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Development of a Disassembly Methodology for DFE

In One Volume

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Declaration

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

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Prologue

The research described in this thesis was developed as part of the Information Management for Green Design (IMAGREE) Project. The IMAGREE Project was funded by Enterprise Ireland under Strategic Research Grant Scheme as a partnership project between Galway-Mayo Institute of Technology and CIMRU University of Galway. The project aimed to develop a CAD integrated software tool to support environmental information management for design.

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Glossary

BOM	Bill of Materials
CAD	Computer Aided Design
CBR	Case Based Reasoning
CE	Concurrent Engineering
DFD	Design for Disassembly
DFE	Design for the Environment
DFMA	Design for Manufacturing and Assembly
DFR	Design for Recycling
DPP	Disassembly Process Plan
ECD	Environmentally Conscious Design
ECM	Environmentally Conscious Manufacturing
ECP	Environmentally Conscious Production
EOLV	End of Life Vehicles
ESP	Environmentally Superior Products
IAS	Impact Assessment System
LCA	Life Cycle Assessment
LCD	Life Cycle Design
SAM	Structure Assessment Method
WEEE	Waste of Electrical and Electronic Equipment

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Chapter 1. Thesis Motivation and Layout

1.1 Introduction
1.2 Driving Forces for Environmentally Conscious Design
1.3 Objectives and Approach
1.4 Thesis Layout
1.5 Summary

1.1 Introduction

Introducing a new product into the market initiates a production activity, which uses resources and creates waste. Lately the large amount of new products as well as the old ones, which have became obsolete, is leading to damage on the natural environment. That impact has been noticed since the Industrial Revolution and some of the clearest effects are pollution of water, lands and air. This pollution in extreme cases can even change the natural life cycles of some places where its ecosystem can be in danger.

The problem was identified as serious four decades ago and since then, in some cases, major effort has been put in place to correct emissions. Although the research and first measures were a good starting point, it is clear that those corrective measures are not enough to face such a big problem in a realistic manner. Once it is clear that a corrective approach is not sufficient, preventive measures must be applied. The challenge is to modify current design and manufacturing practices to consider environmental attributes in products and processes. This "simple" change is quite difficult if it is not applied carefully. This is because designers might face conflictive decisions which usually are time consuming. Moreover, designers are already under pressure to meet existing schedules and strict cost requirements that implies resistance from them to change their current practices.

In this cost-effectiveness problem the consumers also play an important role. This is because they decide if buying environmentally friendly products is a worthwhile practice even in cases where the final cost may be higher.

1.2 Driving Forces for Environmentally Conscious Design

The environmental degradation derives mainly from three sources as follows [Roc99]:

- The excessive consumption of energy and natural resources [Kim97a]
- The irrational disposal of wastes [Fus96] [Kim97a]
- The increased emission of toxic substances [All95]

The degradation of ecosystems is ever increasing and consequently public opinion and governments are pushing industry to consider the environmental performance of its products and to control the environmental damage derived from their activities [Roc99]. Environmentally Conscious Manufacturing (ECM) is a term that has been coined to enclose the initiatives taken in response to environmental degradation. Two main driving forces for Environmentally Conscious Manufacturing can be identified as follows:

- Government Driven Pressures
- Market Driven Pressures

Government driven pressures include the introduction of new taxes (Eco-tax) and new legislation. One example of eco-tax is the variation of fees according to the emissions of a factory or also the taxation of vehicles depending on an emission test.

Eco-legislation is a set of compulsory rules that people and companies have to comply with. Examples of eco-legislation are directives like Waste of Electrical and Electronic Equipment (WEEE) in the electronic sector, and End of Life Vehicles (EOLV) in the automotive industry. Usually these laws set some targets that their products have to meet if they want to be sold on the market.

Market driven pressures have diverse sources but in essence most of them are mainly driven by customer's requirements. Roche lists a set of market drivers as follows [Roc99]:

- Industrial standards
- Eco-labelling schemes
- New environmental markets
- Marketing benefits

- Supplier requirements
- Product differentiation
- Costs savings

1.3 Objectives and Approach

The aim of this research will be to investigate the already existing DFE approaches in order to create new disassembly methodologies that can be appropriately integrated into current design practices. This entails the investigation of ways to incorporate the DFE practices into Computer Aided Design tools.

The aim of the research programme was achieved through the following set of objectives:

- Review and understanding of the state of the art on design methodologies and practices
- Achieve a complete understanding of existing DFE tools and methodologies available in the literature
- Study of basic needs for efficient DFE practice including
  - Early implementation of DFE in the design process
  - Integration of DFE into CAD systems and the design process
- Continuous improvement of the existing DFE Workbench software tool
- Testing of the DFE Workbench tool by means of industrial case studies using scientific methods
- Research in the area of Design for Disassembly through journal and conference papers
- Development of a methodology, in the area of Design for Disassembly, to find the optimal disassembly routes in any product to be implemented in the DFE Workbench software tool
- Testing, validation and documentation of the new methodology
- Publication of the results of the research in journal and conference papers

1.4 Thesis Layout

The thesis is divided in six chapters that summarise the research and testing carried out by the author. Figure 1.1 presents a schematic of the structure of the thesis which in essence represents the objectives and approach to work described in the previous section.

Chapter one

This first chapter explains the problems created by the production activities and why environmentalism has emerged. Later the driving forces behind environmentally conscious design are discussed. This chapter also presents the objectives of the research as well as the approach to the work. Finally it explains the thesis layout.

Chapter two

Chapter two begins defining the Environmentally Conscious Manufacturing term and explaining its two constituents: Environmentally Conscious Design and Environmentally Conscious Production. Furthermore widely used tools and concepts like Life Cycle Assessment and Design for the Environment are described. This chapter also addresses the product design process, explaining a recent model in design that merges environmental concerns into the design process. A design framework derived from that design model is also described. The chapter finishes presenting a new product concept called the Extended Product, which has emerged in response to the requirements enforced by consumers and legislation.

Chapter three

Chapter three presents an extensive literature review in the area of disassembly. It begins by defining the aims of disassembly in the context of this research. Next, two sections address the required background (in representation and analysis techniques) necessary to understand different approaches and solutions to the problem found in the literature. Later, the author divides the disassembly problem in four different groups that comprises similar approaches to disassembly. Issues like modularity and product structure are also addressed in this chapter explaining the advantages of modularity and certain product structures. Overlap and tradeoffs among Design for Assembly and Design for Disassembly is investigated in a later section deriving some recommendations to achieve a successful integration of both concepts. An extensive survey of Disassembly Software is also presented showing comparisons among the different packages. Finally the DFE Workbench software tool is explained in order to present to the reader the tool in which the new disassembly methodology has to fit. T

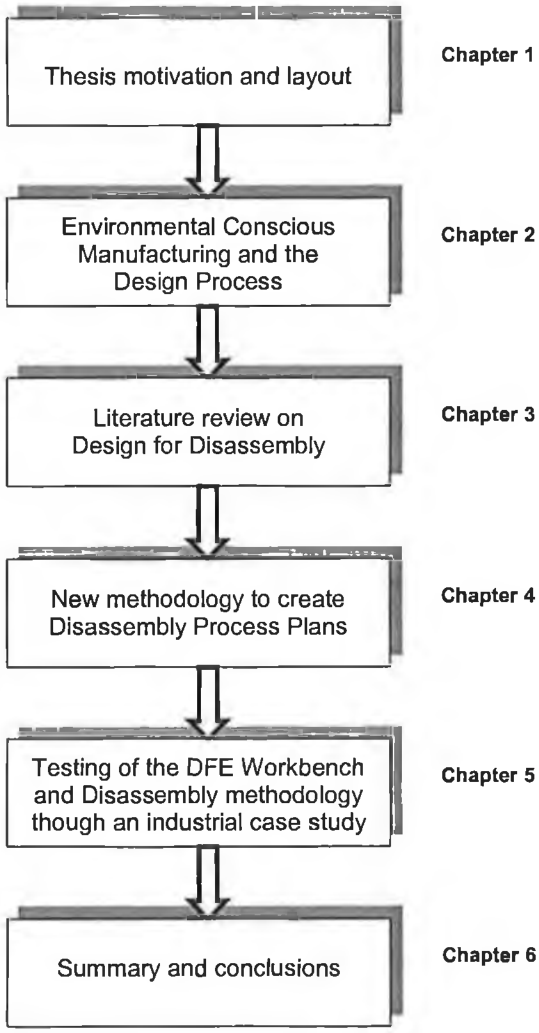

Figure 1.1: Thesis layout

Chapter four

Chapter four proposes a new methodology for the creation of Disassembly Process Plans. As the methodology is going to be implemented in software, computational issues will be taken into account. The chapter starts explaining the difficulty of the problem and why a heuristic algorithm has been chosen. Next, the basic structure of the algorithm precedes the specification of the user input. The different modules of the methodology are further examined by means of several examples that illustrate the features of the technique. Finally, issues like obstructions and modularity are further explained and integrated in the methodology in order to optimise and cope with complex product structures

Chapter five

Chapter five begins by describing the DFE Workbench software tool and how it has been developed in order to meet the latest requirements driven by consumers and government agencies. The functionality of the tool is tested by means of an industrial case study from one of the industrial partners. The chapter also shows the capability of the tool to create all kind of reports, including Disassembly Process Plans. Finally, an outline of the mayor improvements made with the DFE Workbench is given.

Chapter six

Chapter six presents a thesis overview followed by some conclusions drawn from the research carried out. Finally ongoing development and further work is described.

1.5 Summary

This first chapter explains the problems created by the production activities and why environmentalism has emerged. Later government and market pressures are identified as the driving forces behind environmentally conscious design. This chapter also presents the objectives of the research as well as the approach to work. Finally it explains the thesis layout and gives a brief summary of every chapter.

Chapter 2. Environmentally Conscious Manufacturing and the Design Process

2.1 Introduction
2.2 Environmentally Conscious Manufacturing (ECM)
2.3 Impact Assessment; Life Cycle Assessment (LCA)
2.4 Design for the Environment
2.5 Environmentally Conscious Design and the Product Design Process
2.6 The Design Process Chain
2.7 The Life Cycle Process Chain
2.8 New Model of Design
2.9 The PAL Framework
2.10 The Extended Product
2.11 Summary

2.1 Introduction

This chapter sets the basis of environmental design, defines important concepts and shows the relationships among them. It begins defining the Environmentally Conscious Manufacturing term and explaining its two constituents: Environmentally Conscious Design and Environmentally Conscious Production. Furthermore widely used tools and concepts like Life Cycle Assessment and Design for the Environment are described. The chapter also addresses the product design process, explaining a recent model in design that merges environmental concerns into the design process. A design framework derived from that design model is also described. The chapter finishes presenting a new product concept called the Extended Product, which has emerged in response to the requirements enforced by costumers and legislation.

2.2 Environmentally Conscious Manufacturing (ECM)

Environmentally Conscious Manufacturing (ECM) is concerned with developing methods for manufacturing new products from conceptual design to final delivery and ultimately to the end-of-life (EOL) so that the environmental standards and requirements are satisfied [Gun99]. In other words, ECM involves the development of products so that their overall negative environmental effects are minimised [Gun99, Isa96, Wat92, Wei94] and, according to Gungor and Gupta, ECM consists of the following two issues [Gun99]:

- understanding the life cycle of the product and its impact on the environment at each of its life stages that is, an impact assessment or Life Cycle Assessment
- making better decisions during product design and manufacturing so that the environmental attributes of the product and manufacturing process are kept at a desired level that is, Design for Environment (DFE) evaluations

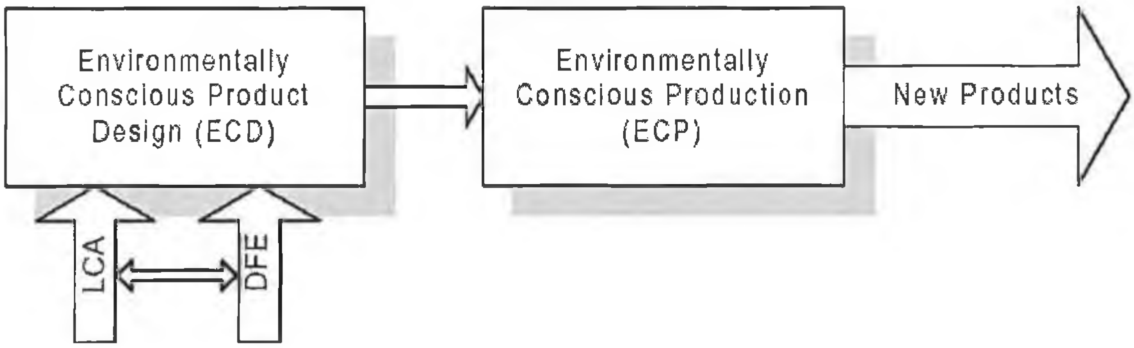

Figure 2.1: Schematic of Environmentally Conscious Manufacturing [Gun99]

The author thinks that the model introduced by Gungor and Gupta does not correspond completely with other tendencies of environmental design, which do not consider DFE as another tool such as LCA. In practice, DFE actively helps the designer to enhance the environmental attributes of an emerging design and therefore the author believes that LCA should be embedded in DFE rather than work in parallel. The term DFE no longer refers only to a set of guidelines oriented to improve the environmental characteristic of a design; in contrast, DFE is a broader term that can replace ECD (see Figure 2.2) and in this thesis the terms ECD and DFE will be interchangeable. In addition, LCA considerations should be also taken when designing the production processes so that the overall impact of the manufacturing phase will be reduced.

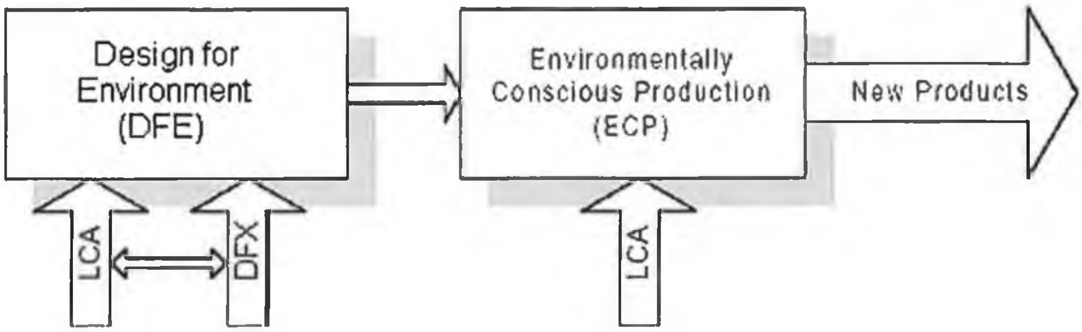

Figure 2.2 Model of Environmental Design taken in this research

According to the previous discussion, ECM consists in two areas as follows [Gun99]:

- Environmentally Conscious Design (ECD) or Design for Environment (DFE)
- Environmentally Conscious Production (ECP)

According to Gungor and Gupta *Environmental Conscious Design* (like Design for Environment) aims to design products with certain environmental considerations [Gun99]. ECD is supported by tools like Life Cycle Assessment and concepts like DFE [Gun99], which will be further explained in subsequent sections. In addition LCA and DFE, the traditional design process have to change in order to include concepts such a Life Cycle Design which is a basic requirement for the development of Environmentally Superior Products (ESPs).

Environmentally Conscious Production issues must be also considered in order to have a complete view of environmentally conscious manufacturing [Sar95, Fik96, You97]. These issues include selecting energy sources necessary for production, designing cooling systems, and handling hazardous byproducts [Gun99]. Currently, numerous production techniques, material handling systems, and energy sources are available. Therefore, it is required the development of tools to aid in the optimal selection of the different parameters involved. For example, Bock [Boc91] developed a tool to come up with a good material and process combination. Similar models have been developed to analyse how the selection of different manufacturing processes effects the environment [Sri95, Whi95].

2.2.1 Difficulties Applying DFE

One of the difficulties applying DFE is that the environmental performance of products or processes has not been defined in an absolute sense. This means that so far there is no metric that measures the level of environmental superiority of the candidate design. However, there are some approaches to measure environmental performance along the entire life-cycle (Eco-Indicator, Gabi, MET point or IZM/EE toolbox among others) but these are typically used to compare different design solutions. For example a product could be completely made from renewable materials, use renewable energy and decay completely at the end of his life. This product seems to be the greenest one. Now consider that there is a second product with the same characteristics that the previous one but it uses less energy during its use phase so therefore, the environmental performance of the second product compared with the previous one is better.

A product or process is rarely the optimum in every facet and tradeoffs are required. For example, to improve the fuel efficiency of cars the most effective measure has been proved to be making them lighter. This can be achieved by introducing new materials such as titanium or replacing the existing ones (mainly steel) for others like aluminium or plastic. These changes can bring higher energy efficiency during the use phase of the car but a greater use of energy and resources during the material extraction stage for the car.

2.3 Life Cycle Assessment (LCA)

The use of Life Cycle Assessment (LCA) techniques is increasing rapidly. It is mainly used to assess the environmental consequences associated with the different life cycle stages of a product, process or activity. Here a detailed definition stated by Fava in 1990 and adapted by Lindfors et all in 1995 is presented.

> *"...Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product system, or activity by identifying and quantitatively describing the energy and materials used, and wastes released to the environment, and to assess the impacts of those energy and materials uses and releases to the environment. The assessment includes the entire life cycle of the product or activity, encompassing extracting and processing raw materials; manufacturing; distribution; use; re-use; maintenance; recycling and final disposal; and all transportation involved. LCA addresses environmental impacts of the system under study in the areas of ecological*

systems, human health and resource depletion. It does not address economic or social effects…" [Lin95 after Fav90]

In general, all the Life Cycle Analysis definitions are based on the same principle. This principle is that LCA takes a holistic view of all the life cycles of the product, process or activity and it measures the environmental impact caused. LCA can be used to:

- Measurement of environmental performance in a company
- Way to identify opportunities to improve ecological issues of products
- Support in the decision-making process
- Method to demonstrate compliance with eco-labelling scheme directives.

Those objectives give an idea of the importance that currently this technique has. Furthermore they also show the versatility of this method since it can be applied to different areas in a company for example: a product, a process, a department in the company or even the whole company. As a consequence of this importance many organisations have invested resources in the study of LCA techniques.

The longevity of the items is an important factor that influences the overall environmental impact since the longer one product can be used the less products have to be produced and consequently lower damaged is created. One of the drawbacks of LCA, identified by the author, is that it does not consider the longevity of the manufactured goods. Therefore, further studies have to be carried out to assess the environmental friendliness of the products for example how easy is to take apart the components of a product or how easy is to service it.

2.3.1 Carrying Out an LCA

As we know in order to carry out an LCA all the life cycle phases for the product, process or activity must be included, from raw materials extraction to final disposal. But besides all this information, a complete LCA involves some other stages omitted previously but of great relevance to get successful results from the study. The four stages of any LCA are [Con93, ISO97]:

- Definition of goals and scope of the analysis
- Inventory analysis

- Impact assessment
- Interpretation of results

Global definition and scoping is generally recognised that this stage is extremely important, because the result of the LCA is heavily dependent on the decisions taken in this phase [Goe00, EEA98]. It can be subdivided in several sub-steps (after [Alt97, Lin95]):

- Statement of objectives
- Definition of the product and its alternatives
- Choice of system boundaries
- Choice of environmental parameters
- Choice of aggregation and evaluation method
- Strategy for data collection

During the scoping, the product, process, or activity is defined for the context in which the assessment is being made. The scoping process links the goal of the analysis with the extent, or scope, of the study, i.e. what will or will not be included. For some applications, an impact analysis will be desired or essential. In these cases, the preparation of the inventory is not a stand-alone activity. The scoping process will need to reflect the intent to define and collect the additional inventory data for the impact analysis. Although scoping is a part of life-cycle analysis initiation, there may be valid reasons for re-evaluating the scope during the study. This is likely to happen during the next stage i.e. the collection of data in the inventory analysis phase.

Inventory analysis is considered as the core of the LCA method and it is an inventory of all the industrial processes that occur during the life cycle of a product [Vin93]. The inventory analysis can be used as a support tool to identify and evaluate opportunities to reduce the environmental effects associated with a specific product, production process, package, material, or activity. This tool can also be used to evaluate the effects of resource management options designed to create sustainable systems. Figure 2.3 shows the framework for the Life cycle inventory phase

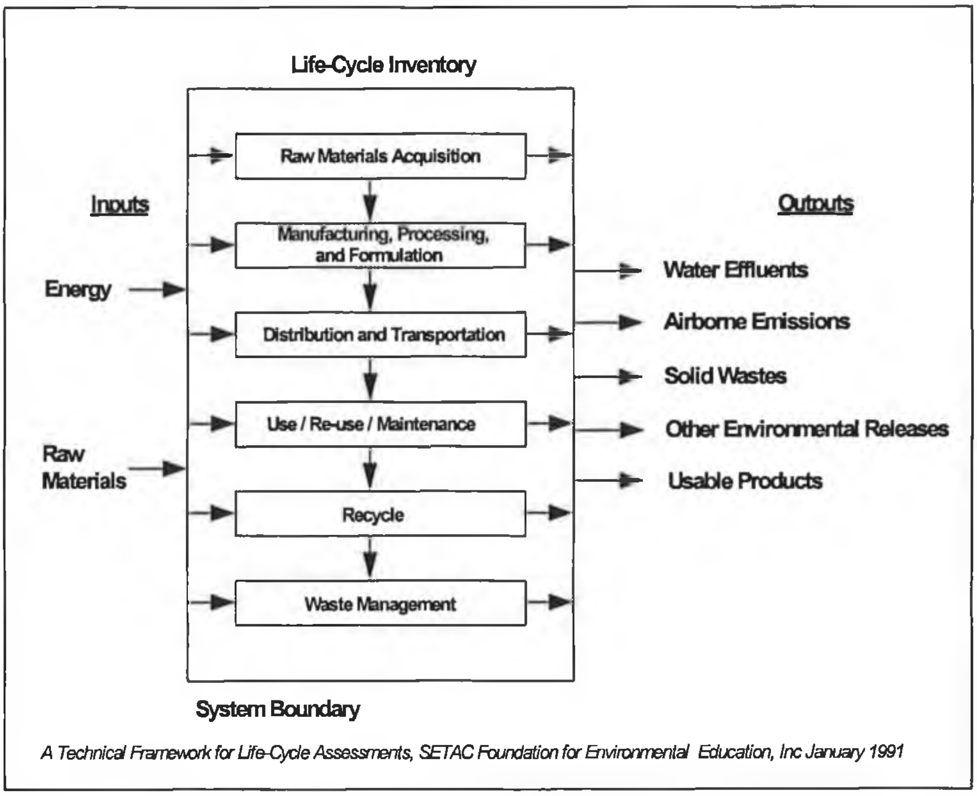

Figure 2.3: Framework for life cycle inventory [SET93]

Life-Cycle Inventory is a detailed relation inputs to and outputs coming in and out the system under study. Here we have to take in account not only flow of materials through the system but also energy use and some other factors as for example already manufactured products coming into the system. All this information has to be translated in more specific environmental loads as emission of certain substances or consumption of resources. The result is called table of impacts and there each emission has to be added up giving the final magnitude for it. Figure 2.4 is an example of the table of impacts for the production of 1 kilogram of PS. The table of impacts will be used in the next phase (Impact assessment) to identify more specific environmental consequences as for example ozone layer depletion or global warming.

Emissions	**Magnitude**	**Unit**
CO2	1.6	Kg
HCl	4.00E-05	kg
HF	1.00E-06	kg
NOx	2.40E-02	kg
SOx	3.40E-02	kg

Figure 2.4: Table of impacts for the production of 1 kilogram of PS [Ase99]

Life Cycle Inventories can be used internally by organisations to support decisions in implementing product, process, or activity improvements but can be also extremely useful to inform external agencies about environmental performance (e. g. governmental agencies and customers). Moreover, industry is aware of the importance of these issues and for example most of the car manufacturers have joined together creating IMDS (International Materials Data System). This initiative aims to specify, archive and maintain all materials used for these car manufactures in an attempt to meet the obligations placed on them, and thus on their suppliers, by national and international standards, laws and regulations [IMD02].

Finally, the inventory process seems to be a simple process but, in practice, it is subjected to several practical and methodological problems. The most common problems to be faced at this stage are the proper definition of the boundaries of the system that is how far one should go in including processes belonging to the product concerned. Other problems can be geographical variations of impacts and difficulty of access or quality of the data (after [Goe00]).

The *Impact Analysis* component is a technical, quantitative, and qualitative process to characterise and assess the effects of the resource requirements and environmental loading (atmospheric and waterborne emissions and solid wastes) identified in the Inventory stage as a table of impacts. This analysis should address both ecological and human health impacts, resource depletion, and possibly social welfare. Other effects, such as habitat modification and heat and noise pollution that are not easily amenable to the quantification demanded in the Inventory, are also part of the Impact Analysis component.

An important distinction exists between Life-Cycle Impact Analysis and other types of impact analysis. Life Cycle Impact Analysis does not necessarily attempt to quantify any specific actual impacts associated with a product or process. Instead, it seeks to establish a linkage between the product or process life cycle and potential impacts. These impacts are always difficult to interpret, and usually a double problem appears:

1. There are not sufficient data to calculate the damage to ecosystems by an impact [Goe00].

2. There is no generally accepted way of assessing the value of the damage to ecosystems if this damage can be calculated [EEA98, Lew96, Goe00].

Various systems have been developed for evaluation of the impacts.

The *Interpretation of Results* phase is also called Improvement Assessment [Vin93]. This phase is the last one in LCA and pursues the options to reduce the environmental impacts of the product, process or activity under study. This stage is composed of three sub stages [Goe00]:

- Analysis of the damages in the ecosystems identifying the processes from which they derive
- Identification of improvement options
- Prioritisation of solution options identified in terms of different factors such as, effectiveness, feasibility, consumer preferences and economic issues

2.3.2 Different LCA Approaches.

The main purposes and objectives of an LCA are recognized in the first phase i.e. the goal and scoping definition. Here is where we identify the availability and quality of data that we expect to get as well as the time and resources available to carry out the study. Depending on all those factors three different Life Cycle Assessment approaches can be identified [Chr97].

- Conceptual LCA
- Simplified LCA
- Detailed LCA

Figure 2.5 shows the relationship between the three approaches and the need of resources and data. The main difference among the approaches is the quantity and quality of the data. The approach must be holistic and must include all the life cycle stages of the product process or activity.

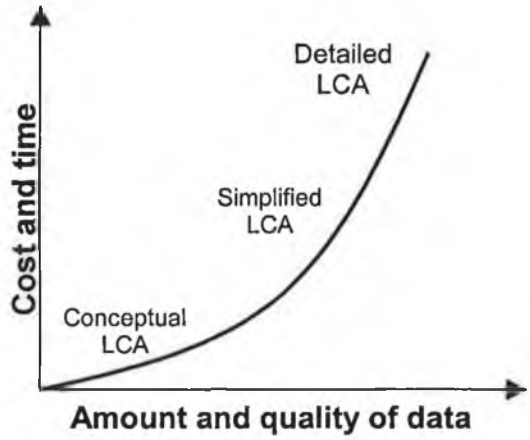

Figure 2.5: Different approaches of LCA [Ase99]

2.3.3 Simplified Assessment Methods

The development of a full or detailed LCA is a tedious task that in some cases could take up to six months and consequently, it is impossible to use this technique in design. Simplified assessments methods have already been proposed or implemented in order to avoid some of the data complexity for full LCAs [EEA98]. Simplifications in the assessment procedure can be accomplished by summarizing the results, by defining intermediate data exchange levels or by reducing the scope of process data and weighing or evaluation factors involved. Examples for such indicator systems, where the soundness of a product is expressed in only one number, are the Swedish EPS system, the Swiss critical flow model, the Eco-Indicator 95/99 method, IZM/EE toolbox, KEA ('Cumulative Energy Expenditure') or MIPS ('Material Intensity Per Sequence'). In this research, the Eco-Indicator methodology is used as the LCA technique to perform the environmental evaluation. Next section explains briefly this approach to LCA.

Eco-Indicator 95/99 model

The Eco-Indicator method, developed by PRé Consultants [Goe00] under the supervision of the Dutch NOH and implemented in the SimaPro 5 LCA software. It uses full LCA modules for energy and raw material production and gives one value (milipoint) per unit of material used or per unit of energy used. This value is the weighted sum of ecological impact classes similar to the SETAC proposals. The structure of the evaluation is shown in Figure 2.6.

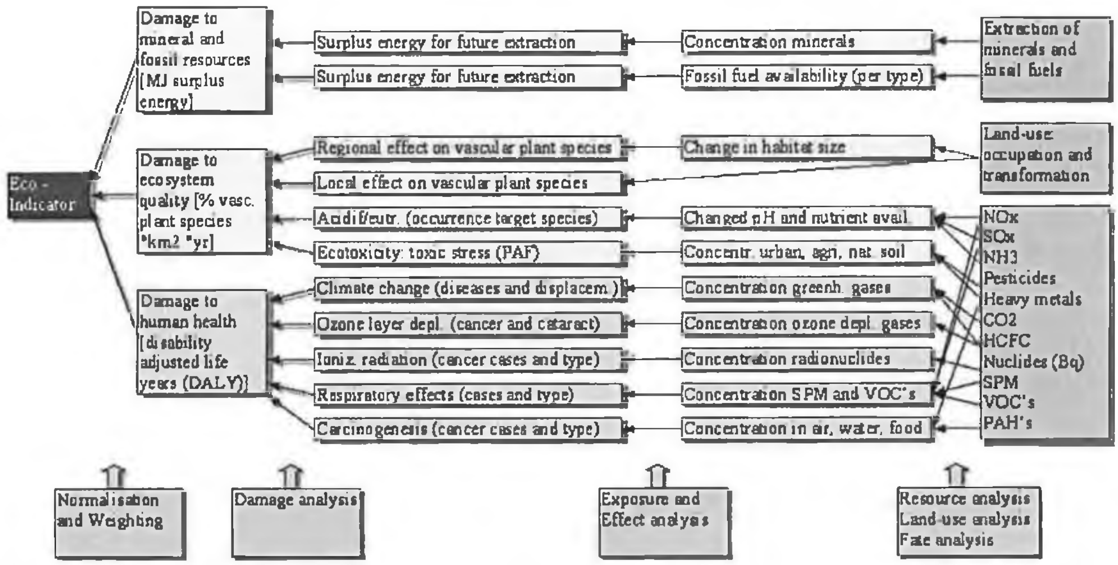

Figure 2.6: The Eco-Indicator 99 model [Goe00]

The designer is encouraged to use these material assessments without knowing the specifics of the evaluated processes, e.g. a number for copper production may usually be applied without having to understand the investigated processes. When a material is missing in the database, it has to be investigated with the same scope and method by the original database supplier. This is especially complicated for disposal and recycling strategies for products or materials which are less common or need special treatment.

2.4 Design for the Environment Guidelines

The concept of Design for Environment was created in the last decade by a group of electronic firms that wanted to take environmental consideration' in their products. Fiksel sees DFE as a specific collection of design practices aimed at creating eco-efficient products and processes [Fik96]. Besides he defines Design for Environment as the systematic consideration of design performance with respect to environmental, health, and safety objectives over the full product and process life cycle. Roche identifies the objectives of DFE as four generic and interrelated strategies as follows [Roc99]:

- Select low impact materials and processes over all life cycle phases.
- Reduce life cycle resource consumption (Materials and Energy)
- Reduce life cycle waste streams (Materials and Energy).

- Resource sustainment by facilitating first life extension and post first life extension, i.e. reuse, remanufacture and recycling.

One of the problems is that these objectives are far too general to be applied by designers at their desk so it is necessary to create certain guidelines to help them. Those design guidelines are part of a big concept called Design for X-ability in which different groups of strategies can be founded. Among them, those related to the development of ESPs are mainly: Materials Selection, Design for Disassembly, Design for Recyclability and Design for Reusability.

A compilation of DFE guidelines widely used in the industry is presented in the following sections. Several sub classifications can be defined but here, some of them due to their similarity have been joined in an attempt to simplify their description. Due to the focus of the research presented in this thesis, Chapter 3 includes an extensive description of the Design for Disassembly techniques and its different approaches.

2.4.1 Materials Selection

This is a critical point in the design phase. Depending on the materials we choose to make the components of our products we will have diverse environmental impacts. This is not only due to the impact of the material itself but also the processes associated with it. For example titanium is a material with very good engineering properties but its complex manufacturing processes make it not only expensive to use but also poor in environmental terms.

Issues to be addressed in selection of materials can be divided in two main choices,

- Renewable materials and,
- Non-renewable materials

The ideal situation is when renewable materials are used (e.g. wood). This is not always possible and in order to find certain properties in materials it is necessary to use non-renewable sources. Special care has to be put in place when choosing those trying to avoid hazardous materials, which once disposed of, could incur a large environmental impact. In actual practice different industries identify (flag) the use of hazardous materials and try to find means to change them for others with better environmental performance. For example the electronic sector defined cadmium and lead as hazardous. Lead appears as constituent of the welding material used to link all the components to the electronic boards. Currently large amount of research is being carried out to find and evaluate the new lead-free solder substitutes. In the same way cadmium has been part of most of the batteries used in mobile devices. Continuous research has brought new chemicals, which provides superior performance because batteries are lighter and smaller than previously, while having lower toxicity.

Once the materials have been chosen, it is necessary to be able to identify them. It is important to mark plastics as well as other materials. In polymers marking is carried out by means of print in the mould of the part. This not only ensures its recyclability but it also avoids any material contamination due to foil labels, which also contain adhesives. Different standards are already in place to mark materials as for example ISO 11469 for plastics.

2.4.2 Design for Recycling

Products tend to wear out and become obsolete. This implies that, even when they still retain some value, at the end of their useful life they have to be replaced by new products. The discarded products are made predominantly with non-renewable materials of limited availability and therefore the greenest approach is to recover those materials and create new products with them. So far difficulties in recovering materials and recycling technologies has lead to massive disposal in landfill sites. However this is changing and new recycling methods are emerging transforming material recycling into an interesting option for manufacturers. The practice of recycling is good for supporting sustainability because it helps to stop the consumption of non-renewable sources and besides it also helps to save energy. Then Design for Recycling pursues the improvement of the recyclability of products. The problem has to be faced in some different ways to be solved efficiently. First and probably most important the design of the product should include the higher percentage of recyclable materials possible. For example the use of composite materials must be avoided due to they are not recyclable yet. The minimisation of materials variety is also a good strategy in designing recyclable products because it enables easy and effective classification.

On the other hand the product has to be easy to take apart. It means that the disassembly of its parts has to be fast and easy. This is very important because the lower the disassembly time is the smaller will be the economical loses in this phase. Once the parts have been taken apart recyclers need to identify the different materials so the labelling or material identification of the different parts is very important.

Special care has to be taken during design to avoid any contamination of the materials. Paper or foil labels, adhesives, coatings and finishes are made with different materials to the surface where they are attached. In practice for us this means that in fact we don't only have one part but two, the part itself and the coating or finishing.

2.4.3 Design for Product Life Extension

This category would include some DFE methodologies with similar characteristics. Those methodologies are:

- Design for Maintenance and Serviceability
- Design for Upgradability
- Design for Reuse
- Design for Remanufacturing

Those four have been grouped together because their final goal is to increase the useful life of products. Product life extension implies massive environmental savings because the production of new products (with all the environmental burdens attached to them) is avoided.

Design for Maintenance and Serviceability pursues an easy maintenance of products so that they can be repaired without difficulties. This avoids the disposal of equipment with small problems, which is not fixed due to the cost and overall complexity of the reparations. The objective of *Design for Upgradability* is to manufacture goods easy to upgrade. This means, products that after a service period have become obsolete and can be updated by changing some of the parts and keeping the rest of it. This links directly with *Design for Reuse* methodology in which the main goal is to find opportunities to reuse parts in later products once the current one has become obsolete. Finally *Design for Remanufacturing* pursues the refurbishment and later reuse of parts. This can be confused with Design for Reuse but they are two separate strategies. Design for Reuse looks at product level in opposition to

Remanufacturing which instead of reusing the whole product, it aims to component or subassembly level that is, opportunities to recover discrete parts or subassemblies in order to introduce them in the manufacturing chain. All these methodologies need easy disassembly of components so the Design for Disassembly guidelines becomes the core in all of them.

