DOCTOR OF PHILOSOPHY

Methodology for the Integration of Economic, Environmental and Functional Issues in Complex Product Design

Grote, Claus Arno

Award date:
2008

Awarding institution:
Coventry University

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by Claus A. Grote

April 2008

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CLAUS A. GROTE

**A thesis submitted in partial fulfilment
of the University`s requirements
for the degree of Doctor of Philosophy**

April 2008

Coventry University in collaboration with Caterpillar U.K. Ltd.

Für meine Familie, die mich immer unterstützt hat und ohne die dieser PhD nicht möglich gewesen wäre

Acknowledgements

I would like to express my gratitude to the following people that were involved in this project in various different ways:

- Dr. Ray Jones for his continuous helpful input and advice during the course of this research
- Prof. Gordon Blount for his support, ideas and extensive knowledge benefiting the project
- Dr Jane Goodyer for her constant support and guidance even after moving to New Zealand
- Ella Jobson at Caterpillar U.K. for her input to the project and for making the information required from Caterpillar easily available
- Anybody else at Caterpillar U.K. who was involved in the project especially Emma Peek, Ed Coombs and Iain J. Chambers
- My colleagues at Eco3 Ltd. – Mark Shayler, Leigh Holloway, Oliver Jenkins, Claire Corbett and all the others. They supported me in so many different ways so thanks.
- Geraint Williams at the International Automotive Research Centre in Warwick
- And most of all my parents Arno and Gertraud who supported me continuously. Without them I could not have achieved this.
- Furthermore I would like to thank my sister Christiane and her husband Michael for their moral support and for being there for me.

Abstract

This research evaluates the problems that design engineers face when trying to include environmental issues in product design without jeopardizing other design issues. A thorough review of current literature, tools and methodologies on the topic is given whilst their gaps and shortcomings are revealed and the need for a new methodology is formulated. This sets the starting point for the research and the development carried out during this research.

A methodology is proposed in this thesis that helps manufacturers of complex products apply the Eco-Design principle and the whole life cycle approach without compromising the economic performance of their products. On one hand the primary objective outlined for the methodology is to include three different issues in product design: economic impact, environmental impact and functional issues whilst avoiding a trade-off. On the other hand, since the methodology is applicable to complex products, the secondary objective is to align and integrate two separate issues: alignment of the design process progress and the product hierarchy. In order to achieve those objectives existing design tools, such as the TRIZ (Theory of Inventive Problem Solving) matrix and the DfX (Design for X) method, are integrated.

Furthermore a computer support tool in the form of a user interface is developed that is based on the theoretical framework of the methodology. This user interface allows for a quick analysis of a product and the production of design suggestions in order to enhance the product characteristics.

The validation of the research is presented through examples and the application of case studies of different products. This case study approach helps to develop and apply findings during the methodology development and validate the functionality and flexibility of the proposed methodology.

Areas of future work which can help increase the knowledge base, scope and applicability of the work carried out are identified.

Table of Content

List of Figures

Glossary of Terms

Downcycling: Downcycling is the recycling of a material into a material of lesser quality.

Design for Environment (DFE): The process of considering all the possible environmental implications of a product or system using the principles of concurrent engineering.

Design for X (DFX): Design for X covers a wide array of specific design guidelines. Each design guideline addresses a particular issue that is either caused by or effects the characteristics of a product.

Eco-Indicators: This is a method of assigning an environmental impact to a material, product or system. Eco- indicators may be a single overall figure or may be presented as a number of separate elements.

Environmental Impact Assessment (EIA): A technique used for identifying the environmental effects of a product or a project.

Life-Cycle Assessment (LCA): To conduct an LCA requires the user to make detailed measurements or predictions for the financial or environmental impact of a product during all its life cycle stages, from the mining of the raw materials used in its production and distribution, through to its use, possible re-use or recycling, and its eventual disposal.

OEM (Original Equipment Manufacturer): An OEM is responsible for the design and manufacture of a product.

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

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

1. Introduction

During the early nineties sustainability and the Life Cycle Concept was proposed as one of many solutions for various problems such as a growing world population and a change in the industrial culture to come: ‘This new industrial culture is primarily driven by rapidly increasing problems concerning environmental damage, huge amounts of waste, occupational health damage and increasing use of non-renewable resources’ [AJ93]. As a result of these developments legislative pressure is forcing companies to re-evaluate the environmental performance of their products. Various legislations for specific product groups have been issued by the European Union (EU) to reduce the environmental impact of products. This has put a lot of pressure on companies to comply with these new regulations and still keep up their global competitiveness but only if an integrated sustainable approach can help companies function in a more efficient way without destroying the basis they depend on as for example raw materials. Sustainability means that a company can continue to exist without a depletion of the inflow (such as material) and without affecting the market and the stakeholders to an extent that would end the demand for the product or service after a period of time.

As shown in figure 1.1 the world population will further grow over the course of the next 40 years. More products and services will be required to satisfy the market needs. This makes a sustainable approach even more important.

Fig 1.1 has been removed due to third party copyright. The unabridged version of the thesis can be viewed at the Lanchester Library, Coventry University

Figure 1.1: World population size: past estimates and medium-, high- and low-fertility variants, 1950 – 2050 [UNI98]

The “Eco-Design of Energy using Product Directive” (EuP) [EUR05a] recently emerged as a legislative development of the “Integrated Product Policy” (IPP) [COM03]. It is a principle that is supposed to force companies to produce more sustainable and environmentally friendly products or services based on the Life-Cycle approach. In order to apply this principle complications arise from the trade-off with other design issues such as costs and from lack of knowledge of how to apply Eco-Design by the design engineer. These complications are especially apparent in the case of a complex product due to the fact that the product structure & product hierarchy needs to be considered in addition to the life-cycle issue. Furthermore complex products result in longer design phases (compared to simple products) hence a methodology is required that can be applied during all the various design stages of product design.

The aim of the methodology described in the thesis is an incorporation of the Eco-Design principle and economic issues covering the whole life-cycle of various complex products. Even though the various parameters used for this methodology are similar to the Eco-Design parameters from the EuP directive the favoured outcome is a methodology applicable to all complex products supporting compliance with current and future legislation. As a result of the process the environmental and economic impact should be lowered.

1.1 Background

Since various current methodologies focus on different steps within the life cycle of a product it is possible that a shift of the environmental impact might occur from one life cycle stage to another. Thus the overall environmental performance of a product is not enhanced but the impact is just shifted. Eco-Design is a design methodology that avoids a life cycle stage impact shifting. Eco-Design is the enhancement of the environmental performance of a product concentrating on the product design process only not taking into account the business management aspect. Furthermore it is nothing more than intelligent design with a focus on environmental impact reduction and efficiency improvement moving from process efficiency and process regulation towards product efficiency and product regulation through its lifetime.

The biggest potential to enhance a product's environmental performance over its whole life cycle is during its development and design process. Sophisticated design support tools and methodologies such as: Design for Assembly (DfA), Design for Disassembly (DfD), Design for Environment (DfE), Product Life Cycle Management (PLM) are already in existence. The main problem is that they are not easy to apply for the design engineer due to the fact that environmental knowledge is required as stated by Sun et al [SHE03].

Nowadays the environmental impact is another aspect during the development and design stage on top of issues such as quality, costs, customer satisfaction and functionality. Dealing with the environmental design issues on top of current design issues can cause severe problems for the design engineer in terms of trade-offs. The design engineer is faced with additional tasks and requirements and consequently has a tremendous amount of different complex criteria to consider as stated by Rebitzer [RFL+00].

The research described in this thesis focuses on the development of a method to help with the design decision process, gain more control of how a design creates an impact on the environment and use existing principles and tools to aid continuous product improvement. In this regard it does not make sense to focus on environmental issues only. The triple bottom line [GRE04] concept links the financial, the environmental and the social effects of a product. All three must be kept in mind since they affect each other.

Using this concept it would not make sense to decrease a products' environmental impact whilst its costs are increasing immensely. Although this research focuses on Industrial Engineering Design and rather large and complex products, the proposed methodology is applicable to various different kinds of products with little modification. The Eco-Design methodology developed in the course of this research is validated using three different case studies. The validation process was started using a very simple case study and then moved on to a more complex subject. The outcome of these case studies is presented in chapter 6.

1.2 Current situation for manufacturers and shift in legislation

Currently European manufacturers have to deal with an increase of competition from industrial emerging countries due to globalization. The increase of competition in the market is naturally strongly linked to the type of product but an increase in market pressure is a fact for most product groups. This has a bigger impact on SMEs (small to medium-sized enterprises) than on the global players. This is due to the fact that large companies and globally organized companies are in a position to outsource their operations more easily to countries with low production costs. Nonetheless most manufacturers within the European Union are affected by this. This effect of globalization on European manufacturers started as a result of the end of the cold war beginning in the 1990s and is currently being felt by companies in various industrial sectors.

At about the same time in the early nineties environmental issues were becoming more and more important on a global scale. Especially within the European Union an increase in the pressure for sustainable solutions and products is growing. Various directives have been issued by the European Union with the goal of a more sustainable market and to reduce the environmental burden.

These legislations focus on different product types specifically such as the "Waste of electrical and electronic equipment" (WEEE) directive and the

“Restriction of hazardous substances” (RoHS) directive which both concentrate on the electronic and electrical product segment. A Directive that has a focal point on the automotive sector is the “End-of Life” (ELV) vehicle directive. Furthermore there is the “Eco-Design of energy using Product” (EuP) directive – a recently emerged directive that applies to the product design phase explicitly by making an Eco-Design approach mandatory.

All of these directives fall under the wider umbrella of the “Integrated Product Policy” (IPP) which is more of a philosophy than a strict directive and still under development. The Integrated Product Policy (IPP) seeks to minimize the environmental impact of a product by looking at all Life Cycle Stages of it and taking action where appropriate. Hence the IPP serves more as a guideline and gives companies ideas how to reduce the environmental impact of their products. The more specific directives such as WEEE, RoHS, ELV or even the EuP set very specific restrictions on the following issues:

- Restricted use of some raw materials and substances (toxicity)
- End-of Life treatment specification
- Restrictions of energy use
- Application of Eco-Design measures

This has put a lot of pressure on companies to comply with these new regulations and still keep up their competitiveness. It can be a very difficult task for companies to comply with such environmental legislation and keep up their global competitiveness and profitability.

On the other hand the sustainable approach can help companies at a very well-organized level without destroying their very basis of existence. Sustainability means that a company or party can exist infinitely without risking running out of goods they require to function. Furthermore the market and the stakeholders are a key consideration since they either finance or are directly influenced by decisions. Another good advocating factor in favour of a sustainable approach is the symbiosis of financial and environmental product performance improvement.

1.3 Applying Eco-Design – challenges and opportunities

The application of the Eco-Design principle can be a difficult task for the design engineer. How difficult the task is depends highly on the complexity of the product, availability of information and level of proficiency of the design procedure. The earlier that measures are taken during the design process the bigger the impact and the lower the cost as stated by Rebitzer [RF00]. Thus it is sensible to embed the Eco-Design principle into the very early product design phases like conceptual design.

One of the biggest problems for the design engineer nowadays is not only that he has to deal with various design issues e.g. costs, reliability, quality, environmental impact as described before but due to the nature of the product and the design process the following issues need to be taken into account as well: Life Cycle Assessment and the Product Hierarchy.

All three of these issues combined help the design engineer to identify the area with the biggest impacts and the greatest potential for improvement.

To give an example based on an automotive product:

In case that the design engineer chooses to investigate the costs linked to the automotive product and then wants to identify which components cause the major contribution and during which Life Cycle stage. A possible answer could be that the Life Cycle Stage with the biggest impact is the use phase and the component that contributes the biggest cost impact is the chassis due to its high weight and hence bigger contribution to the fuel consumption of the complete component. This impact is based on direct and environmental cost total combined.

Opportunities from applying the Eco-Design principle are not only a reduction of the environmental impact. Indeed the economic product performance should play a key role. This is by necessity a pragmatic approach that has to address the cost issue [LG01]. Further opportunities are the creation of greener markets for the product, improve the reputation of the company and just adding another positive selling argument to convince potential buyers.

So the challenge is to integrate the Eco-Design principle into the current design process whilst keeping all the other issues in mind too. This can be quite demanding especially for small to medium-sized enterprises. For the short term strategy of a company it means additional costs and additional manpower which must be allocated to integrate this principle into a company's product design procedures. While large companies can afford to consider these measures for the benefits of their long term performance, the situation is different for SMEs. This is due to higher competitive and customer pressures and a smaller labour-force. SMEs cannot afford in-house solutions for this problem and that is why they would benefit from a toolkit that can be easily applied. However in terms of the long term strategy it can mean reduced costs, more efficient design complementing lean manufacturing and giving a competitive edge in new markets.

1.4 Problem definition

So the problem for the design engineer with the emerging legislation on Eco-Design is how to integrate it into the current design process.

As discussed in the preceding sections the environmental impact is just one of many design issues. Various sources suggest that the long term market acceptance and thus the success of a product depends on three major factors which are directly linked to the sustainability concept: environmental sustainability, financial sustainability and social sustainability [GRE04] [WND01] [GJB06] [VBB02]. The financial sustainability performance can be measured and benchmarked by using direct costs. The environmental sustainability can be benchmarked by the use of Eco-indicators and further figures such as emissions. However the social sustainability is very difficult to measure and relate to the financial and environmental aspects.

Furthermore the trade-off of certain design measures regarding their impact on costs and the environmental impact needs to be considered. It would not make sense to reduce the environmental impact whilst the product costs go up immensely. This would result in a loss of competitiveness and profit for the producer and finally mean that the product fails in the market. For this reason an integrated approach is required that combines the environmental and financial product performances. Measures taken to alter the product design need to reduce both the financial and the environmental impact during the whole life cycle of the product.

On the topic of the Whole Life Cycle (WLC) of the product, manufacturers might argue that they will only benefit from a reduced financial and environmental impact during the manufacturing stage. But there are two major reasons why this argument is flawed and will soon be outdated. On the one hand recent legislation such as the WEEE and the ELV Directive regarding the End-of Life phase within the European Union is forcing manufacturers to get involved with their products at all Life Cycle Stages. In these two cases the manufacturer has to carry the financial burden of the product at its End-of Life. On the other hand a shift in the marketing strategy of many product sectors occurred over the past few years. This shift is that many producers move away from simply offering a product that is for sale to a service that is being rented. A good example for this is the automobile. In the past most customers wanted to "own" the product and simply paid the sale price. Re-occuring costs for the customer are a result of servicing. At present the market is shifting away from this model and moves towards the service for rent option. This usually is a form of leasing of the desired vehicle. The customer does not have to pay the full product price or for servicing of the vehicle. He merely pays a yearly fee and "rents" the product on a yearly basis. Due to this shift in the market approach the producer stays the owner of the product with full control over all product life cycle stages. Hence a reduced financial and environmental impact benefits the producer without regard to the specific life cycle stage. But even if the manufacturer simply sells a product a reduction of financial or environmental impact during any other life cycle stage will still be an advantage. For example a reduced financial and environmental impact during the use phase of a product can make the product more attractive to customers due to reduced running costs or the creation of greener markets.

Apart from the trade-off problem between financial and environmental impacts of the product, current design tools lack the smart application of existing product design enhancement tools. Hence no intuitive design methodology is applied but the product design problem is only patched up leading to a trade-off patchwork instead of producing an inventive solution.

Another shortcoming of many current design tools and software based design tools is that they are only intended to be applicable at a fairly advanced stage of the design process as it is explained in further detail in section 2.7. This might be feasible in the case of simple products but for rather complex products this approach is not possible due to time constraints and it is preferable that a tool can be applied from the very early design stages. Even though various tools exist that take the product structure and hierarchy into account they do not use an integrated approach. Meaning that they do not include all of the three following simultaneously: economic, functional and environmental issues.

1.5 Objective and scope of research

The objective of the proposed research is the development of a methodology to help the design engineer apply the Eco-Design principle for complex products without jeopardizing the cost efficiency. Hence within the methodology the environmental and financial impacts of the product are to be taken into account. To show the functions and principles of the methodology a simple software based user interface is proposed.

Current literature, which is evaluated in more detail in section 2, suggest that a toolkit is required that evaluates a product on the basis of environmental costs and identifies possibilities of improving the economic and environmental behavior of a product during its life cycle [GFS98]. Moreover the methodology has to identify areas with the greatest impact and biggest potential for improvement and then generate design enhancement suggestions that can easily be applied by the product design engineer. A continuous product improvement is the result of this with a lower environmental impact of the product and a better competitiveness due to lower costs.

Additionally, products require any methodology to integrate the product-structure and product-hierarchy, otherwise the trade-off and effects of a design decision become too difficult and time extensive to handle and weigh against each other. The following product and component design properties should be covered by such a methodology whilst all the life cycle stages are considered as well:

1. Characteristics of the product as a whole
2. Functional units of the components
3. Material used and component size
4. Resource use during the whole life-cycle of the product

So to summarize: main focus is to combine the environmental and economic considerations during the design of complex products. In order to achieve this functionality needs to be taken into account in order to create components with a lower impact by increasing their functional efficiency. As stated before the methodology should be applicable in a manner that aligns the progress of the design process. This is possible for the complex product situation by streamlining the product hierarchy and the design progress.

2. Literature Review

2.1 Introduction to chapter 2

This chapter reviews the current literature in the field of Eco-Design, sustainable development and Life Cycle Assessment – basically methods and theories used to reduce the environmental impact of a product. A look at the theoretical background of these methods is provided as well as the current situation of related legislation within the EU that is driving the need for a more sustainable product design process. This review covers the following topics: Sustainability, Life Cycle Assessment (LCA), legislative issues, Life Cycle Costing, the Design Process in general and current best practice.

Since a vast amount of literature has been published on these topics within the last 10 to 15 years this literature review represents a selection of the pieces of literature that have a direct effect on the development of the Eco-Design methodology presented in this thesis. The information presented within this literature review does not claim to give a complete overview of all literature available on the topics of Eco-Design or sustainability but only the ones relevant to the research carried out. This was possible by selecting the pieces of literature that appeared to be most relevant for the research.

Furthermore all the existing tools and methods that were adopted in this methodology are reviewed and explained in detail on how they were integrated. Not all methods and tools described in this chapter are used within the methodology though but they were considered during the course of the research. Some of the tools and the concepts behind them are used to help with the idea generation process and the actual methodology development process.

2.2 Legislation

During the last three decades environmental concerns have gained more and more importance in public discussion. Within the legislative process of the EU about 10 years ago these environmental concerns started to be manifest in the form of specific legislation. Since the methodology developed during this research is mainly based on the EuP directive and the IPP directive these are discussed in greater detail whilst other related legislation is discussed more briefly. The methodology is based on those two directives since the IPP is the main framework regarding environmental aspects in products design and the EuP directive, as a result if the IPP, deals with the Eco-Design principle specifically.

2.2.1 The "Eco-Design of energy using products" (EuP) directive - 2005/32/EC

In 2003 the EuP emerged as the first directive with a focus on Eco-Design. The EuP directive has its origin within the IPP directive since non-strategy blueprints exist and the key principle is the improvement of the environmental performance of a product throughout its life-cycle by systematically integrating environmental aspects at the earliest stage of its design [EUR05b]. Moreover the EuP is based on the Life Cycle Assessment principle which is sometimes referred to as the "cradle to grave" approach. The LCA principle considers the environmental or economic impact of a product in all its Life Cycle stages and hence avoids a shifting of them from one stage to another [GFS98]. The Life Cycle stages of a product include, as stated within the EuP Directive [EUR05c]:

1. Raw Material Extraction
2. Manufacturing
3. Packaging, Transport and Distribution
4. Installation and Maintenance
5. Use
6. Disposal

The EuP is a framework for setting Eco-Design requirements for "energy using products" and provides a set of requirements which must be considered during product design and before the products can be placed on the market [DEF06].

It defines which energy using products are covered: In principle – “*any* energy using products except for means of transport of people or goods” [EUR05c]. To be more specific: ‘A product which, once placed on the market and/or put into service, is dependent on energy input (electricity, fossil fuels and renewable energy sources) to work as intended’ [ECO06a]. So far within the development of the EuP 14 product groups have been identified by the European Commission as a focus for the next steps of the EuP, such as a feasibility evaluation based on case studies. Currently a lot of work has been carried out by the European Commission on boilers and water heaters. This is stated in the preparatory studies [BRO06a]: e.g. Boilers, Water Heaters, Personal Computers, etc. These product groups can broadly be covered by five areas: Heating, lighting, consumer electronics, white goods and motors. There are no immediate obligations for manufacturers yet but the EuP will enable detailed implementing measures to be brought forward for specific products over time. Figure 2.1 gives a timeline of past, current and future events regarding the EuP Directive. It starts with the proposal for the EuP in 2003 through the adoption by the council in 2005 and finally the proposed development of Eco-Design requirements from 2008 until 2010.

Date	Event
August 2003	Original EuP proposal tabled by EC
June 2004	Member States agreement on text
April 2005	Agreement with European Parliament
June 2005	Adoption by the Council
July 2005	EuP Directive (2005/32/EC) published
August 2005	Entry into force in EU
End of 2006	Creation of Consultation Forum
Q1 2007	1st meeting of Consultation Forum
Q2/Q3 2007	1st meeting of Regulatory Committee:
July 2007	Adoption of EuP Working Plan
2007 -2009	Planning for the adoption of Eco-Design implementing measures for 14 product groups including: - Public Street Lighting - Battery Chargers - Computers - Televisions - Office Lighting - And various other product groups
2008	First implementing measures
2008 - 2010	Eco-Design requirements to be developed for: – Solid fuel boilers – Laundry driers – Industrial air compressors – Electric heating appliances (incl. heat pumps) – Domestic or industrial lighting – Set top boxes – Vacuum cleaners

<u>Figure 2.1:</u> Timeline of the EuP legislation development

2.2.2 The “ Integrated Product Policy” (IPP) - COM(2003) 302 final

As stated in section 1.2 the IPP is still under development and the closest thing to a directive is the “Communication from the Commission to the Council and the European Parliament” [COM03]. The Integrated Product Policy (IPP) seeks to minimize the environmental impact of a product by looking at all life cycle stages of it and taking action where appropriate. In 1998 the European Commission held a workshop on IPP trying to identify “definitions, objectives and priorities” of the IPP [EUR98]. The workshop was followed by two studies, carried out on behalf of the Directorate-General of the Environment of the European Commission by Ernst & Young. The studies were intended to support the decision and development process of what IPP should exactly be and how it should be implemented. During those studies it became apparent that the IPP should be taking a life cycle perspective as a basic principle: ‘They [policies] must be concerned with resource efficiency or environmental impacts across more than a single stage of the product life cycle. Ideally they would be concerned with the total life cycle’ [ERN98].”

Whilst the European Commission is still in the process of developing a common European IPP, which is far from being finished, the European Commission issued further studies in 2004 [THS04] to identify products that have the ‘greatest environmental impact from a life cycle perspective’. Further measures that are being taken include a number of expert workshops with the aim of ‘inform[ing] the Commission about particular aspects of IPP to help the Commission in framing its ideas for the forthcoming follow-up Communication on IPP’ [EUR01a].

A study by Rubik [RS02] reviewed and evaluated the development process of the IPP so far and clarified the potential but also the pitfalls of the IPP regarding its goal to enhance the European market in terms of economic and environmental performance.

Date	Event
December 1998	IPP Workshop Brussel European Comission[EUR98]
1996 – 2000	Ernst & Young Study on IPP & reports[ERN98] [ERN00]
February 2001	Green Paper on IPP (COM(2001)68final) [EUR01b]
June 2003	Communication on IPP (COM(2003)302final) [COM03]
June 2004 – 2006	IPP Pilot Projects with Nokia & Carrefour[NOK05] [CFF05]
December 2005	Final Report "Development of Indicators for IPP" [EUR04]
First half 2006	Results of IPP working groups on product information and reporting formats
December 2006	Action plans for greening public procurement by member states
2007	Commission identifies the products with the greatest potential for environmental improvement

Figure 2.2: Timeline of the IPP legislation development

Figure 2.2 displays an evolution timeline of the IPP within the European Union. The IPP is still under development even though some progress has been made by the European Commission in setting principles. The overall aim and guideline of the Integrated Product Policy is to create a more sustainable market with products that cause less environmental impact without causing economic pressure for the companies. With a pragmatic future prospect the Integrated Product Policy could issue obligations for specific products to apply a form of Life-Cycle Assessment [POL05].

2.2.3 Other related legislation

2.2.3.1 "End-of Life Vehicle" (ELV) directive **-** 2000/53/EC

'In 1997, the European Commission adopted a Proposal for a Directive which aims at making vehicle dismantling and recycling more environmentally friendly, sets clear quantified targets for reuse, recycling and recovery of vehicles and their components and pushes producers to manufacture new vehicles also with a view to their recyclability' [EUR05d]. This directive is called the End-of Life Vehicle Directive or ELV. The ELV directive basically promotes recycling of vehicles at their End-of Life stage by setting certain re-use and recovery targets in percentage of total vehicle weight. For example the ‘EU draft on ELV outlined that car manufacturers must re-use or recover 85% [by weight] of ELV [End-of Life Vehicles] by 2006’ [SBJ04]. This is a requirement for all the car manufacturers that sell their products on the European market. Thus during the last couple of years all the manufacturers have been investing a lot of money in order to be prepared and comply with that legislation.

2.2.3.2 “Waste of Electronic and Electrical Equipment” (WEEE) directive - 2002/96/EC

The WEEE directive enforces the recovery and recycling of waste electrical and electronic equipment at the end of their life. Additionally it places a legal and financial responsibility upon producers of electronic and electrical equipment to recover and recycle a proportion of products at the end of their life. This responsibility may be as high as 80% by weight and can be discharged directly or via third parties [ECO06b]. The following aims are the foundation of the WEEE directive [ENV06]:

The first is a reduction of the waste arising from electrical and electronic equipment (EEE).

The producers of EEE are now responsible for the environmental impact of their products especially at the End-of Life stage when they become waste. Via this approach producers are getting more involved in all life cycle stages of their products instead of manufacturing and transportation only.

2.2.3.3 “Restriction of Hazardous Substances” (RoHS) directive - 2002/95/EC

The RoHS Directive was published in January 2003 by the European Commission. It is somewhat complementary to the WEEE Directive described in section 2.2.3.2. Its main purpose is to reduce the environmental effect of toxicity in electrical and electronic equipment [EUR03].

The RoHS Directive stands for "the restriction of the use of certain hazardous substances in electrical and electronic equipment". This Directive bans the placing on the EU market of new electrical and electronic equipment containing more than agreed levels of lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyl (PBB) and polybrominated diphenyl ether (PBDE) flame retardants [NAT06].

2.3 Sustainability

The word sustainability was used for the first time in 1712 by the German forester and mining scientist Hans Carl von Carlowitz in his book Sylvicultura Oeconomica. During the 1970s and 1980s various organizations picked up on the topic of sustainability again under the umbrella of economics.

The Brundtland Commission defined sustainable development as development that ‘meets the needs of the present without compromising the ability of future generations to meet their own needs.’ [UNI87]. This definition is accepted by most governmental bodies in the European Union and has even become a widely-used and accepted international definition of sustainable development. [U.K05] – ‘Globally we are not even meeting the needs of the present let alone considering the needs of future generations. By “we” the author means the western countries and to be more specific its society as a whole. Sustainability means that a process can be carried on indefinitely. The industrial revolution has increased productivity by twohundredfold. What took 200 workers during the mid 18th century could be done in the early 19th century in the same amount of time by a single worker [WAA04]. The growth continued even though not at such a high rate: between 1870 and 1992 the productivity increase per worker was approximately 10-fold based on the GDP (Gross domestic product) per capita on average in the industrial countries according to Broadberry [BRO06b]. This development and the further increase in productivity by the means of further inventions during the 19th and 20th century accelerated industrial growth mostly in the industrial nations. Jay Forester predicted that this growth will come to a halt within the 21st century due to limited natural resources [FOR61]. A recent event in 2004 illustrated and proved that these predictions could be realistic. In this year the raw material prices and to be more specific the steel prices increased due to a higher demand on the Chinese market [HAG04].

2.3.1 The exhaustible raw material problem as a driver for sustainability

So the main goal of future research and developments is to find solutions to replace those finite resources by sustainable solutions. More and more people are feeling the urge to implement further sustainable solutions to safeguard their own quality of life and the welfare of their immediate environment and surroundings. An example of the urgency of sustainable solutions is the event in early 2005 when 131 mayors of large U.S. cities such as New Orleans and Seattle joined the Kyoto Protocol and implemented a number of sustainable measures even though the U.S. government did not at the time [SAN05]. The reason for this was that the mayors had to deal with a lot of costly problems that were due to damage to the environment and similar effects.

2.3.2 Market demand as a driver for sustainability

Another driver for sustainability is market demand created by public environmental awareness [TEU97]: ‘Increased public awareness of environmental issues has led to growing concern with the environmental implications of product designs and processes of manufacturing’ [SRC00]. Companies nowadays set a high value on how their product is being perceived by the public in terms of its environmental impact. This fact can have a substantial impact on how a company presents itself and even to change their name and logo to gain an image change and enhance their public perception [ROW06]. Furthermore it can provide an additional competitive edge for the company if their product is more sustainable than similar products from the competition. An example for such a “new” green market is the Compact Fluorescent Lights (CFL), a light bulb that consumes up to 25% less energy whilst providing the same illumination level [EAR06] or recycled paper which has a bigger share of the paper market than virgin paper [SCO06]. Some parties claim that these solutions are not more environmentally friendly since for example the CFL bulbs contain toxic substances that cause a greater impact at the products EoL but studies have shown that in the long run the overall environmental impact is reduced.

2.3.3 Legislation as a driver for sustainability

A third driver for sustainability is legislation. Especially within the European Union various legislations are coming into place with the goal of creating a more sustainable European market. ‘Since European and national legislation is shifting responsibility for discarded products more and more to the producer, the need for efficient tools to evaluate and improve products with regard to their environmental impact is increasing’ [FMT00] .

However sustainable development is not only an issue on the European level but on the national levels of the EU members as well. In ‘January 1994 the British Government Panel on Sustainable Development was set up to provide independent advice to the Government on strategic sustainable development issues’ [TIC99]. A follow-on project by the British Government ‘launched its new strategy for sustainable development, “Securing The Future”, in conjunction with a Strategic Framework on 7 March, 2005’ [U.K05]. Even on a district level, IPP initiatives are formed [BAV05] to support a sustainable approach to product design.

2.4 Life Cycle Assessment

Life Cycle Assessment (LCA) or Life Cycle Analysis as it is sometimes referred to is a method which quantifies certain values of products and services during their entire life cycle. ‘The LCA methodology has developed over the past two decades, predominantly in Europe but also in the USA and more recently in Asia’ [LG01].

The most common application is in the field of Life Cycle Costing [PSW02] and LCA was adopted as a tool for environmental impact evaluation. Today LCA is a commonly used tool by design engineers to evaluate the environmental impact of a product they intend to design as lined out by Lewis and Gertsakis also [LG01]. “They direct their attention not only at product composition, or at the processing stage that they themselves are involved with, but also at the whole physical life cycle of the product, from raw materials to end-of-life” [HEI02].

The aim of an environmental LCA tool is to "identify possibilities of improving the environmental behaviour of the system that is under consideration" [GFS98].

2.4.1 Life cycle stages of a product

A common basis is formed by the following five stages:

1. Raw Material Extraction
2. Manufacturing
3. Packaging and Transport
4. Use
5. Disposal and End-of Life (EoL)

Variations of these five steps can be found within the EuP directive which consists of six steps [EUR05b]. The different stages are accurately charted, and for each stage an inventory is made of the energy and material consumption and of the emission into the environment. This makes it possible to identify those points or processes where improvement can be achieved at the environmental level.

2.4.2 LCA at the design stage

If the design process stage is considered as part of a product`s Life Cycle then it is certainly the one with the biggest impact on the environmental performance. Figure 2.3 provides a visualisation of how such an integration of the design process into the product`s Life Cycle looks. Basically it shows that the decisions made at the product design process set the product performance for its Whole Life Cycle .

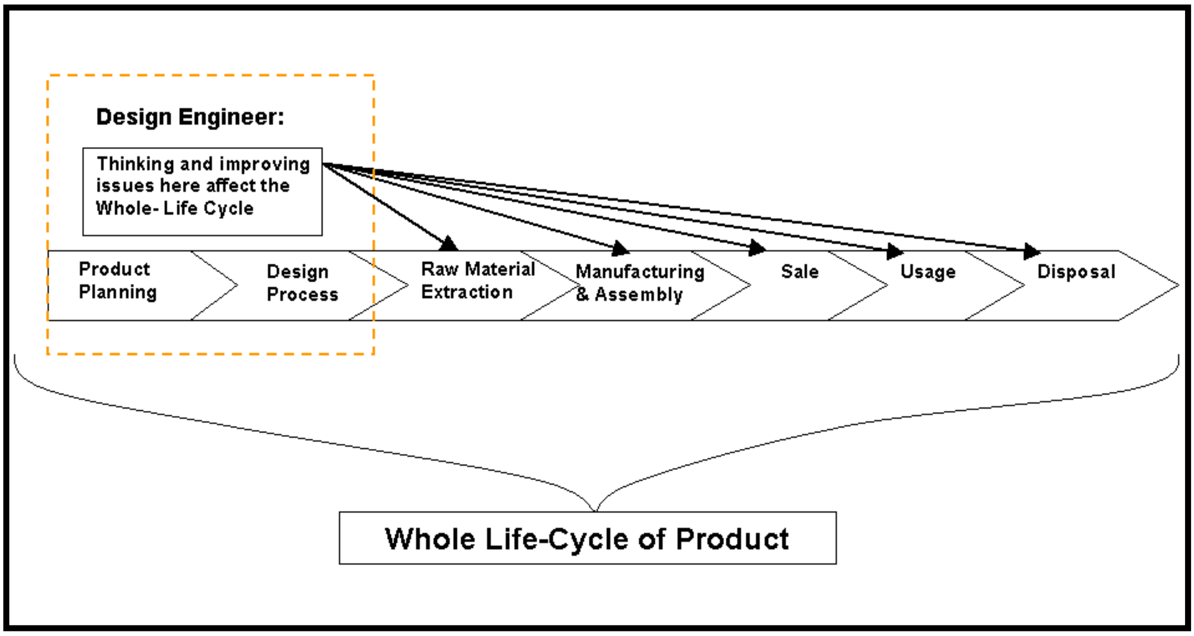


Figure 2.3: Whole Life Cycle of a product including the design process [GRO05]

Sun and Han point out the environmental impact reduction opportunitites of LCA only: 'compared with approaches focusing on one complete product life cycle, an integrated systems approach can provide measures to administrating the environmental effects of using energy, materials, and capital.' [SHE03].

Another class of toolkit which performs an environmental LCA and impact assessment is the "SimaPro" LCA Software [PRE07] and the methods described by Holloway [HOL97]. These tools are very precise in defining the environmental impact of an existing product and can be used for re-designing an existing product. Unfortunately design enhancement suggestions on different hierarchy levels are not included and the economic aspects of the resulting design decisions are not quantified. This is explored in further detail in the following section 2.7.

Instead of focusing on environmental issues only the LCA can be used to improve both environmental and economic product performance at the same time as for example in the case of energy consumption [EM96].

2.4.3 Problem of shifting the impact between the Life Cycle stages

The main reason for including the LCA concept during the design stage is that a shifting of impacts either economic or environmental can be avoided. For example if the design engineer makes certain changes to reduce the environmental and economic impact during the use stage this can have a contrary effect during the manufacturing stage [HH01]. Hence the impact is shifted from one Life Cycle Stage to another.

To give an example in the case of a car if steel is used as a building material the environmental and economic impact during manufacturing is relatively low, because it does not take that much energy to produce and manufacture the raw material steel, and the main impact occurs during the use stage. If on the other hand aluminium is used as a main building material the environmental and economical impact during the use stage is lowered. This is due to the fact that a lighter vehicle consumes less fuel resulting in less CO_2 emitted and less fuel to be purchased by the consumer. Thus the environmental impact is merely shifted from the use stage to the raw material extraction stage since aluminium production consumes on average ten times the amount of energy as steel production – 17 MJ required for steel compared to 200 MJ required for aluminium per kg of material [GRA06]. This amounts to 11kg more CO_2 emissions per kg of aluminium compared to steel: steel has a CO_2 footprint of 1 kg per kg material compared to CO_2 footprint of 12 kg for aluminium. An extensive Life Cycle Cost Analysis taking into account the carbon footprint for “Aluminium versus Steel in Passenger Cars” has been conducted by Ungureanu et al. [UDJ07]. Ungureanu`s verdict is that only the ‘right combination of these two materials in automotive industry […] would help to reduce total costs and greenhouse gas emissions over the life-cycle of the vehicle and to improve the safety.’

To carry out an LCA during the design process and consider all the issues linked to a product`s Life Cycle can be a difficult endeavour depending on how well Life Cycle issues are integrated in the current design process and how sophisticated current design methods are applied.

Once the LCA is established product design changes can be easily incorporated and thus solutions of reducing the impact over the product`s life cycle can be found without the risk of shifting the impact that is being evaluated – either environmental or economic.

Recapitulating it can be said that Life Cycle Assessment has to be the basis of further methods and applications at the design stage. If any measures are introduced to help with the product design process and bring a more scientific and structured approach to how the product design process is tackled by the design engineer then the LCA is the key.

2.4.4 Life Cycle Costing

The first applications of the Life Cycle Assessment methodology were related to product costing which started about 20 years ago. Sheldon proposed a Life Cycle based design approach based on costing [SPJ90]. The "Design for Whole Life Costs" is applied at the Design Stage since 'It is now an accepted fact that in the production of engineering artefacts, the major cost is inherently fixed in any finished product are introduced by the engineering designer and not within manufacturing'. Additionally it is projected that by designing for Whole Life Cost of a product a company can gain competitive edge and increase profitability.

2.4.4.1 Sheldons` approach to LCA

Sheldon identifies a variety of methods to carry out Cost Estimating in Engineering Design [SHP91]: Design for Cost, Costing for Design, Costs Analysis and Cost Modelling in Design. All these methods have in common that cost is the major product characteristic to focus on. All the design decisions by the design engineer have the goal of reducing cost of the product either at a certain Life Cycle Stage or within the product structure / hierarchy by reducing the costs of a certain component.

The article identifies the following three elements as the main drivers for competitiveness under the umbrella of Design for Cost: Timeliness, Quality and Affordability. The environmental issue is not considered to be a major part of a products´ life cycle.

2.4.4.2 Willcox`s approach to LCA

Willcox presents techniques to optimize and manage concept design techniques on the topic of the Product Whole Life Cost [WIL95]. A major finding of the Willcox thesis is a "Basic Approach to WLC" which consists of three distinct steps:

1. Minimise product and task complexity without compromising functionality.
2. Design for preferred support modes if complexity can be reduced no further. Look for trade-off with additional parameters such as weight or materials.
3. LC analyses are undertaken at product level and then in the context of the system and direct costs are separated from indirect costs.

The ultimate aim of the Willcox method is to highlight features which are most sensible to the profitability of a business. Furthermore it is stated that during the design phase the "Manufacturing" Life Cycle Stage largely dominates design decisions due to the lack of cost data linking design decisions to the Whole Life Cycle of the product. This lack of data can also be an issue regarding environmental data.

2.4.4.3 Harrison's approach

Emerging as an enhancement of Life Cycle Costing the Harrison concept tries to integrate the environmental issue of recyclability "within a whole life cost methodology" [HB00]. In the paper an example is given 'where the increasing complexity of product design can produce economic justifications for design for recycling'. Furthermore a new tool is presented 'for evaluating automotive recyclability in the design process, within a whole life cost methodology'. The developed business model approach reviews automotive design practices and has adapted Life Cycle analysis techniques to give special consideration for recyclability and costing of alternative automotive design strategies. Within the tool presented by Harrison the environmental impact is simplified to EoL issues only, recycling issues to be more specific. In this approach the economic and environmental impact are not integrated under the umbrella of the Life Cycle Approach.

2.5 The product design process

The design process of a product is fundamentally all the planning and creative processes involved before the product is manufactured. This includes setting very basic physical boundaries and characteristics to meet the market or customer needs as well as the layout of production facilities, the arrangement of the product service during the use stage of the product, supplier network setup and many more concerns. During the product design the Whole Life Cycle of a product is configured and it is the main factor if the product is going to be successful in the market.

To give a basic definition: ‘Product Design is a field that uses various processes to develop physical solutions to specific needs’ [SHE07].

2.5.1 Creative problem solving in product design

The whole process of product design can be evaluated from various scientific angles. Lumsdaine [LUM95] takes a look at the product design process from the social point of view based on the interaction of the people involved, their different ways of thinking and the cultural background. Furthermore they identified the five steps illustrated in figure 2.4.

Fig 2.4 has been removed due to third party copyright. The unabridged version of the thesis can be viewed at the Lanchester Library, Coventry University

<u>Figure 2.4:</u> Product Design model by Lumsdaine [LUM95]

In Lumsdaine`s model each of the product design phases can best be solved by a different type of thinking approach as displayed. Unfortunately in reality those resources in the form of human resources are not always available. Hence the product design engineer or the product design team members must possess two or more of those types of thinking.

Ulrich [UE00] presents the design process as a “a sequence of steps that transform a set of inputs into a set of outputs” which is a more mathematical than social approach.

2.5.2 The product design process within industry

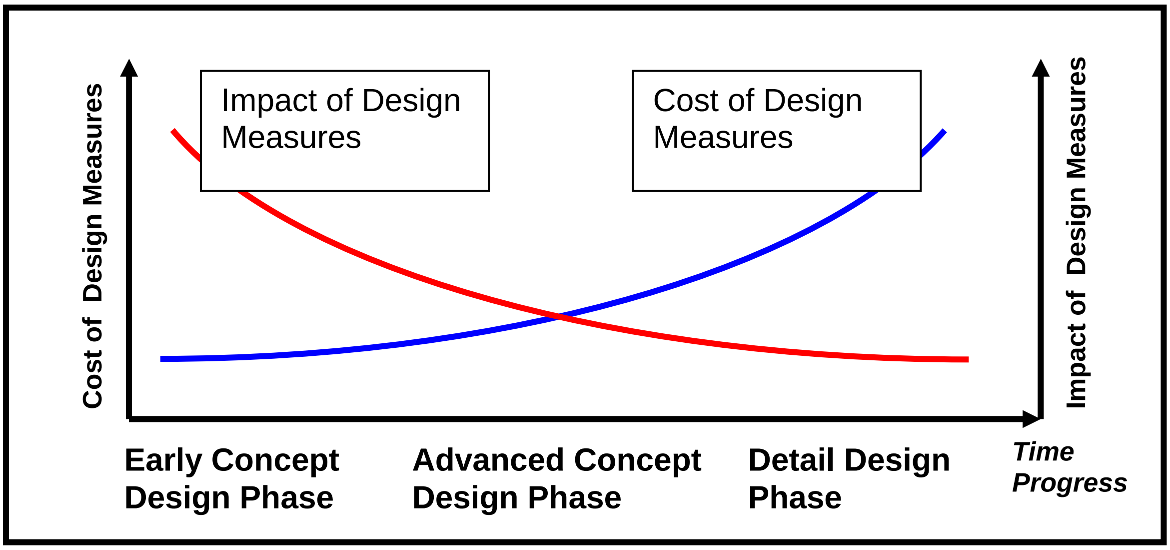
The method of how product design is essentially carried out in industry can vary greatly. It is greatly influenced by factors such as company size, company culture such as hierarchy structure, market type, number and aggressiveness of competitors, market standards and legislative requirements to produce documentation.

Larger companies usually have a very detailed product design procedure that can be measured and requires the creation of files once a small step within this procedure is finished. Moreover in the case of larger companies the design process is not restricted to the engineering department only. On the contrary all functional departments in the form of representatives are involved such as project management and finance, marketing and customer service and quality assurance. In Small and Medium-sized Enterprises (SMEs) the product design procedure can look a lot more pragmatic. In many cases there are no procedures or generation of documentation for benchmarking and controlling. Hence if errors are made it can be rather difficult to find out at what point they occured and how to overcome it in the future. Besides it will be very difficult and a lot of time has to be invested if an SME or any other company is thinking about introducing an ISO standard without having design procedures in place.

As stated in section 1.1 and shown in figure 2.4 the design process is very challenging since there are various issues that need to be considered by the design engineer which environmental performance is just one. It is impossible to consider all these issues at the same time whilst designing a product. As Eder states ‘Engineering designers cannot be expected to have all the knowledge needed to design a product effectively’ [EDE01]. The success of this design process is highly dependent on the number of people involved, availability of information, complexity of the product and various other issues [WON03]. Even though various tools are available to enhance the product design and thus its performance over its life cycle it can be rather tricky to find the right one. Hence a great amount of time is spent during the design process to find design tools for specific problems and apply them to support continuous improvement of a product. This is made even more difficult since there is the necessity to include technical, economic and environmental information in those tools simultaneously [GFS98].

2.5.3 Relationship of impact and cost of design measures

One issue considered during the product design is cost. Figure 2.5 shows the impact of design measures and the actual cost of applying those design measures at the different stages of product design. As stated by Ulrich and Eppinger [UE95] the earlier a design decision is made during the design process the less it is going to cost to make the changes and the bigger the impact on the product layout. Hence making the right decisions early in the design process helps to save costs and time due to faster development to market time. This "Get it right the first time" approach can only be established if the designer has enough information early on.



<u>Figure 2.5:</u> Relationship of impact and cost of design measures

The main concerns during the design process in the last decades were cost control [SHP91] or quality [OVE91]. However during the last two decades environmental issues regarding products have gained more and more attention by the public. This makes it a priority during the product design process as well.

2.6 Material and process databases

The use of several databases is considered as a source of information. The main issues that can be covered by such databases regarding the product design are:

- Impact of the material choice on all life cycle stages
- Impact of processes during manufacturing
- Impact of transportation options on the transportation life cycle stage

2.6.1 Cambridge Engineering Selector:

One of the most advanced databases is the "Cambridge Engineering Selector" (CES) [GRA06] which includes information on environmental and economic material and process properties. The database is developed by Granta Design and delivers information on over 6000 materials such as: average price, density, CO_2 footprint, embodied energy, etc. Figure 2.6 shows a screenshot of the CES database where information regarding a certain type of aluminium is listed.

Fig 2.6 has been removed due to third party copyright. The unabridged version of the thesis can be viewed at the Lanchester Library, Coventry University

Figure 2.6: Screenshot of information on aluminium of the CES EduPack 2006

2.6.2 MatWeb – Material Property Database

Another database that was considered during the course of the research is the "MatWeb - Material Property Database" [AUT06] which is shown in figure 2.7. MatWeb is a searchable database of material data sheets, including property information on thermoplastic and thermoset polymers, metals, ceramics, fibers and other engineering materials. Figure 2.7 shows a screenshot of the MatWeb database, in this specific case on the building material aluminium.

Fig 2.7 has been removed due to third party copyright. The unabridged version of the thesis can be viewed at the Lanchester Library, Coventry University

Figure 2.7: Screenshot of information on aluminium of MatWeb database

2.6.3. The IMDS – International Material Database

The "IMDS - International Material Data System" [MAT04] is a material database developed by the automotive industry. All the materials used in vehicle construction are archived and managed within the IMDS database. It is not a database per se but very distinctively designed to help during the design process of automobiles: First a list of parts is created and then certain materials are assigned. Its suitability as a source of material information is very limited due to the fact that registration is required and that it does not work as a standalone database.

2.6.4 The EcoTransIt database

The “EcoTransIt” database [STI06] is a transportation database and an independent tool and was jointly developed by five European rail companies. “EcoTransIt” compares the energy consumption and emissions of freight transported by rail, truck, ship and aircraft. It also takes intermodal transport services and the different technical standards of the vehicles into account in the calculations. Even though “EcoTransIT” does not deliver data for the U.K. specifically it was assumed that the data it delivers for other European countries is very similar to the U.K.. For example if a lorry consumes a certain amount of fuel over a set distance in Germany it is assumed that the same lorry consumes the same amount of fuel in the U.K.. There is no reason or indicator that this is not the case.

2.7 Currently available tools to reduce the environmental impact of products

Various tools are available today to measure and reduce the environmental impact of products. These tools can be based on one or more of the environmental design methodologies such as Design for Environment (DfE), Eco-Design, Environmentally Conscious Design, Sustainable Product Design or many more.

There is a vast array of different tools for different purposes, many of them focus on certain life cycle stages only. For example methodologies described in published work are for the use at the End-of Life stage of a product only [RK99] [IED94] [SW97] [MSP96] but the life-cycle approach is not applied here at all. The focus is on only one stage of the life-cycle of a product. Therefore a shift of the environmental and financial impact from one stage to another can occur which is not favorable. “ReSicled” [PSW02] is another tool. It ‘ […] helps the design engineer to improve a product on the basis of multicriteria and multiscenarios recoverability assessment’. Even though various interesting methods regarding the recoverability of plastic are applied the focus is still the End-of Life step in the life cycle.

Another solution is given by Vogtlaender on combining environmental and economic requirements in product design with his `model of the Eco-costs / Value Ratio` [VBB02]. This method measures the ecological impact of each `step in the product chain which is then expressed in terms of money, the so called eco-costs`. However, this method does not take into account the product hierarchy, meaning taking into account the various levels (e.g. whole product level, component level, etc), but focuses on the product as a whole only. Furthermore the functionality of a product is not considered.

To tackle the problem of integrating the environmental design issue into the product design process without compromising the other design issues such as costs, functionality and so on many software tools have been and are currently being developed.

In the following section the most popular ones, according to the author of this thesis, are reviewed:

2.7.1 SimaPro 7

The SimaPro 7 tool is the most widely used LCA software. It offers a high level of flexibility, parameterised modeling, interactive results analysis and a large included database. The results are solely expressed as environmental impacts based on the Whole Life Cycle (WLC) approach and no consideration of the economic impact is made.

First released in 1990, SimaPro 7 is a proven, reliable and flexible tool used by major industries, consultancies and universities. The SimaPro 7 tool is developed by and sold through the "Pre Consultants" company which is based in the Netherlands. With users in over 50 countries, SimaPro 7 continues to be the most successful LCA software worldwide, and is used for the assessment of products, processes and services [PRE07]. Figure 2.8 gives an example on how SimaPro can benchmark different designs regarding their environmental impacts.

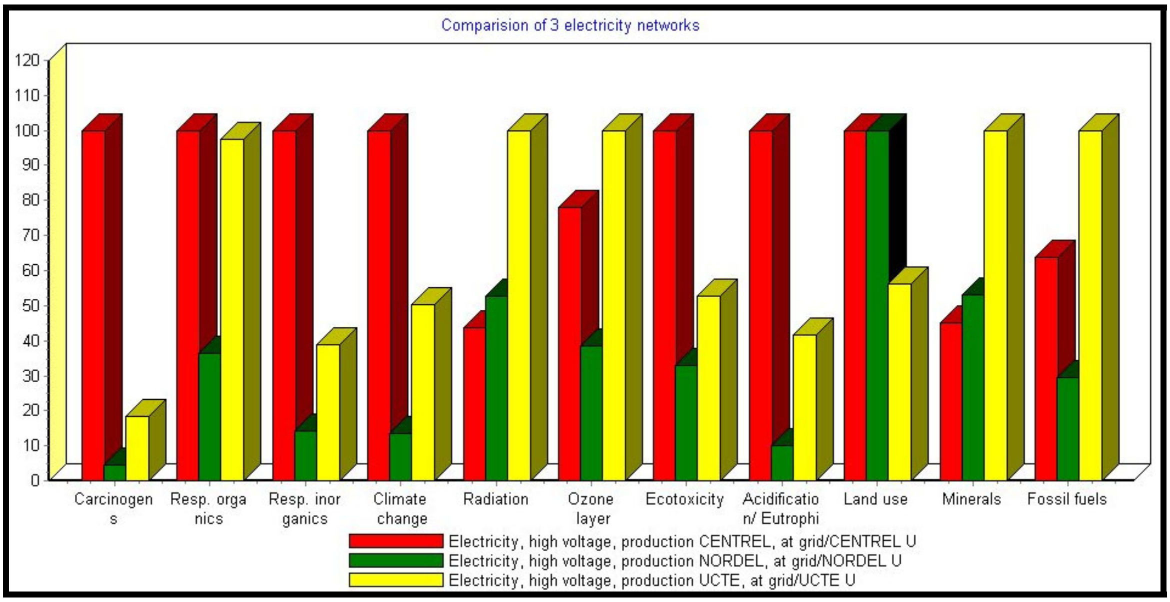


Figure 2.8: Environmental Impact benchmarking by SimaPro

To allow the designer to compare products and processes in environmental terms SimaPro uses different impact assessment methods and thus different principles of comparison as shown in figure 2.8. The bottom line is that the SimaPro software helps to conduct a very thorough Life Cycle Assessment of products or services with a very scientifically sound data assessment and evaluation method. But the shortcomings of this tool are clearly in the area of relating an economical figure to these environmental impacts evaluated. Hence it can be difficult to make economically sound decisions based on this tool alone. A trade-off between environmental and economic impacts is the likely shortcoming of the SimaPro tool.

2.7.2 Eco-Scan life 3.1

Eco-Scan life 3.1 [TNO06] is a Life Cycle Assessment software developed by TNO – "Nederlandse Organisatie voor toegepast natuurweetenschappelijk". It evaluates the environmental impact of a product based on Eco-Indicator 99. The Eco-Indicator 99 method is both a science based impact assessment method for LCA and a pragmatic Eco-Design method [PRE07]. It offers a way to measure various environmental impacts, and shows a final result in a single score.

Internal databases are used to assign an Eco-Indicator 99 environmental impact score to all the different components and processes. The economic issues of a product are not considered in any way. Hence the Eco scan life 3.1 tool is not integrated into the design process alongside issues like financial performance, quality, functionality.

2.7.3 LCA Light

The LCA Light tool is an easy-to-use Life Cycle Assessment (LCA) tool that was developed by ABB. The aim of the LCA Light tool is to allow the user to make [ABB03] quick evaluations of:

- products
- different materials
- different transport strategies
- different recycling rates

The LCA Light software tool is completely online, hence server based. Only three of the common five Life Cycle stages are considered: Manufacturing, Operation – which is similar to the Use stage, and Recycling – which is similar to End-of Life stage.

The results can be produced to reflect the environmental impact for various different impact categories: global warming potential, acidification potential, ground level ozone formation potential, nitrification potential and ozone depletion potential. Additionally the impact result can be given as an EPS 2000 indicator score, which is further described in section 2.14, and the Eco-Indicator 99 score.

There are various other environmental design and LCA tools on the market and others are regularly created. SimaPro 7 is the most advanced and popular on the market. Eco Scan life 3.1 and LCA light are good examples for the smaller and simpler tools that are available. Within this work it was not possible to cover all available environmental design and LCA software tools on the market because there are too many to consider.

2.8 The Eco-Design Principle

Eco-design aims to generate products and services in a way that reduces the use of non-renewable resources and the environmental impact. Sustainable design is often viewed as a necessary tool for achieving sustainability. It is related to the more heavy-industry-focused fields of industrial ecology and green chemistry, sharing tools such as life cycle assessment and life cycle energy analysis to judge the environmental impact or greenness. Furthermore it aims to follow the Triple Bottom Line principle that will be discussed at a later stage in section 2.10. This means in addition to the environmental impact described above Eco-Design takes into consideration economic and environmental issues to improve the design of a product. As explained in section 2.2.1 Eco-Design is moreover based on Whole Life Cycle Assessment. All life cycle stages of a product need to be taken into account in order to avoid a trade-off of impacts between the distinct life cycle stages.

In addition there are various product design issues that Eco-Design can address. The EuP directive covers the most common ones that give a strong focus on environmental impact:

1) Weight & Volume of product
2) Recycled Materials Used
3) Resource Consumption (energy, water, etc.)
4) Hazardous Substances
5) Consumables for Use & Maintenance
6) Ease of Re-use & Recycling
7) Incorporation of used components
8) Extension of Lifetime
9) Waste generated (incl. hazardous)
10) Emission (to air, water, soil)

The Eco-Design legislation described in section 2.2 takes on the core principles of Eco-Design itself:

- Based on Whole Life Cycle Assessment
- Reduction of all environmental impacts

- Only apply changes to the product design if the economic performance and functionality of the product is not put at risk

As stated by Akermark the Design Engineer plays the crucial role in the implementation of the Eco-Design principle [AKE03]. There are currently various tools used by design teams to apply the Eco-Design principle. Unfortunately most of them consider the environmental impact only and focus on a single design phase during which they can be used. Mathieux [MFM04] regarding such tools concludes that they ‘differ widely in the environmental impacts they consider, the design phases during which they can be used, the input data that is needed to use them, the results that can be obtained or the actor who can use them’. But to successfully implement the Eco-design principle it is imperative to ‘recognise that environmental impacts must be considered during the design process , [but only] along with all the usual criteria’ such as functionality and economical considerations [LG01]. The method proposed by Park attempts to integrate environmental and economic impact under the umbrella of Eco-Design facilitating on a four method comparison technique: it `involves consideration of both environmental and economic aspects in the end-of-life stage of a washing machine, and to suggest priorities for recycling and Eco-design of the washing machine’ [PTJ06]. Park´s method is indeed successful in the integration of economical and environmental issues, although it tends to focus on the End-of Life stage only.

2.9 Sustainable design

Sustainable Design is often linked to Eco-Design as just another synonym for it. By applying sustainable design to a product it is safeguarded that the product can be produced indefinitely. This is not taking into account the company`s management issues and impacts from day to day procedures of the company producing the product but issues directly related to the products´ life cycle only. In the very early stage of the development of sustainable design the environmental aspect was the main focus point: originally 'Environmentally' Sustainable Product Design has recently been updated and changed to 'Entirely' Sustainable Product

Design to represent the range of different factors involved in Sustainability. This includes economical and social considerations as well [GRE04].

In the U.K. the “UK Sustainable Development Strategy” which was implemented in March 2005 sets out a policy agenda that challenges design at all levels [RIS05]: `Measures to accelerate sustainable consumption and production lie at the heart of the Strategy. This includes initiatives to promote the supply of sustainable goods and services (“supply push”) as well as creating demand (“demand pull”). In the study by Irwin the opportunities are explored for design to help shift both production (products and processes) and consumption onto a more sustainable basis. This is the first attempt to implement a U.K. wide sustainable design framework.

Sustainability means implementing thinking that ensures that companies are able to exist for an indefinite future based on economic, environmental and social issues. Nevertheless various legislative issues by the EU are not based on a sustainable approach. They force certain measures onto companies that focus on the environmental issues only and do not take into account the economical and social sustainability. Especially in the case of economic sustainability a lot of companies feel the pressure of losing competitiveness due to the pressure from environmental legislation.

2.10 Triple Bottom Line

The Triple Bottom Line is a concept to measure the effectiveness of sustainability. Or as defined by Greenwood [GRE04] “Sustainability is usually measured according to Environmental, Financial and Social factors. The success of businesses is normally measured on the 'Bottom Line', or financial profit/loss. The success of sustainable systems is therefore measured on the Triple Bottom Line, including social and environmental profit or loss alongside financial ones. ”Sustainability requires that the system does not make a loss in any of the three areas. However, in reality this means that the system must aim to make a profit, in order that the inevitable occasional losses balance out and do not result in the degradation and collapse of the system. Furthermore the “triple bottom line”, a.k.a. “3BL” or “People, Planet, Profit”, captures an expanded spectrum of values and criteria for measuring organisational (and societal) success; economic, environmental and social. ‘A commitment to Corporate Social Responsibility brings with it a need to institute triple bottom line reporting’ [WIK07a].

So a company has to perform in a sustainable way meaning that it can carry on indefinitely. To put this in context with each of the three factors: it has to perform in a sustainable economic way means that the cash inflow and revenue from the sale of the company`s products or services needs to be at least equal to the total costs of running the company including wages, taxes, facility running costs and so on. In reality the company has to make a profit also in order to be sustainable. In order to do so the most important factor is that the company’s products or services are in demand by the customer. If that is not the case a company will not be profitable even though a large amount of cash inflow can be generated from interest and other sources.

