hpinfo/globalcitizenship/environment/productdesign/endoflife.html

Appendix 1

The following design considerations are made for Case 1 where a car door is designed to fulfil basic functions.

1. What are the functions of the product?
- Protect passengers from the outside environment
- Protect passengers from collisions and side impacts
- Reduce noise and vibrations
- Must open and shut

2. What is the current design idea?
- Door comprises of two components assembled together

3. What are the best-suited materials?
- Metals e.g. steel, aluminium

Approximately 76% by weight of the average car is metal, most of which is comprised of sheet steel. However, in the last two decades, use of non-ferrous metals such as aluminium and magnesium has gained popularity as they can be tailored so as to provide adequate strength and help in overall weight reduction. Apart from this, Aluminium is one of the most cost effective materials to recycle.

4. Which manufacturing processes can one use to tailor these materials?
- Metal stamping, pressing

5. What joining techniques can one use to assemble the two components together?
- Welding and crimping, mechanical fasteners e.g. screws, bolts

6. How is the door assembled onto the car frame?
- Hinges and Bolts

7. Is the product easy to produce?

- Yes, manufacturing processes such as metal stamping and pressing have been used in industry for a number of years. Therefore, apart from experience in working with these materials, industry has developed economic production techniques.

8. Is the product easy to assemble?

- Yes, welding and crimping are joining methods manufacturers are familiar with. Other joining techniques include mechanical fasteners such as screws and bolts.

9. Are the production costs reasonable?

- Yes

10. Is maintenance easy?

- Damage incurred would result in the entire door having to be replaced with a new one.

As mentioned in Chapter 4, the design considerations 1 – 10 are strategic considerations and enable fulfilment only of primary functionality of the product. DfE has not been incorporated, thus limiting reuse of the product. The objectives of the design methodology proposed in Chapter 3 are not being met through use of the above design principle.

Appendix 2

The following design considerations are made for Case 2 where environmental issues are integrated in the design process.

1. What are the functions of the product?
- Protect passengers from the outside environment
- Protect passengers from collisions and side impacts
- Reduce noise and vibrations
- Must open and shut
- Minimise overall environmental impact

2. Does the previous design fulfil these functions?
- Yes, the previous design uses materials such as steel and aluminium that provide strength. The materials are easily tailored into the required geometric form. A shortcoming of the previous design is that it requires destructively disassembly, which limits its reuse and recycling capabilities.

3. What are the best-suited materials?
- Metals e.g. steel, aluminium, plastics, metal/plastic hybrids.

4. Are the materials reusable?
- Metals such as steel and aluminium can be recycled. Plastics are also easily recyclable.

5. Which manufacturing processes can one use to tailor these materials?
- Metal stamping and pressing, Plastic extrusion and thermoforming

6. What is the impact of the manufacturing processes on the environment?
- Metal extraction and production requires energy and also chemical treatments that have adverse effects on the environment. Metals are used widely and therefore the impact of metals can only be minimised and not done away with completely.

Plastic production involves the use of harmful chemicals and can have adverse effects on the environment as well as humans. However, plastics can be recycled, reducing unnecessary emissions and reduction in energy consumption.

7. What joining techniques can one use to assemble the three modules together?
- Mechanical joining techniques with the help of fasteners e.g. screws and bolts made out of not just metals, but also plastics

8. Is the door easily assembled onto the car frame?
- Yes, with the help of hinges and bolts

9. Is maintenance easy?
- Yes, mechanical fasteners enable non-destructive disassembly, thus minimising the damage product components suffer. This enables reuse and recycling.

10. Are the production costs reasonable?
- Yes, design already being applied by companies such as Faurecia and Brose.

11. Can components be reused?
- Yes, Design for Disassembly (DfD) along with materials and manufacturing processes considerations ensure product components can be used again. DfD ensures non-destructive assembly. The materials and processes considerations make increase reccyclability.

12. Is product environmentally friendly?
- More environmentally friendly than previous design due to integration of Design for Disassembly (DfD) to incorporate non-destructive disassembly methods in design.

The above design tool not only considers fulfilment of primary functionality and manufacture of the proposed product, but also looks at ways of implementing DfE. For instance, design considerations 4 and 6 help designers analyse the potential for reuse of materials and also the impact of the manufacturing processes that are used to tailor these materials. This is an instance of LCA being implemented. Further, disassembly methods have been carefully studied so as to optimise the reuse of product components through non-destructive disassembly. It is assumed that information needed to compare materials, manufacturing processes, assembly and disassembly methods is easily available. In reality, however, designers require a means of comparing and analysing various data. This can be achieved through the use of a tool such as an ontology combined with a specially constructed process model.