Along with an easy disassembly, modularity is a very important aspect to take in account when designing with those strategies in mind. The clear definition of diverse modules, with different functions, will enhance life extension because of the easy upgradability, reusability and maintainability of modules. This modular approach usually leads to standardization of interfaces so that new designs can be fitted without need of changes in any of the components. The best example to illustrate this is a computer in which several modules are attached to one main component (mother board) that is in charge of managing them. These modules are for example graphic card, hard disk or even the screen. Moreover, they are linked to the rest of the computers by means of standard interfaces. In this modular design parts have different and independent roles and can be changed if defective or upgraded if obsolete.

2.4.4 Other DFE Methodologies

Many other DFE methodologies have been reported in the literature. The most relevant are presented in this section. Design for Simplicity has the objective of reducing the complexity of products and processes. The more complex a product is the higher the risk of failure and more difficult is any operation to fix problems. It encourages to reduce the number of parts, advice which is already known from design for manufacturing and assembly techniques. It also suggests the design of multifunctional parts that can be used for diverse purposes. Finally it proposes the design of parts that can be used in many different products.

The last strategy of interest is the product miniaturization. This mainly pursues the use of small quantities of materials by means of making small parts and products. This also want to point at every material saving opportunity, for example the addition of holes in certain plastic parts does not affect their performance but they can save significant quantities of plastic in a large production of parts.

2.4.5 General Comments

After a closed study of the DFE methodologies two general thoughts can be extracted.

- Overlapping among methodologies and,
- Tradeoffs between methodologies

The idea of overlapping among methodologies means that the application of one guideline usually has impacts in more environmental characteristics of the product, i.e. Design for Disassembly is beneficial in any of the disciplines of Design for Life Extension and also in Design for Recycling. There is also a considerable overlap with other DFX disciplines such as design for manufacture and design for assembly. For example, reducing the complexity of a design leads to fewer parts, lower assembly costs and simpler disassembly.

Tradeoffs between methodologies means that sometimes a design change may imply a benefit in one product's attribute but some other could be weakened. For example the design of a car needs high performance materials and low weights to save some energy during the use phase. Therefore composite materials can be the best choice due to their low density and good engineering properties. However later on, when applying Design for Recycling guidelines, the designer will be asked to eliminate composite materials since they are not recyclable. In all cases the decisions will be taken after defining exactly the type of product to be designed, for example, a disposable product and a extended product.

2.5 DFE and the Product Design Process

Product design or product development is the process of mapping customer, corporate, and governmental requirements into a product that can be produced and marketed [Ulr95]. This process is complex, interdisciplinary, time consuming and involves many tradeoffs. Product design includes every technical aspects of the product like purchasing of components, manufacturing, assembly, service or obsolescence [Bor00]. Besides functional requirements, a product must meet many other requirements to be sold successfully, for example final cost, market standards and lately the new environmentally-based requirements like energy efficiency, recyclability or elimination of materials of concern. Designers have to make tradeoffs among all these requirements and this is not always an easy task [Bor00].

The development of a product generally begins by identifying customer needs. Once this information is gathered and analysed some design requirements have to be defined. These requirements identify the attributes in which the design will be assessed and after that, new product concepts are created. This usually involves intense brainstorming sessions and it is mainly here where the behaviour of the product along its life cycle is defined. That concept determines how the product will perform its function, its general shape dimensions and structure. Thus it is also here where environmental performance of the new design should be addressed. After the concept has been finished CAD models bring a more accurate picture of the final product. It is at this moment when different types of specialized design take place, those are the so-called Design for X, which includes the Design for Environment guidelines (DFE). Finally, the design has been finished and the product is ready to be manufactured [Bor00]. Figure 2.7 locates environmental practices in the product design process.

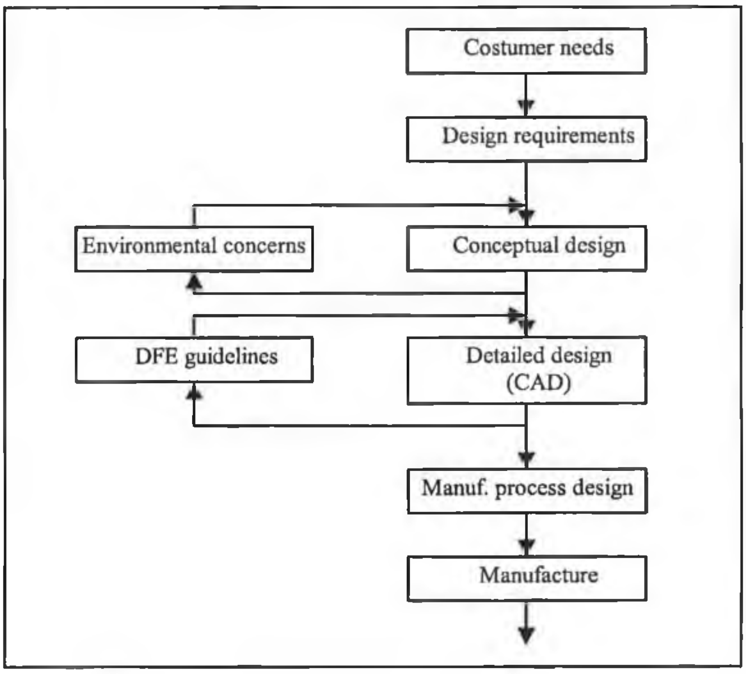

Figure 2.7. Schematic of traditional design and environmental considerations

Figure 2.8 shows the relationships between commitment, ease of change and product knowledge during the design process. It becomes apparent that the ease of change is smaller as the knowledge of the product is higher. This problem is not new but could become a major obstacle in designing ESPs because the understanding of various demands on the product will take more time due to the increased complexity, which may lead to late modifications.

In response to this problem the engineering design philosophy “Concurrent Engineering” (CE) was introduced during the 90s. CE has two elements that help to resolve two main design problems [Cha98] [Hsi01]:

- Cross-functional teams: Specialists from different disciplines represent knowledge of the whole life cycle. Needs and requirements are directly addressed to the project manager which increases his knowledge about the product within a short time period.
- Focus on concept phase: Management activities are highest at the beginning of the product development. This way changes or improvements can easily be done.

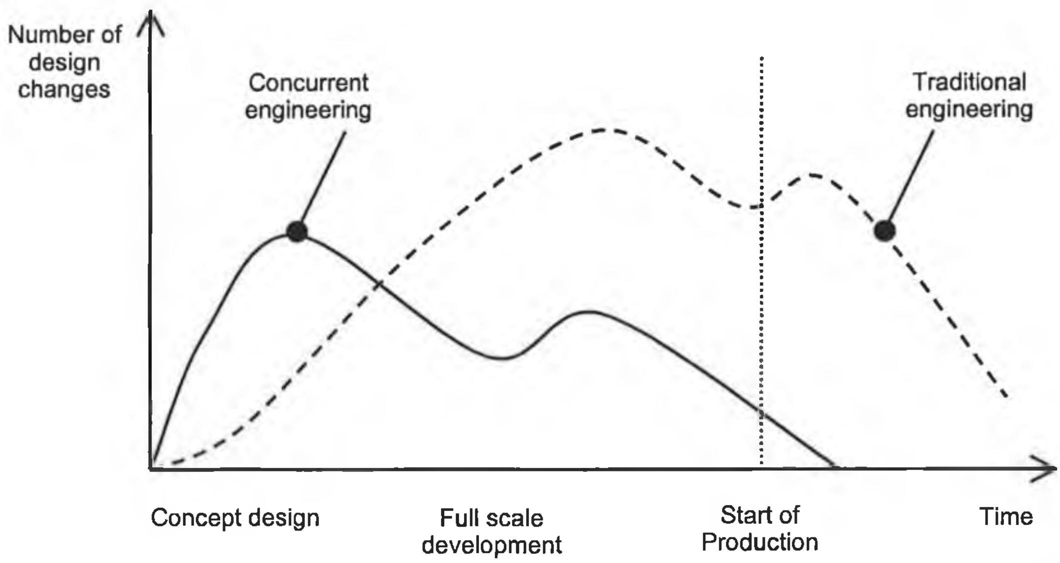

Figure 2.8: Relationships in the Design Process for new Products [Ulr00] [Kea01]

Figure 2.9 compares design changes with traditional design methods and CE. The conclusion from the chart is that CE is necessary in the development of ESPs; However, ECD is much more than only CE, ECD is Life Cycle Design. In subsequent sections will be explained how ongoing research in the area of design unifies and complements these design concepts in order to create a new model and framework in design.

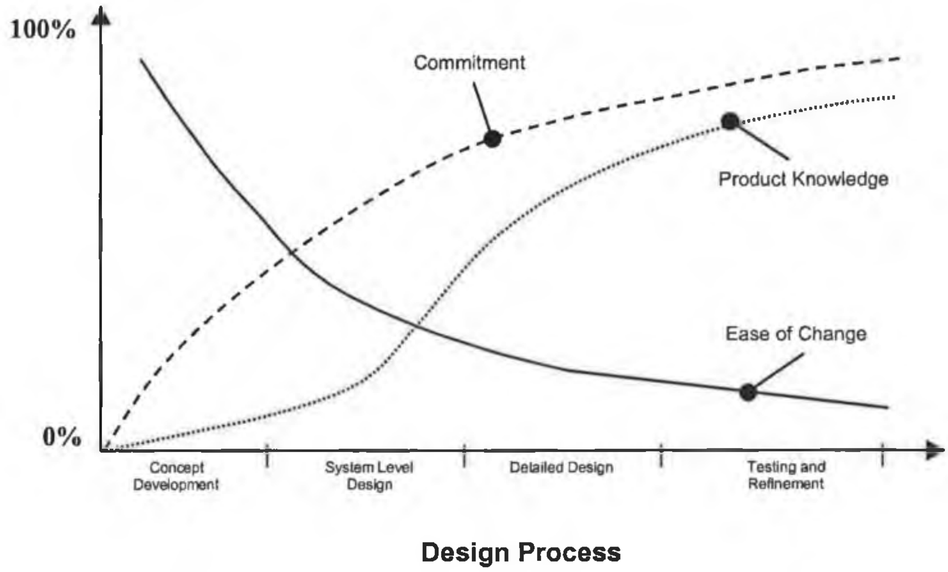

Figure 2.9: Comparison of CE and the traditional engineering [Una00].

2.6 The Design Process Chain

Figure 2.10 shows a generic design process model which has been synthesised by Roche from a number of prescriptive design models described in his research [Roc98][Roc99]. The model can be described by: (a) the *degree of embodiment* and (b) the *solution space.* The vertical axis describes the degree of *embodiment of a design*, which ranges from the general to the specific stages of design. In the early stages of embodiment, the solution space is very large due to the large number of solution possibilities. However, as the design evolves this solution space becomes narrower until there is one specific solution, i.e. the final design [Roc01].

There are four generic phases of the design process identified in Figure 2.10, i.e. *requirements definition, functional definition, general design* and *detailed design.* It should be clear that these design phases are not discrete phases in the design process, rather they are effected through a series of recurrent problem solving cycles that are used effectively to evaluate diagnose and improve the design as the design evolves. It is therefore essential that DFE tools and methodologies should be integrated throughout all phases of the design process. Also, research has shown that decisions made in the earlier phases of the design process have the largest influence in the final design [Hay88] [Hub96] [Roc98]. This is compounded by the fact that the amount of information available, on which to make concrete decisions, is very limited in these early phases. Clearly, the development of DFE tools and methodologies in the earlier stages of the design process are likely to be highly effective in supporting the development of ESPs [Roc01].

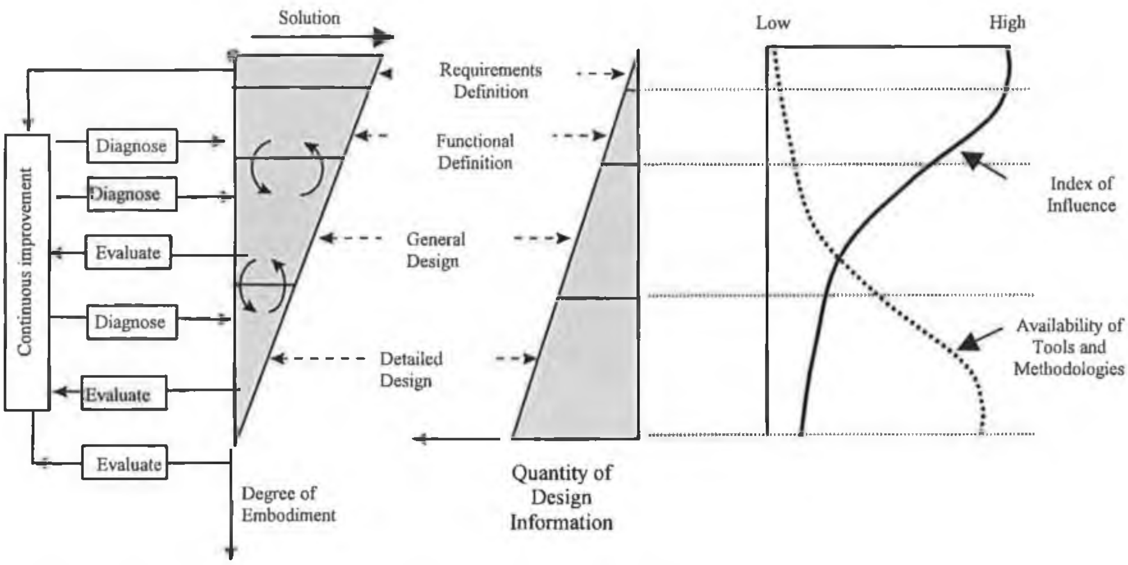

Figure 2.10: Design Process Model [Roc98][Roc99].

2.7 The Life Cycle Process Chain

There are many DFE strategies and each requires the inclusion of specific product characteristics. As the DFE field addresses the full product life cycle it is useful to address these approaches in the context of the life cycle model presented in Figure 2.11.

In this model the physical product passes through four generic phases in its lifetime, i.e. *raw material extraction*, *manufacture*, *use* and *end of life*. In each of these phases materials and energy are consumed either directly into the product or given off as waste streams. When the product reaches the end of life a decision has to be made to reuse, remanufacture, recycle or dispose of it. Similar decisions have to be made regarding the materials and energies entering the waste stream.

2.8 New Model in Design

As discussed previously, all processes in a product's life cause environmental damages. Therefore to perform an effective ECM, the designer has to consider in design all the possible processes in the product's life. Research shows that in order to support the designer in this new design practice two different, but interrelated process chains have to be simultaneously considered (after [Gru00, Roc99]).

- The traditional design process in product development, where a product created and lately described using information carriers such as technical drawings or CAD model data.
- The life cycle process chain with all the material and energy flows from the extraction of raw materials to the disposal of the product.

Although both processes are different they influence each other having multiple interfaces with high flow of information. Figure 2.12 proposes a new design model for ECD which explains the concept of life-cycle product design. It also shows the complexity of the problem and brings up the need of further help to the designer.

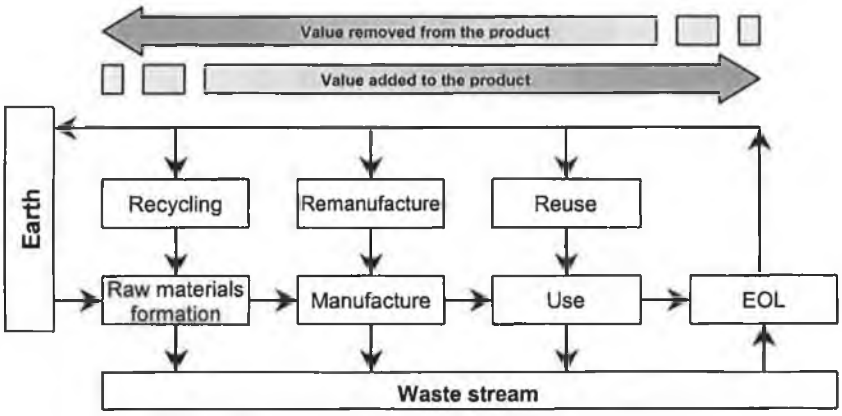

Figure 2.11: Product Life Cycle Chain [after Roc99].

Traditional models of the design process have focused on the development of tools to improve the performance of a part of the life cycle of the product, e.g. design for manufacture or design for assembly. The result is a proliferation of tools to aid the designer at individual life cycle stages [Ish92, Mol95]. As discussed in the previous section, new models must take a more holistic view, i.e. focus on the total life cycle system, to include raw material extraction, manufacture use and end of life [Kim97a, Alt93, Alt97, Lee93, War96].

2.9 The PAL Framework

In the model, shown the previous section (see Figure 2.12) life cycle information is acquired through a set of life cycle design information loops, i.e. design for raw material extraction, design for manufacture, design for use and design for end of life. The design process transforms this information into product design characteristics, which are subsequently embedded in the product. Therefore there is a need for a new design model to cater for the life cycle design information transformation loops and to support the development of new methodologies and tools to assist the designer in the creation of ESPs.

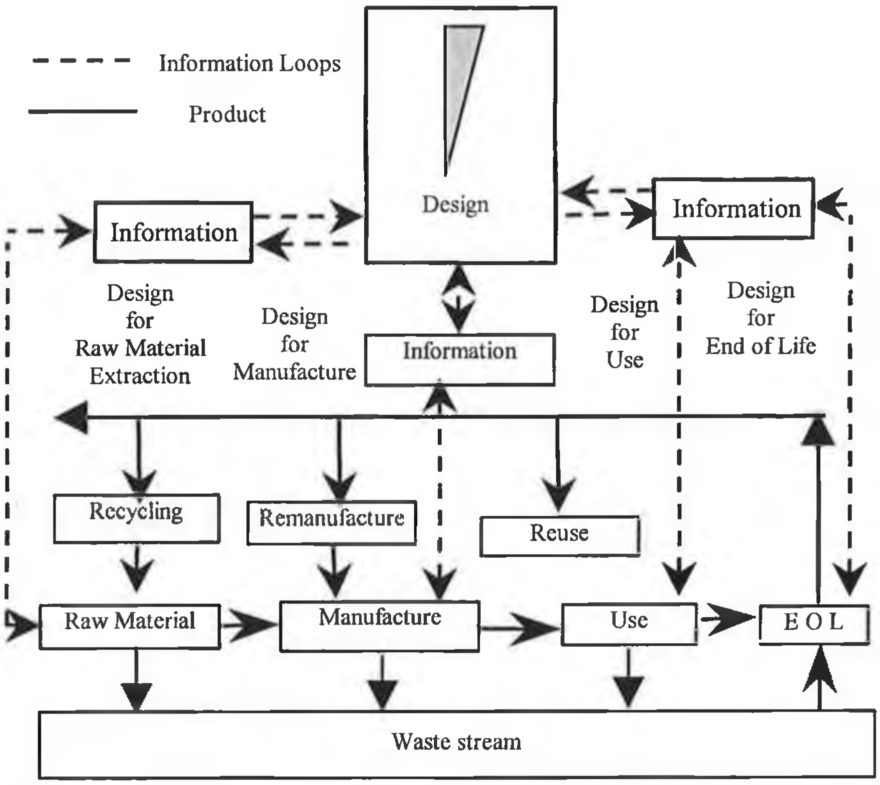

Figure 2.12. Design information loops [Roc99].

Roche proposed that the life cycle design process could be represented by a tri-axial information transformation space, i.e. design phase, activity and information axes (see Figure 2.13) [Roc99]. The model represents the transformation of information through four generic stages of design (namely requirements definition, functional definition, general design and detailed design), i.e. the transformation of information from more abstract statements of requirements to more concrete details on the final design. The vertical axis is based on a synthesis of models (particularly prescriptive design process models) from the literature [Fin89, Cro94, Jon96, Pug91, Hub96, Wal96, Evb96, Bay96, Pah96]. These phases are not discrete events within the design process, rather the designers engage in a set of decision-making cycles continuously improving the design at each level of abstraction. The problem solving cycle can be viewed as the instrument or mode of information transformation in each phase of the design process, hence a problem solving cycle is adopted to describe the activity axis of the design transformation space, i.e. the steps analyse, synthesise and evaluate

[Hub, Deb89, Cro94, Coy90]. The phase and activity axes define the boundaries of a design process plane. It is implicit in this plane that problem solving occurs explicitly at different levels of abstraction in the design process. This affects the types of problem solving that can occur, and hence the types of tools and methodologies used.

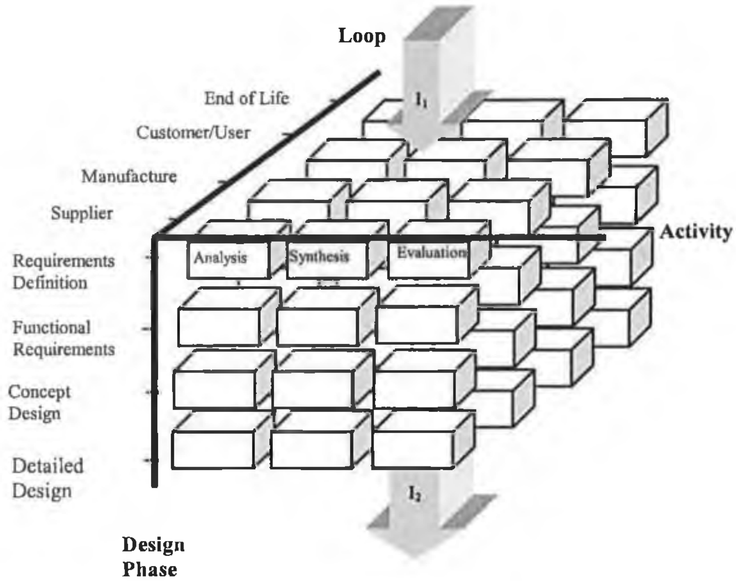

Figure 2.13. Tri-axial information transformation space for life cycle design, (PAL) Framework, adopted for the design of ESPs [Roc01]

As defined earlier ESPs require a life cycle design view. The design information loops (used to describe the third axis of the transformation space) described in Figure 2.12 represent the source of information for each life cycle phase of the product and also as a focus for life cycle methodologies and tools. The activity and loop axes bound a life cycle problem-solving plane. This plane ensures the analysis, synthesis and evaluation of life cycle information throughout each phase of the design process. In summary the model in Figure 2.13, called the PAL framework, is proposed as a life cycle design framework to support the development of methods, methodologies and tools to aid life cycle design decisions. It is proposed to adopt this model for the development of information architectures, tools and methodologies to support the design of ESPs.

2.10 The Extended Product

Global competition has been forcing manufacturers to seek new business opportunities through the provision of benefits to costumers which have evolved over the last 30 years from the delivery of functionality at minimum cost to the delivery of high quality customisable products in ever reducing lead times. The delivery of these benefits was through the optimisation of the product realisation processes, mainly manufacturing activities e.g. the evolution from make to stock to engineer to order models [Bro95]. Consequently designers tended to optimise product's features and problems that used to arise at the manufacturing phase. Nowadays the picture has changed significantly; manufacturing processes are highly sophisticated and opportunities for manufacturing based competition are increasingly limited. In addition, environmental awareness, legislation (e.g. EOLV and WEEE) and standards (e.g. ISO 14000) are forcing companies to take responsibility for their products at every stage of the products life cycle. As a result, there is an observed shift towards seeking competition at the design, use and end of life stages of the product life cycle (see Figure 2.14).

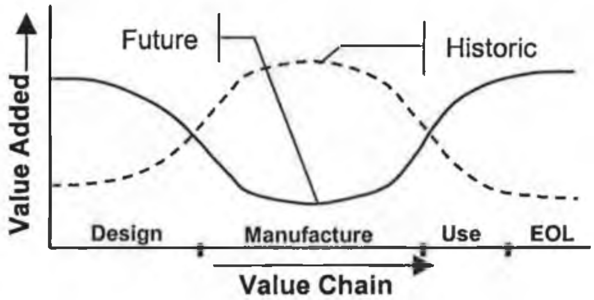

Figure 2.14: Shift in Value Added along the Value Chain [Bro95].

Coupling of these relevant issues over the last decade has stimulated the evolution of the traditional concept of a product. In the early nineties Alting and Pedersen [Alt91] talked about leasing products as a way to increase manufacturers interest in life-cycle-design and subsequently environmental superiority. By the mid nineties Gale talked about customer management approaches to the delivery of services rather than products to customers [Gal94]. Kimura and Tomiyama et al. predicted the emergence of two new types of product for the future [Kim97] [Tom94]. Firstly, products that sustain functional growth and have theoretically, unlimited lives; such products would require high quality structures that both facilitate and create value from the operation, maintenance, service, repair and upgrade activities. Secondly, items of social capital that have shorter life cycles and would consist of structures that facilitate value creation from manufacturing, recycling and reuse activities. In essence, the coupling of all these ideas is encompassed in the emerging concept of *extended product* that encourages manufacturers to provide a service via the product, rather than by the product.

Thoben et. all [Tho01] adopted a three ring model (see Figure 2.15) to describe the extended product concept identifying three main constituents: *core product, tangible product* and *non-tangible product*. The core product provides the functionality of the product; in a car for example the core would be the chassis, engine and wheels. This core product is wrapped by a ring that represents the *tangible features* of the product, for example style of design or quality of finishing. It does not perform any essential function representing basically the packaging of the functional product. However, issues like fashion or brand prestige play an important role from a marketing viewpoint. Finally, the outer ring refers to the *intangible assets* of the product and comprises the added services offered by the company that sells the product or the right to use it. This layer promotes communication among the different players along the product's life cycle. It also includes post-sale services (e.g. maintenance of the car) being recognised as a key factor to achieve costumer satisfaction and therefore companies' success.

In this new model, manufacturers will aim to increase the functional and physical life of the product (to minimise cost of replacement) and to capture as much value from the product by reusing end of life subassemblies and systems in new products. From a business viewpoint, competition among companies in the market place will be based on the minimum operating costs as well as the quality of services provided via (rather than by) the product to the customer.

Extended products by their nature require the adoption of different design strategies to traditional products. Firstly they include embedded life cycle information (structural and life cycle data) that facilitates servicing throughout their entire working life cycle including end of life. Structural data includes bill of materials (BOM) data that facilitates life cycle services, e.g. material content, optimum disassembly times and paths. Life cycle data relates to data acquired throughout the operational life of the product, e.g. working conditions or repair and upgrade history. Secondly, extended products support functional and physical life extension and end of life approaches. Physical life extension is realised by embedding characteristics such as robustness, reliability, serviceability and maintainability. Functional life extension is facilitated by designing modular structures that provide upgrade paths and reusability of crucial components. End of life approaches are achieved by developing structures that facilitate product and material recovery (e.g. remanufacture and recycling) in addition to safe disposal by means of the easy identification and removal of hazardous components.

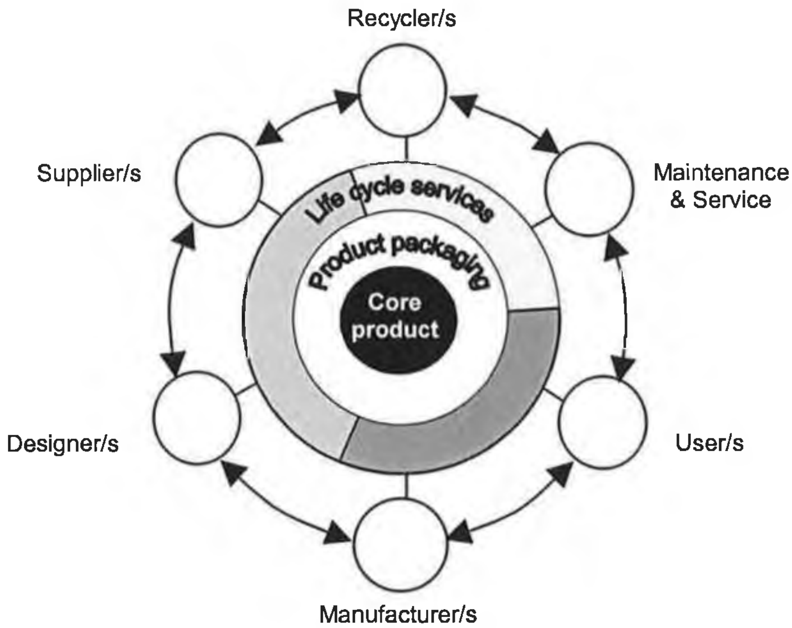

Figure 2.15: Layered model of extended products (after [Tho01])

Extended products must have certain characteristics that allow value added activities during operation and at the end of life. Figure 2.16 shows characteristics and strategies that support extended products.

To facilitate the design of extended products in the most cost-effective fashion it is necessary to define methodologies and to create tools to help designers in their task. Research carried out at the authors' institutions plus intensive testing with industrials partners, has led to a new software tool called the DFE Workbench which will be further explained and tested in Chapter 5. This tool was primarily conceived as a Design for Environment (DFE) tool, as DFE concepts resonate strongly with those of DFxp (e.g. Design for Disassembly, Design for Serviceability or reduced environmental impact). The DFE Workbench supports the design and life cycle information of extended products. The evolution of the tool has been highly influenced by the industry and academia.

Characteristic (How)	Strategy (How / What)	Objective (What)
Modularity	Functional life extension	Add value during operation and end of life.
Upgradeable		
Robustness	Physical life extension	
Serviceable		
Reliable		
Maintainable		
Easy to disassemble	End of life approaches	
Possibility to Remanufacture		
Recyclable		
Reusable		
Part of product family to facilitate reuse		
BOM, users guide, drawings, etc	Structural Data	
Logbook, product history	Life cycle data	

Figure 2.16: Characteristics of extended products [Mue02]

2.11 Summary

In this chapter current practices in environmental design have been explained. It defines important concepts such as Environmentally Conscious Manufacturing, Design for Disassembly or Life Cycle Assessment and shows the relationships among them. The chapter also addresses the product design process, explaining how environmental concerns have affected the traditional product design. Moreover, a recent model in design that merges environmental concerns into the design process is described. In addition, a design framework derived from that design model is also explained. The chapter finishes presenting a new product concept called the Extended Product, which has emerged in response to the requirements (e.g. environmental, performance and cost) enforced by costumers and legislation.

Chapter 3. Literature Review in Disassembly

3.1 Introduction

3.2 Disassembly Definition

3.3 Modularity and Product Structure

3.4 Representation Techniques

3.5 Analysis Techniques

3.6 Design for Assembly and Disassembly Integration

3.7 Disassembly Software Review

3.5 The DFE Workbench

3.8 Summary and Conclusions

3.1 Introduction

As discussed in chapter two, environmental design is a complex task that has to be supported by methodologies and tools. One of the aims of the author during this period was to investigate further developments of the DFE Workbench software tool (described at the end of this chapter), which helps the designer in the development of environmentally superior products. The disassembly methodology was identified as one of the weaknesses in the functionality of the tool. In order to propose a different approach to overcome this problems, research on the disassembly area is essential to understand the complexity of the problem. This chapter presents an extensive literature review on the area of disassembly. It starts defining the aims of disassembly in the context of this research. Next, two sections address the required background (in representation and analysis techniques) necessary to understand different approaches and solutions found in the literature. Later, the author divided the disassembly problem in four different groups that comprise similar approaches to disassembly. Issues such as modularity and product structure are also addressed in this chapter explaining the advantages of modularity and certain product structures. Overlap and tradeoffs among Design for Assembly and Design for Disassembly is investigated in a later section deriving some recommendations to achieve a successful integration of both concepts. An extensive survey on Disassembly Software is presented showing comparisons among the different packages. Finally, this chapter describes the DFE

Workbench software tool in order to show where the disassembly methodology fits in the tool and what are requirements that a new methodology must meet.

The aims of disassembly are diverse. One of them is to regain the value added to goods and materials [Pen96], and this can be achieved by recovering materials and components as well as extending the life of the items by operations like maintainability in which disassembly is also involved. On the other hand, the protection of the environment has become an important issue and today safe disposal of products is a must. It therefore becomes clear that disassembly is a key factor along the life cycle of the product, since it is the primary process which enables other sub-process to be carried out. These sub-processes are the following: [after Pen96]

- Maintainability
- Serviceability
- Product recovery (reuse and remanufacturing)
- Material recovery (recycling)
- Controlled disposal

Recent interest in the different life cycle stages of products has stimulated enthusiasm among designers for disassembly, an area of product development that up to now has not been given a serious consideration. This chapter is a compilation of important issues related to disassembly in addition to a review of previous work carried out in this field.

3.2 Disassembly Definition

Disassembly may be defined as a systematic method of separating a product into its constituent parts, components, subassemblies, or other groupings [Gup94]. It is a key factor along the product's life cycle as it affects directly life stages like use and end of life and is the core of operations such as maintainability or dismantling for recycling.

Depending on the characteristics of the process, disassembly can be classified in different groups. Firstly, according to the integrity of parts we can divide disassembly operations in two: [Jov93]

- Destructive Disassembly
- Non-Destructive Disassembly

Destructive disassembly is mainly performed in material recovery tasks as well as in the safe disposal of components. In this case the condition of the parts is irrelevant since the main purpose is to recover the constituent materials or to safely dispose of others; damage therefore in products' interfaces and links are not a problem. On the other hand, it is necessary to carry out non-destructive disassembly in operations where the integrity of the products is essential to perform such a task successfully. These operations are maintainability tasks or product recovery scenarios such as would occur when the end of life strategy for the product is reuse or remanufacturing.

Another widely spread classification of disassembly is the extent to which the disassembly is carried out. This leads to the following categorisation:

- Partial Disassembly
- Complete Disassembly

There are several factors influencing the level of disassembly and, as a result, complete disassembly is rarely achieved. For example, management financial decisions are frequently responsible for the interruption of the disassembly process when the recovery cost is greater than the value of the recovered items. Furthermore, in dismantling for recycling, there is no need to separate two parts of the same material since they are going to be thrown into the same recycling bin in order to start the recycling process, which will be identical for both parts.

The term disassembly itself comprises several approaches to the problem and, consequently, it can be divided in different areas, which focus on different perspectives. The author proposes the following categorization:

- Design for Disassembly
- Disassembly Levelling
- Disassembly Planning and Scheduling
- Disassembly Sequencing

This new categorization aims to divide the disassembly problem in an attempt to fit the different areas of research found in literature. The next sections aim to explain the main characteristics of each area, in addition to giving a literature review of disassembly in each categorisation. It is important to note than some of the research work founded in the literature overlaps more than one category.

3.2.1 Design for Disassembly

Design for disassembly focuses on how to design products for ease of break down at a later stage. To assist in pursuing this goal research has produced a set of guidelines that help the designer in the same way as the rest of DFX practices. Clearly these guidelines are only effective when applied at the design stage of the product, when it is still possible to change some of the product's characteristics.

Jovane et al. explain in their research that design for disassembly criteria can be classified according to the benefits they offer. The main advantages arising from a disassembly-oriented product design are: [Jov93]

- less work needed to recover recyclable parts and materials
- more uniformity and predictability of product configuration
- simple and fast disconnecting operations
- easy manual or automated handling of removed parts
- easy separation and post-treatment of recovered materials and residuals
- reduction of product variability

Under these goals we can also identify more specific design rules directly related to the products' attributes and these are as follows [after Jov93 and Fik96]:

- *Less Disassembly Work*
    - reduce product complexity
    - reduce number of parts
    - combine elements
    - modular design
    - limit material variability

    - use similar or compatible materials
    - group harmful materials into subassemblies
    - provide easy access for harmful, valuable and reusable parts
- *Predictable Product Configuration*
    - avoid ageing and corrosive material
    - protect parts and fasteners against soiling and corrosion
- *Easy Disassembly*
    - use fasteners easy to remove or destroy
    - minimise number of fasteners
    - use the same fasteners for many parts
    - provide easy access to disjoining, fracture or cutting points
    - avoid multiple directions and complex movements for disassembly
    - set centre-elements on a base part
    - avoid embedded parts of incompatible materials
    - avoid adhesives and welds
    - avoid threaded fasteners
    - accessible drainage points
- *Easy Handling*
    - reduce product dimensions
    - reduce weight
    - leave surface available for grasping
    - avoid non-rigid parts
    - enclose hazardous substances in sealed units
- *Easy Separation*
    - avoid secondary finishing (painting, coating, plating, etc.)
    - provide marking of different colours for materials to separate

    - avoid parts and materials likely to damage machinery (shredder)

- *Variability Reduction*
    - use standard subassemblies and parts
    - design multifunctional parts
    - minimise number of fastener types

Kroll and Carver identify from the literature four different sources of difficulty in performing dismantling tasks, and they suggest that designers should be able to get feedback from them. The sources of difficulty are [Kro99]:

- Accessibility
- Positioning
- Force
- Task-performance base time

In [Kro96] [Han96] and [Kro99] a methodology to evaluate ease of disassembly is presented. This method was developed following manual disassembly experiments. It consists of a disassembly evaluation chart (see Figure 3.1), which helps to organize the disassembly information and the entry of difficulty scores assigned to the tasks. The evaluation process involves the simulation or manual disassembly of the product and requires the designer to choose the difficult scores and record them in the chart. A catalogue assists the selection of these scores where different tasks have associated values. The catalogue was developed with the MOST system [Zan80], which provides standard time data for the performance of sequences of basic motions. Once the chart is completed, some steps may be taken to improve disassembly performance.