Nowadays companies have an impact on the environment and on social issues of society. In the words of Savitz [SW06] ‘The truly sustainable company would have no need to write cheques to charity or 'give back' to the local community, because the company's daily operations would not deprive the community, but would enrich it.’

2.11 ISO 14000

ISO 14000 is series of standards produced by the International Standards Organization (ISO) which is still under preparation and covers a number of environmental topics. ‘ISO 14001, which was published in 1996, lays down a model for an environmental management system that can be adopted by any organization and can be certified by an accredited certifying body’ [ST 05]. This model is very similar to “Eco-Management and Audit Scheme” (EMAS) [WAL03], produced by the European Community in 1993.

Out of this whole series of standards a few apply to specific product related issues and can be used as tools for the IPP methodology:

1. Life Cycle Assessment related ISO 14000 tools:

- ISO 14040 - Life Cycle Assessment - Principles and Framework [INT97]
- ISO 14041 - Life Cycle Assessment - Goal and Scope Definition and Inventory Analysis [INT98]

- ISO 14042 - Life Cycle Assessment - Life Cycle Impact Assessment [INT00a]
- ISO 14043 - Life Cycle Assessment - Life Cycle Interpretation [INT00b]

2. Environmental aspects and performance related ISO 14000 tools:
   - ISO 14031 - Environmental performance evaluation [INT99]
   - ISO 14062 – Integrating Environmental aspects [INT02a]
3. Specific material not within ISO 14000:
   - ISO 17422 – Plastics – Environmental Aspects – General guidelines for their inclusion in standards [INT02b]

The ISO guidelines are mainly of a supportive nature and can be difficult to apply by the design engineer: the person applying the standard to help with the companies organizational procedures should ‘use the standard as a road map’ .

2.12 Environmental impact assessment methods

There are various different principles of how to measure the environmental impact caused by a product. Figure 2.9 displays the most common ones used as of March 2007 which are mentioned by PRE Consultants [PRE07] as the most important source and several other sources. PRE Consultants are described in more detail earlier in section 2.7.1. They are the developers of the SimaPro 7 tool which is one of the most successful LCA tools currently available. Within this tool the user can choose from an array of Impact Assessment methods and some of those are listed in figure 2.9. But additionally further Impact Assessment methods are included from other literature sources and other LCA and environmental impact tools to give a complete picture of methods currently available. The methods described can measure the environmental impact only without any regard to economic considerations.

Impact Assessment Method	Comparison Principles	Source of literature
Eco-Indicator 95	Characterization, Normalization and Evaluation	[GDC96]
Eco-Indicator 99	Characterization, Damage Assessment, Normalization and Evaluation	[GS01]
CML 92	Characterization, Normalization	[PRE07]
CML 2 (2000)	Characterization, Normalization	[GUI05]
EDIP/UMIP	Characterization, Normalization, Weighting	[WHA97]
EPS 2000	Characterization, Damage Assessment and Evaluation	[STE99a]
Ecopoints 97	Characterization, Normalization and Evaluation	[PRE07]
Impact 2002+	Characterization, Damage Assessment, Normalization and Evaluation	[JMC03]

Figure 2.9: Environmental Impact Assessment Methods

2.12.1 Definition of comparison principles:

In this section the comparison principles are explained: These principles have the purpose of making it possible to compare various different environmental issues based on a score system. For example without the comparison principles it would be difficult to weigh and benchmark the effects from environmental impacts against each other e.g. Soil acidification impact against depletion of copper reserves [STE99a].

2.12.1.1 Characterization:

Different substances (e.g. emissions) are aggregated within each class to produce an effect score. Additionally a weighting score is added since some substances have more intense effects than others.

2.12.1.2 Normalization:

A mathematical process that adjusts for differences among data from varying sources in order to create a common basis for comparison. 'Many methods allow the impact category indicator result to be compared by a reference (or Normal) value. This means the impact category is divided by the reference. The reference may be chosen, but often the average yearly environmental load in a country or continent, divided by the number of inhabitants, is used as the reference. The environmental load as defined by Oskam is the 'Observed (or predicted) environmental concentration of a compound in an environmental compartment'. The European Nuclear Society [EUR07] defines the environmental load as the 'Disturbance in ecological systems caused by humans, resulting in deviations from normal behaviour'.

2.12.1.3 Weighting:

Some methods allow weighting across impact categories. This means the impact (or damage) category indicator results are multiplied by the weighting factors, and are added to form a total score. Weighting can be applied on normalized or non-normalized scores, as some methods, like EPS, do not have a normalization step.

2.12.1.4 Evaluation:

The Evaluation of results is one step of the interpretation of a conducted Life Cycle Assessment in which the findings of either the inventory analysis or the impact assessment, or both, are combined consistent with the defined goal and scope in order to reach conclusions and recommendation.

2.12.1.5 Damage Assessment:

Environmental damage caused by a product regarding various environmental effects e.g. heavy metals, acidification,etc [GS01].

2.12.1.6 Midpoint damage approach

In mathematics the midpoint (also known as class mark in relation to histogram) is the middle point of a line segment. It is equidistant from both endpoints. Relating to environmental impact assessment the midpoint damage approach is an attempt to combine the life cycle inventory results of substances and the category endpoint. Figure 2.10 below, which is extracted from the ISO14042: 2000, shows the relationship between this life cycle inventory – the emissions of substances, and the category endpoint – the impact these emissions have. As stated by BRE [BRE05] 'Indicators could be based on inventory, the end point, or a midpoint approach (or intermediate variable approach) taking account of the environmental mechanism'. For example, indicators for acidification could be:

- Inventory: Tons of SO_2 emissions
- Midpoint: Tons of Acidifying emissions measured relative to 1 ton SO_2
- Endpoint: Hectares of Forest killed by Acidification.

In other words the midpoint damage approach creates a direct link between the inventory and endpoint as shown in figure 2.10.

Fig 2.10 has been removed due to third party copyright. The unabridged version of the thesis can be viewed at the Lanchester Library, Coventry University

Figure 2.10: Concept of category indicators [INT00a]

Besides there are several midpoint categories e.g. Human toxicity, Ozone layer depletion, Non-renewable energy, etc. These midpoint categories can be merged into a few damage categories such as Human Health, Resources, Ecosystem quality and so on.

2.12.1.7 Distance-to-target approach

"Distance-to-target" means that 'the further away current environmental conditions are to an established target the more serious it is to worsen those conditions' as stated by Kirchain [KIR06]. Good examples for distance to target weighing are emissions like CO_2 or NO_X emission whereas current values are compared to values a few years back or to desired values.

2.12.2 Definition of impact assessment methods

2.12.2.1 Eco-Indicator 95:

The Eco-indicator 95 method was developed under the Dutch NOH programme – ‘‘National Research Programme for Recycling of Waste’’. The programme was initiated by the “Netherlands Ministry of the Environment” with the purpose of the ‘research, evaluation, feasibility and comparative studies of several [biomass digestion] plants’ and hence to improve the treatment of biological waste as stated by Negro et al [NHS06] and the Dutch ‘Energie en Milieuspectrum’ Journal [EM 93]. The Eco-indicator method was then further developed by the PRE consultants [PRE07] in a joint project with Philips Consumer Electronics [PHI07] , NedCar (Volvo/Mitshubishi) [NED07], Océ Copiers [OCE07], Schuurink, CML Leiden [LEI07], TU-Delft [TU 07], IVAM-ER (Amsterdam) and CE Delft [CEN07]. The Eco-Indicator 95 is basically a figure which rates the environmental impact of a material or process, based on data from a life cycle assessment and summarizing various environmental impact. ‘The higher the indicator, the greater the environmental impact. The Eco-indicator brings environmental assessments within the designer`s reach’ [GDC96]. As Bovea [BG04] put it ‘The characterisation factors match those considered in the CML method, although specific categories for toxicity have been included, namely, heavy metals, carcinogenic substances, winter smog and pesticides. The weighting principle is based on a mixture of the distance-to-target approach and the damage approach: weighting factors are calculated as the ratio of the actual inventory value for each effect category, with additional subjective weighting to represent significance on human health and ecosystem impairment’.

2.12.2.2 Eco-Indicator 99:

It mainly focuses on materials and processes and produces environmental impact scores based on three environmental issues:

- Ecosystem quality
- Human health
- Resources

‘The Eco-indicator 95 methodology is used frequently by designers but it is criticised by environmental experts at the same time because some environmental aspects were not accounted for in the method. The new Eco-indicator 99 method includes many more aspects and is therefore more complex than the 95 version but the resulting Eco-indicators are still the same user friendly units’ [GS01]. It can be stated that the Eco-indicator 99 is an advancement and updated version compared to the Eco-indicator 95. Furthermore it no longer includes the ‘distance-to-target’ weighing principle as the Eco-indicator 95 does.

2.12.2.3 CML 92 and CML 2 (2000):

CML stands for “Centre of Environmental Studies” of the University of Leiden. The CML 92 method is one of the first impact assessment methods developed for LCA. The CML 2 (2000) is advancement of it and is based on its core principles. Both CML methods use a midpoint damage approach which is explained earlier and has a direct link between the inventory and endpoint.

The CML Guide provides a list of impact assessment categories grouped into:

- Obligatory impact categories (Category indicators used in most LCAs)
- Additional impact categories
- Other impact categories

Both methods are similar to the Eco-indicator 95 and 99 method regarding their basic impact assessment categories. They are based on the same basic environmental issues: Ecosystem quality, Human health and Resources or sometimes referred to as resource depletion. But both methods attempt to include additional categories to give a more complete picture.

2.12.2.4 EDIP/UMIP:

EDIP stands for “Environmental Design of Industrial Products” programme and it was organized by the Technical University of Denmark and five leading Danish companies [WHA97]. UMIP is the Danish translation and name of EDIP. The project was sponsored by the Danish Environmental Protection Agency (EPA) and the Confederation of Danish Industries. It was developed in 1996.

2.12.2.5 EPS 2000:

It stands for “Environmental Priority Strategies” in product design (default methodology). The EPS system is mainly aimed to be a tool for a company’s internal product development process. The EPS 2000 default method is an update of the 1996 version. The impact categories are identified from five safeguard subjects: human health, ecosystem production capacity, abiotic stock resource, biodiversity and cultural and recreational values [PRE07].

2.12.2.6 Impact 2002+:

Jolliet [JMC03] outlines that the IMPACT 2002+ life cycle impact assessment methodology proposes a feasible implementation of a combined midpoint/ damage approach, linking all types of life cycle inventory results (elementary flows and other interventions) via 14 midpoint categories to four damage categories. For IMPACT 2002+, new concepts and methods have been developed, especially for the comparative assessment of human toxicity and Eco-toxicity. Human Damage Factors are calculated for carcinogens and non-carcinogens, employing intake fractions, best estimates of dose-response slope factors, as well as severities. The transfer of contaminants into human food is no longer based on consumption surveys, but accounts for agricultural and livestock production levels. Indoor and outdoor air emissions can be compared and the intermittent character of rainfall is considered. Both human toxicity and Eco-toxicity effect factors are based on mean responses rather than on conservative assumptions. Other midpoint categories are adapted from existing characterizing methods (Eco-indicator 99 and CML 2002). All midpoint scores are expressed in units of a reference substance and related to the four damage categories human health, ecosystem quality, climate change, and resources. Normalization can be performed either at midpoint or at damage level. This means that the Impact 2002+ methodology is flexible enough to either apply a normalization filter to produce a midpoint result or for the benchmarking of the damage level such as hectares of grassland destroyed by acidification.

But there are certain limitations to the IMPACT 2002+ methodology also: ‘several impact categories have not been considered that far, such as impacts on marine environment, noise. Currently there is research underway to include these categories and overcome some further limitations.

All the methods described before focus on measuring the environmental impact of a product. Most of them achieve this by assigning a numerical value to either one or several different environmental impact categories. The reason for using different environmental impact assessment methods is to ensure that decision-makers consider environmental impacts before deciding whether to proceed with new projects or the development of products.

2.13 FMEA (Failure Mode and Effect Analysis)

FMEA is a tool used in various industries to identify and rank potential errors and problems of products still under design. ‘It is a powerful design tool to analyze engineering systems and it may simply be described as an approach to conduct an analysis of each potential failure mode in the system to examine the results or effects of such failure modes on the system’ [DHI99].

Furthermore there are three different types of FMEA

1. **Design-Level FMEA**:

   Stops product failures related to design; validation of design parameters chosen for specified functional performance requirement; evaluation of design alternatives; useful tool to establish priority for design improvement actions.

2. **System-Level FMEA**:

   Highest-level FMEA that identifies system failure modes at early conceptual design.

3. **Process-Level FMEA**:

   Prevents failures related to manufacturing process.

In the words of Stamatis [STA03] Failure Modes and Effects Analysis (FMEA) is a tool widely used in the automotive, aerospace, and electronics industries to identify, prioritize, and eliminate known potential failures, problems, and errors from systems under design before the product is released.

Even though FMEA is a tool used to mitigate risks during the design before they occur it can be specified to serve specific purposes. Recent FMEA research such as the “Cost based FMEA” are focusing on improving traditional FMEA limitations. ‘Identify and prioritise the process part of potential problems that have the most financial impact on an operation’ [RI03].

At an early stage of the research Failure Mode and Effect Analysis (FMEA) was considered to be an integral part of the proposed methodology. Even though it was not used as a key tool in supporting the product design process via integration certain elements may still be used.

2.14 TRIZ – Theory of Inventive Problem Solving

2.14.1 Overview

The abbreviation TRIZ stands for Theory of Inventive Problem Solving in the original Russian and it was developed by Genrich S. Altshuller. He was a Russian mechanical engineer who served in the Soviet Navy as a patent expert. One of his main tasks was to help inventors apply for patents and on occasions to help solve certain problems as well. What he derived from these experiences was a need for a standard method to produce inventive solutions. 'Over subsequent years his desire to structure the inventive process resulted in a range of tools and approaches based on empirical analysis' [SM03]. It can be said that Altshuller believed that problems stem from contradictions (one of the basic TRIZ concepts) or tradeoffs between two or more elements, such as 'If we want more acceleration, we need a larger engine – but that will increase the cost of the car' [MAZ04]. That is, more of something desirable also brings more of something else undesirable, or less of something else also desirable. One of the basic constituents of TRIZ is the so called TRIZ Matrix. It has "40 Improving Features" on the Y-Axis and "40 Worsening Features" on the X-Axis. Figure 2.11 shows an extract of a few improving and worsening features of the TRIZ matrix. The user picks one feature of his product or component he wants to improve and then a feature that causes problems doing so. The TRIZ Matrix then shows the user which of the 40 inventive principles he can use to overcome this.

Fig 2.11 has been removed due to third party copyright. The unabridged version of the thesis can be viewed at the Lanchester Library, Coventry University

<u>Figure 2.11:</u> The TRIZ Matrix – extract of improving and worsening features [MD96]

But this is just one of the features TRIZ offers. Furthermore it offers a systematic approach to innovation; by learning TRIZ and following its rules it is possible to accelerate creative problem solving for both individuals and project teams. Companies that successfully apply TRIZ are using the success and knowledge of the whole world, and are not dependent on the spontaneous and occasional creativity of individuals, or groups of engineers, within their organisation. TRIZ is not just powerful for technical problem solving but is also successfully used on a wide range of management issues.

"Out-of the box thinking", a phrase used so often in current best practice management and engineering, is the key principle of the TRIZ methodology and its application. The general case for abstracting a solution system is illustrated in figure 2.12. The TRIZ principle allows innovative results to be generated by taking a step back from the problem at first hand. Then by defining what the problem is and taking it out of the context of the field it occurred in, for example engineering, and looking for solutions in other scientific fields helps to generate the most innovative solutions without relying on trial and error.

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Figure 2.12: **The TRIZ general model [BBL04]**

The TRIZ methodology claims that, ‘Inventive problems can be codified, classified and solved methodically, just like other engineering problems’ [KAP96]. As stated by Stratton [SM03] there are three premises on which the theory may be viewed:

1. The ideal design with no harmful functions is the goal
2. An inventive solution involves wholly or partially eliminating a contradiction
3. The inventive process can be structured

2.14.2 TRIZ in Eco-Design

Rudimentary models to combine eco-innovation and TRIZ have emerged fairly recently [CC04]. Technological advances often impact on the environment and many sources suggest that an innovative product gains its economic usefulness on the back of environmental performance, hence calling for an improved approach [SHE97] p125.

A very interesting theory on how to integrate TRIZ into the design process is proposed by Cavallucci [CAV01]. He states that the design engineer ‘must formalise their design procedures using tools and methods which will enable them to develop design projects in the shortest possible time while guaranteeing that the solutions found will be innovative’. Cavallucci talks about the design process in general and not about Eco-Design in a specific manner. Additionally it is mentioned that there are certain limitations of the TRIZ theory that makes it even more difficult for the design engineer to apply: the TRIZ theory is a rather vague method and the derivation of suitable solutions for specific problems can be rather difficult and time consuming. Besides 'it is difficult to form a model for a specific, complex problem' and 'no precise recommendation is given as to how a contradiction should be formulated to a specific problem'. It can be derived from all this that a methodology and user interface are helpful during the design process that help the design engineer to produce inventive solutions. Cavallucci [CAV01] presents the development laws for the technical systems which were devised by Altshuller as a path for further research or at least a guiding principle in implementing a TRIZ approach in the design process. There are eight laws from different categories which are described in the following:

2.14.2.1 The static laws – *the static laws give a motionless vision of the system*

Law 1 - Wholeness of parts:

For a system to ensure its main function, it must have four fundamental parts ideally fulfilling their role in the functioning of the system: the engine, the transmission, the working element and the control element.

Law 2 – Conductible energy flow:

A necessity for the functioning of a component is the circulation of energy through the system. The energy transmission within and between components can be material (camshaft, gearwheel, lever, fluid, gas) or a field (magnetic, electric, thermal) or a combination of the two.

Law 3 – Coordination of the rhythm of different parts:

To guarantee an optimal function of a component it is essential to establish a coordination in the rhythm of all parts such as frequency, vibration or resonance.

2.15.2.2 The cinematic laws – *here the system is observed in a broader time and space*

Law 4 – Increase in ideality

This law is linked to the level of ideality of a system. A factor for it is:

$$\frac{Useful\,Functions}{(Harmful\,Functions + Functions\,related\,To\,Costs)} = D$$

In this equation D is the design efficiency or the rate of ideality approach. There are various other equations to determine the factor of ideality. Willcox [WIL95], p.40-44 suggests the use of various parameters for the numerator and denominator to determine the ideality factor depending on the design goal as shown in figure 2.13:

Numerator	**Denominator**
Number of essential parts	Number of non-essential parts
Number of functional parts	Number of non functional parts
Number of recyclable and re-usable parts	Number of toxic parts or parts going to landfill

<u>Figure 2.13</u>: Numerator and denominator to evaluate the ideality factor

Law 5 – The unequal development of the parts

This law is based on the fact that parts of a component or product system can be at different evolutionary levels in their development. The more unequal the development of the parts, the more complex the system becomes.

Law 6 – Transition towards a super-system

This law applies once a product has exhausted all its development potential. Here certain components or parts are merged into one to form a super system. Thus the number of components or parts is reduced resulting in a lower product complexity.

2.14.2.3 The dynamic laws – *laws 7 and 8 are means of projecting the system into the future”*

Law 7 – Transition from the macro-level to the micro-level
The notion of macro-level to micro-level is directly linked to the observed structural level (solid, granulated, powder, liquid, fields). In miniaturisation all technical systems evolve from macro-to micro level. A good example for this is the development of ‘cooking systems from wood burning stove to gas ranges to electric ranges to microwave ovens’ [MAZ04].

Law 8 – Increase in dynamics and controllability.
According to this law technical systems always strive towards a higher level of dynamics and controllability. Examples can be to move a rigid system towards segmentation or to better controllability due to a transition of control fields from mechanical fields to electrical fields, then magnetic fields and finally electro-magnetic fields.

2.15 DFX - Design for X

DFX is the name for a large collection of specific design guidelines. The DFX methodologies and design guidelines address different phases of the product`s Whole Life Cycle. Thus if they are slightly modified they are an ideal solution to overcome problems in product design and generate design suggestions for specific life cycle steps of a product. It is taken that the design engineer has the means to determine which life cycle step actually causes the biggest impact in terms of financial obligation or environmental hazard.

‘Under the label Design for X a wide collection of specific design guidelines are summarized. Each design guideline addresses a particular issue that is a) caused by, or b) affects the characteristics of a product’ [WIK07b]. If the DFX methods are applied correctly they can support the generation of ideas and technical solutions to overcome, control, improve or even invent particular characteristics of a product. ‘From a knowledge-based view, the design guidelines represent an explicit form of knowledge, that contains "knowing-how-to" information’. However, two problems are prevalent. First, this explicit knowledge (i.e. the design guidelines) was transformed from a tacit form of knowledge (i.e. by experienced engineers, or other specialists). ‘Thus, it is not granted that someone who is outside of the subject area, will comprehend this generated explicit knowledge, because it will still contain embedded fractions of knowledge or respectively include non-obvious assumptions, also called context-dependency’ [DS97].

2.15.1 The DFX tools in detail

The DFX tools have been commonly used since the 1990’s basically starting off with the basic principle of ‘Design for Assembly’ (DFA) and its variants [HM98], the DFX toolset has grown extensively since. Since each focus on a single step of a product life cycle or certain design issues it is not easy to integrate them in the design process or even in a Whole Life Cycle methodology. A generic DFX framework was suggested by Mak and Huang to help apply the DFX tools but this toolkit does not include environmental or economic considerations or even a technique to pinpoint the life cycle step with the biggest impacts. McAloone [MCA00] states that certain tools of the DFX methods can be applied at very specific design stages only.

As stated by Huang [HUA96] DFX has been considered for Eco-Design in a very limited way only using the “Design for Environment” (DFE) tool out of the complete set of tools. It is considered possible to use the whole DFX toolset and combine it with the Life Cycle Assessment approach. Doing this makes it possible to target the life cycle stage and even the specific issue here to improve the environmental and economic impact. To give an example for this: If at the Early concept phase it is found that a car has its biggest impact during the use stage the methodology recommends principles to the user derived from Design for Quality (DFQ) and Design for Serviceability (DFS). This can be to enhance the tolerance parameters for the engine and thus make it run more efficiently. The economic and environmental impact are reduced simultaneously because a higher engine efficiency means reduced petrol use and thus reduced costs for the user and reduced emissions. Figure 2.14 shows an excerpt of DFX tools available.

Name of Tool	**Life Cycle it can apply to**
DFA (Design for Assembly)	Manufacturing
DFD (Design for Disassembly)	Use, Disposal
DFM (Design for Manufacture)	Manufacturing
DFQ (Design for Quality)	Manufacturing, Use
DFR (Design for Recycling)	Raw Material Extraction, Disposal
DFS (Design for Serviceability)	Use
DFT (Design for Testability)	Manufacturing, Use

Figure: 2.14: DFX into Design

In the following sections the main DFX principles used are explained in more detail:

2.15.1.1 DFA – Design for Assembly

Design for Assembly is the DFX tool most widely used in industry. DFA is a tool that helps to design products with ease of assembly in mind. If a product is made up of fewer parts it will take shorter time to assemble it, thereby reducing costs related to assembly and the environmental impact per product. In addition, if the parts are provided with features which make it easier to grasp, move, orient and insert them, this will also reduce assembly time and the economic and environmental impacts by using less energy (e.g. lighting) per product. The reduction of the number of parts in an assembly has the added benefit of generally reducing the total cost of parts in the assembly. This is usually where the major benefits of the application of design for assembly occur. There are a number of different methods on the topic of DFA. Huang [HUA96], p.47 identified the following three:

- **Hitachi AEM** (Assemblablity evaluation method): It was first developed in 1976 and has been subject to continuous evolutionary changes and improvements since. It focuses on two factors, the assemblability evaluation score *"E"* and the estimated assembly cost ratio *"K".*
- **Lucas DFA**: This method is a result of the collaboration between Lucas Engineering with the University of Hull. This method revolves around the need to complete a form called the assembly flowchart and it involves assigning and summing penalty factors associated with potential design problems.
- **Boothroyd-Dewhurst DFA:** Geoff Boothroyd started in 1977 to develop the Design for Assembly method (DFA). 'This method helps to estimate the time for manual assembly of a product and the cost of assembling the product on an automatic assembly machine' [BD83]. The method identifies the most important factor in reducing assembly costs as the minimisation of the number of separate parts in the component or product. Three simple criteria are introduced to determine theoretically whether any of the parts in the product could be eliminated or combined with other parts. These criteria can be used to estimate total assembly time and to rate the quality of a product design from an assembly viewpoint.

2.15.1.2 DFD – Design for Disassembly

Design for Disassembly provides for products that are easy to take apart and thus save time and resources at the use stage and end-of life stage. 'The focus of DFD is to improve the design of a product so that it can be disassembled with the least environmental impact and cost' [GCA00]. The main elements of this tool are fasteners used and a product`s structure (e.g. modular design) that provides easy disassembly. Ease of disassembly is an advantage during the Use stage because it makes it easier to take the product apart for service, repair or upgrading certain components or parts (by replacing them). Moreover DFD improves the impact at the End-of Life because a product can be disassembled more easily and this making it more attractive for Recycling and Re-Use which can help reduce the economic and environmental impact. A major issue is the use of fasteners and connection methods.

2.15.1.3 DFM – Design for Manufacture

Design for manufacturability supports the fabrication of single parts or components thus it is based on an integral design in mechanical engineering terms. Additionally DFM helps to reduce the product development times by avoiding flaws in product design and design features of components that are difficult to machine [HP91]. The DFM method leads to an improvement of the manufacturing process and reduced time and energy required for the creation of each product. Thus the environmental impact as a result of energy use is reduced as well as the economic impact due to enhanced production speed and energy cost during manufacturing per product unit.

2.15.1.4 DFQ – Design for Quality

Design for Quality works on the basis that many solutions to a given function are generated and then the one that is considered most suitable is chosen. Aspects that are closely linked to quality issues are especially important for the Design for Quality method. If the DFQ is applied correctly it can reduce errors during the raw material stage and the use stage. During the raw material stage the use of best suitable materials can lead to a better environmental and economic performance. Throughout the Use stage Design for Quality makes the product last longer and increases reliability. The DFQ principle and how it is applied to product design is described in the publication by Huang [HUA96].

2.15.1.5 DFR – Design for Recycling

Design for Recycling helps to produce design solutions that improve the End-of Life scenario of a product. A key issue here is the material used to build the product. First of all the material needs to be recyclable and secondly it has to achieve a certain market value before recycling can even be considered. An issue here is the trade off in terms of economic impact and environmental impact between transportation and recycling. If the costs of transportation and the environmental impact created by it from emission exceeds the revenue from recycling then this option has to be discarded. Furthermore there is the issue of material recycling fatigue as mentioned by Saman [SAM05]: Various materials can only be recycled for a certain number of times (e.g. plastics). After each recycling phase the materials` properties deteriorate. Other materials can be recycled indefinitely (e.g. steel). In addition the waste scenario of the product and the actual amount of products reaching a dismantling and recycling facility needs to be considered as well.

2.15.1.6 DFS – Design for Servicability

Design for Servicability means that measures are taken that allow a quick and easy servicing of a product if required. Especially in the case of extended product life cycle length and an extended duration of the product`s use stage ease of servicabilty gains importance. ‘Unlike design for assembly, producability, etc., design for serviceability (DFS) commonly occurs in the later stages of the design process’ [BEI92].

2.15.1.7 DFT – Design for Testability

Design for Testability is mainly used in the field of software engineering and electronics engineering. With DFT, problems can be identified early in the design, which might occur during the Manufacturing stage and the Use stage of a product.

2.16 Summary of current best practice

There are various practices and developments that came into place recently with the purpose of supporting the design engineer in the endeavour of reducing the environmental impact of a product. Due to the fact that the methodology described in this thesis is merging various aspects of product design – mainly economic, environmental and functional issues - it has to be clarified that no other current tool, practices or development combines all of these 3 issues. In addition to this the methodology is based on the Whole Life Cycle of a product. This is described in the following:

First of all there are current practices that are based on the Whole Life Cycle Approach – thus being based on the LCA approach -and the ones that focus on one certain Life Cycle Step only - most commonly the End-of Life Stage.

Secondly the biggest portion of current practices either take into account the financial aspects – called Life Cycle Costing if based on the Whole Life Cycle Approach – or the environmental aspects only. The following figure 2.15 shows the most important publications on practices and developments and the specific area they fall in: Either LCA or non-LCA based or focusing on either economic or environmental impact or both. Even though some of the current practices are based on the LCA approach and actually take into account both – the economic and the environmental impact they do have shortcomings compared to the methodology described later in this thesis.

	LCA based methods	Source of literature	Non-LCA based methods	Source of literature
Economic/ financial impact based	Designing for Whole Life Costs at the Concept Stage	Sheldon [SPJ90]	Business Model Approach : Design versus Economic Considerations	Harrison [HB00]
	The Management of Concept Design Techniques for Optimising Product Whole Life Cycle Cost	Willcox [WIL95]	Framework of End-of-Live Vehicle (ELV) Value Analysis for Automotive Design Assessment	Saman [SBJ04]
	The economic life cycle	Evans [EM96]	Using cost based FMEA to enhance reliability and serviceability	Rhee [RI03]
	Approximate Product Life Cycle Costing Method for the Conceptual Product Design	Park [PSW02]	The Impact of Product Identity Information on Effectiveness of Product Disassembly Processes	Parlikad [PAR03]
Environ mental impact based	A methodology and support tool for environmentally conscious design and manufacture	Holloway [HOL97]	Environmental aspects when manufacturing products mainly out of metals and/or polymers	Zackrisson [ZAC03]
	Environmental Design Industrial Template (EDIT): A software tool	Spicer [SW97]	EcoDE - An environmental component design evaluation tool	Lye [LLK02]
	Design of environmentally friendly products using indicators	Lenau [LB01]	Product End-of-Life Categorization Design Tool	Rose [RK99]
	Identifying the Environmental Impact Drivers and Tradeoff Options in the Life Cycle of Automobiles	Rebitzer [RF00]	'Green Design Advisor': A tool for design for environment	Feldmann [FMT00]
	Life Cycle Assessment: A Tool for Design for Environment	Teulon [TEU97]	Environmental analysis model for modular design of electromechanical products	Qian [QIA03]
	The Life Cycle Concept as a Basis for Sustainable Industrial Production	Alting [AJ93]	A systematic approach to environmental strategies in product development (EPS) - Models and data of the default method	Steen [STE99b]

Figure 2.15: Publications on current practices and developments – part 1

	LCA based methods	Source of literature	Non-LCA based methods	Source of literature
Both (Economic and environ mental impact based	Economic and ecological aspects in product life cycle evaluation	Westkaemper [[WND01]]	Design for product retirement and material life-cycle	Ishii [IED94]
	A proposed tool to integrate environmental and economical	Senthil [ST03]	A New Methodology for Ease-Of-Disassembly in Product Design	Shetty [SRC00]
	LCA as a tool in the design process of parts, products and systems	Gediga [GFS98]	The use of Environmental Management Accounting (EMA) for identifying environmental costs	Jasch [JAS02]
	A design methodology for the strategic assessment of a product`s eco-efficiency	Lye [LLK01]		
	A multi-agent negotiation-based decision framework for extensible product life cycle	Li [LI,03]		

Figure 2.16: Publications on current practices and developments – part 2

2.17 Chapter reflections

As shown in this literature review there are various methods and tools that are supposed to help lower the environmental impact of a product and call for a more sustainable approach to product design. The drivers for this are for example various EU legislations currently being established. These legislations do not specify how to integrate the environmental issues into product design, rather they set the standard in the form of a lowered environmental impact. It is felt by the author that a lowered environmental impact achieved during the product design process cannot be achieved on the back of economic and functional issues thus creating a trade off. There are various tools and methods available that help the design engineer with the environmental impact and sustainability issues. However there is a considerable gap in what those methods can or aim to achieve and how easily these can be integrated in the design process especially in the case of complex products. On one hand tools such as SimaPro consider the environmental impact only during product design. On the other hand there are a few tools that make an attempt to integrate environmental and economic issues of product design but they achieve this to an unsatisfactory level due to a missing integrated approach. They rather consider one issue first and then move on to the second issue thus producing a trade off problem. In addition then the functionality of a product, and its components, is not considered which is an integral part of an inventive solution. So there is a gap in the current literature and methods available. This gap calls for an inventive approach to integrate environmental, economic and functional product issues whilst using the latest material and transportation databases. Furthermore inventive product design tools such as the Theory of Inventive Problem Solving (TRIZ) and Design for X (DFX) should be part of this solution. This is suggested in various pieces of literature but no advanced method or tools exist that could actually be applied easily by the design engineer. This gap in current methods and tools made the need for research work clear with the goal of developing a product design methodology that takes all those missing items into account and produce a tool to support the design engineer of complex products.

3. Development of the Methodology

3.1 Introduction to Chapter 3

Based on the literature review the need for a new and inventive approach became apparent in supporting the design engineer during the Eco-Design process. In this third chapter the methodology and how it works is explained in detail. Furthermore it is shown how the methodology gives a new approach to Eco-Design and actually satisfies the needs that arose in the literature review.

First of all it is explained how the methodology takes a new approach to Eco-Design and in what ways it forms a unique way of supporting the product design process. Then the basic configuration of the methodology is explained and showing the three distinct phases of the methodology and the user interface as a result of this. The three distinct phases are called Early Concept phase, Advanced Concept phase and Detail Design phase and each is explained in a separate section including schematics and in-detail descriptions.

Moreover it is clarified in this chapter how the methodology integrates economic and environmental product impacts which is the basic objective of the methodology development and implies a main challenge of the research. Furthermore in order to take the most efficient advance towards the improvement of the product in terms of environmental and economic issues the evaluation of the products' performance is addressed by importing and aligning the product functionality. The TRIZ matrix which is the integral adopted method in order to align product functionality with environmental and economic product performance is explained in detail in section 3.10.1. Further existing methods and tools used to overcome the various challenges of developing a methodology and user interface are also described in this chapter.

Within this chapter it is not only explained how the methodology was developed including all the difficulties encountered but the operation of the methodology is explained in parallel to its development.

3.2 Aims of the methodology

As pointed out in the literature review there is a gap in the current tools and methods available on the market. It appears that even though various tools and methods described in the literature provide the user with a tool to measure the environmental impact or the economic impact (but not both in an integrated way) the user is left with identifying the design issues and the measures to be taken in order to improve the product. That is why a methodology that arises from the gap in the literature should produce design suggestions after the areas of major impacts are identified. The design suggestions produced can be based on the approach of delivering specific proposals for improving certain life cycle stages of the product that cause the biggest impact. But furthermore another element should be included that sets a proposed methodology apart from the current tools and methods. This element is the production of inventive product design suggestions that help to reduce the impact of a certain Life Cycle Stage on one hand and help the design engineer to take action in a most effective way. Instead of making limited corrections to the product design the efficiency should be reviewed checking the necessity of certain measures and then making the most inventive decision even if that means that certain components become obsolete if they do not fulfill a purpose.

3.3 Shortcomings of current practices

In this section the shortcomings and limitations of currently available methods and practices are investigated.

3.3.1 Restrictions and limitations of LCA

Even though the Life Cycle Analysis principle supports the user to identify either the biggest economic or the biggest environmental impact of a product design, whilst avoiding a shift between the different Life Cycle stages, the tool has certain restrictions and limitations.

Currently the main focus and goal of LCA is to compare the environmental performance of products and services and to be able to choose the one with the smallest impact. The term life cycle refers to the idea that complete assessment requires the evaluation of all life cycle stages involved. The author sees a possibility within the LCA to carry out a combined environmental and economic product analysis instead of focusing on one of the two aspects.

As mentioned by Willcox [CAT08]: “it is possible for predictions to differ from actual expenditure by as much as an order of magnitude”.

The results produced by the LCA can only be seen as a measure to identify the Life Cycle step that causes the biggest impact, be it the economic, environmental or similar. The results cannot claim absolute accuracy and they are subject to availability and accuracy of input information used in the course of the analysis. This is due to the nature of the analysis: Even if two products that are exactly identical are evaluated their total cost impact for all the life cycle stages can differ depending on the exact circumstance during all their life cycle stages.

As stated by Park [PSW02] Life Cycle Analysis tools can only produce approximate results that “allow the design engineer to make comparative [Life Cycle] estimations between different product concepts”. Hence the comparative approach between different products or different designs of a product is the key element of the LCA.

3.3.2 The TRIZ matrix and its shortcomings

Even though the TRIZ matrix represents a key element in overcoming the obstacle of integrating the product functionality with economic and environmental issues of product design it has certain shortcomings. The two main shortcomings and complications that can arise whilst trying to gain inventive design suggestions and solutions from the TRIZ method are:

- Difficulties in translating the product design issues into contradiction statements
- Problems of interpreting inventive design principles by the user

Cavalucci [CAV01] identifies the main issues of applying the TRIZ method is being able to eliminate a contradiction. To be more exact there are four main problems that could occur when applying the TRIZ method:

1. Imprecision of the definition on what a contradiction is
2. No exact recommendation is given on the formulation of a contradiction regarding a specific problem
3. Generic nature of the design parameters and suggestions within the matrix
4. Interpreting the basic design principles

As stated by Schild [SH04] a major shortcoming is that TRIZ is highly complex which makes it difficult to use for an untrained user. ‘If a company wants to apply TRIZ using internal resources the company needs to provide TRIZ-training.’

So to summarize the statements made in this section, due to the complex nature of TRIZ it can be rather difficult for the design engineer to apply it and use it effectively during the design process. In addition it can be challenging to translate certain product functions and design issues into contradiction statements. Also the interpretation and selection of results represents another shortcoming of the current TRIZ matrix.

A proposed methodology should try to overcome the described shortcomings whilst integrating it into its framework and to make the design suggestions produced as specific for each product design case and easy to apply by the user as possible.

3.3.3 Focus on certain aspects only

There are various methods already available that focus on a single Life Cycle aspect only – most commonly the End-of Life Stage. An example for this is the work of Kwak [KHC07]. In order to carry out a complete and sensible product design assessment all five Life Cycle Stages have to be incorporated – being based on the LCA approach – thus mitigating a shift of the impact between different Life Cycle Stages. Furthermore an integrated approach of economic and environmental issues is a focal point of the proposed methodology. The need for this is described in some literature sources. One of the few publications that mentions the need for an integrated approach is the paper by Westkamper [WND01]

The third group of aspects that are included and merged within this thesis` methodology are the design process progress and the product hierarchy. It is felt that for complex products the product hierarchy is a major issue to be included besides for example material or transportation aspects. Many methods and tools do not take into account either the design process progress or the product hierarchy.

3.3.4 Patchwork problem

As described in the prior sections there are many different tools that take different factors and issues into account in order to support the design engineer. The result of this is that many companies have an array of different tools and methods that focus on very specific product design issues. Several methods might be applied to conduct product costing, life cycle costing and deal with cashflow in general. Those tools and methods are often used within different departments of the company without any link to each other thus missing a central data collection and comparison.

Within the design department alone there might be various tools in use to help with the environmental and economic impact evaluation such as databases, environmental impact evaluation tools, life cycle Analysis tools and several more. Further methods and tools used within the design department– usually software based – are used to design the product itself, e.g. CAD systems.

Hence the design engineer has to deal with various different tools that are aimed at very specific problems and he has to find a way of integrating all of them during the product design process. The author titled this problem the “Patchwork Problem” since various different tools and methods need to be patched together for the product design process representing a very difficult task for the involved parties due to the Design Data Management.

This can be a highly challenging and time consuming task and it might even turn out to be impossible to apply every tool without running the risk of trade-offs.

Furthermore many of those tools and methods are not really integrated within the design process: the design engineer can only apply them at the end of the design process and has to go back all the way to the beginning of the design process in order to apply findings from these methods. This option becomes less viable the more complex the products are.

Due to this problem a methodology is required to overcome this problem needs to tie in the economic and environmental product performance in an integrated way right from the beginning of the design process of complex products helping the design engineer in the decision making practice. This would make the use of several, but probably not all, tools and methods used separately within the design department obsolete and the design engineer can implement various different design issues all at once by applying the methodology and the proposed user interface.

3.3.5 Current design tools require preparation and time effort to be applied

Another important factor of practicability of currently available tools and methods that aim at supporting the product design process is the time effort necessary to apply them most efficiently. The current set of tools available to help with economic and environmental issues of product design are either a loose collection of various tools such as the ISO 14000 standards which takes a lot of time and knowledge from a well experienced design engineer or similar to be put in place for future procedures, or software tools like the SimaPro [PRE07] toolkit or similar which are very specific and require training for the design engineers to apply them. This is not to mention the financial aspect of putting both of them in place: costs of the actual tool or method available on the market.

Another issue is the fact that some tools try a ‘one size fits all approach’ covering simple products and services up to highly complex products. This can result in a solution that does not really support different types of product design to a sensible detail but instead each one to an unsatisfactory degree. In more detail this means that some tools available on the market try to offer a solution that covers all product and service types on the market. Unfortunately in many cases the LCA results produced for many cases are too generic.

Moreover some of the environmental impact tools require the design engineer to have at least some knowledge in the fields of sustainable development and life cycle assessment as for example the SimaPro 7 [PRE07] tool described in section 2.7.1 does. In most cases this requires some form of training since most design engineers are not familiar with this area of science.

Another factor that adds to the confusion is the fact that there are several semi-professional software tools available on the market each each taking a different approach to Eco-Design or Life Cycle Assessment. Additionally some of the tools available only measure the environmental impact only without giving any design advice. This can be difficult to use and translate into changes to the product design for some of the users.

3.4 Inclusion of existing design tools

Since the environmental impact and the economic impact are very different in their nature and they are usually measured using very different indicators the first main challenge was to find a way to compare them. The indicator used to measure the economic impact is usually by assigning cost in the form of the local currency.

The indicators used to measure the environmental impact can be various as described in chapter 2: e.g. emissions such as carbon emissions (kg of CO_2), embodied energy (MJ per kg of material), Eco-Indicator (millipoints per kg) and so on.

Within the course of this research different ways of aligning and integrating the two issues (environmental and economic impacts) were investigated and considered but the most promising one appeared to be to assign a cost factor to the environmental impact of the product. For example if a product causes a certain amount of carbon emissions during manufacturing the resulting cost was the taxation of carbon emissions. In the case when the product causes waste during its use the assigned environmental cost are from the waste treatment. This made it possible to compare the two different issues within a life cycle assessment and consequently find the major impact areas in terms of life cycle stage and product structure. This allows for the application of cost figures to an array of different environmental impacts and thus being able to compare the direct cost of a product and the environmental impact.

It has to be decided within the course of the proposed research which databases should be linked into the methodology and to what extent modifications to them are necessary.

Further tools and methods that may be linked in are the TRIZ matrix and DfX as the major tools, and various small applications for the minor problems that might occur during the development of the methodology. The TRIZ matrix is proposed to be one of the solutions to produce highly inventive design suggestions for the product design. The DfX tool has to be considered to be integrated for the design suggestion production mainly. It might be able to adopt certain ideas from it to set up a design suggestions framework that delivers design suggestions targeted at product enhancement with a specific focus on certain life cycle stages.

Additionally a way has to be found to align the product structure and the design progress. This is due to the fact that the proposed methodology aims at complex products in which case it is not enough to evaluate a product as a whole but a closer look at the product structure is necessary. Besides that in the case of complex products the design process is a tedious and long one as opposed to the design process of rather simple products. Thus it is considered to find a way to align the product structure and the progress of the design process in order to increase efficiency of the proposed methodology and make it more convenient for the user.

3.5 Proposal for a new approach to Eco-Design

The aim of the Eco-Design principle is in essence the reduction of a product's environmental impact without creating a negative trade-off with other design criteria, such as costs and functionality. The author feels that instead of focusing on the environmental issue only an integrated approach is required in order to address all three issues equally – environmental impact, economic impact and product functionality – instead of improving one issue first and then minimizing the trade off with the other two issues.

Even though the initial setup of the methodology intended to support compliance with the EuP Directive it cannot be claimed that it would ensure compliance for all product types with current and future legislative issues of the EuP Directive. Within the methodology a more basic approach to the Eco-Design principle is needed to help the design engineer to set the groundwork during product design for the compliance of an energy-using product with the EuP Directive. Nevertheless the basic principles set out in the EuP Directive of the European Union will be covered by the methodology and user interface. First of all the EuP Directive aims to reduce the environmental impacts of products across the whole of their life cycle. This is the key principle of the EuP. Additionally the EuP states that the product structure and hierarchy should be taken into account which will be covered by the methodology. Furthermore there are ten Eco-Design parameters that should be taken into account:

1. **Weight & volume of product.**

   Within the Eco-Design process the weight and volume of the product should be reduced. These are mainly predetermined by: material choice, products` purpose & specification, technological advancement of the product market.

2. **Use of recycled materials.**

   Use of recycled material generates a closed loop and thus a more sustainable product. This can lower the environmental impact as well as the cost since recycled materials are often less expensive than virgin raw materials.

3. **Resource consumption**

   Resources defined by the EuP include energy and water.

4. **Hazardous substances**

   The hazardous substance issue must be covered by the methodology since components and parts can be identified that have to be treated and go to hazardous substance landfill at the end-of life. The toxicity potential of parts must also be considered within the methodology.

5. Consumables for Use and Maintenance

Consumables have to be considered within the methodology and specific information has to be given by the user.

6. Ease of re-use and recycling

This EuP parameter must be embedded within the methodology, most likely via an end-of life scenario evaluation for the whole product, each component and each part.

7. Incorporation of used components

The financial and environmental impact evaluation of the product should take into account whether product components and even parts are re-used and fed back into the life cycle of a new product generation. Figure 3.1 illustrates this.

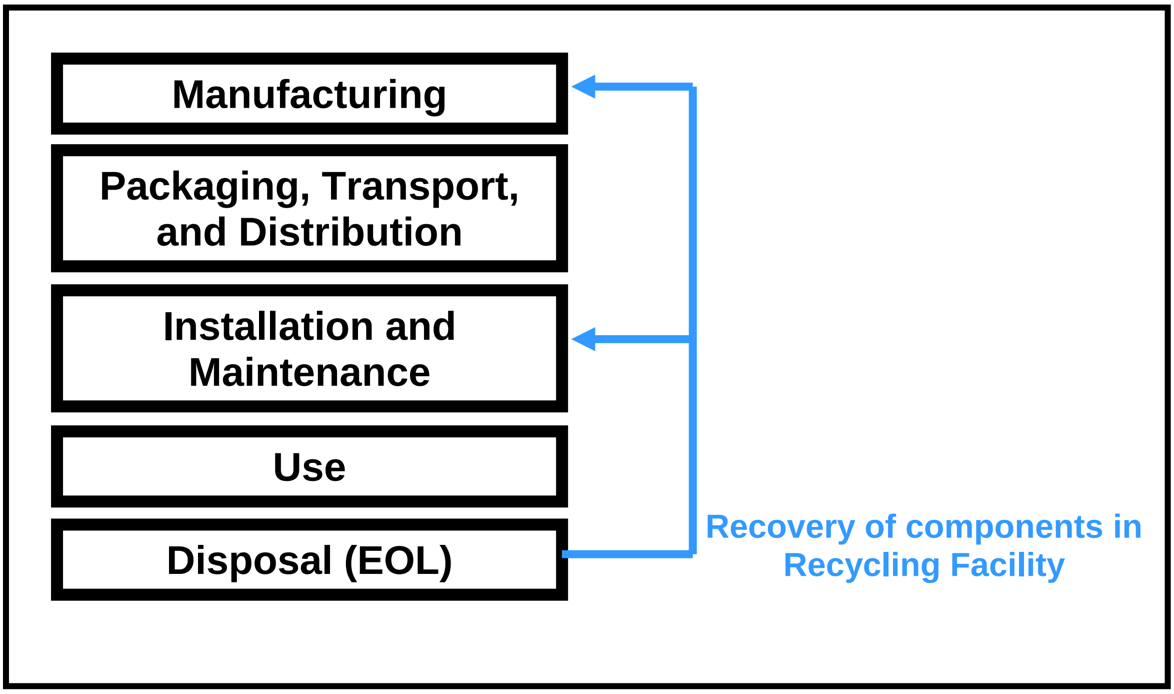


Figure 3.1: Recovery of components in a Recycling Facility

8. Extension of Lifetime

A product should be designed in a way that it can be repaired instead of being discarded. Hence easy access and repair-ability should be considered during the product design phase. The average life cycle length will be considered as a starting point for calculations within the methodology.

9. **Waste Generated**

The methodology and user interface must acknowledge waste as a result of the life cycle stages manufacturing, use and end-of life (disposal) as shown in figure 3.2.

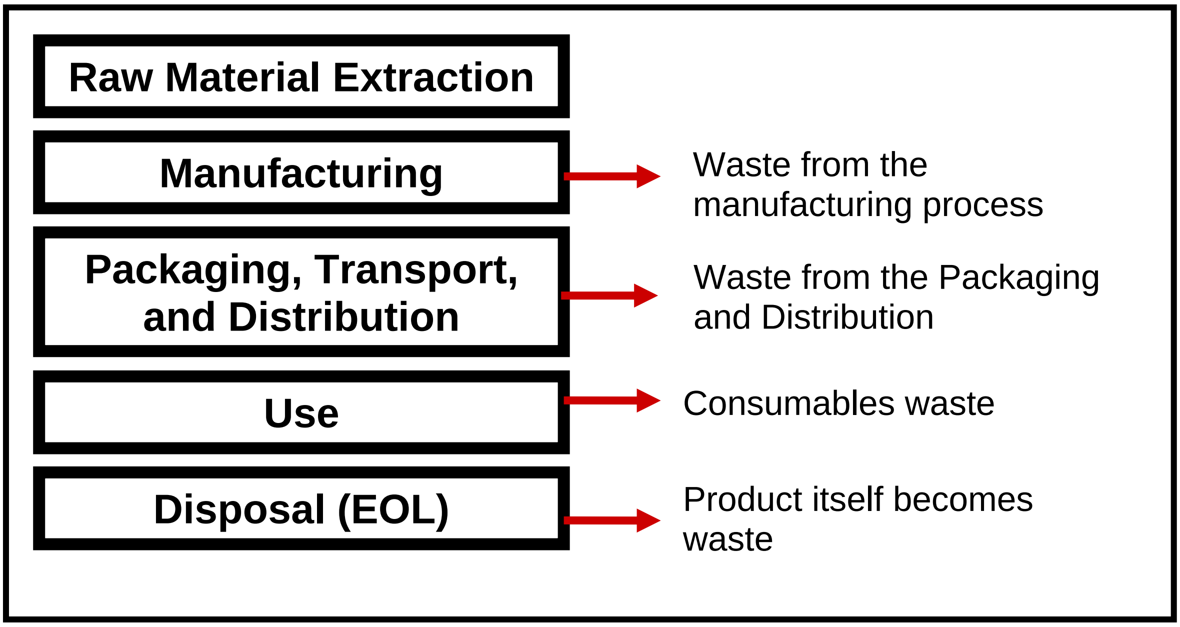


Figure 3.2: Waste generated during the product`s whole Life Cycle

10. **Emissions**

The environmental and economic impact of emissions as a result of raw material production, manufacturing processes and energy use during the manufacturing stage, the transportation stage and the product use stage must be taken into account within the methodology.

Dealing with the environmental design issues on top of current design issues can cause a serious struggle for the design engineer in terms of trade-offs. The design engineer is faced with additional tasks and requirements so consequently there is a huge amount of different complex criteria to consider [RF00]. By devising a methodology that addresses the shortcomings identified it is possible to consider various different design criteria such as environmental and economic impact as well as functionality and product structure. Most possible trade-offs of product design are avoided by considering most design issues simultaneously but a complete avoidance of trade-offs is impossible to achieve due to the nature of the process. Moreover the methodology supports the design engineer in finding an innovative and effective improvement of the product design ensuring continuous improvement.

3.5.1 Integration of environmental and economic issues

The first and foremost outcome that will address the shortcomings of most current practices on the market is the integration of environmental and economic issues. As discussed earlier most methods and tools currently on the market focus either on the environmental or the economic impact. Only a small fraction of current practices either promotes for an integrated approach or even introduce the groundwork on how to achieve this.

As stated by Gediga [GFS98] a methodology is required that evaluates a product on the basis of environmental costs and identifies possibilities of improving the economic and environmental behaviour a product during its life cycle. Furthermore it has to identify areas with the greatest impact and biggest potential for improvement and then produce design enhancement suggestions that can easily be applied by the product design engineer. This leads to compliance with legislation due to a continuous improvement of the environmental impact and better competitiveness as a result from lower product costs either for the producer or the customer.

Most companies see the integration of environmental issues as another design factor that complicates the design process further and will cost them money at the end of the day. 'The application of Eco-Design […] can mean a burden as well as an opportunity for large companies. For the short term strategy of a company it means additional costs and additional manpower which must be allocated to integrate this principle into a company's product design procedures' [GJB06].

The differences of those practices presented can be reviewed in figures 2.15 and 2.16. To give an example how the methodology works for a specific case: the energy use during the products` manufacturing life cycle stage can be measured in both economic (or direct) cost and environmental cost. The direct cost would be what the company currently pays for its electricity bills. The environmental cost could be measured by applying the “Climate Change Levy” tax to the amount of energy used. This environmental cost is then added to the direct cost to product the total cost of energy use during manufacturing.

To provide more detailed information regarding the environmental cost driver for energy use at manufacturing: ‘The Climate Change Levy (CCL) was introduced in April 2001. The CCL is an energy tax that adds approximately 15% to typical energy bills of UK businesses’ [CCL06]. In the case of the Manufacturing Life Cycle step this CCL tax is paid for by the producer of the product and it will probably have an impact on the consumer via the increased price per product unit even if it is a small fraction only. The figure 3.3 shows the “Climate Change Levy Tax Calculator” which helps companies to evaluate their tax cost based on the various energy sources used by the company.

Fig 3.3 has been removed due to third party copyright. The unabridged version of the thesis can be viewed at the Lanchester Library, Coventry University

Figure 3.3: The Climate Change Levy Tax Calculator [CCL06]

There are various other factors that contribute to the product's environmental costs which should be part of the methodology. A few examples for environmental impact costs drivers are given in the following:

- Costs of product packaging disposal during Transportation Life Cycle - which is usually covered by the consumer even if it is via an indirect way such as Council Tax
- Costs of hazardous material outflow during Use Life Cycle (e.g. oil change for a car) – covered by the consumer during servicing.
- Hazardous material treatment cost at the product's End-of Life in the case that hazardous substances are part of the building material of the product. This environmental impact cost can be covered by various sources depending on the product and its End-of Life scenario. For example in the case of a producer take back scheme the producer of the product has to cover this cost.

The purpose of this is to give a complete picture of Life Cycle costs of a product including costs that are currently not fully paid by either one of the stakeholders but that will occur in some form as costs in the future and be paid for by a third party. A good example for this is the cost of transportation for setting up a "Take Back Scheme" for products reaching their End-Of Life Stage. This is for example coming into place in the form of various new legislations such as the WEEE (Waste of Electronic and Electrical Equipment) Directive [ENV06] and the costs of this are not included in most Life Cycle Cost evaluations.

Improving the environmental impact on the back of increasing certain direct costs is avoided by this merged approach. Instead a simultaneous reduction of the products` Life Cycle cost and the products` life cycle environmental impact can be achieved. Thus a continuous product improvement can be made whilst avoiding a trade off.

3.5.2 Alignment of design process progress and product hierarchy

Another approach that will be included in this methodology and that will set it apart from current practices on top of integrating environmental and economic aspects is the alignment of Design Process and Product Hierarchy. Due to the fact that the purpose of the methodology is to evaluate complex products it became obvious at a very early development and research stage that the product hierarchy has to be included in some way. Figure 3.4 shows a schematic of the product hierarchy structure.

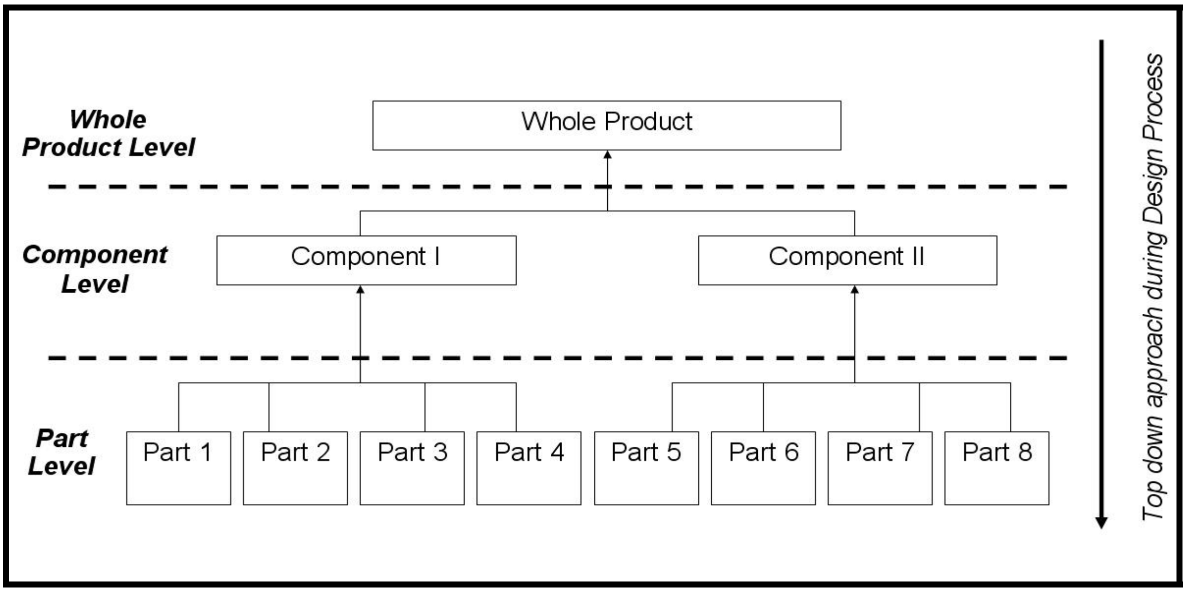


Figure 3.4: Product Hierarchy Structure

The proposed methodology does not focus on the re-design of an existing product mainly, as in most methodologies, but on new products or a new variant of an existing product. Nevertheless it is possible to apply the methodology to an existing product design in order to enhance it. One of the key requirements, that was set early on in the methodology development process, was that product hierarchy structure would be included. At that point it was not established if a bottom up or top down approach would be chosen: Bottom up meaning that the product is evaluated on the lowest hierarchy part level first and then moved towards a higher level of the product hierarchy with the progress of the product design process. A top down approach starts analyzing the product at the whole product level first and then move down the hierarchy levels. A top down approach was chosen for this methodology due to the fact that at a very early design phase of new product only information regarding the whole product is available. Once the design process advances information regarding product components become available. Then at the final stages of product design data regarding every single part is obtainable. Hence the proposed methodology is applicable in a manner parallel to the product design process covering all its stages from early concept to the detail design.

A main reason for the decision to integrate the product hierarchy and the design process is that the product structure and hierarchy is of importance for complex products and should be considered during the product design process. Thus complex products require an integration of the product structure and product hierarchy, otherwise it will be nearly impossible to consider all the trade-off effects of a design decision. Hence a design evolution hierarchy is developed that makes it possible to allocate a certain progress stage in the product design to a certain level within the product hierarchy.

There are three distinct phases in the methodology, each focusing on different levels of the product structure due to their availability. At the early concept design phase information regarding the product as a whole is evaluated. At a more advanced design concept phase when information regarding functional units and components of the product is available information is evaluated by the methodology in a separate step. Finally at the detail design phase specific information regarding parts are evaluated such as material used and size of material.

Due to the integration of product hierarchy and the product Life Cycle it is possible to benchmark the impact within the product hierarchy and within the Life Cycle Stage. For example a motor vehicle may have its biggest impact as a whole product during the use phase but the biggest impact of a certain component may occur at the end-of-life (EoL) stage, due to toxicity.

It became obvious during the methodology development that instead of integrating and merging both issues into the methodology, synergies and common ground between the product hierarchy and the progress of the design process had to be found. The similarity found was that during most product design procedures at the very beginning - Early Concept phase – specifications are set for the product as a whole. Also most of the information available to the design engineer is regarding the product as a whole. To give an example: when designing a product most design engineers start setting certain boundaries and specifications which the product as a whole has to meet.

When moving ahead with the design process to the Advanced Concept stage the design engineer is able to move down one level in the product structure or product hierarchy. He arrives at the component level and most likely puts together a list of certain components: thus the product will be able to fulfil its purpose. Functions of each component are already an issue here.

The next and final phase of the product design process is the Detail Design phase. At this design phase the design engineer moves down one more level within the product hierarchy and arrives at the part level. It became obvious that in order to align both the “Progress of the Design Process” and the “Product Structure Hierarchy” that the top down approach is the only logical course of action. This is shown in figure 3.5 – Design Evolution Hierarchy Chart. For example during the early phase of product design the methodology focuses on the product as a whole. After some time has passed the design process reaches a more detailed phase (e.g. Advanced Concept Phase) and more detailed information regarding the product becomes available going down to the component level.

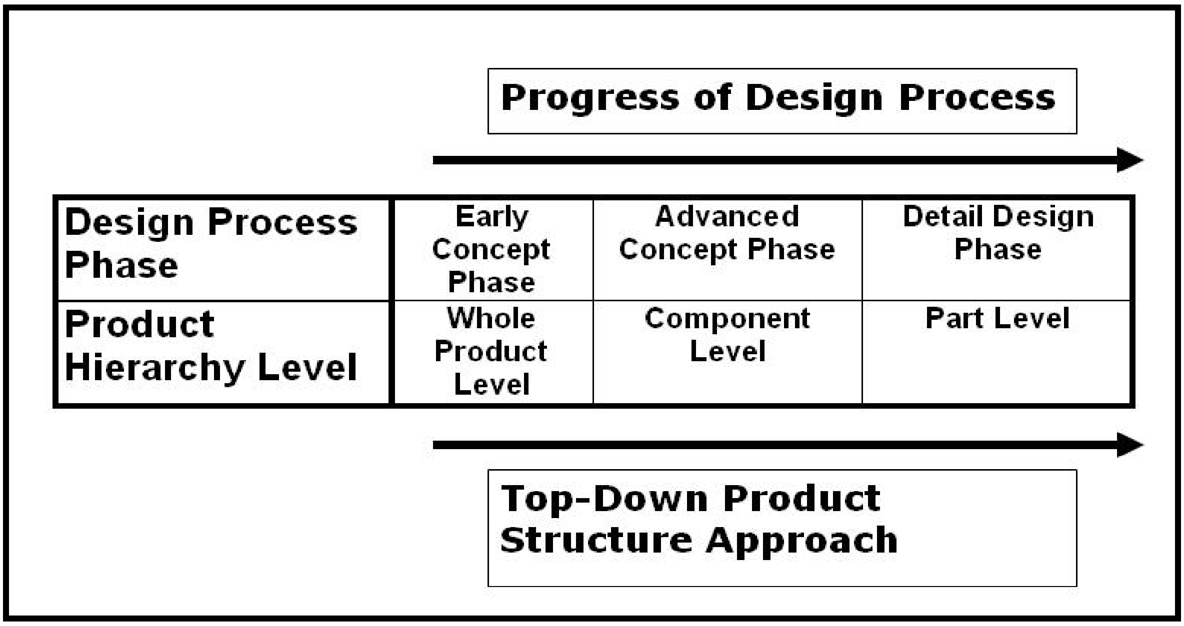


Figure 3.5: Design Evolution Hierarchy Chart

Hence the methodology and the user interface can be applied at all stages of the design process in a step by step approach. This method is more efficient for complex products in terms of time consumption and time of concept to market than just to evaluate the product design for improvement potential at the very end of the whole design process.

3.5.3 Application and integration of the functionality issue via the TRIZ matrix

There is only a limited amount of literature and methods available that deal with the integration of the TRIZ matrix into the Eco-Design process. During this section the few pieces of literature that are available and propose to integrate the TRIZ matrix to create inventive results are investigated. Furthermore they are benchmarked in terms of what they achieve compared to the proposed methodology created as a result of the research described in this thesis.

Chang suggests in his paper [CC04] the ‘conflict-problem-solving CAD software, Eco-Design Tool, which integrates TRIZ into the eco-innovation idea’. His approach is based on the seven major eco-efficiency elements for companies suggested by the WBCSD (World Business Council of Sustainable Design) [LEH00]:

1. Reduce the material intensity of its goods and services (material reduction)
2. Reduce the energy intensity of its goods and services (energy reduction)
3. Reduce the dispersion of any toxic materials (toxicity reduction)
4. Enhance the recyclability of its materials (material retrieval)
5. Maximize the sustainable use of renewable resources (resource sustainable).
6. Extend the durability of its products (product durability).
7. Increase the service intensity of its goods and services (product service).

Furthemore Chang`s method is based on the attempt to combine TRIZ engineering parameters with these 7 eco-efficiency elements by Liu and Chang which is shown in figure 3.6.

Fig 3.6 has been removed due to third party copyright. The unabridged version of the thesis can be viewed at the Lanchester Library, Coventry University

<u>Figure 3.6:</u> "Table for relationship of engineering parameters and eco-efficiency elements" [CL03]

Even though it is proposed in this literature that the TRIZ matrix can support eco-innovation design tremendously, its perceived weakness is that economic issues are not included at all. This might lead to the effect that whilst the eco-efficiency might be increased, and thus the environmental impact is reduced based on functionality, using the TRIZ principle within Chang`s method can lead to an economic trade-off. This shortcoming is addressed in the proposed methodology because all three issues are integrated within it: functionality, environmental impact (or eco-efficiency) and economic impact.

Another method that recommends the integration of TRIZ into the Eco-Design process is developed by Low [LLW+01] and it is called "Manufacturing a Green Service: Engaging the TRIZ Model of Innovation". It advertises the generation of 'innovative environmentally friendly solutions via TRIZ models, based on the theory of inventive problem solving' (TRIZ) and investigated their ability to systematise this approach. On the one hand the article focuses on the context of transforming products to services mainly rather than product design itself. On the other hand the method proposal described is at an early stage of development and does not show any potential of a tool that can easily be used. Thus the shortcomings of this method are its lack of usability, its focus on services instead of product design itself and the entire exclusion of the economic issue.

All the articles and methods that present an inclusion of the TRIZ matrix in order to address the functionality issue during product design do so mainly focusing on the environmental issue, called eco-efficiency in certain articles. No article proposes to integrate the three issues of functionality, environmental impact and economic impact into the product design process. Thus the methodology developed in the course of this research addresses the shortcomings of current practises and methods.

3.5.4 Integration of the DfX method

The Design for X (DfX) method can be used to help optimise the product design for certain Life Cycle stages. For example with the application of design for recyclability a product can be augmented in terms of its end-of-life performance. In this section various current methods and practices are reviewed that propose the integration of DfX methods into product design and how the proposed methodology improves this.

Bariani investigated in 2004 in his paper the possibility of a symbiosis of TRIZ and a DFX tool called design for manufacture and assembly (DFMA) with promising results [BBL04]. The paper focuses on only one of the various DfX tools: design for manufacture and assembly instead of attempting to include others also. Thus it benefits the manufacturing life cycle stage only instead of all five life cycle stages not taking the whole life cycle into account for the product design.

Tichem and Storm discuss a model that uses the DfX tools in order to help the designers in the structuring of products, taking into account a number of life-cycle considerations [TS97].The presented model of the design serves as a basis for developing support on product structuring within DFX. The model described in the paper shows three issues: execution of design activities, results of design activities and coordination of design activities. The scope of the research described in the paper is ‘limited to product structuring; hence, the result of the design activities as regarded in the research is a set of related product structures’.

No regard to economic or environmental issues is given. Furthermore the model and framework discussed in the paper is at a very early theoretical stage and no usable or testable software based interface exists.

Huang and Mak [HM98] present a ‘generic framework for applying specific DFX tools.’ This framework uses various DfX principles to support the user with the enhancement of the product design. A major shortcoming of this framework is ‘the full DFX functionality can only be achieved with active participation from the human user(s).’ Thus it requires the involvement of a design engineer who is familiar with the DfX principle on one hand and the framework cannot be applied easily by an untrained user. On the other hand it takes even the trained user quite some time to apply the framework for a standard product resulting in a very tedious task in the case of highly complex products. This shortcoming needs to be addressed within the proposed methodology and resulting user interface. This is due to the fact that all the various DfX principles are used and integrated to produce design suggestions for the various scenarios depending on the environmental cost and direct cost impact. Thus the user does not have to be familiar with the DfX principle at all, the methodology takes care of everything. This is explained in more detail in the following section.

The proposed methodology helps apply the right DFX tool for the relevant problem. Basically the design suggestion matrix at all three product design phases - Early Concept design, Advanced Concept design and Detail design – is based on the DfX principles. Some of the design suggestions are taken from the ideas of the DfX tools whilst others are derived from brainstorming and other available tools. Within the methodology this works out as follows: Once the life cycle stage with the biggest and most severe economic and environmental impact is evaluated by the methodology the design suggestion matrix produces concepts and suggestions for how to reduce this impact. As explained before, the basic framework for this was developed based on the various DfX principles but it was enhanced by using various other methods and ideas also as well as the knowledge of the author. Furthermore the examples for the improvement potential are used from practical literature sources and the author`s work experience. Their purpose is to give the user a better understanding on how the improvement suggestions could be applied and to give a practical example. Two DfX principles are actually integrated in the design suggestion matrix for this life cycle stage as shown:

- Design for disassembly (DfD)
- Design for recycling (DfR)

All the current practices available that are either based on the DfX method or integrate it in various different approaches into their product design support methodology have one thing in common. They all require the user to be experienced or at least aware of the DfX method and its various principles (for example Design for recycling). The proposed methodology addresses this shortcoming since it includes various DfX principles in its design suggestion matrix. So the methodology can support the user, even if not an expert in the field of DfX, in finding product design solutions linked to the DfX method.

3.5.5 Easy and intuitive to apply user interface

A major advantage of the proposed methodology is that it evolves from a theoretical methodology to a complete software based user interface which is very easy and intuitive to use. Whilst many methods and frameworks described in the preceding chapters make use of software in order to make it easier for the user to apply them, in most cases the software is at a premature state and it cannot yet be stated that it can be used intuitively.

The software based user interface aims at generating helpful design suggestions for the user, in most cases the design engineer. All that is required from the user is the preparation of various general input information data that should be easily obtainable. The rest is carried out by the user interface itself: production of environmental and economical impact results based on the input information. Furthermore inventive product design suggestions are produced that are based on economic, environmental and functional issues and that are embedding the TRIZ matrix as well as the DfX methods in their framework.

When the user has to provide information, the direct cost and environmental cost impact is evaluated by the methodology and user interface. The last step is the production and display of design suggestions which are easily applicable. This is the case for all three stages of the product design progress and its parallel product structure hierarchy level.

3.6 Basic configuration of the methodology

Taking the preceding requirements into account a framework was devised that will be described in this and subsequent sections.

The methodology developed in the course of the research and described in this chapter does not focus on the re-design of existing products but on new products or a new variant of an existing product. Hence it has to be applicable in a manner parallel to the product design process covering all its stages from early concept to the detail design. Complex products require an integration of the product structure and product hierarchy, otherwise the trade off and effects of a design decision become too complicated and time extensive to weigh against each other. Hence a design evolution hierarchy is developed that makes it possible to allocate a certain progress stage in the product design to a certain level within the product hierarchy. Thus synergies between the issues of product structure and the progress of the design process are found and taken into account in a streamlined approach.

The methodology consists of three distinct phases each focusing on different levels of the product structure due to their availability. At the Early Concept phase of the product, design information concerning the product as a whole is used for the methodology. At the Advanced Concept phase of the design process when information on the individual product components is available, functionality is considered in addition to life cycle information. Finally at the Detail Design phase specific information regarding parts are evaluated such as material use, end-of life scenario of the part and weight.

Further detail on the individual methodology product design phases – Early Concept phase, Advanced Concept phase and Detail Design phase – are given in section 3.7.

Furthermore the TRIZ methodology and the DFX toolkit are integrated into the proposed methodology to produce inventive product design enhancement suggestions. This is discussed in further detail in the following sections. During the course of the research it is found that the DfX principle can be adopted to generate design suggestions during all of the three main steps of the methodology. The TRIZ matrix on the other hand is used as a solution to overcome the issue of addressing the functionality of the product during the product design phase 2: Advanced Concept stage whilst improving the economic and environmental performance of the product at the same time.

Social effects are very difficult to measure and could not be taken into account during this phase. A good example for a social effect is the reduction of quality of life in the area where the manufacturing facility is based due to nuisance from noise and odour from the production process.

Hence in a quantitative process only the direct costs and costs resulting from the product's environmental impact are evaluated. For each life cycle stage overall costs are given based on the following four main cost driver groups: energy costs (e.g. electrical or fuel), emission related costs and material cost. Each of these main groups can be split into direct costs and costs resulting from the environmental impact (called environmental cost within the user interface). These costs are quantified for each product unit instead of the whole yearly production volume.

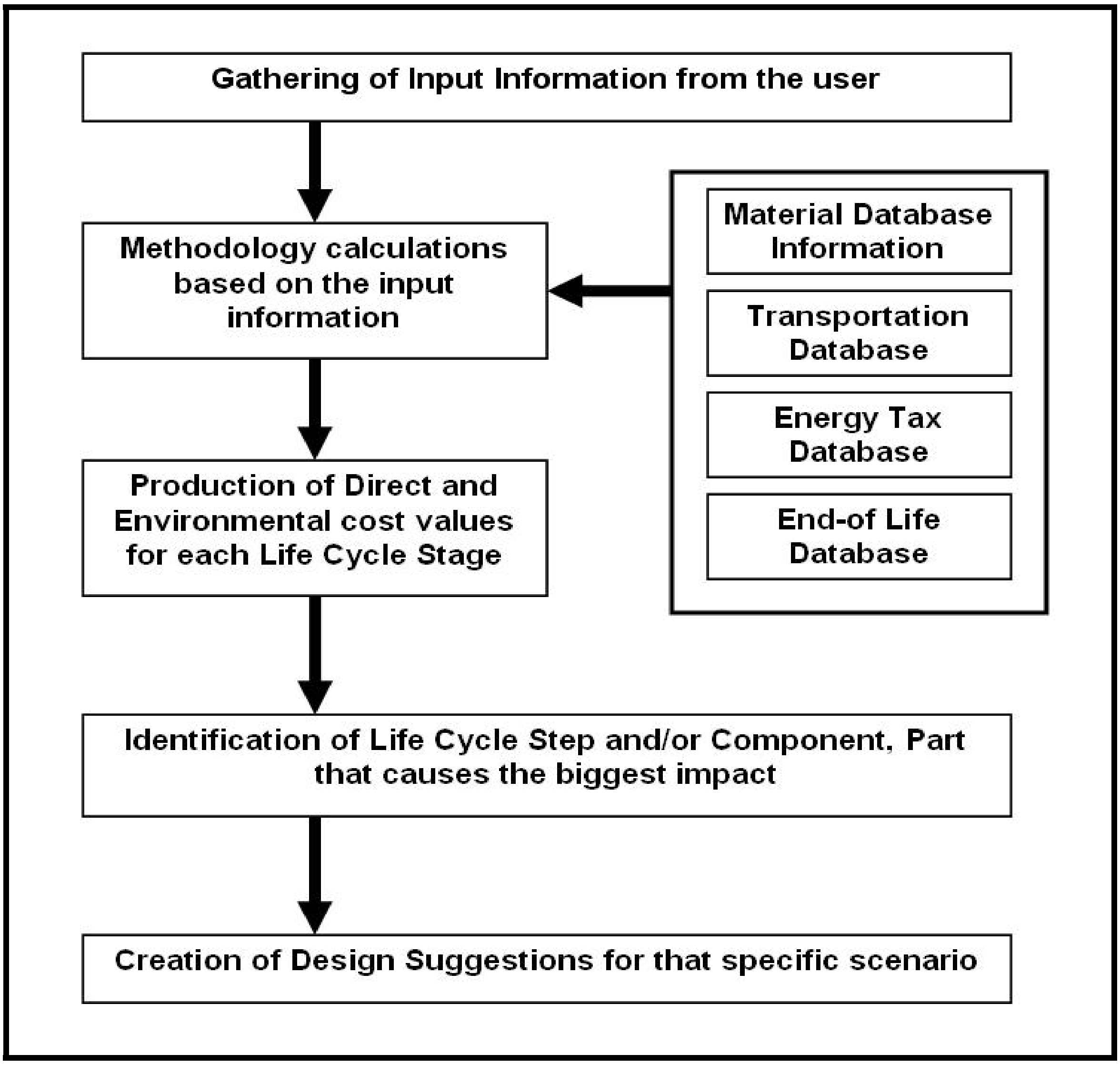
The input phase is divided into the collection of general information and the collection of information for each life cycle stage. The methodology uses the input to identify the potential environmental and economic cost drivers. The area with the biggest impact and hence the biggest potential for improvement will be associated with one of the five life cycle stages. Moreover the impact may be narrowed down to one specific issue in a definite area of the product's profile such as "stand-by energy" consumption during the Use stage.

Furthermore a flowchart of how the methodology was devised and developed can be found in figure 3.24 at the end of this section titled chapter reflections.

3.7 System overview – three distinct phases

The proposed Eco-Design methodology consists of three main phases of product design: Early Concept phase, Advanced Concept phase and Detail Design phase. The application of the methodology in three distinct steps helps to avoid a time consuming re-design of the product, rather than if Eco-Design and LCA is only applied at the end of the design process. Figure 3.5 shows the design process phases and the product hierarchy level in more detail. This is particularly valuable in the case of complex products since a complete product re-design could take several months and a loss of any competitive advantage.

There are three distinct phases in the methodology each focusing on different levels of the product structure due to their availability: At the early concept design phase information regarding the product as a whole is evaluated. At a more advanced design concept phase when information regarding functional units and components of the product is available information is evaluated by the methodology in a separate step. Finally at the detail design phase specific information regarding parts are evaluated such as material used and size of material. During this calculation process various items of database information are linked in such as material, transportation and various others. Subsequently design enhancement suggestions are produced by the methodology based on which life cycle step causes the biggest impact and on particulars from the input information given. Figure 3.7 gives an overview of the general course of events for each of the three main phases of the methodology.



<u>Figure 3.7:</u> Basic Configuration of the methodology for each of the three methodology phases

Even though the basic configuration for all three methodology phases is similar there are differences. In the following each of the three methodology phases is described briefly – a more detailed portrayal is given in sections 3.8 – 3.10:

The Early Concept phase is conducted at the beginning of the design process when the basic parameters for a new product or a variant product are being determined. It considers the product as a whole since that is the only information available to the Design Engineer early in the design process. Hence this information has to be provided by the user and the methodology then produces results in terms of direct costs and environmental cost for the product as a whole. Furthermore design suggestions are given to support the improvement of the whole product.

During phase 1 – Early Concept – input information regarding the product as a whole is required from the user. Then the methodology evaluates the input and produces results for each life cycle stage of the product. The results show different types of costs:

- Direct costs (costs that can be directly linked to the product excluding labour costs, e.g. material costs, fuel costs)
- Environmental costs (costs resulting from an environmental impact, e.g. Eco-taxes, toxic substance treatment, etc.)
- Total costs (the sum of both direct and environmental costs)

When the major impact life cycle stage is evaluated the methodology produces design suggestions in order to help the user – usually a design engineer – enhance the product and lower the direct cost and environmental cost thus both impacts.

Once the design process advances further information regarding the individual product components becomes available: thus the next level of the product hierarchy is reached – the component level. This phase of the methodology is called Advanced Concept phase. Again input information is provided by the user and the methodology utilizes this. The Advanced Concept phase includes a functional analysis of the product components and a complete direct and environmental cost LCA of each component.

The next and last phase is called Detail Design phase. It uses specific information regarding parts and evaluates aspects such as materials used, weight of the part, complexity and so on. Similar to the proceedings of phase 2 – Advanced Concept phase – the part is identified that causes the biggest total cost impact and then design suggestions for this individual part are given.

The main challenge of the work was to find a way to integrate the environmental, economical and functional issues of product design. Throughout phases 1 and 3 various different product design feature issues are integrated as part of the methodology. Moreover during phase 2 the product design feature issue of functionality is taken into account using the TRIZ and DfX matrix thus producing an original method. The contradiction matrix and the 40 inventive principles of the TRIZ matrix need to be amended to achieve this goal. Then inventive principles are allocated to certain component functions instead of relying on the improving and worsening features.

Furthermore a solution needs to be developed in order to align and measure environmental and economic product performance whilst producing design suggestions for the part hierarchy level. Furthermore key findings of the research include the limitations of this approach, as well as the trade off issue during product design between the different life cycle stages and the incorporation and availability of information used from databases.

3.8 Early Concept Phase

As described in the previous section the first phase of the methodology that focuses on the whole product level is called Early Concept phase. Figure 3.8 shows the workflow diagram of this phase.

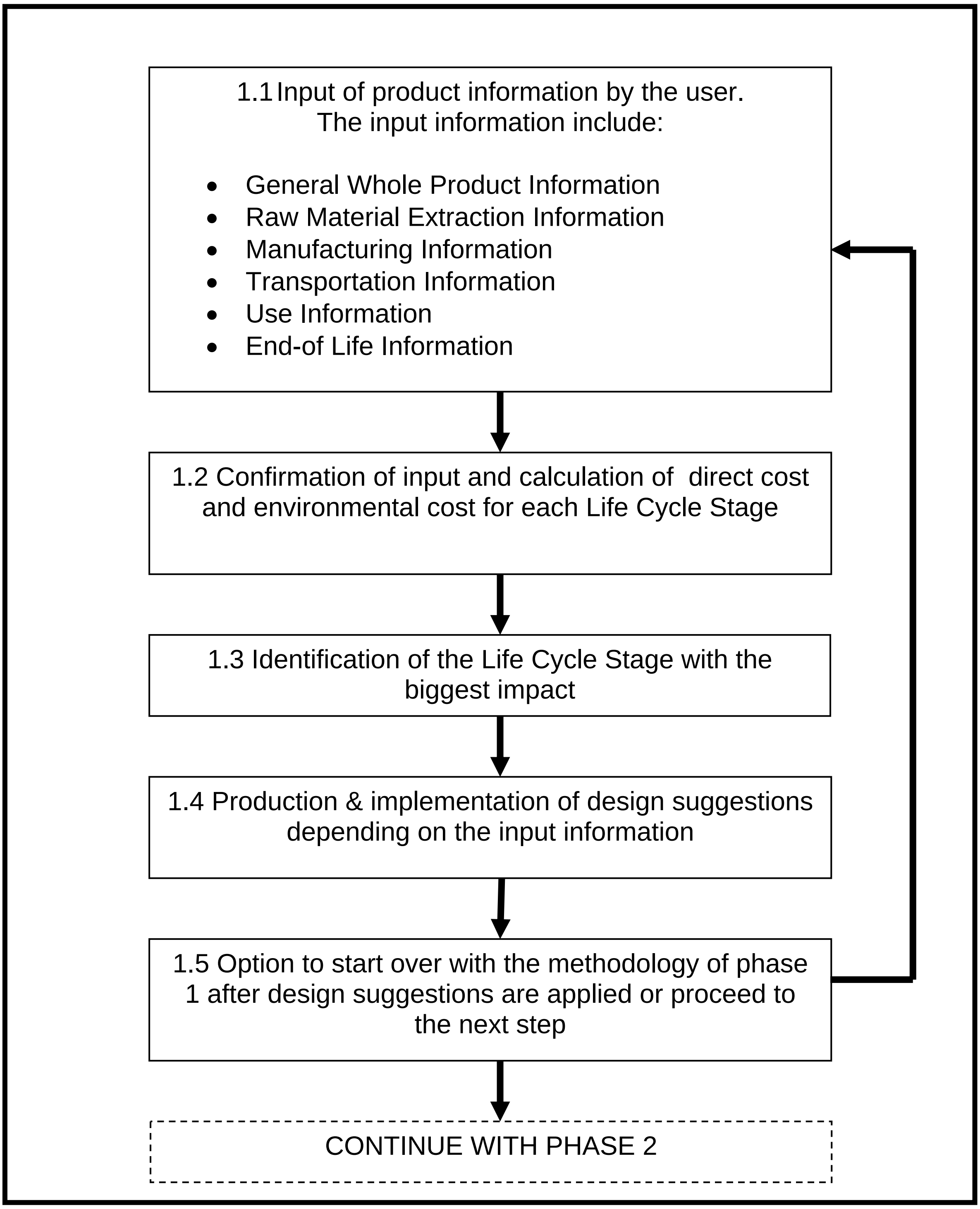


Figure 3.8: Workflow diagram of the methodology – phase 1 – Early Concept phase

Step 1.1 of the methodology that is shown in figure 3.8 is about gathering input information from the user. There are basically two types of input information that are collected from the user. On one hand general information regarding the product as a whole is assembled such as product use frequency or production volume (per year).

Then in step 1.2 the input information is confirmed and the methodology evaluates the Direct Cost, the Environmental Cost and the Total Cost – The sum of Direct Cost and Environmental Cost. Appendix A.2 shows in detail how the results are produced within the context of the user interface and the methodology. This is done for each Life Cycle Stage of the whole Product: Raw Material Extraction, Manufacturing, Transportation, Use and End-of Life. Additionally the percentage of Total Cost share for each Life Cycle Stage is given.

Based on this the life cycle stage that causes the biggest impact is identified in step 1.3 of the methodology – which is basically the life cycle stage with the highest value in percentage of total cost share.

After that the methodology produces Design Suggestions based on which Life Cycle Stage causes the biggest impact and based on certain input parameters. For this the methodology identifies the Life Cycle stage with highest total cost value. Then a catalogue called the Design Suggestion matrix is accessed that supplies design suggestions that best suit the reduction of the environmental and economic impact of the Life Cycle Stage in question. But the Design Suggestion matrix takes into account certain input information parameters. For example if a certain input information supplied by the user does not exceed a specific value certain design suggestions are not given back to the user since they are not suitable in that case.

Hence the Design Suggestions are not simply based on which Life Cycle Stage causes the biggest Total Cost impact but are flexible and dependent on constraint of the input information data. This is step 1.4 of the figure 3.8.

The next step (1.5) takes place after the design suggestions have been applied to the current whole product design. Here the user can re-evaluate the product design and see what effects the changes in design based on the design suggestions of the user interface can have in terms of reduced direct and environmental costs. The user also has the option to proceed to the next step and continue with phase 2 of the methodology – Advanced Concept phase. This concludes phase 1 of the methodology.

3.9 Advanced Concept Phase

During the Advanced Concept phase a functional analysis of the product components is the focal point. The reason for this is that at this phase, during the product design, information on different functional components is available but not necessarily detailed information on all parts of the product. Figure 3.9 shows the workflow diagram of the Advanced Concept phase methodology.

Throughout step 2.1 of the methodology input information regarding the different components of the product is collected. There are five types of information collected for each of the components.

The first and most important type is information regarding the component function. Three different functions can be assigned for each component hence the methodology also collects the following information: one primary function of component and two secondary functions of the component.

The second type of input information used for the second phase of the methodology is called general information and it is similar to the general information of phase 1. In the following a complete list of those input information chosen for the methodology is given:

- Name of the component
- Primary function of component
- Secondary functions of components
- Number of parts used for the component
- Number of materials used for the component
- Re-Use potential of component at end-of life
- Toxicity potential of component at end-of life
- End-of life scenario of component
- Main material of the component
- Estimated weight of component

- Participation of main material to total component weight
- Is the component manufactured on site where the whole product is being assembled?
- Additional yearly raw material cost for component
- Does the component require packaging when delivered to the final assembly?
- Average weight of that packaging
- Average cost of the incoming component packaging
- Average disposal cost of that incoming packaging
- Cost of component if purchased from supplier
- Does the component rely on material inflow to function?
- Does the component create a material outflow?
- Does the component rely on energy inflow (such as LPG)?
- Does the component rely on electric energy inflow?
- Does the component rely on consumable to function?
- Maximum EoL treatment cost of component (e.g. due to toxicity)
- Component treatment cost if it is re-used (e.g. cleaning cost)
- Dismantling cost of component
- Fastener used for component (in %) – adhesives, rivets or staples, snap fit, threaded fasteners, welding
- Does the component move with respect to all the other assembled components?
- Does the component require to be made out of a different material than the other components?
- Is the component separate from the rest of the components?

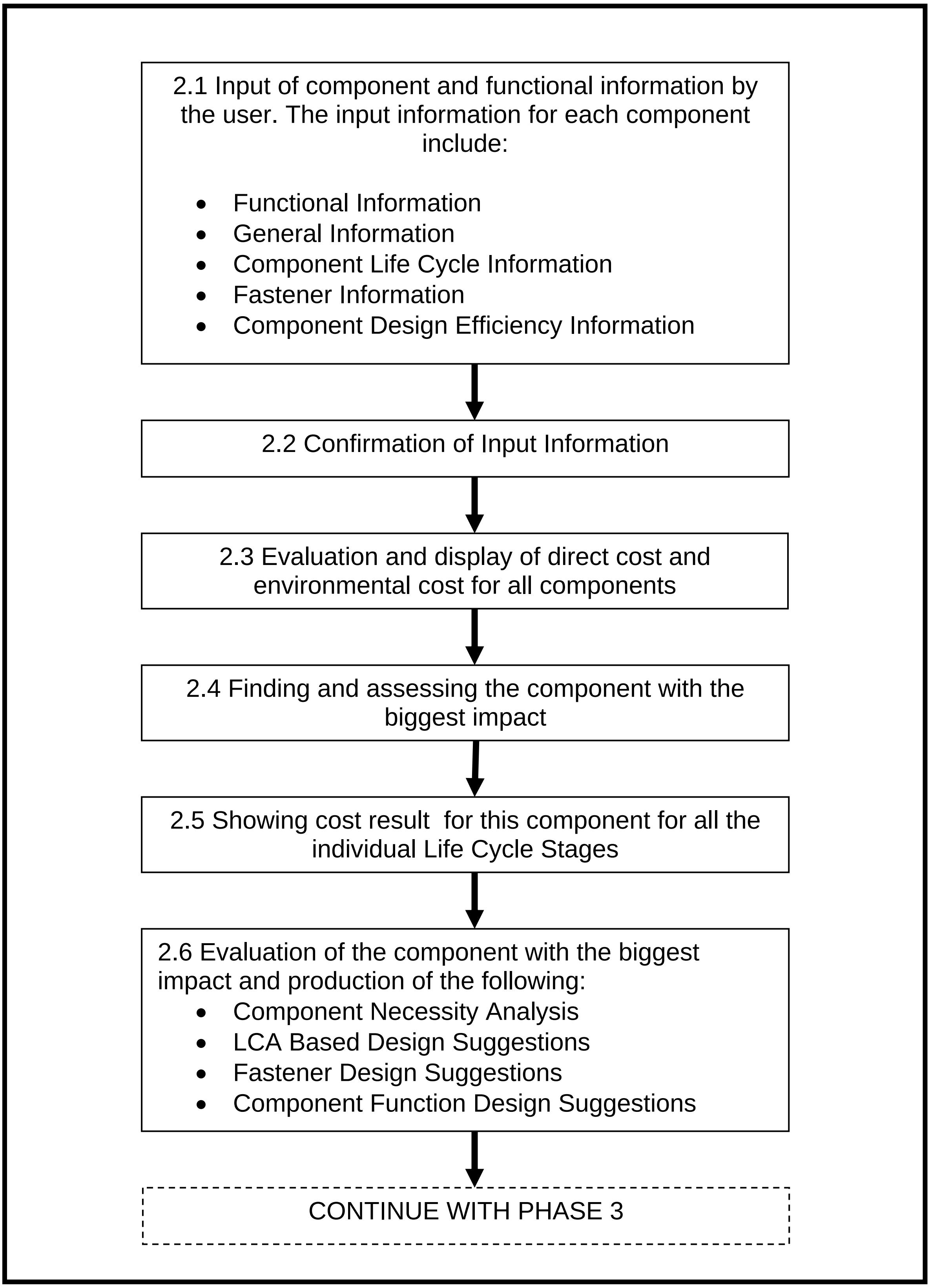


Figure 3.9: Workflow diagram of the methodology – phase 2 – Advanced Concept phase

Additionally the third type of input information is basic component life cycle information. This information is gathered for each component also in order to conduct a full Life Cycle evaluation for each part and produce cost results (environmental and direct cost) at step 2.3 of the methodology. The fourth type of input information is regarding the fasteners used for each of the components. The choice was restricted to 5 different fasteners – such as adhesives or welding – and the percentage used for each of the components.

The fifth and last type of information collected during step 2.1 is called Component Design Efficiency information. Appendix B.2 gives further details in the information collected for the Component Design Efficiency Analysis. This information is essential so the methodology can conduct a necessity analysis for each of the components and actually help the user eliminate components that are not essential for the product function and the product as a whole. Information collected here is:

- Does the component move with respect to all the other assembled components?
- Does the component require to be made out of a different material than the other components?
- Is the component separate from the other components?

During step 2.2 of the methodology the user confirms the input data given for all the components and proceeds to the results stage. Once this step is completed the results of the various components, similar to the phase 1 of the methodology, are given as direct cost and environmental cost for each of the components. Again the detailed equations on how the results are produced are provided in appendix B.8 in the form of “MS Excel” tables. Based on the results the component that causes the biggest cost impact is evaluated during step 2.4 and the results for each of the five life cycles for this component are determined during step 2.5 of the methodology.

The following information is produced by the methodology and given back to the user:

- Component name
- Life Cycle that causes the biggest impact for this component,

- The various cost results

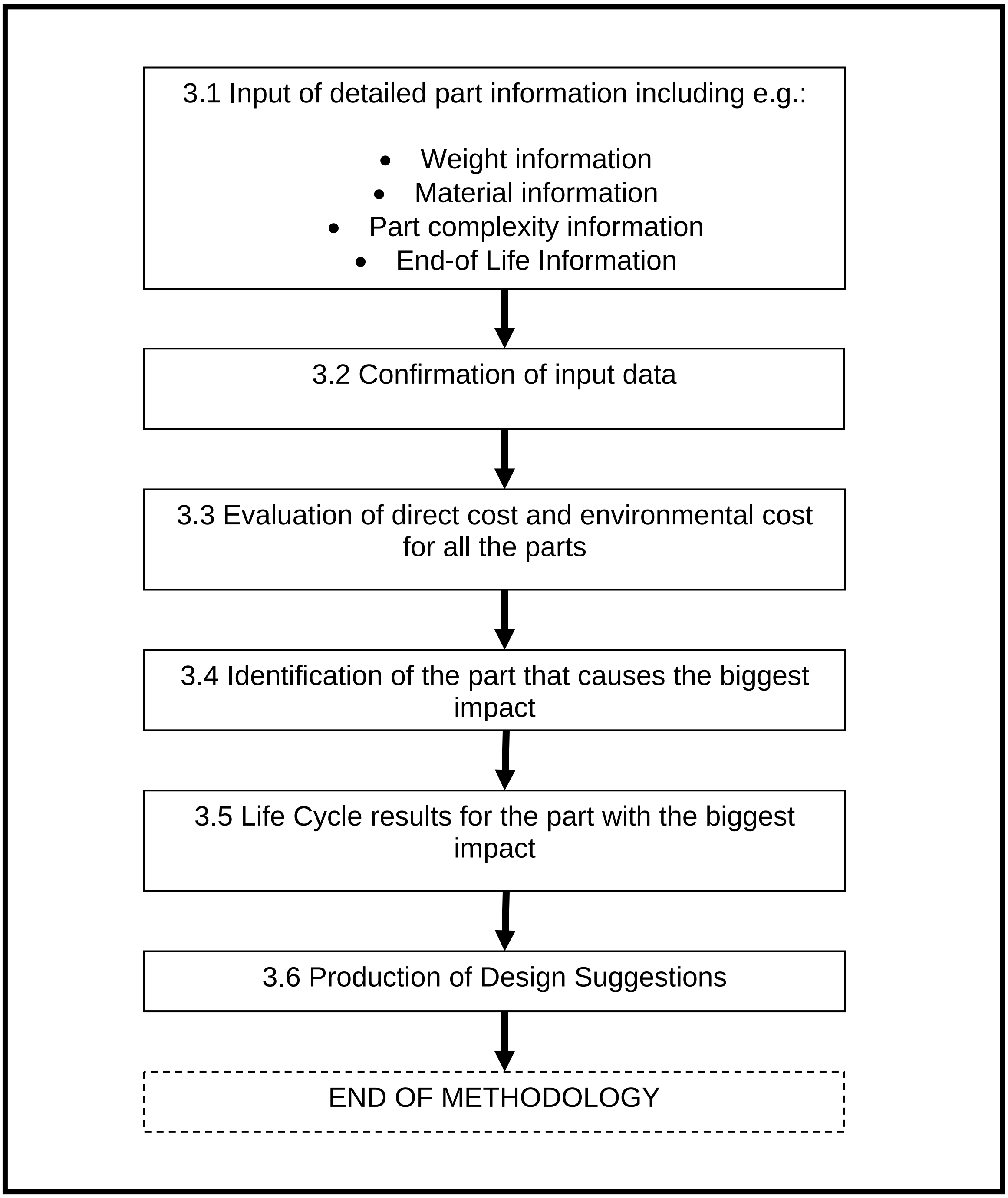
During step 2.6 various design suggestions for this individual component are produced based on the input information taken in step 2.1 of the methodology. Appendices B.7, B.9 and B.10 give further detail on how the design suggestions are produced within the methodology and user interface. They include the following categories mentioned before:

- Component necessity analysis
- LCA based design suggestions
- Fastener Design Suggestions
- Component Function Design Suggestions

3.10 Detail Design Phase

At the final phase of the methodology which is called Detail Design phase the parts of the component that cause the biggest impact as identified during phase 2 are evaluated. Figure 3.10 shows the workflow diagram of this final phase.

Input data regarding the component parts is garnered during step 3.1 of the methodology. The data that is collected for each part separately includes information on part weight, materials used, part complexity, part toxicity and various other details.



<u>Figure 3.10:</u> Workflow diagram of the methodology – phase 3 – Detail Design phase

After step 3.1 is finished the user has the option to go back to change certain input parameters or alternatively confirm the input information in case all the input information seem to be correct. This is step 3.2 described in the workflow diagram.

The methodology then uses the input information from step 3.1 as well as information saved from the methodology phases 1 and 2 – Early Concept phase and Advanced Concept phase – and calculates the environmental and direct cost of the various parts. Appendix C.2 shows the detailed information on how the results are produced. The results from that calculation are given back to the user as is the identification of the part that causes the highest impact in terms of total cost. The maximum number of parts is restricted to 10 as shown in figure 4.10. This restriction is due to limits to the programming effort.

After the part with the biggest impact is evaluated the methodology conducts a Life Cycle Analysis to further break down the direct cost and environmental cost for this specific part. Then the Life Cycle Stage which causes the biggest impact for that specific part is evaluated step 3.5 of the methodology shown in figure 3.10.

Now the methodology produces design suggestions for that part. In the case of the Detail Design phase the design suggestions are made up of 61 separate design suggestions. A design suggestion matrix, that was developed as part of this research, is used to find out which design suggestions best suit the specific situation of the part. This design suggestion matrix is based on six main common issues of part design:

- Weight
- Complexity
- Material
- Energy
- Legislation
- Necessity

For each of the six main issues several design suggestions are assigned as illustrated in figure 3.11 and 3.12. Figure 3.11 shows the design suggestions chosen when part complexity is the main issue and figure 3.12 displays the design suggestions when energy use of the part is the main issue. The design suggestion matrix has the purpose of aiding in assigning various design suggestions (Z01 – Z95) to a certain Life Cycle stage of the part such as raw material extraction or use. Further details on the design suggestions matrix, including all the six main issues, is supplied in appendix C.3. The different design suggestions assigned to the raw material extraction stage are displayed in appendix C.4 which also shows how the design suggestions are assigned to each of the Life Cycle stages.

	Complexity			
Code	Design suggestion	Further Instructions	Examples	Life Cycle Step(s) involved
Z21	**3. Reduce the complexity of the part [Application of DfA (Design for assembly) principles] :**			**Manufacturing**
Z22	3.1 Consider ease of assembly during product design			**Manufacturing**
Z23	3.2 Reduce the mix of materials of the part			**Raw Material Extraction, Manufacturing, EoL**
Z24	3.3 Reduce the mix of fasteners	Reduction of different types of fasteners used		**Manufacturing, EoL**
Z25	3.4 Reduce the complexity of the geometrical shape of the part if possible	Easier to manufacture		**Manufacturing**
Z26	3.5 Merging (TRIZ principle 5)	Bring closer together or merge identical features of the part design thus making the part less complex		**Manufacturing**
Z27	**4. Application of DfM (Design for manufacture) principles**			**Manufacturing**
Z28	4.1 Design the part for easy of manufacturing	Is it possible to reduce the manufacturing steps (Review the part design and identify areas that are not essential)		**Manufacturing**
		Review the possibility to carry out two manufacturing processes in one step		
		Review the ease of handling of the part during the manufacturing process:		

Figure 3.11: **Design Suggestion Matrix – Complexity Issue**

	Energy			
Code	Design suggestion	Further Instructions	Examples	Life Cycle Step(s) involved
Z60	**8. Transportation**			**Transportation**
Z61	8.1 Review logistics and evaluate a different method of transportation from supplier and to distributors	Weigh delivery time issue against financial and environmental impact	E.g switch from plane to sea ship	**Transportation**
Z62	8.2 Set up a supplier network that is highly efficient	Is it possible to choose a supplier that is located closer to the prodcution facility. Reduction of component cost due to reduced transportation costs.		**Transportation**
Z63	**9. Application of DfS (Design for servicability, reliability and maintainability) principle**			**Use**
Z64	Take measures to increase the time between servicing		E.g. Two decades ago time between servicing for cars was appr. 10 000km; nowadays it is up to 25 000km or more.	**Use**
Z65	**10. Energy Inflow**			**Use**
Z66	**10.1 Active**	Reduce the active amount of energy required by the part and increase efficiency measures		**Use**
Z67	**10.2 Passive**			**Use**
		Design out the standby function of the component and the part		**Use**
Z68	**11. In the case the part is produced in site: Reduce CO2 emissions from a process on site not inlcuding energy production**			**Manufacturing**

<u>Figure 3.12:</u> Design Suggestion Matrix – Energy issue

3.11 Joining environmental and economic impact

The main purpose of the methodology described is to integrate the environmental and the economic impact of a product whilst considering product functionality also. This procedure helps to avoid considering the three issues separately and thus avoids trade-offs between them.

The costs as a result of the environmental impact of a product used in the methodology are various and can be assigned to all the five life cycle stages as well as various environmental issues. In the following all the environmental costs considered are listed as well as the life cycle stage they are part of:

1. Climate change levy cost as a result of
    1.1 Materials production (at raw material extraction stage)
    1.2 On site CO_2 emissions (at manufacturing stage)
    1.3 Electrical energy used for production facility (at manufacturing stage)
    1.4 Material inflow (gas, fuel) for production facility (at manufacturing stage)
    1.5 CO_2 emissions as a result of getting goods to and away from manufacturing facility (at transportation stage)
    1.6 Electrical energy used during product use (at use stage)
    1.7 Material Inflow (gas, fuel) during product use (at use stage)
    1.8 CO_2 emissions as a result of transportation (at end-of life stage)
2. Waste treatment and disposal issues at production facility (at manufacturing stage
3. Packaging disposal (at transportation stage)
4. (Toxic) material outflow treatment (at use stage)
5. Consumable disposal (at use stage)
6. Eco-Taxes (at use stage)
7. Environmental cost as a result of product treatment (at end-of life stage)

3.11.1 Relation of environmental cost to the new approach of Eco-Design

As described in the previous section 3.10 the environmental cost considered and covered by the methodology can be assigned to various environmental issues and the life cycle stages also. But furthermore the ten parameters described in section 3.5 as part of the fundamental Eco-Design principle are covered and taken into account via the environmental cost of the methodology. Further details on how the direct cost and environmental cost are evaluated are displayed in appendix A.2. These costs evaluations were developed during the research of this Thesis. In the following it is described how the methodology implements each of them in the form of the environmental costs:

1. Weight & volume of product

These issues are part of the input information requested from the user in the form of overall product weight, component weight and part weight. Moreover complexity is taken into account to cover issues such as product volume (in terms of size). Those input figures are part of most of the environmental cost calculations. There are no limits for the input information in terms of “out of range” values.

2. Use of recycled materials

The use of recycled material is considered at the end-of life stage only for all product design phases though – Early Concept phase, Advanced Concept phase and Detail Design phase. The materials used for product design can be declared as going to recycling and thus a reduced environmental cost impact is considered.

3. Resource consumption

Resource consumption -in the form of environmental costs from energy use, water use and other resources such as consumables or fuel use - is considered for all product design phases. Examples are energy use during the manufacturing process or consumables treatment cost at the use phase.

4. Hazardous substances

Hazardous substances are measured and go into the environmental cost calculations as part of the manufacturing stage, use stage and end-of life stage data input: During manufacturing the amount of hazardous substances as a result of the production process is examined. During the use stage the impact from material outflow creating a necessity for hazardous substance treatment is judged and during the end-of life stage the fraction of the product that goes to hazardous landfill is recognized.

5. Consumables for use and maintenance

Consumables are part of the use stage and they are part of the methodology’s environmental cost calculation for that stage.

6. Ease of re-use and recycling

This issue is taken into account at the end-of life stage for all product design phases. The user has the option to choose – amongst various other options - re-use or recycling as an end-of life scenario for the whole product, certain components or parts. This has a direct impact on the environmental cost calculations at this stage.

7. Incorporation of used components

Incorporation of used components is considered during the Advanced Concept phase and Detail Design phase of the methodology. Here it is possible for the user to assign certain components or parts to be re-used and thus reduce the environmental costs for the raw material extraction stage and the manufacturing stage from producing new parts.

8. Extension of lifetime

The average life of the product is part of the general information input and has an effect on the calculations of several environmental costs.

9. Waste generated

This issue is treated in various forms such as:

- Waste treatment as part of the manufacturing process
- Packaging waste during the transport stage
- The product, components or parts themselves can become waste generated at the end-of life stage

10. Emissions

Emissions are mainly covered via implementing the climate change levy and carbon tax scheme into the calculation of environmental costs. This is described in more detail in the following section.

3.11.2 Environmental cost and the carbon impact

As described in the previous sections carbon impact is a big part of how the methodology evaluates the environmental cost for the product and thus assigns an environmental impact value. During the development of the methodology a decision was necessary on which types of emissions and their correlating environmental cost impact should be taken into account. At national level in the United Kingdom, and in the European Union also, the Climate Change Levy (CCL) [CCL06] puts a tax on energy consumption and is applied to electricity, gas, coal and liquified petroleum gas (LPG). Even though it is not applied to domestic supplies yet the decision was made to do so in the course of the development of this methodology to be able to assign an environmental cost figure to carbon (CO_2) emissions from domestic energy use. Furthermore the CCL assigns a certain amount of carbon emissions to a certain amount of energy use – depending on the type of course e.g. electricity, gas – it also then assigns a tax cost to the amount of carbon emissions. This value is used within the methodology as a basis to allocate a certain environmental cost value to the carbon emissions produced and thus measure the impact of the emission financially. Appendix A.3.3 makes available the detailed figures on this issue.

A further reason to focus on the carbon emissions as a major issue is that within most internationally recognized emission trading schemes and emission reduction treaties such as the European Union emission trading scheme or the Kyoto Protocol the main focus is given to carbon emissions even though other emissions are considered.

All these reasons led to the decision to include carbon emission as the only emission to air considered within the methodology and hence it being the only environmental cost driver for air emissions. This is based on an overall European energy statistic regarding how much CO_2 is created per kWh produced since not all energy production processes cause CO_2 emissions.

3.11.3 Negative externalities

When assigning an environmental cost value to carbon emissions and dealing with carbon taxes the expression of negative externalities as an economic principle plays a major role. In this section it is explained in detail what the expression negative externalities means and how this principle works.

Negative externalities are usually mentioned in recent literature interrelated to the carbon tax principle. As stated by Herber `Instead, an efficient carbon tax must be levied upon the negative externalities themselves, the carbon emissions which result from the use of such fuels. Ideally, this would take the form of an excise tax imposed upon each unit of carbon emitted when fossil fuels are used to produce energy for consumption and production activities such as automobile driving and factory operations` [HR95]. 'Carbon tax is based on the economic principle of negative externalities**.** Externalities are costs or benefits generated by the production of goods and services.' [DOW07] Negative externalities are basically costs that will occur in the future but nobody has made a financial commitment to them yet. A good example for this is emissions: 'when businesses or homeowners consume fossil fuels, they create pollution that has a societal cost; everyone suffers from the effects of pollution.' A cost effect from this could be medical treatment cost of people in the future due to pollution. Another example is the treatment cost of hazardous materials in products such as batteries. If the batteries are disposed of neither the user nor the producer pays for the hazardous substance treatment at the moment but the society as a whole since it is included in the overall waste treatment cost. That raises the issue of who will pay for those costs in the future. They are basically part of the Whole Life Cycle Cost of a product – the environmental cost to be more specific – thus they are considered in the LCA cost calculation of this methodology. This makes it possible to integrate the real product costs further in terms of environmental cost even though they are not assigned in most actual financial appraisals of a product`s whole life cycle impact. In recent years the European Union issued producer take back legislations for various different product markets, such as the automotive or electronic product markets. These legislations basically require the original equipment manufacturer (OEM) legally to take back their products at their EoL. Thus this recent change in legislation shift the financial burden at the products end-of life back to the producer.

During the development of this methodology the author felt that this is a big issue and that most tools currently on the market do not take it into account fully. Thus the issue of negative externalities was fully integrated as a part of environmental cost within the methodology.

3.12 LCA and DfX principles

Life Cycle Assessment (LCA) is a key principle of Eco-Design and of the methodology developed in the course of this research. Furthermore the Design for X (DfX) principles can support the process of creating a design suggestion matrix for the proposed methodology in order to lower direct cost and environmental cost impact of the evaluated product. As explained in chapter 2.17 the DfX tools are basically used in a modified way in the methodology proposed in this thesis to help with the setting up of design suggestions for specific life cycle stages that cause the biggest impact. Thus whilst three separate design suggestion matrices are part of the methodology – one for each of the three product design phases – they all make use of the various DfX principles to create design suggestions in order to lower specific life cycle impacts.

The design suggestions that can be derived for all the five life cycle stages from the DfX principle can support the development of a design suggestion matrix during the course of building up a methodology. They can be used as a basis for a design suggestion matrix development whilst further design suggestions could be accumulated and built into it.

3.13 Importing and aligning the product functionality

In order to enhance the product performance in terms of environmental impact and economic impact it was felt from an early stage of the methodology development that product functionality also needs to be taken into account. This is due to the fact that a design engineer cannot compromise product functionality in order to reduce cost or environmental impact. In other words if a product does not fulfil the functions it is set out to do the reduction in cost and environmental impact becomes irrelevant. By focusing on the product functionality the designer can concentrate on the essential features required for the product and design out unnecessary parts and components. Furthermore the functional efficiency can be improved by looking at the overall purpose of the whole product and its components. Functional efficiency means that a product or component is less (functional) efficient the more parts are required to carry out the function. The Identification of Synergies of component functions can help to reduce the product complexity and help to reduce environmental and economic impact simultaneously.

3.13.1 The alignment of the TRIZ matrix

The collection of primary and secondary function parameters makes it possible to apply a modified TRIZ matrix. The modified TRIZ matrix is a simplified version of the original with a focus on Eco-Design solutions. In it, instead of looking for an improving and a worsening feature per se, the improving feature is replaced by an enhancement of the environmental and economical impact performance aim. Thus after the main and secondary functions for each component are selected the methodology applies one or more of the 40 inventive principles that has proven to maintain the components` functionality whilst lowering its impact. This procedure is carried out for each component and design enhancement suggestions are generated. The aim of this is to reduce the complexity of the components leading to a more cost effective component with a reduced environmental impact.

Rudimentary models to combine eco-innovation and TRIZ have emerged fairly recently [CC04]. The developer of the CES database [ABC04], which is discussed in chapter 2.8, calls for an innovative approach to Design in general which is supported by the database: Even though the TRIZ matrix is not mentioned here it is clear that it comprises the perfect solution that Ashby calls for in his case study [ASH05]. The case study evaluates a crash barrier and what the differences in material choice are for the static solution (at the side of the road) or the dynamic solution (bumper attached to vehicle). Here the TRIZ matrix can give inventive solutions the design engineer did not consider and reduce the environmental and economic impact whilst improving functionality. An example of a case study in which TRIZ was applied for a very similar scenario can be found in Shahid`s “A Case Study in Continuous Product Development” article [SHA05]. In it the problem of a collision between a car and street lighting is discussed which is similar to the barrier case study by Ashby. The main purpose of the paper is to generate ideas on how to increase the safety to ‘improve the survivability of the impact of a speeding vehicle with a timber pole’. Even though the case study refers to safety issues and can be overcome by TRIZ the relation to the methodology of this thesis is that whilst the safety can be increased the same is valid for the economic and environmental impact. Instead of improving the safety feature on the car and thus increasing the weight of the car which would result in an increase of environmental and economic impact during its use phase, the design objective is to improve the street lighting. Safety is treated as a functionality issue here. Thus by looking for innovative solutions for an existing functional problem by using TRIZ, the environmental and economic impact can be reduced or at least not increased.

It can be stated that an integration of TRIZ in the eco-design process, especially for the improvements at the component level, can help finding inventive and effective solutions on the basis of functionality. The functionality is a mere vehicle for inventive design solutions and alternatives to reduce the environmental impact and the costs of a component thus assuring a continuous improvement. As Abdalla found out in a case study approach ’30 % more ideas have been generated when TRIZ has been introduced’ [AB05].

3.13.2 Amendments to the TRIZ matrix

To better incorporate the TRIZ matrix into the proposed Eco-Design methodology the need for certain amendments and extensions of the basic improving/worsening features of the contradiction matrix became evident. The basic need for such a development has been formulated before by Low [LLW+01]: 'The adaptation of conventional TRIZ to facilitate an innovative thinking to sustainable service design holds great potential but will require substantial development, both likely to involve the extension of the 40 core principles as well as those found in the original contradiction matrix.' Thus during the course of this research the contradiction matrices basic configuration underwent substantial changes. The extent and details of those proposed changes are explained in detail in this section.

1) Six new improving and worsening features are created

First of all it was obvious that the 39 existing improving and worsening features need to undergo a re-evaluation to make them fit for the specific purposes of Eco-Design. Furthermore there was the need for additional improving and worsening features that would better target the requirements of an Eco-Design approach. Thus six new improving and worsening features are created in order to better target the nature of environmental and economic issues in improving the product design. Figure 3.13 shows these new features including a short description. They are included in the re-engineering of the TRIZ matrix which is described at a later point and can be seen in figure 3.14.

40	Use of substance by moving object	Similar to feature 19 but instead of energy a certain substance or matter is required that is unrelated to any energy matters that are directly linked to production of energy for movement. This substance that is being used can have several purposes such as cooling (indirect energy related), reduction of friction,
41	Use of substance by stationary object	Same.
42	Ease of transportation	The degree of facility, comfort or effortlessness in transporting the object/system. This is highly linked to weight, shape and durability of it. Furthermore packaging can be an issue.
43	Frequency	This is highly linked to any characteristic that can be linked to frequency in general. Also wavelength plays a role since it is a result of the frequency.
44	Ease of re-use & recycling	The degree of facility, comfort or effortlessness in recycling and re-using the object/system or parts of it
45	Efficiency	The extent to which a system/object positively or negatively makes use of resources, substances and time.

Figure 3.13: Six new improving and worsening features developed during the research

The six new features shown in figure 3.13 are the product of extensive collection and brainstorming sessions. Initially a great number if new improving and worsening features were collected in order to make the TRIZ matrix better suitable for the purpose of Eco-Design and the overall aim of the methodology to be developed. But only the six principles with the greatest potential were chosen and then added to the original TRIZ matrix.

2) Six new inventive principles are produced

Additionally to better target the needs of integrating the component functionality issue into Eco-Design six new inventive principle are created - these are produced in order to make the matrix fit the purposes of the methodology better and better target improving the economic and environmental impact by increasing product component functionality efficiency. Figure 3.14 shows the six new inventive principles that are produced. A full list of all the inventive principles including the six new ones is given in appendix B.4.

No.	Name	Method	Example(s)
41	**Aligning of functions**	Align two or more different functions to enhance and amplify the favoured result.	(Aircraft) gas turbine engine use the torque and speed produced by the turbine to power a compressor that enhances the airflow through the system. Same for the turbocharger
42	**Increase the re-usability and re-cyclability**	• Change the material used • Remove the factor that keeps the substance or product from being re-used or recycled (e.g. toxicity) • Increase the financial value of the component or product	• Switching from plastic bags to paper bags increases the recyclability • Removing lead in soldering makes electronics easier to re-use (e.g. filler material) • By putting a deposit on bottles and crates the re-use is increased
43	**Compromise**	• Find similarities in the two existing methods and create a new solution based on these • Create a method that is made of parts of both existing ones	• A Turbofan is a compromise between a Turboprop (low altitude) and a Turbojet (high altitude) • An intermediate tyre is a compromise between a slick tyre and a rain tyre for the specific case of a half dry track condition
44	**Accumulative principle**	• Find a way to initiate a self amplifying effect or make use of the exponential effects	• Compound interest • Nuclear reaction in a power plant • Turbo Charger in a car
45	**Air or gas to create pressure difference**	• Find a way to contain a gas or air that has higher pressure than the surrounding to provide lifting • Create a gas or air flow to create a useful force	• Hover Craft • Air cushion packaging • Helicopter • Leaf Blower
46	**Application of obsolete principle**	• Apply an obsolete and out-of date principle to generate an innovative approach • review past solutions in the field and think about how re-invent them.	• Solar sail used for space travel (based on wind sail for sea travel) • Vacuum Tubes are used again in amplifiers to produce a very distinct and warm sound even though they were considered obsolete at one time.