- Calculation of the overall disassembly efficiency of the design. This score is based on a theoretical minimum number of parts as well as minimum effort to disassemble a component.
- Identification of areas for improvement by reviewing a summary of the evaluation results
- Detailed feedback for redesign can be obtained by examining the numbers in the chart.

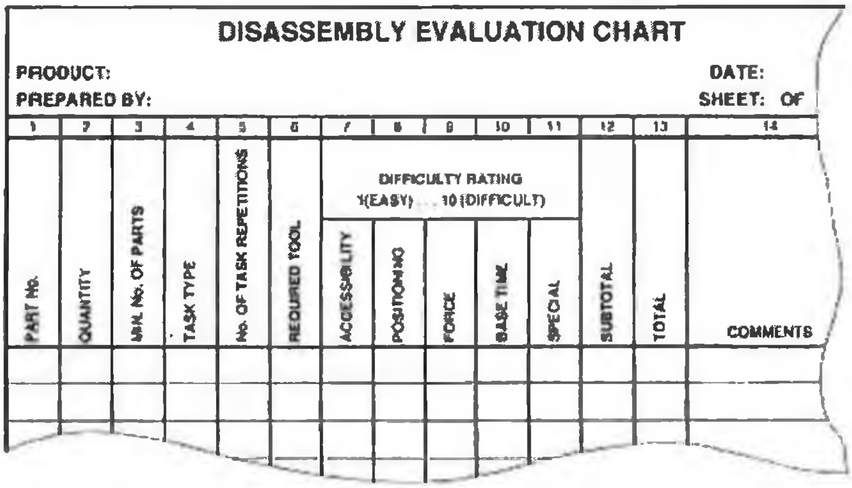

Figure 3.1:Structure of the disassembly evaluation chart [Kro99]

The author thinks that this evaluation method is limited to simple product structures and more work should be done in order to automate and facilitate the identification of weaknesses in the design. The identification of the minimum number of parts, too, is seen as difficult and subjective since there are many issues involved in the design of a product.

3.2.2 Disassembly Levelling

Disassembly levelling refers to the problem of "how far to disassemble", that is, find the disassembly level in which one variable (e.g. cost, revenue and time) is optimised [Gun99]. In general optimisation of one variable does not necessarily lead to the optimisation of the others; for example, the minimisation of the environmental impact is usually expensive and therefore the cost variable is not optimised. It is important to note that, due to resource consumption during the disassembly process, the minimum environmental impact is not reached when the product is completely disassembled.The main variables that can be the object of optimisation are:

- Profit
- Environmental impact

Figure 3.2 represents the economical problem of disassembly. Navin-Chandra [Nav94] identifies several sources of cost that usually contribute to the cost curve, and these are as follows:

- Disassembly
- Testing
- Repair/remanufacturing
- Quality assurance

Navin-Chandra also includes possible changes in design to allow for recovery but the author thinks that this issue should be considered at the design stage rather than a possible disassembly scenario. On the other hand, some revenue is obtained from recovering materials and parts, and this is reflected by the revenue curve.

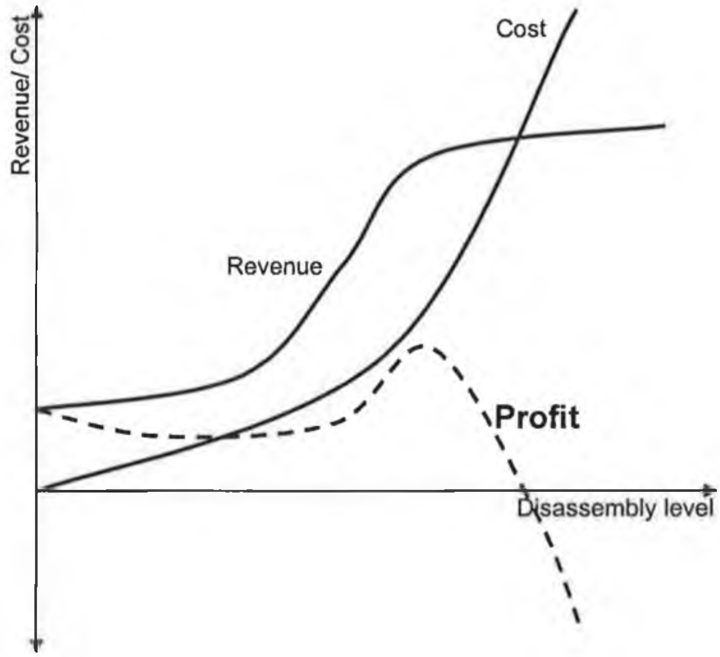

Figure 3.2: Disassembly level and profit relationship [Nav94]

Several groups have studied this area of disassembly, among them, Navin-Chandra [Nav94] presents an approach in which the aim is to optimise the recovery plan, involving a certain level of disassembly. He argues that from an environmental viewpoint partial disassembly is better than trying to recycle every last nut and bolt. His disassembly algorithm needs a structural description of the product in which the fasteners are also treated as parts. This description is built into a table where for each part it is necessary to specify the obstructions in every direction (±X, ±Y, ±Z), i.e. parts that do not allow movement of the target component in the selected direction.

After the table is completed the disassembly algorithm requires the systematic application of the following two rules:

- If any part is unobstructed in any direction, then it can be removed in that direction.
- If any part is held only by a joint in some direction, then it can be removed by undoing that joint.

The rules are applied recursively and the disassembly plan is created. As an alternative, Navin-Chandra [Nav94], also tried to map the problem in the same terms of the "travelling sales person problem" (TSP), but his two different models where unsuccessful and he decided to keep the previous algorithm. Several handicaps where found and reported in his paper while trying to tailor the disassembly problem to the TSP.

3.2.3 Disassembly Process Planning

Disassembly process Planning is concerned with the creation of the requisite Process Plans for the breakdown of assemblies. A Disassembly Process Plan (DPP) is a process sheet showing the sequence of disassembly operations as well as other related information. It is used like a roadmap to guide maintenance people or dismantlers during disassembly operations. For a simple product this might be unnecessary but when products become complex the availability of this information is essential. The main information provided by a Disassembly Process Plan is as follows:

- Disassembly routes
- Disassembly times
- Tools required
- Cost associated to tasks

The disassembly route provides information on how to get to the part to be removed i.e. it specifies the order in which other components have to be removed prior to the removal of the desired part. This is also widely known as "Disassembly sequencing" and some authors identify it as the core of DPP [Vee96]. Disassembly time gives an idea of the total time the process will take and it also can be useful to estimate costs. The system needs certain data to create the DPP. This data is mainly related to structural issues like fastening relationships, contact among parts, modules or obstructions. Also, a detailed database of fasteners has to be in place to run almost any methodology, and should relate to the disassembly times required for unlocking the joints in addition to the tools required for these operations. The author is not aware of any existing database that meets these requirements. In some cases [Kro96] [Kro99] [Han96] the MOST system [Zan80] was used; it basically provides standard time data for the performance of sequences of basic motions but it was not designed for application in a disassembly scenario.

Vujosevic et al. [Vuj95] present a research focused on maintainability issues. In their paper they introduce a method to generate disassembly sequences, times and costs as well as some other features that were implemented in a software package named MAW (Maintainability Analysis Workspace), which will be described in section 3.7. In order to run the algorithm proposed for the generation of disassembly sequences and other results it is necessary to have the structural data for the parts and subassemblies of the product which is the object of analysis. The authors divide this data in two groups: hierarchical and qualitative relationships. The hierarchical refers to the hierarchy of the relationship between parts and assemblies. This is the bill of materials of the product, and its input is assumed to be automatic from a design data server. On the other hand, the qualitative relationships refer to more detailed information about the actual product and the physical connections or relationships. They also divide this categorisation into four specific interactions in the way that a part can be covered by, attached, connected or engaged to some other. The designer must define these relations and these are the basis for the generation of the disassembly sequence. The output is a list of tasks that guide the personnel through the disassembly operation. Each task has associated with it some time created with a previous system called Methods Time Measurement (MTM) [May48]. The total disassembly time is the sum of the times required to perform every job. Finally, from this time the cost is calculated simply by multiplying the time by the labour cost. One of the negative aspects of the method is that the actual sequence is limited to the parts that make up the subassembly, since it is assumed that all other subassemblies can be executed in a single disassembly step.

3.2.4 Disassembly Planning and Scheduling

Disassembly Scheduling is concerned with the study of the scheduling activities in product and material recovery. It can be applied mainly to remanufacturing and reuse activities and, to a certain extent, to recycling activities.

According to Gungor and Gupta [Gun99], inventory control and production planning are well understood for conventional manufacture systems. However, these practices are not directly transferable to recycling or remanufacturing environments. For example, in conventional MRP as it is applied at the assembly stage, there is a single source of demand and several sources of procurement that have to be planned according to the requirements of the root item. On the other hand, in the case of disassembly the demand occurs at the other end of the product structure i.e. the components, and the procurement source is the root item or product [Tal97].

Guide and Srivasatava [Gui97] list several factors that contribute to the higher complexity of modern remanufacturing systems in comparison to traditional ways of manufacturing. These are the following:

- probabilistic recovery rates of parts from the inducted cores which implies a high degree of uncertainty in material planning
- unknown conditions of the recovered parts until inspected, thus leading to stochastic routings and lead times
- the part matching problem (units are often composed of serial numbered specific parts and components, in addition to common components)
- the added complexity of a remanufacturing shop structure
- the problem of imperfect correlation between the supply of core elements and the demand for remanufactured units
- uncertainties in the quantity and timing of returned products

From an inventory point of view there exist also some additional complications such as the demand for increased storage facilities for recovered products and the necessity of keeping track of partially disassembled products and their level of dismantling; furthermore reusable parts and new ones have also to be considered [Gun99]. These issues lead to management inventory complications where traditional rules cannot be applied.

Although Disassembly Planning and Scheduling has not been studied in as much detail as the disassembly levelling or the disassembly process planning, some approaches based on reverse MRP techniques have been reported. For example, Gupta and Taleb [Gup94] presented an algorithm that can be applied to a product structure in which there is a certain demand for components and a need to know the number of root items to disassemble in order to fulfil the demand [Tal97a][Gup99]. One of the problems of this algorithm is that it does not work properly when applied to products that have common parts and materials. In an attempt to solve this difficulty, Taleb et al [Tal97a] cross-linked Bills of Materials for products to address what they call "part and material commonality". Their significant contribution has led to the creation of a new algorithm which solves the problem. The author believes that the scheduling of disassembly for several different products can be efficiently performed by cross linking the different bills of materials for those products and applying the improved algorithm. This can be observed in Figure 3.3.

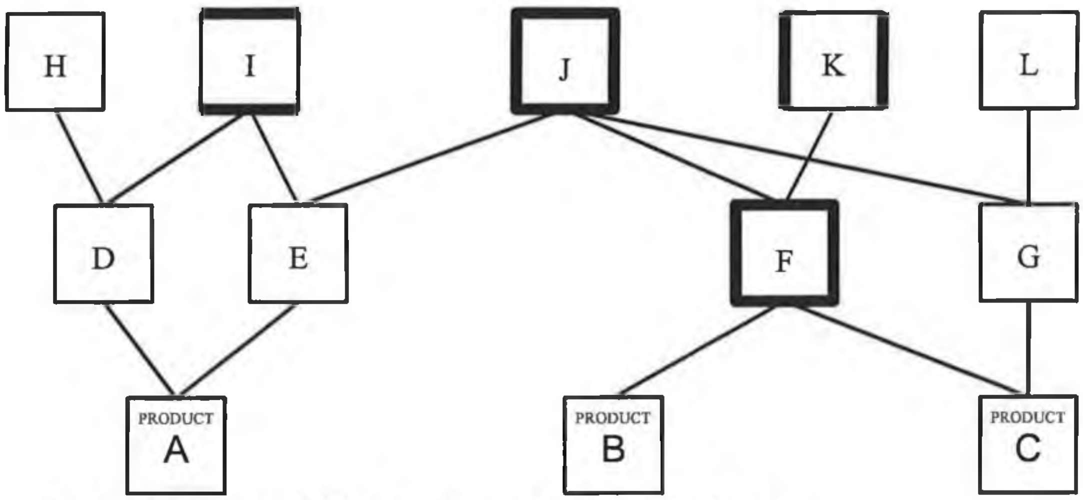

Figure 3.3: Cross-linked BOM for different products [Tal97b]

3.3 Modularity and Product Structure

Modular properties and structure type are key factors that highly influence the overall disassembly performance of a product. In essence, modular design addresses the design of products in which its components can be grouped according to the function they perform in the product. The advantage of a successful modular design is that, in these products, the modules are separable and interchangeable with others from different products [Roc99]. Nowadays products are becoming more and more sophisticated and therefore their structure could become too complex. The creation of modular subassemblies is a way of simplifying product structure as well as disassembly tasks. In addition, Figure 3.4 outlines the main advantages achieved through modular design:

Development	Parallel design of modules leas to reduced development time Simplified product planning Possibility of using and creating "carry over"
Manufacturing	Common modules lead to high volume and scale of economy advantages Rational material handling of modules instead of products Utilisation of investments in specialised manufacturing processes Decreasing reworking by testing modules Possibility for good work organisation
Product variant	Possibility to adapt product to different markets by having some modules as "variants"
Purchasing	Suppliers offer modules which may be cheaper to make in house Lower logistic costs
After Sale	Possibility of upgrading Simplified maintenance and service Possibility of rebuilding a product Modules are easy to disassemble for recycling, reuse and remanufacture

Figure 3.4: Benefits of Design for Recycling [Eri96]

From a disassembly perspective the main benefits of modular design in Figure 3.4 appear in the "After sale" stage of the product, which mainly covers use and end of life of the items.

Product structure is concerned with the way that the different components of the product are assembled [Roc99]. Three main types of structures can be extracted from the literature: [Kro96, Ben97, Roc99]

- Layered structure
- Hierarchical structure
- Complex structure

In a *layered structure* the constituent parts are assembled one on top of the other in the same way a sandwich is prepared. Usually components are linked with a limited number of parts having simple interfaces among them. An example of layered structure is a mobile phone or a computer keyboard. (see Figure 3.5)

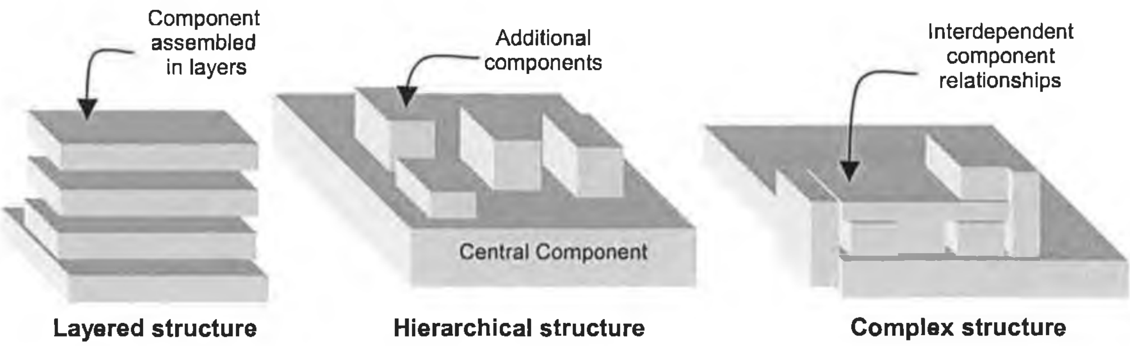

Figure 3.5: Product structure types [Roc99]

A *hierarchical structure* is composed of a main component to which the rest of the parts are linked. An example of this can be the mother board of a computer which has several components attached to it.

Finally the *complex structure* does not have any special characteristics. Here the components have multiple links to one another and the interfaces among them can be highly intricate. Despite the fact that this product structure is the most widespread, it is not desirable. In practice, the disassembly of units with complex structures is more difficult and time consuming than the disassembly of layered or hierarchical ones; therefore, when possible, every effort has to be made to avoid this product configuration.

3.4 Representation Techniques

There are several ways in which the relationships between the components of a product can be described; among them, the most widely used are those that utilise graph-based approaches. In addition, some attempts to model the disassembly process as a Petri net has been reported in the literature. This section introduces the basis of graph and Petri net theory in order to introduce the reader to the basic terminology.

3.4.1 Graph Theory

Graphs represent diagrams which consist of nodes joined together either by lines or by arrows. They are met in many fields such as engineering, physics or mathematics. Graphs usually represent a structure of a system, process, product or organisation. They can be considered as an abstraction of reality and therefore they are used as a powerful tool to solve a lot of different problems [Pen96]. Next, the mathematical definition of graphs is presented (from [Joh97]): A graph (or undirected graph) G consists of a set V of vertices (or nodes) and a set E of edges (also called arcs) such that each edge e∈E is associated with an unordered pair of vertices. If there is an unique edge e associated with the vertices v and w, then e=(v,w) or e=(w,v). In this context, (v,w)and edge between v and w in an undirected graph and not an ordered pair.

A directed graph (or digraph) G consists of a set V of vertices (or nodes) and a set E of edges (also called arcs) such that each edge e∈E is associated with an ordered pair of vertices. If there is a unique edge e associated with the ordered pair (v,w) of vertices, then e=(v,w) which denotes and edge from v to w.

The concept of graphs has been largely applied to the disassembly problem with limited success. Some analogies to the Travelling Salesperson Problem have been investigated but no problem statement that fits disassembly has been found [Nav94].

Additionally diverse variants of graphs have been proposed or adopted to model the disassembly of a product and facilitate the study. The most important are:

- Liaison Graph
- Disassembly Tree
- AND/OR Graphs

3.4.1.1 Liaison Graph

Frequently an assembly is represented as an attributed liaison graph. Following the same notation as before, an attributed liaison graph is a connected graph G=(V,E), with V representing vertices and E representing the set of edges. A vertex is associated to each part of the assembly and a edge is assigned to each liaison. A liaison is said to exist between a pair of parts if one part constrains the freedom of motion of the other either by a direct contact or by obstructing it [Lee90]. A label is attached to each vertex to describe attributes associated with the part for example part geometry contact surfaces or physical properties. Similarly a label is attached to every liaison to describe the attributes related to the liaison which may include information such as type of liaison (fastener, obstruction), type of interconnection (fastener type) or mating surfaces among others [Lee90].

3.4.1.2 Disassembly Tree

A disassembly tree is a connected, acyclic graph in which the root item represents the assembly, the leaf items are the constituent parts and the internal vertices correspond to different subassemblies. This representation is completely different than the Bill of Materials of the product since every vertex (except leaf vertices) corresponds to a disassembly task that divides the subassembly in two or more subassemblies or parts (see Figure 3.6). In contrast, the BOM defines the subassemblies in terms of functional modules, that is, a group of components that together perform a determined function. For example, Figure 3.6 shows A_0 divided in A_1 and A_2 by means of task T_0.

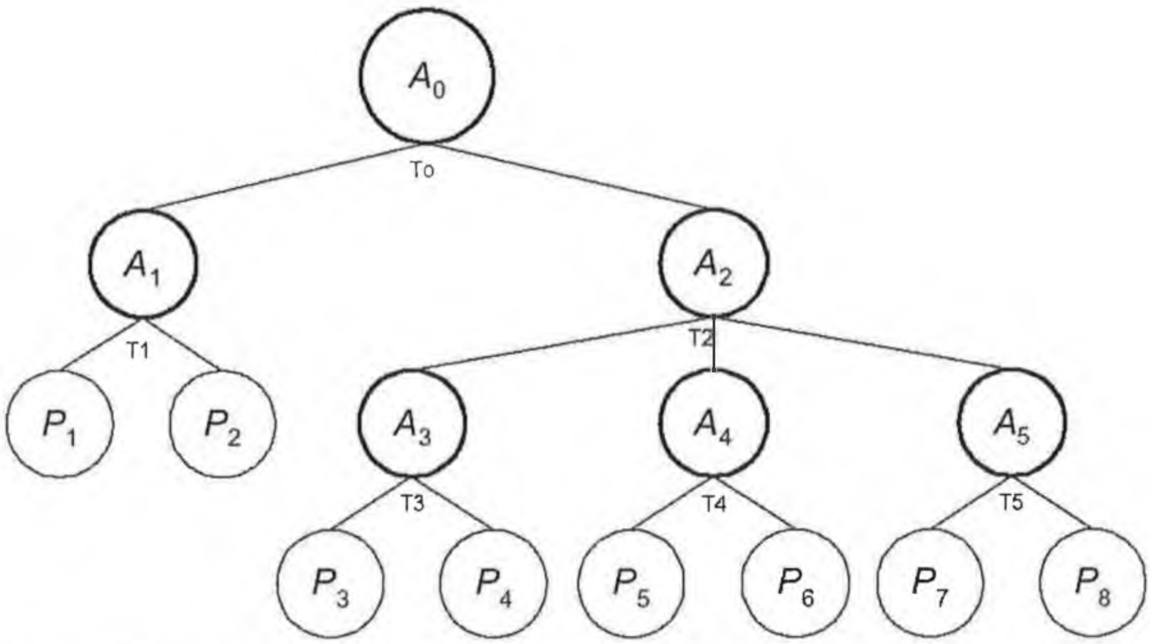

Figure 3.6: Disassembly tree for product Ao

This representation does not allow direct recognition of the sequence of task to carry out in order to disassemble the product.

3.4.1.3 AND/OR Graphs or Hypergraphs

And/or graphs are directed graphs, in which edges emanating from the same node are either in an AND relation or an OR relation with each other. In the disassembly context, each node in the and/or graph of a product represents a possible subassembly. Edges in the graph emanating from the same node are partitioned via an AND relation, so that edges {(u, v0), (u, v1) . . . (u, vm)} are all in an AND relation to each other, if and only if sub-assembly u can be disassembled by a single operation into sub-assemblies v0, v1, . . . , vm. (Equivalently, a single joint connects them to form u). An implicit OR relation exists between different AND groups emanating from the same node, meaning that if {(u, v), (u, w)} and {(u, x), (u, y)} are two such groups, then it is possible to disassemble u into either v and w or x and y. It is easy to see that such an and/or graph is always acyclic, and that each disassembly plan of the product corresponds to a sub-tree of this graph [Pnu97]. Therefore, a disassembly tree is just a particular case of the and/or graph.

The and/or data structure is already used to find optimal assembly plans for a product's data, and hence in an automated CAD environment is either directly available or easily computable from other 'design for assembly' data structures [Hom91].

The recovery graph of a product is also another tool that has been used in disassembly. Pnueli and Zussman did work on this area and proposed that a recovery graph is also an and/or-graph, where with each node and each group of AND edges, a recovery value is associated. For a node v, this recovery value, c(v), is the end-of-life value (cost/benefit) incurred by recycling (or dumping) v without further disassembly [Pnu97]:

$$c(v) = \max\{c_{reuse}(v), c_{use-on}(v), c_{utilize}(v), c_{dump}(v), c_{shred}(v)\} \text{ [Pnu97]}$$

For a group of AND edges, say {(u, v), (u, w)}, the recovery cost, c(u, v, w), is the cost of disassembling the sub-assembly, represented by u, into the sub-assemblies represented by v and w. It is important to note that in a recovery graph, all feasible disassembly plans are represented, and are done so in a compact form [Pnu97].

To find more about AND/OR graphs and their properties, the reader is referred to a paper written by Homem de Mello and Sanderson [Hom90] in which they discuss about AND/OR graphs applied to the assembly and disassembly problem giving further explanation of this type of graphs and their properties.

3.4.2 Petri Nets

Petri nets are a graphical and mathematical technique useful for modelling concurrent, asynchronous, distributed, parallel, nondeterministic, and stochastic systems. Petri net models can be analysed to determine both their qualitative and quantitative properties. Petri nets have recently emerged as a promising approach for modelling manufacturing systems, and have been used for assembly process planning [Moo98a, Moo98b].

Mathematically, a Petri net is a directed graph G=(V, E), where V=P∪T and P∩∅ Any edge e in E is incident on one member of P and one member of T. The set P is called the set of places and the set T is called the set of transitions. In other words a Petri net is a directed, bipartite graph where the two classes of vertex are called places and transitions [Joh97].

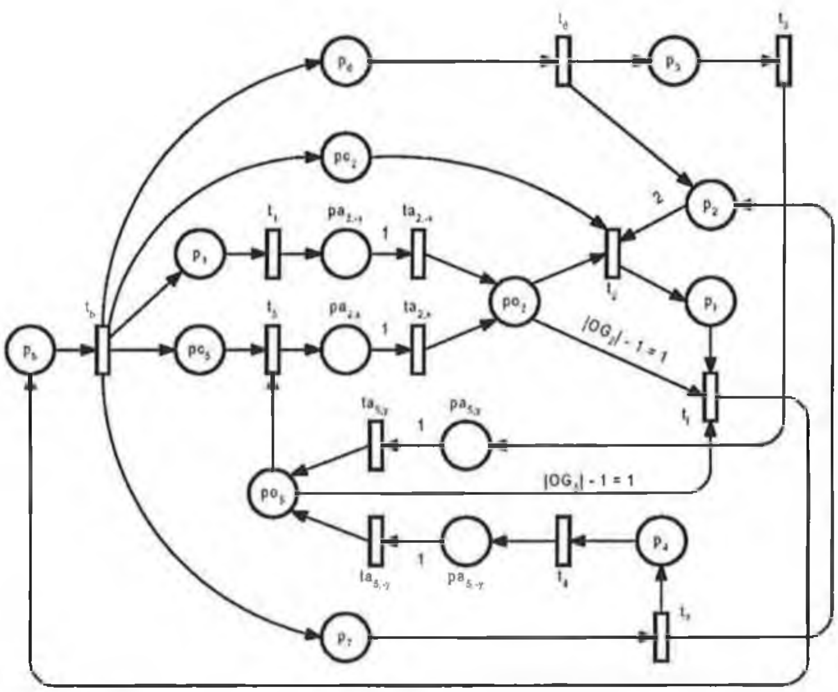

Figure 3.7: Example of a Petri net applied to disassembly [Moo98a]

The Petri net, as an abstract and formal information flow model, has the capacity to model and analyse serial and concurrent events and resource constraints. Characterized by its flexibility and efficiency in modelling and analysis of complex systems, the Petri net has therefore been applied to many fields. Its place, transition and token movement together provide a specification and graphical representation of assembly systems and operational planning knowledge, and can be used to model alternative process plans. Applying a Petri net-based approach to represent alternative process plans is useful for solving the problems of flexible process modelling and sequencing in a computer integrated manufacturing environment. On the other hand, the Petri net possesses the potential to be integrated into an artificial inteligent framework with knowledge representation, automated reasoning and decision making [Zha00].

3.5 Analysis Techniques

In the literature different authors refer to different analysis techniques that they use to solve the disassembly problem. This sections gives a brief introduction to these techniques.

3.5.1 Case Based Reasoning

CBR is based on the idea of utilizing solutions to past problems to solve new problems. The solutions to 'similar' problems can be retrieved from a case memory of solutions, and applied to the new problem. When a CBR system is presented with a similar problem, it does not re-reason from an initial set of facts and rules. Instead, it uses the plan that embodies the reasoning already utilized in the retrieved solution [Vee99a].

There are several advantages that CBR brings to the disassembly problem. First, the approach has an ability to learn any of the problem solving strategies available to PFD. Second, if there are already well-developed approaches to solving a particular portion of the problem, CBR can use them directly as a sub-plan under the larger plan of solving the total problem. Third, CBR is flexible. In its simplest form, it could just re-execute a previous plan that was derived, regardless of the domain of the problem. The knowledge base of a CBR solver is the result of successful attempts at solving problems. A CBR solver could come seeded with initial plans, but it is not a necessity. Whatever the user does, in order to achieve the process planning goals, will be mimicked. Therefore CBR presumes no problem solving paradigm; it can utilised only the techniques it has been taught. Finally, CBR is intuitive and can be induced from a process planner's experience. CBR allows a planner to solve the problem several times before a plan associated with the goal is enacted. This also helps the planner to effectively improve the original plan by carrying out the necessary modifications as the solution to the problem evolves [Zei97][Vee99a].

In general, CBR can be described in terms of five different tasks: mapping, retrieval, adaptation, revision, and storage [Kol93]. The flow and interaction of CBR with the disassembly process plans is described as follows (see Figure 3.6).

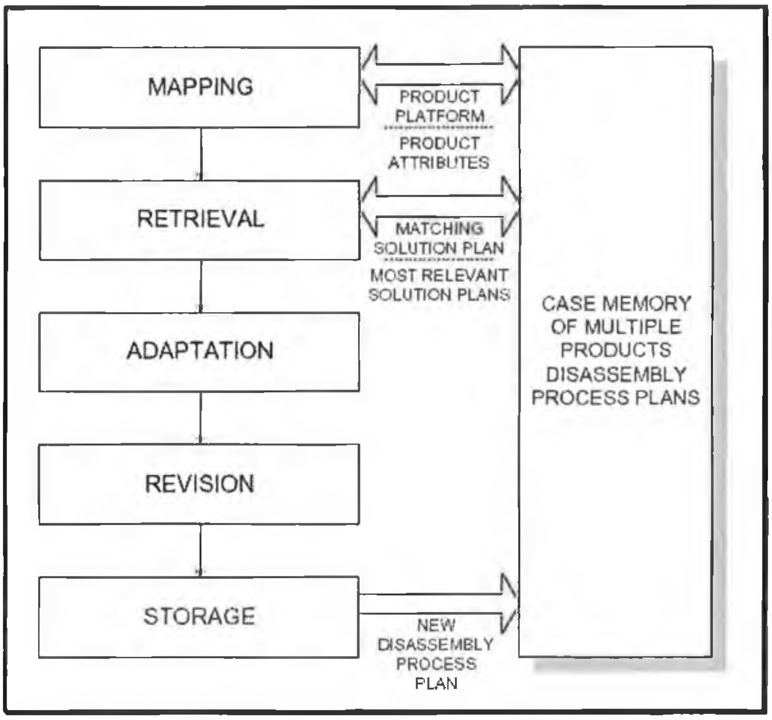

Figure 3.8 Case-Based Reasoning System for Disassembly Process Planning [Vee99a]

Mapping. Recalling a case from case memory is a pattern-matching problem that is based on the specification of a new problem. In order to map cases in case memory, the specification of a new problem is transformed into a pattern to be matched. The pattern may be taken directly as the user input specification or it may be modified, for example, to include an order of importance of the attributes [Vee99a].

Retrieval. The retrieval task in CBR searches case memory for matches between individual cases and the pattern that serves to index the cases. Each case in case memory may be compared to the pattern, or the pattern may provide a set of indices to partition case memory, thus only a relevant subset of cases are compared with the pattern. Retrieval can be based on a perfect match, where the pattern is found exactly, or on partial matches. If partial matches are retrieved, a threshold may be set to determine when a partial match is close enough (always retrieve the best plan) [Vee99a].

Adaptation. This function is responsible for applying the case solution from a retrieved problem to the problem at hand. In some problems, a selected case provides a solution to the new problem. In most problem solving, however, the selected case needs to be modified to be appropriate as a solution to the new problem. Adapting a case from case memory to solve a new problem requires additional knowledge. The form this knowledge takes depends on how adaptation is done. The original case is called a base case, while the adapted case is called a derived case [Vee99a].

Revision. This is the actual running of the adapted plan against the problem. Application of the new plan needs to be evaluated in order to prepare it for storing. Zeid et al. [Zei97] suggest that a revision process can be modelled as a sequence of transitions from an initial or existing state of DPP, to its final state. Therefore, the revision process is necessary and useful in making sure that the final state of the plan is valid before storing it in the case memory for future use [Vee99a].

Storage. This is concerned with adding and organizing the readjusted plan to the case memory. Once the plan is revised, it is introduced to the case memory to be stored. Whenever a new plan is introduced to the case memory, a storing procedure is activated. Indeed, if the plan deems satisfactory, the plan is stored, and if not, it may be discarded [Vee99a].

3.5.2 Branch & Bound Algorithms

Branch and Bound is a general search method, which finds the optimal solution by keeping the best solution found so far. If a partial solution cannot do better than the best, work on it is abandoned [Bla02]. This may be implemented as a backtracking algorithm, which is a modified depth first search, or using a priority queue ordering partial solutions by lower bounds (current and least possible completion), which is a best first search.

For example if we wish to minimise a function f(x), where x is restricted to some feasible region (defined, e.g., by explicit mathematical constraints). To apply branch and bound, one must have a means of computing a lower bound on an instance of the optimisation problem and a means of dividing the feasible region of a problem to create smaller subproblems. There must also be a way to compute an upper bound (feasible solution) for at least some instances; for practical purposes, it should be possible to compute upper bounds for some set of nontrivial feasible regions.

The method starts by considering the original problem with the complete feasible region, which is called the root problem. The lower-bounding and upper-bounding procedures are applied to the root problem. If the bounds match, then an optimal solution has been found and the procedure terminates. Otherwise, the feasible region is divided into two or more regions, each strict subregions of the original, which together cover the whole feasible region; ideally, these subproblems partition the feasible region. These subproblems become children of the root search node. The algorithm is applied recursively to the subproblems, generating a tree of subproblems. If an optimal solution is found to a subproblem, it is a feasible solution to the full problem, but not necessarily globally optimal. Since it is feasible, it can be used to prune the rest of the tree: if the lower bound for a node exceeds the best known feasible solution, no globally optimal solution can exist in the subspace of the feasible region represented by the node. Therefore, the node can be removed from consideration. The search proceeds until all nodes have been solved or pruned, or until some specified threshold is meet between the best solution found and the lower bounds on all unsolved subproblems [Sam97].

3.5.3 Genetic Algorithms

Genetic algorithms are based on a probabilistic research technique introduced by Holland in 1972 [Cac01]. These types of algorithms have been especially valued in the last few years because they fit into many kinds of problems; genetic algorithms, in fact, have a scope that is independent of the individual problem considered. This means that such algorithms are able to optimise very complex functions without having a specific knowledge of the problem they are trying to solve. The aforesaid characteristic has lead to define genetic algorithms as "blind": in fact they are able to obtain useful information for the analysis of the considered problem through the simple evaluation of arrays of parameters. The principle ruling these algorithms is the "natural selection process"

In order to solve a specific problem, a genetic algorithm creates a population of individuals, each one made by a chromosome (array of parameters which represents a specific solution) and its cost function. The genetic algorithm modifies the population by means of probabilistic methods in order to find an optimal solution.

The search for the solution starts from any positive changes in the parents that appear in the offspring. This method considers chance as well as environmental factors that make a specific chromosome more or less fit for such environment.

The task of the algorithm is to use the information acquired during the execution of a specific cycle and to transmit the positive characteristics from one population (parents) to the next (offspring) by selecting the chromosomes that fit best into the environment, i.e. the chromosomes having the best evaluations. A genetic algorithm has usually five constituent modules [Cac01]:

- Initialisation: randomly creates the first chromosome population
- Evaluation: assess the population's chromosomes with an evaluation function
- Population: determines the pair of chromosomes fit for reproduction
- Reproduction: creates offspring chromosomes by means of genetic crossover and mutation operators.
- Generation: substitutes current chromosome population with new offspring chromosomes.

The systematic application o of this process creates new generation of chromosomes that evolve towards the solution of the problem [Cac01].

3.6 Design for Assembly and Disassembly Integration

Contrary to traditional manufacturing, product life-cycle design involves the optimisation of products' attributes that affect the diverse stages of the product life-cycle. This more holistic approach forces designers to take into account diverse methodologies such as design for assembly and design for disassembly, which sometimes would lead to conflicting design solutions.

Boothroyd and Alting [Boo92] ensure that design for assembly (DFA) provides a systematic procedure for analysing proposed designs from the point of view of assembly and manufacture. This leads to simpler and more reliable products, which are cheaper to manufacture. According to them, experience shows that besides the previously cited benefits, products that are easy to assemble are also easier to disassemble and reassemble, thus facilitating operations such maintainability or remanufacturing. However, experience also shows that this is not always the case and there are some conflicts between both methodologies. For example, assembly operations like welding or the use of adhesives might have beneficial effects in assembly since they are quick and reliable processes but they are non-reversible fastening relationships and consequently they may prevent or impede disassembly.