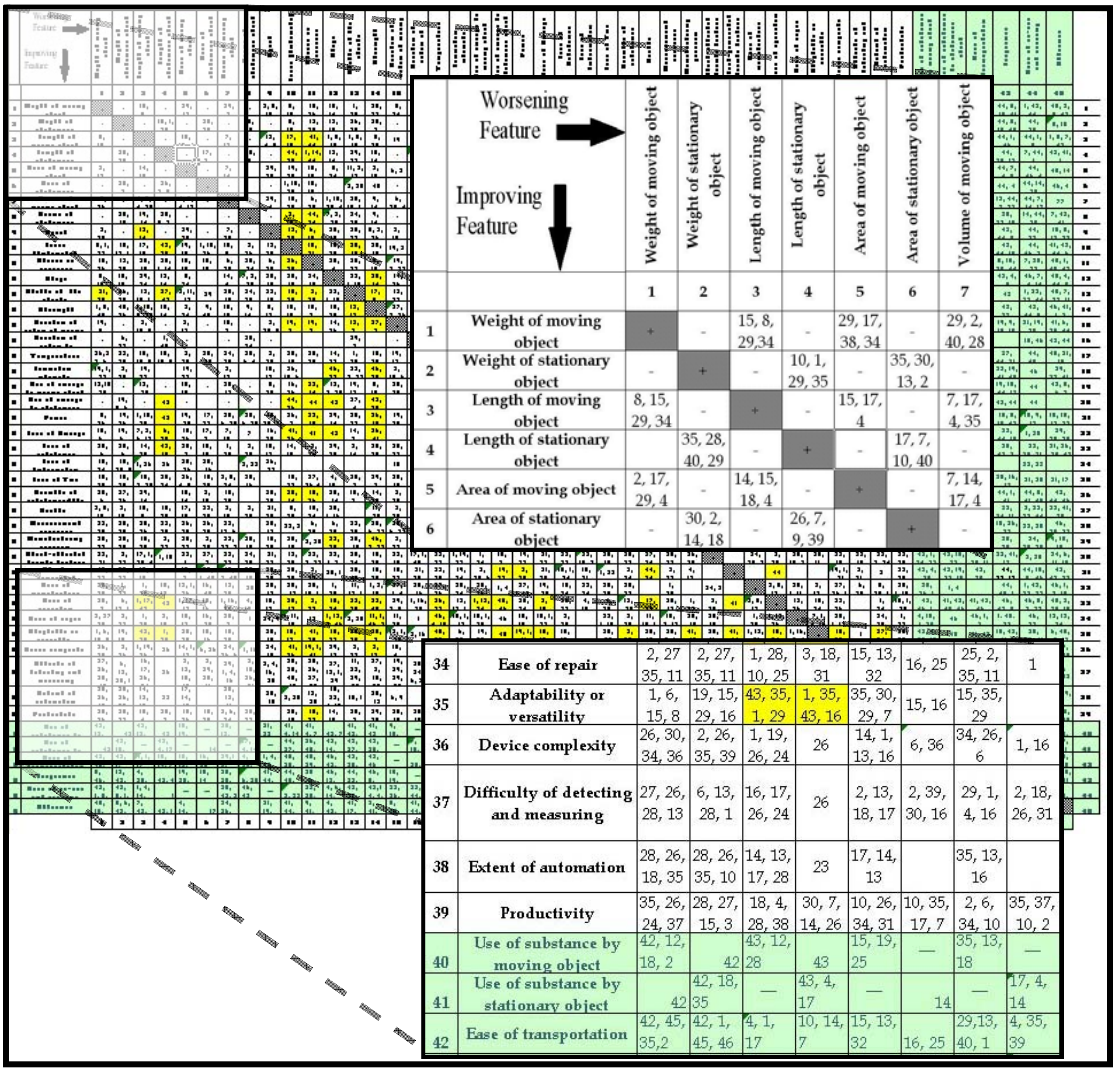
Figure 3.14: Six new inventive principles

As shown in figure 3.14 six new inventive principles were created. On one hand they directly promote a more environmentally friendly design as for example the principle 42 “Increase the re-usability and recyclability”. On the other hand the principles have a more generic character. Nonetheless when applied they can help reduce costs and environmental impact. If the principle 41 is reviewed it does not link to the reduction of the environmental impact at first sight. But for the turbocharger example it is possible to achieve the same amount of horsepower with a smaller engine and thus reduced fuel consumption. And less fuel consumption results in reduced direct costs and a reduced environmental impact from emissions.

3.) Survey and Re-engineering of the original TRIZ contradiction matrix

The whole TRIZ matrix is surveyed and tested for suitability within the proposed methodology. It is found that even though it can help in integrating functional, environmental and economic issues, further work and remodelling of it is necessary to make it fit for Eco-Design purposes. Initially the matrix is expanded and enlarged by an additional set of six improving and worsening features highlighted in green. Furthermore the whole of the contradiction matrix is reviewed and altered as the yellow markings in figure 3.15.

The way it was adapted within the proposed methodology was via a two step approach. Firstly a list of 30 functional principles was produced based on case studies and a brainstorming and elimination process. Then, as it can be seen in figure 3.16 the improving and worsening features of the TRIZ matrix that are best suitable for the functional principles were chosen, including the new developments described in the prior sections. Then in the next step a list with the inventive principles suggested by the TRIZ matrix for each of the functional principles is created as shown in figure 3.17. In the next step the most suitable inventive principles for each functional principle were chosen as displayed in figure 3.18.



	Worsening Feature → / Improving Feature ↓	Weight of moving object	Weight of stationary object	Length of moving object	Length of stationary object	Area of moving object	Area of stationary object	Volume of moving object
		1	2	3	4	5	6	7
1	Weight of moving object	+	-	15, 8, 29,34	-	29, 17, 38, 34	-	29, 2, 40, 28
2	Weight of stationary object	-	+	-	10, 1, 29, 35	-	35, 30, 13, 2	-
3	Length of moving object	8, 15, 29, 34	-	+	-	15, 17, 4	-	7, 17, 4, 35
4	Length of stationary object		35, 28, 40, 29	-	+	-	17, 7, 10, 40	-
5	Area of moving object	2, 17, 29, 4	-	14, 15, 18, 4	-	+	-	7, 14, 17, 4
6	Area of stationary object	-	30, 2, 14, 18	-	26, 7, 9, 39	-	+	-

34	Ease of repair	2, 27 35, 11	2, 27, 35, 11	1, 28, 10, 25	3, 18, 31	15, 13, 32	16, 25	25, 2, 35, 11	1
35	Adaptability or versatility	1, 6, 15, 8	19, 15, 29, 16	43, 35, 1, 29	1, 35, 43, 16	35, 30, 29, 7	15, 16	15, 35, 29	
36	Device complexity	26, 30, 34, 36	2, 26, 35, 39	1, 19, 26, 24	26	14, 1, 13, 16	6, 36	34, 26, 6	1, 16
37	Difficulty of detecting and measuring	27, 26, 28, 13	6, 13, 28, 1	16, 17, 26, 24	26	2, 13, 18, 17	2, 39, 30, 16	29, 1, 4, 16	2, 18, 26, 31
38	Extent of automation	28, 26, 18, 35	28, 26, 35, 10	14, 13, 17, 28	23	17, 14, 13		35, 13, 16	
39	Productivity	35, 26, 24, 37	28, 27, 15, 3	18, 4, 28, 38	30, 7, 14, 26	10, 26, 34, 31	10, 35, 17, 7	2, 6, 34, 10	35, 37, 10, 2
40	Use of substance by moving object	42, 12, 18, 2	42	43, 12, 28	43	15, 19, 25	—	35, 13, 18	—
41	Use of substance by stationary object	42	42, 18, 35	—	43, 4, 17	—	14	—	17, 4, 14
42	Ease of transportation	42, 45, 35,2	42, 1, 45, 46	4, 1, 17	10, 14, 7	15, 13, 32	16, 25	29,13, 40, 1	4, 35, 39

<u>Figure 3.15:</u> The re-engineered TRIZ contradiction matrix

Then a number of inventive principles for certain contradiction situations are changed and replaced with more suitable ones to better serve the purpose of the methodology. A detailed image of the re-engineered TRIZ contradiction matrix can be found in the appendix B.3. Further changes to the TRIZ matrix in order to integrate the principle of functionality within the methodology are implemented – most prominent by the streamlining of the contradiction principle of TRIZ. Those are explained in the following section.

3.13.3 Streamlining of the contradiction principle of TRIZ

In order to obtain helpful design suggestions to enhance the component functionality during the Advanced Concept phase the process of obtaining inventive suggestions from the contradiction matrix is re-invented. This is due to the fact that within the methodology and the user cannot be asked to pinpoint various contradicting principles from the rather complex contradiction matrix. Instead during this research a method and way of streamlining the contradiction principle is found and explained in detail in this section.

First of all there was the need for a method that helps develop function based design solutions for each component during the Advanced Concept phase. The aim is to increase the functionality of each component whilst reducing the environmental and economic impact. Hence a process is created that makes it possible to assign inventive principles directly to a combination of primary and secondary product functions whilst using the reformulated TRIZ matrix described previously. For this purpose a component function catalogue is developed that contains the 30 most basic principles listed below:

1 - Produce Torque (e.g. motor)
2 - Produce Internal Movement (e.g. motor)
3 - Produce Temperature Change (e.g heating element)
4 - Cover Other Components from Contamination (e.g. engine cover)
5 - Move the Whole Product (e.g. wheels)
6 - Penetrate Object (e.g. drill, cone strainer)
7 - Stabilize Composition and Structural Integrity (e.g. steel beam)
8 - Regulate or Control Movement (e.g. clutch)
9 - Regulate or Control Pressure (e.g. valve)
10 - Regulate or Control Other (e.g. light intensity sensor)
11 - Influence Stream or Flow (e.g. car spoiler, regulating valve)
12 - Transfer or Transport Energy (e.g. cable)
13 - Transfer or Transport Matter (e.g. pipe, conveyor belt)
14 - Store Energy (e.g. battery, flywheel)
15 - Store Matter (e.g. fuel tank)
16 - Reduce Sound (e.g. hood)
17 - Create or Enhance Sound (e.g. loudspeaker)
18 - Compensate for Shock or Impact (e.g. spring in car suspension)
19 - Reduce Vibration or Resonance (e.g. damper in car suspension)
20 - Create Vibration or Resonance (e.g. microwave oven)
21 - Provide Interface for User (e.g. PC screen, speedometer)
22 - Provide User with Measure to Influence Product (e.g. keyboard, switch)

23 - Increase Ease of Handling of the Product (e.g. tennis racket grip, rubber grip)

24 - Hold Element in Place (e.g. car seat, cavity on phone handset charger)

25 - Create Grip between Product and Surface (e.g. tyres on a car)

26 - Convert Matter - Mechanically (e.g injection moulding)

27 - Convert Matter - Chemically (e.g. combustion engine)

28 - Convert Matter - Other Physical (e.g. nuclear power plant)

29 - Convert Energy Type (e.g. industrial magnet converts electrical to magnetic field energy)

30 - Lock Function (e.g. padlock lock, integrated lock)

These 30 basic principles were produced by reviewing several different products and case studies and actually looking specifically at the components and their functions. During the development of a streamlined and simplified contradiction principle of TRIZ it was necessary to find out which inventive principle – including the six newly created ones – can be assigned. For this purpose a list of these 30 component functions was drawn against improving and worsening features of the amended TRIZ matrix. As shown in figure 3.16 the author evaluated which Improving Features and which Worsening Features apply for each of the 30 Component functions.

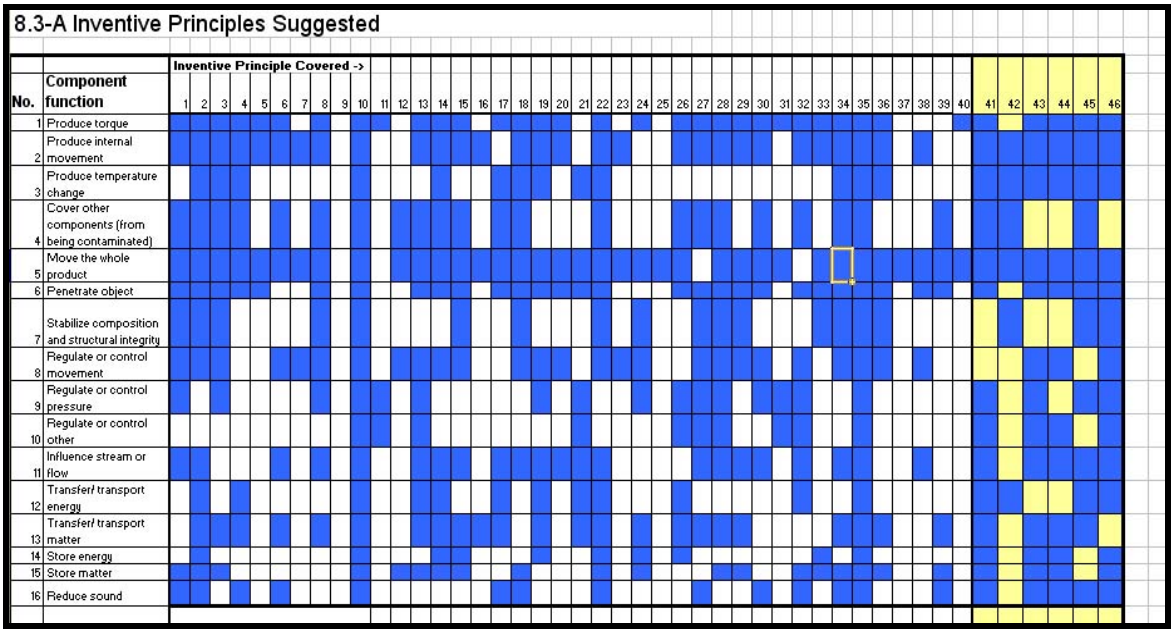
8.3 List of component functions

No.	Component function	Example	Improving Feature of TRIZ matrix	Worsening Feature of TRIZ matrix	Chosen Inventive Principle of those suggested
1	Produce torque	motor	1, 3, 9, 12, 21, 29, 33	11, 13, 15, 17, 22, 23, 27	1, 2, 3, 4, 5, 13, 14, 15, 18, 19, 28, 29, 34, 35, 41,43, 44
2	Produce internal movement	motor	9, 12, 21, 29	1, 3, 5, 7, 9, 11, 12, 15, 17, 19, 22	1, 2, 3, 4, 5, 7, 10, 13, 14, 15, 18, 19, 20, 22, 28, 29, 34, 35, 36, 38, 41, 43, 44, 45, 46
3	Produce temperature change	heating element	12, 16, 17, 21	17, 22, 26	3, 4, 21, 22, 44
4	Cover other components (from being contaminated	engine hood	4, 6, 12, 13, 14	10, 11, 15, 17, 21	1, 2, 3, 4, 13, 17, 27, 28, 34, 41, 42, 45
5	Move the whole product	wheels	3, 7, 9, 13, 19	1, 12, 13, 17, 22, 23, 29	1, 3, 4, 13, 14, 15, 28, 31, 34, 36, 37, 38, 39, 40, 41, 43, 44, 45, 46
6	Penetrate object	drill, cone strainer	9, 11, 12, 13, 14, 15, 21, 31	1, 12, 13, 17, 22, 23, 29	1, 3, 4, 5, 10, 13, 15, 17, 18, 19, 21, 22, 27, 33, 34, 35, 36, 41, 43, 44, 45, 46
7	Stabilize composition and structural integrity	beam,	12, 13, 14, 23, 27	10, 11, 30	1, 3, 14, 24, 35, 45, 46
8	Regulate or control movement	clutch	9, 19, 21	1, 3, 5, 7, 22, 23, 25, 28, 29, 30, 37	6, 13, 14, 15, 18, 19, 20, 23, 28, 29, 44

Sheet1 Sheet2 Sheet3

Figure 3.16: Evaluation of Component functions against Improving and Worsening Features and Inventive Principle

It has to be kept in mind though that the chosen inventive principles shown in figure 3.16 are the filtered results of the total amount suggested. As figure 3.17 clarifies there were too many inventive principles suggested for each of the component functions. The blue fields are the inventive principles suggested by the revised TRIZ matrix and the streamlining methodology and the white and yellow fields not suggested.



<u>Figure 3.17:</u> Component Functions and Inventive Principles Suggested

To filter out unsuitable inventive principles suggested total results were tested for suitability by the application of the case studies used for this research. Figure 3.18 shows the inventive principles that are considered as suitable for each product function highlighted in black whilst the inapplicable ones are highlighted in grey. It has to be mentioned that figures 3.17 and 3.18 only show a part of the function catalogue which consists of 30 functions in total. The six new inventive principles which are described in figure 3.14 are already included at this point.

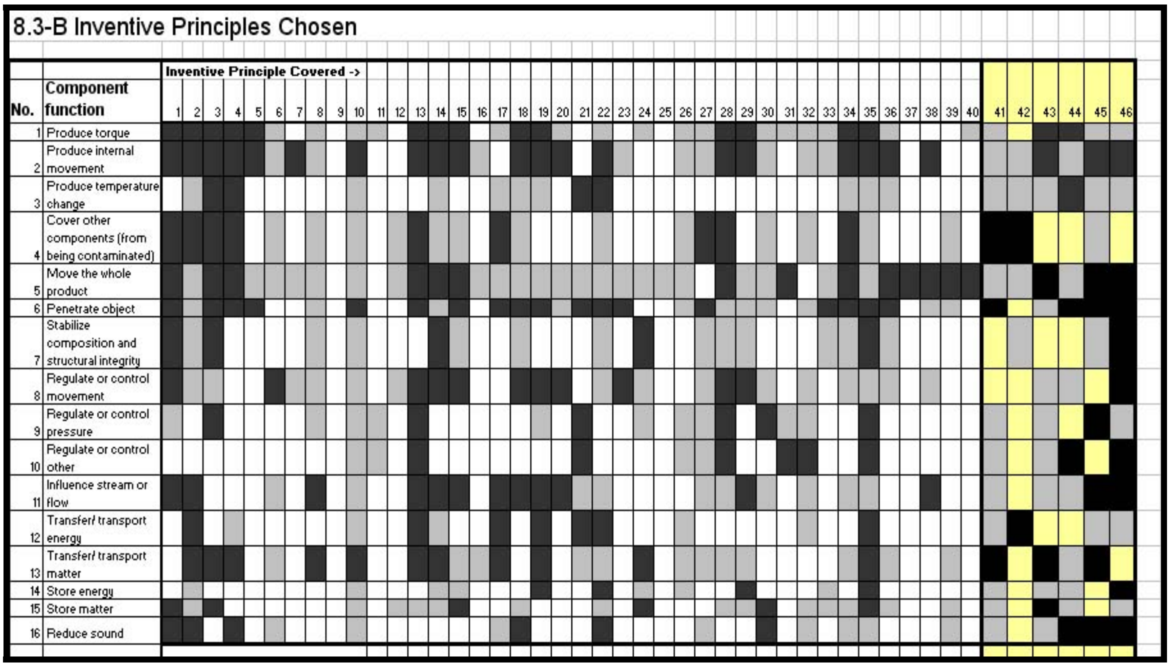


Figure 3.18: Catalogue of component functions and inventive principles actually chosen

The product design suggestions resulting from the streamlining of the TRIZ matrix help improve the product components' design of all three product features simultaneously. All the necessary details on how the contradiction principles of the TRIZ matrix were streamlined, as described above, can be found in appendices B.3, B.4, B.5, B.6 and B.7.

3.14 Integration of databases

As mentioned in chapter 2 - Literature Review there are various databases that are used within the methodology in order to produce environmental and direct cost results. The databases are mainly used in an adapted form in order to support the main functions of the methodology. In this section the main databases used and the way in which they are integrated within the methodology are described.

The choice of materials has a major impact on all the life cycle stages of all product design phases. Thus an adapted form of a database was required that covers assorted, necessary material properties such as weight, rigidity, production energy, carbon footprint from production, possible end-of life scenarios amongst various others. Based on the various different existing databases a representative one is created as part of the methodology that covers 19 representative materials from various material groups. A representative database is partly based on existing databases:

- Cambridge Engineering Selector[1]
- MatWeb – Material Property Database[2]
- The IMDS – International Material Database[3]

The representative material database is displayed in figure 3.19.

[1] Available as a student edition via Coventry University
[2] Available as a free online material property database
[3] Available during the early stages of methodology via the industrial partner and the public version also

No.	Material group	Material class	Material name	Cost range in £ per kg		Density range in kg/ m3		Embodied Energy in kWh / kg		CO2 footprint in kg/ kg		Recyclable	Downcycle	Energy recovery	Biode gradable	Landfill
				From	To	From	To	From	To	From	To					
1	Ceramics & Glasses	Glasses	Silica Glass	3.6	5.9	2170	2200	8.3	9.2	1.61	1.78	X	X			X
2		Technical Ceramics	Alumina	7	10.6	3800	3980	13.75	15.2	2.67	2.95		X			X
3	Hybrids	Composites	CFRP (Carbon fibre reinforced composites)	11.1	13.1	1500	1600	72	79.4	21.1	23.4		X	X		X
4		Foams	Flexible Polymer Foam (MD)	1.8	1.9	70	115	31.4	34.7	4.78	5.28		X	X		X
5		Natural	Hard Wood - Oak	1.8	2.4	660	800	0.56	1	-1.16	-1.05		X	X	X	X
6	Metalls	Ferrous	Cast Iron - ductile	0.35	0.39	7050	7250	4.6	5.06	0.97	1.07	X	X			X
7			High Carbon Steel	0.29	0.49	7800	7900	6.75	7.47	2.06	2.28	X	X			X
8			Low Carbon Steel	0.25	0.43	7800	7900	6.2	6.9	1.9	2.1	X	X			X
9			Stainless Steel	1.4	1.7	7600	8100	24.4	23.7	4.9	5.4	X	X			X
10		Non-Ferrous	Copper alloys	2	2.4	8930	8940	17.5	19.4	4	4.4	X	X			X
11			Aluminium alloys	0.96	1.17	2500	2900	51	56.4	11.6	12.8	X	X			X
12	Polymers and Elastomers	Elastomers	Polyurethane	2.1	2.5	1020	1250	30.3	33.3	4.47	4.94	X	X	X		X
13		Thermoplastic	ABS	1.4	1.7	1010	1210	25.3	28.3	3.27	3.62	X	X	X		X
14			PC	2.1	2.5	1140	1210	29.2	32.2	3.8	4.2	X	X	X		X
15			PE	0.98	1.08	939	960	21.4	23.6	1.95	2.16	X	X	X		X
16			PP	0.81	0.89	890	910	20.9	23.1	2.07	2.29	X	X	X		X
17			PS	0.84	0.9	1040	1050	26.7	29.4	2.85	3.13	X	X	X		X
18		Thermosets	Phenolics	0.95	1.07	1240	1320	23.9	26.4	2.83	3.12	X	X	X		X
19			Polyester	1.03	1.17	1040	1400	23.3	25.8	2.7	3	X	X	X		X

<u>Figure 3.19:</u> Representative Material Choices

For most of the energy use and carbon emissions data, needed to evaluate the impact during the transportation life cycle stage required a new database to be created which was developed with the help of the "EcoTransit"[4] database. Figure 3.20 a screenshot of a database showing the Energy & Resource Impact of Transportation.

2.3 Energy & Resource Impact of Transportation (per 100 tons of transported material including container)

Mode of Transportation	Distance (in km)							*Comment*
	57	107	198	518	940	2105	5000	Litre Diesel equivalent / kWh
based on the following route	Osnabrueck - Muenster	Oldenburg - Osnabrueck	Hannover - Muenster	Muenster - Stuttgart	Cottbus - Basel	Lublin - Nantes		
Lorry	150 / 1470	280 / 2770	520 / 5120	1400 / 14000	2500 / 25000	5600 / 56000		Litre Diesel equivalent / kWh based on a 40 tons, EURO2 lorry
Train	66 / 660	150 / 1500	240 / 2400	700 / 7000	1200 / 11800	2600 / 26000		Litre Diesel equivalent / kWh based on average train, electrified
	52	89	207	519	985	2134		
based on the following route	Bremen - Oldenburg	Hannover - Wolfsburg	Osnabrueck - Oldenburg	Hamburg - Duesseldorf	Regensburg - Osnabrueck	Hamburg - Budapest		
Inland Ship	70 / 725	120 / 1160	270 / 2700	730 / 7160	1170 / 12000	2700 / 27000		Litre diesel equivalent / kWh amount
		91	179	526	1059	2027	4904	
based on the following route		Hamburg - Cuxhaven	Hamburg - Emden	Hamburg - Brugge	Kiel - Calais	Helsinki - Le Havre	Luebeck - Sassari	
Sea Ship		50 / 520	90 / 900	270 / 2740	540 / 5400	1035 / 10500	2500 / 25000	litre diesel equivalent / kWh amount
	64	134	241	512	1043	2011	4950	
based on the following route	Duesseldorf - Koeln	Hamburg - Hannover	Hannover - Duesseldorf	Stuttgart - Amsterdam	Koeln - Oslo	Stockholm - Rom	Hamburg - Amsterdam - Kemi - Paris -Frankfurt	
AirPlane	1623 / 16000	3400 / 34500	6110 / 60500	13000 / 130000	26450 / 265000	51000 / 520000	125500 / 1260000	litre diesel equivalent / kWh amount

Figure 3.20: Energy and Resource Impact of Transportation

Based on the findings from the database shown in figure 3.20 average values for fuel consumption and CO_2 emission figures for various modes of transport were calculated. Amendments were necessary since within the "EcoTransit" database it is only possible to enter a city as a starting point and another city as a destination – which can in part be seen in figure 3.20 also. Since the methodology described in this thesis works differently in which it requires average distances a thorough conversion of the EcoTransit figures has been carried out. As a result a database has been developed by the author that produces average values on fuel consumption and CO_2 emissions per weight unit transported per distance for a certain mode of transport e.g. 1kg of CO_2 emissions are produced for the transportation of 50 tons of goods over a distance of 100km by train assuming efficient loading. The final results that were used within the context of the methodology are displayed in figure 3.21. There are various other

[4] Available as a free online ecological transportation information tool [[STI06]]

Excel files that cover resulting cost and carbon emission due to transportation. These can be found in appendix A.3.1 of this thesis.

2.5 Average Energy use per km & related costs (for 100t per km)

Mode of transport	Short Haul (<100km)	Medium Haul (100 - 500km)	Long Haul (500 - 2000km)	Comment
Lorry	2.68	2.64	2.58	lorry
Train	12.8	12.7	12.5	kWh, based on average train, electrified
Inland Ship	1.35	1.34	1.25	litre diesel equivalent
Sea Ship	0.57	0.51	0.51	litre diesel equivalent
Airplane	255	253.5	252	kWh, based on medium size cargo plane

COMMENT: The values and prices shown are subject to change due to market fluctuations and inflation ration and valid at the following date July 2007

Figure 3.21: Average Energy use per km and related costs

3.15 Evolution of the methodology from Excel spread sheets to Visual Basic

A major task of the research was the transcription from "MS Excel" spread sheet based equations that make up the methodology to an easy to use software package. The purpose of this software package is to easily demonstrate how the methodology works and furthermore to easily show and prove the logic behind it. The whole methodology and the framework of equations, design suggestions and linked-in customized databases is developed based on Excel spread sheets from the very beginning of the research in order to make a migration to a software based user interface easier.

The programming language used for the software package is Visual Basic since initial reviews showed that it supports easy linking-in of Excel spread sheets. Unfortunately the equation Excel spread sheets and the design suggestion excel spread sheets could not be linked into the Visual Basic interface and thus all the equations details are converted into the code language.

Figures 3.22 and 3.23 allow for a direct comparison of how the methodology looks like in terms of programming language code: figure 3.22 shows the equation (direct and environmental cost related to the manufacturing stage) as it is shown within the Excel sheets whilst figure 3.23 shows the same equation as it appears in the Visual Basic coding. Further details of the Excel spread sheet equations can be found in appendix A.2.

2.2 Costs related to environmental impact - II		
Manufacturing		
	Related Letter Formula	
1. On Site CO2 Emission Cost	Direct Cost	Environmental Cost
m (CO2 Emissions) / yearly production x Carbon trade value		**C01 / A01 x L06**
+		
2. Energy Cost for Production & Facility		
amount (kWh) / yearly production x [current energy costs + CCL value]	**C02 / A01 x [C03] / 100**	**C02 / A01 x [L01]**
+		
3. Material Inflow Cost		
3.1 Material for energy production *(e.g. LPG, gas, etc.)*		
amount / yearly production x [current mat. Cost + CCL]	**{C04,C06,C08 or C10} / A01 x [C05,C07,C09 or C11]**	**{C04,C06,C08 or C10} / A01 x [L02 - L05]**
3.2 Other material *(water, or other)*		
amount / yearly production x current mat. Cost	**{C12, C14 or C16} / A01 x {C13, C15 or C17}**	
+		
4. Material Outflow Cost		
amount / yearly production x [waste treatment + waste disposal costs]		**C18 / A01 x C19**
		C20 / A01 x [C21 + C22]

Figure 3.22: **Direct and environmental cost equations in the Excel Sheet format**

```
'2. Manufacturing Calculation
'2.1 Direct Cost
'assign calculated value

Dim Res04 As Double = 0


Res04 += CDbl(frm131.txtC02.Text) / CDbl(frm11.txtA01.Text) * CDbl(frm131.txtC03.Text) / 100
Res04 += CDbl(frm131.txtC04.Text) / CDbl(frm11.txtA01.Text) * CDbl(frm131.txtC05.Text) / 100
Res04 += CDbl(frm131.txtC06.Text) / CDbl(frm11.txtA01.Text) * CDbl(frm131.txtC07.Text) / 100
Res04 += CDbl(frm131.txtC08.Text) / CDbl(frm11.txtA01.Text) * CDbl(frm131.txtC09.Text) / 100
Res04 += CDbl(frm131.txtC10.Text) / CDbl(frm11.txtA01.Text) * CDbl(frm131.txtC11.Text) / 100

Res04 += CDbl(frm132.txtC12.Text) / CDbl(frm11.txtA01.Text) * CDbl(frm132.txtC13.Text) / 100
Res04 += CDbl(frm132.txtC14.Text) / CDbl(frm11.txtA01.Text) * CDbl(frm132.txtC15.Text) / 100
Res04 += CDbl(frm132.txtC16.Text) / CDbl(frm11.txtA01.Text) * CDbl(frm132.txtC17.Text) / 100

frm31.txt05.Text = roundNum(Res04)


'2.2 Environmental Cost

Dim Res05 As Double = 0


Res05 += CDbl(frm131.txtC01.Text) / CDbl(frm11.txtA01.Text) * 10
Res05 += CDbl(frm131.txtC02.Text) / CDbl(frm11.txtA01.Text) * 0.0043
Res05 += CDbl(frm131.txtC04.Text) / CDbl(frm11.txtA01.Text) * 0.0015
Res05 += CDbl(frm131.txtC06.Text) / CDbl(frm11.txtA01.Text) * 0.0015
Res05 += CDbl(frm131.txtC08.Text) / CDbl(frm11.txtA01.Text) * 0.0007
Res05 += CDbl(frm131.txtC10.Text) / CDbl(frm11.txtA01.Text) * 0.0015
Res05 += CDbl(frm132.txtC18.Text) / CDbl(frm11.txtA01.Text) * CDbl(frm132.txtC19.Text) / 100
Res05 += CDbl(frm132.txtC20.Text) / CDbl(frm11.txtA01.Text) * (CDbl(frm132.txtC21.Text) + CDbl(frm132.txtC22.Text)) / 100


frm31.txt06.Text = roundNum(Res05)
```

Figure 3.23: **Direct and environmental cost equations in the Visual Basic coding format**

It has to be stated that it made the programming of the user interface a lot easier having developed the methodology based on Excel sheets and with a later software package in mind.

3.16 Chapter reflections

In the course of this chapter a detailed look is taken at the various work packages that were necessary in order to complete the methodology and the resulting user interface as a whole.

This chapter has furthermore illustrated how the methodology for the application of the Eco-Design principle of complex products was developed in detail. This includes the separate challenges that needed to be overcome to fulfil the initial goals set out in the sections 1.4 Problem Definition and 1.5 Objective and Scope of Research. This showed that the methodology supports a continuous product improvement and compliance with legislation without jeopardizing competitiveness.

All the functions of the methodology have been described in detail as well as their purpose and application.

Figure 3.24 shows a flowchart of the methodology development which helps to understand and navigate through the work described in this chapter. It shows an overview of how the methodology was developed starting with comparing several product design issues, such as environmental issues or functionality issues, with the current methods and if they are covered within them. Shortcomings in the currently available methods were established and the need for a new methodology surfaced as a result of this. Afterwards the basic configuration of the proposed methodology was established in order to overcome those shortcomings and a proposal for a new approach was created. This led to the methodology development linking in several existing tools, such as the TRIZ matrix, DfX toolkit or the LCA principle, in order to integrate all the appointed design issues within the methodology. Moreover various databases are included within the methodology framework, for example a material database or a transportation database. The final outcome of the development conducted in the course of this research is in effect a “Methodology for the Integration of Economic, Environmental and Functional Issues in Complex Product Design” as well as a user interface to demonstrate its functions. The methodology presented in this thesis offers a new approach that is different from the ones presented in the few pieces of literature that propose the integration of economic and environmental impacts in product design.

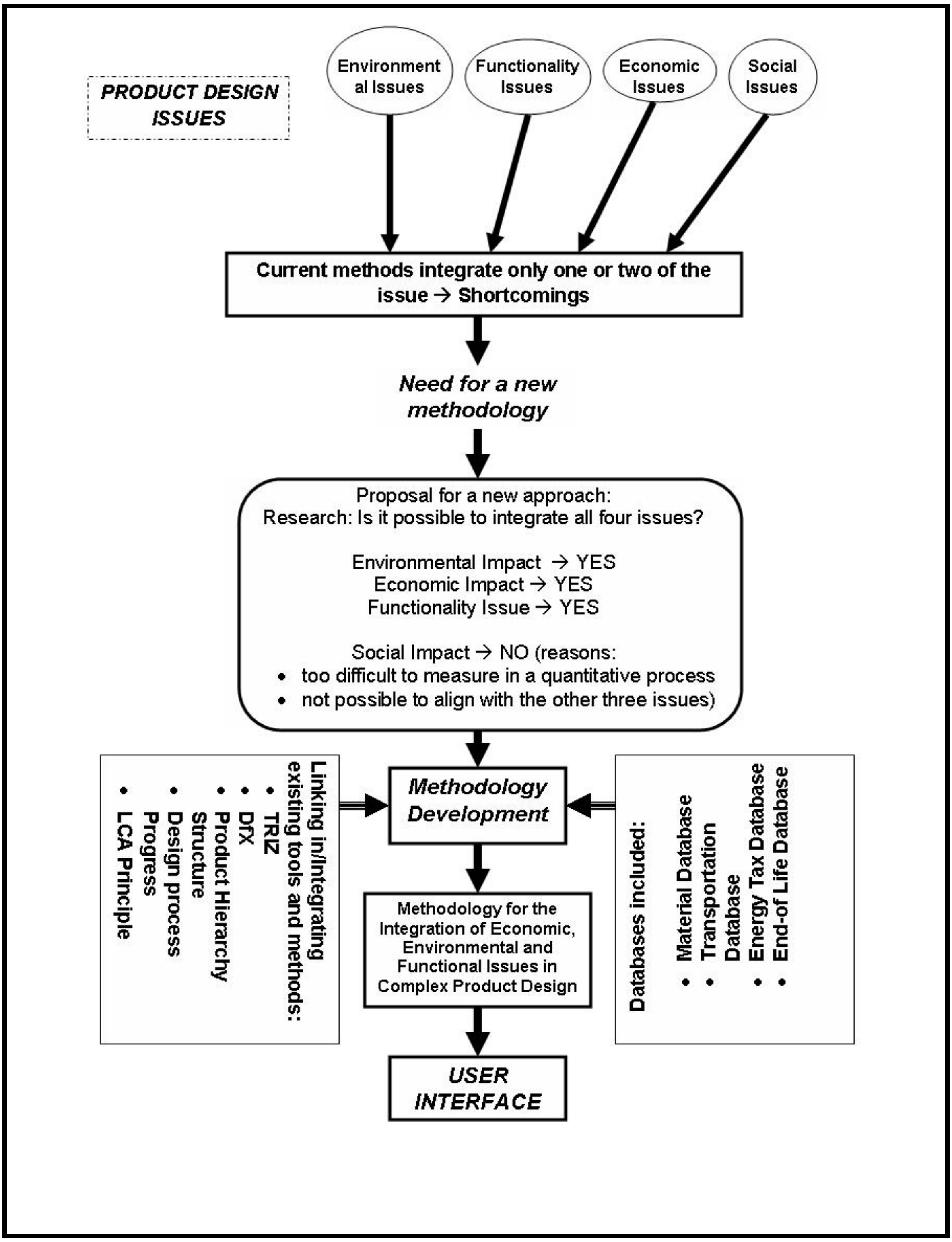


Figure 3.24: Methodology development flowchart

4. Software to demonstrate the methodology

4.1 Introduction to chapter 4

It was clear at a very early stage of the methodology development that a software based user interface was required in order to show how the developed methodology works. Thus the decision process on what software to use was integrated at a very early stage of the methodology development which made it easier to design certain features of the theoretical methodology in a way which made them easier to be integrated via the software and programming work at a later stage. There is an explanation in this section which programming languages were considered, how a suitable programming language was chosen and what the benefits of it are regarding the methodology implementation.

4.2 Chosen software and programming language

Parallel to the methodology development various programming languages were reviewed in order to find one that supports the embedding of Excel based datasheets and support the acquisition of a great amount of input data without the need for storing this acquired data in extensive databases.

The programming languages considered were C++, C#, Java, and Visual Basic. Due to the fact that Java, C++ and C# require advanced experience in programming languages in order to achieve building of a user interface in the limited time available they could not be considered a realistic options.

The software chosen to build a screen based user interface is Visual Basic.Net. ‘Visual Basic .NET (VB.NET) is an object-oriented computer language that can be viewed as an evolution of Microsoft's Visual Basic (VB) implemented on the Microsoft .NET framework. Its introduction has been controversial, as significant changes were made that broke backward compatibility with older versions and caused a rift within the developer community.’ [CAT03].

Furthermore it was selected due to various reasons: it supports the building of a visual user interface easily whilst being Microsoft based which makes the integration of Microsoft based objects and graphics fairly simple. In addition to that, programmers using VB.NET can build Windows-based applications that leverage the user interface features available in the Windows operating system. Another advantageous feature is that rapid application development tools are found in Visual Basic .NET, including drag-and-drop design and code behind forms. No complex resize coding is required either since it features an automatic control resizing element. New controls such as the in-place menu editor deliver visual authoring of menus directly within the Windows Forms Designer. Also it is a software that can be learned quickly which keeps the time from first steps to the final application to a minimum. Figure 4.1 shows the VB.NET development interface within the Microsoft Visual Basic Studio integrated development environment. To be more exact part of the visual basic code for phase 1 is shown. It is possible to test how the coding works and test it for errors and weaknesses before compiling it. This makes it easy to sort out all problems with the coding as well as to conduct a sensitivity analysis on the results produced without the need to go back and forth between the development environment and the final compiled software.

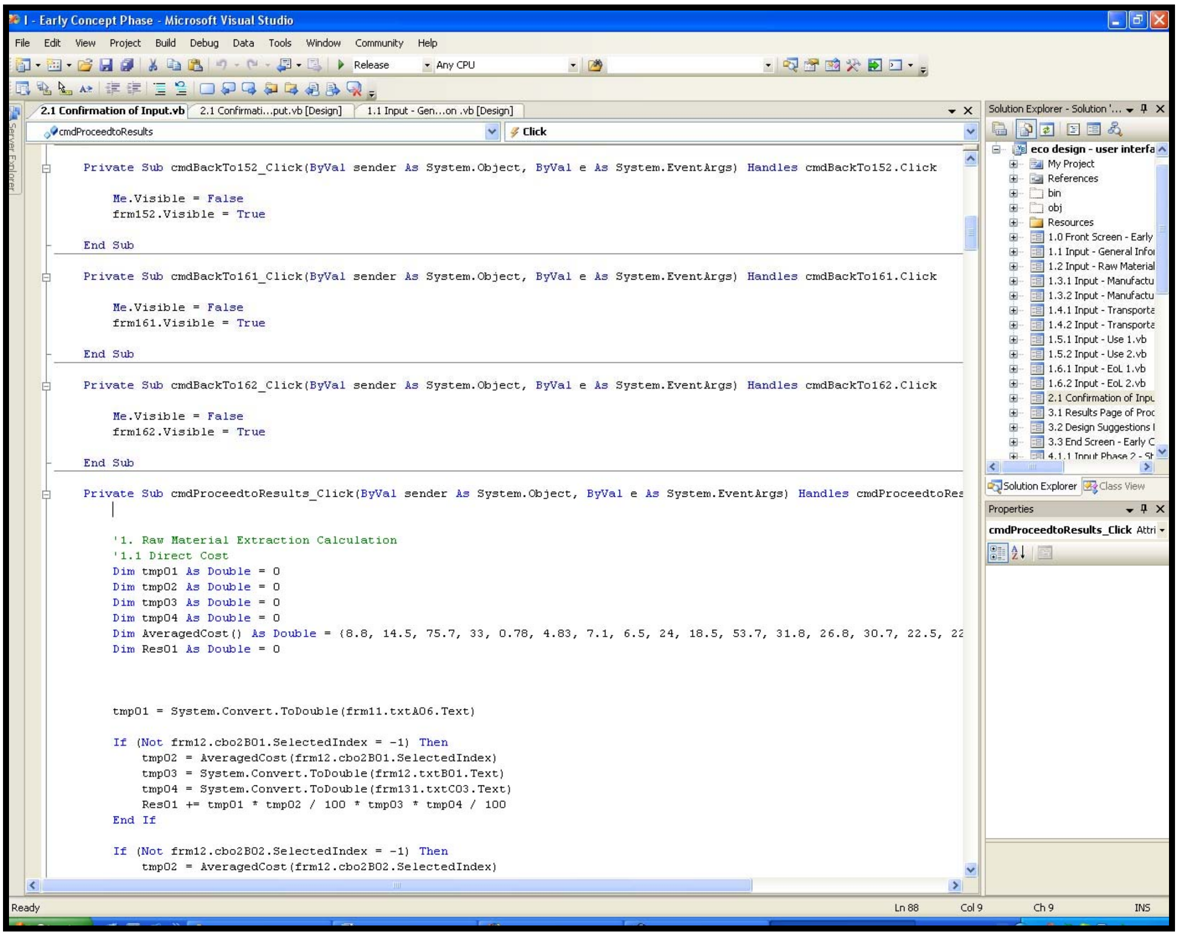


Figure 4.1: Screenshot of the VB.NET programming environment

Figure 4.2 shows the start screen of the user Interface. For the programming of the user interface the following Visual Basic version was used: “Microsoft . NET Framework – Version 2.0.50727” which is part of the “Microsoft Visual Studio 2005” environment.

Figure 4.2: Screenshot of the Start Screen of the User Interface

4.3 Flowchart of the user interface

As described in the previous chapter the structure of the methodology is similar for each of the three design phases:

I. Input of information from the user
II. Using this information and several databases to evaluate environmental cost and direct cost
III. Presentation of life cycle results
IV. Presentation of design suggestions

Within the user interface this procedure is conducted during each design phase with different types of input information requested and different types of results produced depending on the necessities of the specific design phase under evaluation.

4.3.1 Early Concept Phase

Figure 4.3 shows the flowchart of design phase 1 – Early Concept phase and how the screens of the user interface are aligned. The first screen is the starting screen containing the institution information and the name of the research student.

The following screens 1.1 to 1.6.2 have the purpose of gathering information from the design engineer or user of the interface. Screen 1.6.2 does not always appear depending what type of end-of life scenario is chosen. Screen 2.1 lets the user go back to the various input information screens in case the user wants to make a correction to the information provided or optionally the input information can be confirmed and the user can continue to the results page. Furthermore screen 2.1 contains all the coding necessary to carry out the life cycle calculations of phase 1.

Then the end screen is reached, which is shown in figure 4.4, where the user has the choice to start over with phase 1 and go back to screen 1.1. The other option is to return to screen 2.1 – Confirmation of Input or to continue to the phase 2 of the user interface. If the user chooses to proceed and continue with phase 2 the phase 1 terminates.

Once phase 1 of the user interface comes to an end with clicking on the "Quit Phase 1 of the user interface and proceed to phase 2" button of the end screen phase 2 is started and the user has no option of returning to phase 1 without having to restart the program.

A table with all the information collected from the user in screen 1.1 General Information is shown in figure 5.4.

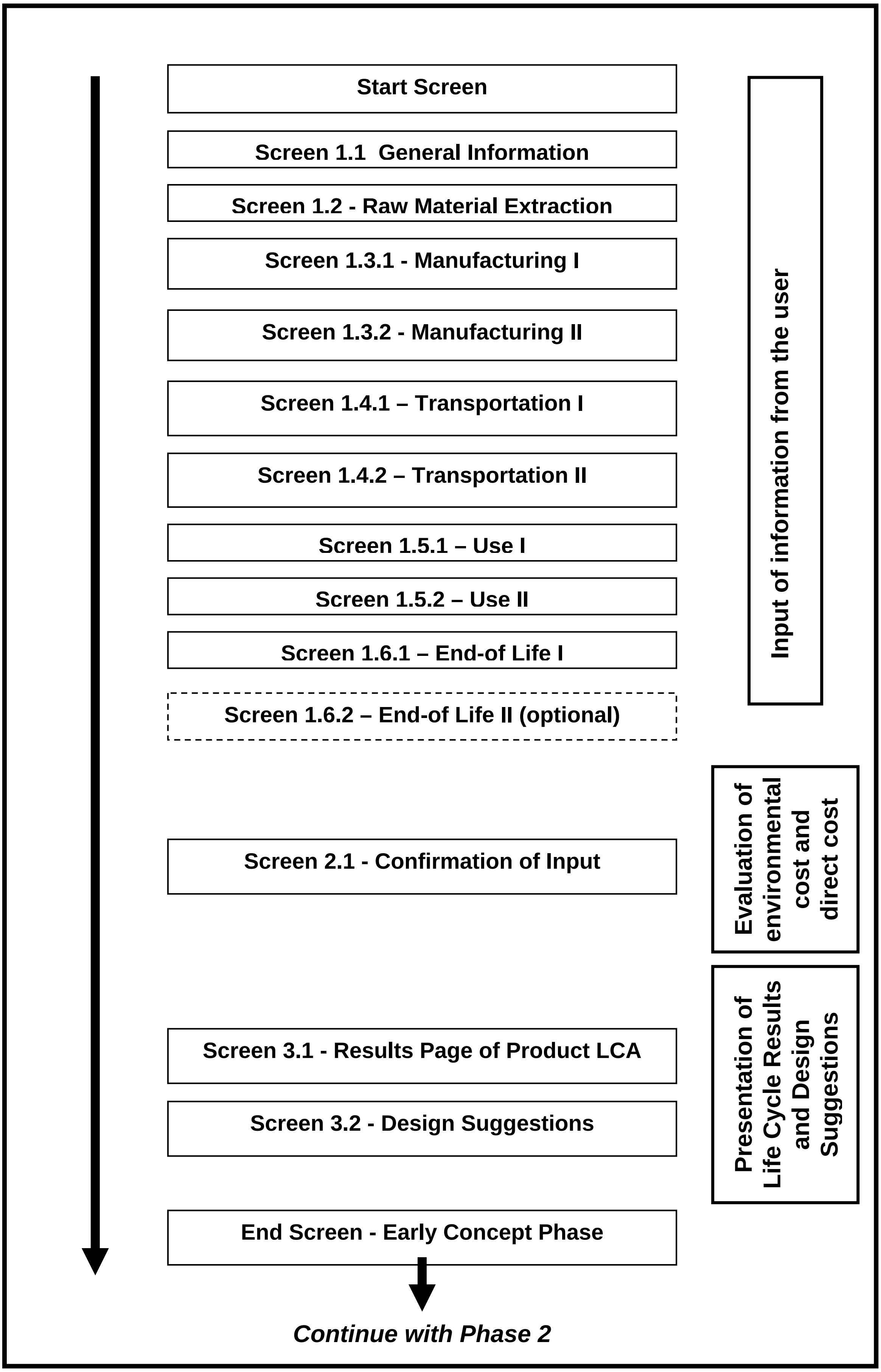
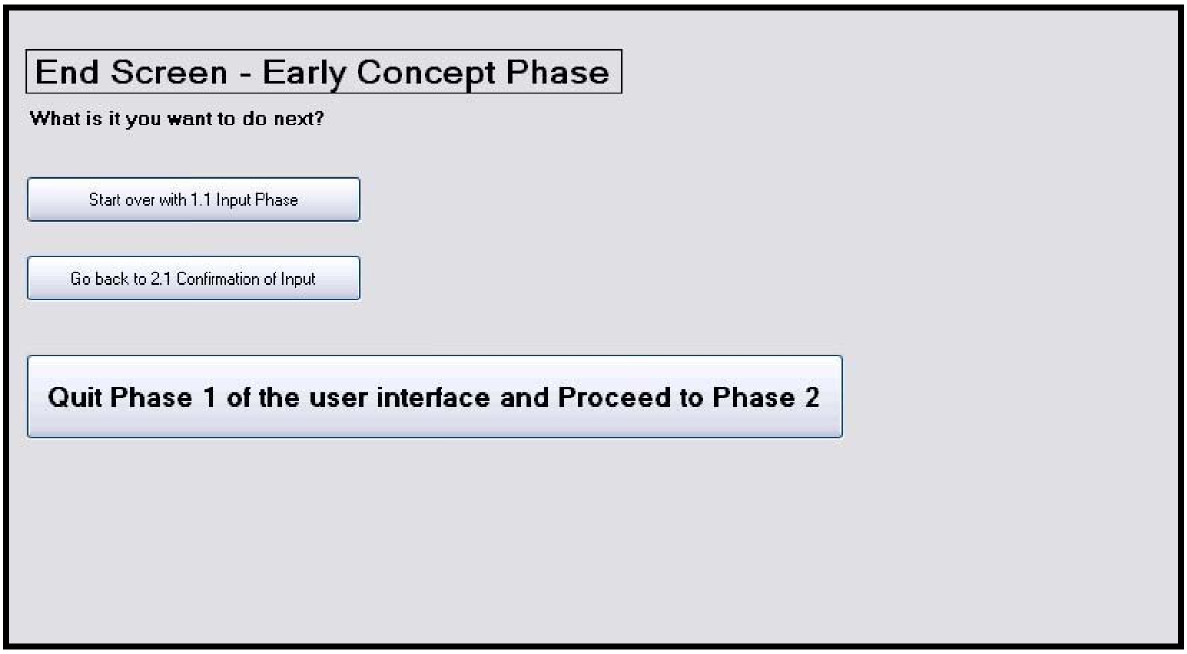


Figure 4.3: Flowchart User Interface – phase 1 – Early Concept phase



<u>Figure 4.4:</u> End Screen – phase 1

4.3.2 Advanced Concept Phase

The 5 screens of the input of information within the user interface can be broken down into three distinct episodes:

- General information input
- Fastener information
- Necessity analysis

All the information is gathered for all the components of the whole product which are restricted to a total of 6 components within the current user interface due to practical issues and the disproportionate effort in programming which would have seriously delayed the completion of the software based user interface. The input information collected from the general information input is used for the results page displaying the direct cost and the environmental cost. Furthermore this input information is used for certain aspects of the design suggestions. The input data gathered during the fastener information screen and the necessity analysis screen (screen 4.2 and screen 4.3) is used for the production of the various design suggestions of this phase 2 only.

As shown in figure 4.5 after all the input information is collected the user has the choice to go back and make certain changes to the information given or to proceed to the results page at the screen 5.1 – Confirmation of input. All the Visual Basic coding necessary for the impact calculation is embedded in this screen, similar to phase 1.

The next screen of the user interface, called Screen 6.1 - Results Page of Component Impact, displays the direct cost impact for all of the 6 components in total without listing the different life cycle stages separately. Thus the sum of direct cost and environmental cost for all the life cycle stages of each component is shown as displayed in figure 4.6. As the figure shows the “Impact Ranking of Components” only identifies the component with the biggest impact and does not rank the rest of the components. This is due to severe difficulty in the programming which would have taken a long time to overcome. The problem is time related only meaning that it would have taken a disproportionately long time to solve this problem within the programming language used. After consulting several experts of the Visual Basic language it was decided that it is not worthwhile spending a long time to overcome this issue since it is not that beneficial in demonstrating the methodology.

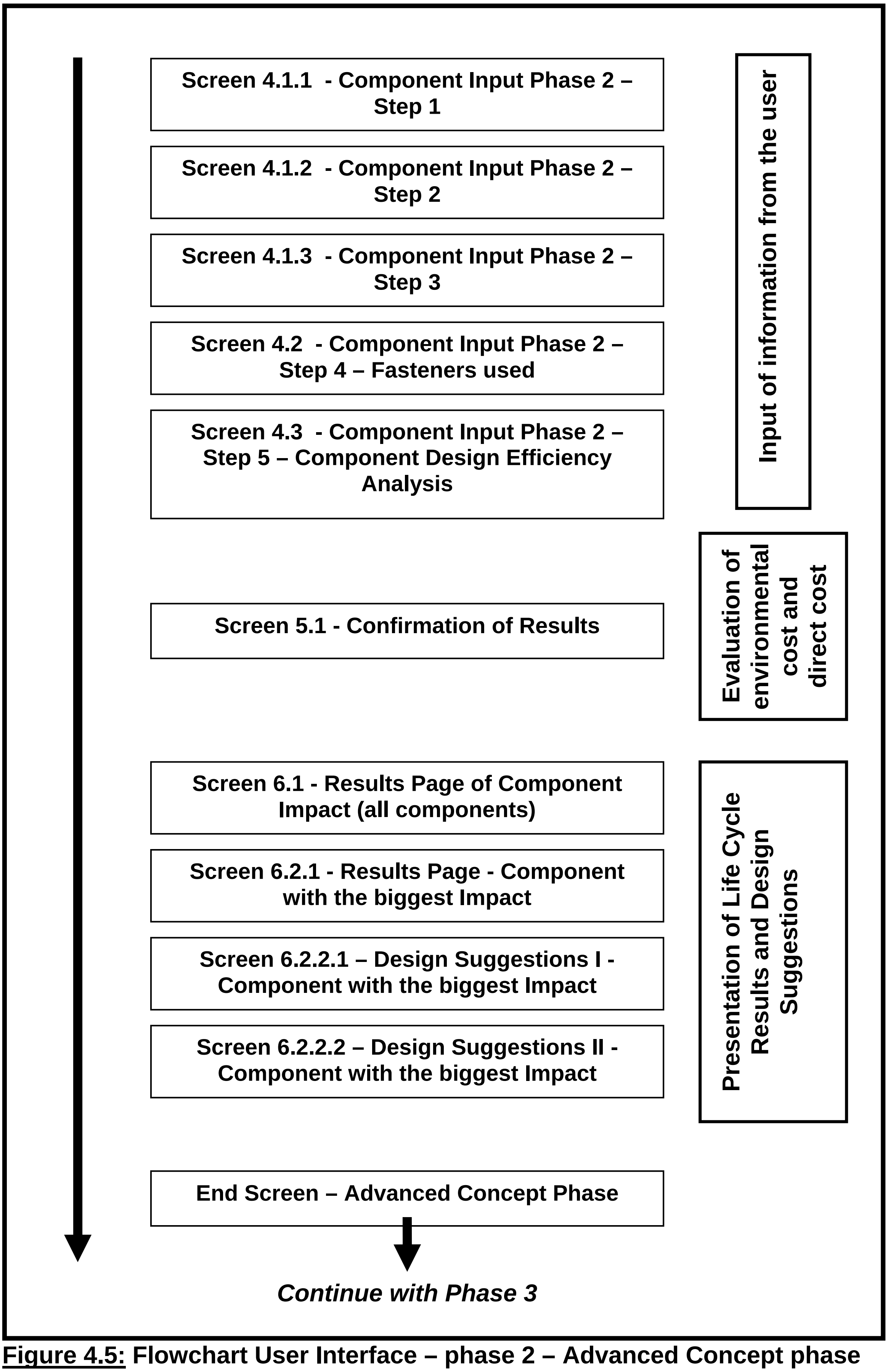
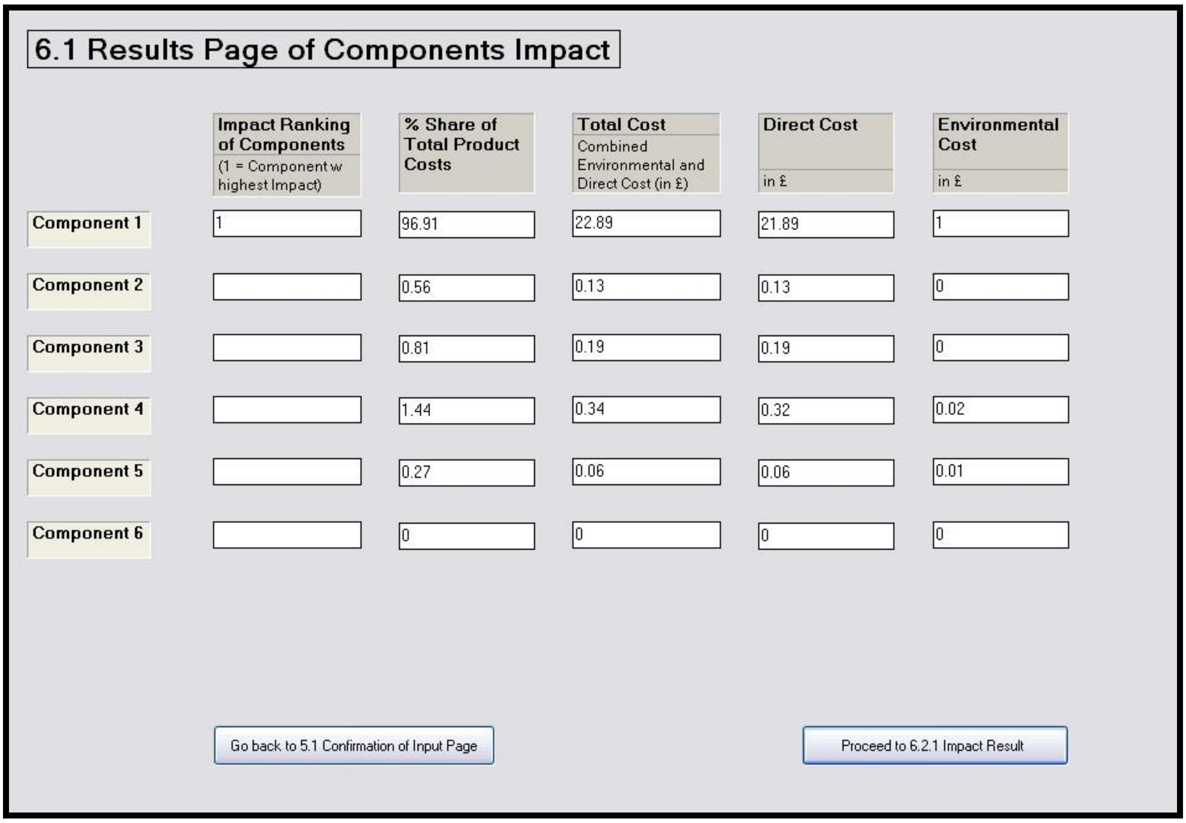


Figure 4.5: Flowchart User Interface – phase 2 – Advanced Concept phase



6.1 Results Page of Components Impact

	Impact Ranking of Components (1 = Component w highest Impact)	% Share of Total Product Costs	Total Cost Combined Environmental and Direct Cost (in £)	Direct Cost in £	Environmental Cost in £
Component 1	1	96.91	22.89	21.89	1
Component 2		0.56	0.13	0.13	0
Component 3		0.81	0.19	0.19	0
Component 4		1.44	0.34	0.32	0.02
Component 5		0.27	0.06	0.06	0.01
Component 6		0	0	0	0

Go back to 5.1 Confirmation of Input Page

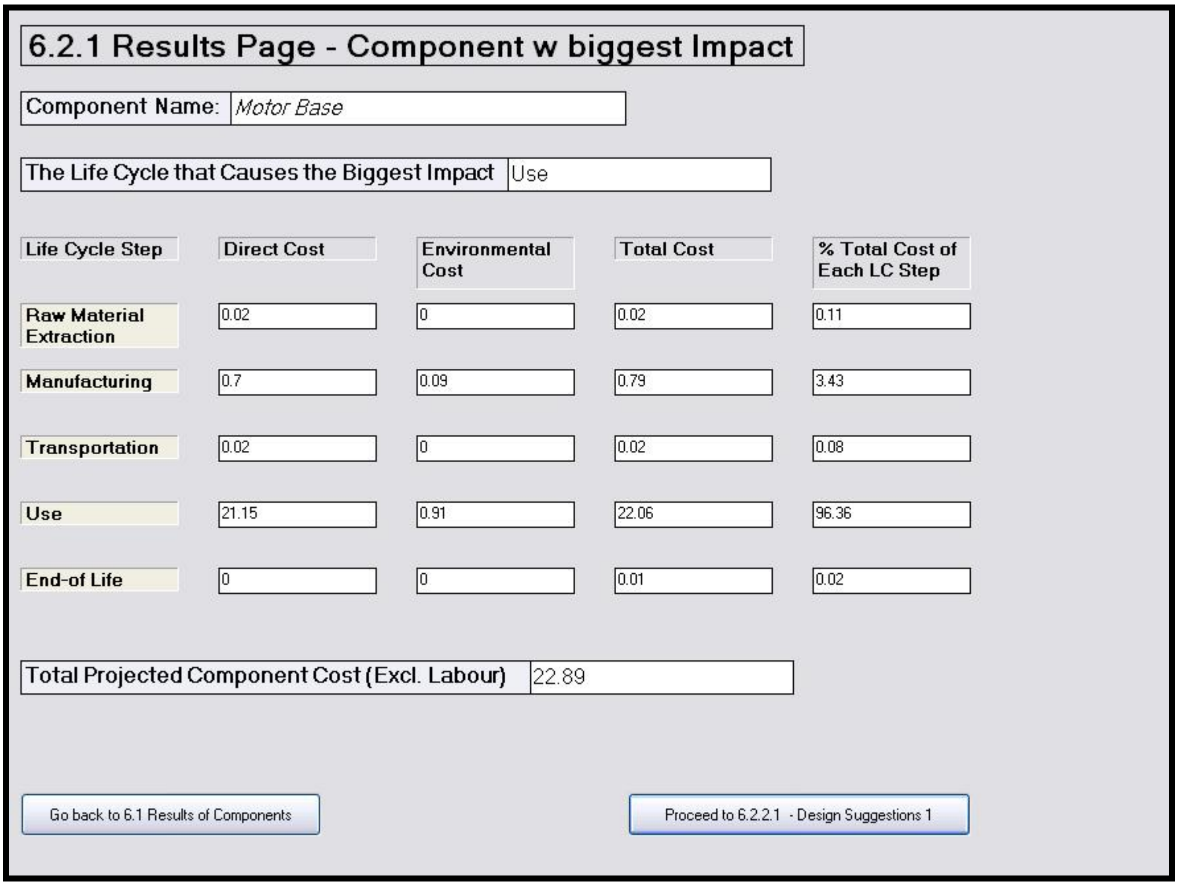
Proceed to 6.2.1 Impact Result

<u>Figure 4.6:</u> User Interface Screen 6.1 - Results Page – Case Study 1

In addition to the direct cost and environment cost this screen contains:

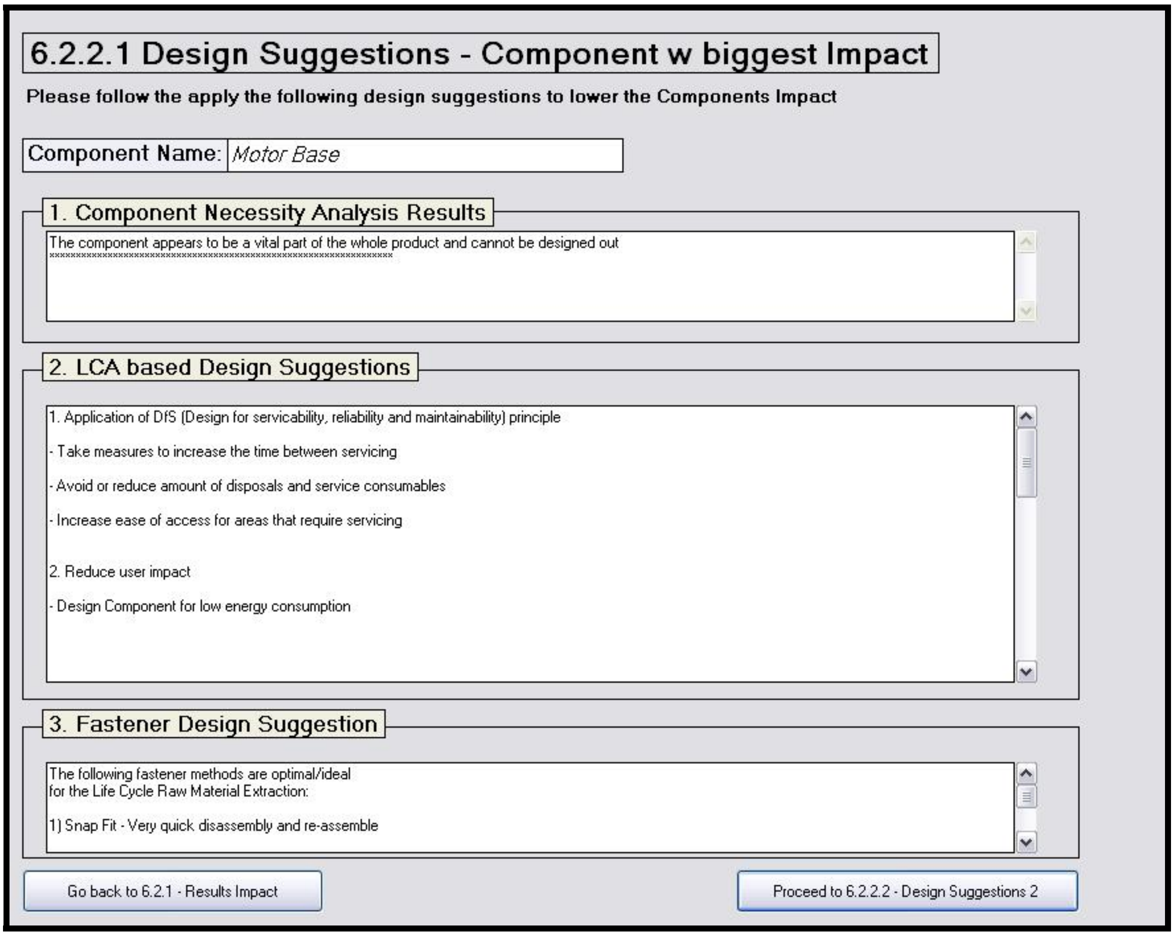
- the total cost – as a result of the former two
- the percentage share of total product cost
- Impact ranking identifying the component with the highest impact

The next screen 6.2.1 shows the impact results for the component with the biggest impact identified previously. Here every single life cycle of this component is shown in terms of the various cost impacts as well as component name and the life cycle stage that actually causes the biggest Total Cost impact. Figure 4.7 shows this screen based on the citrus press case study.