Shu and Flowers [Shu99] studied the conflict between design for remanufacture and the rest of design for X methodologies like assembly or recycling. In their work they identify three possible failures during disassembly and reassembly:

- Failure of the fastening or joining material during disassembly or reassembly. For example, rivets and welds are typically destroyed during disassembly, and the head of a threaded fastener may become damaged during the operations.
- Failure of the part during disassembly or reassembly. For a joint that uses threaded fasteners, this includes stripping of the internal threads in the part; and in cases where the fastening method is integrated in the part, such as with snap fits, the snap breaks.
- The third is failure of the part during fastening-method extraction. Fastening-method extraction occurs after the fastening method has failed and entails removal of fastening elements from the part. For example, if the disassembly tool bit damages the head of a screw, the part may be damaged while extracting the stripped screw. If an insert is damaged, the part is harmed when the insert is removed.

This classification also leads to different consequences according to the type of failure. In most cases, the consequence of fastener damage is fastener replacement, the result of part failure is rework if the damaged part can be repaired and part replacement if the damaged part cannot be repaired. Clearly, these costs have to be minimised in order to avoid unexpected expenditure.

The problems outlined above are likely to appear when considering maintenance or diverse end-of-life strategies in a product that was purely designed for assembly. Consequently, special consideration needs to be given to disassembly in design without compromising ease of assembly. To achieve successful integration it is essential to have excellent communication and teamwork between designers and engineers [Kuo01].

In an attempt to unify the set of guidelines provided by the DFX methodologies to be considered in lifecycle design, a table has been created (see Figure 3.9) showing whether each of the guidelines should or should not be considered according to the strategy presented. Numerous conclusions can be extracted from the analysis of the table. The first conclusion is that similar needs in terms of assembly, disassembly and reassembly are found in operations of serviceability, maintainability, reuse and remanufacturing. This means that the operations mentioned previously are complementary. This is also observed when comparing the recycling and controlled disposal columns of the table.

Interesting conclusions can be also extracted focusing on the possible incompatibility of design for assembly and disassembly rules. Guidelines that mainly influence early stages of design are highly beneficial or at least show no effect for all the possible scenarios. These kinds of guidelines are often related to product structure and complexity. The main conflict comes later in detailed design when the fastening relationships are completely defined. Here, for example, a designer considering only assembly issues would go for quick and reliable fasteners like, for example, welds, ignoring that eventually they would have to be unfastened. The idea is to use non-permanent fasteners as well as re-usable ones and to avoid the type of fasteners that are part of a component and have to be broken in order to remove the joint (such as with certain snap-fit and clip components). The term re-usable fastener refers to the type that can be done and undone without damaging the parts of the product or decreasing the joint reliability after several disassembly/reassembly cycles. These re-usable fasteners are essential in maintainability, service, re-manufacture and re-use operations and therefore work has to be done to replace or redesign the fasteners that do not meet these basic requirements. An example of this type of damage to a part by a fastener is when two parts are secured by means of thread-forming screws in a plastic base. Due to maintainability or re-manufacturing operations these screws may be removed and reinserted creating new threads in the plastic that can decrease the reliability of the joint [Shu99].

Guideline [Cor87][Jov93][Fik96][Kuo01]	ASSEMBLY	DISASSEMBLY			
		Service and Maintainability	Re-use and Re-manufacturing	Recycling	Controlled disposal
Minimize number of parts	Yes	Yes	Yes	Yes	Yes
Minimize complexity	Yes	Yes	Yes	Yes	Yes
Modular design	Yes	Yes	Yes	Yes	Yes
Minimize number of fasteners	Yes	Yes	Yes	Yes	Yes
Minimize fasteners types	Yes	Yes	Yes	Yes	Yes
Minimize material variety	No effect	No effect	No effect	Yes	Yes
Use similar or compatible materials	No effect	No effect	No effect	Yes	Yes
Avoid multiple directions and complex movements	Yes	Yes	Yes	Yes	Yes
Avoid aging and corrosive materials	No effect	Yes	Yes	No effect	No effect
Protect parts and fasteners against soiling and corrosion	No effect	Yes	Yes	No effect	No effect
Use fasteners easy to remove or destroy	No effect	Yes	Yes	Yes	Yes
Avoid threaded fasteners	Yes	No	No	Yes	Yes
Avoid permanent fasteners (welds, adhesives etc)	No	Yes	Yes	No effect	No effect
Provide fasteners integrated in parts (snap fits, thread-forming screws, etc)	Yes	No	No	Yes	Yes
Avoid finishing in parts	No effect	No effect	No effect	Yes	No effect
Provide suitable lead-in chamfers	Yes	Yes	Yes	No effect	No effect
Automatic alignment	Yes	Yes	Yes	No effect	No effect
Easy access for locating surfaces	Yes	Yes	Yes	No effect	No effect
Symmetrical parts or exaggerate asymmetry	Yes	Yes	Yes	No effect	No effect
Simple handling and transportation	Yes	Yes	Yes	Yes	Yes
Avoid visual obstructions	Yes	Yes	Yes	Yes	Yes
Avoid operational obstructions	Yes	Yes	Yes	Yes	Yes
Avoid simultaneous fitting operations	Yes	Yes	Yes	No effect	No effect

Figure 3.9: Overlapping between assembly and different disassembly scenarios.

Finally, it is important to note that in conflicting situations the decision should be based on objective criteria about the expected life cycle of the product, for example, stud welds could be used to secure the blade of a disposable razor since the integrity of the fasteners will not be an issue at the end of life of the assembly.

3.7 Disassembly Software Review

This section describes the most important software tools that address the disassembly of a product in one way or another. Figure 3.10 shows the chronological evolution of this type of software and also it summarises the main characteristics of every package. The remain of this section further explains the research carried out by the different groups that create the tools.

Name of Tool	Year	Author	Main Characteristics
DFMA: Design for Service and Design for Environment modules	1992	Boothroyd & Dewhurst	Two modules: service and environment Link to B&D DFA software User defines the disassembly sequence Graphical representations of costs, revenues and environmental impacts according to disassembly level
LASER	1993	K. Ishii	Product recovery focus Estimates disassembly and recycling costs Calculates disassembly times based on estimations for removal of components input by the user Allows different scenarios by specifying subassemblies (clustering)
ReStar	1993	Navin-Chandra	Product recovery focus DPP creation with sequence and times Optimisation of the recovery problem in terms of profit Considers clusters of compatible materials
MAW	1995	R. Vujosevic	Overall maintainability focus Maintainability evaluation Calculation of disassembly sequences, times and costs Simulation and animation of activities Consideration of human factors
EDIT	1995	M.R. Johnson & M.H. Wang	Focus on maximising profit at disposal stage Addresses compatibility of materials and modularity by means of defining subassemblies (clustering) Finds disassembly level and sequence which maximises profit
DFD optimisation	Mid 90s	H.C. Zhang	Economic focus. Tries to reduce the total life cycle cost of products.
BAMOS & INTEGRA	1996	Jan Klett	Computer based information system for disassembly Product structure & data editor Manage and select proper design rules

Name of Tool	Year	Author	Main Characteristics
AMETIDE	1997	T. Gaucheron, P. Sheng E. Zussman	Estimate disassembly times Specification of end-of-life strategy for parts: reuse, recycling, remanufacturing, safe disposal Database of fasteners and alternative disassembly methods Classification of tasks with ergonomic considerations
PCR	1999	T.C. Kuo, H.C. Zhang S.H. Huang	Focus on disassembly for recyclability Considers and creates modularity based on structural relationships (clustering) Requires important input from the user The output is a disassembly tree
Salvage	1998	Peter Sandborn	Mainly economical cost of assembly disassembly and reassembly operations Developed for electronic products Doesn't create any disassembly sequence
DIRECT	2001	G. Dini, F. Failli, M. Santochi	Overall recycling focus CAD integration Generation of clusters that can be sorted based on recovery value, weight, material homogeneity or a combination of them Economic evaluation of disassembly operations Generation of disassembly sequences for every part and cluster

Figure 3.10: Outline of disassembly software packages

Boothroy & Dewhurst

Boothroy & Dewhurst are pioneered the creation of tools to assist the designer during the improvement of design prototypes. In the mid 80s they launched their first product called DFMA, which helped designers to synthesise design characteristics from a Design for Manufacturing and Assembly perspective. Since the first launching several new versions of the application were released that enhanced the functionality of the tool. Along with the releases, new requirements of design were identified such as the optimisation of maintainability and end-of-life operations. These two requirements were implemented in two separate modules that link the main application, which still is DFMA. While inputing the data in DFMA a kind of process sheet is built up which specifies the bill of materials (BOM) of the product, the fasteners required and other operations in manufacturing and assembly processes.

This is the main information that we can import from the service and environmental modules of the DFMA tool. In the Design for Service module the user identifies the service tasks and inputs the disassembly sequence required for servicing each of the target parts. Besides, more information about special difficulties encountered during the service process can be also entered in the system and it will affect the final results. Next, the software creates the reassembly sequences by reversing the disassembly plan previously created. During this process the program calculates labour times and costs for the operation described as well as an indicator called DFS index, which is based on the cost of the service item and the cost of replacing it [Boo00].

The Design for Environment module of DFMA focuses on the analysis of the disassembly and the expected end-of-life for the product. The first step is to specify all the components of the product in disassembly order, including disassembly operations [Boo00]. This implies that the program is not creating any disassembly sequence based on the product structure. Another possible input to the program is the specification of added difficulties in the processes, like the need for two people, difficult access to specific fastener or "heavy items". Furthermore, environmental data is input in a separate window; here the materials and manufacturing processes are specified as well as the end-of-life strategy. This information is required to obtain the environmental impact metrics, which in this case is the MET point (Materials Energy Toxicity method [Bre97]). Once the data is in the system the application makes the required calculations and provides some graphs (see Figure 3.11) that help the designer to analyse the design of the product. The information displayed is the profit as well as the environmental impact along the disassembly level of the product, which in this case is monitored by the disassembly time.

The program can be used to automate calculations but it does not optimise any variable. The disassembly process plans have to be implemented by the designer so that in a complex product this task could be very complicated and should be automated in some way. It is also the author's opinion that this type of software should provide decision support to the user during the evaluation and improvement processes.

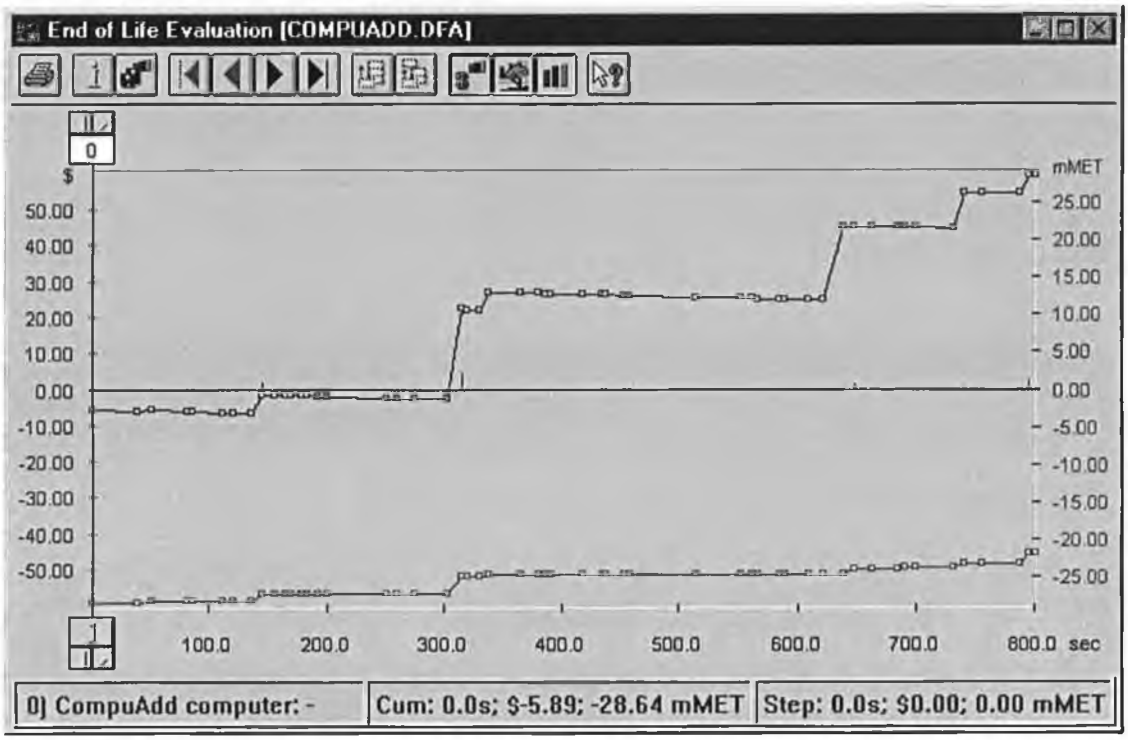

Figure 3.11: End-of-Life Evaluation from DFMA Design for Environment module [Boo00]

LASER

The LASER Tool [Ish94] allows the user to specify a design in terms of graph and part connections (Figure 3.12 left), and then it allows the user to assess disassembly and recycling costs. The user can change materials and joints to improve the design. It is also possible to create subassemblies by selecting and grouping different parts in what the authors call "clumps". This allows the user to consider partial disassembly strategies [Nav94]. The input data for LASER is guided by different data pages, which prompt information to the user. These data pages are related to end-of-life, assembly and maintainability analysis, which allow the user to specify data like type of materials, weights, cost estimate or time forecasts for removal of the product's parts.

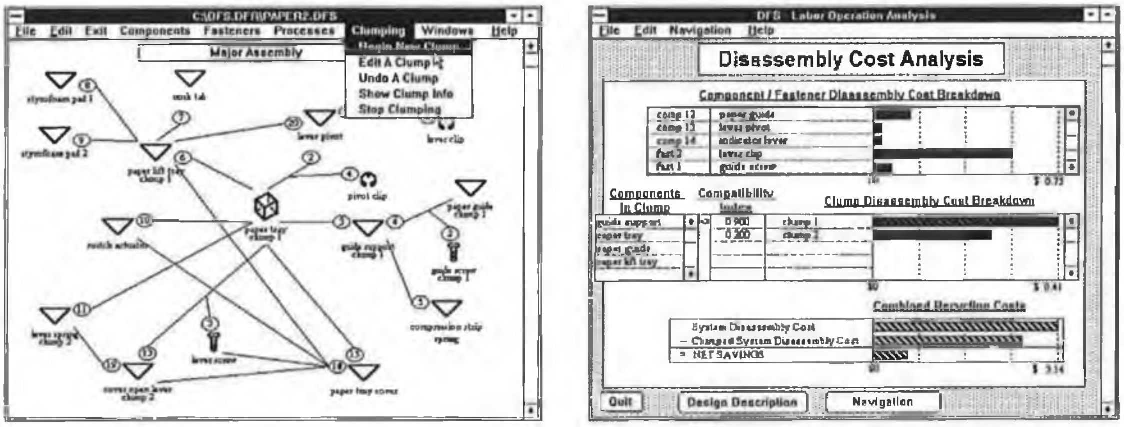

Figure 3.12: Linker interface and recyclability results from LASER [Ish93]

The outputs of the program are several screens with graphs (Figure 3.12 right) that show the results of the disassembly times and life-cycle costs calculations. The main drawback of this tool is that the user has to input time estimate for disassembly operations and therefore, the main difficulty of automatic calculation of dismantling times and sequences remains unsolved. The prototype runs in a PC-Windows environment using the Toolbook software construction kit.

ReStar

The ReStar tool was developed by Navin-Chandra [Nav94] approximately at the same time than the LASER tool which has been already described. His functionality is very similar and it was also planned to optimise the recovery problem. On one hand, the main disadvantage respect to LASER is that, ReStar needs much more input from the user but on the other hand, the higher automation of ReStar allows the user to perform tasks more efficiently. The concept of the core algorithm necessary to create the DPPs has been already described in section 3.2.2; in addition the implementation of this algorithm in a software tool provides more functionality and versatility than the manual method since, while the application is creating the disassembly sequence it is also keeping track of times, costs and revenues. As opposition with LASER this tool calculate disassembly times and costs for the operations based on a database that contains this information. Furthermore, the identification of subassemblies composed by compatible materials is also considered and as these subassemblies will not be separated it results in time and costs savings. The main disadvantage of this tool is the large input particularly when dealing with complex products. Navin-Chandra argues that ReStar has been designed to be a CAD tool, which certainly would simplify the input, however he doesn't explain this integration in his work. The application has been designed on a Unix and Mach/OSF1 workstations and has been implemented in Common Lisp and TK/TCL.

MAW

MAW (1995) [Vuj95b] stands for Maintainability Analysis Workspace. This software is intended to establish an environment to enhance communication between maintainability engineers and designers. It is also used to evaluate maintainability in design, helping the user to identify design features that cause problems and proposing design modifications to improve these situations. According to Vujosevic, MAW supports maintainability analysis by providing the following capabilities [Vuj95c]:

- Importation of geometric and non-geometric information about the design model
- Preparation of the design model for human-design interaction and animation
- Definition of quantitative and qualitative requirements
- Definition of maintainability personnel using anthropomorphic database
- Identification of all feasible disassembly sequences
- Automatic hand tool selection
- Planning, design, simulation, and animation of maintenance tasks
- Estimation of time and costs of the maintenance tasks
- Human factor analysis of maintenance tasks
- Assessment of design maintainability
- Execution of design modifications recommended in order to eliminate identified maintainability problems

MAW is implemented in C and Motif Toolkit for X Window System, and runs on a Silicon Graphics workstation [Vuj95]

EDIT

In their paper Johnson and Wang [Joh95] present the application EDIT (Environmental Design Industrial Template). This program uses a quantitative evaluation of disassembly paths based on an index proposed by the authors and named *Profit and Loses Margin index* (PLM). Next equation shows how the calculation is carried out at every point in disassembly.

PLM = Reclamation value – Disassembly cost – Disposal cost [Joh95]

In EDIT the analysis starts describing the relationships between components and the disassembly operations required; in fact, the user has to define the disassembly process. This can be carried out in the graphical interface of the program by adding different icons representing: parts, subassemblies, disassembly operations, free nodes, disposable clusters and compatible material clusters. After the description of the process it is necessary to input recovery values for parts and subassemblies that later will be used in order to calculate the PLM indexes. The software also enables the user to specify alternative operations that could be performed at a certain stage in the disassembly process; these interchangeable operations give the same result in disassembly terms but they can lead to different PLMs. The next step is to narrow the search space in an attempt to reduce the problem size. This reduction is based on four criteria as follows: (1) clustering of compatible materials (2) clustering negative PLM nodes for disposal (3) clustering similar disassembly operations and (4) maximizing parallelism and yield. Next the PLM is calculated for different disassembly configurations and an optimal disassembly sequence is chosen based on the maximum benefit (i.e. maximum PLM) reclaimable. EDIT runs under Ms Windows and was coded in C+ +.

Design for Disassembly Optimisation

Zhang presented a new software tool named *Design for Disassembly Optimisation*, which was probably developed in the mid nineties [Zha9X]. His research formulates an economic model for disassembly operations, taking into account sequence-dependent disassembly cost, release-dependent disposal costs, group values of reclaimed parts, and disassembly precedence relationships. A simulated annealing algorithm was employed in order to find the economically optimal sequences producing a maximum return value, and to advise as to where the disassembly operation should stop.

BAMOS & INTEGRA

Klett [Kle96] investigated how to create products easy of disassembly and therefore he always viewed the problem from design. The objectives of his research were

- Evaluation of current products and identification of weak points
- Take a holistic view of the product to optimise weak points and generate design rules for early stages of design
- Expansion of the existing disassembly design knowledge and development of a computer based information system.
- Integration of the information system in CAD

These objectives led to two peaces of software called BAMOS and INTEGRA. The first one is an editor in which the structure of the product and other information as materials and weights can be established. The purpose of BAMOS is to help the designer to analyse the data and evaluate the design. The second software, INTEGRA, will assist the user to enhance the disassembly characteristics of products, handling and providing proper design rules for the product under development.

AMETIDE

The goal of the AMETIDE project is to provide a tool for the designer to efficiently optimise disassembly constraints in product design. Gaucheron et al. [Gau97] [Gau97b] argue that because the sum of local optimisations never lead to a global optimisation, it is necessary to introduce two different levels of consideration for disassembly issues: the micro level which looks at part level and the macro level which considers the entire assembly. This software bring in what the creators called micro disassembly planning model, which basically guides the designer to evaluate the time disassembly of a part, and then the macro disassembly sequence planning model, which optimises a list of disassembly operations.

PCR

Kou et al. [Kou00] implemented their research on disassembly in a software tool called PCR (Personal Computer Recycling). The logic behind this tool focuses on a modular disassembly rather than the generation of optimal sequences. The result is a disassembly tree and its major purpose is to assist designers in evaluating the easy of disassembly and recyclability of the product being designed [Kou00]. The evaluation starts creating a graph of the product in which the vertices are the parts and the edges are the fastener relationship among parts. Next, from this graph, the adjacency matrix is extracted, which the researchers suggest it could be extracted from the CAD representation of the product. After this, the product is divided into subassemblies by means of an already existing cut-vertex1 search algorithm. It is important to note that the new subassemblies found don't share any functional feature and its configurations are based on the assembly relationships of components. The next step is to define the precedence relationship among components for which the six main directions of the coordinate system are chosen i.e. ±X, ±Y and ±Z. These precedence relationships are represented by means of a matrix for every direction. These matrixes will be filled up with 1 or 0 depending if one part does or does not obstruct the corresponding part in the established direction. This task is considered input from the user and for big assemblies it would imply huge amount of work, for example, for an assembly composed by 25 parts the input would mean 3750 entries. Kuo et al. consider the automation of this task taking advantage of the CAD environment in which you can identify collisions among parts when moving them along certain directions. They conclude that this is not a perfect solution since in most of the cases the disassembly directions do not follow a straight path in one direction and it rather is a combination of movements. Finally, from the adjacency matrix and the combination of precedence relationship matrixes they create a disassembly tree for the product.

1 A vertex whose deletion along with incident edges breaks up the remaining graph into two or more disconnected pieces. Also known as articulation point [Bla02].

Salvage

With the Salvage tool [San99], Peter Sanderson presents a methodology that mainly considers economic issues that arise at assembly, disassembly and reassembly operations along the life cycle of an electronic product. He also assesses the quality of the items and the influence of this factor in the final cost. This research doesn't address any structural issues of the product and therefore a disassembly process plan can't be extracted from this software.

DIRECT

The latest software tool found in the literature is called DIRECT which stands for disassembly recycling tool. A good explanation of the software can be found in an article of Dini et al. [Din01] in which they expose the evaluation process and main characteristics of the tool. In their research the authors propose a system for the generation of optimal disassembly sequences from a recycling point of view. Figure 3.13 shows a schematic representation of the DIRECT system that subsequently will be explained.

The main input to the system are the CAD models of the product. From them DIRECT extracts most of the relevant information to perform the evaluations. This information includes fastening relationship among components and freedom of movement of components along the CAD coordinate system directions by means of automated displacement of parts in the virtual environment and a collision check. With this data two sets of three matrixes directly related to the three main directions X, Y and Z are created. One of these groups refers to contacts among parts along the given direction and the other stores the connection relationships i.e. fasteners between parts. After this, the disassembly sequences could be already calculated but the authors propose the creation of multiple clusters (in this case Dini et al. call them subassemblies) without any clear target like for example could be material compatibility among parts. After all the clusters have been created the software sort them according to three main criteria as: weight, material homogeneity and theoretical value. At this point the user must pick the combination of clusters that suit the problem better. Finally, disassembly sequences are created through a simulated extraction of each component and each cluster, which includes the actual direction of the translation. The software performs several more calculations with extra information stored in a database that contains disposal costs, market value of materials or labour costs among others [Din98]

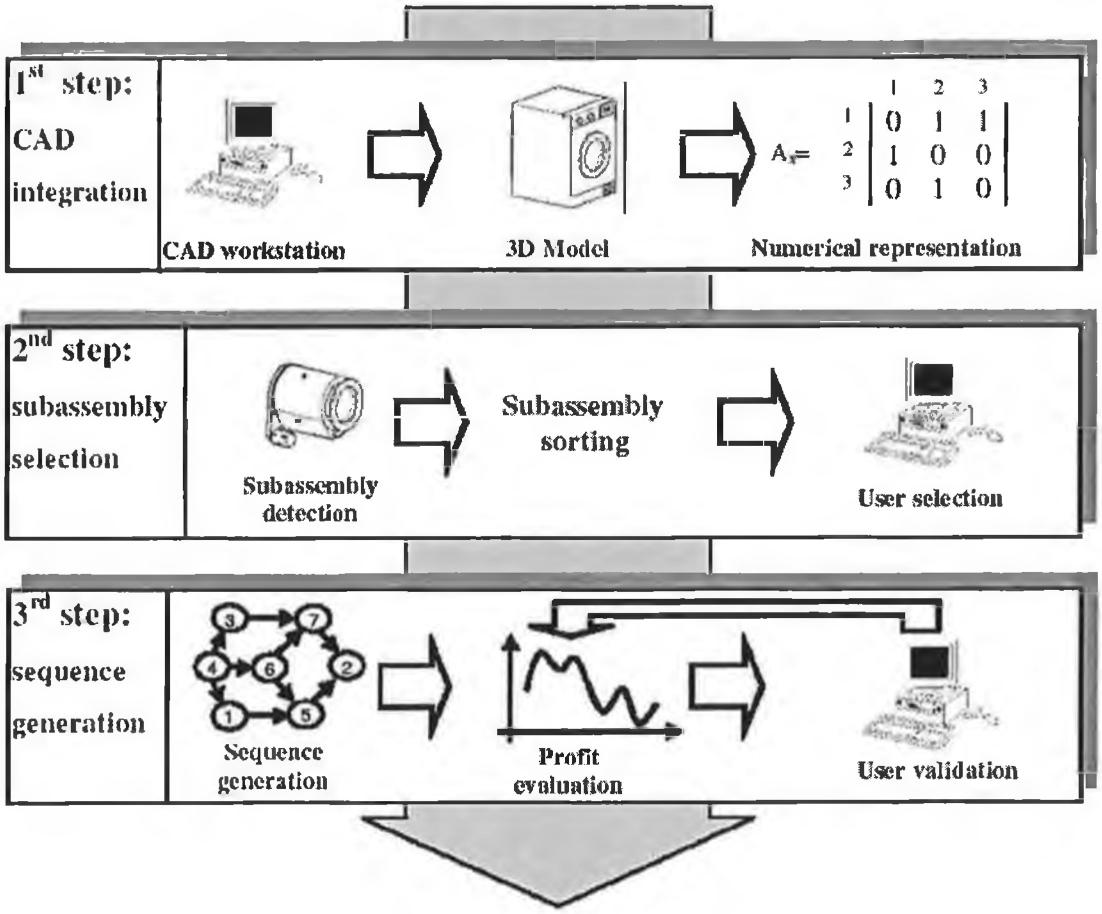

Figure 3.13: Structure of DIRECT system [Din01]

The author thinks that the random creation of clusters is not the best approach to the recovery problem since eventually two different clusters could share the same part. Besides, from a life cycle point of view, the consideration of functional modules rather than random clusters enhances operations like reuse, remanufacturing or upgradability of the product. Here again the disassembly precedence is examined according to the three main directions of the CAD coordinate system; as stated before, the author thinks that disassembly operations are usually more complex and therefore this approach would not suit any product.

3.8 The DFE Workbench

The DFE Workbench has been developed at the authors' institution over the last six years. The first aim of this project was to create a Design for the Environment tool to help industry to comply with the new environmental legislations and standards. Early research created a manual methodology that by means of special charts and some reference information supported the evaluation and improvement of emergent designs. The main drawback of this approach (identified by industrial partners) was that it was too time consuming and it was not appropriately integrated in the designer's environment. To overcome these problems a software version of the tool was created. Whilst this speeded up the evaluation process it did not solve the whole problem and the full integration into a CAD environment used by the designer was the next step forward. This integration enabled quick and reliable synthesis of raw data directly from the design prototype avoiding any disruption in the creative process of the designer. At this stage of development, the DFE Workbench performed analysis, synthesis, evaluation and improvement of products' life cycle features helping designers to manage *General* and *Detailed* design information. Continuous industrial testing and validation of the tool (with partners from the electronic, electro-mechanical and vehicle sectors) drove the needs that in time were reflected in the tool. Therefore the functionality of the DFE Workbench evolved with the practical emergence of the extended product concept in industry, thereby resulting in a tool to support not only environmental concerns but also design of extended products (DFxp).

The consideration of shared information which underlies the extended product concept along with the feedback gathered from the industrial testing influenced the architecture of the DFE Workbench evolving from a simple desktop CAD integrated application to a suite of tools fully integrated across the enterprise. As a result, the DFE Workbench supports three levels of integration (see Figure 3.14) to meet these requirements. The three levels of integration are as follows:

- DFE Workbench Desktop
- DFE Workbench Enterprise
- DFE Workbench Global

It has to be noted that most of the evaluation and improvement process can be carried out at either part and/or product system level depending on the phase of development of the prototype.

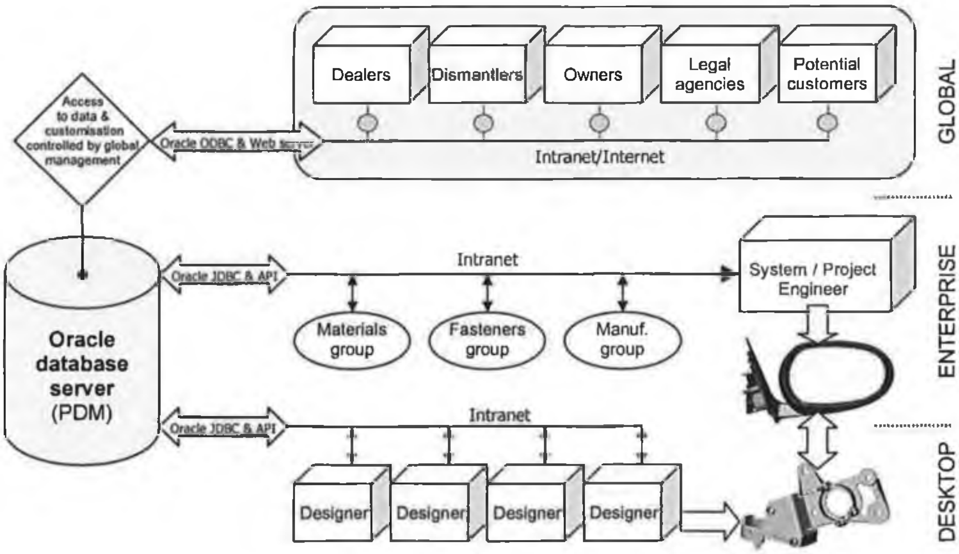

Figure 3.14: Three levels of integration of the DFE Workbench [Die02]

The DFE Workbench allows the user to create different versions of an existing project to support 'what if' analysis and comparison. A new version of a DFE project will be simply a controlled copy of an existing project ready to accept new modifications. This feature avoids any loss of information, facilitates the comparison of design solutions and also enables the tracking of the evolution of the design. In this context, information previously stored in the database can facilitate inexperienced designers to review products already created in order to inform and assist the current phase of development.

It is important to note that both the IAS and SAM evaluations are continuous improvement processes that prioritise the problems and give advice to improve them. The improvement process continues until the designer considers that the new prototype has been adequately optimised and then a decision is made to cease evaluation.

3.8.1 DFE Workbench Desktop

The DFE Workbench Desktop is a software tool integrated into a CAD environment that has been created to assist and advise designers during the development of products. The tool uses an intranet to connect to the main oracle databases where relevant information required in design is stored. At present the application has been fully integrated into two CAD systems, namely Pro/Engineer 2001 and Solid Works 2000. This allows the appropriate data to be automatically synthesised from the virtual prototype and evaluated using different DFE tools integrated within the DFE Workbench. Each of the variables evaluated are prioritised and advice is given to the designer on alternative product or process characteristics that will enhance that variable. Data is then re-synthesised from the (new) model starting a continuous improvement process that continues until either there are no other alternatives for further improvement or the desired solution is attained.

The data input into the DFE Workbench is much quicker and easy than any other software tool previously developed. This input can be done via two modes:

1. directly from the evolving model
2. from the user

In practice, the designer starts the input with the creation of the CAD models. As the design of every part evolves, the user can also input relevant data necessary to carry out subsequent evaluations. This is done automatically from the designer's desktop since it is linked to the main Oracle database of the company.

The DFE Workbench desktop consists of five agent-based modules: Impact Assessment System (IAS Agent), Structure Assessment Method (SAM Agent), Advisor Agent, Knowledge Agent and Dynamic Report Generator Agent (see Figure 3.15).

The *Impact Assessment System (IAS Agent)* uses the existing methodology called Eco-Indicator (95 and 99) which is an abridged quantitative approach to Life Cycle Assessment (LCA) [Goe00]. However, the DFE Workbench has been designed in such a way that it can be customised to include other LCA methodologies. The IAS agent automatically extracts the appropriate information from the virtual prototype performing synthesis, evaluation, prioritisation and improvement of environmental data related to a single part, subassembly or the entire product system. It is important to note that the reduction of the environmental impact is one of the goals pursued by DFxp. Industry is aware of the importance of the environmental burden that their products create. As an example, one of the initiatives to address these issues is that most of the car manufacturers have joined together creating IMDS (International

Materials Data System). This initiative aims to specify, archive and maintain all materials used for these car manufactures in an attempt to meet the obligations placed on them, and thus on their suppliers, by national and international standards, laws and regulations [IMD02]. Ways to facilitate this task by means of the DFE Workbench are currently being investigated as part of the IAS Agent.

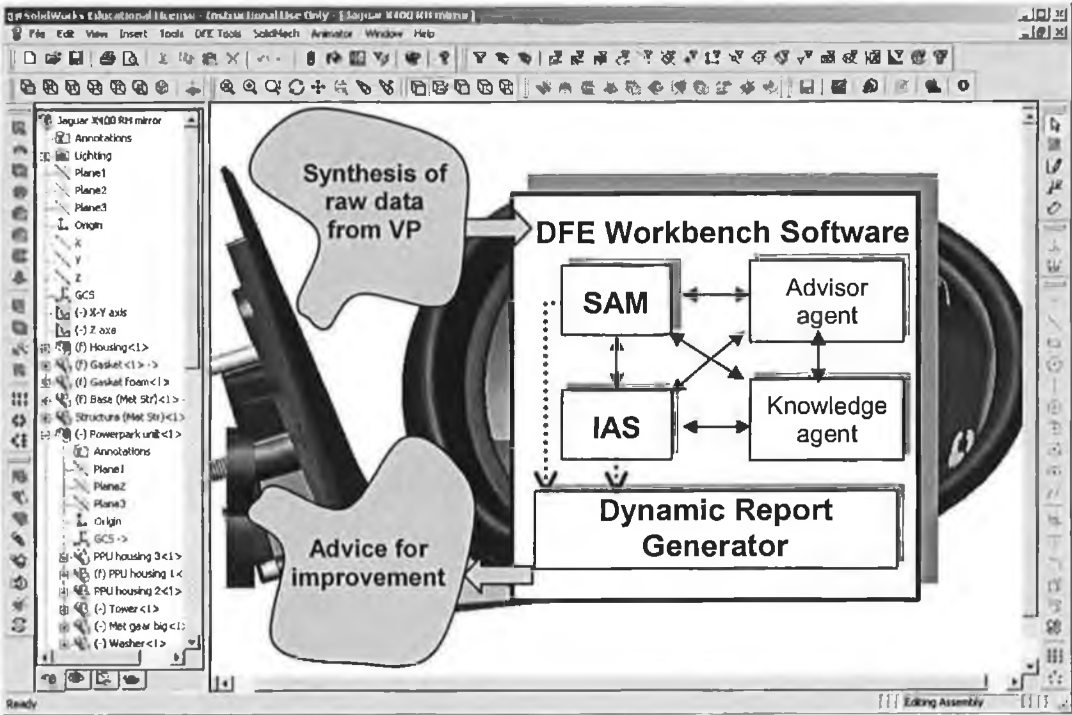

Figure 3.15: DFE Workbench Desktop architecture.

The first data input feeds the IAS agent. It is related to the different life cycle stages of the product and it covers all the possible processes associated with the pieces in the course of its life, as for example raw materials extraction, manufacturing processes, part finishing, transport, usage and end of life. As a result, the application will be able to calculate the overall environmental impact according to the Eco-Indicator methodology as well as other metrics. Figure 3.16 shows the interface to establish the life cycle information; in this picture it is also possible to see that the DFE Workbench has his own menu and toolbar in SolidWorks, which will be used to run the modules of the application.

The *Structure Assessment Method (SAM Agent)* looks at the structure of the emergent virtual prototype in order to enhance structural characteristics of the product in the context of DFE. It is a complex methodology, which quantitatively measures and records data including:

- % Hazardous material content
- % Recycled material content
- % Recyclable material content
- Variety of materials
- Content material types among others
- Total standard disassembly time and total part removal time
- Number and types of tools required for disassembly
- Number and types of fasteners
- Components serviceability
- Material compatibility (taking into account fasteners)

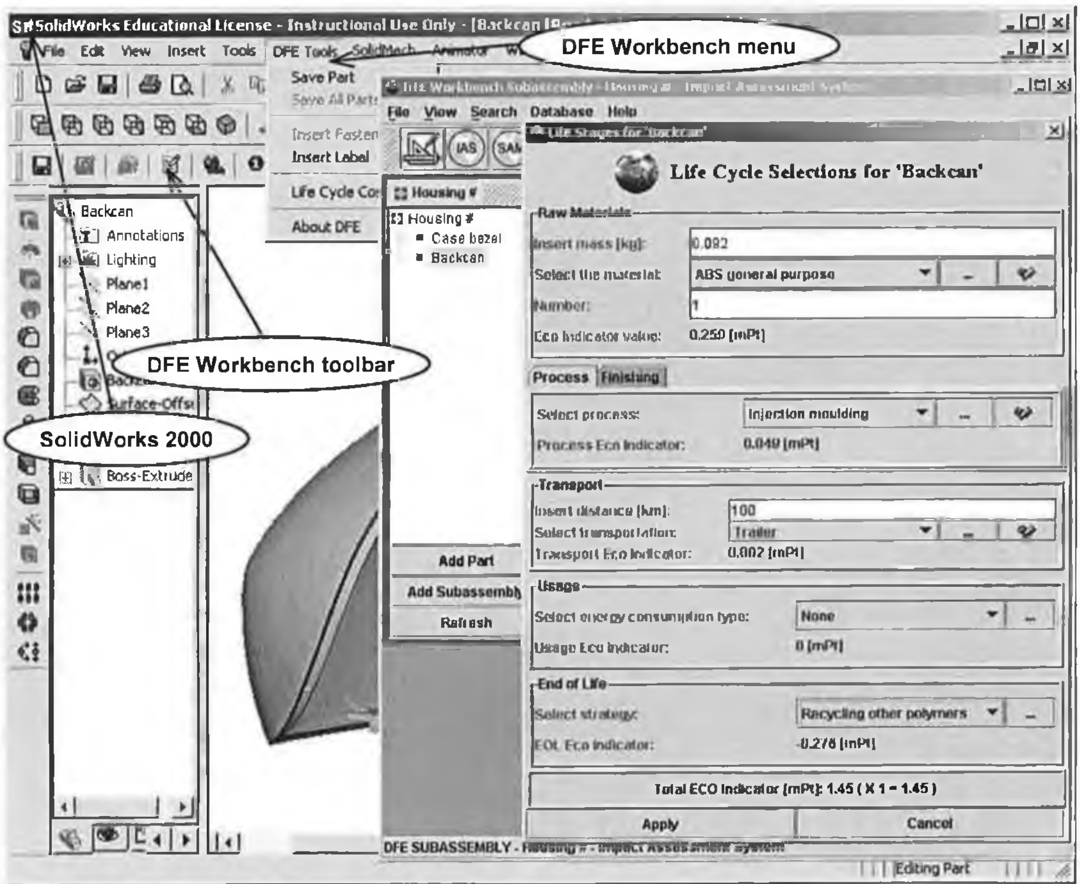

Figure 3.16: Life cycle selections for the 'Backcan' part

Coupling between all variables is managed and recorded by the DFE Workbench. The SAM evaluation supports the extended product concept since it enhances product attributes like extended useful life, serviceability and recyclability. In these evaluations the disassembly methodology proposed in Chapter 4 becomes the core engine, since for example, it calculates disassembly times and routes, identifying type of fasteners and tools. To accomplish these calculations the DFE Workbench needs more data about the structural characteristics of the product. The input into this agent will be in a similar way than the IAS data was defined. The data to be included is mainly: links among parts, product structure (BOM) and obstructions between parts.

The *Advisor Agent* has two functions: firstly to prioritise variables generated by the IAS and SAM tools; secondly it provides advice giving the designer different alternatives to enhance either the environmental performance or structural characterises of the emergent design. For example the advisor agent may suggest alternative materials or processes to reduce the environmental impact of a product. The alternatives are chosen from the main database making changes very efficient.

The *Knowledge Agent* provides information to the designer in a consultative mode. For example the designer can use this module to find a material with specified mechanical and/or environmental properties to be used in the design. In order to carry out this task in the most efficient manner a user interface interrogates the main database and reports the results of the query.

The *Report Generator Agent* automatically generates reports on the product presenting data extracted from the virtual prototype, the main database and also information obtained from the analysis process. The reports are made available in two ways, either printed and viewed locally (in DFE Workbench Desktop and Enterprise), or via World Wide Web through an extranet model to people who may need information provided by the tool (a feature supported by the DFE Workbench Global). The advantage of this technology is that it provides the most updated information since any changes in design are automatically reflected in the main database. This also resonates well with the implicit information sharing required to support the extended product.

3.8.2 DFE Workbench Enterprise

The *DFE Workbench Enterprise* has been developed to be used by the system/project engineer and therefore it gives a holistic view of the environmental and structural features of the entire product system. It has been designed to operate in an

Intra/Extranet platform, which enables collaboration, information and methodology sharing, thereby facilitating concurrency in design. Numerous designers, using the DFE Workbench Desktop, create components and therefore the database already contains the required information. This allows the DFE Workbench Enterprise to work both outside and inside the CAD environment. In addition, it shares the same principals that the DFE Workbench Desktop i.e. it extracts relevant data and performs evaluation, prioritisation and improvement of the design solution. The application also identifies the subassembly that has the highest environmental impact or the undesired structural properties. Additionally the user can drill down into component information when required in order to make the desired changes.

Additionally the DFE Workbench Enterprise allows the different functional departments within the enterprise to input and update specific data into the DFE Workbench databases (e.g. materials department update materials database) as well as allowing them to synthesise data and generate reports as the design evolves (e.g. for reporting purposes).

Finally, the DFE workbench enterprise also uses collaboration technologies such as chat, application sharing, white board, and videoconferencing to support teamwork among designers in a distributed design environment.

3.8.3 DFE Workbench Global

The *DFE Workbench Global* has been developed as an Intra\Inter\Extranet application that supports communication reporting and sharing of the information generated by the DFE Workbench Desktop and Enterprise. It operates through a Virtual Private Network Application (VPN) using security protocols and allowing various users to log in and view, upload or copy data from the main database that has been customised for their specific needs. The DFE Workbench Global may also be used via an intranet for interdepartmental reporting or information on specific issues like the preferred materials for specific components or preferred fasteners. The DFE Workbench Global has been developed as an extremely flexible application that supports a high degree of customisation.

3.9 Summary and Conclusions

This chapter presents an extensive literature review in the area of disassembly. It starts defining the aims of disassembly in the context of this research. Next, two sections address the required background, in representation and analysis techniques, necessary to understand different approaches and solutions to the problem found in the literature. Later, the author divides the disassembly problem in four different groups that comprises similar approaches to disassembly. Issues like modularity and product structure are also treated in this chapter explaining the advantages of modularity and certain product structures. Overlap and tradeoffs among Design for Assembly and Design for Disassembly is investigated in a later section deriving some recommendations to achieve a successful integration of both concepts. The research on the disassembly problem is complemented by an extensive survey of Disassembly Software tools, which are presented showing comparisons among the different packages. The research shows that there is not a suitable methodology that finds optimal disassembly times and routes and therefore a new methodology will have to be developed to overcome this drawback. This new methodology will be part of the DFE Workbench, a tool that has been fully described at the end of this chapter.

Chapter 4. A New Methodology to Assist in the Creation of Disassembly Process Plans

4.1 Introduction
4.2 A Heuristic Algorithm to Create Disassembly Process Plans
4.3 Obstruction Types
4.4 Modularity Considerations
4.5 Summary

4.1 Introduction

Chapter 3 describes the different approaches to the Design for Disassembly problem. One of the conclusions based on this research was that there is not a suitable methodology that supports the designers in the evaluation of the disassembly attributes of an emergent design. This chapter introduces a new methodology, which based on a simple input data, assist in the calculation of near-optimal disassembly sequences routes and times. Furthermore, issues like obstructions and modularity are further explained and integrated in the methodology in order to optimise and cope with complex product structures.

4.2 A Heuristic Algorithm to Create Disassembly Process Plans

The disassembly sequence problem is NP[2]-complete [Moy97]. This implies that the requisite search trees of a full search algorithm grow exponentially as the number of parts in a product increases. Consequently, in complex products structures, a complete search for the optimal disassembly sequences may be infeasible. In that case, contrary to a full search algorithm, heuristic algorithms are computationally less expensive and they are capable to achieve satisfactory results. This section presents a new heuristic algorithm, which based on a basic user input, identifies the essential sequences and operations necessary to disassemble complex products.

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[2] Non-Polinomial

The algorithm has been divided in five main modules which perform different tasks and are also fed by different data. The five modules of the algorithm are:

1. Disassembly tree generation
2. Disassembly sequence recognition
3. Disassembly sequence reorganisation
4. Clusters recognition and disassembly sequence optimisation
5. Generation of disassembly process plan

The input made by the user (discussed in section 4.2.1) feeds the first unit of the whole algorithm which is concerned with the creation of a special disassembly tree. The output of this first module feeds the second one and so on until the fifth module gives the last output which corresponds to the disassembly process plan. As the modules are linked to one another, it is essential to keep the right sequence in order to obtain adequate results.

In the remaining of this section the new algorithm is further explained and also diverse examples are presented to illustrate the features and capabilities of this new technique.

4.2.1 User Input

The process starts when the user inputs the required data to feed the first module and run the whole algorithm. This data can be recorded in three tables that give the necessary information about the structure of the product. These tables are as follows:

- Fastening relationships among components (F)
- Obstructions between parts (O)
- Fasteners obstructed by parts (FO)

The *fastening relationships* table (F) includes all the joints between parts. In some cases in order to secure the parts, the joints may require additional mechanical hardware such as, screws or nuts. At this point the only relevant information to run the algorithm is that two parts are joined to one another and this is the only thing that will be recorded in the table. Later, additional information will be required in order to create the actual Disassembly Process Plan (DPP). This supplementary information is general data about the properties of certain fasteners such as standard disassembly times and required tools to undo the joints; as this information does not depend on the structure or type of the product, it is already available to the user avoiding any further loos of time for the designer.

The table of *obstructions* between parts (O) has to be filled up by the designer and it includes the parts that, being joined or not to the target part, have to be necessarily removed before removing the element that is meant to be disassembled. The designer has to apply his expertise and knowledge of the product in order to identify the different obstructions just by looking at the design of the prototypes. The recognition of these obstructions is a critical point and special care has to be taken to obtain reliable results.

The access to a fastener can be also obstructed by a part, which therefore have to be taken away before unfastening the joint. This information is recorded in the table of *fasteners obstructed by parts* (FO)

4.2.2 Disassembly Tree Creation

At this point the input data is finished and the generation of the disassembly trees is the next step. Figure 4.5 represents the first part of the algorithm. This module creates a special disassembly tree which will be used by the second module to find a first disassembly sequence.

The disassembly tree generated by this module is divided into different levels. Level 0 represents the level of the part object of study, that is, the part for which the disassembly plan is going to be generated. Successive levels contain diverse activities that have to be carried out in order to disengage the objects in the immediately inferior level. Figure 4.1 represents a simple example which will be used to explain the idea presented above. In this case the product is constituted by three parts (three square boxes, P1, P2 and P3) and some physical constrains (walls around parts).

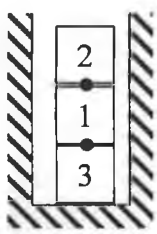


Figure 4.1: Boxes assembly

The links among parts have been represented as small black dots and therefore the list of fasteners (F) should include two joints, one between P1-P2 and another one between P1-P3. The list of obstructions will be created by looking at the figure, where it is possible to notice that on one hand, to get P3 out it is necessary to remove P1 first and, on the other hand, to remove P1, P2 has to be taken apart primary. In this example therefore, there are two direct obstructions among different components that have to appear in the table of obstructions. Finally, in order to show the capability to handle obstruction of fasteners, the link P1-P3 has been set as if it is obstructed by P2. Figure 4.2 shows the results of the data input for the assembly in Figure 4.1.

Fasteners (F)	Obstructions (O)	Obstructions of fasteners (OF)
P1 linked to P3	P3 obstructed by P1	Fastener (P1 – P3) obstructed by P2
P1 linked to P2	P1 obstructed by P2	

Figure 4.2: Input table for boxes assembly

P1 has been chosen to show the disassembly tree creation process and, since it is the part to be disassembled, it will appear in the level 0 of the tree (see Figure 4.3). Firstly, there is a search in (O) for parts that may obstruct P1. In this case P1 is obstructed by P2 and consequently P2 should appear in the disassembly sequence before P1. In other words, P2 has to be taken out before P1 and that is why it appears in a superior level in the disassembly tree. The search in the obstruction list continues until no more parts obstruct the target element (in this case P1). Next, the search will start in the fasteners list (F). From this list, every link in which P1 is involved will be recorded in the next higher level because P1 can only be removed after all its links have been undone. The recursive application of this simple idea to all the objects at the different levels of the tree ensures that all the parts (and/or links) in lower levels are ready to be removed (or undone) if the parts and links of higher levels have been removed and undone. Consequently, this also means that since there is nothing obstructing the parts and links that appear in the highest level (level 3 in the example) they can be removed straight away. Once the highest level has been cleared, the objects in the second highest level are free and can also be removed and so on until the part in level 0 is reached.

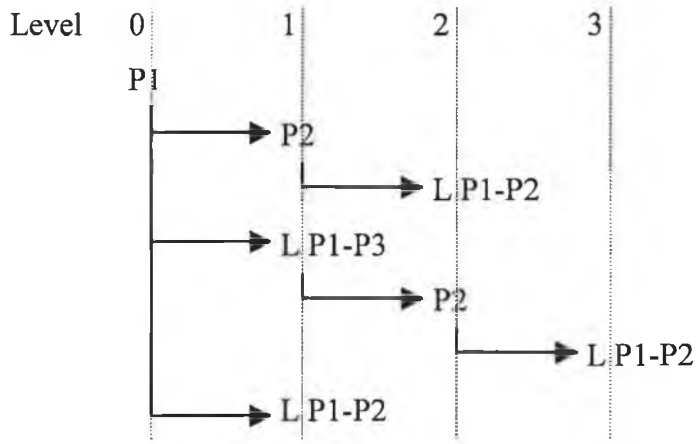


Figure 4.3: Disassembly tree for boxes example

Figure 4.5 is the flow diagram that creates the disassembly trees. As already stated the inputs are the three lists (F, O, OF) and the output is another table in which the elements are recorded in the column of the corresponding level. In the algorithm *target* refers to the part or fastener that is going to be searched in the tables. The first target is the original part to be disassembled (P1 in the previous example) but this target will vary as the algorithm examines higher levels of the tree. For instance, at the beginning of the previous example the target will be P1, and subsequently P2, L P1-P3, L P1-P2, again L P1-P2, again P2 and finally L P1-P2 for the third time.

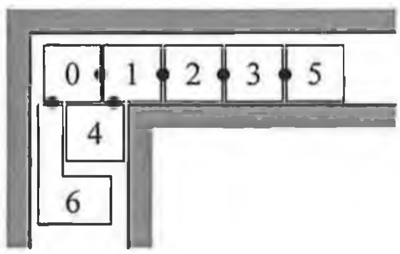


Figure 4.4: Blocks example

The term *object* refers to any of the elements in the disassembly tree; *object.next* then, makes reference to the next object in the disassembly tree. This next object can reside in the same level than the current target or in a superior level.

For further understanding of the algorithm the assembly shown in Figure 4.4 is going to be analysed. Figure 4.6 expose the input tables that run the algorithm.

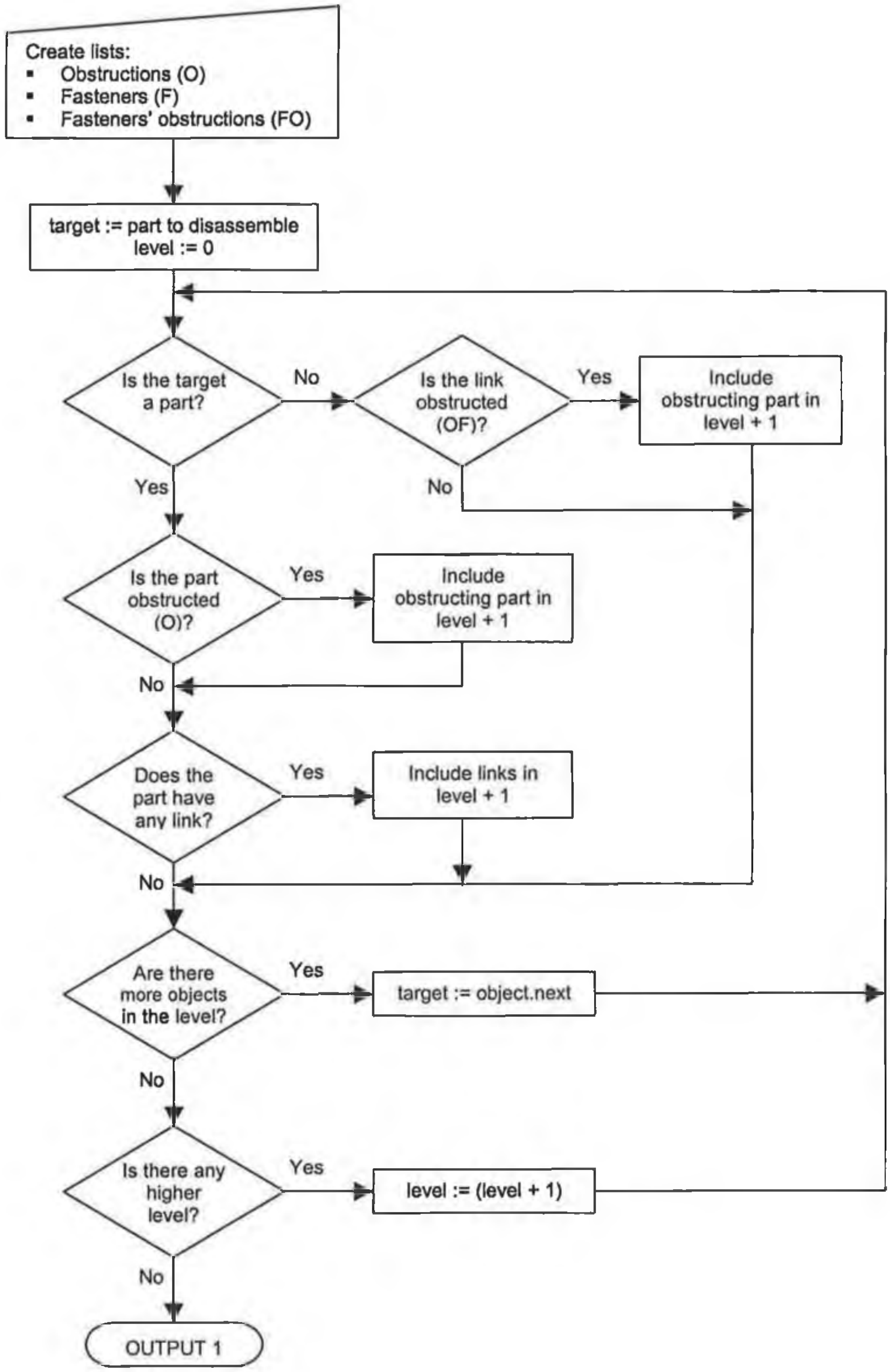


Figure 4.5: Module 1; disassembly tree generation

Obstructions (O)	Fasteners (F)	Obstructions of fasteners (OF)
P1 obstructed by P2	P1 linked to P2	Fastener (P1 – P4) obstructed by P6
P2 – P3	P1 – P4	
P3 – P5	P2 – P3	
P4 – P6	P3 – P5	
P6 – P2	P6 – P0	
P0 – P1	P1 – P0	

Figure 4.6: Input for blocks example

The first part of the methodology was applied to P1 and the output is presented in Figure 4.7. In this case, 6 is the highest level of the tree and from it, it is also clear that in order to disassemble P1 the first thing that has to be done is to unfasten the link between the parts P3 and P5.

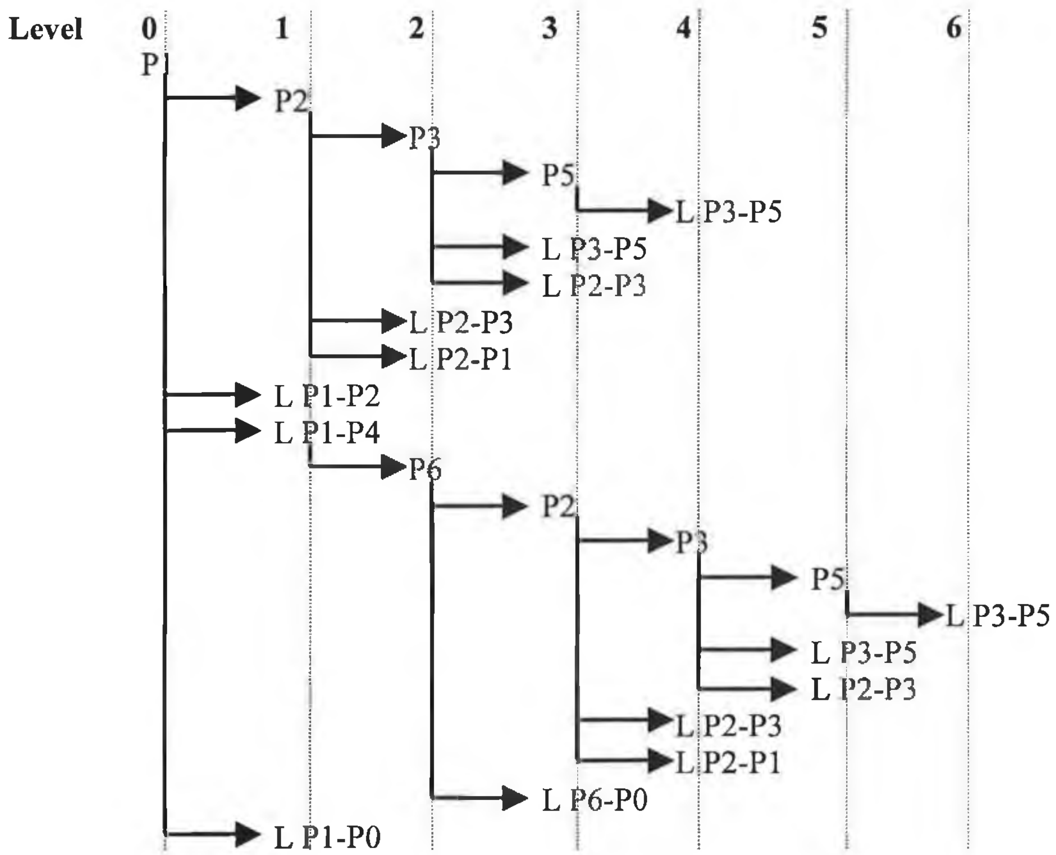


Figure 4.7: Disassembly tree for blocks example

Another important feature of the algorithm presented in this section is that, it is meant to be as general as possible with the intention that it can be applied to complex product's structures. To show the ability of this method to handle complex product's structures, Figure 4.8 introduces an example which will be used in subsequent sections to explain additional functionality of the tool.

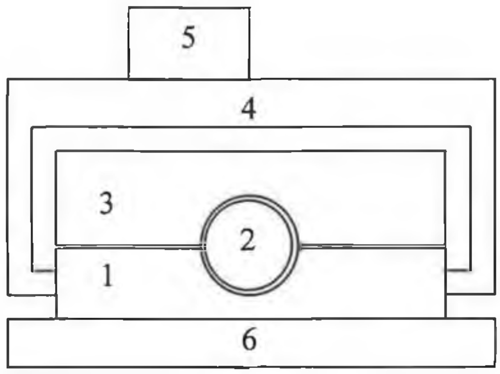


Figure 4.8: Complex product

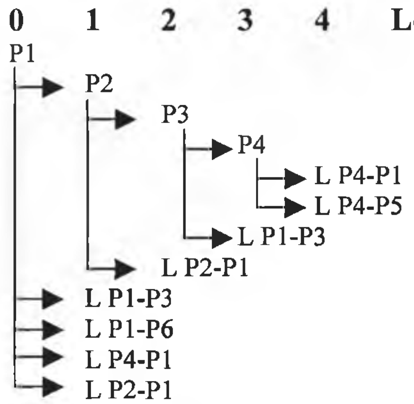
The requisite input, which describes the assembly in Figure 4.8, is presented in Figure 4.9. In this case, the obstructions of fasteners have been omitted for simplicity.

Obstructions (O)	Fasteners (F)
P2 – P3	P5 – P4
P3 – P4	P4 – P1
P1 – P2	P1 – P3
	P2 – P1
	P1 – P6

Figure 4.9: Input for complex product

The methodology here presented, has been thought to be implemented in a software tool and therefore, the information should be easy to handle by a computer. The disassembly tree shown until now may give the user a better idea of the constrains among parts and the moment in which they should be addressed but, on the other hand, the creation of such tree structure in a computer is more difficult than to handle simple matrices. In practice, this special disassembly tree can be easily represented as a matrix, which consequently can be handled more easily by a computer. This way of storing the information consists in creating a matrix in which the columns correspond to the different levels of the disassembly tree and the objects are recorded filling up the rows of its correspondent level. The final results given by the algorithm are the same no matter the technique with which the disassembly tree has been stored.

Figure 4.10 shows the results given by the algorithm when applied to the complex product in Figure 4.8. In this picture the two variants (tree, left and matrix, right) can be compared.



Level 0	1	2	3	4
P1	P2	P3	P4	L P4-P1
null	L P1-P3	L P2-P1	L P1-P3	L P4-P5
null	L P1-P6	null	null	null
null	L P4-P1	null	null	null
null	L P2-P1	null	null	null

Figure 4.10: (l) Disassembly tree for complex product. (r) Equivalent matrix

4.2.3 Disassembly Sequence Recognition

Currently, the disassembly tree (or matrix) has been generated and now a disassembly sequence has to be identified for the part that is object of study. This task is performed by the second module of the algorithm which has been called disassembly sequence recognition (see Figure 4.11).

This second module generates the list of actions necessary to complete the disassembly of the specified part. The list is based on the objects of the disassembly matrix, which in practice, is the input to the module. The generation of the sequence is carried out by means of a search that begins at the highest level of the matrix and ends at the root level (or product to disassemble). During this search all the objects in each level are read and the elements that are not already present in the sequence list are included at the end of it, ensuring that no essential actions are left out.

Once more it has to be noticed that the algorithm calls *object* to the elements that appear in the disassembly tree (or matrix), and it calls *actions* to the different components of the disassembly sequence list.

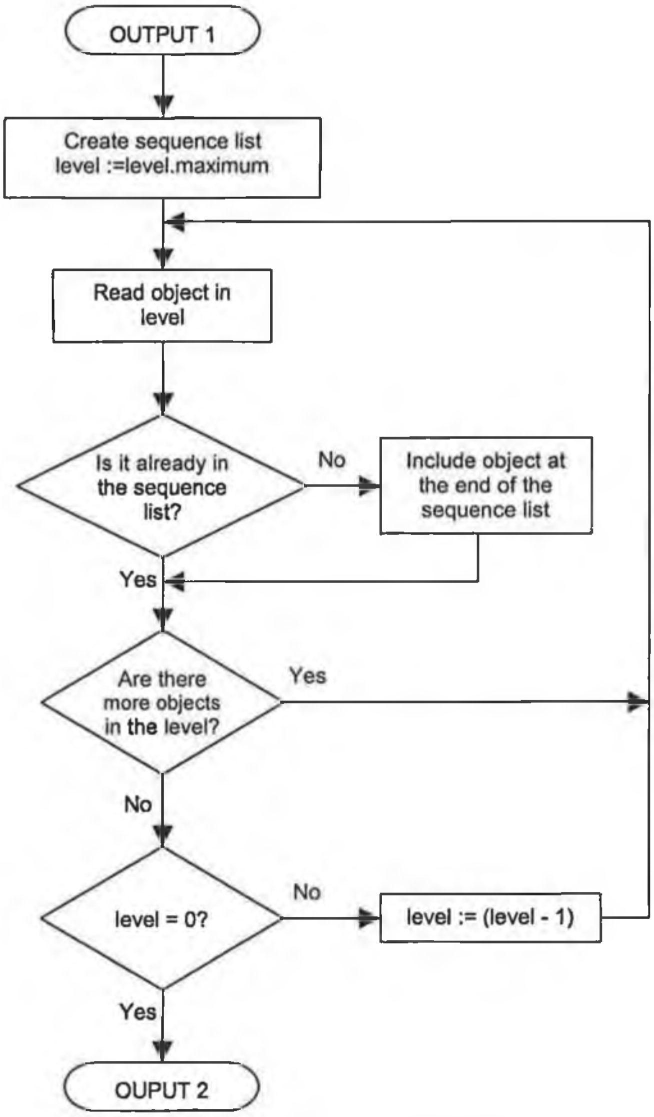


Figure 4.11: Module 2; disassembly sequence recognition

If this module is applied to the disassembly tree generated by the first part of the algorithm for the blocks example in Figure 4.7 the disassembly sequence for the part P1 is the following:

L P3-P5 → P5 → L P2-P3 → P3 →L P2-P1 → P2 → L P6-P0 →

→ P6 → L P1-P4 → L P1-P0 → P1

Applying the two first modules of the algorithm to the example in Figure 4.4 it is possible to obtain the disassembly sequences for the rest of the components. These sequences are as follows:

- P0 sequence: L P3-P5 → P5 → L P2-P3 → P3 → L P2-P1 → P2 → L P6-P0 → P6 → L P1-P4 → L P1-P0 → P1 → P0
- P2 sequence: L P3-P5 → P5 → L P2-P3 → P3 → L P2-P1 → P2
- P3 sequence: L P3-P5 → P5 → L P2-P3 → P3
- P4 sequence: L P3-P5 → P5 → L P2-P3 → P3 → L P2-P1 → P2 → L P6-P0 → P6 → L P1-P4 → P4
- P5 sequence: L P3-P5 → P5
- P6 sequence: L P3-P5 → P5 → L P2-P3 → P3 → L P2-P1 → P2 → L P6-P0 → P6

In the same way the disassembly sequences planned for the example of Figure 4.8 are the followings:

- P1 sequence: L P4-P1 → L P4-P5 → P4 → L P1-P3 → P3 → L P2-P1 → P2 → L P1-P6 → P1
- P2 sequence: L P4-P1 → L P4-P5 → P4 → L P1-P3 → P3 → L P2-P1 → P2
- P3 sequence: L P4-P1 → L P4-P5 → P4 → L P1-P3 → P3
- P4 sequence: L P4-P1 → L P4-P5 → P4
- P5 sequence: L P5-P4 → P5
- P6 sequence: L P1-P6 → P6

4.2.4 Disassembly Sequence Reorganisation

The creation of this third module (Figure 4.14) attempts to overcome small problems derived from the recognition of the disassembly sequence directly from the disassembly matrix. The two problems addressed by this unit are.

- Logic organization of tasks (actions)
- Inclusion in list parts that have been completely unlocked

On one hand, the sequence list provided by the second module is slightly dependent on the order in which the fasteners and obstructions have been entered in the system. This does not mean that the sequence generated is wrong and these variations are caused because usually at any point of disassembly there are several actions that can be performed. An example of this situation is when there are different fasteners that have to be undone and they are ready to be unlock; the difficulty here, is to choose the best order, the most efficient one.

On the other hand, there are some parts that may not affect directly the disassembly sequence of a component but, as they belong to the product, they have links with the rest of the constituents. After some disassembly tasks, all the links of some of these parts (that do not affect directly) may be disengaged and therefore the part is free. In such a case, the free part will be also included in the disassembly list regardless if it is necessary its removal or not. The inclusion of this element in the list will be carried out when the last link has been unfastened.

To illustrate this, some more components have to be added to the complex product structure (Figure 4.8). The new assembly and the input data are shown in Figure 4.12 and Figure 4.13 respectively.

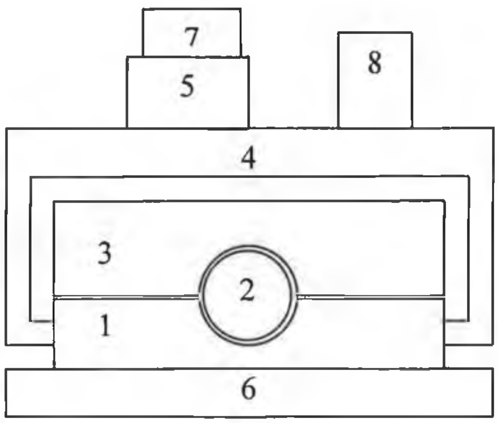


Figure 4.12: Example 4 based on complex product.

The basic input is the basically the same than previously, the only change is the addition of the links between the two new parts and the rest of the assembly.

Obstructions (O)	Fasteners (F)
P2 – P3	P5 – P7
P3 – P4	P5 – P4
P1 – P2	P4 – P8
	P4 – P1
	P1 – P3
	P2 – P1
	P1 – P6

Figure 4.13: Input for example 4

With this data the output from the second module gives the following sequence for P1:

L P4-P8 → L P4-P1 → L P4-P5 → P4 →L P1-P3 → P3 →

→ L P2-P1 → P2 → L P1-P6 → P1

The first thing to do is to unfasten the link between P4 and P8. This action leaves P8 completely free of links and since it is not obstructed by anything it can be removed. This is identified by the logic of the third module, which includes P8 in the disassembly sequence list just after the last link is undone. As a result the new disassembly sequence for P1 is the following:

L P4-P8 → P8 → L P4-P1 → L P4-P5 → P4 →L P1-P3 → P3 →

→ L P2-P1 → P2 → L P1-P6 → P6 → P1

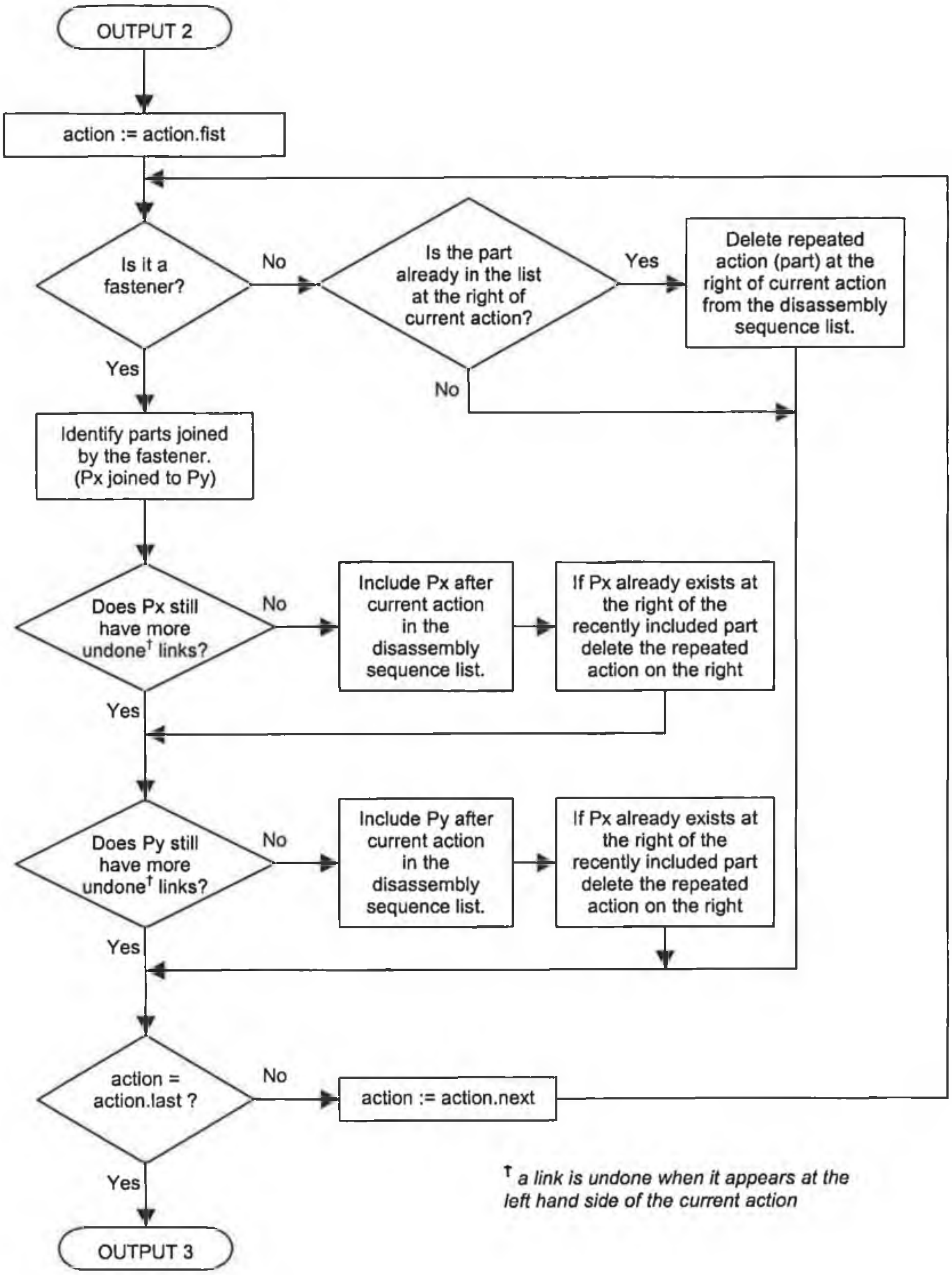


Figure 4.14: Module 3; disassembly sequence reorganisation

4.2.5 Clusters Recognition & Disassembly Sequence Improvement.

At this point, the algorithm has created a feasible disassembly route for a chosen component. The question now is if this sequence can be optimised in one way or another by means of avoiding unnecessary tasks. In order to answer this question the existing methodology was applied to several products, and the results were compared with the manual sequences built by a designer. Discordance in these results led to further research which was intended to seek optimisation opportunities considering both, the structure of the product and the disassembly sequence already created.