<u>Figure 4.7:</u> User Interface Screen 6.2. 1 - Results Page – Case Study 1

Afterwards the user can proceed to the design suggestion screen 1 which aims to reduce the economic and environmental impact of the product based on the component necessity analysis, life cycle based design suggestions and fastener design suggestions. Screen 6.2.2.1 displays the functionality based design suggestions produced based on the integration of the TRIZ method as shown in figure 4.8.



<u>Figure 4.8:</u> User Interface Screen 6.2.2.1 – Design Suggestions 1 – Case Study 1

4.3.3 Detail Design Phase

The last phase of the user interface is the detail design phase which focuses on the separate parts of the component with the biggest impact. This last phase focuses on the evaluation of the parts of product with the biggest impact only whilst all other parts are neglected. The reason is that the user interface supports the design enhancement process of the product where it is most effective which is to start with the single component that causes the biggest impact.

As shown in figure 4.9, phase 3 of the user interface starts with the input of information from the user similar to phases 1 and 2. In the course of screen 7.1.1 and 7.1.2 information on the parts is gathered. Screen 7.1.1 contains the following information

- Name (of part)
- Weight
- Number of materials
- Material 1
- % of part made from material 1
- Material 2 (if existent)
- % of part made from material 2

And screen 7.1.2 contains the following information

- Material 3 (if existent)
- % of part made from material 3
- Internal part number (of available)
- Main fastener used
- Manufacturing complexity of the part
- Toxicity potential
- EoL scenario of the part

Figure 4.10 shows the screen 7.1.2 of the user interface in the case of the citrus press case study. Certain information input fields are greyed out because in the previous screen the user selected less than 3 materials for the “Number of materials” input parameter. On these screens the component name with the biggest impact that has been identified during phase 2 of the user interface is shown also so that the user knows which part information is required.

Phase 3 of the user interface is limited to a total of 10 parts per component due to the same reason that phase 2 is limited to a maximum of 6 components because of programming practicality. It has to be mentioned though that the research methodology of phases 2 and 3 is not restricted to a certain number of components or parts and theoretically an unlimited number can be evaluated – the limitation is only caused by time and practicality restrictions in the programming process. Furthermore a greater number of parts and components could have resulted in a longer time required for the user to interpret the results.

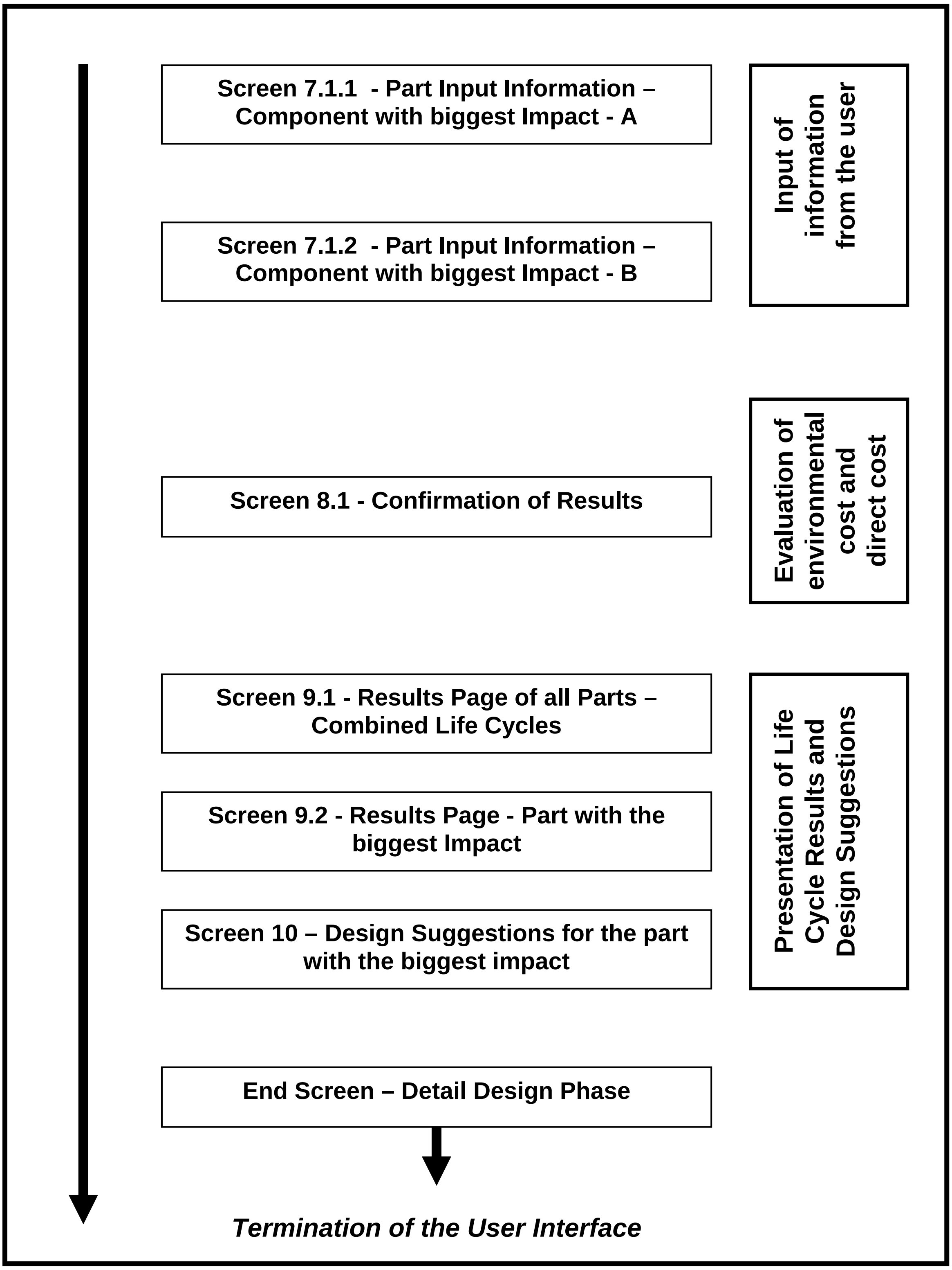
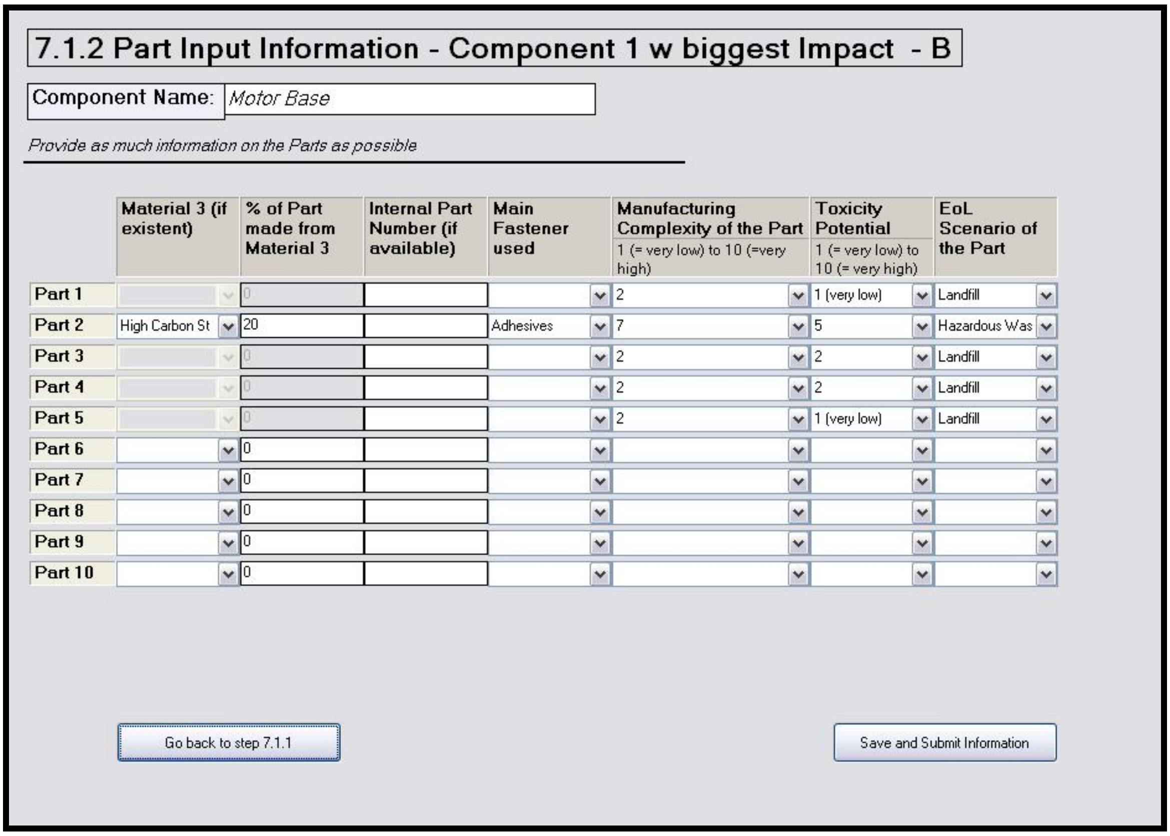


Figure 4.9: Flowchart User Interface – phase 3 – Detail Design phase



7.1.2 Part Input Information - Component 1 w biggest Impact - B

Component Name: *Motor Base*

Provide as much information on the Parts as possible

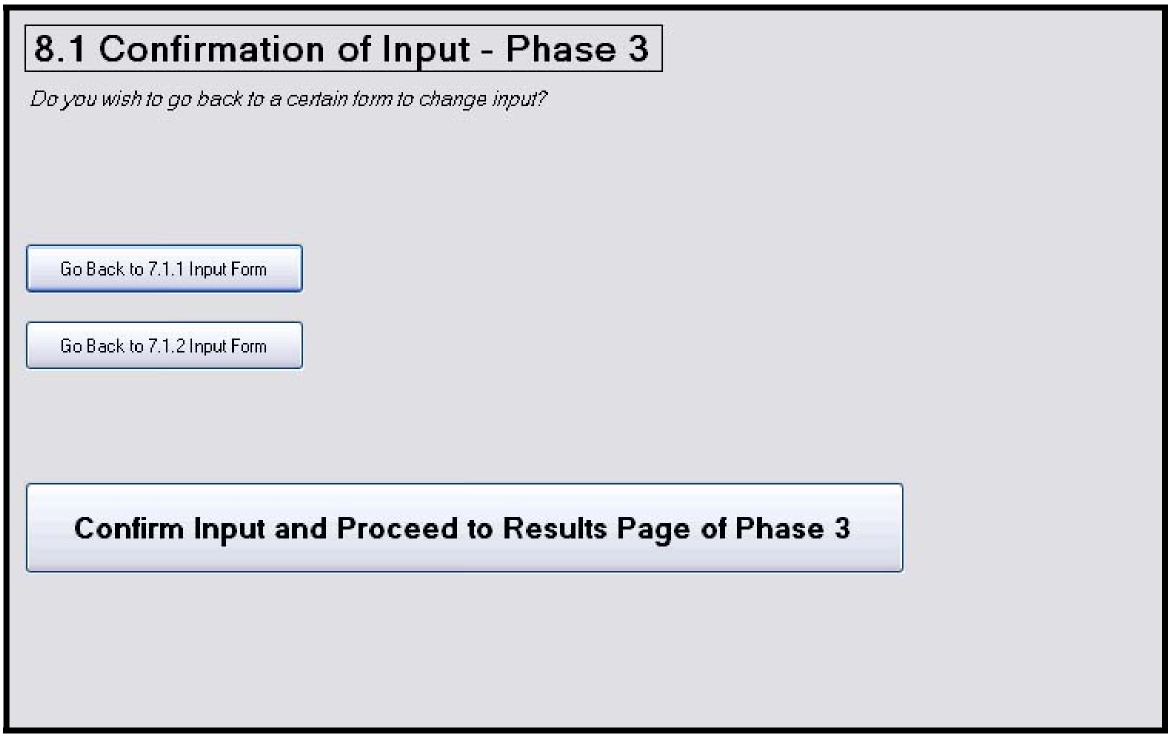
	Material 3 (if existent)	% of Part made from Material 3	Internal Part Number (if available)	Main Fastener used	Manufacturing Complexity of the Part 1 (= very low) to 10 (=very high)	Toxicity Potential 1 (= very low) to 10 (= very high)	EoL Scenario of the Part
Part 1		0			2	1 (very low)	Landfill
Part 2	High Carbon St	20		Adhesives	7	5	Hazardous Was
Part 3		0			2	2	Landfill
Part 4		0			2	2	Landfill
Part 5		0			2	1 (very low)	Landfill
Part 6		0					
Part 7		0					
Part 8		0					
Part 9		0					
Part 10		0					

Go back to step 7.1.1

Save and Submit Information

Figure 4.10: Screenshot - Part Input Information – Component with biggest Impact – B – Citrus Press Case Study

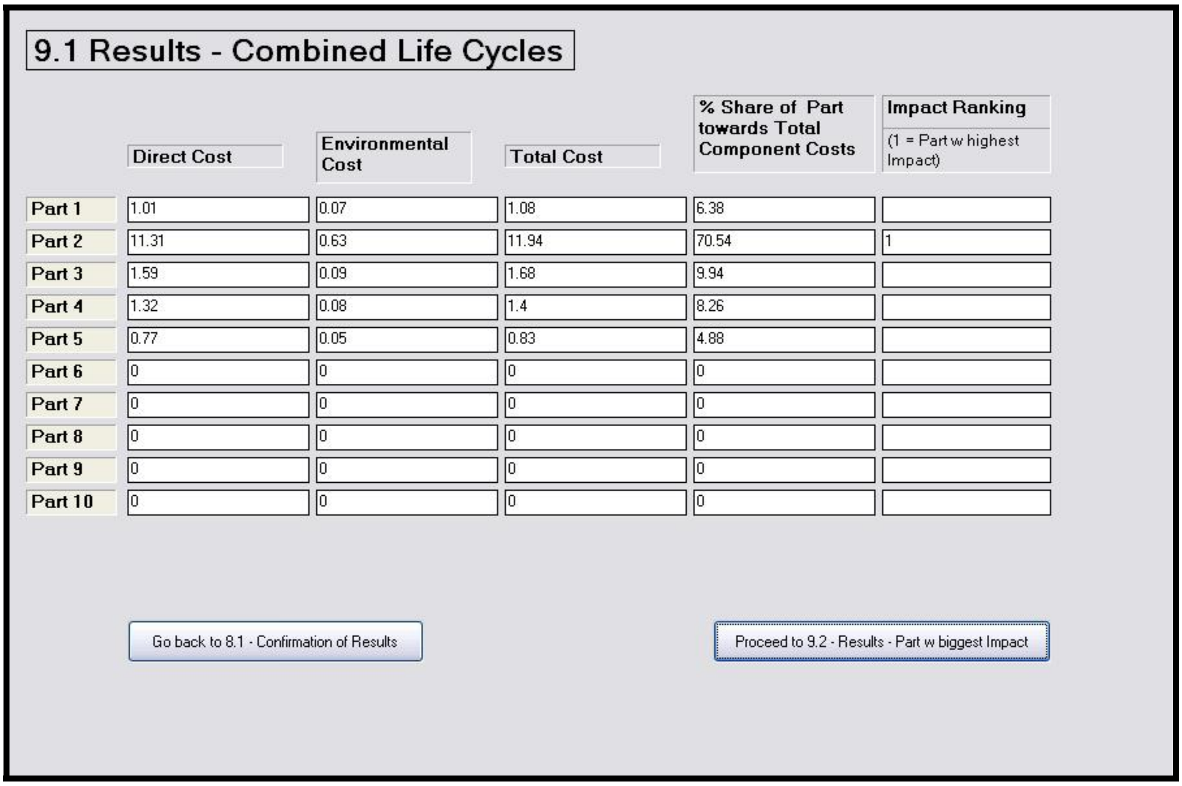
After all the necessary data is collected screen 8.1 lets the user choose either to continue and display results of the impact assessment for all parts or to go back to screen 7.1.1 and start again with the part input information process. Figure 4.11 shows this screen 8.1.



<u>Figure 4.11:</u> Screenshot – Confirmation of Input – phase 3 – Citrus Press Case Study

Similar to phases 1 and 2 of the user interface, screen 8.1 contains a major part of the coding necessary for the evaluation of environmental cost and direct cost of the parts.

Screen 9.1 shows the results for all parts of the component with the biggest impact in terms of environmental cost, direct cost and total cost as displayed in figure 4.12. The results for each part are a product of the combined life cycle of each part thus the sum of the raw material extraction stage, manufacturing stage and the other three life cycle stages. The next aspect of screen 9.1 is the identification of the part that causes the biggest impact as identified via the impact ranking column in figure 4.12. As the figure shows the "Impact Ranking of Components" identifies the component with the biggest impact only as it is described earlier for screen 6.1. This is also due to programming issues.



9.1 Results - Combined Life Cycles

	Direct Cost	Environmental Cost	Total Cost	% Share of Part towards Total Component Costs	Impact Ranking (1 = Part w highest Impact)
Part 1	1.01	0.07	1.08	6.38	
Part 2	11.31	0.63	11.94	70.54	1
Part 3	1.59	0.09	1.68	9.94	
Part 4	1.32	0.08	1.4	8.26	
Part 5	0.77	0.05	0.83	4.88	
Part 6	0	0	0	0	
Part 7	0	0	0	0	
Part 8	0	0	0	0	
Part 9	0	0	0	0	
Part 10	0	0	0	0	

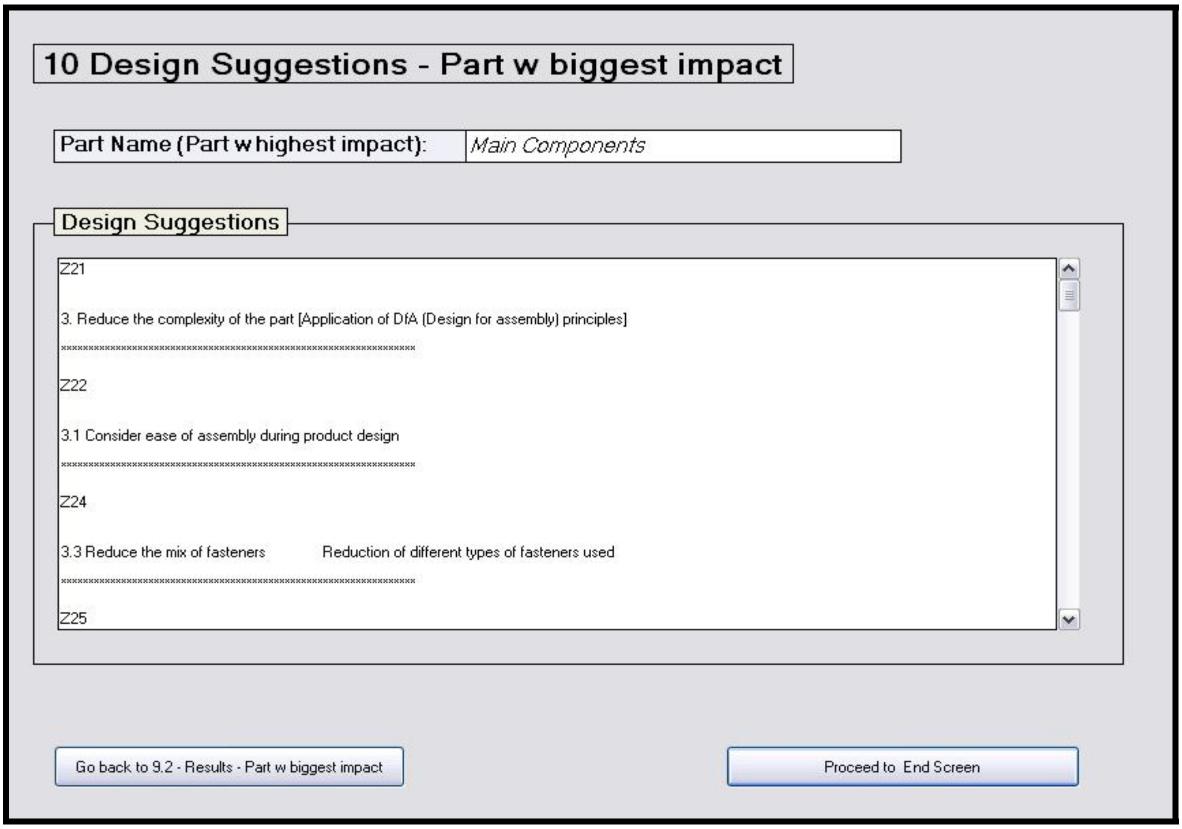
Go back to 8.1 - Confirmation of Results

Proceed to 9.2 - Results - Part w biggest Impact

<u>Figure 4.12:</u> Screenshot - Results – Combined Life Cycle – Citrus Press Case Study

Afterwards the part that causes the biggest impact is evaluated in screen 9.2 displaying all the costs for all the life cycles of the part. This will be explained in more detail in the following case study walkthrough (section 5.4).

Screen 10 provides design suggestions for the part with the biggest impact which is evaluated based on the input information from screens 7.1.1 and 7.1.2. Figure 4.13 shows how the design suggestion matrix is integrated within the user interface and how the design suggestions are displayed. The user can enhance the part design effectively by applying those design suggestions.



<u>Figure 4.13:</u> Design Suggestions – Detail Design phase – Case Study 3 – Telehandler complete

The final screen of the user interface is the end screen of the Detail Design phase and the user has the option to return to screen 7.1.1 and start again with phase 3, go back to screen 8.1 – confirmation of input screen – or to click on the "Quit Phase 3 of the user interface and Exit program" button and terminate the program.

4.4 Chapter reflections

During this chapter 4 details are given on the programming language that was used in order to produce the user interface. Furthermore details on the number of lines of code and the general effort necessary are made. Then all the 3 phases of the user interface are explained thoroughly. This includes details on the input information gathered from the user for each phase as well as how the cost results are produced. Moreover the design suggestions screens of the user interface are explained.

Finally it can be stated that the software provides for a quick and easy to use application which identifies the Life Cycle stages and product areas with the biggest impact efficiently and produces design suggestions quickly. This is based on feedback received from the industrial partner.

5. Application of the Research

5.1 Introduction to Chapter 5

The fifth chapter describes how the research is tested. This deals specifically with the trial of the developed methodology based upon the three case studies used: Citrus Press, Telehandler Hood and Telehandler complete.

Each of these have different life cycle characteristics and product complexities.

5.2 Establishing a collaborating company

In order to develop the proposed methodology a collaborating company needed to be established in order to supply information for the case studies. After a thorough search a firm called Caterpillar agreed to collaborate and support the development of the methodology and the research in general by supplying information regarding one of their products

5.3 The case studies

The Case Studies used are very different in their configuration, complexity and the product types they are based upon. The reason for this is that a broad spectrum of different case studies can better validate if the methodology works in a sensible way. Ideally the chosen case studies differ in various characteristics as well as product complexity in order to prove that the methodology and subsequently the user interface and can be applied to a wide array of different product and does not work for a specific product type only. Besides it proves the validity of the equations used, the sensibility of data used and the mathematical framework the methodology is based upon.

For the validation process of three different case studies seems adequate to proof that it works in the intended way. The three chosen case studies used are:

- A Citrus Press
- A distinct part of a Caterpillar Telehandler – The engine hood
- A complete Caterpillar Telehandler TH460B

The data used to validate for the complete Telehandler and the Telehandler Hood was available due to research collaboration with the Caterpillar Desford/Leicester facility of Caterpillar U.K. All the necessary data required in order to conduct the case studies sensibly was gathered during various meetings with representatives of Caterpillar at the Desford Site. Moreover they helped to find a suitable product part and complete product to base the case study on. This is the Telehandler Hood for the case study 2 and the Telehandler complete for Case Study 3. Even though all the data for case studies 2 and 3 was based on Caterpillar products it has to be stated that care and attention to the confidentiality of information was paramount. In order to protect Caterpillar's intellectual property the data used for the case studies was partly manufactured and does not guarantee validity of any data used in the case studies.

For the data Citrus Press case study an off the shelf product was used from a major U.K. supermarket chain. Comparison and alignment data for this case study were easily obtainable by dismantling the product, literature and internet search as well as interviewing companies based in the electronic and electrical industry.

5.3.1 Case study 1 - Citrus Press

During the quest for a suitable case study 1 certain parameters were set in advance that should be met by the product in question:

- The product should be an energy using product
- Household item
- Medium product complexity (estimated based on the number and shape complexity of the parts)
- No more than 10 different materials used
- Preferably an electricity using product

- Easily available for further examination
- Price Range of £ 5 – 20
- Average Life Cycle of approximately 5 years
- High volume product

The product was used as a development medium for the methodology so that these characteristics were necessary for this early stage of work. After reviewing several products the Citrus Press was considered as suitable for a case study. This simple household item was chosen with the intention of showing how all the three main phases of the methodology can be applied within the user interface.

Also this Case Study was used to show the functions and benefits of the proposed methodology and user interface in a journal paper [[GJB07]].

Figure 5.1 shows and explosion view of the Citrus Press product on the left hand side and a schematic of its main components and the Product Structure - how the components are linked to each other - on the right hand side.

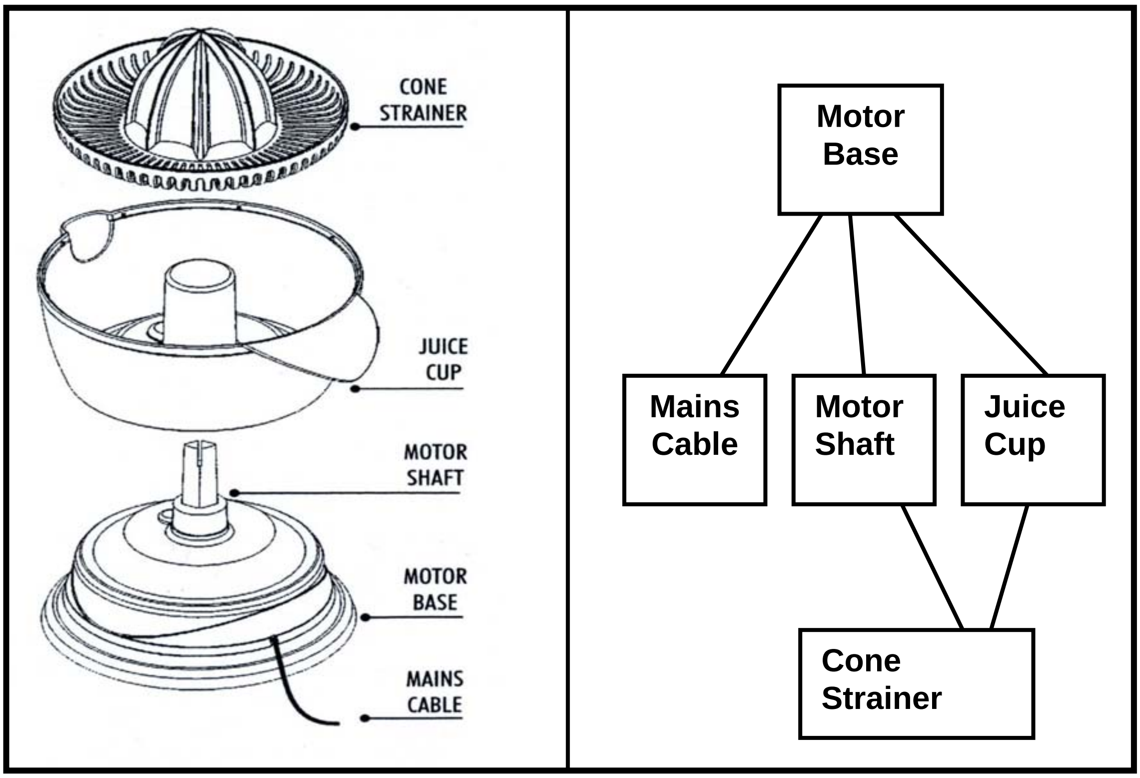


Figure 5.1: **Citrus Press & Product Structure**

5.3.2 Case study 2 - Telehandler Hood

Whilst searching for a suitable case study 2 which should be slightly more complex than the Citrus Press of Case Study 1 it was decided that, since the Case Study 3 would be based on a complete product built by Caterpillar U.K., it would be best to choose a particular part of this complete product. During the collaboration with Caterpillar U.K. Ltd. two components of the TH460B Telehandler product were considered as a suitable case study 2:

- The Telehandler Hood
- The Telehandler Fuel Tank

Figure 5.2 shows the Telehandler Hood with the main attachment parts.

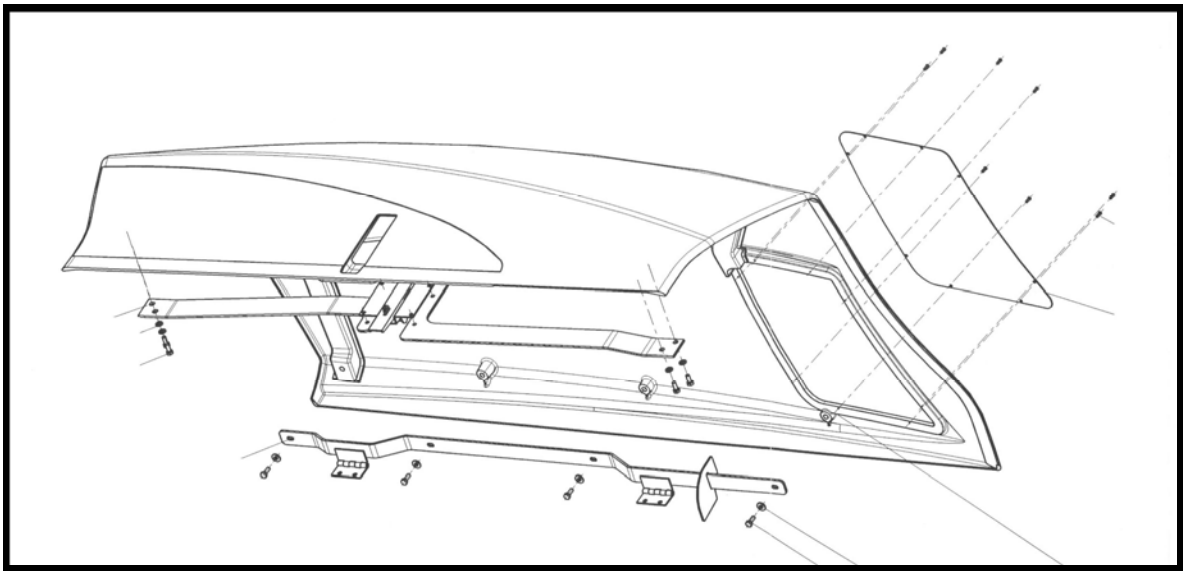


Figure 5.2: Cut out of a technical drawing of the TH460B Telehandler Hood and its main components

The decision was made to select the Telehandler Hood due to several characteristics of the component for a case study evaluation. The reasons for choosing the Telehandler Hood over the Telehandler Fuel Tank are given in the following:

- The Hood consists of 88 parts in total, including attachment parts and surrounding parts, while the Tank consists of less than 20 parts – this provides for a better testability of the user interface and sets the case study apart from the Citrus Press Case study in terms of complexity

- A lot of parts used are standard parts easily available on the market like nuts and bolts which gives the Case Study a more representative quality for other products also
- The materials used within the Hood have a reasonable variety and are more representative for the Telehandler as a whole product

In terms of complexity and weight the Telehandler Hood is situated between the other two case studies.

5.3.3 Case study 3 - Telehandler complete

The case study 3 was actually chosen before the Case Study 2 for reasons described in the previous section. Since the research and the development of the methodology is conducted in collaboration with the Leicester facility of Caterpillar U.K. it made sense to select a product manufactured at this Caterpillar facility in order to have all the necessary information easily available.

The Leicester facility is dedicated to the assembly of small construction machines, ‘typically used on building and construction sites - Backhoe Loaders, Small Wheel Loaders, Mini Hydraulic Excavators and Compact Wheel Loaders’ [CAT06]. During multiple meetings with Caterpillar representatives the Telehandler product – the TH460B model to be more exact – was chosen and is shown in figure 5.3.

Fig 5.3 has been removed due to third party copyright. The unabridged version of the thesis can be viewed at the Lanchester Library, Coventry University

Figure 5.3: Catalogue picture 1 of the TH460B Telehandler [CAT03], copyright Caterpillar U.K. Ltd.

Out of the Caterpillar Telehandler product range the TH460B is located right in the middle; there are three smaller models – in terms of operating weight and rated load capacity – and two larger ones. The usual field of operation for a Telehandler is a construction site or agricultural use.

Additionally the machine has the versatility to attach different work tools to the end of the boom. Possible attachments include a bucket, carriages, pallet forks, lift arms and so on. Mostly the pallet fork attachment is used to move loads to and from places out of reach for a conventional forklift. For example, Telehandlers have the ability to remove palletized cargo from within a trailer and to place loads on rooftops and other high places.

The Telehandler product actually represents the target product group this methodology and the user interface are developed for: Complex products that rely on energy - in the case of the Telehandler in the form of diesel fuel mainly to function. It consist of approximately 5000 parts, weighs a little more than 10 tonnes and is sold at a unit cost of approximately £100 000. Its diesel engine, that powers the drivetrain as well as the hydraulic and electrical systems produces 74.5 kW.

The user interface is tested against the Telehandler Case Study 3 is in depth and the results are shown and thoroughly discussed in the following chapter

5.4 In detail walkthrough of the user interface based on case study 3

The three case studies presented in the earlier chapter proved to be very helpful during the development phase of the methodology and the user interface and the testing of results produced by the user interface. All the reference data was collected during the collaboration with caterpillar, internet and library research as well as interviewing people in the related product fields.

The purpose of this section is to show how the user interface was thoroughly tested against the case study data and to discuss the validity of the results produced by it. All three phases of the user interface are evaluated in detail and various screenshots are displayed in order to support the argument made and to better visualize how the user interface works.

Even though the user interface was tested against all three case studies a detailed walkthrough based on case study 3 – the Telehandler complete - only is given only since to give details on all three would have resulted in little extra benefit.

All the data used within this case study 3 has been gathered in collaboration with Caterpillar U.K. Ltd. The results produced by the user interface are accurate regarding their intended purpose but they depend strongly on the accuracy of the input information given. Furthermore the cost results of the methodology cannot claim a 100% accuracy since they depend on certain estimates in input data from the user and from the databases – e.g. such as price range in material cost. The results produced are accurate enough to get a general idea and estimate of the overall Life Cycle cost of a product excluding labour costs. This is then used to pinpoint the Life Cycle that cause the biggest impact for either the whole product, the component and the part as well as identifying the component that causes the major impact during phase 2 of the user interface and to identify the part that causes the biggest impact during phase 3.

5.4.1 Early Concept Phase analysis

During the early concept phase the following type of information is collected from the user: General input information on one hand and life cycle related input information on the other hand.

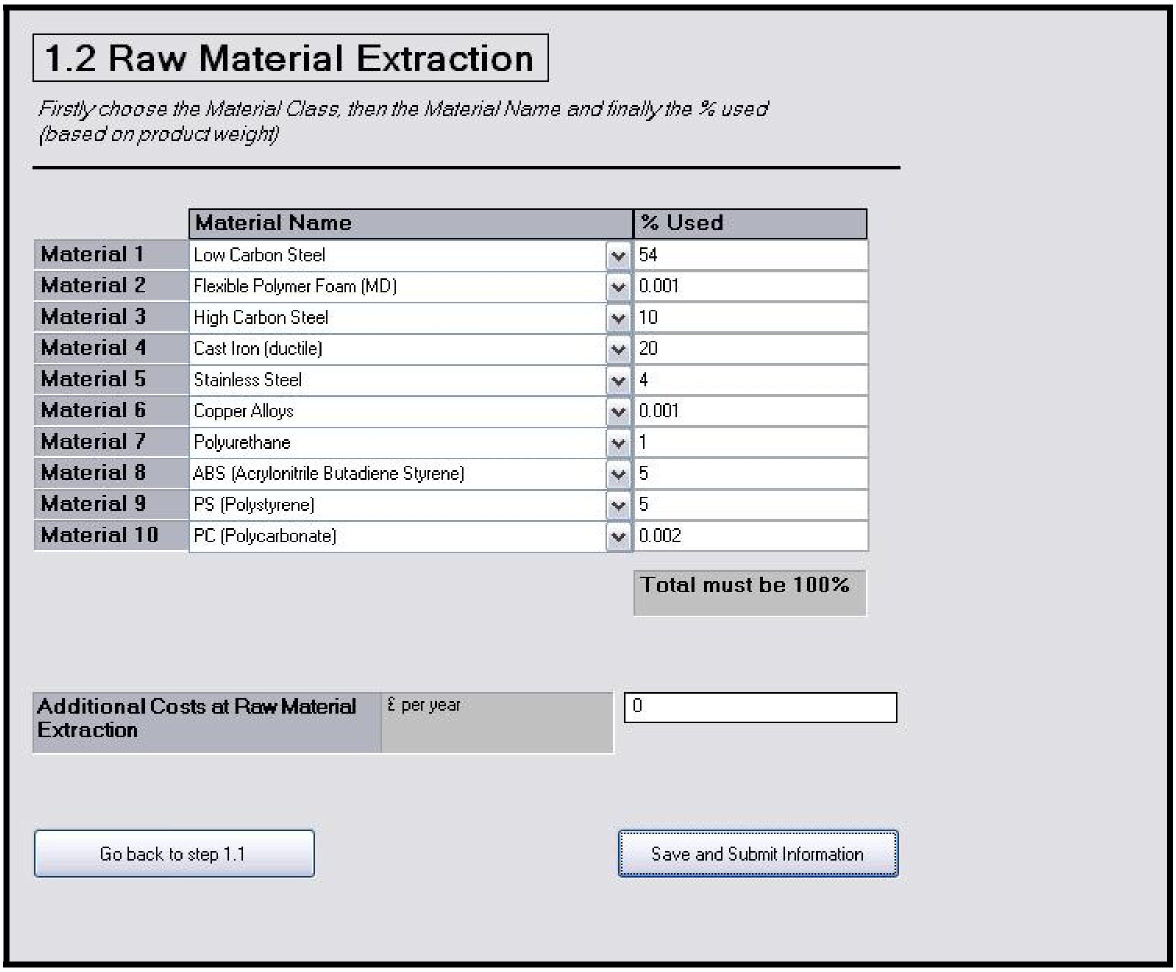
The general information used for the information input is the following in the case of the Telehandler complete:

Input Information	**Value**	**Units**	**Source of Information**
1) Production Volume	5000	Units per year	Caterpillar interview
2) Product Use Frequency A	45	Weeks per year	Caterpillar interview
3) Product Use Frequency B	5	Days per week	Caterpillar interview
4) Product Use Frequency	6	Hours per day	Caterpillar interview
5) Overall Product Weight	10500	Kg per unit	TH460B Specification Catalogue
6) Average Life Cycle Length	10	Years	Caterpillar interview
7) Number of Materials used	80	n	Caterpillar interview
8) Domestic Electrical Energy Price	10	Pence per kWh	Internet & company research
9) Average Number of Parts	5000	n	Caterpillar interview

Figure 5.4: General Information for Telehandler complete and source of information

Most of this general information was gathered during the meetings with Caterpillar U.K. representatives. Some of the provided data can be defined as an absolutely exact figure such as the overall product weight others are estimates based on years of experience by Caterpillar representatives such as the product use frequency or the average life cycle length.

Figure 5.5 shows the materials selected which covers the life cycle stage of raw material extraction. Even though the Telehandler is built up of a total of 80 different materials only the 10 most important ones are listed. The importance of the materials used for a product is directly linked to their contribution to the total product weight. To give an example: For a component that weighs 10 kg all the materials with a weight of 1kg are listed but certainly materials with a weight lower than 1 gram are not. Thus always the most important materials are listed. The "% Used" of the user interface always relates to weight rather than volume or another physical dimension.



<u>Figure 5.5:</u> Screenshot of the Raw Material Extraction Information Screen of the User Interface

For the user interface only 19 representative materials can be chosen due to programming practicality reasons. If a material is not available within the user interface the user should always select the next similar material. For example if a very specific type of low carbon steel is used the user has to select the material “Low Carbon Steel”. Even though the material properties might not be a total match the results produced will be valid enough.

The main issues during the manufacturing stage of the Telehandler complete are electrical energy and natural gas used to run the production facility as well as water use. Exact figures used for the case study are based on production facility size, and yearly energy and water bills of comparable sized production facilities. This is shown in figure 5.6. Screenshots whilst all the figures can be found in the appendix D.

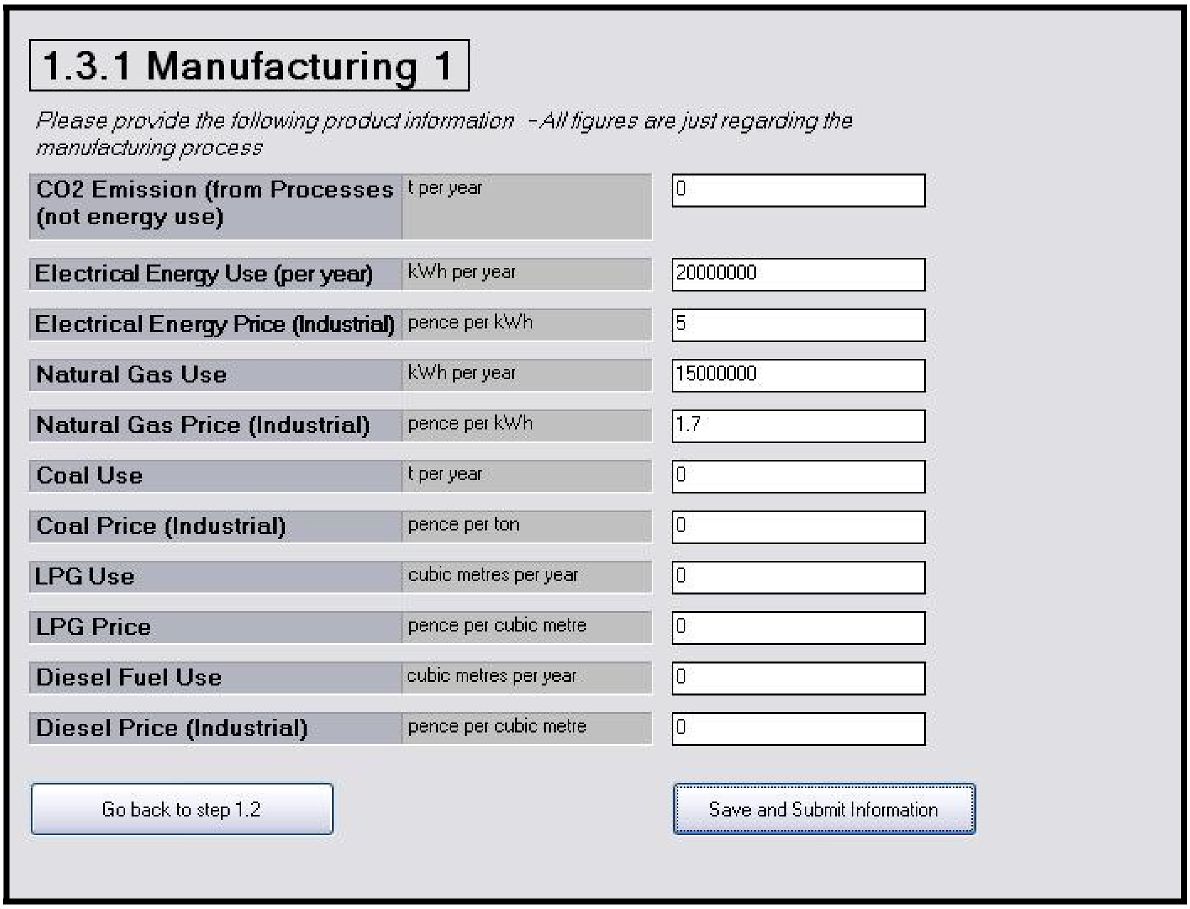


Figure 5.6: Screenshot of the Manufacturing Information Screen of the User Interface

Figure 5.7 shows screen 1 of the Transportation Life Cycle. The information provided include information on percentage of parts delivered by suppliers – the rest is assumed to be manufactured on site – and the different mode of transportation for those supplier parts. As figure 5.7 shows screen 1 deals with the incoming transportation issues whilst screen 2 covers the outgoing transportation – from the production facility to the user or retailer. The two screens are very similar in the type of information they request from the user. Furthermore 5 representative modes of transportation can be selected only:

- Lorry
- Train
- Inland Ship
- Sea Ship
- Airplane

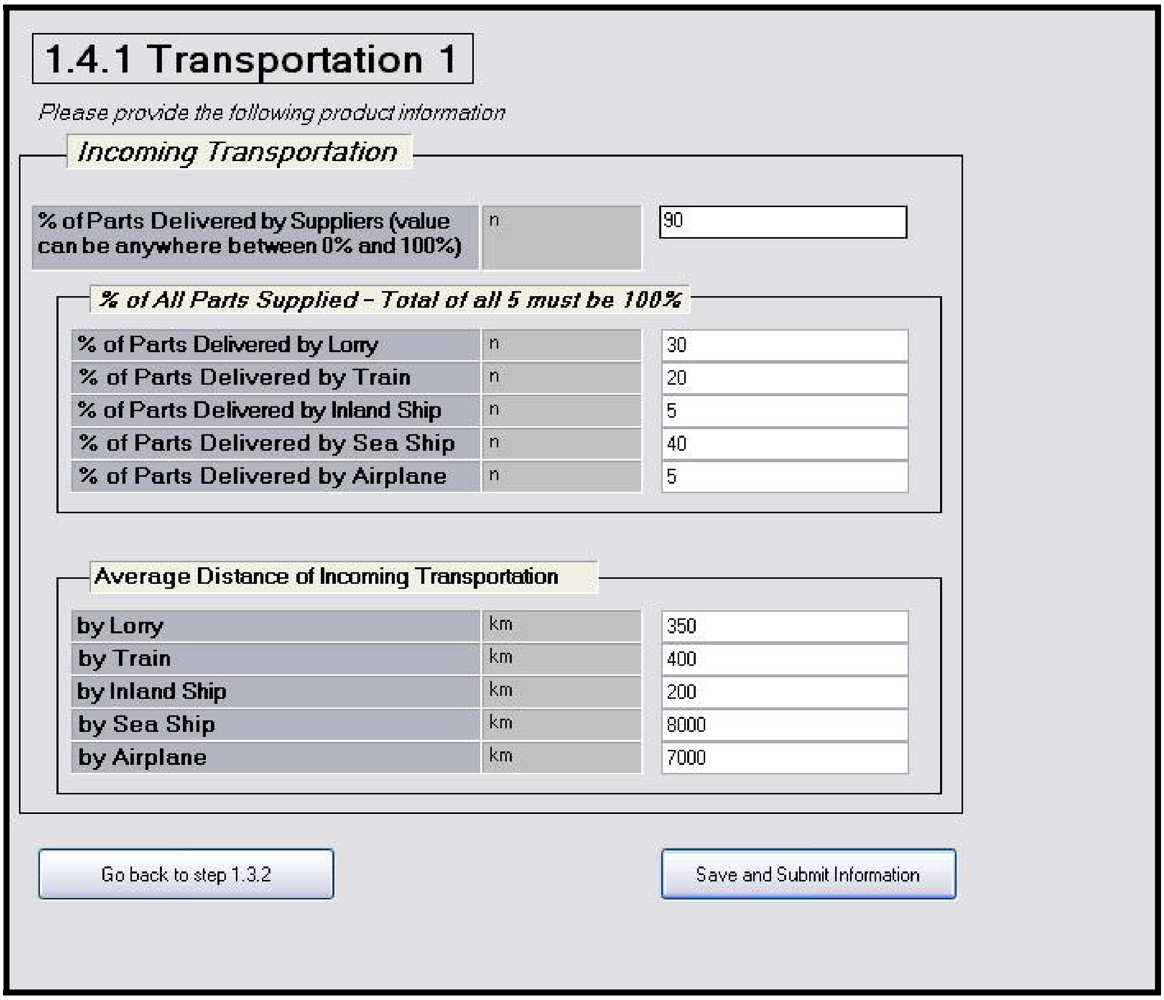
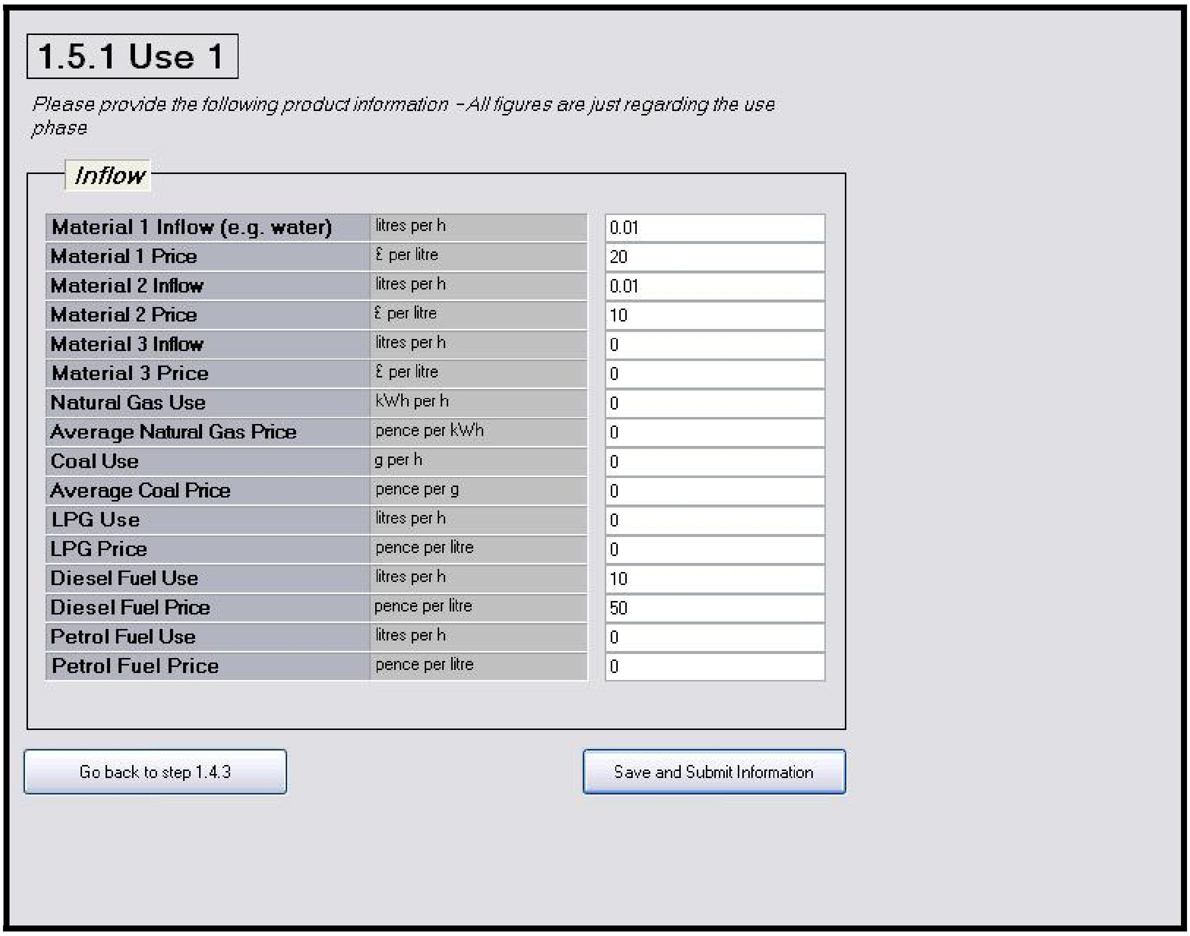


Figure 5.7: Screenshot of the Transportation Screen I of the User Interface

All the details for the Use Life Cycle Stage of the complete Telehandler are shown in figures 5.8 and 5.9. The use 1 screen deals with the material inflow during the product use which is in the case of the Telehandler is:

- Material 1 = 0.01 litres per hour of Hydraulic Fluid
- Material 2 = 0.01 litres per hour of Engine Oil
- 10 litres per hour of Diesel Fuel use



<u>Figure 5.8:</u> Screenshot of the Use Screen I of the User Interface

As shown in figure 5.9 the screen 2 of the Use Life Cycle within the interface request information regarding material outflow, (electric) power consumption and consumables used. The main issues for the Telehandler case study are the outflow of engine oil (material 4 outflow) and hydraulic fluid (material 5 outflow) due to leakage. No electrical power is consumed by the Telehandler since it is completely self-sufficient and relies on diesel fuel as its main energy source only.

The consumables used are oil filters and engine filters and average figures for this are provided as shown.