The disassembly route generated for the part P1 of the assembly in Figure 4.12 was:

L P4-P8 → P8 → L P4-P1 → L P4-P5 → P4 →L P1-P3 → P3 →

→ L P2-P1 → P2 → L P1-P6 → P6 → P1

In contrast with this, the expected disassembly sequence constructed by a designer would be only:

L P4-P1 → L P1-P3 → P3 → L P2-P1 → P2 → L P1-P6 → P6 → P1

The discordance between the calculated and the expected results is because so far the algorithm realises that P4 has to be taken out before P3 and, P3 has also to be removed in order to take away P1. However, the algorithm does not acknowledge that there is no need to undo all the links that P4 have with other elements. In other words, in order to gain access to P3 it is enough to undo the link between P4 and P1 and remove the cluster formed by {P4-P5-P7-P8}. Considering this issue, the actions L P4-P8, P8 and L P4-P5 are no longer necessary and consequently the total disassembly time will decrease.

The development of a solution for this problem was based on Graph Theory. The product is modelled as a graph in which the parts correspond to the vertexes and the links among parts are the edges of the graph. Figure 4.15, shows the graph representation for Example 4.

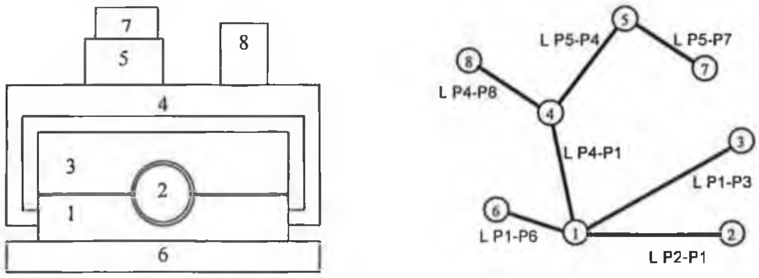


Figure 4.15: Graph representation for Example 4

If the edges in the graph of Figure 4.15 are removed in the reverse sequence stated by the disassembly list, is reached a situation in which a fraction of the assembly is completely separated from the rest. The progress eliminating the links among parts is shown in Figure 4.16. This figure also shows how the cluster formed by {P4-P5-P7-P8} has been disjointed from the rest of the graph, which in this case and, due the simplicity of the assembly, it was only connected to P1.

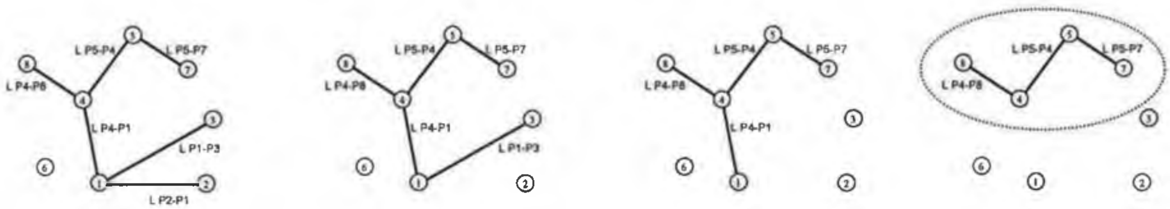


Figure 4.16: Evolution of graph in reverse order

The vertex L P1-P4 is called *cut-vertex* since it divides the graph in two unconnected sub-graphs. In the same way L P1-P6, L P1-P2 and L P1-P3 are also cut-vertexes but their relevance is lower since their elimination only releases one part from the principal sub-graph[3] and not a cluster like in the case of L P1-P4.

Once a cluster has been created, all its components, including the links among the parts, will be removed from the disassembly list. Instead, the parts that make up the cluster will be included in the disassembly sequence list just after the cut-vertex that caused the division of the graph. Next, the new disassembly sequence is presented.

$$\text{L P4-P1} \rightarrow \{\text{P4-P5-P7-P8}\} \rightarrow \text{L P1-P3} \rightarrow \text{P3} \rightarrow \text{L P2-P1} \rightarrow$$

$$\text{P2} \rightarrow \text{L P1-P6} \rightarrow \text{P6} \rightarrow \text{P1}$$

[3] Principal sub-graph refers to the sub-graph in which the part to be disassembled is included.

The cluster found by the fourth module of the algorithm is presented in brackets naming all its components. This last sequence corresponds to a near-optimum process in which unnecessary operations have been excluded.

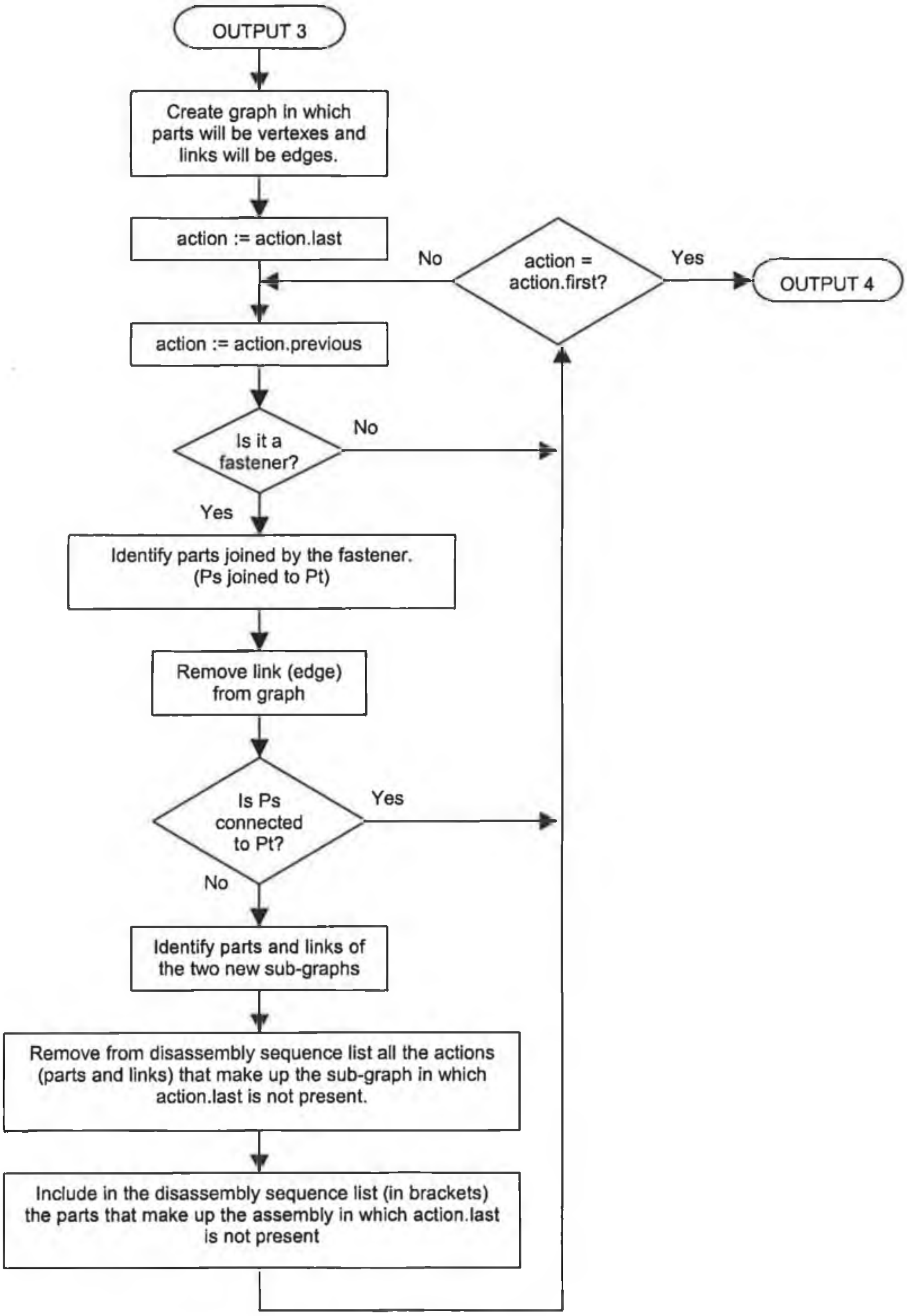


Figure 4.17: Module 4; clusters recognition & disassembly sequence improvement

4.2.6 Generation of Disassembly Process Plan

The algorithm ends with the fifth module (see Figure 4.19), which presents the results from the previous modules, and finally creates a disassembly process plan. However, this part of the methodology is not only concerned with a user friendly appearance of the results but it also performs a number of calculations as well as tasks of gathering information and search in existing databases. The main calculation executed by this section is the time that takes to remove the selected component. This is carried out based on the requisite tasks stated in the already existing disassembly sequence. These tasks refer either to the removal of some components or the disconnection of links among parts. Then, the disassembly time for an element is the sum of the times that every task has associated. On one hand, the simple action of taking one part away from the assembly is going to be neglected but a time-penalty dependent on the weight of the part (or cluster) could be easily introduced to model this type of job. On the other hand, unfastening tasks have time associated which depend on the type of fasteners used to secure the items and also the number of fasteners per joint. In order to get this times the algorithm has to do a search in predetermined tables of the standard times previously referred (see Appendix 1 for reference). Along whith the disassembly time for every task, the disassembly process plan can show extra information such as tools required to carry out the tasks and any other relevant information that can be easily customised. Figure 4.18 shows an example of disassembly process plan generated for the part P1 from Example 4.

Disassembly Process Plan for part P1				
#	**Task**	**Tool required**	**Time [s]**	**Additional info.**
1	Unlock flat screw between P4 and P1	Flat screwdriver	17	
2	Remove cluster {P4-P5-P7-P8}			Weight: 1600 grams
3	Unlock bolt between P1 and P3	Nut driver	23	
4	Remove part P3			Weight: 400 grams
5	Unlock press fit between P2 and P1	Prybar	7	
6	Remove part P2			Weight: 175 grams
7	Unlock flat screw between P1 and P6	Flat screwdriver	17	
8	Remove part P6			Weight: 300 grams
9	Remove part P1			Weight: 500 grams
Total disassembly time			**64**	

Figure 4.18: Example of disassembly process plan for P1 from Figure 4.12

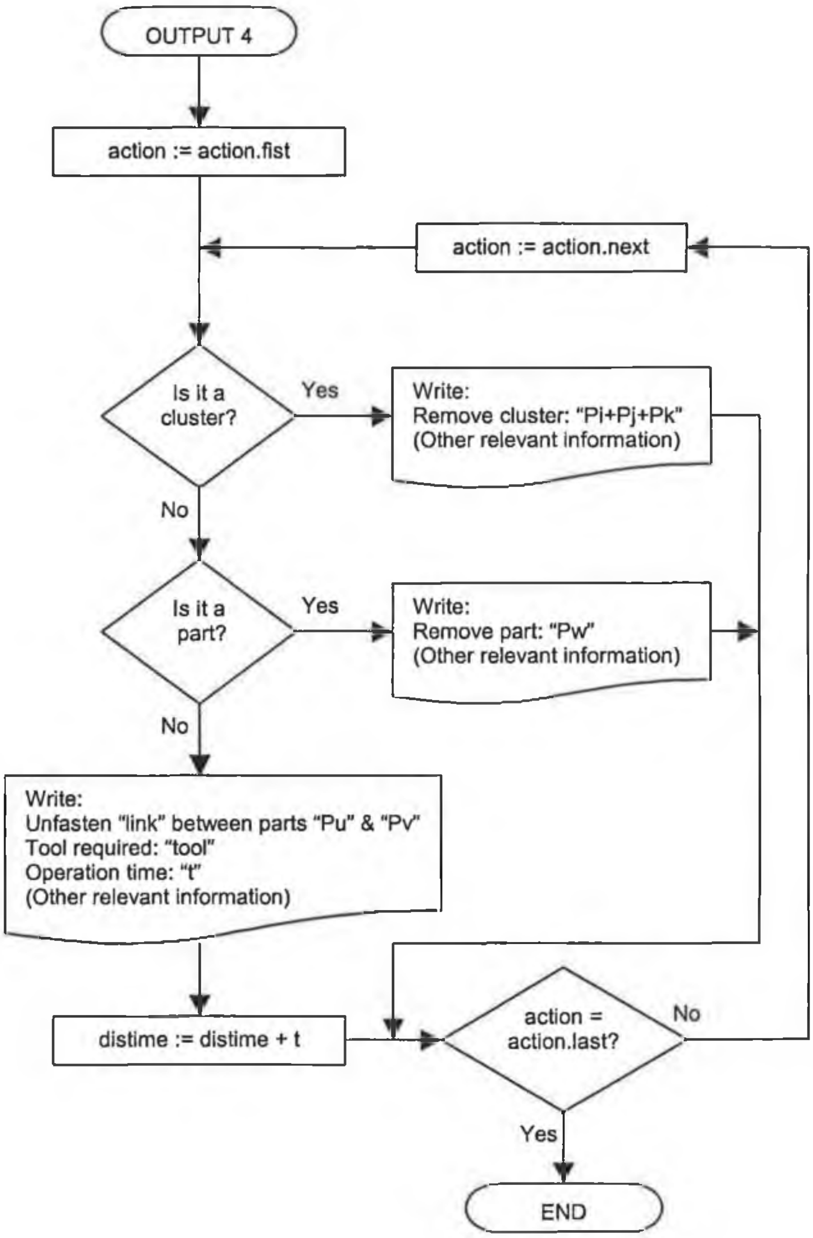


Figure 4.19 : Module 5; generation of disassembly process plan

4.3 Obstruction Types

Obstructions are parts that, having direct contact or not with the target element, have to be taken apart before the target component is removed from the assembly. The obstructing parts can be both, parts in direct contact with the obstructed item, and/or parts with no contact with the target part.

One of the limitations of research up to date is that the obstruction relationships are limited to simple AND and simple OR relationships. There is not much research about complex AND/OR relationships among the parts in a product. The author is not aware of any other attempts to address this issue with the exception of the studies of two groups of people: Moore et al [Moo98a][Moo98b] and, Gungor and Gupta [Gun01].

4.3.1 Including AND-Obstructions in the Methodology

An AND relationship exists between components c1 and c2 in relation to c3, if both c1 and c2 must be removed prior to c3 [Moo98b].

The AND-obstructions are directly accepted by the methodology. The user just has to add as many obstructions per part as the design requires, and apply the algorithm previously described, which treats several AND-obstructions in the same way that described in section 4.2.2. To illustrate this, Figure 4.20 shows an example of the required modifications in the obstruction list to apply the existing algorithm successfully.

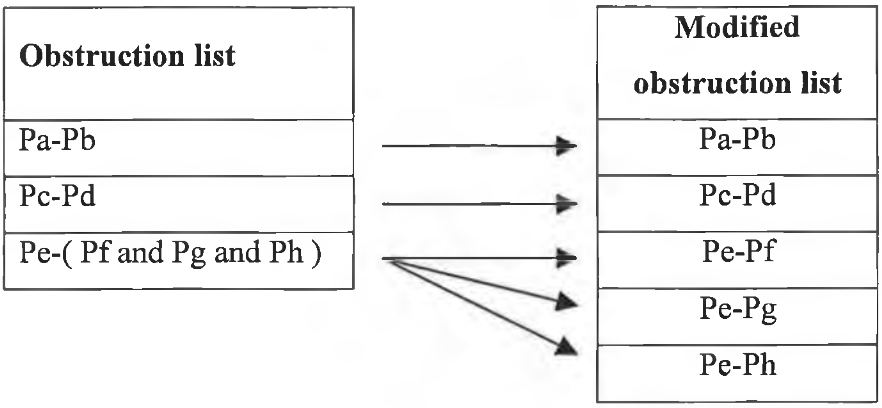


Figure 4.20: Modification in obstruction list to address AND-obstructions

4.3.2 Including OR-Obstructions in the Methodology

An OR relationship exists between parts c1 and c2 in relation to c3, if either c1 or c2 must be removed prior to c3 [Moo98b]. This can be explained graphically by means of Figure 4.21 in which the *ball* can be taken out in two different ways. The first one, following *D1* direction, involves the removal of the *lid* attached to the top of the *box*. On the other hand, to take away the part in direction *D2*, the disengagement of *door1* and *door2* is necessary.

OR-obstructions give alternatives on how to disassembly a product consequently, the direct insertion of this issue in the disassembly tree, like the one presented before, is infeasible. Instead the author proposes the calculation of all the alternative disassembly process plans for the part object of study and then select the most appropriate. This solution bears the creation of simple disassembly lists with all the alternatives reflected in the original obstruction list. The number of cases to be created is equal to the product of all the alternatives registered. For example, the original table of obstruction in Figure 4.22 presents two parts obstructed. One of them has two alternative obstruction and the other three therefore, the total number of obstruction lists to be created will be 2×3=6.

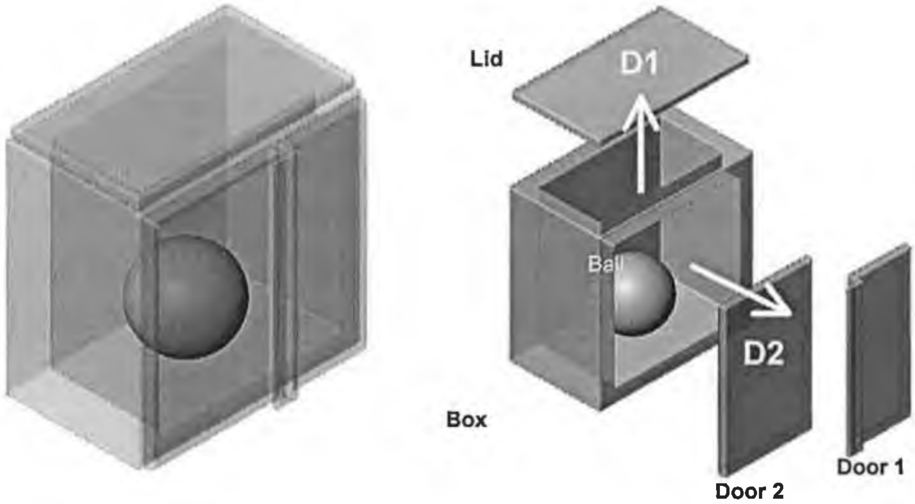


Figure 4.21: Example of OR-obstruction

4.3.3 Including Complex AND/OR Relationships in the Methodology

In general, the list of obstructions of any common product is usually a combination of AND and OR relationships which lead to complex definition of the obstructions among parts. Therefore, a complex AND/OR relationship exists between parts c1, c2, and c3, in relation to c4, if c1 along with either c2 or c3 must be removed prior to c4 [Moo98b].

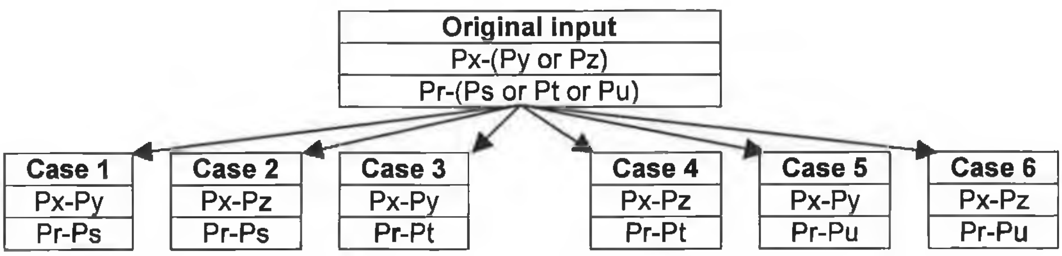


Figure 4.22: Alternative obstruction lists generated from input with OR-obstructions

Here, as in the case of OR-obstruction several obstruction lists will have to be created to enclose all the possibilities specified in the original input.

4.4 Modularity Considerations

This issue applies to big assemblies in which the components have been divided in different functional units called modules or subassemblies. In this case the idea remains the same and the obstructions of parts with other components that belong to another subassembly have to be included in the list of obstructions of the obstructed part. In practice, an input that refers to an element from another assembly acts as a link between both subassemblies, which now have to be considered as a bigger and more complex structure.

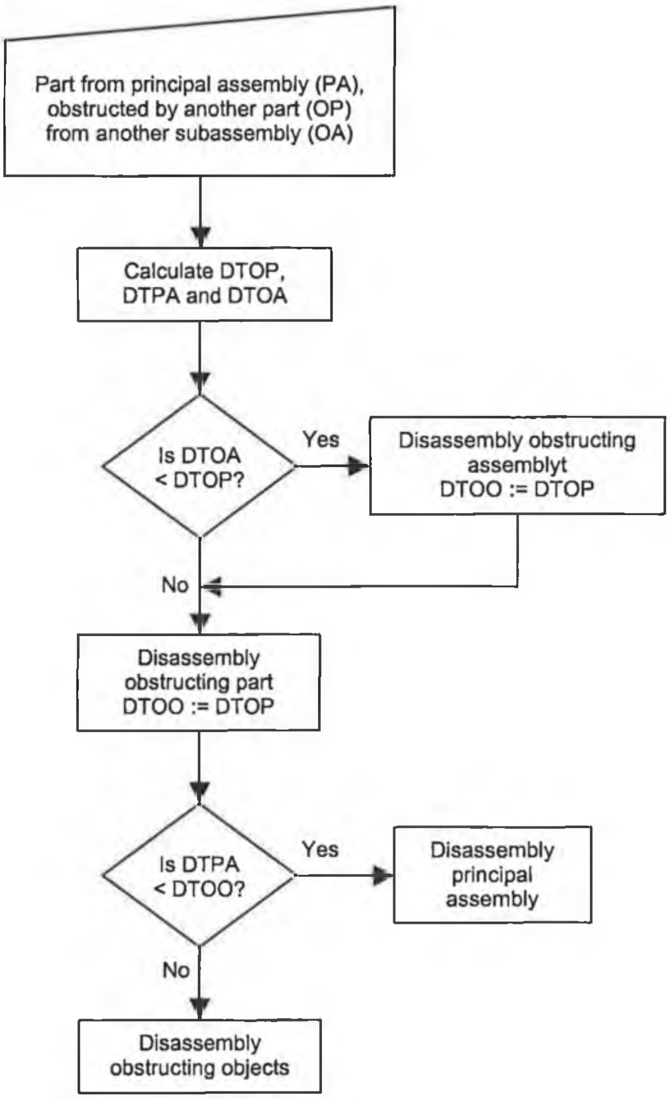


Figure 4.23: Modularity optimisation flow chart.

The concept of modular design also seeks the simplification of disassembly tasks and in general the removal of a module is frequently easier and faster than the subtraction of any of its constituent parts. For this reason the consideration of modularity in the creation of the disassembly process plans is a good strategy to optimise these tasks. The optimisation here considered will look at four different factors:

- DTOP: disassembly time of obstructing part from external subassembly[4]
- DTPA: disassembly time of principal subassembly[5]
- DTOA: disassembly time for the whole subassembly to which the obstructing part belongs
- DTOO: disassembly time of obstructing objects.

At every stage this metrics are compared to one each other according to the algorithm shown in Figure 4.23 and the best choice is made.

4.5 Summary

The chapter proposes a new methodology for the creation of Disassembly Process Plans. This methodology is going to be implemented in software and there fore some computational issues had to be taken into account. The chapter starts explaining the difficulty of the problem and why a heuristic algorithm has been chosen. Next, the basic structure of the algorithm precedes the specification of the user input. The different modules of the methodology are further examined by means of several examples that illustrate the abilities of the technique. Finally, issues like obstructions and modularity are further explained and integrated in the methodology in order to optimise and cope with complex product structures.

[4] External subassembly is a subassembly which does not contain the target part but interferes in its disassembly.

[5] Principal subassembly refers to the subassembly in which the part object of study resides.

Chapter 5. Testing and Validation; a Case Study using the DFE Workbench

5.1 Introduction
5.2 Product description
5.3 Input data process
5.4 Evaluation and improvement
5.5 Reporting results
5.6 Outline of improvements made using the DFE Workbench
5.7 Summary

5.1 Introduction

As already stated, the disassembly methodology described in Chapter 4, has been designed in such a way that it can be integrated in the DFE Workbench. This tool has been recently re-coded by one of the team members, Camelia Chira, as part of her Masters work and research. The parallel work progress of both the author and the programmer (with the respective disassembly methodology and coding) made impossible the full codification of the methodology and consequently only modules 1, 2 and 5 of the disassembly algorithm were integrated in the DFE Workbench. In addition to this, some considerations about modularity were taken into account although they do not fully cover the issues addressed in section 4.4.

This chapter aims to test the functionality of the tool by means of an industrial case study from one of the industrial partners. The testing briefly covers the main aspects of the tool in order to give a holistic view of the package and how it helps the designer in the development of environmentally superior products. Later the chapter will focus on the testing of the structural characteristics of the tool, especially those that make use of the disassembly methodology (that has been partially integrated in the software package). The results delivered by the tool will be compared with those obtained by the manual use of the methodology and also by the logic disassembly route that a designer would identify for the selected components. This chapter finishes with a summary and a set of conclusions will be drawn in order to determine if the methodology and/or the current integration satisfy the requirements of such type of tool.

5.2 Product Description

The assembly selected for this case study is an external rear view mirror (see Figure 5.1) that is currently fitted in the Jaguar X-400, which is one of the vehicles produced for one of the industrial partners involved in the testing and further development of the tool.

Figure 5.1: Jaguar X-400 door mirror used for the development of the case study

This product combines different types of parts ranging from electronic components to plastic pieces. The whole assembly has been divided in eight main subassemblies and, in total, it contains fifty-three parts including fasteners (see Figure 5.2).

5.3 Input Data Process

As explained in Chapter 3, the input to the DFE Workbench can be done in two modes, directly from the evolving model or manually by the user. As part of the input, the author created the CAD models of the Jaguar mirror using both SolidWorks 2000 and Pro/Engineer 2001. As the design process was evolved the different parts were saved in the DFE Workbench and the necessary IAS information (described in Chapter 3) was also included in the databases.

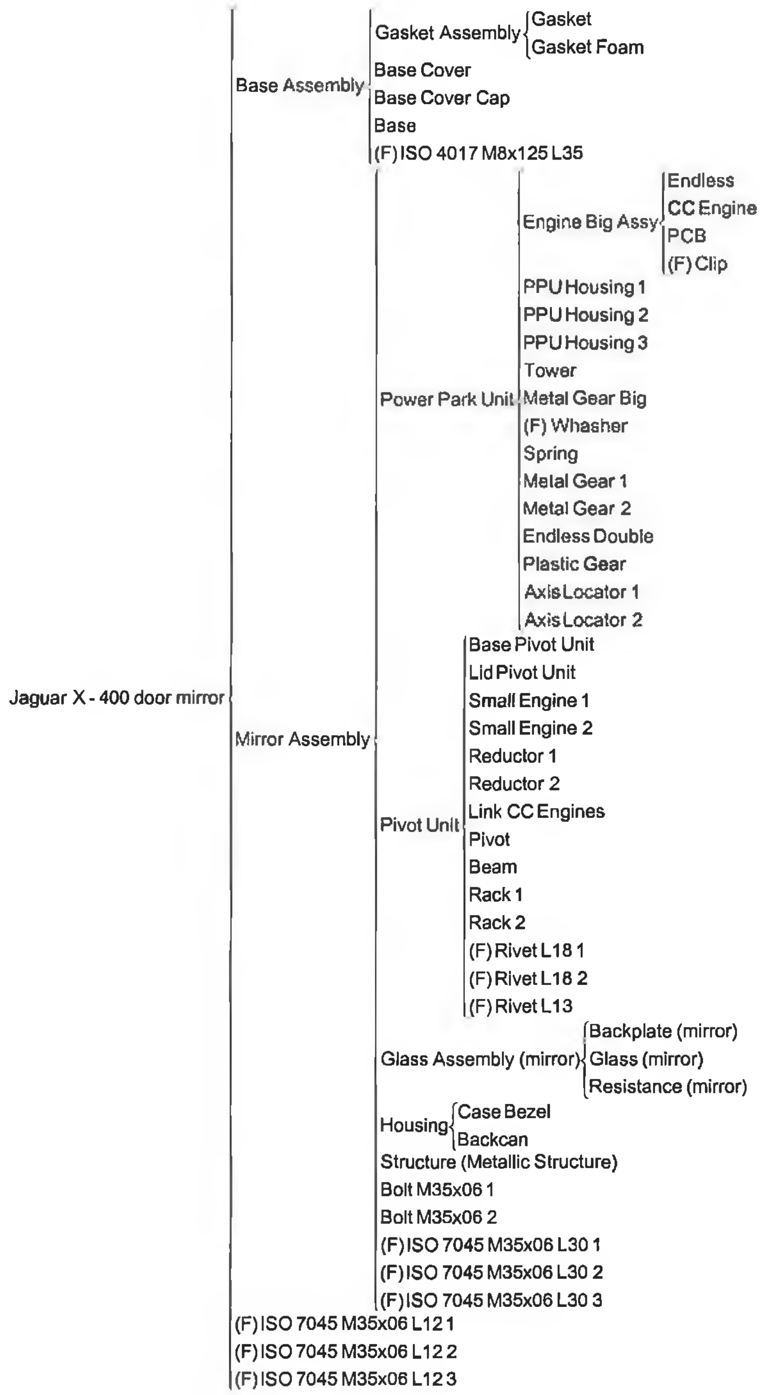


Figure 5.2: Bill of Materials for the door mirror

Once all the parts that comprise the product were created, they were assembled to form the virtual prototype of the final product. At this point the main product's structure (BOM) and IAS data (life cycle information) were already in the database.

The next step was to determine other structural data of the assembly, which provides the necessary information to run the SAM agent and the disassembly methodology proposed in Chapter 4. This input includes the specification of relations between parts, the definition of obstructions between components, the identification of materials, and to mark serviceable components. For the Jaguar mirror the fasteners among parts are fully described in Appendix 2. This first input corresponds in the methodology to the *list of fasteners (F)* described in section 4.2.1 and, for example, a link between the 'Tower' (from the 'Powerpark unit' subassembly) and the 'Base' (from the 'Base assembly') by means of 3 Philips head screws was created. Appendix 2 also shows that the tool required to unfasten the joint is a Philips driver and that the time required to remove the joint is 39 seconds. On the other hand, Appendix 3 includes the obstructions defined for the mirror, which correspond to the *list of obstructions (O)* in the disassembly methodology, for example the 'base' is obstructed by the 'gasket'. It is important to note that the current level of integration does not allow the user to include complex obstruction relationships and therefore the ability of the methodology to find the best among alternative routes.

During the input data process, the advisor agent is also active and it notifies the user when an undesirable selection occurs. For example, during the data input, a designer could decide to create a joint between the 'backcan' and the 'case bezel' by means of planar adhesive. In that moment, the DFE Workbench realises that the planar adhesive is a non-reversible joint therefore, if the 'backcan' and 'case bezel' are made of incompatible materials, the combination becomes non-recyclable. This situation is alerted by means of a message-box which gives a brief explanation of the problem and advice; it also gives the designer the opportunity to accept the advice and make appropriate changes based on the advice or alternatively leave the specified joint (see Figure 5.3). If the user makes the suggested modifications the final assembly will have better performance from an environmental and extended product perspective, since the parts will become reusable and remanufacturable, easy to service and also recyclable. On the other hand, if due to some reason the designer wants to go ahead with his original idea, he can dismiss the substitution of the planar adhesive. However, this decision will automatically trigger the change of the previously specified end of life strategy (for the 'backcan' and the 'case bezel') from recycling to landfill, disabling the recycling option while this non-reversible joining relationship exists. Currently the main input to the system is done and the next step is the evaluation and improvement of the emergent design.

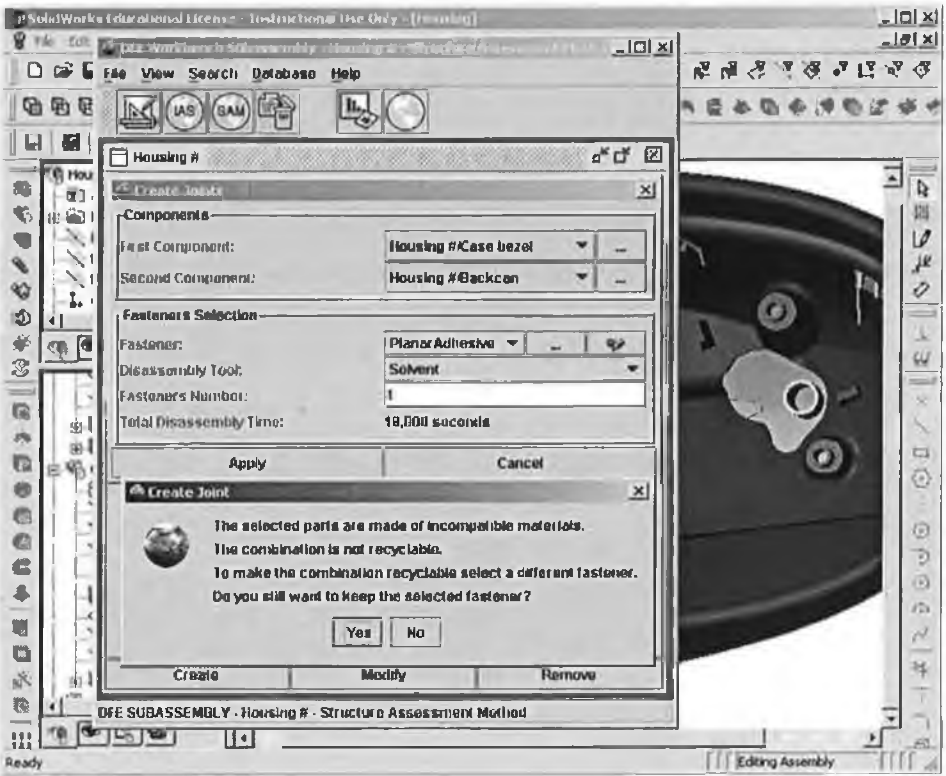


Figure 5.3: Advisor agent prompt during definition of joints between parts.

5.4 Evaluation and Improvement

This section will describe the evaluation of the Jaguar mirror using the DFE Workbench. This evaluation has been divided in two subheadings that refer to the IAS and SAM evaluation. Although this thesis focuses on structural issues, specially in those affected by disassembly operations (included as part of the SAM agent), a brief discussion about the evaluation and improvements made using the IAS agent is given in order to show the capabilities of the tool in designing environmentally superior products (ESPs).

5.4.1 Evaluation Using IAS Agent

The evaluation started with a quick look at the general information (Figure 5.5 shows the general information for the '*mirror assembly*') of the door mirror where it was noticed a low rate of recyclability. The value, just below 30%, would miss the target that lately has been set by the legislation (EOLV) in 85% of the total mass of the car before 2006. The low percentage reached is because there is a high number of components (43%) in which the material composition cannot be identified and consequently this situation avoids their recyclability; the simple insertion of labels will improve significantly this problem. To perform this task the DFE Workbench provides the user with standard labels that can be placed in the required components of the prototype just by drag and drop as shown in Figure 5.4. The DFE Workbench detects the inclusion of these labels, which now are part of the CAD models, and appropriate changes are automatically made, for example, it recalculates the recyclable content of the whole assembly. In this case the identification of materials was enough to meet the legislative requirements.

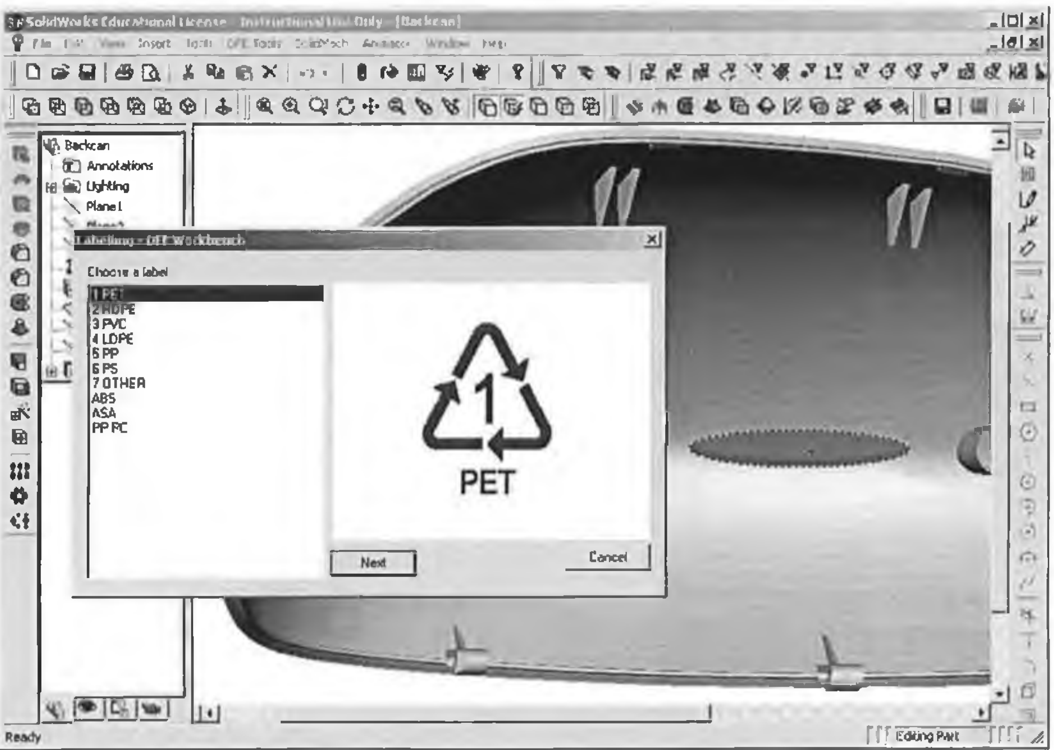


Figure 5.4: Labelling function of the DFE Workbench

The DFE Workbench can also identify the highest contributors to the environmental impact helping the designer to take a holistic view of the product in order to identify the worst situations overall. This is can be done by clicking in the prioritisation button of the application. Figure 5.5 shows the prioritisation window and how the application finds that the highest contributor to the environmental impact is the *structure* component being the material type (Al99) the main source of impact. This means that the environmental burden caused for the part as it is, is mainly caused for the type of material used to manufacture it and is not located in the manufacturing processes, or any other life cycle phase of the part. The prioritisation window gives three choices to the user: (1) cancel the current process, (2) ignore the component and find the next highest problem, or (3) get advice from the application. If the designer clicks the advisor button, a new window will pop up giving a list of alternative materials that the advisor agent has selected from the databases. The materials reported have similar properties than the original and are reported in decreasing environmental impact.

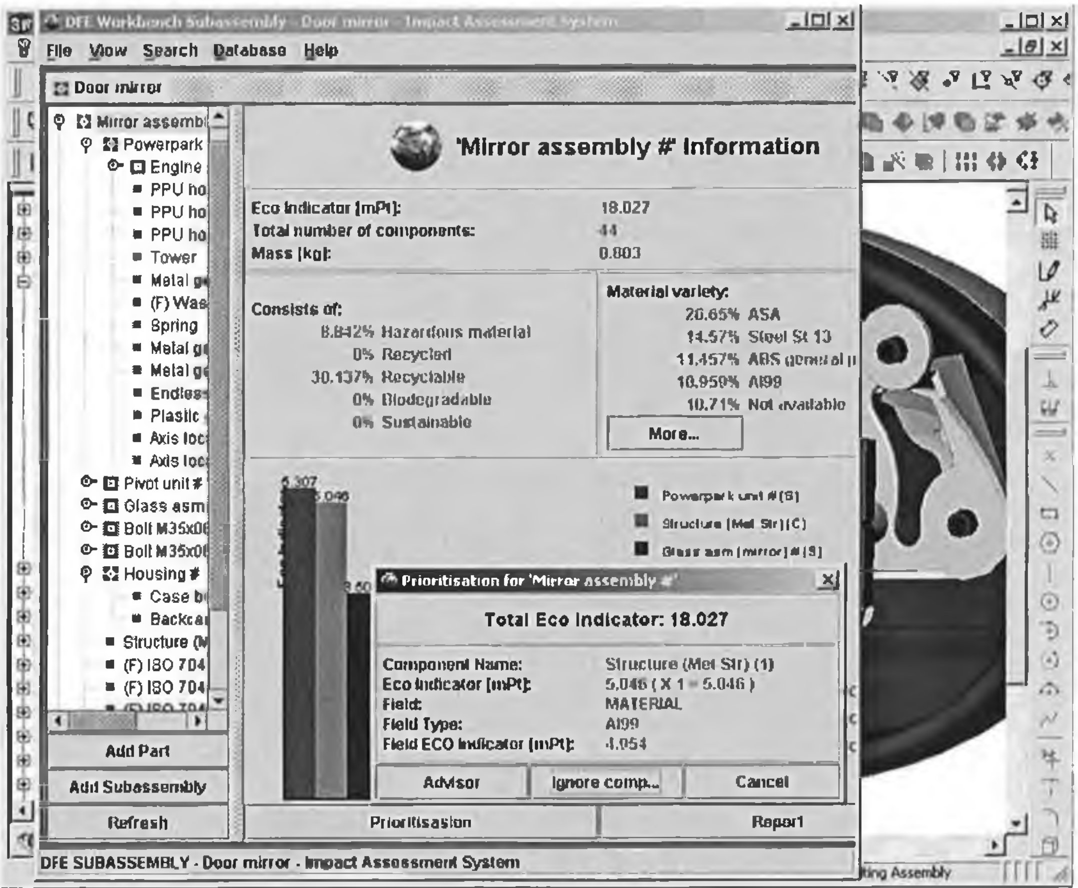


Figure 5.5: IAS agent prioritisation in door mirror assembly.

An important modification in a design, as it is the change of the material type of a part, has to be verified to ensure the quality and reliability of the prototype. The integration of the DFE Workbench in the designer's environment enables the user to take advantage of the CAD capabilities to perform further evaluations, for example, a stress or dynamic study by means of a finite element analysis (FEA).

5.4.2 Evaluation Using SAM Agent

The SAM Agent works with the designer as the product is assembled in the CAD environment; this was already discussed in section 5.3 where the use of non-reversible fasteners between parts (in particular between those made of incompatible materials) was notified to the designer giving him the chance to modify this situation. Whilst SAM evaluates other structural characteristics, as this research developed a disassembly methodology, the focus of the case study will be to demonstrate the recyclability and disassembly features of the DFE Workbench

Ease of disassembly of a product highly influences processes like, serviceability, maintainability, remanufacturing, reuse and end of life. To evaluate them, SAM calculates disassembly time and routes, which helps the designer to identify and improve cases where disassembly times are too high. The disassembly algorithm generates dismantling routes and times for the components from the structural information already existing in the system. The principal data used are the fastening relationships among parts, the obstruction characteristics of components, and the modularity of the assembly.

The prioritisation of the adverse situations is not purely based on the disassembly time but it also takes into account other issues (e.g. frequency of disassembly). For a car this information can be input in the same way as a maintenance plan; for example, if a filter has to be changed every 15.000 Km over an expected life for the car of 300.000 Km the application will know that the filter is serviceable part that has to be replaced frequently and therefore it will bring it up in the prioritisation list. Coupling between reliability and serviceability considerations should be studied in order to achieve an improved optimisation of both serviceability and maintainability tasks.

The 'door mirror' does not have any serviceable element but in order to show this feature, the heater ('resistance' component in BOM shown in Figure 5.2) at the back of the 'glass (mirror)' part has been marked as a serviceable component. The DFE Workbench calculates a disassembly time of 203 seconds for the heater, which is clearly smaller than the disassembly time of many other components of the 'door mirror' (e.g. 'Rack 1' takes 233 seconds in Figure 5.6[6]). However, based on the maintainability characteristics of the assembly, the prioritisation module will identify this part as a priority for improvement.

[6] Note that 'resistance' belongs to the 'Glass Assembly (mirror)' and that is the reason why it does not appear in Figure 5.6. The part removal time for the 'Resistance' component can be obtained from the 'Glass Ass (mirror)' SAM screen shot shown in Appendix 2.

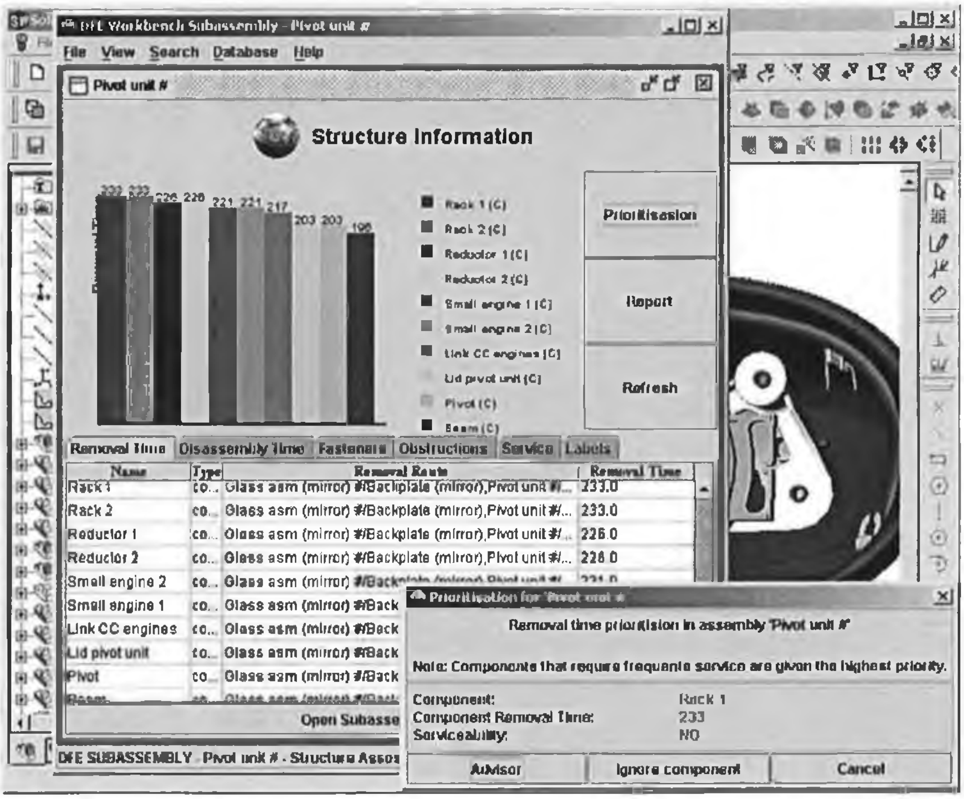


Figure 5.6: SAM evaluation in 'pivot unit' assembly.

The advisor agent presents all the fastening relationships involved in the disassembly of the component of study. This detailed information aids the designer to focus on the main problems while the advisor also provides alternative fastener for the selected joints. In the case of the heater, a priority problem was identified in the joint between the 'glass' and the 'backplate', which has to be unfastened in order to get to the heater. In this case the simple substitution of one fastener for another one was not enough and the redesign of the 'backplate' was required to bring the disassembly time for the resistance down to 70 in the new design from 203 seconds in the original design.

5.5 Validation of Disassembly Methodology

For further testing and validation of the methodology and the integration on the DFE Workbench, the 'pivot unit' subassembly has been chosen. This subassembly comprises 14 components that can be identified in Figure 5.7. The description of the product in terms of fastener relationship among parts and obstructions are shown in Appendix 2 and 3 respectively.

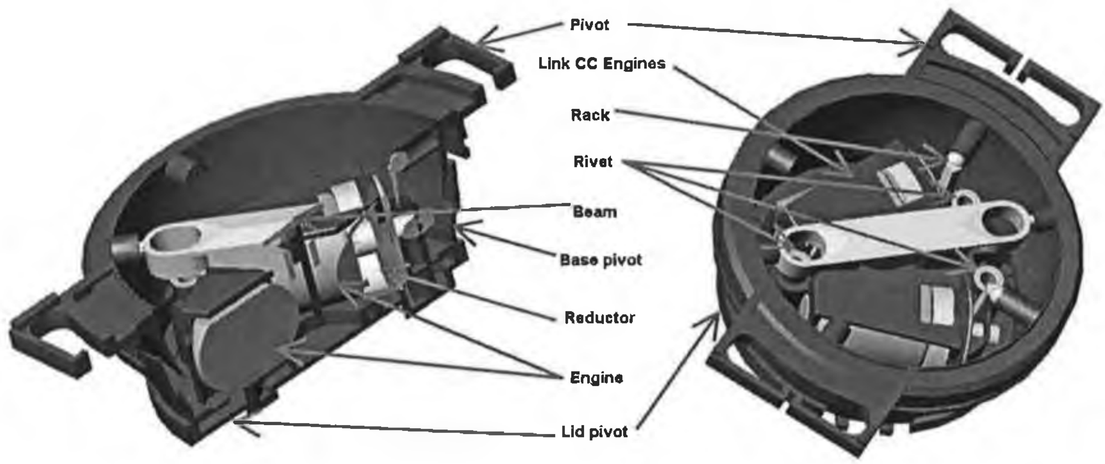


Figure 5.7 'Pivot unit' subassembly

Primarily the two first modules of the disassembly algorithm were manually applied to the 'pivot unit' giving the following disassembly sequences:

- Pivot: L Pivot – Rack 2[7] → L Pivot – Rack 1 → L Pivot Beam → Pivot
- Link CC Engines: L Beam – Pivot → L Beam – Base → L Link CC Engines – Base → Rivet L18 1 → Rivet L18 2 →Rivet L13 → Beam → Link CC Engines
- Rack 1: L Beam – Pivot → L Beam – Base → L Link CC Engines – Base → Rivet L18 1 → Rivet L18 2 →Rivet L13 → Beam → L Reductor 1 – Engine 1 → L Reductor 1 – Base → Link CC Engines → L Rack 1 – Pivot → Reductor 1 → Rack 1
- Rack 2: L Beam – Pivot → L Beam – Base → L Link CC Engines – Base → Rivet L18 1 → Rivet L18 2 →Rivet L13 → Beam → L Reductor 2 – Engine 2 → L Reductor 2 – Base → Link CC Engines → L Rack 2 – Pivot → Reductor 2 → Rack 2
- Beam: L Beam – Pivot → L Beam – Base → Beam
- Base Pivot: L Base – Beam → L Base – Reductor 2 → L Base – Reductor 1 → L Base – Lid → L Base – Link CC Engines → L Base – Engine 1 → L Base – Engine 2 → Base

[7] This means that there is a link between the Pivot and the Rack2 that has to be undone

- Reductor 1: L Beam – Pivot → L Beam – Base → L Link CC Engines – Base → Rivet L18 1 → Rivet L18 2 →Rivet L13 → Beam → L Reductor 1 – Engine 1 → L Reductor 1 – Base → Link CC Engines → Reductor 1
- Reductor 2: L Beam – Pivot → L Beam – Base → L Link CC Engines – Base → Rivet L18 1 → Rivet L18 2 →Rivet L13 → Beam → L Reductor 2 – Engine 2 → L Reductor 2 – Base → Link CC Engines → Reductor 2
- Engine 1: L Beam – Pivot → L Beam – Base → L Link CC Engines – Base → Rivet L18 1 → Rivet L18 2 →Rivet L13 → Beam → L Reductor 1 – Engine 1 → L Base – Engine 1 → Link CC Engines → Engine 1
- Engine 2: L Beam – Pivot → L Beam – Base → L Link CC Engines – Base → Rivet L18 1 → Rivet L18 2 →Rivet L13 → Beam → L Reductor 2 – Engine 2 → L Base – Engine 2 → Link CC Engines → Engine 2
- Lid pivot: L Lid – Base → Lid

The 'rivets' are considered as fasteners and they have been omitted in the previous list. Anyway as they are not obstructed by any part their removal route consist in the part itself.

The list of operations described above corresponds closely to the disassembly routes that a designer would create by looking at the product. The small differences noticed would be addressed and efficiently solved by the third module of the algorithm, which as explained in the previous chapter, reorganises the disassembly sequences and includes parts that have been completely disengaged from the product. A good example to illustrate this is the case of the disassembly route for the 'Base'. In the sequence presented, one of the operations is the removal of the only link between the 'Lid' and the rest of the assembly, which means that the 'Lid' will be completely free. In practice, the 'Lid' will be taken away after undoing that link however, the operation of removing the 'Lid' does not appear in the sequence proposed. This can be noticed as a small flaw but the consideration of the third module of the algorithm can easily solve it.

Once has been proven that the results from the manual operation of the disassembly methodology correspond to the reality, the next step is to compare the manual methodology with the results obtained through the DFE Workbench. Appendix 4 shows the disassembly process plans for the different assemblies. Figure 5.8 shows part of the disassembly process plan generated by the DFE Workbench. It includes the name of the part, the removal time for the part and the disassembly route identified. It has to be noted that every part is preceded by the name of the assembly to which it belongs, that is, 'Glass asm (mirror) /Backplate (mirror)' refers to the 'Back plate (mirror)' part from the 'Glass asm (mirror)'.

Pivot unit	
Base pivot unit (comp)	
Removal Time (sec):	60
Disassembly Route:	Base pivot unit
Beam (component)	
Removal Time (sec):	196
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Beam
Lid pivot unit (comp)	
Removal Time (sec):	203
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Mirror assembly /(F) ISO 7045 M35x06 L30 3 >> Mirror assembly /(F) ISO 7045 M35x06 L30 2 >> Mirror assembly /(F) ISO 7045 M35x06 L30 1>> Lid pivot unit
Link CC engines (comp)	
Removal Time (sec):	217
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Pivot unit /Beam >> Pivot unit /(F) Rivet L18 2 >>Pivot unit /(F) Rivet L18 1 >> Pivot unit /(F) Rivet L13 >> Link CC engines
Pivot (component)	
Removal Time (sec):	203
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Pivot
Rack 1 (component)	
Removal Time (sec):	233
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Pivot unit /Beam >> Pivot unit /(F) Rivet L18 2 >> Pivot unit /(F) Rivet L18 1 >> Pivot unit /(F) Rivet L13 >> Pivot unit /Link CC engines >>Pivot unit /Reductor 1 >> Rack 1
Reductor 1 (component)	
Removal Time (sec):	226
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Pivot unit /Beam >> Pivot unit /(F) Rivet L18 2 >> Pivot unit /(F) Rivet L18 1 >> Pivot unit /(F) Rivet L13 >> Pivot unit /Link CC engines >>Reductor 1
Small engine 1 (comp)	
Removal Time (sec):	221
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Pivot unit /Beam >> Pivot unit /(F) Rivet L18 2 >> Pivot unit /(F) Rivet L18 1 >> Pivot unit /(F) Rivet L13 >> Pivot unit /Link CC engines >>Small engine 1

Figure 5.8 Extract of disassembly process plan for 'pivot unit'

Next the sequences calculated exclusively for the 'Pivot unit' are going to be analysed, therefore parts that belong to subassemblies other than 'Pivot unit' will be omitted. The inclusion of external components to 'Pivot unit' will be discussed later. There are substantial differences between the sequences given by the software and the ones obtained by the manual calculation. The main difference is that the software does not show the operations related to the removal of the links. As this information is also calculated by the methodology it should appear in order to generate complete disassembly plans. The comparison between the removal of the parts and the sequence of the operations shows that the software tool gives the right results. In some cases the software output have slight differences in the order in which the parts are taken apart but since the all the processes given by the tool are possible at the time they appear in the sequence this variations are not consider as a flaw.

As mentioned before, the disassembly route from the DFE Workbench includes parts from other subassemblies. This is because the 'Pivot unit' is a subassembly of a bigger product, which is the Jaguar mirror. It is important to take this in account since the disassembly of every component of a subassembly could be affected by other parts from other assemblies (this issue is addressed in section 4.4). In this case the 'Pivot unit' is inside the housing and furthermore it is obstructed by the 'Glass asm (mirror)'. This obstruction was also included in the DFE Workbench and based on that input, the complete sequence of operations (including external subassemblies) should be generated. The author considers that, at the moment, this feature is not working properly since only some of the 'Pivot unit' components include in their list the 'Backplate' element as part of the overall disassembly route. In addition, the removal of the 'Backplate' would not be the most efficient way to gain access to the 'Pivot unit' since the removal of the whole 'Glass asm' is quicker than the complete removal of the 'Backplate'. New versions of the tool should look at solving this problem.

5.6 Reporting Results

As explained in section 3.8.1, all the data gathered and generated with the DFE Workbench resides in the Oracle databases and can be easily presented using the Report Generator Agent. In practice any kind of report can be created displaying diverse information and also according to some specific structure and style. For demonstration purposes, the report generator console (see Figure 5.9) already contains some predetermined reports that can be viewed, printed or saved in different formats (e.g. text, html, pdf and xls).

The availability of disassembly process plans (DPP) is very important to carry out disassembly tasks in an effective way. The DFE Workbench can create the required DPP automatically including disassembly routes, disassembly times and the necessary tools to do the job. Figure 5.9 illustrates part of the DPP created by the application for the door mirror. In it the disassembly route and time is shown for all components.

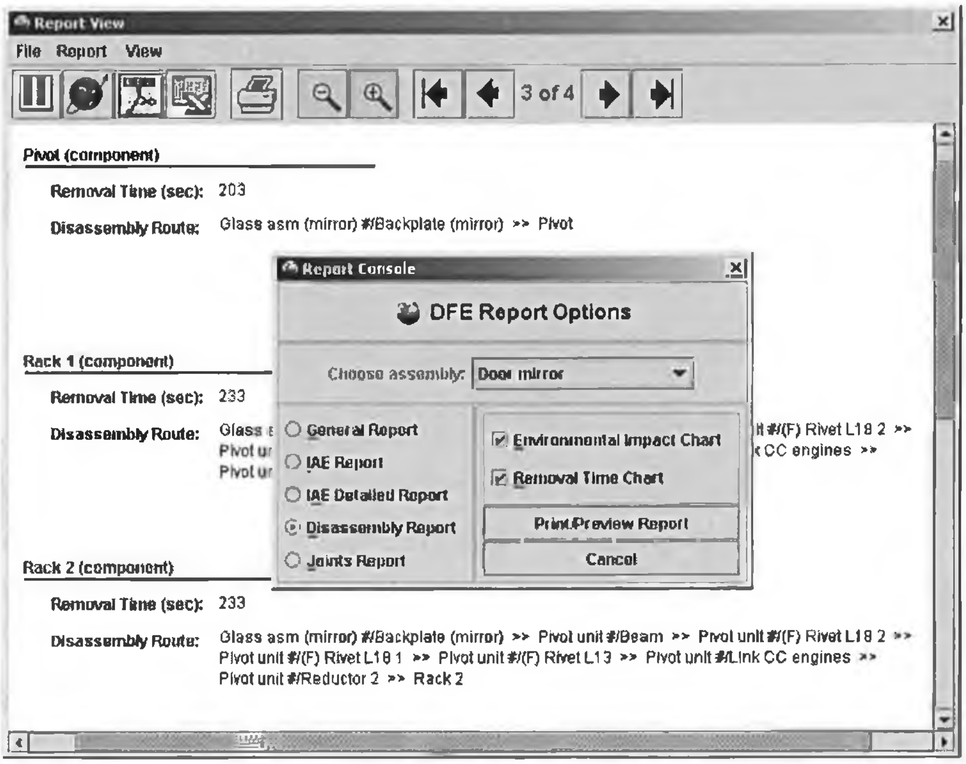


Figure 5.9: Disassembly Process Plan for 'Door mirror' assembly.

5.7 Outline of Improvements Made Using the DFE Workbench

Several modifications to the 'door mirror' were carried out using the DFE Workbench; this section presents an outline of the major improvements.

Firstly the capability of the application to track mass allowed the comparison of the total weight which was decreased by 25%. This weight reduction was possible as a result of some changes in the material types of some parts. Additionally, these changes also reduced the variety of materials by 15%. The overall environmental impact was decreased by 35% whilst the recyclability of the product increased from 30% to 90%. These improvements made it possible to meet the legislative requirements of the EOLV. Finally, looking at structural issues, 14 non-reversible fastening relationships were substituted for reversible ones whilst the number of fasteners and the total disassembly time (-20%) were reduced.

5.8 Summary and Conclusions

In this chapter the functionality of the tool was tested by means of an industrial case study from one of the industrial partners. The case study starts by describing the product to be assessed; after, the data input is explained. The evaluation of the has been divided in two different sections, the evaluation using IAS and the evaluation using SAM. The SAM agent addresses the evaluation of the structural characteristics of the product. Therefore the disassembly methodology works inside SAM and helps the designer to improve operation like maintainability or disassembly for recycling. A separate section compares and evaluates the disassembly routes generated via three modes (1) a designer, (2) the manual calculation of the disassembly sequences with the methodology and (3) the results given by the two first modules integrated in the DFE Workbench. Three main conclusions can be extracted from the testing.

- The correct utilisation of the methodology generates a reliable list of operations that leads to the disassembly of a component.
- The DFE Workbench finds the correct removal route inside a subassembly
- The current level of integration of the disassembly methodology into the DFE Workbench does not allow the user to input complex obstructions relationships like OR and AND/OR. The AND obstructions are accepted.
- Whilst the DFE Workbench gives good results at subassembly level, it currently does not give the optimum disassembly sequence when the product contains several subassemblies. This problem can be overcome applying the manual methodology rigorously.

On the other hand, this chapter also shows the capability of the tool to create all kind of reports, including Disassembly Process Plans. Finally an outline of the mayor improvements made with the DFE Workbench is given.

Chapter 6. Summary and Conclusions

6.1 Thesis Overview

6.2 Results and Conclusions

6.3 Ongoing and Further Development

6.4 Summary

6.1 Thesis Overview

The first chapter started explaining the problems created by production activities and why environmentalism has emerged. Later the driving forces behind environmental conscious design were discussed finding that government measures and market reasons were the two main drivers. This chapter also presented the objectives of the research and it finished explaining the thesis layout.

Chapter two defined the Environmentally Conscious Manufacturing concept as well as its constituents (Environmentally Conscious Design (or DFE) and Environmentally Conscious Production). Furthermore widely used tools and concepts like Life Cycle Assessment and Design for the Environment guidelines were described. This chapter also addressed the product design process, explaining a recent model in design that merges environmental concerns into the design process. A design framework derived from that design model was also described. New requirements in design (from environmental legislations and standards) coupled with a lack of opportunities for design improvements at the manufacturing stage of the product lead to a situation where the traditional concept of product is no longer valid. Chapter two finished presenting a new product concept called the Extended Product, which has emerged as a result of the seek for new business opportunities in companies.

Environmental design is a complex task that has to be supported by methodologies and tools. The task of the author during the development was also the further development of the DFE Workbench software tool (described in chapter 3), which helps the designer in the development of environmentally superior products. One of the weaknesses in the functionality of the tool was identified in the Disassembly methodology. In order to propose a different approach to overcome previous problems, research on the Disassembly area was essential to understand the complexity of the problem. Chapter three presented an extensive literature review on the area of disassembly. It started defining the aims of disassembly in the context of this research. Next, two sections addressed the required background (in representation and analysis techniques) necessary to understand different approaches and solutions to the problem found in the literature. Later, the author divided the disassembly problem in four different groups that comprise similar approaches to disassembly. Issues such as modularity and product structure were also addressed in this chapter explaining the advantages of modularity and certain product structures. Overlap and tradeoffs among Design for Assembly and Design for Disassembly was investigated in a later section deriving some recommendations to achieve a successful integration of both concepts. An extensive survey on Disassembly Software was also presented showing comparisons among the different packages. This research lead the development of a disassembly methodology that has to be integrated in the DFE Workbench therefore this tool is also described to the reader.

Based on the background acquired in Chapter two and three, Chapter four proposed a new methodology for the creation of Disassembly Process Plans. As the methodology was going to be implemented as a peace of software, computational issues were taken into account. The chapter started explaining the difficulty of the problem and why a heuristic algorithm was chosen. Next, the basic structure of the algorithm preceded the specification of the user input. The different modules of the methodology were further examined by means of several examples that illustrated the abilities of the technique. The chapter finished addressing issues like obstructions and modularity which were further explained and integrated in the methodology in order to optimise and cope with complex product structures

In chapter five the functionality of the tool was tested by means of an industrial case study from one of the industrial partners. The case study starts by describing the product to be assessed and after, the data input is explained. The evaluation of the product has been divided in two different sections, the evaluation using IAS and the evaluation using SAM. The SAM agent addresses the evaluation of the structural characteristics of the product. In addition, the methodology and integration of the methodology into the DFE Workbench is tested with an example and some conclusions are extracted. The chapter also showed the capability of the tool to create all kind of reports, including Disassembly Process Plans. Finally, an outline of the mayor improvements made with the DFE Workbench (on the Jaguar mirror) was given.

This thesis concludes with the sixth chapter in which a thesis overview is presented followed by some conclusions drawn from the research carried out. Ongoing development and further work is also described in this chapter.

6.2 Results and Conclusions

Three sets of conclusions can be extracted from the different sections of this thesis.

From the study of the design process coupled with environmental concerns the following conclusions have been identified (after [Roc01]):

- The design of Environmentally Superior Products (ESPs) requires a life cycle approach.
- Methodologies and tools must be integrated as early as possible in the design process, as well as being integrated throughout the design process, i.e. integrated through all design phases identified in the PAL framework.
- The PAL framework is a very powerful support for the development of tools and methodologies to support life cycle design activities
- Life Cycle Analysis is an important tool in the development of environmentally superior products, however quantitative abridged LCA approaches are more likely to be of use to cater for the dynamic nature of the design process. Improvement methods need to be provided to support the design engineer in selecting reduced impact materials and energies.
- Approaches must be developed to extend the first life and post first life of products, e.g. design for reuse, remanufacture and recycling.

The findings of the disassembly research and the new methodology proposed are as follows:

- A heuristic algorithm is more suitable for the purpose of this type of application since they require less data input and, in addition, they are computationally less expensive than full search algorithms.

- The research shows that currently there is not a methodology that assists in the calculation of disassembly routes and times that can be adopted in the DFE Workbench.
- In general the existing methodologies require high input from the user.
- The new methodology can be applied to any type of product addressing issues such as modularity and complex combinations of obstruction (AND, OR and AND+OR)
- The methodology is capable to find near-optimal paths from the combination of obstructions.

Finally the following conclusions resulted from the testing of the DFE Workbench software:

- The correct utilisation of the methodology assist in the generation of a reliable list of operations that leads to the disassembly of a component.
- The DFE Workbench finds the correct removal route inside a subassembly
- The current level of integration of the disassembly methodology into the DFE Workbench does not allow the user to input complex obstructions relationships like OR and AND/OR. The AND obstructions are accepted.
- Whilst the DFE Workbench gives good results at subassembly level, it currently does not give the optimum disassembly sequence when the product contains several subassemblies. This problem can be overcome applying the manual methodology rigorously.

6.3 Ongoing and Further Development

As the concept of Extended Product involves also Environmental Design, the author proposes the investigation of a new methodology that would guide the designer in the development of such a product type.

Further investigation about the links and potential coupling of serviceability and maintainability issues could be considered in an attempt to enhance the prioritisation and advisor module of the DFE Workbench software tool.

In reference to the disassembly methodology proposed in this thesis, the automatic identification of obstructions (by the CAD application) should be studied in order to decrease the input from the user. In addition, during the industrial testing was envisaged a great interest in the creation of animations of the disassembly tasks. Once the disassembly sequence has been identified, the generation of these animations (generally *.avi files) can be done from the CAD workstation by means of defining appropriate trajectories for the parts. Due to their similarity, the identification of obstructions and the automatic generation of animation files for the disassembly tasks could be merged and studied as part of a new Master thesis. In such research a new methodology to find both obstructions and appropriate paths should take advantage of the CAD's functionality in order to find collisions among components in an assembly.

Another line of research could focus on how the fixturing of the assembly affects the disassembly of the product and therefore the times involved in the requisite tasks.

In line with the codification of the disassembly methodology, the author recommends the codification of modules three and four of the methodology. Furthermore the tool could easily work with complex combination of obstructions in order to help the user to find better solutions. On the other hand the modularity considerations of a product need to be reviewed to obtain reliable results from the tool. Finally the redesign of the predefined disassembly process plans should include all the operations identified by the methodology, that is, the removal of parts and the disengagement of fasteners.

Finally, the DFE Workbench is undergoing continuous development at the authors' institution to meet the following goals [Die02]:

- Construction of a Life Cycle Costing (LCC) module
- Addition of new evaluation tools apart from IAS and SAM
- Integration of a work-flow manager
- Further development of the interfaces for various departments on the same organisation, for example, materials department or fasteners department.
- Development of agents to handle the information management between design teams and other members of the organisation

- Development of a conceptual design tool to assist the decision making process associated with the development of various types of products at the early stage of design

6.4 Summary

The chapter starts presenting a thesis overview. This has been followed by three sets of conclusions extracted from different chapters. Finally the chapter ends giving some recommendations for further work are described as well as the current development of the DFE Workbench.