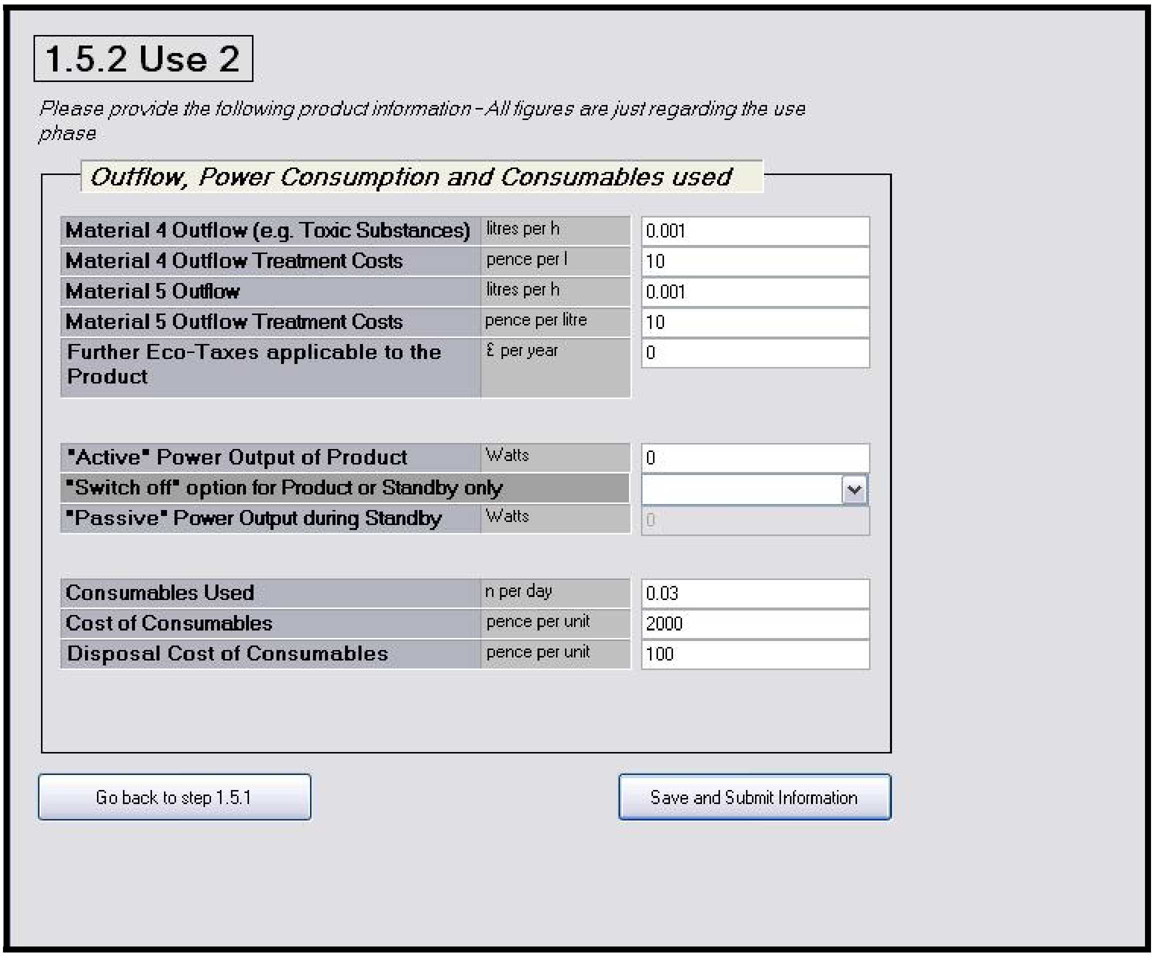


Figure 5.9: Screenshot of the Use Screen II of the User Interface

The End-of Life scenario chosen for the Telehandler is “Setting up a Take Back Scheme”. Albeit this might not be valid for every single Telehandler it is the most likely scenario due to the high value of the product and the current changes in company responsibilities. This means that sooner or later companies legally have to take back their industrial equipment at their End-of Life or change their company strategy from production to services. In the case of Caterpillar this could mean that instead of selling the Telehandler products via their distribution network they switch to leasing their product to the customer. This means more control and involvement for Caterpillar in terms of the product's whole life cycle. First developments in this direction are the recently started Cat Rental Store chain.

Screen 1 of the End-of Life stage within the user interface lets the user choose details on the most likely End-of Life scenario of the product and cost and revenues of running the End-of Life treatment facilities. Screen 2 calls for input information in the disassembly possibility of the product and the percentages of the product going to different End of Life treatment options e.g. Incineration or Recycling which can be reviewed in figure 5.10.

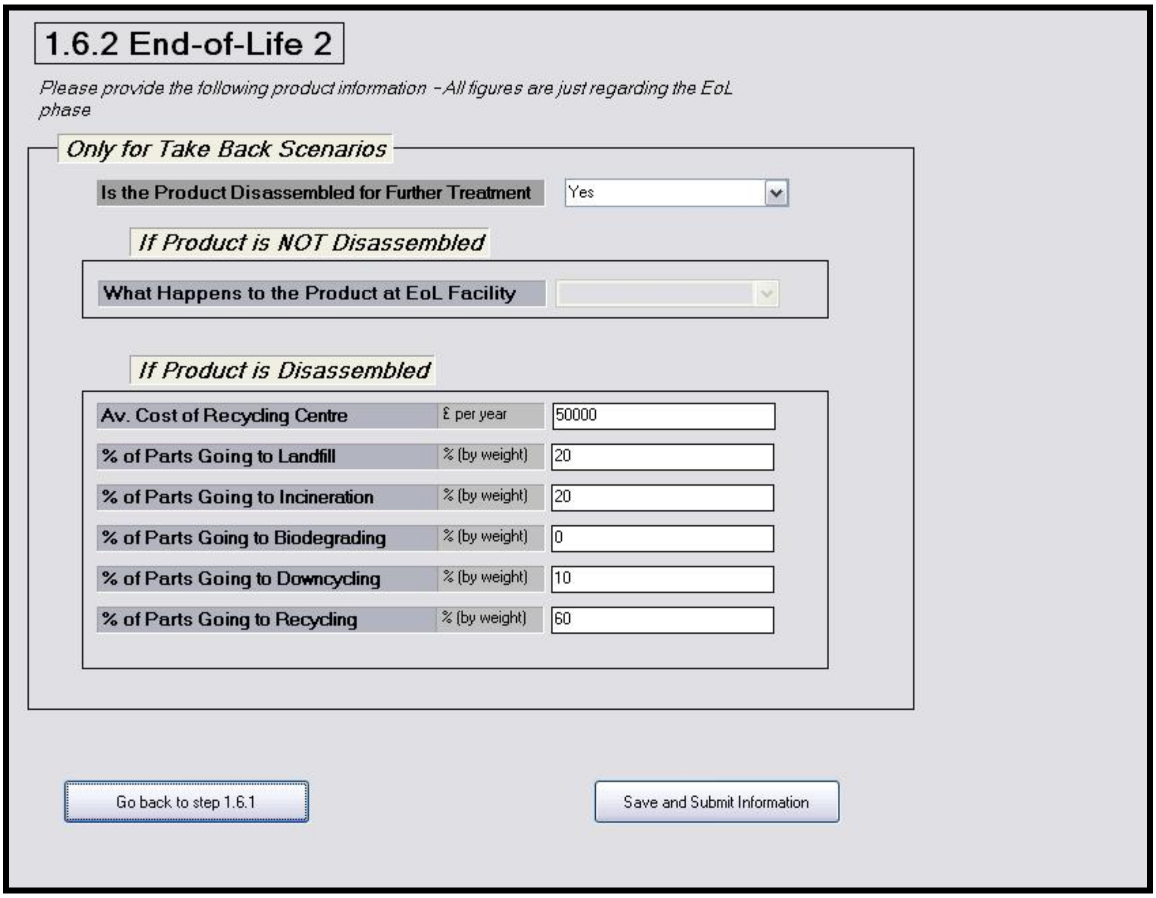
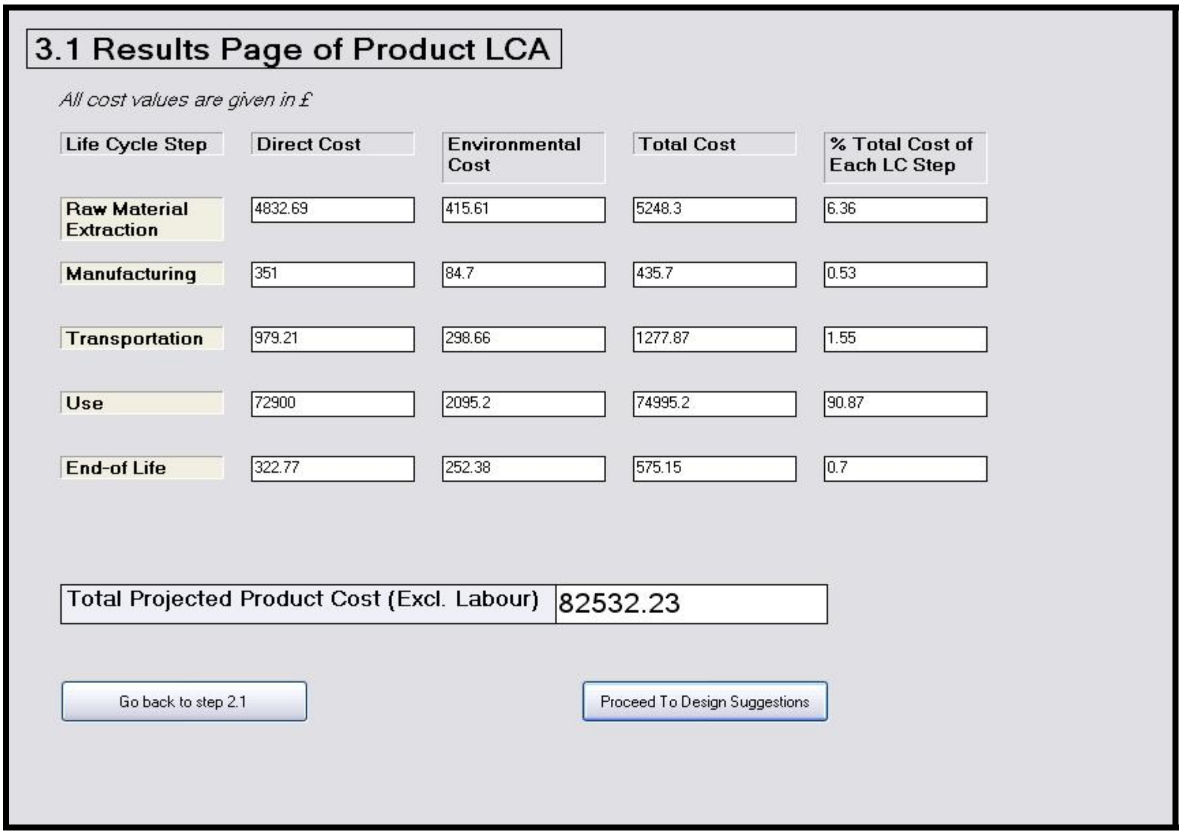


Figure 5.10: Screenshot of the End-of Life Screen II of the User Interface

After all the input information is collected for the Telehandler case study and the "Confirm Input and Proceed to Results Page" button is activated the results of the product LCA are given as figure 5.11 illustrates. The total projected product cost for all the Life Cycle Stages of the Telehandler combined is £82532.23 which is excluding labour cost. The result is not too surprising since the initial estimates that were based on raw material cost, manufacturing costs and fuel costs were hinting at an average total cost of below £100 000. The Life Cycle Stage that is identifies to cause the biggest total cost impact is Use. It causes 90.87% of the total costs of all Life Cycles combined, which is nearly £75000.


3.1 Results Page of Product LCA

All cost values are given in £

Life Cycle Step	Direct Cost	Environmental Cost	Total Cost	% Total Cost of Each LC Step
Raw Material Extraction	4832.69	415.61	5248.3	6.36
Manufacturing	351	84.7	435.7	0.53
Transportation	979.21	298.66	1277.87	1.55
Use	72900	2095.2	74995.2	90.87
End-of Life	322.77	252.38	575.15	0.7

Total Projected Product Cost (Excl. Labour)	82532.23

Go back to step 2.1

Proceed To Design Suggestions

<u>Figure 5.11:</u> Screenshot – Results Page of Product LCA – Telehandler complete

This total cost can be split into £72900 of direct cost and £2095 of environmental cost. The cost impact driver is clearly the diesel fuel use and the direct cost are a result of buying the fuel (excluding any environmental tax) and the environmental cost is a result of emission taxes and material outflow treatment cost. The Life Cycle Stage that causes the second biggest impact is the Raw Material Stage with a direct cost impact of £4832.69 and an environmental cost impact of £415.61. The participation to the total projected product cost is 6.36%

and reasons for the high impact here is the relatively high weight of the product and the use of considerably highly priced raw materials.

Based on the Life Cycle Stage that is identified on the “Results Page of Product LCA” at Screen 3.1 appropriate Design Suggestions - to enhance product performance at this specific Life Cycle Stage are shown in the screen 3.2 Design Suggestions. The design suggestions are not fixed solely on the Life Cycle Stage with the biggest impact but they depend on the magnitude of certain input information parameters also. In the case of the Use phase as the impact driver for example:

- Amount of material 1 inflow
- Amount of natural gas use
- Amount of coal use
- “Active power output whilst product is switched on” figure
- "Passive power output during standby” figure
- Number of consumables used

Thus for example various evaluated products that share the same Life Cycle Stage with the biggest impact the Design Suggestions created can be totally different: Figure 5.12 shows some of the design suggestions created for the Telehandler. It is possible to use the scrollbar on the right hand of the textbox to reveal more design suggestions. The design suggestions produced for the Telehandler case study are as they were expected: Some are applicable and actually very helpful for improving the product design whilst others are not applicable and feasible for this case study-

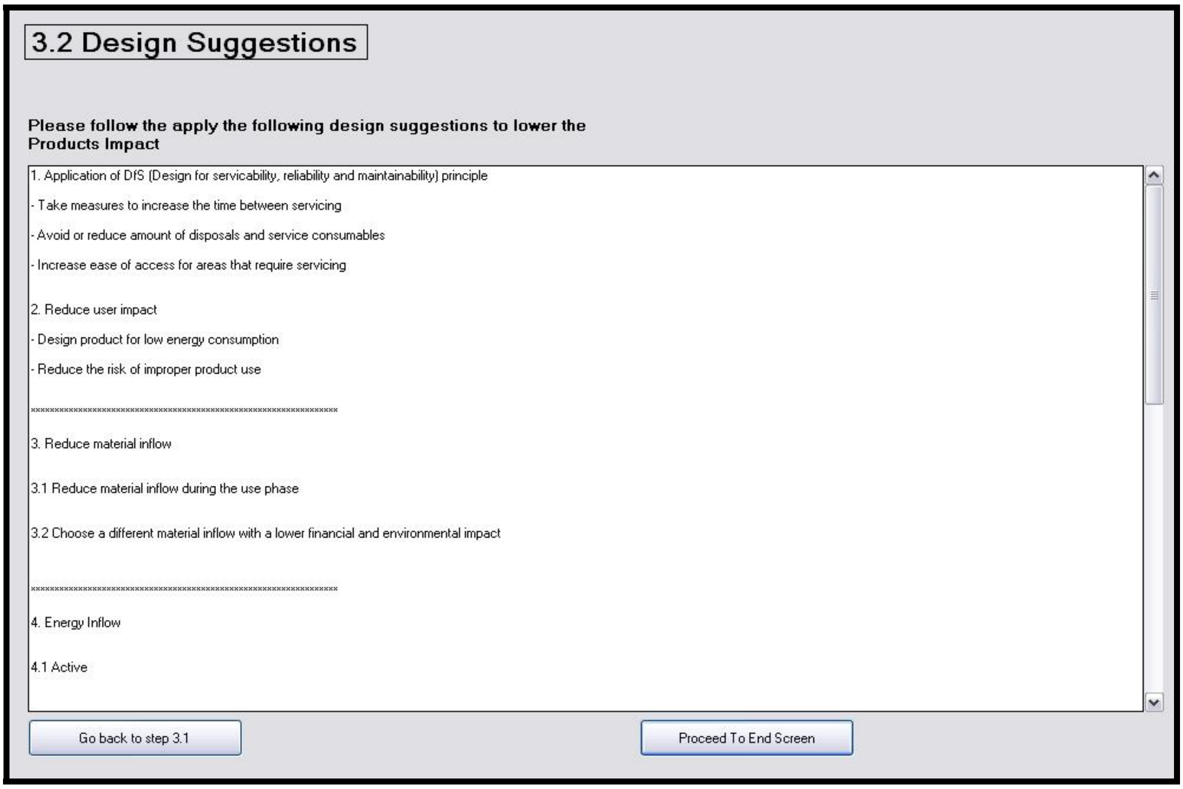


Figure 5.12: Screenshot – Screen 3.2 Design Suggestions – Telehandler complete

The design suggestions produced are listed in the following figures 5.13, 5.16 and 5.17 together with a detailed explanation how they can be interpreted for the Telehandler case study:

User Interface Design Suggestion	In Detail Instruction	Interpretation for the Telehandler Case Study
1. Application of DfS (Design for serviceability, reliability and maintainability) principle	- Take measures to increase the time between servicing - Avoid or reduce amount of disposals and service consumables - Increase ease of access for areas that require servicing	• Is it possible to design the various filters for a longer life cycle and thus extended service periods? • Use filters that can be cleaned instead of filters that need to be disposed of. • Can the use of a better type of engine oil increase time between servicing • Improve the access for serviceability to parts and consumables
2. Reduce user impact	- Design product for low energy consumption - Reduce the risk of improper product use	• Increase the efficiency of the main energy source of the Telehandler – the diesel engine
3. Reduce material inflow	- Reduce material inflow during the use phase - Choose a different material inflow with a lower impact	• Think of alternative measure to reduce the material inflow of diesel fuel, hydraulic fluid, engine oil and water • Is it possible to reduce leakage by using highly efficient sealings

<u>Figure 5.13:</u> Design Suggestion Interpretation for the Early Concept phase - Telehandler Case Study - I

User Interface Design Suggestion	In Detail Instruction	Interpretation for the Telehandler Case Study
4.1 Energy Inflow Active	4.1.1 Reduce the active amount of energy required by efficiency increase measures	Increase the efficiency of the diesel fuel engine
	4.1.2 Choose a different type of energy source and evaluate financial and environmental impact	Evaluate alternative engine and power types for the Telehandler – e.g. electrical, gas, etc. – and test them for efficiency
	4.1.3 Evaluate if it is possible to reduce the energy consumption of the product during idle process install automatic switch-off function or similar	Install a energy saving measure, e.g. engine start stop function depending when energy is required, e.g. similar to the “Micro Hybrid Drive” used for the smart vehicle [[SMA08]]
	4.1.4 Take the Climate Change Levy into account and investigate impact on customer or product user	This is automatically included in the Environmental Costs shown in screen 3.1 of the methodology. Is it possible though to use an energy source with a lower carbon footprint?

Figure 5.14: Design Suggestion Interpretation for the Early Concept phase - Telehandler Case Study - II

User Interface Design Suggestion	In Detail Instruction	Interpretation for the Telehandler Case Study
5.1 Treat consumable as a product	- Evaluate the Life Cycle Impact of a consumable by treating it as a regular product - Use matrix to find out what the biggest financial and environmental impact of the consumable is and at which (consumable) Life Cycle step it occurs - Investigate solutions to reduce the impact of the consumable during its Life Cycle step with the biggest impact	Take a closer look at all the consumables used for the Telehandler: Filters, Sealings, Hydraulic tubing and so on
5.2 What is the purpose of the consumable		Review the purpose of all used consumables – if they do not have one then the can be designed out
5.3 Can the consumable be designed out?	Is the consumable part of the products main function - If yes: Consumable cannot be designed out If no: Is it possible to avoid use of consumable by using smart design	Same as 5.2
5.5 Reduce Waste caused by Consumables	- Some consumables create waste during their use - Re-use of consumable - Re-design consumables to avoid waste	- Is it possible to manufacture the consumables used out of a different material that causes a smaller impact at their EoL?

<u>Figure 5.15:</u> Design Suggestion Interpretation for the Early Concept phase - Telehandler Case Study - III

All the design suggestions and interpretations for the Telehandler case study should help reduce the direct cost and environmental cost impact of the product as a whole. During the next phase 2 that is described in the following section 5.4.2 the individual components of the whole product are evaluated.

5.4.2 Advanced Concept phase analysis

During the Advanced Concept phase the user interface gathers information regarding general component information, fastener information and component necessity analysis information.

Screen 4.1.1, 4.1.2 and 4.1.3 are used for the gathering of general component information such as name of the component, information regarding its functions, complexity, physical factors, production costs and various others. Figure 5.16 shows the first information input screen listing all the six main components of the Telehandler product: Telescopic Beam, Drivers Cab, Ladder Frame, Suspension and Steering System (including Braking), Engine (incl. Powertrain) and the Hydraulic System. The various input data gathered from the user in screens 4.1.1 – 4.1.3 of the general input information is numbered 1 (Name of Component) to 26 (Dismantling Cost of Component).

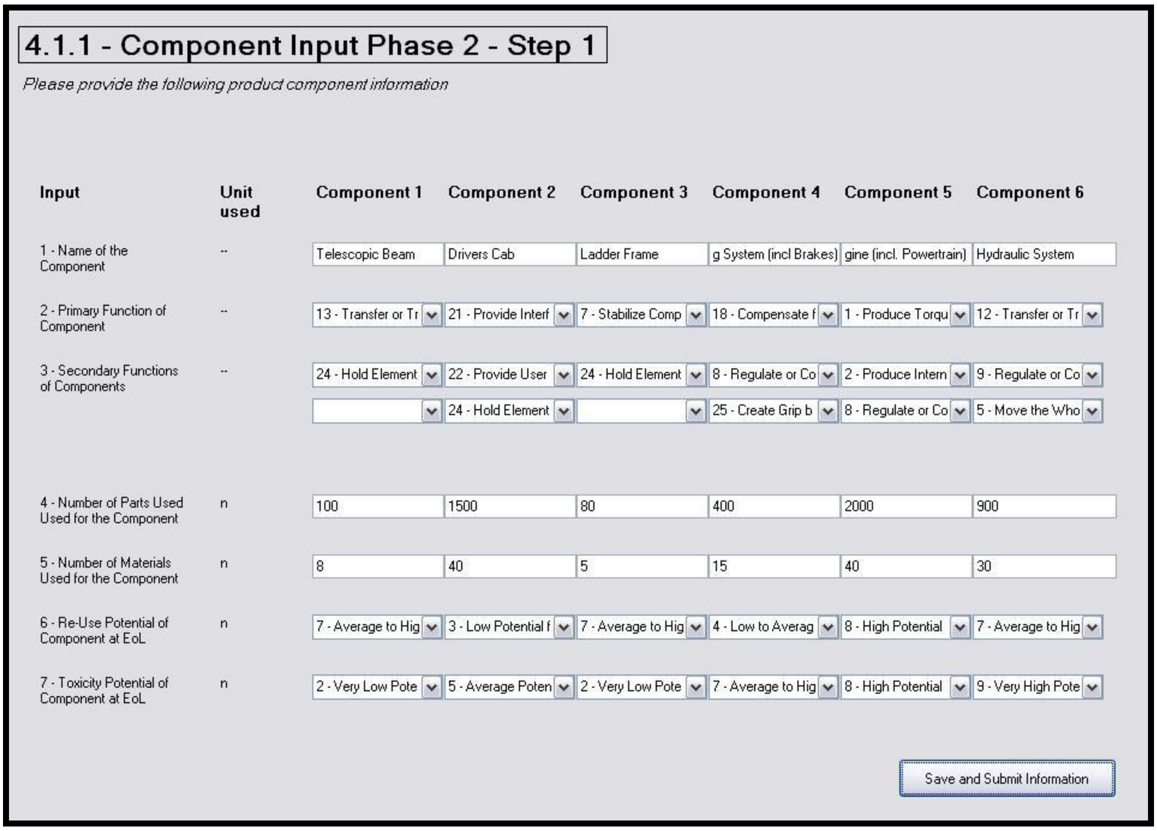
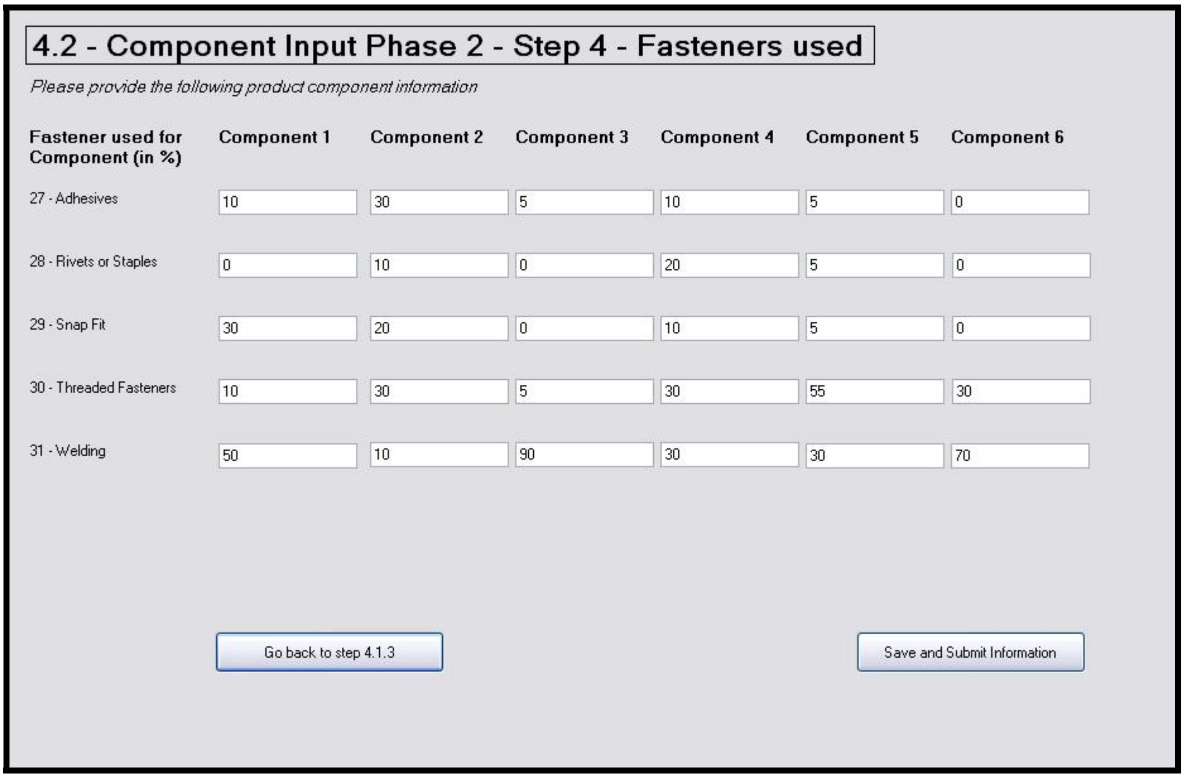


Figure 5.16: Information Input Step 1 during the Advanced Concept phase – Telehandler Case Study

As shown in figure 5.17 the screen 4.2 of the user interface phase 2 requests input information regarding the fasteners used for each of the components. There are 5 types of fasteners the user can chose from:

- Adhesives – any kind of bonding agent such as glue
- Rivets or Staples
- Snap Fit connection – e.g. snap fit coupling of garden hose
- Threaded Fasteners – e.g. bolts and nut
- Welding – all types of joins materials by causing coalescence.



4.2 - Component Input Phase 2 - Step 4 - Fasteners used

Please provide the following product component information

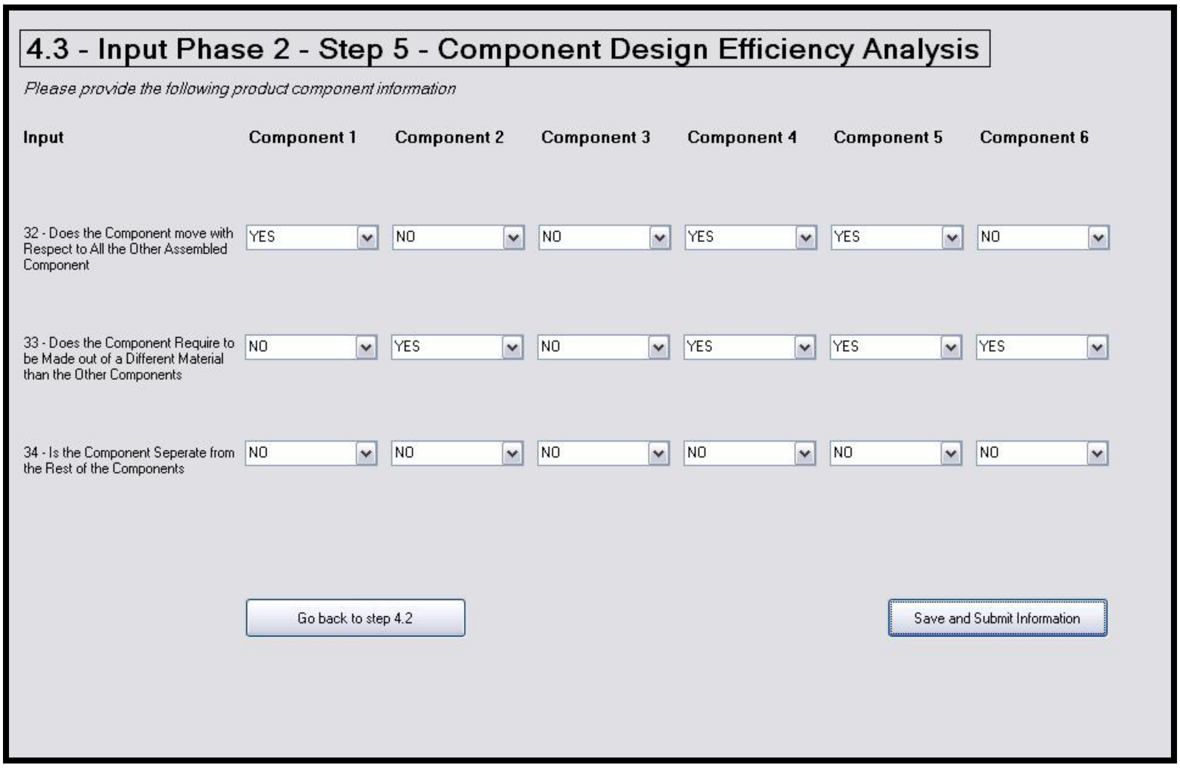
Fastener used for Component (in %)	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6
27 - Adhesives	10	30	5	10	5	0
28 - Rivets or Staples	0	10	0	20	5	0
29 - Snap Fit	30	20	0	10	5	0
30 - Threaded Fasteners	10	30	5	30	55	30
31 - Welding	50	10	90	30	30	70

Go back to step 4.1.3

Save and Submit Information

Figure 5.17: Information Input Step 4 during the Advanced Concept phase – Telehandler Case Study

During the last step of the information input information is gathered regarding a component design efficiency analysis. The information collected during the screen 4.3, along with information collected during the first three screens (screen 4.1.1 to screen 4.1.3), provides for an in depth analysis if the component in question is necessary for the product as a whole to fulfil its main purpose and to function properly. Feedback is then given back to the user at the Design Suggestions as the component necessity analysis results. Figure 5.18 shows the information requested during this step and the information provided for the case study 3 Telehandler complete. The three different types of information collected for each of the six components actually help to evaluate if the component in question is really necessary and essential for the whole product. In some cases after several redesigns of a product line certain components and be designed out and thus the whole product becomes a more efficient design.



<u>Figure 5.18:</u> Information Input Screen - Component Design Efficiency Analysis - Telehandler Case Study

After the information input collection from the user concludes with the step 5 the user has the option to go back to each of the five input screens to make changes. Furthermore the user has the option to confirm the input information given and proceed to the results page of phase 2. The screen of the user interface is called “5.1 Confirmation of Input – phase 2”.

Once the user chooses to confirm the input and proceed to the results page the screen “6.1 – Results Page of Components Impact” is displayed. The results of the Telehandler case study are given in figure 5.19. The sum of Total Cost from all 6 components amounts to a total of **<u>£80425.20.</u>** Compared to the whole product cost from phase one, which is **<u>£82532.23</u>**, the deviation is marginal and in the range of 2.5%. Reasons for divergence between the total cost of the whole product from phase 1 and the sum of total cost of all six components in phase 2 is due to various issues. The main ones are that more detailed information is available at the Advanced Concept phase compared to the Early Concept phase. Furthermore it has to be kept in mind that the methodology and user interface cannot claim a total accuracy in cost evaluation. The cost is rather used to gain an average overview of the costs excluding labour cost and to identify the Life Cycle Stage that causes the biggest impact and the component that causes the biggest impact. To put the results into perspective the typical selling price of the Telehandler product in the U.K. is a little bit over £100 000.

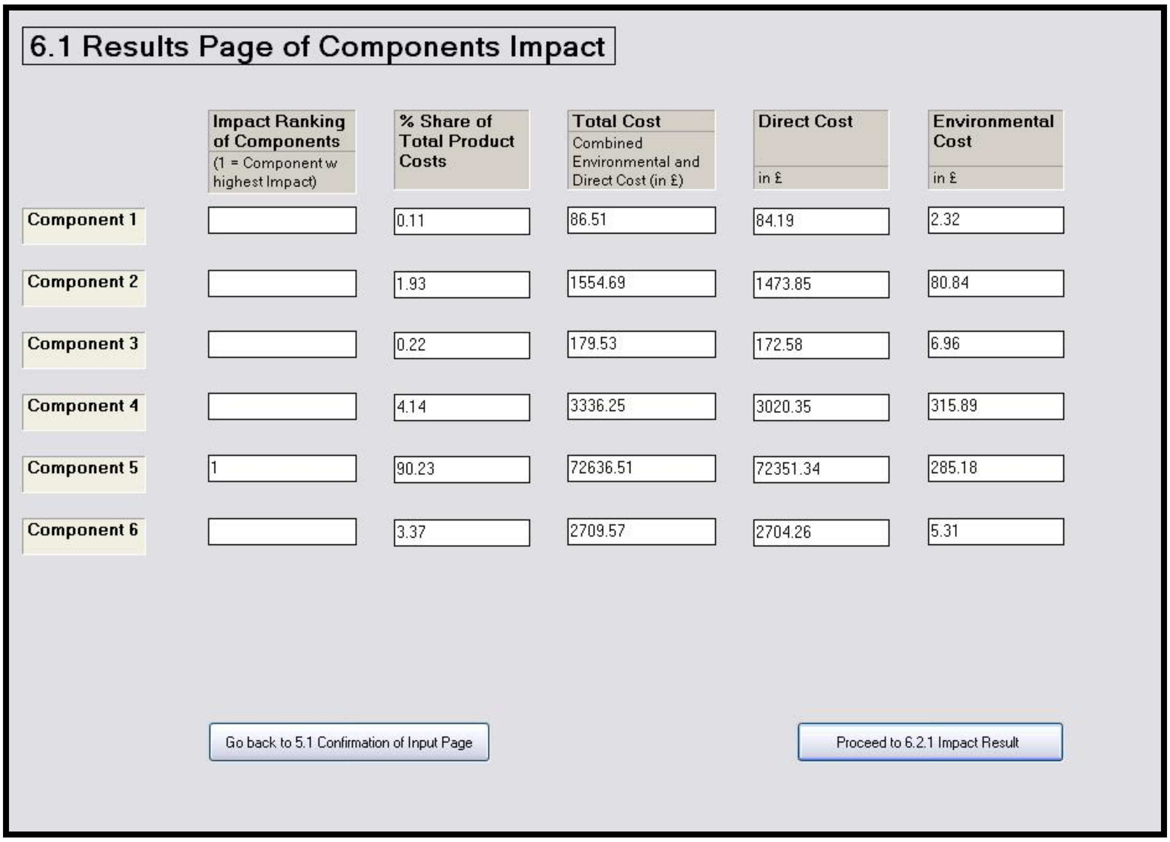
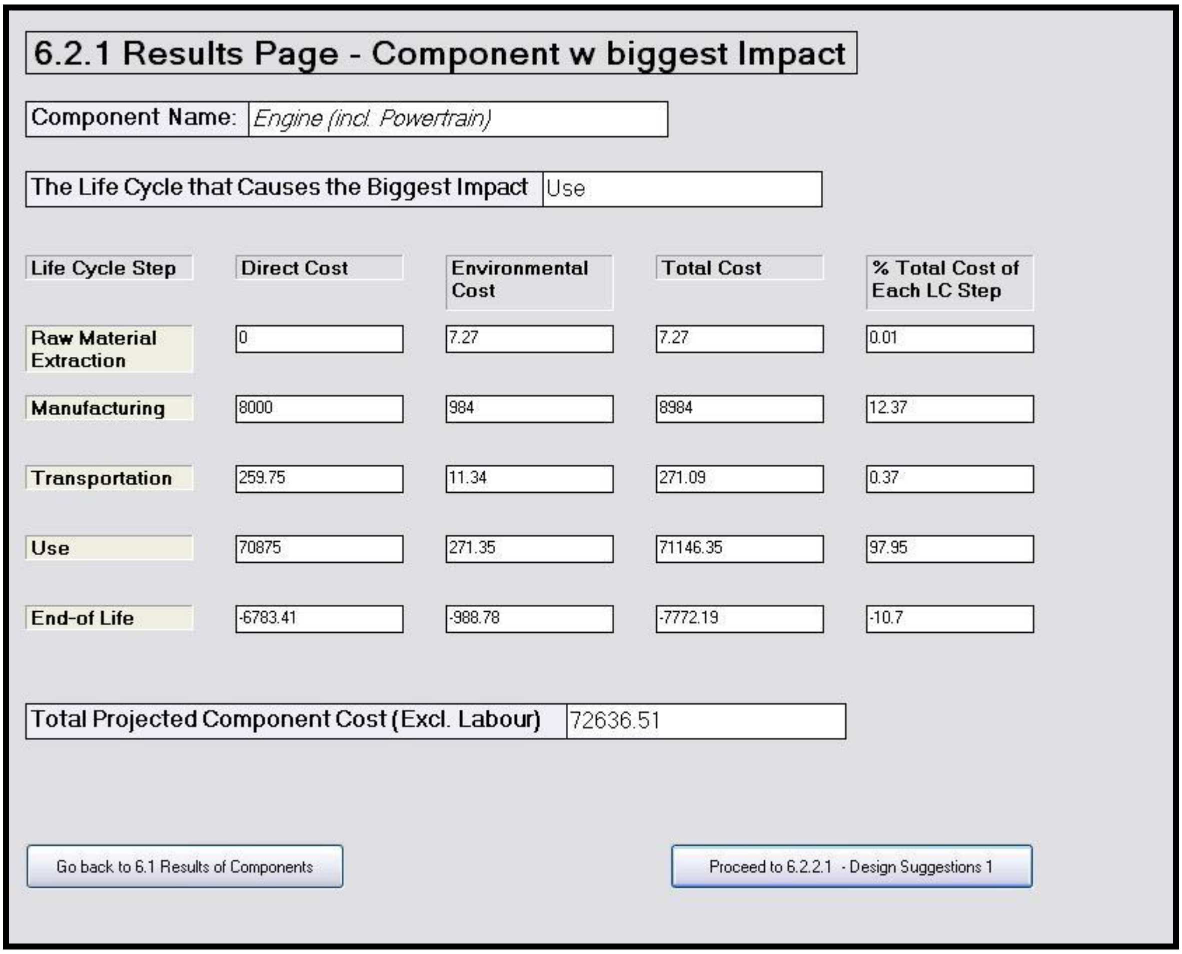


Figure 5.19: **Results Page of Components Impact - Telehandler Case Study**

As displayed in figure 5.19 the component 5 causes the biggest impact with a share of 90.23% of total product cost and a total cost of £72636.51. As shown in the prior figure 5.16 the component 5 is the Engine of the Telehandler. Once the user clicks the proceed button this component is evaluated in terms of its Life Cycle Impact in user interface screen 6.2.1 which figure 5.20 shows.



6.2.1 Results Page - Component w biggest Impact

Component Name: Engine (incl. Powertrain)

The Life Cycle that Causes the Biggest Impact: Use

Life Cycle Step	Direct Cost	Environmental Cost	Total Cost	% Total Cost of Each LC Step
Raw Material Extraction	0	7.27	7.27	0.01
Manufacturing	8000	984	8984	12.37
Transportation	259.75	11.34	271.09	0.37
Use	70875	271.35	71146.35	97.95
End-of Life	-6783.41	-988.78	-7772.19	-10.7

Total Projected Component Cost (Excl. Labour): 72636.51

Go back to 6.1 Results of Components

Proceed to 6.2.2.1 - Design Suggestions 1

Figure 5.20: Results Page - Components with biggest Impact - Telehandler Case Study

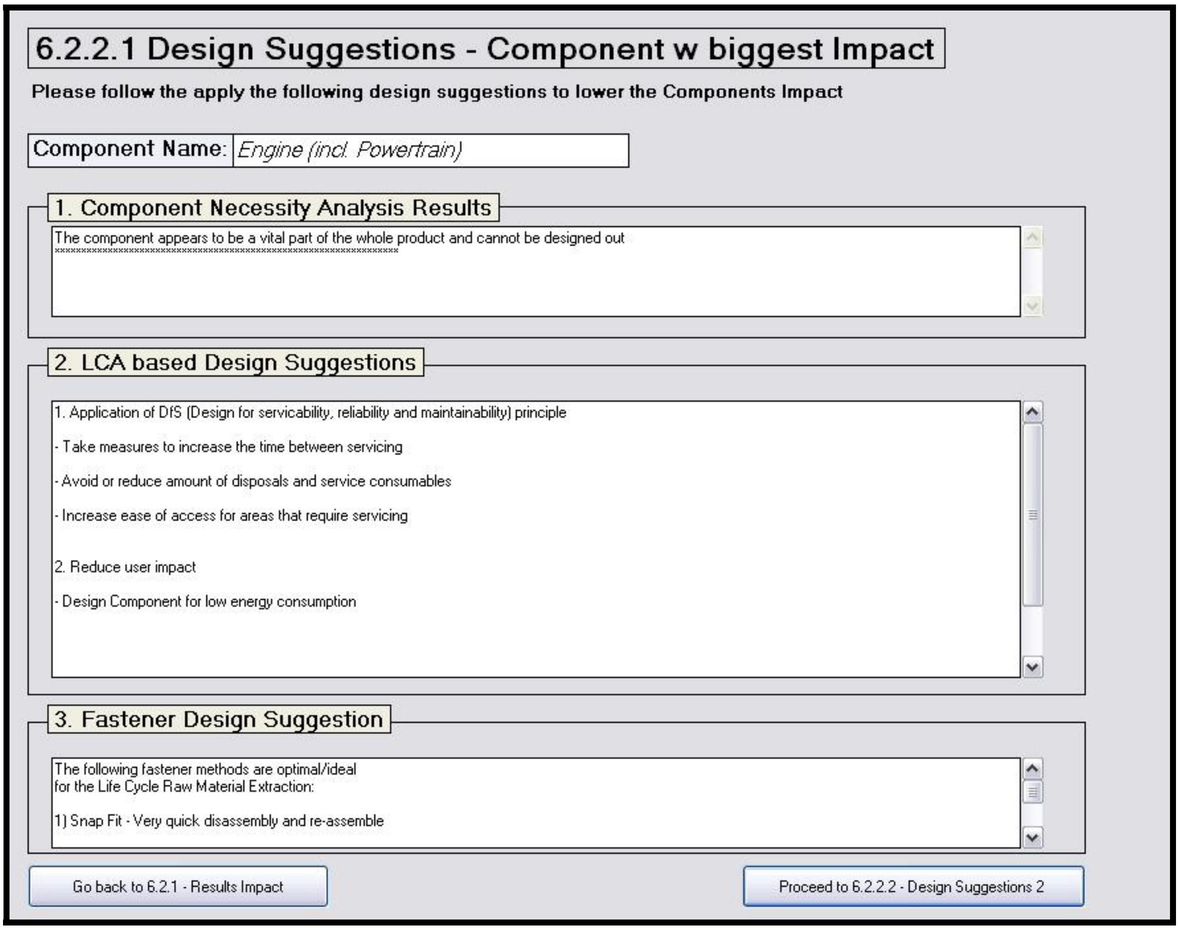
At the top of the screen the component name, that is closer evaluated and causes the biggest impact of all six components, is shown. Below that the "Life Cycle that Causes the Biggest Impact" is displayed which is the "Use" Life Cycle in the case of the Engine component. The Use Life Cycle causes £70875 of direct cost and £271.35 of environmental cost which amounts to a 97.95% total cost share of the combined Life Cycle Total costs. The Life Cycle with the second biggest impact is the Manufacturing Life Cycle Stage for the Engine component. It causes Total Cost of £8984.

What is peculiar about the results of this screen is that the Life Cycle called "End-of Life" causes a negative direct and environmental and thus total cost impact of £ -7772.19. The reason for this is that during the input information screens "Re-Use" was chosen as the End-of Life Scenario of the component. This means that at the products End-of Life if the engine is still in good running condition it can be used as a spare part for another product making it not required to produce a new engine and thus saving cost. Thus the engine creates revenue at its` EoL Life Cycle Stage as it can be sold as a spare part. The “Total Projected Component Cost (Excl. Labour)” for the engine is £72636.51. To give more detail regarding this: If a producer moves from throwing away components to the concept of re-using them he can reduce the product costs due to savings at the EoL stage. Unfortunately re-commission costs are not included within the methodology.

Based on the evaluated Life Cycle that causes the biggest impact and various other input information such as Component Design Efficiency Analysis data, component fastener information and component function information Design Suggestion for the component with the biggest impact - the “Engine” component in this case - are produced. Screen 6.2.2.1 illustrates the first three design suggestion areas:

1. Component Necessity Analysis Results
2. LCA based Design Suggestions
3. Fastener Design Suggestions

As shown in figure 5.21 the component “appears to be a vital part of the whole product and cannot be designed out” which makes absolute sense since the engine powers the whole Telehandler and without the engine the Telehandler could not function.



<u>Figure 5.21:</u> Results Page - Components with biggest Impact - Telehandler Case Study

The results of the LCA based Design Suggestions are provided completely in figure 5.22 along with a detailed explanation how they can be interpreted for the Engine component of the Telehandler case study. The LCA based design suggestions for the Engine component are very similar to the design suggestions produced for the whole product in phase 1 because the Life Cycle Stage that causes the biggest impact is the same for both: the “Use” Life Cycle Stage. The design suggestions for the Advanced Concept phase can be found in appendix B.10 in detail.

User Interface Design Suggestion	In Detail Instruction	Interpretation for the Telehandler Case Study
1. Application of DfS (Design for serviceability, reliability and maintainability) principle	- Take measures to increase the time between servicing - Avoid or reduce amount of disposals and service consumables - Increase ease of access for areas that require servicing	• Use higher quality materials, that might be more expensive to purchase, to increase overall engine life and time between servicing • Think about alternative ways to increase mean time between servicing of the engine
2. Reduce user impact	- Design product for low energy consumption	• Increase the efficiency of the main energy source of the Telehandler – the diesel engine • Evaluate new and alternative concept for the engine which are currently being developed in the automotive sector – e.g. coupling a battery powered electric motor with a small petrol engine that acts as a generator

<u>Figure 5.22:</u> Design Suggestion Interpretation for the Advanced Concept phase - Telehandler Case Study - I

The recommended fastener types for the Engine Component as shown in figure 5.21 are:

- Snap Fit - Very quick disassembly and re-assemble
- Threaded Fasteners - Easy disassembly and re-assembly; Ease of availability if fastener is destroyed

Threaded Fasteners are already the main fastener type for the engine itself but it could benefit the product if the consumables, especially the filters used, are relying in Snap Fit fasteners where possible. The issue here is the reliability and durability of the snap fit connections for extended service and life periods. Appendix B.9 provides the connection method list used in order to enhance the fastener type applied to the product design.

But the most inventive design suggestions are displayed in screen 6.2.2.2. which can be found in appendix D-9. Here inventive design suggestions are produced for the Engine component and they are based on functionality. In figure 5.23, 5.24 and 5.25 all the design suggestions produced for the Telehandler case study are listed.

Function based Design Suggestion	Further Instructions	Example
INVERSION - The other way round	a. Instead of an action dictated by the specifications of the problem, implement an opposite action b. Make a moving part of the object or the outside environment immovable and the non-moving part movable c. Turn the object upside-down	- Abrasively cleaning parts by vibrating the parts instead of the abrasive
SPHERIODALITY - Curvature	a. Replace linear parts or flat surfaces with curved ones; replace cubical shapes with spherical shapes b. Use rollers, balls spirals c. Replace a linear motion with rotating movement; utilize a centrifugal force	- Computer mouse utilized ball construction to transfer linear two-axis motion into vector motion
DYNAMICS	a. Make an object or its environment automatically adjust for optimal performance at each stage of operation b. Divide an object into elements which can change position relative to each other c. If an object is immovable, make it movable or interchangeable	- A flashlight with a flexible gooseneck between the body and the lamp head - A transport vessel with a cylindrical-shaped body. To reduce the draft or a vessel under full load, the body is comprised of two hinged, half-cylindrical parts which can be opened.
MECHANICAL VIBRATION	a. Set an object into oscillation b. If oscillation exists, increase its frequency, even as far as ultrasonic c. Use the resonant frequency d. Instead of mechanical vibrations, use piezovibrators e. Use ultrasonic vibrations in conjunction with an electromagnetic field	To remove a cast from the body without injuring the skin, a conventional hand saw was replaced with a vibrating knife - Vibrate a casting mold while it is being filled to improve flow and structural properties

Figure 5.23: Complete List of Function based Design Suggestions during phase 2 for the Telehandler Case Study - I

Function based Design Suggestion	Further Instructions	Example
PERIODIC ACTION	a. Replace a continuous action with a periodic (pulsed) one b. If an action is already periodic, change its frequency c. Use pulsed between impulses to provide additional action	- An impact wrench loosens corroded nuts using impulses rather than continuous force - A warning lamp flashes so that it is even more noticeable than when continuously lit
MECHANICS SUBSTITUTION	a. Replace a mechanical system by an optical, acoustical or olfactory (odor) system b. Use an electrical, magnetic or electromagnetic field for interaction with the object c. Replace fields 1. Stationary fields with moving fields 2. Fixed fields with those which change in time 3. Random fields with structured fields d. Use a field in conjunction with ferromagnetic particles	- To increase the bond between metal coating and a thermoplastic material, the process is carried out inside an electromagnetic field which applies force to the metal
PNEUMATICS AND HYDRAULICS	a. Replace solid parts of an object by gas or liquid. These parts can use air or water for inflation, or use air or hydrostatic cushions	- To increase the draft of an industrial chimney, a spiral pipe with nozzles was installed. - When air flows through the nozzles, it creates an air-like wall, reducing drag. - For shipping fragile products, air bubble envelopes or foam-like materials are used.

Figure 5.24: Complete List of Function based Design Suggestions during phase 2 for the Telehandler Case Study - II

Function based Design Suggestion	Further Instructions	Example
COMPROMISE (between two already existing methods to create a solution for a specific case)	a. Find similarities in the two existing methods and create a new solution based on those b. Create a method that is made of parts of both existing ones c. Use parts 1 and 3 from method A and parts 2 and 4 from method B.	- A Turbofan is a compromise between a Turboprop (low altitude) and a Turbojet (high altitude) -An intermediate tyre is a compromise between a slick tyre and a rain tyre for the specific case of a half dry track condition
USE ACCUMULATIVE PRINCIPLE	a. Find a way to initiate a self amplifying effect or make use of the exponential effects.	- Compound interest - Nuclear reaction in a power plant - Turbo Charger in a car

Figure 5.25: Complete List of Function based Design Suggestions during phase 2 for the Telehandler Case Study - III

The Function based Design Suggestions are numerous and not all can be applied in the case of the Telehandler Engine. Furthermore it has to be stated that an engine is one of the most researched and evaluated components in the industry and inventive improvement options that have not been tried before might not be very easy to find since a lot of companies have already invested research and finances to achieve that. The case would have been different if the component in question would not have had so much industrial and research attention in the past. Nevertheless the Function based Design Suggestions chosen and the Interpretation for the Engine component of the Case Study are shown in figure 5.26. The most promising ones are selected with the biggest potential of improvement.

Chosen Design Suggestion	In Detail Instruction	Interpretation for the Telehandler Case Study
PERIODIC ACTION	a. Replace a continuous action with a periodic (pulsed) one b. If an action is already periodic, change its frequency c. Use pulsed between impulses to provide additional action	- Is it possible to switch of the diesel engine of the Telehandler whilst it does not need full power? For example the excess power produced by the diesel engine could be stored in electrical form (battery hybrid system) or air pressure form (gas pressure tank). Whilst the Telehandler system only needs a minimal amount of power the Diesel engine could switch of automatically and the energy could be provided by the storage system such as an electric motor for the battery hybrid system.
COMPROMISE (between two already existing methods to create a solution for a specific case)	a. Find similarities in the two existing methods and create a new solution based on those b. Create a method that is made of parts of both existing ones c. Use parts 1 and 3 from method A and parts 2 and 4 from method B.	- Evaluate a combination of two energy generating systems (hybrids) such as Petrol/Diesel engine and electric motor (battery powered) Gas turbine and flywheel energy storage system Diesel Engine and electric motor (external energy powered)
USE ACCUMULATIVE PRINCIPLE	a. Find a way to initiate a self amplifying effect or make use of the exponential effects.	- Use turbo charger combination for the Diesel Engine to increase power and eventually use a smaller sized Diesel engine with lower fuel consumption.

Figure 5.26: Complete List of Function based Design Suggestions during phase 2 for the Telehandler Case Study - IV

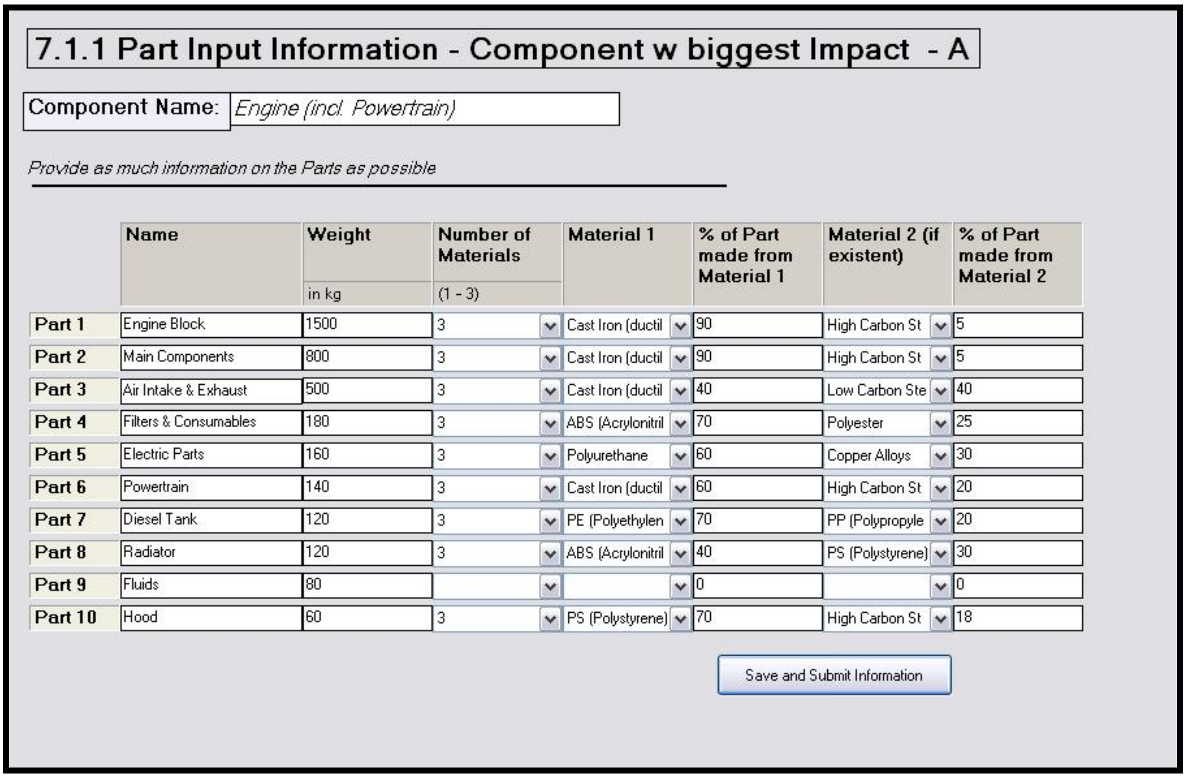
After the Function based Design Suggestions are shown in screen 6.2.2.2 of the user interface and the user has applied the suggestion to the current design of the component the next and last screen of phase 2 is the end screen. Here it is possible to either start over with phase 2 completely by choosing the option “Start over with 4.1.1 Input phase 2” right from the beginning or to choose the option “Go back to 6.1 Results of the Components”. Also the user can choose to “Quit phase 2 of the user interface and Proceed to phase 3” which concludes phase 2 and phase 3 of the user interface is started.

5.4.3 Detail Design Phase analysis

During phase 3, Detail Design phase, information regarding the separate parts of the component with the biggest impact is collected. Within the Telehandler case study this means that the parts of the Engine component (including the Powertrain) are examined. The parts of the Engine component are:

1. Engine Block
2. Main (engine) components
3. Air Intake & Exhaust
4. Filters & Consumables
5. Electric Parts
6. Powertrain
7. Diesel Tank
8. Radiator
9. Fluids
10. Engine Hood

Figure 5.27 and 5.28 shows both of the two information input screens at phase 3. The information is given for the 10 parts of the Engine component listed above. Afterwards the user can go back to each of the two information input screens or proceed to the results page at screen 8.1 “Confirmation of Input”.