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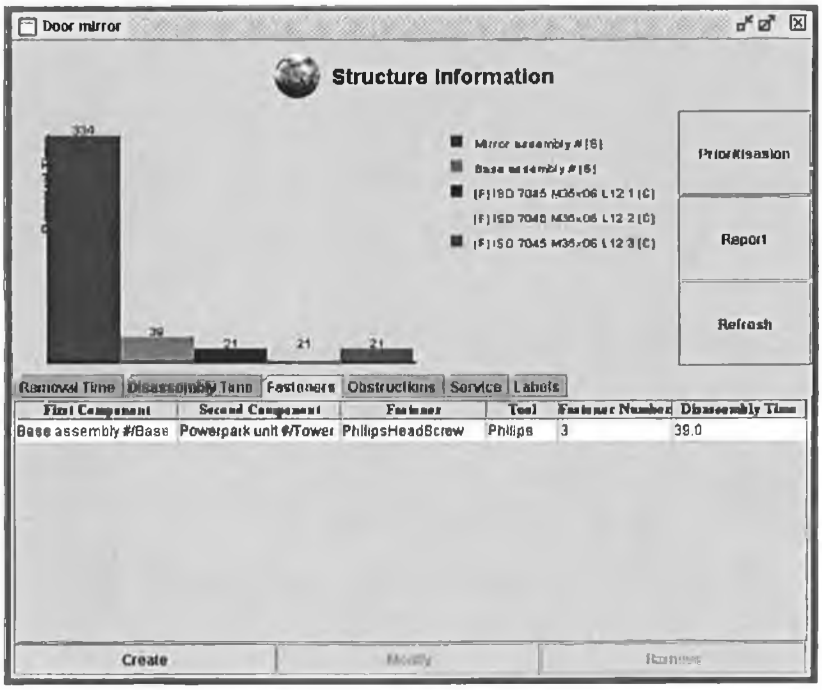
Appendix 1

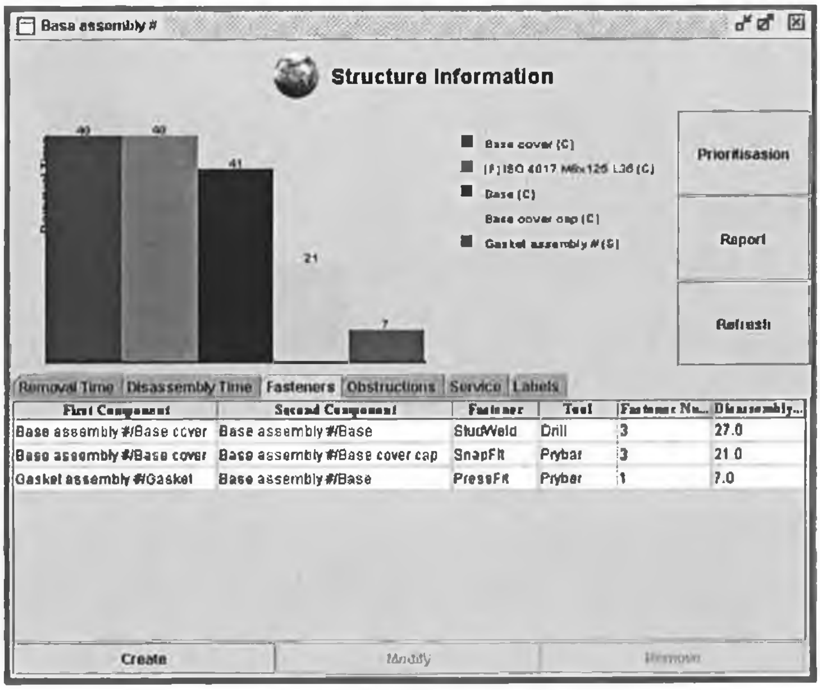
Screen shot from the fasteners database of the DFE Workbench

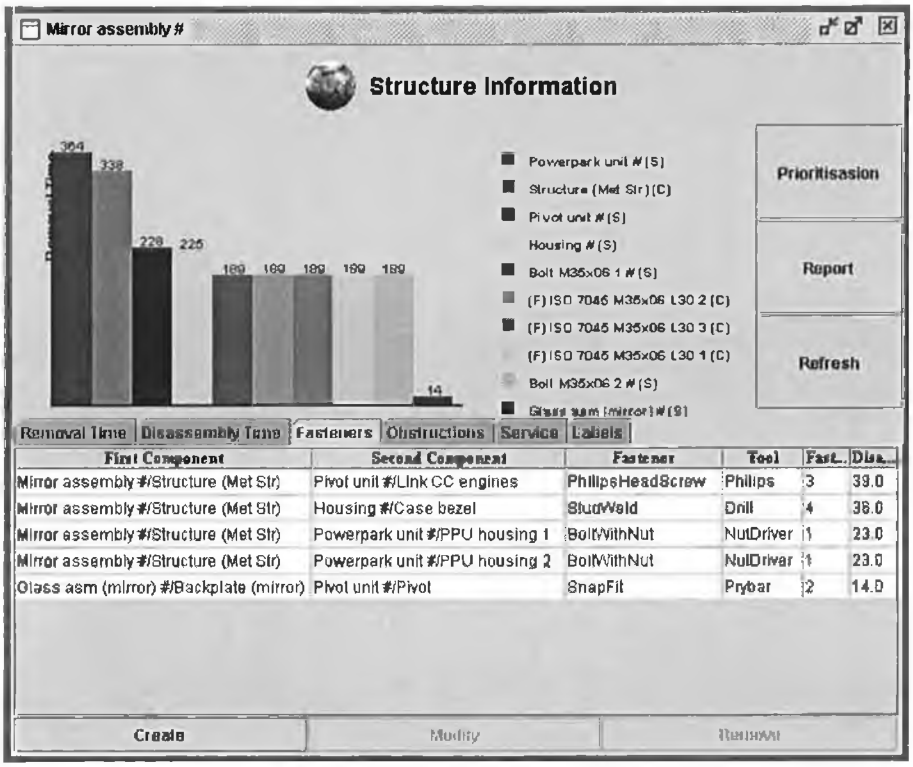
Fastener	Tool	Disassembly time
Washer	None	2
FitIn	None	2
SpringClips	SpecialTool	5
Hook	Prybar	7
SpotAdhesive	Prybar	7
UltrasonicWelding	Prybar	7
MouldedIn	Prybar	7
Ratchetfasteners	Prybar	7
PressFit	Prybar	7
SnapFit	Prybar	7
SolventBonding	Prybar	7
FocusedInfrared	Prybar	7
SolderWeld	Desolder	9
StudWeld	Drill	9
BlindPlasticRivets	Knife	9
Rivet	Shears	11
ScrewInsert	HammerAndChisel	12
PhilipsHeadScrewWithInsert	Philips	13
PhilipsHeadScrew	Philips	13
FlatHeadScrewWithInsert	Flathead	17
FlatHeadScrew	Flathead	17
Nut	NutDriver	23
BoltWithNut	NutDriver	23
HexScrew	NutDriver	23
PlanarAdhesive	Solvent	18,000

Appendix 2

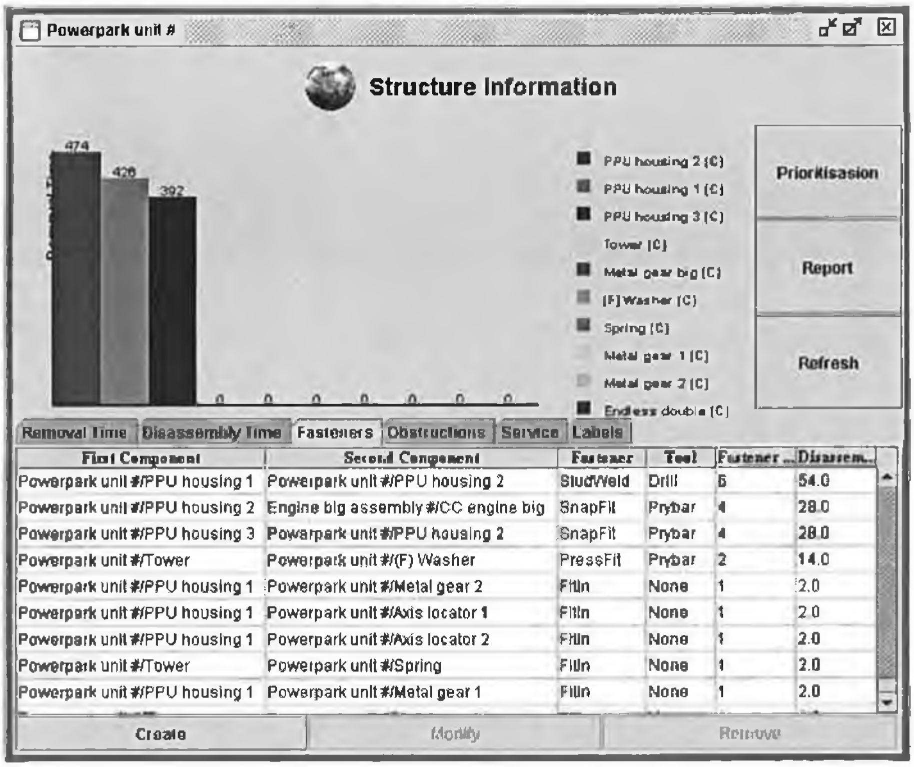
Screen shots including the fastening relationships among components in every subassembly. The part removal time is also shown in the upper graph.







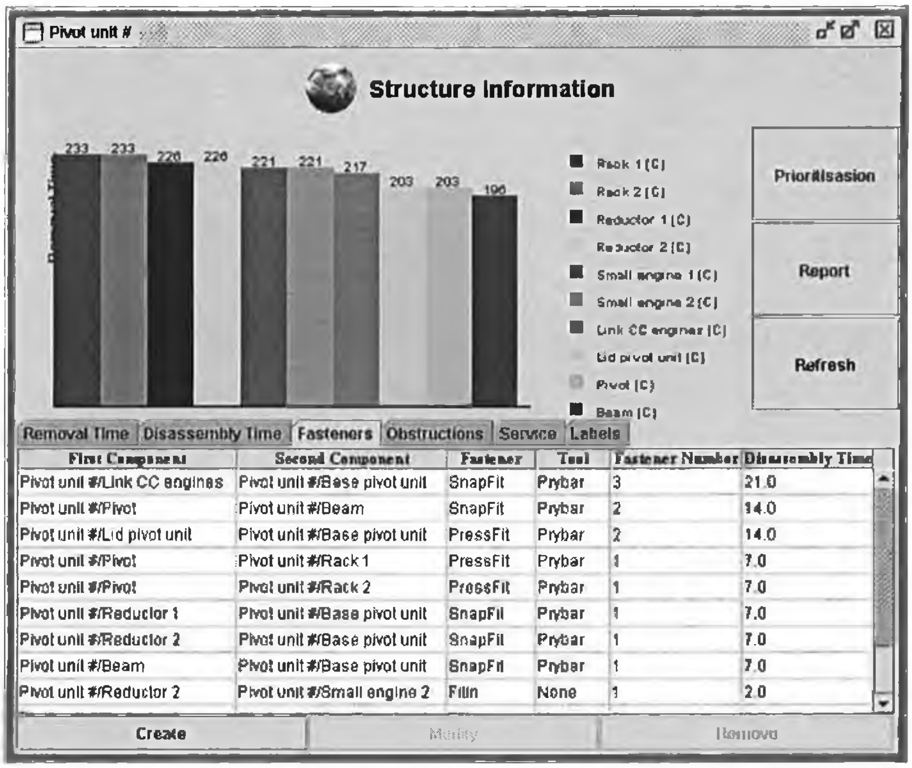
First Component	Second Component	Fastener	Tool	Fast...	Disa...
Mirror assembly #/Structure (Met Str)	Pivot unit #/Link CC engines	PhilipsHeadScrew	Philips	3	39.0
Mirror assembly #/Structure (Met Str)	Housing #/Case bezel	StudWeld	Drill	4	38.0
Mirror assembly #/Structure (Met Str)	Powerpark unit #/PPU housing 1	BoltWithNut	NutDriver	1	23.0
Mirror assembly #/Structure (Met Str)	Powerpark unit #/PPU housing 2	BoltWithNut	NutDriver	1	23.0
Glass asm (mirror) #/Backplate (mirror)	Pivot unit #/Pivot	SnapFit	Prybar	2	14.0



First Component	Second Component	Fastener	Tool	Fastener ...	Disassem...
Powerpark unit #/PPU housing 1	Powerpark unit #/PPU housing 2	StudWeld	Drill	6	54.0
Powerpark unit #/PPU housing 2	Engine big assembly #/CC engine big	SnapFit	Prybar	4	28.0
Powerpark unit #/PPU housing 3	Powerpark unit #/PPU housing 2	SnapFit	Prybar	4	28.0
Powerpark unit #/Tower	Powerpark unit #/(F) Washer	PressFit	Prybar	2	14.0
Powerpark unit #/PPU housing 1	Powerpark unit #/Metal gear 2	FitIn	None	1	2.0
Powerpark unit #/PPU housing 1	Powerpark unit #/Axis locator 1	FitIn	None	1	2.0
Powerpark unit #/PPU housing 1	Powerpark unit #/Axis locator 2	FitIn	None	1	2.0
Powerpark unit #/Tower	Powerpark unit #/Spring	FitIn	None	1	2.0
Powerpark unit #/PPU housing 1	Powerpark unit #/Metal gear 1	FitIn	None	1	2.0

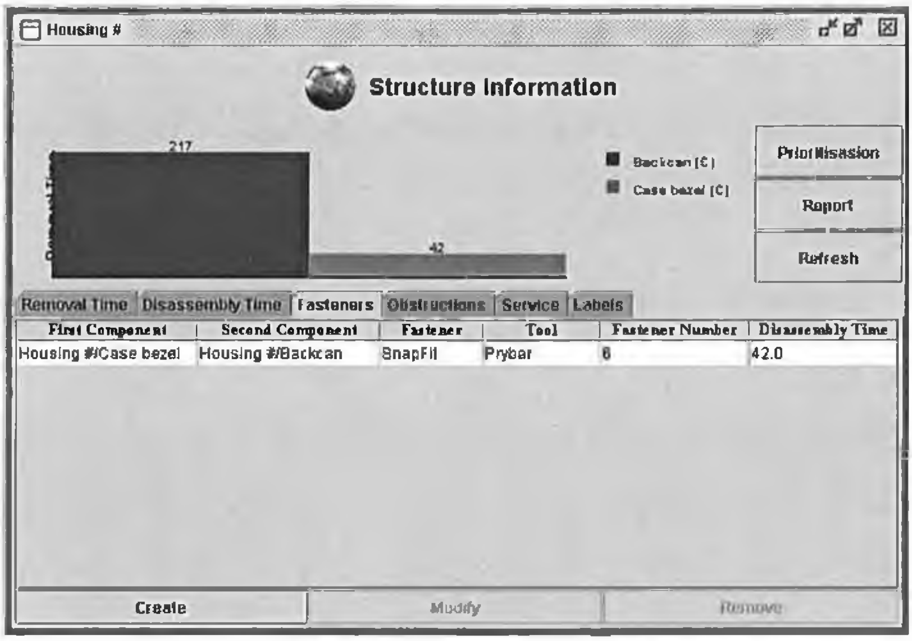
Include in 'Powerpark unit' assembly (fasteners hidden in the screen shot):

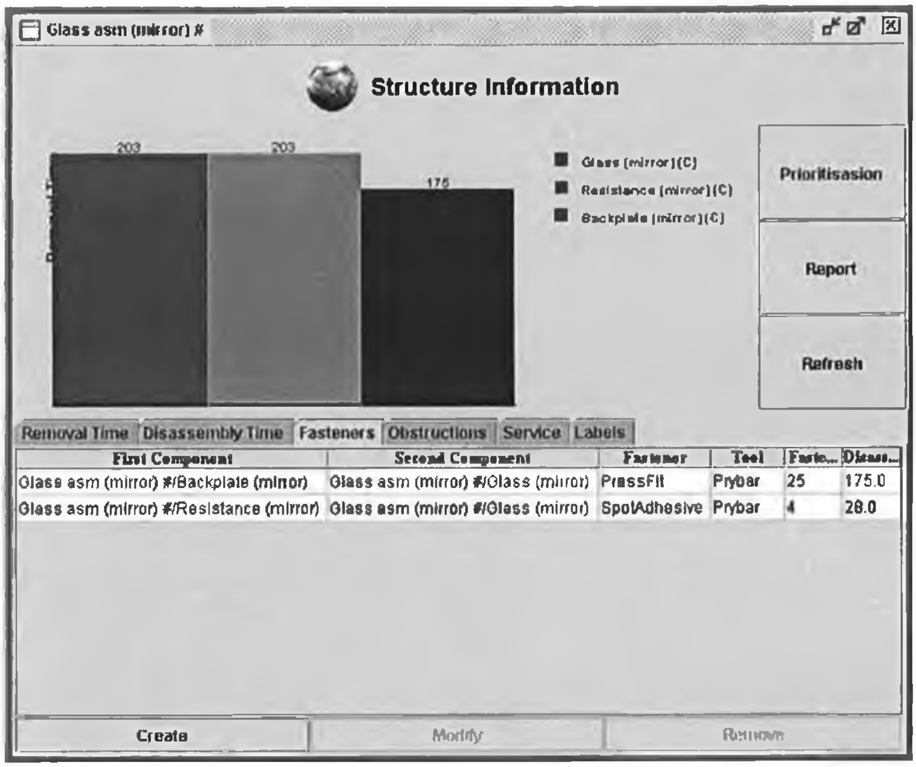
Powerpark unit/Tower	Powerpark unit/Metal gear big	FitIn	None	1	2.0

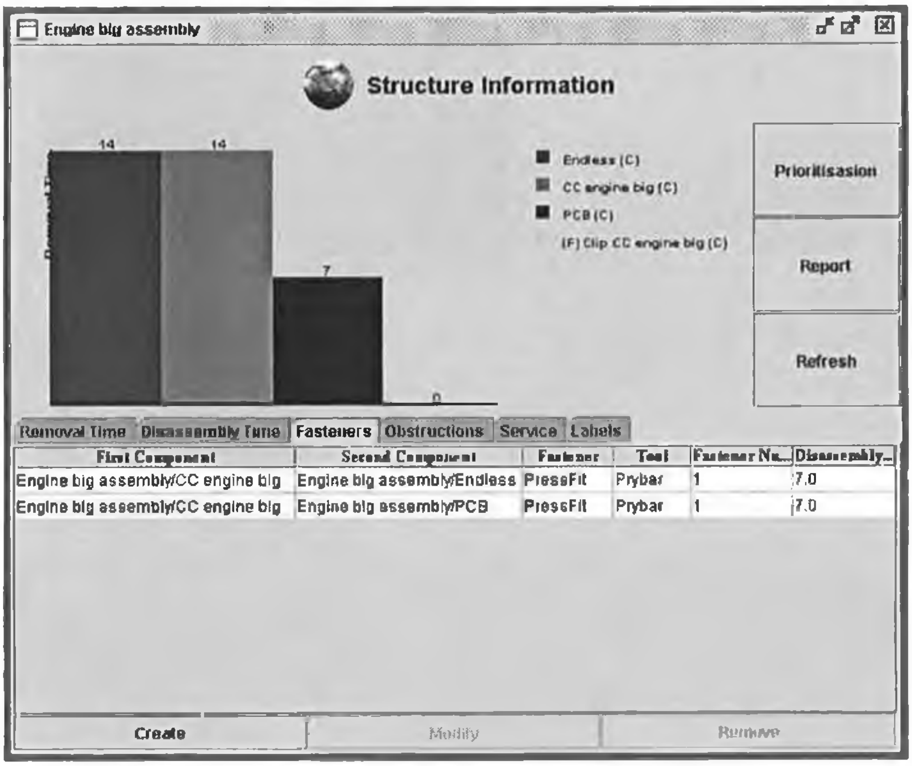


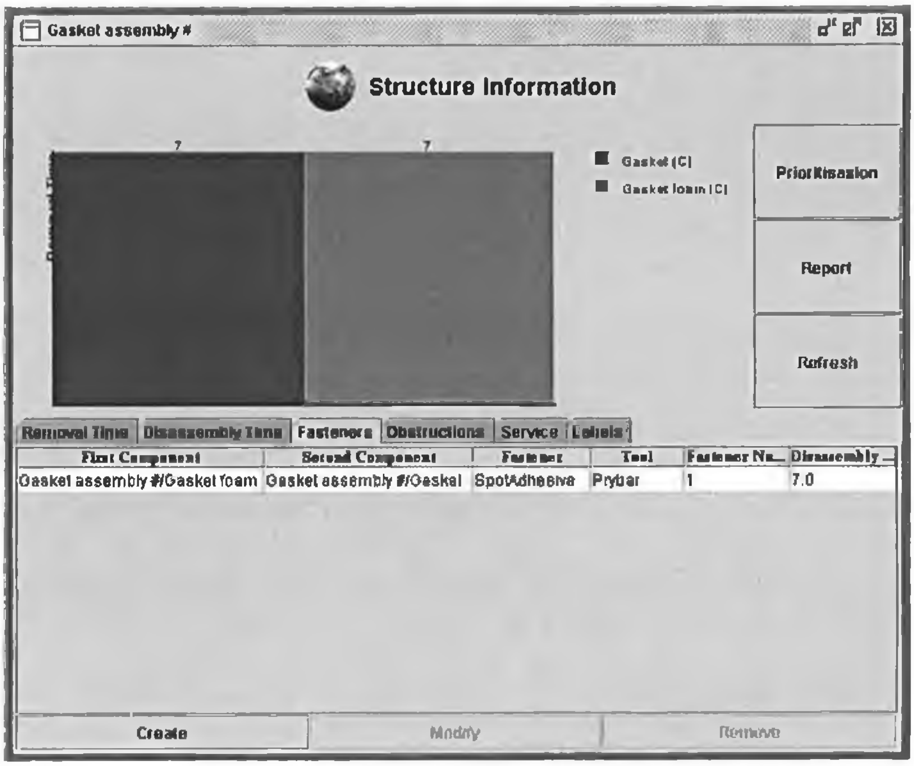
Include in ‘Pivot unit’ assembly (fasteners hidden in the screen shot):

Pivot unit/Reductor 1	Pivot unit/Small engine 1	FitIn	None	1	2.0
Pivot unit/Base pivot unit	Pivot unit/Small engine 2	FitIn	None	1	2.0
Pivot unit/Base pivot unit	Pivot unit/Small engine 1	FitIn	None	1	2.0




Glass asm (mirror) #
Structure Information
203
203
175
Glass (mirror)(C)
Resistance (mirror)(C)
Backplate (mirror)(C)
Prioritisasion
Report
Refresh
Removal Time
Disassembly Time
Fasteners
Obstructions
Service
Labels
First Component | Second Component | Fastener | Tool | Faste... | Disass...
Glass asm (mirror) #/Backplate (mirror) | Glass asm (mirror) #/Glass (mirror) | PressFit | Prybar | 25 | 175.0
Glass asm (mirror) #/Resistance (mirror) | Glass asm (mirror) #/Glass (mirror) | SpotAdhesive | Prybar | 4 | 28.0
Create
Modify
Remove


Engine big assembly
Structure Information
14
14
7
0
Endless (C)
CC engine big (C)
PCB (C)
(F) Clip CC engine big (C)
Prioritisasion
Report
Refresh
Removal Time
Disassembly Time
Fasteners
Obstructions
Service
Labels
First Component | Second Component | Fastener | Tool | Fastener Nu... | Disassembly...
Engine big assembly/CC engine big | Engine big assembly/Endless | PressFit | Prybar | 1 | 7.0
Engine big assembly/CC engine big | Engine big assembly/PCB | PressFit | Prybar | 1 | 7.0
Create
Modify
Remove


Gasket assembly #
Structure Information
7
7
Gasket (C)
Gasket foam (C)
Prioritisation
Report
Refresh
Removal Time
Disassembly Time
Fasteners
Obstructions
Service
Labels
First Component
Second Component
Fastener
Tool
Fastener Nu...
Disassembly ...
Gasket assembly #/Gasket foam
Gasket assembly #/Gasket
SpotAdhesive
Prybar
1
7.0
Create
Modify
Remove

Appendix 3

List of obstructions among parts introduced in the DFE Workbench to analyse the Jaguar X-400 mirror.

Jaguar X-400 door mirror

Door mirror/(F) ISO 7045 M35x06 L12 1	Base assembly #/Base cover cap
Door mirror/(F) ISO 7045 M35x06 L12 2	Base assembly #/Base cover cap
Door mirror/(F) ISO 7045 M35x06 L12 3	Base assembly #/Base cover cap

Base assembly

Base assembly #/(F) ISO 4017 M8x125 L35	Base assembly #/Base cover
Base assembly #/Base	Gasket assembly #/Gasket

Powerpark unit

Engine big assembly #/PCB	Powerpark unit #/PPU housing 3
Engine big assembly #/(F) Clip CC engine big	Powerpark unit #/PPU housing 3
Powerpark unit #/(F) Washer	Powerpark unit #/PPU housing 2
Powerpark unit #/Endless double	Powerpark unit #/PPU housing 2
Powerpark unit #/Plastic gear	Powerpark unit #/PPU housing 2
Powerpark unit #/Axis locator 2	Powerpark unit #/PPU housing 2
Powerpark unit #/Axis locator 1	Powerpark unit #/PPU housing 2
Powerpark unit #/Metal gear 2	Powerpark unit #/PPU housing 2
Powerpark unit #/Metal gear 1	Powerpark unit #/PPU housing 2
Powerpark unit #/Spring	Powerpark unit #/(F) Washer
Powerpark unit #/Metal gear big	Powerpark unit #/Spring
Powerpark unit #/Tower	Powerpark unit #/Metal gear big

Mirror assembly

Mirror assembly #/(F) ISO 7045 M35x06 L30 1	Glass asm (mirror) #/Backplate (mirror)
Mirror assembly #/(F) ISO 7045 M35x06 L30 2	Glass asm (mirror) #/Backplate (mirror)
Mirror assembly #/(F) ISO 7045 M35x06 L30 3	Glass asm (mirror) #/Backplate (mirror)
Pivot unit #/Pivot	Glass asm (mirror) #/Backplate (mirror)
Pivot unit #/Beam	Glass asm (mirror) #/Backplate (mirror)
Pivot unit #/Lid pivot unit	Mirror assembly #/(F) ISO 7045 M35x06 L30 1
Pivot unit #/Lid pivot unit	Mirror assembly #/(F) ISO 7045 M35x06 L30 2
Pivot unit #/Lid pivot unit	Mirror assembly #/(F) ISO 7045 M35x06 L30 3
Mirror assembly #/Structure (Met Str)	Pivot unit #/Pivot
Powerpark unit #/PPU housing 1	Mirror assembly #/Structure (Met Str)
Powerpark unit #/PPU housing 2	Mirror assembly #/Structure (Met Str)
Powerpark unit #/PPU housing 3	Mirror assembly #/Structure (Met Str)
Housing #/Backcan	Glass asm (mirror) #/Backplate (mirror)
Powerpark unit #/PPU housing 1	Bolt M35x06 1 #/(F) ISO 7045 M35x06 L45
Powerpark unit #/PPU housing 1	Bolt M35x06 2 #/(F) ISO 7045 M35x06 L45
Powerpark unit #/PPU housing 2	Bolt M35x06 2 #/(F) ISO 7045 M35x06 L45
Powerpark unit #/PPU housing 2	Bolt M35x06 1 #/(F) ISO 7045 M35x06 L45
Powerpark unit #/PPU housing 3	Bolt M35x06 1 #/(F) ISO 7045 M35x06 L45
Powerpark unit #/PPU housing 3	Bolt M35x06 2 #/(F) ISO 7045 M35x06 L45
Bolt M35x06 1 #/(F) ISO 7045 M35x06 L45	Glass asm (mirror) #/Backplate (mirror)
Bolt M35x06 2 #/(F) ISO 7045 M35x06 L45	Glass asm (mirror) #/Backplate (mirror)

Pivot unit

Pivot unit #/Link CC engines	Pivot unit #/Beam
Pivot unit #/Small engine 1	Pivot unit #/Link CC engines
Pivot unit #/Small engine 2	Pivot unit #/Link CC engines
Pivot unit #/Reductor 1	Pivot unit #/Link CC engines
Pivot unit #/Reductor 2	Pivot unit #/Link CC engines
Pivot unit #/Rack 1	Pivot unit #/Reductor 1
Pivot unit #/Rack 2	Pivot unit #/Reductor 2
Pivot unit #/Link CC engines	Pivot unit #/(F) Rivet L1 3
Pivot unit #/Link CC engines	Pivot unit #/(F) Rivet L18 2
Pivot unit #/Link CC engines	Pivot unit #/(F) Rivet L18 1

Housing

None

Glass ass (mirror)

Glass asm (mirror) #/Resistance (mirror)	Glass asm (mirror) #/Glass (mirror)

Engine big assembly

Engine big assembly #/CC engine big	Engine big assembly #/(F) Clip CC engine big
Engine big assembly #/Endless	Engine big assembly #/CC engine big

Gasket assembly

None

Appendix 4

This appendix shows the disassembly process plans created by the DFE Workbench on the Jaguar mirror.

Door mirror

Base assembly (subassembly)

Removal Time (sec):	39
Disassembly Route:	Base assembly

Mirror assembly (subassembly)

Removal Time (sec):	334
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Pivot unit /Pivot >> Mirror assembly

(F) ISO 7045 M35x06 L12 1 (component)

Removal Time (sec):	21
Disassembly Route:	Base assembly /Base cover cap >> (F) ISO 7045 M35x06 L12 1

(F) ISO 7045 M35x06 L12 2 (component)

Removal Time (sec):	21
Disassembly Route:	Base assembly /Base cover cap >> (F) ISO 7045 M35x06 L12 2

(F) ISO 7045 M35x06 L12 3 (component)

Removal Time (sec):	21
Disassembly Route:	Base assembly /Base cover cap >> (F) ISO 7045 M35x06 L12 3

Base assembly

Gasket assembly (subassembly)

Removal Time (sec):	7
Disassembly Route:	Gasket assembly

(F) ISO 4017 M8x125 L35 (component)

Removal Time (sec):	48
Disassembly Route:	Base assembly /Base cover >> (F) ISO 4017 M8x125 L35

Base (component)

Removal Time (sec):	41
Disassembly Route:	Gasket assembly /Gasket >> Base

Base cover (component)

Removal Time (sec):	48
Disassembly Route:	Base cover

Base cover cap (component)

Removal Time (sec):	21
Disassembly Route:	Base cover cap

Mirror assembly

Bolt M35x06 1 (subassembly)

Removal Time (sec):	189
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Bolt M35x06 1

Bolt M35x06 2 (subassembly)

Removal Time (sec):	189
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Bolt M35x06 2

Glass asm (mirror) (subassembly)

Removal Time (sec):	14
Disassembly Route:	Glass asm (mirror)

Housing (subassembly)

Removal Time (sec):	225
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Housing

Pivot unit (subassembly)

Removal Time (sec):	228
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Mirror assembly /(F) ISO 7045 M35x06 L30 3 >> Mirror assembly /(F) ISO 7045 M35x06 L30 2 >> Mirror assembly /(F) ISO 7045 M35x06 L30 1>> Pivot unit

Powerpark unit (subassembly)

Removal Time (sec):	364
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Pivot unit /Pivot >> Mirror assembly /Structure (Met Str) >> Bolt M35x06 2 /(F) ISO 7045 M35x06 L45 >> Bolt M35x06 1 /(F) ISO 7045 M35x06 L45>> Powerpark unit

(F) ISO 7045 M35x06 L30 1 (component)

Removal Time (sec):	189
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> (F) ISO 7045 M35x06 L30 1

(F) ISO 7045 M35x06 L30 2 (component)

Removal Time (sec):	189
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> (F) ISO 7045 M35x06 L30 2

(F) ISO 7045 M35x06 L30 3 (component)

Removal Time (sec):	189
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> (F) ISO 7045 M35x06 L30 3

Structure (Met Str) (component)

Removal Time (sec):	338
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Pivot unit /Pivot >> Structure (Met Str)

Powerpark unit

Engine big (subassemb)

Removal Time (sec): 0
Disassembly Route: Engine big assembly

(F) Washer (component)

Removal Time (sec): 0
Disassembly Route: (F) Washer

Axis locator 1 (comp)

Removal Time (sec): 0
Disassembly Route: Axis locator 1

Axis locator 2 (comp)

Removal Time (sec): 0
Disassembly Route: Axis locator 2

Endless double (comp)

Removal Time (sec): 0
Disassembly Route: Endless double

Metal gear 1 (comp)

Removal Time (sec): 0
Disassembly Route: Metal gear 1

Metal gear 2 (comp)

Removal Time (sec): 0
Disassembly Route: Metal gear 2

Metal gear big (comp)

Removal Time (sec): 0
Disassembly Route: Metal gear big

PPU housing 1 (comp)

Removal Time (sec): 426
Disassembly Route: Glass asm (mirror) /Backplate (mirror) >> Pivot unit /Pivot >> Mirror assembly /Structure (Met Str) >> Bolt M35x06 2 /(F) ISO 7045 M35x06 L45 >> Bolt M35x06 1 /(F) ISO 7045 M35x06 L45>> PPU housing 1

PPU housing 2 (comp)

Removal Time (sec): 474
Disassembly Route: Glass asm (mirror) /Backplate (mirror) >> Pivot unit /Pivot >> Mirror assembly /Structure (Met Str) >> Bolt M35x06 2 /(F) ISO 7045 M35x06 L45 >> Bolt M35x06 1 /(F) ISO 7045 M35x06 L45>> PPU housing 2

PPU housing 3 (comp)

Removal Time (sec): 392
Disassembly Route: Glass asm (mirror) /Backplate (mirror) >> Pivot unit /Pivot >> Mirror assembly /Structure (Met Str) >> Bolt M35x06 2 /(F) ISO 7045 M35x06 L45 >> Bolt M35x06 1 /(F) ISO 7045 M35x06 L45>> PPU housing 3

Plastic gear (comp)

Removal Time (sec): 0
Disassembly Route: Plastic gear

Spring (component)

Removal Time (sec): 0
Disassembly Route: Spring

Tower (component)
Removal Time (sec): 0
Disassembly Route: Tower

Pivot unit

(F) Rivet L13 (comp)
Removal Time (sec): 0
Disassembly Route: (F) Rivet L13

(F) Rivet L18 1 (comp)
Removal Time (sec): 0
Disassembly Route: (F) Rivet L18 1

(F) Rivet L18 2 (comp)
Removal Time (sec): 0
Disassembly Route: (F) Rivet L18 2

Base pivot unit (comp)
Removal Time (sec): 60
Disassembly Route: Base pivot unit

Beam (component)
Removal Time (sec): 196
Disassembly Route: Glass asm (mirror) /Backplate (mirror) >> Beam

Lid pivot unit (comp)
Removal Time (sec): 203
Disassembly Route: Glass asm (mirror) /Backplate (mirror) >> Mirror assembly /(F) ISO 7045 M35x06 L30 3 >> Mirror assembly /(F) ISO 7045 M35x06 L30 2 >> Mirror assembly /(F) ISO 7045 M35x06 L30 1>> Lid pivot unit

Link CC engines (comp)
Removal Time (sec): 217
Disassembly Route: Glass asm (mirror) /Backplate (mirror) >> Pivot unit /Beam >> Pivot unit /(F) Rivet L18 2 >>Pivot unit /(F) Rivet L18 1 >> Pivot unit /(F) Rivet L13 >> Link CC engines

Pivot (component)
Removal Time (sec): 203
Disassembly Route: Glass asm (mirror) /Backplate (mirror) >> Pivot

Rack 1 (component)
Removal Time (sec): 233
Disassembly Route: Glass asm (mirror) /Backplate (mirror) >> Pivot unit /Beam >> Pivot unit /(F) Rivet L18 2 >> Pivot unit /(F) Rivet L18 1 >> Pivot unit /(F) Rivet L13 >> Pivot unit /Link CC engines >>Pivot unit /Reductor 1 >> Rack 1

Rack 2 (component)
Removal Time (sec): 233
Disassembly Route: Glass asm (mirror) /Backplate (mirror) >> Pivot unit /Beam >> Pivot unit /(F) Rivet L18 2 >> Pivot unit /(F) Rivet L18 1 >> Pivot unit /(F) Rivet L13 >> Pivot unit /Link CC engines >>Pivot unit /Reductor 2 >> Rack 2

Reductor 1 (component)
Removal Time (sec): 226
Disassembly Route: Glass asm (mirror) /Backplate (mirror) >> Pivot unit /Beam >> Pivot unit /(F) Rivet L18 2 >> Pivot unit /(F) Rivet L18 1 >> Pivot unit /(F) Rivet L13 >> Pivot unit /Link CC engines >>Reductor 1

Reductor 2 (component)	
Removal Time (sec):	226
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Pivot unit /Beam >> Pivot unit /(F) Rivet L18 2 >> Pivot unit /(F) Rivet L18 1 >> Pivot unit /(F) Rivet L13 >> Pivot unit /Link CC engines >>Reductor 2
Small engine 1 (comp)	
Removal Time (sec):	221
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Pivot unit /Beam >> Pivot unit /(F) Rivet L18 2 >> Pivot unit /(F) Rivet L18 1 >> Pivot unit /(F) Rivet L13 >> Pivot unit /Link CC engines >>Small engine 1
Small engine 2 (comp)	
Removal Time (sec):	221
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Pivot unit /Beam >> Pivot unit /(F) Rivet L18 2 >> Pivot unit /(F) Rivet L18 1 >> Pivot unit /(F) Rivet L13 >> Pivot unit /Link CC engines >>Small engine 2

Housing

Backcan (component)	
Removal Time (sec):	217
Disassembly Route:	Glass asm (mirror) /Backplate (mirror) >> Backcan
Case bezel (component)	
Removal Time (sec):	42
Disassembly Route:	Case bezel

Glass asm

Backplate (component)	
Removal Time (sec):	175
Disassembly Route:	Backplate (mirror)
Glass (mirror) (comp)	
Removal Time (sec):	203
Disassembly Route:	Glass (mirror)
Resistance (mirror) (component)	
Removal Time (sec):	203
Disassembly Route:	Glass asm (mirror) /Glass (mirror) >> Resistance (mirror)

Engine big asm

(F) Clip CC engine big (component)

Removal Time (sec):	0
Disassembly Route:	(F) Clip CC engine big

CC engine big (comp)

Removal Time (sec):	14
Disassembly Route:	Engine big assembly/(F) Clip CC engine big >> CC engine big

Endless (component)

Removal Time (sec):	14
Disassembly Route:	Engine big assembly/(F) Clip CC engine big >> Engine big assembly/CC engine big >> Endless

PCB (component)

Removal Time (sec):	7
Disassembly Route:	PCB

Gasket assembly

Gasket (component)

Removal Time (sec):	7
Disassembly Route:	Gasket

Gasket foam (component)

Removal Time (sec):	7
Disassembly Route:	Gasket foam