7.1.1 Part Input Information - Component w biggest Impact - A

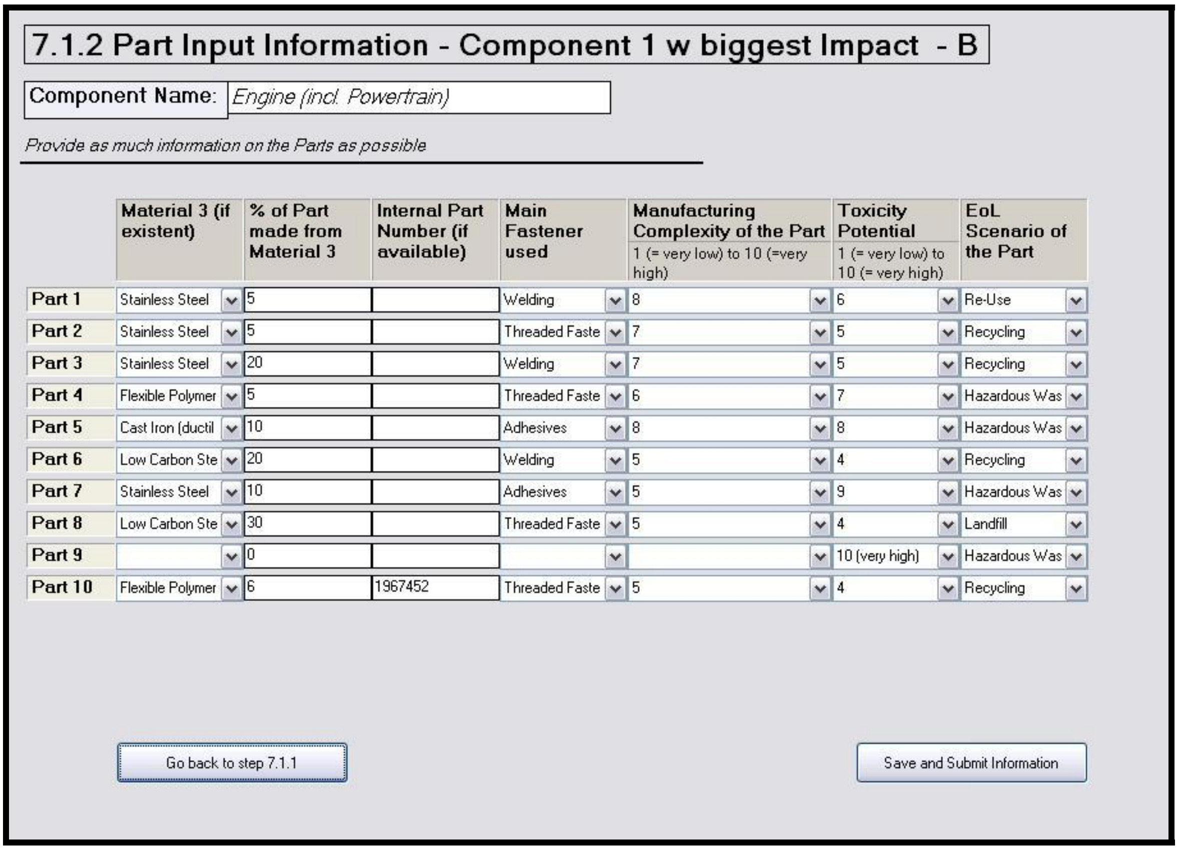
Component Name: *Engine (incl. Powertrain)*

Provide as much information on the Parts as possible

	Name	Weight (in kg)	Number of Materials (1 - 3)	Material 1	% of Part made from Material 1	Material 2 (if existent)	% of Part made from Material 2
Part 1	Engine Block	1500	3	Cast Iron (ductil	90	High Carbon St	5
Part 2	Main Components	800	3	Cast Iron (ductil	90	High Carbon St	5
Part 3	Air Intake & Exhaust	500	3	Cast Iron (ductil	40	Low Carbon Ste	40
Part 4	Filters & Consumables	180	3	ABS (Acrylonitril	70	Polyester	25
Part 5	Electric Parts	160	3	Polyurethane	60	Copper Alloys	30
Part 6	Powertrain	140	3	Cast Iron (ductil	60	High Carbon St	20
Part 7	Diesel Tank	120	3	PE (Polyethylen	70	PP (Polypropyle	20
Part 8	Radiator	120	3	ABS (Acrylonitril	40	PS (Polystyrene)	30
Part 9	Fluids	80			0		0
Part 10	Hood	60	3	PS (Polystyrene)	70	High Carbon St	18

Save and Submit Information

<u>Figure 5.27:</u> First Information Input Screen of phase 3



7.1.2 Part Input Information - Component 1 w biggest Impact - B

Component Name: *Engine (incl. Powertrain)*

Provide as much information on the Parts as possible

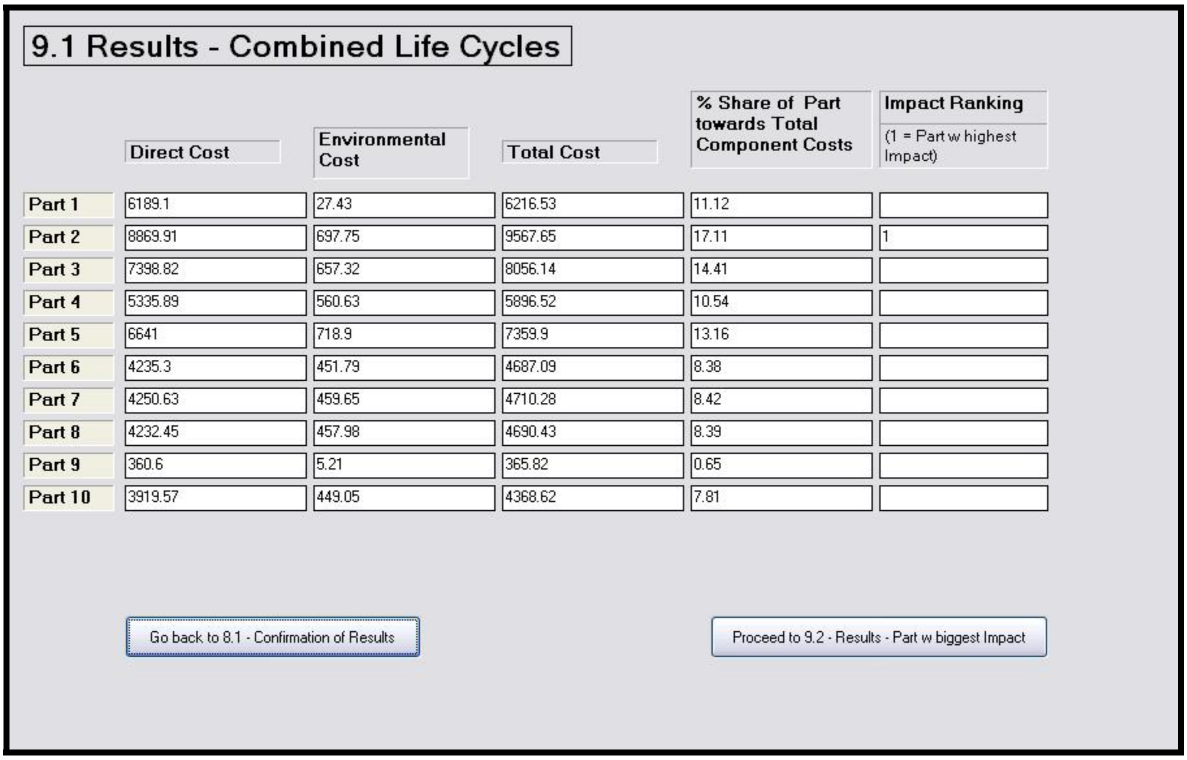
	Material 3 (if existent)	% of Part made from Material 3	Internal Part Number (if available)	Main Fastener used	Manufacturing Complexity of the Part 1 (= very low) to 10 (=very high)	Toxicity Potential 1 (= very low) to 10 (= very high)	EoL Scenario of the Part
Part 1	Stainless Steel	5		Welding	8	6	Re-Use
Part 2	Stainless Steel	5		Threaded Faste	7	5	Recycling
Part 3	Stainless Steel	20		Welding	7	5	Recycling
Part 4	Flexible Polymer	5		Threaded Faste	6	7	Hazardous Was
Part 5	Cast Iron (ductil	10		Adhesives	8	8	Hazardous Was
Part 6	Low Carbon Ste	20		Welding	5	4	Recycling
Part 7	Stainless Steel	10		Adhesives	5	9	Hazardous Was
Part 8	Low Carbon Ste	30		Threaded Faste	5	4	Landfill
Part 9		0				10 (very high)	Hazardous Was
Part 10	Flexible Polymer	6	1967452	Threaded Faste	5	4	Recycling

Go back to step 7.1.1

Save and Submit Information

<u>Figure 5.28:</u> Second Information Input Screen of phase 3

The results of the “Combined Life Cycles” evaluation of all 10 parts of the Engine component is exhibited in figure 5.29. The sum of the Total Cost value from all 10 parts should have a similar value to the Total Cost of the component they are part of which is the Engine in this case. The Sum of Total Cost from figure 5.29 amounts to a total of **£55918.98** for all 10 parts. Compared to the Engine component Total Cost from phase one, which is **£72636.51** the deviation is in the range of 23%. The reasons for this divergence are due to various issues. First of all the Direct and Environmental Cost impact from using energy – in this case of Diesel fuel – is split amongst all 10 parts of the engine since it is not possible to assign it to certain parts only at this level of the product hierarchy.



9.1 Results - Combined Life Cycles

	Direct Cost	Environmental Cost	Total Cost	% Share of Part towards Total Component Costs	Impact Ranking (1 = Part w highest Impact)
Part 1	6189.1	27.43	6216.53	11.12	
Part 2	8869.91	697.75	9567.65	17.11	1
Part 3	7398.82	657.32	8056.14	14.41	
Part 4	5335.89	560.63	5896.52	10.54	
Part 5	6641	718.9	7359.9	13.16	
Part 6	4235.3	451.79	4687.09	8.38	
Part 7	4250.63	459.65	4710.28	8.42	
Part 8	4232.45	457.98	4690.43	8.39	
Part 9	360.6	5.21	365.82	0.65	
Part 10	3919.57	449.05	4368.62	7.81	

Go back to 8.1 - Confirmation of Results

Proceed to 9.2 - Results - Part w biggest Impact

Figure 5.29: Results – Combined Life Cycle of the Detail Design phase – Telehandler Case Study

The part that was identified within screen 9.1 as the one which is causing the biggest Total Cost impact is called “Main Components” with a 17.11% Share of Total Cost or £9567.65. This part does not identify a single part but a small group of parts: the main parts that make up the engine such as pistons, rods or the cylinder-head. A detailed evaluation is shown in screen 9.2 showing all the individual Life Cycle Stage as shown in figure 5.30. The Life Cycle that causes the biggest impact in the case of the "Main Components" is the "Manufacturing" Stage with a 62.26% cost share and a Total Cost of £5957.25. The Life Cycle Stage with the second highest impact is "Use" with a 33.99% cost share and a Total Cost of £3252.4. Thus the Life Cycle Stage that causes the biggest impact is different from the one of the Engine Component in the case of the "Main Components" parts.

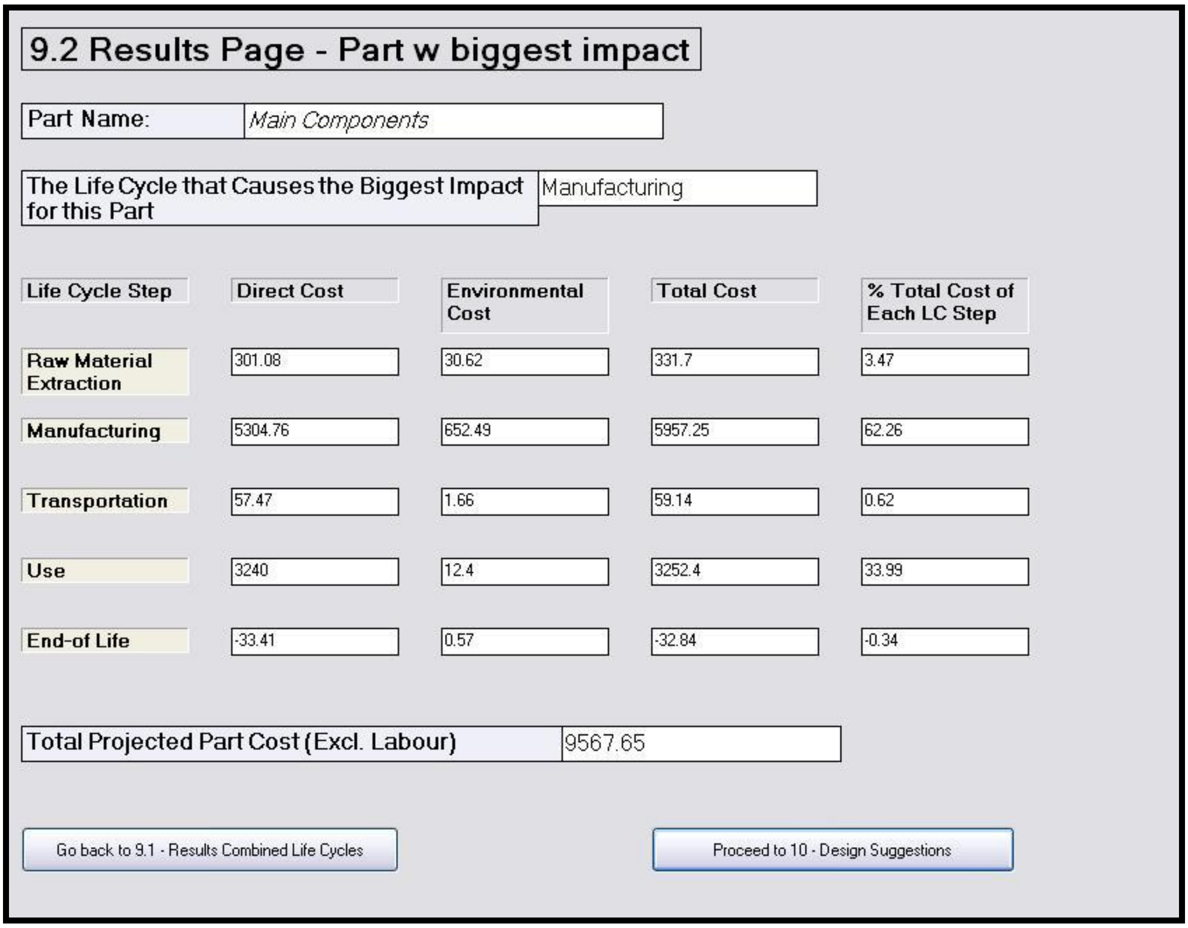
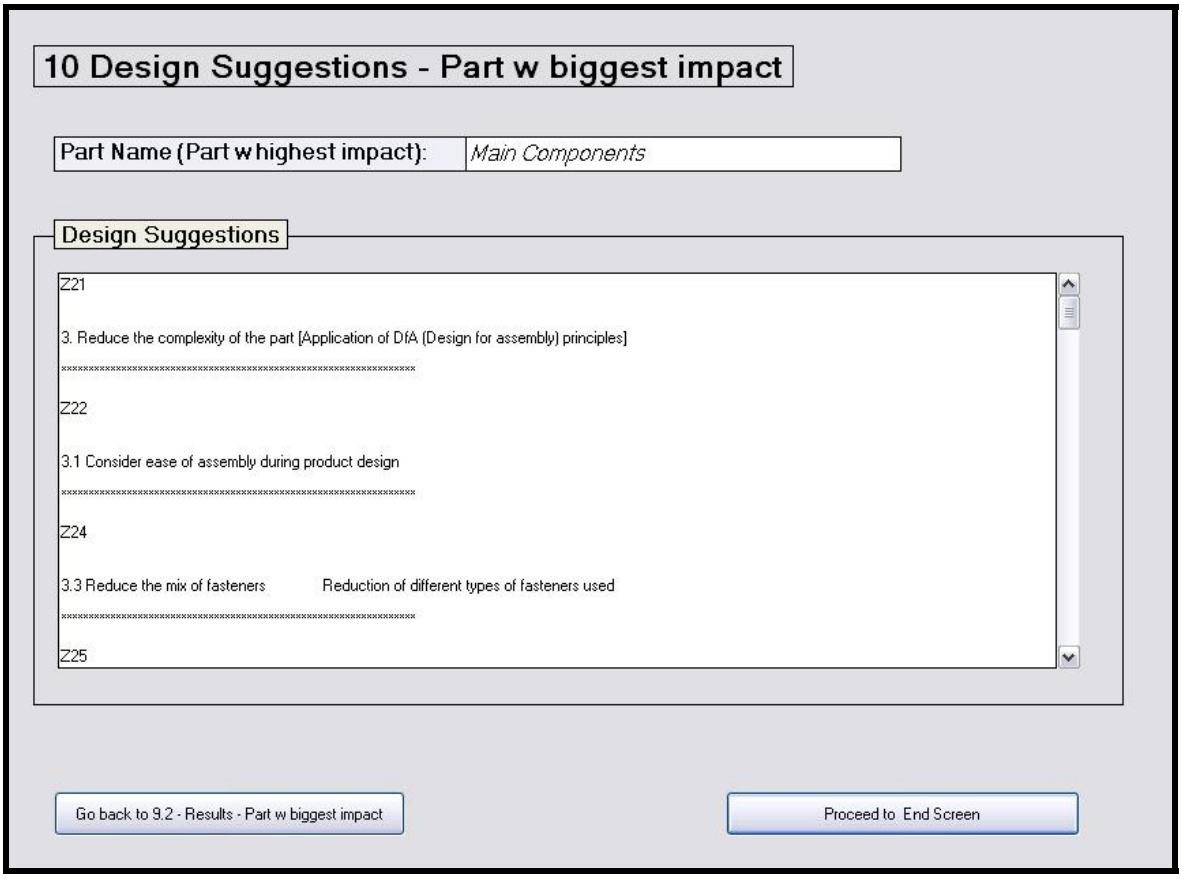


Figure 5.30: Results Page – Part with the biggest impact – Detail Design phase – Telehandler Case Study

In the next step the Design Suggestions are produced based on the Design Suggestion Matrix developed for phase 3 of the methodology. A screenshot of how the Design Suggestions are delivered back to the user is provided in figure 5.31.



<u>Figure 5.31:</u> Design Suggestions – Part with the biggest impact – Detail Design phase – Telehandler Case Study

Since figure 5.31 shows a screenshot of the user interface it is only possible to show a fraction of the Design Suggestions for the "Main Components" part here. In the following figure 5.32 a selection of the Design Suggestions produced by the user interface are shown as well as how they can be implemented for the "Main Components".

Design Suggestion chosen	Implementation of Design Suggestions
Z24 3.3 Reduce the mix of fasteners Reduction of different types of fasteners used	Re-evaluate the number of fasteners used for the “Main Components” – if possible reduce the number of different fasteners used
Z29 4.2 Reduce energy to manufacture the part	Is it possible to manufacture the “Main Components” by using less energy – e.g. more energy efficient casting and forging processes for pistons and piston rod, use of less material, Use of material that requires less production energy
Z30 4.3 Reduce the time to manufacture the part Z43 6. Maximise process efficiency to manufacture part	Is it possible to reduce the manufacturing time for the part and thus reduce manufacturing costs per unit.
Z71 12. Reduce the energy use on site	- Review the energy use at the manufacturing site of the “Main Components. This includes efficiency of lighting system and heating system on site as well as implementing energy preservation measures on site.

Figure 5.32: Implementation of Design Suggestions – Part with the biggest impact – Detail Design phase – Telehandler Case Study

After the design suggestions are implemented the user can proceed to the End Screen of the Detail Design phase. Here it is possible to go back to the start of phase 3 which is screen 7.1.1 or to the screen 8.1 – Confirmation of Input. It is also possible to "Quit phase 3 of the user interface and exit the program". This will lead to a termination of the user interface.

5.5 Reception of the User Interface by Design Engineers from the Industry

This section describes a summary of the feedback from the design engineers of the collaborating company. All the feedback information provided here were gathered during a presentation of the user interface and feedback session with various design engineers.

Firstly all the positive aspects of the user interface are described in this section as they were pointed out during the feedback session. One of the main advantages of the user interface as a whole is that it support the design engineer in conducting a product life cycle analysis, even if not familiar with the concept itself. Furthermore another benefit of the user interface is that it combines direct cost and the environmental impact issues thus avoiding to carry out two separate life cycle analyses. As perceived by the design engineers this is achieved by measuring the environmental impact based on the cost factor which is a sensible approach. Moreover the design engineers stated that the integration of the TRIZ matrix during the second step of the methodology is very helpful and the design suggestions that are produced by this integration can help overcome problems in a more inventive way. Additionally it was mentioned that it can take the design engineer a very long time to conduct a TRIZ evaluation of the components manually, even for a design engineer who is experienced in using TRIZ. The design engineer stated that the user interface reduced the time required for a TRIZ analysis tremendously. The design suggestions for the component design may prove to be very valuable especially in the case of a new product design or a complete redesign of an existing product. Furthermore it was stated that the user interface helps to identify the areas of the complete product design that offer the biggest potential for improvement. Likewise can it prove to be helpful to have a user interface that generates design suggestion that approach the solution finding process of a design problem from a different angle, since the design engineers can be set in their ways in how they approach product design .

This section lists all the disadvantages of the user interface as perceived by the design engineers during the feedback session. One of the biggest issues is the gathering of the input data by the design engineer. First of all it can be a tedious and time consuming task for a design engineer to collect and estimate all the necessary input information data. Moreover if no reliable data is available for the product and the design engineer needs to rely on estimations those can prove to be inaccurate. Another factor that can add to the inaccuracy of the input information data is in the case of the manufacturing stage input information. This data can be difficult to estimate in the case that more than one type of a product is manufactured at one site. Besides this issue it was mentioned that the results in terms of direct cost and environmental cost of the evaluated product are not necessarily applicable to the producer. The next issue is that the user interface does not indicate which input information parameters actually account for the major contribution to environmental and direct cost. A limitation of the user interface to a maximum of six components during step 2 and a maximum of ten parts during step 3 was another issue that was perceived as a disadvantage of the user interface. The appearance and general ease of using the software were the final feedback remarks regarding the disadvantages of the user interface. The background colouring and the choice of colours in general of the user interface could be improved. Additionally the need for help screens and pop-up tags for the various input information fields would be helpful for the user.

5.6 Chapter reflections

Chapter 5 has examined in detail how the research methodology is validated in terms of performance and result sensibility.

Firstly it was explained how a collaborating company was established that was able to support the research with figures for the case studies and what type of company was chosen. The help of a collaborating company and information on case studies made it not only possible to develop the methodology for the “Integration of Economic, Environmental and Functional Issues in Complex Product Design” but it was also possible to develop a software based user interface and use the input information from the case studies to evaluate and investigate the sensibility and robustness of the results.

In addition the software assessment process was explained in this chapter. Various pieces of software language were evaluated in terms of suitability for building a methodology based user interface. All the investigated software languages are listed and reasons are given for picking the one that was used to create the user interface.

Furthermore the mechanism and structure of the user interface is discussed in this chapter in the form of a flowchart explaining the three major Product Design phases it consists of. This explains the basics of how the user interface works.

Afterwards the three chosen case studies are shown that are used to test the user interface prove its robustness and the results produced by it. Each of the three cases is elucidated in detail and a walkthrough of the user interface based on the case study 3 – the Telehandler complete is given.

Even though this chapter has shown that the results produced by the user interface cannot be considered on the spot in terms of cost estimation, due to the nature of the methodology and various factors related to the input information gathering, it is quite clear that such an absolute accuracy is not possible in the context of life cycle costing estimation. The results produced by the user interface do support the user to identify the areas of the biggest Direct Cost and Environmental impact identifying the life cycle stage with the major impact and the area within the product structure also.

In the next chapter the findings and results of this chapter are put in perspective of its perceived weaknesses and advantages. It is also compared to current practises.

6. Review and discussion

6.1 Introduction to chapter 6

The purpose of this chapter 6 is to review all the chapters so far, comment on what have been achieved within them and give reasons why they are part of the thesis. This part is described in the reflective synopsis in order to give an overview of what has been achieved so far.

Problems and shortcomings of the methodology and user interface are described and discussed. These obstacles occurred whilst developing the methodology and the user interface in the course of this research. The problems that occurred were mainly linked to the complexity and nature of the research topic. The main issues here are bound to information itself – specifically the availability, accuracy and accessibility. The purpose of this review of shortcomings is to critically re-examine the weaknesses of the methodology and user interface and give reasons why they either could not be overcome or why they are not relevant for the functionality and robustness.

A last point that is covered by this chapter is the potential for future work resulting from this research and its outcomes.

6.2 Reflective synopsis

The goal of this research was to evaluate the possibility to integrate various design issues such as economic, environmental, functional and social issues whilst avoiding a trade-off and improving the overall product design of a newly developed product. This goal facilitates the development of a methodology and user interface to be created which design engineers can the use to improve the design of complex products.

The introduction chapter 1 reviews the current situation of manufacturers. Moreover an assessment of the legislative pressure they are facing is outlined. This legislative pressure has mainly been arising during the last decade. This review of the legislative situation is mainly done for the European location but several international implications are taken into account. The Eco-Design concept is described as a possible solution to overcome those issues. Then possible opportunities and difficulties arising from applying the Eco-Design principle are investigated. A detailed problem definition, mission statement and description of what it is that this methodology should achieve is given in chapter 1 as well: “the proposed methodology should help producers of complex products overcome legislative burdens and support continuous product improvement” as stated in a problem definition which is the scope of this research.

Afterwards the literature available on this topic is reviewed in chapter 2. This includes legislation with the aim of reducing the environmental impact of products, sustainability as an issue of product design and life cycle assessment as a product design tool. In addition the relevance of life cycle costing methods to the proposed research as well as databases used are evaluated. There are currently various tools that aim at minimising the environmental impact of product design such as the Eco-Design principle or the Triple Bottom Line concept. Chapter 2 also gives an outline of methods that have potential to be incorporated within the methodology in a revised form in order to overcome the problems outlined in the aim of the research.

Chapter 3 analyses the shortcomings of current practises and the gap in literature. From these shortcomings and gap in literature the need for the proposed methodology arises and it is formulated in this chapter. Afterwards the basic configuration of the methodology is described, a system overview is produced and reasons for choosing this specific approach are given.

Since this methodology and the mechanisms of how it functions are difficult to demonstrate a user interface was required. Details of this user interface are given in chapter 4 such as software and programming language chosen in order to conduct the programming and a flowchart of the user interface screens is provided in order to demonstrate the functional flow.

Three case studies are chosen due to the fact that the robustness of results as well as the reliability of the methodology and user interface needed to be tested. Chapter 5 described the application of the user interface to three case studies. It provides an in depth walkthrough of the user interface based on one of the three case studies as an example.

Furthermore the feedback given by the design engineers from industry proved itself to be very useful to reflect on the advantages and disadvantages of the user interface. Especially since it appeared to have the user interface tested by design engineers who are looking for a usable application and who were not involved in the methodology development and programming of the user interface at any point thus providing a independent and fresh look at the software. The feedback and testing by the industry helped to identify areas of future work and improvement of the user interface and methodology

6.3 Perceived weaknesses and limitations of the developed methodology

The methodology that is developed in the course of this research is unique, compared to other methods currently available, because it combines the issues of environmental impact, economic impact and functionality and thus makes for a more complete continuous improvement of the product design. However still there are certain limitations to what the methodology can achieve and how complete the environmental impact evaluation and the economic impact evaluation is. The purpose of this section is to critically list these weaknesses and limitations of the methodology developed during the course of this research and describe their nature and their consequences thoroughly.

6.3.1 Integration of more issues than cost and environmental impact

During the early stages of the methodology development it was decided to base the methodology on the Triple Bottom Line principle [GRE04] described by Greenwood and others. This Triple Bottom Line actually includes the environmental sustainability, the financial (or economic) sustainability and the social sustainability.

After various attempts to include the social issue in the methodology it was considered impossible to achieve due to the complexity of finding a common way to measure all three issues of the Triple Bottom Line. This was confirmed at the DNW conference [DOK05] in Bochum in May 2005 whilst presenting the research methodology proposal in an early form to other researchers in that area (from a variety of backgrounds). Since a cost impact was allocated to the environmental impact to be able to integrate both the environmental and the economic impact, an attempt was made to do the same for the social impact. It proved to be impossible to assign a cost value to the social impact of a product design. Only a weighting of the social impact can be applied to measure the impact. Social sustainability is about creating and maintaining quality of life for people. However the social impact of a product can be a positive one hence improving the quality of life or a negative one worsening the quality of life. Usually products cause both social impacts during the course of their whole life cycle. For example a car increases the quality of life since it makes it easy for people to get from one location to another but it decreases the quality of life also since it generates noise and pollution. It was obvious at an early stage of the research that the social impact cannot be integrated. Thus the improvement or worsening of quality of life for people cannot be measured in terms of costs since it is a highly subjective issue impossible to measure in cost figures.

Although the social sustainability was the only other issue that was seriously considered as another impact to be integrated there were others that were considered at an early stage. These were:

1. Quality – This is another issue that has a big significance in product design and has to be considered by the design engineer. By definition quality is 'the characteristics of a product or service that bears on its ability to satisfy stated or implied needs' [OAK03]. Thus by applying the methodology there may be trade-offs with the quality issue but those are very rare or only minor. This is due to the fact that functionality is a major capacity of the methodology and thus by improving the product functionality whilst reducing product complexity it has the ability to satisfy implied needs and customer expectations. The quality issue was not integrated within the methodology developed in this research because it would have greatly increased the complexity of developing it. Future work could be to evaluate to what degree it might be possible to integrate the quality issue.

2. Reliability – Another matter that has to be kept in mind during the product design process is the reliability of a product. Reliability of a product is basically its ability to function over and over again without failing. A high reliability can be measured by a high value for “mean time between failure” and “mean time between repair and servicing”. Even though current literature suggests that there are various ways to assign a cost value to reliability and thus measure it in terms of costs and make it comparable to the direct cost and the environmental cost of a product, reliability was not included within the methodology. This is due to the same reason as for quality: the complexity of the methodology and its development would have been too high and it proved to be a difficult task to include reliability in addition to the three tasks already included.

3. Customer Demands – This issue is a very general and varying matter in product design since it depends highly on the type of product and thus the type of market and customer. In general it covers the product characteristics that are expected by the customer. To give an example of typical customer demands for a citrus press :
   - The building materials (plastics) in contact with the fruit are safe to be used for food
   - The product components can be dismantled easily for cleaning purposes
   - The components in contact with the fruit are dishwasher safe

   Due to its varying nature this issue could not be measured in terms of costs easily and proved to be impossible to integrate with the existing issues of economic impact, environmental impact and functionality.

6.3.2 Availability of information

Another perceived weakness of the methodology developed is the availability of input information. Even though both the methodology and user interface rely on and link in various databases in order to reduce the information requested from the user some of the required input information could not be available in some cases. In the case of products consisting of components and parts manufactured and assembled in many different countries all over the world the availability of certain types of information might also be limited.

Input information databases linked into the user interface by the methodology include material databases, transportation databases, end-of life treatment databases and energy databases. Nevertheless, as mentioned before, even with all these databases linked in it is not always possible to recover all the information needed for the methodology. As formulated by Mizuki ‘One of the biggest problems that design engineers face with regards to DFE is a lack of reliable data on materials, parts and components, needed for tradeoff decisions’ [MSP96]. In the case when the design engineer is not able to recover exact input information for the user interface it is best to carry out an educated estimation for the input information value in question.

Furthermore during the Early Concept phase and partly the Advanced Concept phase also another difficulty can occur regarding the availability of information. This issue is described by Westkaemper and illustrated in figure 6.1: It has to do with the availability of information and demand for information.

Fig 6.1 has been removed due to third party copyright. The unabridged version of the thesis can be viewed at the Lanchester Library, Coventry University

Figure 6.1: Demand for information compared with actual availability in product life [WAA04]

Paradoxically the availability of (product related) information is very low at those early stages of product design but the demand for information, especially during the design stage, is at its peak. This is chiefly true for completely new products where no information from older evolutionary models is available. With regards to the developed methodology it has to be stated that testing by design engineers revealed though that the information required at the various stages should be relatively easy to obtain.

6.3.3 Regional variances

Other issues that can further add to the perceived weaknesses of the developed methodology are regional deviances. Since most databases and input parameters for the methodology are based on being located in the United Kingdom or Europe in general the produced results may be inaccurate if the user interface is applied in other countries. To give a few examples of parameters used within the context of the methodology that are valid for the United Kingdom only:

All the costs used are based on the pound sterling (£) or pence (p). This includes the results produced for direct and environmental cost as well as all the monetary input information requested from the user. In addition all the cost values obtained from the databases such as cost of transportation or cost of materials are provided in pound sterling.

But it is not only the currency that is set to the British £ value. Thus it is not an always option to overcome this issue by simply applying currency conversion charts to overcome the regional deviances, e.g. from £ sterling to American $. This is due to the fact that a database (probably internet based) would have to be linked into the user interface that is regularly updated and takes into account fluctuations and variations in the exchange rate over time. Due to practicality of the programming process this was not integrated but proves a valuable point for future work. Other regional aspects influence the results as well and in the following a few of them are listed:

- Fuel prices can vary greatly in different areas
- Electricity costs are subject to regional changes and type of production
- Material prices are subject to change depending on the region they are sold in as well as particular time they are sold
- end-of life treatment cost can be very different depending on the worldwide location

Since the methodology and user interface does not provide a regional setting option, this would be an issue to include in future work but it would require extensive work in all areas of the methodology. Thus at the current state of the methodology it is a perceived limitation.

Another issue mentioned in section 3.11.3 is the circumstance that certain costs are not assigned to the environmental impact of products yet but they are still included in the methodology. An example is the Climate Change Levy which puts a tax on energy consumption and which is applied to electricity, gas and so on. This tax is part of the environmental cost of industrial products but not yet of domestic products. Thus if the methodology is applied to domestic products that rely on energy input the environmental costs include this tax even though it is not applied yet. There is a high possibility thought that this tax will also be applied to domestic products in the near future.

6.3.4 Accuracy of information

Not only is the availability of information a perceived weakness of the methodology but also a fourth issue that adds to the limitations of the developed methodology is the accuracy of information used. This can be the input information gathered from the user and the accuracy of information drawn together from the databases. To give an example of this factor: The material price gathered from the material database is an averaged value since the databases used provide a price range for the U.K. market only. For example the price range of “cast iron – ductile” material that can be selected at various points in the course of the user interface is £0.35 - £0.39 per kg. The averaged value £0.37 is used for the methodology database. Thus the accuracy of the results based on this can vary by +/- 5.4%.

In addition the accuracy of information is linked to the time: to stay with the material example the material cost varies over an certain time and is due to various factors. For example material prices change with time as in the case of steel: this raw material price can vary greatly and increase if there is high demand on the world market. The methodology used values for material prices and similar that were valid and up to date of the end of 2007. Future work in this area of methodology may include a link to in databases that are updated continuously.

Another aspect of the accuracy of information is its significant effect on the end result in terms of environmental and economical cost. The problem is that several inaccuracies of information from user input and databases also can add up and create a much greater deviation of results than just one inaccurate value itself. For example if 10 values that are used for the evaluation of a certain life cycle stage cost value only contain an inaccuracy of 5% each the maximum total inaccuracy of the resulting value can be as high as 62%. Even though this is the worst case scenario and the maximum possible deviation it was taken into consideration whilst creating the methodology. Typically the inaccuracies and deviations of several input parameters have a balancing effect.

Rhodes stated that ‘the high degree of uncertainty inherent in the predicted impacts make it extremely difficult to accurately compare industrial systems or to evaluate competing materials, designs or production technology options’ [RHO97]. Even though it is in the nature of an LCA to contain a certain inaccuracy the results produced are exact enough to evaluate and pinpoint the life cycle stage that causes the biggest impact.

Further uncertainties and inaccuracies that can appear in a system such as the proposed methodology are identified by Steen [STE97]: ‘One is the normal uncertainty associated with the determination of a parameter in a given system. The other is associated with the choice of such a parameter value to represent a value in another similar system.’

Albeit inaccuracies do occur in the proposed methodology and user interface it is in the nature of a life cycle evaluation and there is no possible way to eliminate them completely. Regarding the proposed methodology the sensibility of results produced was tested vigorously against the three case studies and it can be stated that even though the methodology is not totally accurate the results produced are sensitive enough to guarantee a working and functioning methodology.

Another major issue is that the gathering of accurate input information can be a tedious and time consuming task for the user and this was also mentioned in the feedback session with the industry. During the development of the methodology it was apparent that it can take a quite some time and be a tedious task to gather all the necessary input information this usually is the case if either the information are gathered for the first time and if information regarding the product are not well documented within the company. If a complete product, component and part database is already in existence within the company the gathering of input information for the user interface can be speeded up tremendously. Furthermore if the design engineer has previously gathered the information for a product, or for parts that are used in other products also, it will shorten the time necessary for following collections of input information and make them less tedious.

6.3.5 Infinity of material flow

Another issue that became obvious to influence the development of the methodology is the extent of information and material flows within the context of a Life Cycle Analysis. Material flows of products or services are infinite realities and can be used in a sensitive and practicable manner only to a certain extent. For example: a desk made out of wood is produced. It is taken into account that the tree for this desk was cut down by a chainsaw. This chainsaw uses oil which had to be produced by a refinery. This could be further traced backwards but with no real benefit for the LCA and at a certain point the amount of information is not manageable. Sun [SHE03] identified various product related characteristics in a material flow which 'may include product composition, materials selection, recyclability, product-use, and product take-back, which are part of environmental supply chain management'

All these factors add up to a vast amount of product life cycle information including direct and indirect material flows. To keep information to a manageable quantity and only include relevant data the definition of system boundaries is necessary.

The next section describes in detail how the boundaries were set in the case of the research methodology.

6.3.6 Setting boundaries for the methodology

As described in the prior sections there can be problems regarding availability, accuracy and completeness of data. The European Commission stated that "Given the diversity of different impacts and the need to reduce the information to simplified indicators, it may be necessary to concentrate on the most significant environmental impacts" [EUR04]. Another source supports this concept: "In LCA in general, and life cycle impact assessment in particular, large uncertainties are involved" [STE99b]. So it was important to set boundaries regarding the life cycle information during the first stages of goal definition and scope of the methodology development. The boundaries of material inflow were set at an early point in time of the methodology development and only information regarding the product in question directly are taken into account because otherwise the amount of information that would have been necessary to be gathered by the user would have accumulated to an impossible task whilst only changing the produced results to a minor degree. For example transportation to the main production site of the product are taken into account, such as transportation from the supplier of parts to the manufacturing site as well as transportation from the manufacturing site to the distribution centre and customer. Transportation issues not taken into account due to complexity for this example are the transportation to the supplier (from their material supplier etc) or the transportation impact from customers driving to a shop (e.g. if the product is for example a citrus press sold at a supermarket or similar).

Even though 'Data mining, […], is a promising answer to the problem of incorporating life cycle information and integrating previous design knowledge into the beginning of the design stages' [ROM03] the current methodology cannot take into account all existing information related to a product or a component.

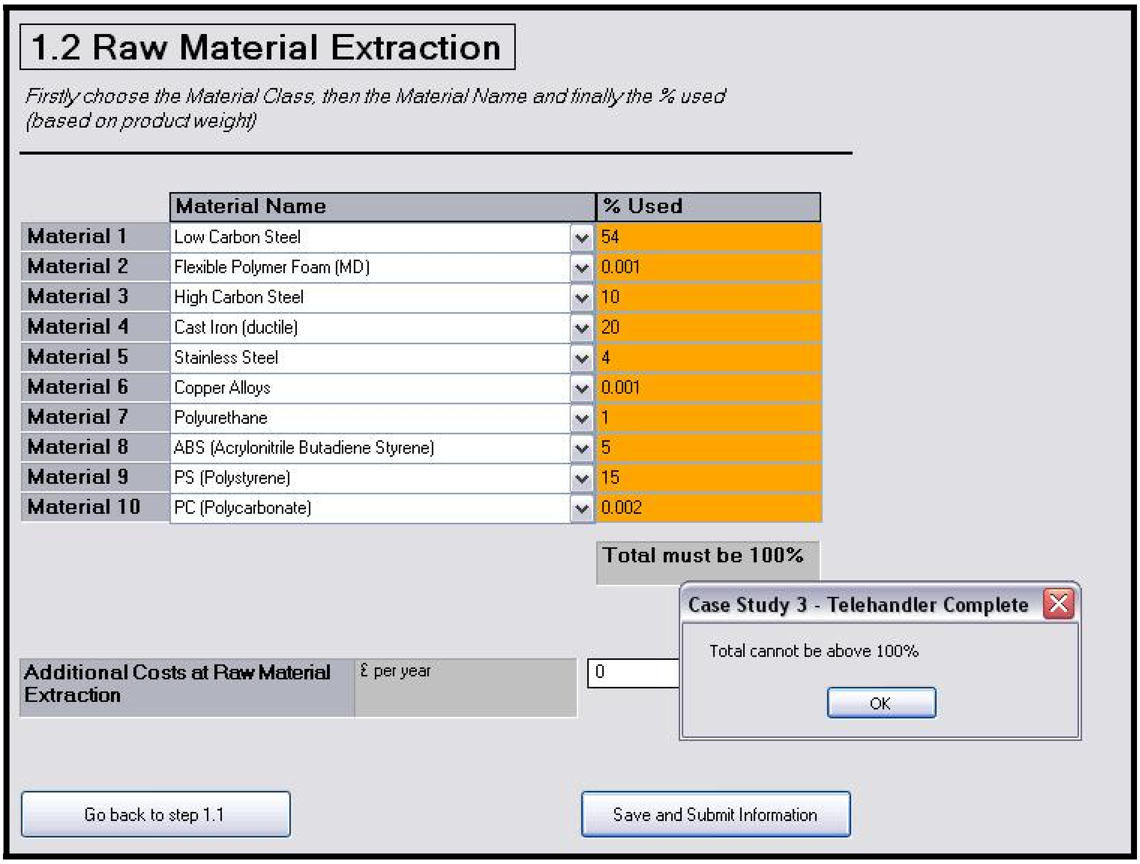
6.3.7 Effect of variation in input data and other issues that can lead to instability of the user interface

Due to the fact that the user interface was tested against the three case studies described earlier the input data it was tested against is well within normal parameters. In the case where the user types in a variation of input data with very large values the stability of the user interface can be jeopardized.

One issue is that very large values within the input data can lead to very large result values that cannot be displayed within the cost value fields due to size restrictions here. Furthermore, if very large values are used for the input data due to the nature of some of the equations used within the framework of the methodology and user interface, they can amplify the input data values exponentially for the results value calculations. This can then lead to instability of the user interface.

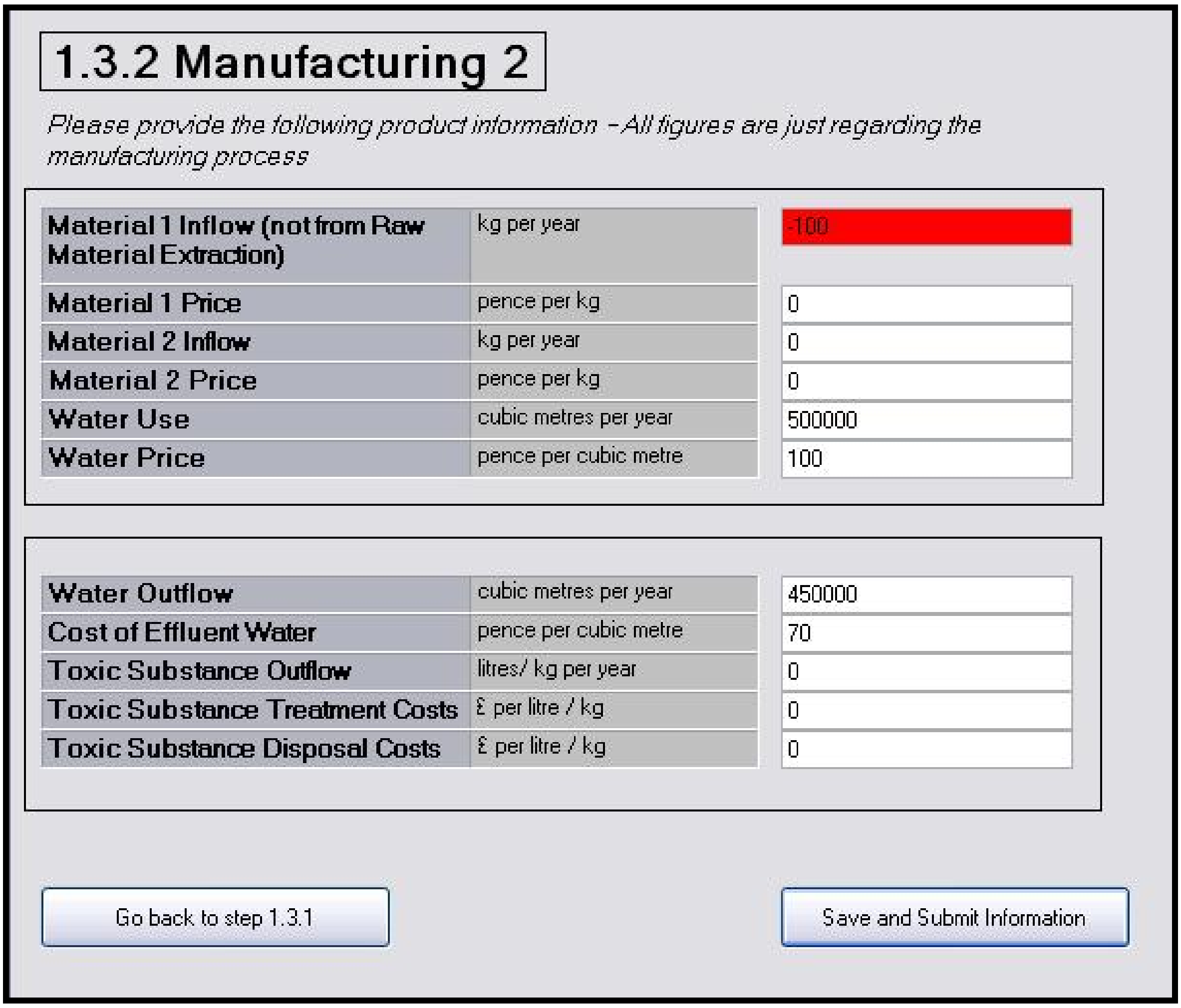
To avoid the user interface program crashing or becoming unstable due to user input data various fail safe measures were taken in order to prevent this scenario.

One fail safe mechanism, which is displayed in figure 6.2, checks if the sum of materials used for the product equals or is below the value of 100%. If it exceeds the 100% value the input screen fields turn orange and an error message is given back to the user stating that “Total cannot be above 100%”. The user has to type in the values again and the user interface lets the user continue to the next screen only if they either add up to 100% or if they stay below 100%.



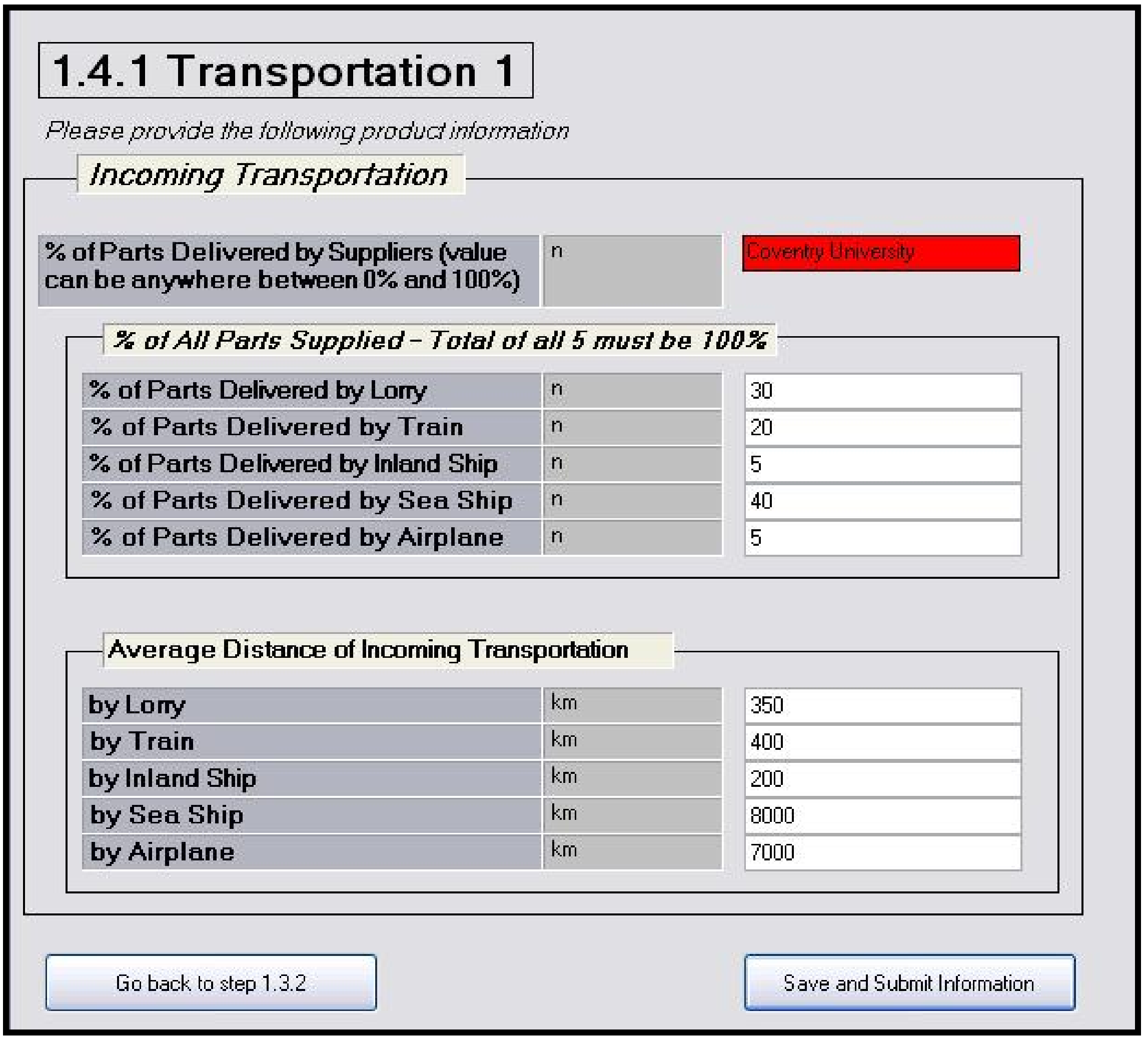
<u>Figure 6.2:</u> Screenshot of fail safe mechanism – Sum of materials used exceeds 100%

Another fail safe mechanism used is that after the user typed in all the input information and clicks on the “Save and Submit Information” button the programming code underlaying the screen checks if all the values are positive. If the user types in a negative value in the case the input data cannot be negative the input information field turns red and the user has to change the value before the user interface continues to the next screen. An example of this is given in screen 6.3: here the user provided the value “-100” for the input parameter “Material 1 Inflow”. Since the material inflow cannot have a negative value the user interface activates the fail safe mechanism and the user has to edit the provided value.



<u>Figure 6.3:</u> Screenshot if fail safe mechanism – negative value entered

Figure 6.4 displayed a third type of fail safe mechanism included in the user interface: If the user types in letters where a numerical value is expected and clicks the “Save and Submit Button” the user interface will flag the input data field with a red colour and the user is not able to proceed to the next screen until the value is corrected. In the case of the screenshot presented in figure 6.4 instead of giving a numerical value for the “% of Parts Delivered by Suppliers” which should be a numerical value between 0 and 100 the user typed in the letters “Coventry University” thus the field is turned red.



<u>Figure 6.4:</u> Screenshot if fail safe mechanism – letters entered instead of numerical value

The fail safe mechanisms described in this section are just a representative selection and there are various more that prevent the user interface software from becoming unstable and actually crashing in case input data is provided that is not computable. This measure avoids the effect of variation in input data that can lead to instability of the user interface.

6.4 Future work

Even though the developed methodology is at a fairly advanced level and the user interface proves the robustness whilst being tested against the case studies there is still room for future work. During this section the possible future work and possible alternative research directions are discussed that could not be followed up in the course of this research.

Further improvements for the methodology and suggestions of future work possibilities are given in the following:

1) Commercialization of the User Interface

Even though a software based user interface exists and this user interface is very easy to use by the design engineer the current status is far from a commercial version that could be sold on the market. Thus it is part of the future work to evaluate all the technical issues as well as the legal issues connected to a commercialisation of the methodology. To clarify the technical issue it will be necessary to get a professional, commercial review on how complex the task is as well as the financial commitment involved. The legal issues include an investigation to find out how the methodology and software product can be protected from plagiarism and illegal copying.

Another potential future work task that was mentioned during the feedback session with design engineers from the industry is that the layout of the user interface. Especially the choice of colours can be improved, as well as the design of controls, integration of help screens and tool tip pop up windows.

2) Integration of more than the three design issues functionality, environmental impact and economic impact

As described in section 6.3.1 possible future work could be to integrate more issues than cost, environmental impact and functionality in order to overcome another perceived weakness. It will be the major part of the proposed work to find out how feasible the integration of further design issues is and how all the issues taken into account in the future shape of the methodology can be aligned. Furthermore in the course of this work it has to be investigated which design issues are mandatory to integrate and actually make sense to integrate whilst others can be considered to be unnecessary and thus be rejected. Firstly though a very basic evaluation has to be carried out to establish if it actually makes sense to integrate more issues than those that are currently part of the methodology and user interface and what would satisfy the customers of the target market.

3) Linking in extensive databases

Currently there are four main databases linked into the methodology. The first one is a material database that includes various data for 19 representative materials.

It will be a major part of the future work necessary to build up a commercialised version of the user interface. In order to do so it will be essential to overcome the perceived weaknesses of regional deviances and accuracy of information described in the prior section and expand the material database used. It is essential to link in a material database that is updated regularly and reflects changes in the markets in terms of prices. Additionally various regional material databases should be linked in also so that the user can select the appropriate location during the start of the user interface and material information that is valid for that location.

Other databases included are a transportation database, a end-of-life scenario database and a carbon trade emission database. All these databases require further work and extension to include regular updates if values and circumstances change as well as a building up of several regional databases to make the information gained from them fit the specific location of the user.

4) Using more than three levels of the product hierarchy

The current methodology and user interface work on three levels of product design process and product hierarchy:

- Early Concept phase

- Advanced Concept phase
- Detail Design phase

Possible future work could be to extend these three levels of the product hierarchy that the methodology is based upon and include maybe four or five levels. It is also an option to base the levels used on input information gathered from the user or a parts diagram. For example if the information provided by the user suggests a highly complex product a total of five product hierarchy levels could be part of the user interface or if the input information suggests a very simple product only two product hierarchy levels could be part. It is the main task of the proposed future work to evaluate if this is possible and to explore possibilities to integrate them into the methodology and user interface

5) Including specific directive issues of EU and international levels

Another option that was evaluated at the beginning of the methodology development during this research was the possibility to include a directive fulfilment option within the methodology. The directive fulfilment option would work the following way: the user provides input information as it is already done in the current methodology framework. The methodology then evaluates which directives apply to the products and, based on the input information, determines if the product actually meets the criteria of the directives. The results are given back to the user with suggestions of what needs to be done to the product design in order to have it meet the directives and legislations that apply.

The directives that apply can furthermore be linked to the regional difference issue. For example if the user suggests that the product is manufactured and sold within the European Union the methodology should filter the directives and apply only the ones that apply in Europe.

Initially the methodology was based on the principles of the EuP (Eco-Design of Energy using Products) Directive and it is highly likely that if the design suggestion of the methodology are applied then the product complies with the targets set out by this Directive or at least that the product design is moved closer to fulfilling the requirements of the EuP. The future work proposed here suggests to incorporating this explicitly for the EuP and actually state if the product meets the requirements of it or not. This information must be given back to the user. Furthermore possible future work can include the same for other European Union Directives as well as international directives.

6) Extending the current maximum components and parts

During the development and programming of the user interface certain limitations and simplifications had to be incorporated in order to meet the strict time schedule and to finish the user interface in the timeframe set out initially. Due to programming complexity the maximum amount of components that can be evaluated in the course of the product design phase 2, Advanced Concept phase, is limited to six. The restriction of component quantity is only an issue in the case of the user interface, the methodology is able to handle a large number of components. Thus future work includes extending and improving the software user interface so it can accommodate more than six components. The restriction also applies to the product design stage 3, Detail Design phase. The maximum number of parts is limited to 10 for the component that causes the biggest impact during product design phase 2.

This was also an issue for the design engineers from the industry who provided feedback regarding advantages and disadvantages of the user interface.

So the challenge of the future work regarding the limitations mentioned is to extend and complement the Visual Basic programming of the user interface so it can accommodate more than six components and more than 10 parts per component.

7) Further develop the “Fastener” option within the methodology

Within the current state of the methodology and user interface the fasteners used to join the different components and parts of the product are taken into account even though to a very basic level only.

8) Incorporating a visual tool to display the product structure in detail

A visual display of the product structure, including all the product component and parts, their relation to each other and the fasteners used to connect them was suggested in the initial proposal of methodology development. Due to constraints in time and practicability of the Visual Basic programming this option was discarded quickly. This does not mean that it should not be part of future work though. The advantages of presenting the user with a visualization of the product structure and hierarchy details are various and well worth exploring:

- It is easier for the user to understand how the product is built up and how the design suggestions can be applied with the biggest positive impact.
- A visualization of the product structure can more easily help identify components that are not absolutely vital and necessary for the product design.
- Presenting a product structure within the user interface can also help to fabricate manufacturing plans for the product in question e.g. the order the components need to be assembled in and possible problems with this process.

6.5 Chapter reflections

Since there are already various methods and tools on the market that are supposed to help the design engineer apply the Eco-Design principle and reduce the environmental impact of a product it is important to explain how the methodology described in the previous chapters is distinct.

The purpose of this chapter is to critically review the methodology, and the user interface as a product of it and compare it to already existing methods and tools.

Afterwards the shortcomings of those current practices and development are outlined and evaluated in great detail. Then the following section explains how the methodology developed in the course of this research addresses those shortcomings of the methods and tools currently available and what characteristics and features make it distinct and attractive for the potential user.

Then the perceived weaknesses of the developed methodology are reviewed in a critique, its shortcomings are reflected upon and reasons are given why it was not possible to avoid those limitations and weaknesses. This is brought into direct context with the methodology development to clarify for the reader why the methodology was developed in its distinct way.

The final element of this chapter is an outlining of options for possible future work and how this could help overcome at least some of the perceived weaknesses. A detailed list of how this future work should be conducted is given also. Furthermore, reasons are given why the suggested future work could not be included in the current layout and framework of the methodology.

7. Conclusions

The main objective of the research was to develop a methodology that supports the design optimisation of products in terms of their environmental and economic impact aiding on the functionality issue as well. The methodology satisfies the current needs of the market that are not covered by other methods and tools available at the moment; the current situation requires an easily applicable solution for including environmental issues into the product design process. The methodology described in this thesis helps to deliver that easy and time efficient solution without compromising other design issues. Several key benefits of the methodology are:

- All design phases from concept to detail design are covered. This allows the methodology to be easily applicable to complex products being based on the product hierarchy.

- An easy to use software interface is devised that allows the user apply the key principles of the methodology quickly and thoroughly.

- The user interface holds the potential to be a strong competitor with current software methods on the market. The only work necessary is to improve the layout and design of the user interface and to make it costumer and sales ready. Also legal obligations, marketing and a sales strategy are required.

- The user interface produces results in terms of economic and environmental figures as well as design suggestions immediately after the input information is gathered. This allows rapid application of the improvement suggestions which gives the user interface a competitive edge over most of the methods already on the market.

- Due to its highly inventive design suggestions, produced by integrating the TRIZ matrix, the DFX principles and other tools, the user interface has a competitive advantage over already existing methods. Whilst most of the already existing methods conduct an impact assessment the methodology described in this thesis produces design suggestions also.

- The methodology aligns product hierarchy in a top down approach and the design phase progress to enhance a products´ eco-performance. This makes it easier for the design engineer to use the methodology since only input information is requested that is available at the time of the design phase. The user interface requests more detailed information, once the product design phase advances, which is available to the design engineer at that time.

- The methodology avoids any trade-off of Eco-Design with other design issues, such as costs and functionality since both are integrated in the methodology.

The methodology and user interface provides support to continuous product improvement and compliance with legislation without jeopardizing competitiveness. The case studies provide the necessary evidence that the methodology works and delivers the performance in real life and not just in a theoretical construct.

The application of the methodology, in parallel to the standard product design process, in three distinct steps helps to avoid a time consuming re-design of the product. This is particularly valuable in the case of complex products since a complete product re-design could take several months and a loss of competitive advantage.

A key part of the methodology is the modification and incorporation of the TRIZ matrix to enhance eco-performance. Aligning the DfX tools and other existing tools helps to bring together the product hierarchy and life cycle thinking. This is necessary for a sensible approach in the case of Eco-design of complex products.

The methodology developed in the course of this research successfully fills the gap identified in current literature and has advantages over the methods already available on the market.

References

[AB05] ABDALLA, A. ; BITZER, B.: *Innovation management methods and tools for sustainable product service systems (With a Case Study).* South-Westphalia University of Applied Sciences, 2005.

[ABB03] ABB: *LCA light tool.* URL http://project.imi.chalmers.se/LCALight/Codenew/GUI-LCALight-Frame.asp?selected_project_id=Anonymous010507102213211 (accessed March 2007).

[ABC04] ASHBY, M.F. ; BRECHET, Y.J.M. ; CEBON, D.: Selection strategies for materials and processes. *In: Materials & Design,* vol. 25,(2004), no. 1, p. 51 – 67.

[AJ93] ALTING, L. ; JORGENSEN, J.: The Life Cycle Concept as a Basis for Sustainable Industrial Production. *In: Annals of the CIRP,* vol. 42, (1993), no. 1, p. 163 – 167.

[AKE03] AKERMARK, A.-M.: *The crucial role of the designer in EcoDesign.* Stockholm, Kungliga Tekniska Hogskolan, 2003.

[ASH05] *Materials for greener environment seminar.* Newcastle upon Tyne : 2005.

[AUT06] Automation Creations: *MatWeb - Material Property Data.* URL www.matweb.com (accessed December 2006).

[BAV05] Bavarian Industry: *Integrierte Produktpolitik - Die lebenswegbezogene Systemsichtweise.* URL http://www.ipp-bayern.de/ (accessed April 2005).

[BBL04] BARIANI, P.F. ; BERTI, G.A. ; LUCCHETTA, G.: A combined DFMA and TRIZ approach to the simplification of product structure. *In: Advances in Engineering Software, vol.* 218, (2004), no. B, p. 1023 – 1027.

[BD83] BOOTHROYD, G. ; DEWHURST, P.: *Design for Assembly – A Designer's Handbook.* Amherst, University of Massachusetts, Department of Mechanical Engineering, 1983.

[BEI92] BRYAN, C. ; EUBANKS, C. ; ISHII, K.: *Design for serviceability expert system.* San Francisco: ASME, 1992.

[BG04] BOVEA, M.D. ; GALLARDO, A.: The influence of impact assessment methods on materials selection for eco-design. *In: Materials & Design* vol. 27, (2004), no. 1, p. 209 – 215.

[BRE05] BRE: *Green Guide Update: BRE Response to Comments on Characterisation Briefing Paper, vol. 3a,.* 2005.

[BRO06a] BROCKLEHURST, F.: *Presentation - Framework Directive for the Eco-design of Energy Using Products (The EuP Directive),* 2006.

[CAT03] Caterpillar: *TH460B – Telehandler, customer catalogue, available online on: www.cat.com (accessed online June 2007).*

[CAT06] Caterpillar: *Caterpillar in the U.K., Offical Caterpillar report,* 2006.

[CAT08] Caterpillar: *International Caterpillar Website.* URL http://www.cat.com (accessed January 2008).

[CAV01] CAVALLUCCI, D.: Integrating Altshuller`s Development Laws for Technical Systems into the Design Process. *In: Annals of the CIRP, vol.* 50, (2001), no. 1, p. 115 – 119.

[CC04] CHANG, H.-T. ; CHEN, J. L.: The conflict-problem-solving CAD software integrating TRIZ into eco-innovation. *In: Advanced Engineering Informatics, vol.* 35, (2004), no. 1, p. 553-566

[CCL06] CCL Discount Scheme: *Climate Change Levy.* URL http://www.cclevy.com (accessed April 2007).

[CEN07] Center for Energy conservation: *Innovation in environmental policy.* URL http://www.ce.nl/eng/ (accessed July 2007).

[CFF05] COLLINS, M. ; FISHER, K. ; FRIPP, E.: *Study and Assessment of Available Information for a Pilot Project on a Teak Garden Chair - Final Report.* 2005.

[CL03] CHEN, J.L. ; LIU, C.C.: An eco-innovative design approach incorporating the TRIZ method without contradiction analysis. *In: Journal of Sustainable Production Design, vol.* 1, (2003), no. 4, p. 262 – 272.

[COM03] Commission of the European Communities: *Communication from the Commission to the Council and the European Parliament - Integrated Product Policy, Building on Environmental Life-Cycle Thinking.* 2003.

[DEF06] Defra: *Framework Directive for the Eco-design of Energy Using Products (EuP Directive) - An Overview and Way Forward.* URL http://www.mtprog.com/approvedbriefingnotes/BriefingNoteTemplate.aspx?intBriefingNoteID=389 (accessed May 2006).

[DOK05] Doktorandennetzwerk Nachhaltiges Wirtschaften e.V.: *DNW.* URL http://www.doktoranden-netzwerk.de/ (accessed March 2005).

[DOW07] DOWDEY, S.: *Introduction to How Carbon Tax Works.* URL http://science.howstuffworks.com/carbon-tax.htm (accessed 10.2007).

[DS97] DOZ, Y. ; SANTOS, J.: *On the management of knowledge : from the transparency of collocation and co-setting to the quandary of dispersion and differentiation.* Fontainebleau, France, 1997.

[EAR06] earth easy: *Energy efficient lighting.* URL http://www.eartheasy.com/live_energyeff_lighting.htm (accessed December 2006).

[ECO06a] Eco3 Ltd.: *Presentation - The ecodesign of products: Unit 2.* Dadlington, Nuneaton: 2006.

[ECO06b] Eco3: *Eco3 homepage.* URL www.eco3.co.uk (accessed April 2007).

[EDE01] EDER, W.E.: Designing and life cycle engineering - a systematic approach to designing. *In: Proceedings of the Institution of Mechanical Engineers - Part B - Engineering Manufacture, vol.* 215, (2001), no. 5, p. 657 – 673.

[EM 93] EM Spectrum: Technieken gft-verwerking op een rijtje. *In: Energie en Milieuspectrum* vol. 8, (1993), no. 14.

[EM96] EVANS, S. ; MCALOONE, T: The economic life cycle. *In: Co-design, vol* 45, (1996), p. 76-80.

[ENV06] Environment Agency: *Waste Electrical and Electronic Equipment (WEEE) Directive 2002/96/EC and 2003/108/EC.* URL http://www.netregs.gov.uk/netregs/legislation/380525/473094/?lang=_e (accessed January 2007).

[ERN00] Ernst & Young: *Developing the Foundation for Integrated Product Policy in the EU - DG Environment, European Commission.* 2000.

[ERN98] Ernst & Young: *European Commission DGXI: Integrated Product Policy - Executive Summary from the Final Report.* 1998.

[EUR01a] European Commission: *Summary of Discussions at the 1st to 7th Integrated Product Policy Expert Workshop.* Brussels, 2001.

[EUR01b] European Commission: *COM(2001) 68 final - Green paper on integrated product policy.* 2001.

[EUR03] European Commission: Restriction of the use of certain hazardous substances in electrical and electronic equipment. *In: Official Journal of the European Union,* vol. 37, (2003), no. 1, p. 19 - 23

[EUR04] European Commission: *Technical Annex - Development of Indicators for Integrated Product Policy,* 2004

[EUR05a] European Commission: Establishing a Framework for the setting of ecodesign requirements for energy-using products and amending Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC of the European Parliament and of the Council. *In: Official Journal of the European Union , vol.* 191, (2005), no. 1.

[EUR05b] European Commission: *Energy-using Products.* URL http://ec.europa.eu/enterprise/eco_design/index.htm (accessed September 2006).

[EUR05c] European Parliament and the Council of the European Union.: Directive 2005/32/EC of the European Parliament and of the Council of 6 July 2005 establishing a framework for the setting of ecodesign requirements for energy-using products and amending Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/E. *In: Official Journal of the European Union* vol.191, (2005), no. 1.

[EUR05d] European Commission: *End of Life Vehicles.* URL http://europa.eu.int/comm/environment/waste/elv_index.htm (accessed August 2005).

[EUR07] European Nuclear Society: *Largest nuclear society for science and industry.* URL http://www.euronuclear.org/info/encyclopedia/e/enviromentalload.htm (accessed June 2007).

[EUR98] European Commission: *Workshop on Integrated Product Policy: A Final Report.* 1998.

[FMT00] FELDMANN, K. ; MEEDT, O. ; TRAUTNER, S.: 'Green Design Advisor': A tool for design for environment. *In: Journal of Electronics Manufacturing,* vol.9, (2000), no. 1, p. 17 – 28.

[GCA00] GLAZEBROOK, B. ; COULON, R. ; ABRASSART, C: *Towards a product life cycle design tool.* San Francisco: IEEE, 2000.

[GDC96] GOEDKOOP, M. ; DEMMERS, M. ; COLLIGNON, M.: *Eco Indicator 95 - Manual for Designers.* 1996.

[GFS98] GEDIGA, J. ; FLORIN, H. ; SCHUCKERT, M.: LCA as a tool in the design process of parts, products and systems. *In: SAE Special Publication,* vol. 1342, (1998), no. 1, p. 131 – 136.

[GJB06] GROTE, C. A. ; JONES, R. ; BLOUNT, G.: *An environmental design decision support methodology to apply the principles of the Integrated Product Policy.* Coventry: Future Manufacturing Applied Research Centre, 2006.

[GJB07] GROTE, C. ; JONES, R. ; BLOUNT, G.: An approach to the EuP-Directive and the application of the economic Eco-design for complex products. *International Journal of Production Research, vol. 45,* (2007), no. 18-19, p. 4099–4117.

[GRA06] Granta Design: *CES Materials & Process Selectors.* URL www.grantadesign.com (accessed January 2007).

[GRE04] GREENWOOD, T.: *Sustainable Product Design.* URL http://www.espdesign.org/index.htm (accessed September 2006).

[GRO05] GROTE, C. A.: *Presentation - A Methodology for the Implementation of the Integrated Product Policy in the field of Automotive Design,* Bochum, 2005.

[GS01] GOEDKOOP, M. ; SPRIENSMA R. ,: *The Eco-indicator 99 - A damage oriented method for Life Cycle Impact Assessment - Methodology Report,* Amersfoort, 2001.

[GUI05] GUINÉE, J.: *LCA resources at CML-IE.* URL http://www.leidenuniv.nl/interfac/cml/ssp/projects/lca2/index.html (accessed April 2006).

[HAG04] HAGENBAUGH, B.: Steel prices soar 66% in a world market 'gone mad'. *In: USA Today* (2004)

[HB00] HARRISON, L.J. ; BLOUNT, G.N.: *Business Model Approach : Design versus Economic Considerations for Automotive Recycling.* Detroit, Society of Automotive Engineers, 2000.

[HEI02] HEISKANEN, E.: The institutional logic of life cycle thinking. *In: Annals of the CIRP* vol. 10, (2002), no. 1, p. 427 – 437.

[HH01] HESSELBACH, J. ; HERRMANN, C.: *Combined Strategies for Recycling -- Product and Process Oriented Benchmarking.* IEEE, 2001.

[HM98] HUANG, G.Q. ; MAK, K.L.: The DFX shell: A generic framework for applzing 'Design for X' (DFX) tools. *In: International Journal Computer Integrated Manufacturing* vol.11, (1998), no. 6, p. 475.

[HOL97] HOLLOWAY, L. P.: *A methodology and support tool for environmentally conscious design and manufacture*, Dissertation, Sheffield, Sheffield Hallam University, 1997.

[HP91] HYEON, H. ; PARSAEI, H.R.: *Concurrent Engineering: The Manufacturing Philosophy for the 90's,* 1991.

[HR95] HERBER, B.P. ; RAGA, J.T.: An international carbon tax to combat global warming: an economic and political analysis of the European Union proposal. In*: American Journal of Economics and Sociology, vol. 54,* (1995), no. 3, p. 257-267.

[IED94] ISHII, K. ; EUBANKS, C.F. ; DI MARCO, P.: Design for product retirement and material life-cycle. *In: Materials & Design,* vol.15, (1994), no. 4, p. 225 – 233.

[INT00a] International Organisation for Standardization: *ISO 14042 - Environmental management - Life cycle assessment - Life cycle impact assessment.* Brussels: European Commitee for Standardization, 2000.

[INT00b] International Organisation for Standardization: *ISO 14043 - Environmental management - Life cycle assessment - Life Cycle Interpretation.* Brussels: European Commitee for Standardization, 2000.

[INT02a] International Organisation for Standardization: *ISO 14062 - Environmental management - Integrating environmental aspects into product design and development.* Brussels: European Commitee for Standardization, 2002.

[INT02b] International Organisation for Standardization: *ISO 17422 - Plastics - Environmental aspects - General guidelines for their inclusion in standards.* Brussels: European Commitee for Standardization, 2002.

[INT97] International Organisation for Standardization: *ISO 14040 - Environmental management - Life cycle assessment - Principles and framework.* Brussels: European Commitee for Standardization, 1997.

[INT98] International Organisation for Standardization: *ISO 14041 - Environmental management - Life cycle assessment - goal and scope definition and inventory analysis.* Brussels: European Commitee for Standardization, 1998.

[INT99] International Organisation for Standardization: *ISO 14031 - Environmental management - Environmental performance evaluation - Guidelines.* Brussels: European Commitee for Standardization, 1999.

[JAS02] JASCH, C.: The use of Environmental Management Accounting (EMA) for identifying environmental costs. *In: Journal of Cleaner Production,* vol. 11, (2002), no. 1, p. 667 – 676.

[JMC03] JOLLIET, O. ; MARGNI, M. ; CHARLES, R.: IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. *In: International Journal of Life Cycle Assessment, vol.* 8, (2003), no. 6, p. 324 – 330.

[KHC07] KWAK, M.J. ; HONG, Y.S. ; CHO, N.W.: An Eco-Architecture-based Approach to Design for Disassembly (DfD). *In:* 19th International Conference on Production Research*,* (2007).

[KIR06] KIRCHAIN, R.: *Presentation - Unit 4: Life Cycle Assessment Session 4: Impact Assessment - 3.080 Economical & Environmental Issues In Materials Selection.* 2006.

[LB01] LENAU, T. ; BEY, N.: Design of environmentally friendly products using indicators. *In: Proceedings of the Institution of Mechanical Engineers - Part B - Engineering Manufacture, vol.* 215, (2001), no. 5, p. 637 -646.

[LEH00] LEHNI, M.: *Eco-Efficiency - Creating more value with less impact.* 2000. (available online) URL: http://www.wbcsd.org/DocRoot/3jFPCAaFgl1b (accessed November 2007).

[LEI07] Leiden University: *Institute of Environmental Sciences (CML).* URL http://www.leidenuniv.nl/cml/ (accessed June 2006).

[LI,03] LI, J.: *A multi-agent negotiation-based decision framework for extensible product life cycle.* Texas Tech University, 2003.

[LLK01] LYE, S.W. ; LEE, S.G. ; KHOO, M.K.: A design methodology for the strategic assessment of a product`s eco-efficiency. *In: International Journal of Production Research, vol.* 39, (2001), no. 11, p. 2453 – 2474.

[LLK02] LYE, S.W. ; LEE, S.G. ; KHOO, M.K.: EcoDE - An environmental component design evaluation tool. *In: Engineering with Computers, vol.* 18, (2002), no. 1, p. 14 – 23.

[LLW+01] LOW, M. K. ; LAMVIK, T. ; WALSH, K. ; MYKLEBUST, O.: Manufacturing a Green Service: Engaging the TRIZ Model of Innovation. *In: IEEE TRANSACTIONS ON ELECTRONICS PACKAGING MANUFACTURING, vol.* 24, (2001), no. 1, p. 10 -17.

[LUM95] LUMSDAINE, E.; LUMSDAINE, M.; SHELNUTT, J.W.: *Creative Problem Solving and Engineering Design.* McGraw - Hill, 1995, ISBN – 9780070390911.

[MAT04] Material Datensystem Verbund: *International Material Data System (IMDS).* URL http://www.mdsystem.com/html/de/home_de.htm (accessed April 2006).

[MAZ04] MAZUR, G.: *Theory of Inventive Problem Solving (TRIZ).* URL http://www.mazur.net/triz/ (accessed September 2005).

[MD96] MANN, D. ; DOMB, E.: *TRIZ - 40 inventive principles with examples.* URL http://www.triz.co.uk/ (accessed August 2005).

[MFM04] MATHIEUX, F. ; FROELICH, D. ; MOSZKOWICS, P.: *Toward a better recovery conscious design of electr(on)ic Eqipment - Benefits of using the new recycled method that integrates prospective recovery technologies and implications for the design practises of the company.* Lausanne, Switzerland: 2004.

[MSP96] MIZUKI, C. ; SANDBORN, P.A. ; PITTS, G.: *Design for the environment - A survey of current practises and tools.* Dallas, TX: IEEE, 1996.

[NAT06] National Weights & Measure Laboratory: *Working with EEE producers to deliver compliance with RoHS in the UK.* URL http://www.rohs.gov.uk/ (accessed July 2007).

[NED07] NedCar: *NedCar.* URL http://www.nedcar.nl/ (accessed June 2007).

[NHS06] NEGRO, S. ; HEKKERT, M. ; SMITS, R.: Explaining the failure of the Dutch innovation system for biomass digestion—A functional analysis. *In: Energy Policy, vol.* 35, (2006), no. 1, p. 925 – 938.

[NOK05] Nokia Corporation: *Integrated Product Policy Pilot Project - Stage 1 Report.* URL http://europa.eu.int/comm/environment/ipp/pdf/impact_nokia.pdf (accessed November 2006).

[OCE07] Oce UK Ltd: *Oce printers copiers scanners plotters.* URL http://www.oce.com/uk/default.htm (accessed June 2007).

[OVE91] OVERBY, Charles: *QFD & Taguchi for the entire life cycle.* Milwaukee, WI, USA: Published by ASQC, Milwaukee, WI, USA, 1991.

[PAR03] PARLIKAD, A.K.: *The Impact of Product Identity Information on Effectiveness of Product Disassembly Processes.* Cambridge, U.K., University of Cambridge, Dept. Of Engineering, 2003.

[PHI07] Philips U.K.: *Philips - Sense and simplicity.* URL http://www.philips.co.uk/index.html (accessed June 2007).

[POL05] POLLET, K.: *EU Integrated Product Policy (IPP), International Conference and workshop on Eco-Labelling,* Taiwan: 2005.

[PRE07] PRe` Consultants: *PRe` Consultants - Life Cycle Tools to improve environmental performance and sustainability.* URL http://www.pre.nl (accessed July 2007).

[PSW02] PARK, J.-H. ; SEO, K.-K. ; WALLACE, D.: Approximate Product Life Cycle Costing Method for the Conceptual Product Design. *In: Annals of the CIRP vol.* 51, (2002), no. 1, p. 421 – 424.

[PTJ06] PARK, P.-J. ; TAHARA, K. ; JEONG, I.-T.: Comparison of four methods for integrating environmental and economic aspects in the end-of-life stage of a washing machine. *In: Resources, Conservation and Recycling, vol.* 48, (2006), no. 1, p. 71 – 85.

[QIA03] QIAN, X.: *Environmental analysis model for modular design of electromechanical products.* Texas Tech University, 2003.

[RF00] REBITZER, G. ; FLEISCHER, G.: *Identifying the Environmental Impact Drivers and Tradeoff Options in the Life Cycle of Automobiles – A Software Based Methodology for the Sound Restriction of System Boundaries.* Detroit, Society of Automotive Engineers, 2000.

[RFL+00] REBITZER, G. ; FLEISCHER, G. ; LICHTENVORT, K ; SCHILLER, U.: *Design for Environment in the Automotive Sector with the Materials Selection Tool euroMat.* München, 2000.

[RHO97] RHODES, S.: *New Directions in Life-Cycle Assessment: Implications for the Automobile Industry.* Detroit, Michigan: SAE Inc., 1997.

[RI03] RHEE, S. J. ; ISHII, K.: Using cost based FMEA to enhance reliability and serviceability. *In: Advanced Engineering Informatics, vol.* 17, (2003), no. 3-4, p. 179 - 188

[RIS05] RICHARDSON, J. ; IRWIN, T. ; SHERWIN, C.: *Design & Sustainability - A Scoping Report for the Sustainable Design Forum.* London, 2005, (available online) URL: http://www.dba.org.uk/aboutdba/documents/S (accessed June 2007).

[RK99] ROSE, C. M. ; KOSUKE, I.: Product End-of-Life Categorization Design Tool. *In: Journal of Electronics Manufacturing, vol.* 9, (1999), no. 1, p. 41 – 52.

[ROM03] ROMANOWSKI, C. J.: *A data mining-based engineering design support system,* Dissertation, Buffalo, State University of New York, 2003.

[ROW06] ROWELL, A.: *BP: Beyond Propaganda.* URL http://priceofoil.org/2006/08/17/bp-beyond-propaganda/ (accessed August 2006).

[RS02] RUBIK, F. ; SCHOLL, G.: Integrated Product Policy (IPP) in Europe - a development model and some impressions. *In: Journal of Cleaner Production, vol.* 10, (2002), no. 1, p. 507 – 515.

[SAM05] SAMAN, M.Z.S.: *Methodology of design for end of life value in automotive engineering,* Dissertation, Coventry, Coventry University, 2005.

[SAN05] SANDERS, E.: *Seattle leads U.S. cities joining Kyoto Protocol.* URL http://www.iht.com/articles/2005/05/15/news/global.php (accessed May 2005). .

[SBJ04] SAMAN, M.Z.S. ; BLOUNT, G. ; JONES, R.: *Framework of End-of-Live Vehicle (ELV) Value Analysis for Automotive Design Assessment, Fifth International Tools and Methods for Competitive Engineering Symposium,* Lausanne, 2004.

[SCO06] SCONZO, J.: *Joe Sconzo's Earth Report.* URL http://www.joearth.com/ (accessed November 2006).

[SH04] SCHILD, K. ; HERSTATT, C.: *How to use analogies for breakthrough innovations.* Technical University of Hamburg, Institute of Technology and Innovation Management, 2004

[SHA05] SHAHID, A.: *Rapid Innovation with TRIZ - A Case Study in Continuous Product Development, Technology Support Services P/L.* Sydney, 2005

[SHE03] SUN, J. ; HAN, B. ; EKWARO-OSIRE, S.: Design For environment : Methodologies, Tools and Implementation. *In: Journal of Integrated Design and Process Science, vol.* 7, (2003), no. 1, p. 59 - 75

[SHE07] SHEDROFF, N.: *An Evolving Glossary of Experience Design.* URL http://www.nathan.com/ed/glossary/ (accessed July 2007).

[SHE97] SAUR, K. ; HESSELBACH, J. ; EYERER, P.: *Life Cycle Considerations as Decision Making Support in the Automotive Industry.* Detroit, Michigan: SAE Inc., 1997.

[SHP91] SHELDON, D. ; HUANG, G.Q. ; PERKS, R.: Design for Cost: Past Experience and Recent Development. *In: Journal Engineering Design, vol.* 2, (1991), no. 2, p. 127 – 139.

[SM03] STRATTON, R. ; MANN, D.: Systematic innovation and the underlying principles behind TRIZ and TOC. *In: Materials Processing Technology, vol.* 139, (2003), no. 1, p. 120 – 126.

[SMA08] Smart website: *Smart Micro Hybrid Drive.* URL http://www.smart.com. – (accessed January 2008).

[SPJ90] SHELDON, D.F. ; PERKS, R. ; JACKSON, M.: Designing for Whole Life Costs at the Concept Stage. *In: Journal Engineering Design,* vol. 1, (1990), no. 2, p. 131 – 145.

[SRC00] SHETTY, D. ; RAWOLLE, K. ; CAMPANA, C.: A New Methodology for Ease-Of-Disassembly in Product Design. *In: Recent Advances in Design for Manufacture (DFM) ASME 2000, vol.* 109, (2000), no. 1, p. 39-50.

[ST05] ST Microelectronics website: *Glossary.* URL http://www.st.com/stonline/press/news/glossary/i.htm (accessed August 2005).

[ST03] SENTHIL, K.D. ; TAN, R.B.H.: A proposed tool to integrate environmental and economical assessments of products. *In: Environmental Impact Assessment Review, vol.* 23, (2003), no. 1, p. 51 - 72

[STE97] STEEN, B.: On uncertainty and sensitivity of LCA-based priority setting. *In: Journal of Cleaner Production, vol* 5, (1997), no. 4, p. 255 – 262.

[STE99a] STEEN, B.: *A systematic approach to environmental strategies in product development (EPS), CPM report,* 1999.

[STE99b] STEEN, B.: *A systematic approach to environmental strategies in product development (EPS) - Models and data of the default method, CPM report,.* 1999.

[STI06] Stinnes AG: *Ecotransit.* URL http://www.ecotransit.org (accessed August 2006).

[SW97] SPICER, A. ; WANG, M.: Environmental Design Industrial Template (EDIT): A software tool for analysis of product retirement. *In: Journal of Cleaner Production, vol.* 5, (1997), no. 3, p. 193 - 198

[TEU97] TEULON, H.: *Life Cycle Assessment: A Tool for Design for Environment.* Detroit, Michigan: SAE Inc., 1997.

[THS04] TUKKER, A. ; HUPPES, G. ; SUH, S.: *Evaluation of the Environmental Impact of Products - Draft Report, IPTS/ESTO project,* 2004.

[TIC99] TICKELL, Sir C.: *British Government Panel on Sustainable Development - Panel`s role in the government`s pursuit of sustainable development.* URL www.sd-commission.org.uk/panel-sd/panel/intro (accessed September 2006).

[TNO06] TNO: *Eco Scan life 3.1.* URL http://www.ind.tno.nl/en/product/ecoscan (accessed August 2006).

[TS97] TICHEM , M. ; STORM, T.: Designer support for product structuring-development of a DFX tool within the design coordination framework. *In: Computers in Industry, vol* 33, (1997), no. 1, p. 155 – 163.

[TU 07] TU Delft: *Delft University of Technology.* URL http://www.tudelft.nl/ (accessed June 2007).

[U.K05] U.K. Government: *Sustainable Development - The Government`s approach - delivering UK sustainable development together.* URL http://www.sustainable-development.gov.uk/publications/uk-strategy/uk-strategy-2005.htm (accessed October 2006).

[UDJ07] UNGUREANU, C.A. ; DAS, S. ; JAWAHIR, I.S.: Life-cycle Cost Analysis: Aluminum versus Steel in Passenger Cars. *In: Aluminium Alloys for Transportation, Packaging, Aerospace and Other Applications,* (2007), p. 11-24.

[UNI87] United Nations: *Report of the World Commission on Environment and Development. - General Assembly Resolution 42/187,* 1987.

[UNI98] United Nations Population Division: *World population estimates and projections - Briefing Packet.* New York, Department of Economic and Social AVairs (DESA), 1998.

[VBB02] VOGTLAENDER, J. ; BIJMA, A. ; BREZET, H. C.: Communicating the eco-efficiency of products and services by means of the eco-costs/value model. *In: Journal of Cleaner Production, vol.* 10, (2002), no. 1, p. 57-67.

[WAA04] WESTKAEMPER, E. ; ALTING, L. ; ARNDT, G.: *Life cycle management and assessment: approaches and visions towards sustainable manufacturing,* keynote paper, Proceedings of the Institution of Mechanical Engineers, vol 215, (2004), Part B, p. 599 – 626.

[WAL03] WALLSTROEM, M.: Commission Recommendation. *In: Official Journal of the European Union, vol.* 184, (2003), no. 1, p. 1 -14.

[WIK07a] WIKIMEDIA FOUNDATION, Inc.: *Triple Bottom Line.* URL http://en.wikipedia.org/wiki/Triple_bottom_line (accessed February 2007).

[WIK07b] WIKIMEDIA FOUNDATION, Inc.: *Design for X.* URL http://en.wikipedia.org/wiki/Design_for_X_Methodologies (accessed March 2007).

[WIL95] WILLCOX, M. D.: *The Management of Concept Design Techniques for Optimising Product Whole Life Cycle Cost,* Dissertation, Coventry, Coventry University, School of Engineering, 1995.

[WND01] WESTKAEMPER, E. ; NIEMANN, J. ; DAUENSTEINER, A.: Economic and ecological aspects in product life cycle evaluation. *In: Proceedings of the Institution of Mechanical Engineers - Part B - Engineering Manufacture,* vol. 215, (2001), no. 5, p. 673 – 681.

[WON03] WONG, L. M.: *Achieving optimal product design by integrating design for production methodology and design automation,* Dissertation, Manitoba, The University of Manitoba, 2003.

[ZAC03] ZACKRISSON, M.: Environmental aspects when manufacturing products mainly out of metals and/or polymers. *In: Journal of Cleaner Production,* vol. 13, (2003), no. 1, p. 43 – 49.

Bibliography

[BRO06b] BROADBERRY, S.N.: *Market Services and the Productivity Race, 1850-2000: British Performance in International Perspective.* Cambridge: Cambridge University Press, 2006, ISBN – 0521867185.

[DHI99] DHILLON, B.S.: *Design Reliability.* Boca Raton, FL: First Edition. Aufl. CRC Press, 1999, ISBN - 0-8493-1465-8.

[FOR61] FORRESTER, J.: *Industrial Dynamics.* Cambridge: M.I.T. Press, 1961, ISBN – 0262060035.

[HUA96] HUANG, G.Q.: *Design for X - Concurrent Engineering Imperatives.* London: First. Aufl. Chapman & Hall, 1996, ISBN – 0412787504.

[KAP96] KAPLAN, S.: *An Introduction to TRIZ - The Russian Theory of Inventive Problem Solving.* Ideation International Inc., 1996. ISBN - 1-928747-00-0

[LG01] LEWIS, H. ; GERTSAKIS, J.: *Design + environment.* Sheffield: Greenleaf publishing limited, 2001, ISBN – 1874719438.

[MCA00] MCALOONE, T. C.: *Industrial Application of Environmentally Conscious Design.* Bury St Edmunds: Professional Engineering Publishing, 2000, ISBN - 1 86058 239 7.

[OAK03] OAKLAND, John S.: *TQM: Text with Cases.* Butterworth-Heinemann, 2003, ISBN – 0750657405.

[STA03] STAMATIS, D.H.: *Failure mode and effect analysis - FMEA from theory to execution.* Milwaukee: ASQ Quality Press, 2003, ISBN – 0873895983.

[SW06] SAVITZ, A. W. ; WEBER, C.: *The Triple Bottom Line: How Today's Best-Run Companies Are Achieving Economic, Social and Environmental Success - and How You Can Too.* San Francisco: 1. Aufl. Jossey-Bass, 2006, ISBN - 978-0787979072.

[UE00] ULRICH, K ; EPPINGER, S.: *Product Design and Development.* New York, London: 2. Aufl. McGraw - Hill, 2000, ISBN – 9780070658110.

[UE95] ULRICH, K. ; EPPINGER, S.: *Product Design and Development.* McGraw - Hill, 1995, ISBN – 0071232737.

[WHA97] WENZEL, H. ; HAUSCHILD, M. ; ALTING, L.: *Environmental Assessment of Products - Volume 1 (methodology, tools and case studies in product development).* Chapman and Hall, 1997, ISBN - 0 412 80800 5.

Appendix A: Early Concept Phase

Within the Appendix A the following information will be given:

A.1 – All the Input Information requested from the user at the Early Concept phase by the user interface are listed which are split up into the following categories: General Information, Raw Material Extraction, Manufacturing, Transportation, Use and End-of Life.

A.2 – Here all the equations are provided necessary to calculate the environmental and direct cost impact of a product. This is the cost impact for the Early Concept phase only. The equations to evaluate the environmental and direct cost impact are divided into the following categories: Raw Material Extraction, Manufacturing, Transportation, Use and End-of Life.

A.3 – In this section all the modified databases are given that are linked into the user interface. These databases are consisting of transportation databases, a material database, a carbon trade emission database, EoL costs and revenue databases and a standby losses of appliances database

A.4 – This is the complete Design Suggestion matrix for the Early Concept phase. This can also be broken down into the following categories: Raw Material Extraction, Manufacturing, Transportation, Use and End-of Life.

A.1 Input from the user – ECP

2.1 Input Information - I General Information (all values are averages)

Input	Units	User Data
Production volume	product units / year	A01
Product use frequency A	weeks per year	A02
Product use frequency B	days per week	A03
Product use frequency C	hours per day	A04
Product use frequency result	hours per year	A05
Overall product weight	kg per unit	A06
Average life cycle length	years	A07
Number of materials used	n	A08
Current electrical energy price (domestic)	pence per kWh	A09
Average number of parts	n	A10

2.1 Input Information - II Raw Material Extraction (all values are averages)

If material used in product is not in the list please select next similar one

No.	Material group	Material class	Material name	% (of product weigth) used	% of different material groups
1	Ceramics & Glasses	Glasses	Silica Glass	B01	
2		Technical Ceramics	Alumina	B02	
3	Hybrids	Composites	CFRP (Carbon fibre reinforced composites)	B03	
4		Foams	Flexible Polymer Foam (MD)	B04	
5		Natural	Hard Wood - Oak	B05	
6	Metalls	Ferrous	Cast Iron - ductile	B06	
7			High Carbon Steel	B07	
8			Low Carbon Steel	B08	
9			Stainless Steel	B09	
10		Non-Ferrous	Copper alloys	B10	
11			Aluminium alloys	B11	
12	Polymers and Elastomers	Elastomers	Polyurethane	B12	
13		Thermoplastic	ABS	B13	
14			PC	B14	
15			PE	B15	
16			PP	B16	
17			PS	B17	
18		Thermosets	Phenolics	B18	
19			Polyester	B19	
20	Other Costs from raw material extraction stage	B20	£ per year		

2.1 Input Information - III Manufacturing

No.	Input	Units	User Data
1	CO_2 emissions (caused by processes only, not energy use on site)	t per year	C01
2	Electrical energy used per year	kWh per year	C02
3	Electrical energy price (industrial)	£ per kWh	C03
4	Natural gas use	kWh per year	C04
5	Natural gas price (domestic)	£ per kWh	C05
6	Coal use	t per year	C06
7	Coal price	£ per ton	C07
8	LPG use per year	cubic metres per year	C08
9	LPG price	£ per cubic metre	C09
10	Diesel fuel use per year	cubic metrers per year	C10
11	Diesel price	£ per cubic metre	C11
12	Material 1 inflow (other than raw materials)	kg per year	C12
13	Material 1 price	£ per kg	C13
14	Material 2 inflow (other than raw materials)	kg per year	C14
15	Material 2 price	£ per kg	C15
16	Water use per year	cubic metres per year	C16
17	Water price	£ per cubic metres	C17
18	Amount of water outflow (to effluent)	cubic metres per year	C18
19	Cost of effluent	£ per cubic metres	C19
20	Material 3 outflow (e.g. toxic substances)	litres/ kg per year	C20
21	Material 3 waste treatment costs	£ per litre/ kg	C21
22	Material 3 waste disposal costs	£ per litre/ kg	C22
23	Material 4 outflow (e.g. toxic substances)	litres/ kg per year	C23
24	Material 4 waste treatment costs	£ per litre/ kg	C24
25	Material 4 waste disposal costs	£ per litre/ kg	C25

2.1 Input Information - IV Transportation

No.	Input	Units	User Data
	Incoming Transportation		
1	% of parts being delivered by suppliers	n	D01
2	% of parts delivered by lorry	n	D02
3	% of parts delivered by train	n	D03
4	% of parts delivered by inland ship	n	D04
5	% of parts delivered by sea ship	n	D05
6	% of parts delivered by airplane	n	D06
7	Average distance of transportation by lorry	Short haul (<100km), medium haul (200-500km), long haul (>1000km)	D07
8	Average distance of transportation by train	Short haul (<100km), medium haul (200-500km), long haul (>1000km)	D08
9	Average distance of transportation by inland ship	Short haul (<100km), medium haul (200-500km), long haul (>1000km)	D09
10	Average distance of transportation by sea ship	Short haul (<100km), medium haul (200-500km), long haul (>1000km)	D10
11	Average distance of transportation by airplane	Short haul (<100km), medium haul (200-500km), long haul (>1000km)	D11

2.1 Input Information - IV Transportation

No.	Input	Units	User Data
	Outgoing Transportation		
13	% of parts transported to retailer by lorry	n	D12
14	% of parts transported to retailer by train	n	D13
15	% of parts transported to retailer by inland ship	n	D14
16	% of parts transported to retailer by sea ship	n	D15
17	% of parts transported to retailer by airplane	n	D16
18	Average distance of transportation by lorry	Short haul (<100km), medium haul (200-500km), long haul (>1000km)	D17
19	Average distance of transportation by train	Short haul (<100km), medium haul (200-500km), long haul (>1000km)	D18
20	Average distance of transportation by inland ship	Short haul (<100km), medium haul (200-500km), long haul (>1000km)	D19
21	Average distance of transportation by sea ship	Short haul (<100km), medium haul (200-500km), long haul (>1000km)	D20
22	Average distance of transportation by airplane	Short haul (<100km), medium haul (200-500km), long haul (>1000km)	D21
24	**Packaging**		
25	Average mass of packaging used for product	kg	D22
26	Average cost of packaging (yearly)	£	D23
27	Average Cost of packaging disposal	£	D24
28	% of packaging diposal cost paid for by the manufacturer	n	D25
30	% of packaging diposal cost paid for by the customer	n	D26
31	% of packaging diposal cost paid for by a third party (e.g. government)	n	D27

2.1 Input Information - V Use

No.	Input	Units	User Data
	Inflow		
1	Material 1 inflow (e.g. water)	litres per h	E01
2	Material 1 price	£ per litre	E02
3	Material 2 inflow	litres per h	E03
4	Material 2 price	£ per litre	E04
5	Material 3 inflow	litres per h	E05
6	Material 3 price	£ per litre	E06
7	Natural gas use	kWh per hour	E07
8	Average price paid for natural gas	pence per kWh	E08
9	Coal use	g per h	E09
10	Average price paid for coal	pence per kg	E10
11	LPG use	litres per h	E11
12	Average price paid for LPG	pence per litre	E12
13	Diesel fuel use	litres per h	E13
14	Average price paid for diesel fuel	pence per litre	E14
15	Petrol fuel use	litres per h	E15
16	Average price paid for petrol fuel	pence per litre	E16

2.1 Input Information - V Use

No.	Input	Units	User Data	
	Outflow			
18	Material 4 outflow (e.g. toxic substances)	litres per h	E17	
19	Costs of material 4 outflow treatment	pence per l	E18	
20	Material 5 outflow (e.g. toxic substances)	litres per h	E19	
21	Costs of material 5 outflow treatment	pence per l	E20	
22	Further Eco-taxes that apply as a result of the product use	£ per year	E21	
23				
24	"Active" power output whilst product is switched **on**	Watts	E22	
25	Is it possible to switch product off or does it go to standby	Switch off/ standby	E23	
26	"Passive" power output during standby	Watts	E24	Use Table 3.2
27	**Consumables**			
28	Consumables used	n per day	E25	
29	Cost of consumables	pence per unit	E26	
30	Cost of consumable disposal	pence per unit	E27	

2.1 Input Information - VI End-of Life

No.	Input	Units	User Data	
1	What is the most likely scenario at products EoL	1 = household waste, 2 = industrial waste, 3 = producer take back, 4 = Other	F01	
2	For scenario 1:	Scenario: 1.1 landfill	F02	
3	For scenario 2:	Scenario: 2.1 landfill, 2.2 incineration	F03	
4	For scenario 3	Scenario: 3.1 Joining a take back scheme, 3.2 Setting up a scheme	F04	
5	For scenario 4	Scenario 4.1 landfill, 4.2 incineration, 4.3 biodegradable, 4.4 Recycling	F05	
6				
7	For scenario 3.1: Joining take back scheme			
8	Cost of joining take back scheme (e.g. WEEE)	Yearly	F06	*Example: http://www.weeecare.com: It costs 6£ per ton to join this scheme*
9				
10				
11	For scenario 3.2: Setting up a take back scheme			
12	Number of required take back facilities (in all of europe)	n	F07	
13	Average yearly running cost of take bake facility	£ / year	F08	
14				
15	Average distance from take back facility to Landfill or recycling center	km	F09	
16	Transport by lorry, train or inland ship	lorry, train or inland ship	F10	

2.1 Input Information - VI End-of Life

No.	Input	Units	User Data	
18	Dissassembly of product for further treatment	YES/ NO	F11	
19	If NO: what happens to the product at EoL facility	Landfill, Incineration	F12	
20				
21	If YES:	average cost of recycling center per year	F13	
22				
23		% of parts going to Landfill (by weight)	F14	Check file 3.3 EoL Costs
24		Average Landfill costs per ton		
25		% of parts going to Incineration	F15	
26		Average incinerations costs per ton		Check file 3.3 EoL Costs
27		% of parts going to Biodegrade	F16	
28		Average biodegrade costs per ton		Check file 3.3 EoL Costs
29		% of parts going to Downcycle	F17	Filler, etc.
30		Average downcycle costs per ton		Check file 3.3 EoL Costs
31		% of parts going to Recycle	F18	
32		Average recycle costs per ton		Check file 3.3 EoL Costs
33				
34	Other costs at EoL (e.g. taxes) as a yearly value		F19	
35				
36	Av. Revenue of Take Back Facility (From Material and Parts Sales)	£ / year	F20	

A.2 Direct and environmental impact cost equations – ECP

2.2 Costs related to environmental impact - I		
Raw Material Extraction		
	Related Letter Formula	
	Direct Cost	Environmental Cost
1. Total Cost (Material):	A06 x (B01 - B19) x database 3.1	
m x % mat. X CES mat. price		
	+	
2.1 Energy Cost for mat. Prod.:		
m x % mat. x CES prod. energy x energy costs	A06 x (B01 - B19) x database 3.1 x C03 / 100	
+		+
2.2 Climate Change Levy Costs		
m x % mat. X CES prod. energy x CCL Value		A06 x (B01 - B19) x database 3.1 x L01
+	+	
3. Other Material Cost	B11 / A01	

2.2 Costs related to environmental impact - II		
Manufacturing		
	Related Letter Formula	
1. On Site CO2 Emission Cost	Direct Cost	Environmental Cost
m (CO2 Emissions) / yearly production x Carbon trade value		C01 / A01 x L06
+		
2. Energy Cost for Production & Facility		
amount (kWh) / yearly production x [current energy costs + CCL value]	C02 / A01 x [C03] / 100	C02 / A01 x [L01]
+		
3. Material Inflow Cost		
3.1 Material for energy production *(e.g. LPG, gas, etc.)*		
amount / yearly production x [current mat. Cost + CCL]	{C04,C06,C08 or C10} / A01 x [C05,C07,C09 or C11]	{C04,C06,C08 or C10} / A01 x [L02 - L05]
3.2 Other material *(water, or other)*		
amount / yearly production x current mat. Cost	{C12, C14 or C16} / A01 x {C13, C15 or C17}	
+		
4. Material Outflow Cost		
amount / yearly production x [waste treatment + waste disposal costs]		C18 / A01 x C19
		C20 / A01 x [C21 + C22]

2.2 Costs related to environmental impact - III		
Transportation		
	Related Letter Formula	
1. Incoming Transportation (for each material)	**Direct Cost**	**Environmental Cost**
η x average product weight x average distance x % Category (e.g. Regional) x [cost of transportation per ton per distance + (CO2 emission per ton per distance x CCL value)]	{D01/100} x A06/1000 x (D07 to D11) x (D02 to D06) /100 x [Table 2.5] / 100	{D01/100} x A06/1000 x (D07 to D11) x (D02 to D06) /100 x [Table 2.6] / 100
2. Outgoing Transportation		
% Category (e.g. Regional) x average distance x Product weight x [cost of transportation per ton per distance + CO2 emission per ton per distance x CCL value]	(D12 to D16) / 100 x (D17 to D21) x A06 / 1000 x [Table 2.5] / 100	(D12 to D16) / 100 x (D17 to D21) x A06 / 1000 x [Table 2.6] / 100
3. Packaging Waste		
Outgoing transportation costs x { m (packaging weight) / m (Overall product weight)}	(D12 to D16) x (D17 to D21) x [Table 2.5] / 100 x D22 / 1000	(D12 to D16) x (D17 to D21) x [Table 2.6] / 100 x D22 / 1000
+		
Cost of yearly packaging (yearly) / yearly production	D23 / A01	
+		
Cost of packaging diposal (yearly) / yearly production		D24 / A01
]		

2.2 Costs related to environmental impact - IV		
Use		
	Related Letter Formula	
1.1 Material Inflow	**Direct Cost**	**Environmental Cost**
Mat. 1-3 x [m consumed / hour] x product use frequency x average life cycle length x cost]	(E01, E03 or E05) x A02 x A03 x A04 x A07 x (E02, E04 or E06)	
+		
1.2 Material Outflow		
Mat. 4-5 x product use frequency x average life cycle length x treatment cost		[(E17 x E18/ 100) + (E19 x E20/ 100)] x A02 x A03 x A04 x A07
+		
2.1 Energy Inflow (For coal, gas, LPG, etc.)		
Energy material x [current average energy price + CCL tax value]	[(E07xE08) + (E09xE10) + (E11xE12) + (E13xE14) +(0.3 x E15xE16)] / 100 x A02 x A03 x A04 x A07	(E07xL03) + (E09xL02) + (E11xL04) + (E13xL05) +(0.7 x E15x E16) x A02 x A03 x A04 x A07
+		
2.2 Energy Inflow (For electricity)		
Active [energy amount (kWh/h) x use frequency (h/year) x average life cycle length (years) x [current average energy price + CCL tax value]	E22/1000 x A02 x A03 x A04 x A07 x [A09] / 100	E22/1000 x A02 x A03 x A04 x A07 x [L01]
+		
Stand by or Leakage [((365x24)h - use frequency) x Energy Amount (kWh/h) x average life cycle length (years) x [current average energy price + CCL tax value]	[8760 - (A02 x A03 x A04)] x A07 x E24/1000 x [A09] / 100	[8760 - (A02 x A03 x A04)] x A07 x E24 / 1000 x [L01]
3. Consumables used		
No. used per day x product use frequency x [price of consumables + price of consumable disposal]	E25 x [A03 x A02] x A07x [E26] / 100	E25 x [A03 x A02] x A07 x [E27] / 100
+		
4. Further Eco-taxes that apply (£ per year per product)		E21 x A07

2.2 Costs related to environmental impact - V

End of Life	Related Letter Formula	
	Direct Cost	Environmental Cost
3. Producer take back scenario		
3.1 Joining take back scheme scenario	F06 / A01	
or		
3.2 Setting up a take back scheme		
3.2.1 Cost of running take back facility	F07 x F08 / A01	
3.2.2 Revenue from running a take back facility	[-] F07 x F20 / A01	
[		
3.2.3 Without disassembly:		
+		
Landfill:	(26) x A06/1000	(24) x A06/1000
or		
Incineration	[-] 70 x A06/1000	32.75 x A06 / 1000
}		
or		
{		
3.2.4 With disassembly:		
I. Recycling / Disassembly facility cost	F13 x F07 / A01	
+		
II. Landfill	F14/100 x 26 x A06 / 1000	F14/100 x 24 x A06 / 1000
+		
III. Incineration	F15/100 x [-] 70 x A06 / 1000	F15/100 x 32.75 x A06 / 1000
+		
IV. Biodegrade	F16/100 x 15 x A06 / 1000	
+		
V. Downcycle	F17/100 x [-] 5.5 x A06 / 1000	
+		
VI. Recycle	F18/100 x [-] 46.5 x A06 / 1000	
}		
]		
4. Other Eco Costs		F19 / A01

A.3 Modified databases

A.3.1 Transportation database

2.6B Related costs per km for 100t (in £)

Mode of transport	Short Haul (<100km)	Medium Haul (100 - 500km)	Long Haul (500 - 2000km)	Comment
Lorry	0.0339	0.0355	0.0354	based on average CCL fee for coal of appr. £5 per ton CO2
Train	0.0298	0.0269	0.025	based on average CCL fee for electricity of appr. £10 per ton CO2
Inland Ship	0.0184	0.0178	0.0176	based on average CCL fee for coal of appr. £5 per ton CO2
Sea Ship	0.0072	0.007	0.0071	based on average CCL fee for coal of appr. £5 per ton CO2
Airplane	0.335	0.3315	0.332	based on average CCL fee for coal of appr. £5 per ton CO2

2.3 Energy & Resource Impact of Transportation (per 100 tons of transported material including container)

Mode of Transportation

	Distance (in km)							Comment
	57	107	198	518	940	2105	5000	Litre Diesel equivalent / kWh
based on the following route	Osnabrueck - Muenster	Oldenburg - Osnabrueck	Hannover - Muenster	Muenster - Stuttgart	Cottbus - Basel	Lublin - Nantes		
Lorry	150 / 1470	280 / 2770	520 / 5120	1400 / 14000	2500 / 25000	5600 / 56000		Litre Diesel equivalent / kWh based on a 40 tons, EURO2 lorry
Train	66 / 660	150 / 1500	240 / 2400	700 / 7000	1200 / 11800	2600 / 26000		Litre Diesel equivalent / kWh based on average train, electrified
	52	89	207	519	985	2134		
based on the following route	Bremen - Oldenburg	Hannover - Wolfsburg	Osnabrueck - Oldenburg	Hamburg - Duesseldorf	Regensburg - Osnabrueck	Hamburg - Budapest		
Inland Ship	70 / 725	120 / 1160	270 / 2700	730 / 7160	1170 / 12000	2700 / 27000		Litre diesel equivalent / kWh amount
		91	179	526	1059	2027	4904	
based on the following route		Hamburg - Cuxhaven	Hamburg - Emden	Hamburg - Brugge	Kiel - Calais	Helsinki - Le Havre	Luebeck - Sassari	
Sea Ship		50 / 520	90 / 900	270 / 2740	540 / 5400	1035 / 10500	2500 / 25000	litre diesel equivalent / kWh amount
	64	134	241	512	1043	2011	4950	
based on the following route	Duesseldorf - Koeln	Hamburg - Hannover	Hannover - Duesseldorf	Stuttgart - Amsterdam	Koeln - Oslo	Stockholm - Rom	Hamburg - Amsterdam - Kemi - Paris -Frankfurt	
AirPlane	1623 / 16000	3400 / 34500	6110 / 60500	13000 / 130000	26450 / 265000	51000 / 520000	125500 / 1260000	litre diesel equivalent / kWh amount
Comment:	based on "http://www.ecotransit.org/"							

2.4 CO2 Impact of Transportation (in tons CO2 per 100 tons of transported material)

Mode of Transportation

	Distance (in km)							Comment
	57	107	198	518	940	2105	5000	
based on the following route	Osnabrueck - Muenster	Oldenburg - Osnabrueck	Hannover - Muenster	Muenster - Stuttgart	Cottbus - Basel	Lublin - Nantes		
Lorry	0.4	0.7	1.4	3.7	6.6	15		CO2 amount based on a 40 tons, EURO2 lorry
Train	0.18	0.3	0.49	1.5	2.5	4.9		CO2 amount based on average train, electrified
	52	89	207	538	985	2134		
based on the following route	Bremen - Oldenburg	Hannover - Wolfsburg	Osnabrueck - Oldenburg	Hamburg - Duesseldorf	Regensburg - Osnabrueck	Hamburg - Budapest		
Inland Ship	0.2	0.31	0.72	1.9	3.1	7		
		91	179	526	1059	2027	4904	
based on the following route		Hamburg - Cuxhaven	Hamburg - Emden	Hamburg - Brugge	Kiel - Calais	Helsinki - Le Havre	Luebeck - Sassari	
Sea Ship		0.13	0.25	0.744	1.5	2.9	6.9	
	64	134	241	512	1043	2011	4950	
based on the following route	Duesseldorf - Koeln	Hamburg - Hannover	Hannover - Duesseldorf	Stuttgart - Amsterdam	Koeln - Oslo	Stockholm - Rom	Hamburg - Amsterdam - Kemi - Paris - Frankfurt	
AirPlane	4.2	8.9	16	34	69.3	133.6	329	
Comment:	based on "http://www.ecotransit.org/"							

2.5 Average Energy use per km & related costs (for 100t per km)

Mode of transport	Short Haul (<100km)	(100 - 500km)	Long Haul (500 - 2000km)	Comment
Lorry	2.68	2.64	2.58	litre diesel equivalent based on 40 tons, EURO2 lorry
Train	12.8	12.7	12.5	kWh, based on average train, electrified
Inland Ship	1.35	1.34	1.25	litre diesel equivalent
Sea Ship	0.57	0.51	0.51	litre diesel equivalent
Airplane	255	253.5	252	kWh, based on medium size cargo plane

<u>COMMENT:</u> The values and prices shown are subject to change due to market fluctuations and inflation ration and valid at the following date July 2007

2.5B Related costs per km for 100 tons (in £)

Mode of transport	Short Haul (<100km)	Medium Haul (100 - 500km)	Long Haul (500 - 2000km)	Comment
Lorry	2.41	2.37	2.32	based on average diesel fuel price of **90p**
Train	1.28	1.27	1.25	based on average electricity costs of **10p** (basic cost of electricity production (without grid and supply costs) nuclear 2.3p/kWh, compared with 3.7p/kWh for onshore wind and 5.5p/kWh - #218)
Inland Ship	1.22	1.20	1.12	based on average diesel fuel price of **90p**
Sea Ship	0.51	0.46	0.46	based on average diesel fuel price of **90p**
Airplane	12.00	11.91	11.84	based on average kerosene price of £ 0.047 / kWh (see supplemental)

<u>COMMENT:</u> The values and prices shown are subject to change due to market fluctuations and inflation ration and valid at the following date July 2007

2.6 CO2 output per km (in tons per 100t)

Mode of transport	Short Haul (<100km)	Medium Haul (100 - 500km)	Long Haul (500 - 2000km)	Comment
Lorry	0.00678	0.0071	0.00707	CO2 amount based on a 40 tons, EURO2 lorry
Train	0.00298	0.00269	0.0025	CO2 amount based on an average train, electrified
Inland Ship	0.00367	0.0035	0.00321	
Sea Ship	0.00143	0.00141	0.00142	
Airplane	0.067	0.0663	0.0664	

A.3.2 Representative material database

3.1 Representative material choices

No.	Material group	Material class	Material name	Cost range in £ per kg		Density range in kg/ m3		Embodied Energy in kWh / kg		CO2 footprint in kg/ kg		Recyclable	Downcycle	Energy recovery	Biode gradable	Landfill
				From	To	From	To	From	To	From	To					
1	Ceramics & Glasses	Glasses	Silica Glass	3.6	5.9	2170	2200	8.3	9.2	1.61	1.78	X	X			X
2		Technical Ceramics	Alumina	7	10.6	3800	3980	13.75	15.2	2.67	2.95		X			X
3	Hybrids	Composites	CFRP (Carbon fibre reinforced composites)	11.1	13.1	1500	1600	72	79.4	21.1	23.4		X	X		X
4		Foams	Flexible Polymer Foam (MD)	1.8	1.9	70	115	31.4	34.7	4.78	5.28		X	X		X
5		Natural	Hard Wood - Oak	1.8	2.4	660	800	0.56	1	-1.16	-1.05		X	X	X	X
6	Metalls	Ferrous	Cast Iron - ductile	0.35	0.39	7050	7250	4.6	5.06	0.97	1.07	X	X			X
7			High Carbon Steel	0.29	0.49	7800	7900	6.75	7.47	2.06	2.28	X	X			X
8			Low Carbon Steel	0.25	0.43	7800	7900	6.2	6.9	1.9	2.1	X	X			X
9			Stainless Steel	1.4	1.7	7600	8100	24.4	23.7	4.9	5.4	X	X			X
10		Non-Ferrous	Copper alloys	2	2.4	8930	8940	17.5	19.4	4	4.4	X	X			X
11			Aluminium alloys	0.96	1.17	2500	2900	51	56.4	11.6	12.8	X	X			X
12	Polymers and Elastomers	Elastomers	Polyurethane	2.1	2.5	1020	1250	30.3	33.3	4.47	4.94	X	X	X		X
13		Thermoplastic	ABS	1.4	1.7	1010	1210	25.3	28.3	3.27	3.62	X	X	X		X
14			PC	2.1	2.5	1140	1210	29.2	32.2	3.8	4.2	X	X	X		X
15			PE	0.98	1.08	939	960	21.4	23.6	1.95	2.16	X	X	X		X
16			PP	0.81	0.89	890	910	20.9	23.1	2.07	2.29	X	X	X		X
17			PS	0.84	0.9	1040	1050	26.7	29.4	2.85	3.13	X	X	X		X
18		Thermosets	Phenolics	0.95	1.07	1240	1320	23.9	26.4	2.83	3.12	X	X	X		X
19			Polyester	1.03	1.17	1040	1400	23.3	25.8	2.7	3	X	X	X		X

A.3.3 Carbon trade emission database

3.2 Current Carbon Trade emission prices

Attention: In the following the carbon trade value is based on the current ***Climate Change Levy*** prices and not the Carbon Trade emission prices (as of 18/01/07)

Source	Price *(£ per kWh)*	
Electricity	0.0043 (L01)	
Coal	0.0015 (L02)	
Gas	0.0015 (L03)	
LPG	0.0007 (L04)	
Diesel	0.0015 (L05)	
	Price *(£ per ton)*	
Per ton of CO2 for industry carbon trade emissions	10 (L06)	*Carbon Trade Emission Price as of October 2006 source: (http://www.spiegel.de/wissenschaft/natur/0,1518,475302,00.html)*

A.3.4 End-of Life costs and revenues

3.3 EoL costs and revenues

Attention: In the following the EoL costs are based on values from 01/2007

Landfill	**Price** *(£ per ton)*		
	Cost / Revenue	**Tax**	**Source of information**
	26	24	MRW, www.letsrecycle.com
		+ £3 per year (e.g. £24 in 2008)	
TOTAL	**50**		

Energy Recovery	**Price** *(£ per ton)*		
	Cost / Revenue	**Tax**	**Source of information**
"Incinerating about 2,200 tonnes per day of waste will produce about 50 MW of electrical power."	550 - 650 kWh [per ton of waste) x (£5 per kWh [industrial price] x 0.05 (efficiency factor as a result from grid losses and costs of distribution, etc)		http://en.wikipedia.org/wiki/Waste_incineration & http://www.ciwem.org/policy/factsheets/waste.asp
	-150		
		CO^2 footprint x CCL levy tax	
		0.275 (t CO2 per ton of incinerated waste) x £10 per ton of CO2 (CCL Levy cost)	http://www.naei.org.uk/emissions/kb.php?action=showpost&question_id=28
		2.75	
	Running Cost of Facility + Average Transportation cost (100,000 tonne/year incinerator will produce 7 MW)		http://www.ciwem.org/policy/factsheets/waste.asp
	80		
		Further treatment of hazardous residues	
		30	
TOTAL	**-37.25**		

3.3 EoL costs and revenues

Attention: In the following the EoL costs are based on values from 01/2007

Biodegrade	**Price** *(£ per ton)*		
	Cost / Revenue	**Tax**	**Source of information**
	Fee for green waste disposal (average):		http://www.letsrecycle.com/prices/compostingPrices.jsp
	25		
	compost/mulch sales prices (average)		http://www.letsrecycle.com/prices/compostingPrices.jsp
	-10		
TOTAL	**15**		

Downcycle	**Price** *(£ per ton)*		
	Cost / Revenue	**Tax**	**Source of information**
For ceramics and glasses	(Due to handling cost £10 per ton -£12.5 revenue for mixed glass		http://www.letsrecycle.com/prices/glassPrices.jsp
	-2.5		
For hybrids	(Due to shredding cost £5 per ton -£6 revenue for filler		Case studies
	-1		
For metalls	(Due to shredding cost £5 per ton -£6 revenue as filler		
	-1		
For polymers and elastomers	(Due to shredding cost £5 per ton -£6 revenue as filler		
	-1		
TOTAL	**-1.4**		

3.3 EoL costs and revenues

Attention: In the following the EoL costs are based on values from 01/2007

Recycle	Price *(£ per ton)*		
	Cost / Revenue	Tax	Source of information
For ceramics and glasses	(Due to handling costs £10per ton - £30 revenue from sale		http://www.letsrecycle.com/prices/glassPrices.jsp
	-20		
For hybrids	Recycling not possible		
	--		
For metals	Due to handling costs £20 (incl.seperation shredding and transportation) - £ 66.5 revenue (based on average value for various metals (12/2006))		http://www.letsrecycle.com/prices/metalsPrices.jsp
	-46.5		
For polymers and elastomers	Due to handling costs £20 (incl.seperation shredding and transportation) - £93 revenue (based on average value for various metals (12/2006))		http://www.letsrecycle.com/prices/plasticsPrices.jsp
	-73		
TOTAL	[-] 46.5		

A.3.5 List of standby losses of appliances

Appliance	Standby	Leaking Electricity	
	Power Use	U.S. total	% of total
	(W/unit)	TWh/yr	energy use
Telephony			
Telephone Answering Devices	3.2	1.84	High
Cordless Phones	2.3	1.22	High
Portable Audio			
Portable Stereos (boomboxes)	2.2	1.34	88%
Home Audio			
Compact Audio Systems	9.0	4.02	93%
Rack Audio Systems	4.0	1.83	61%
TV/VCR/Set-top Boxes			
Color TVs	4.2	5.65	21%
Projection TVs	2.0	0.07	6%
VCRs	4.0	3.84	75%
TV/VCR Combinations	9.1	0.52	45%
Cable Boxes	11.0	3.58	83%
Digital Satellite Systems	13.8	0.76	83%
Video Games	2.0	1.07	70%
Personal Care			
Toothbrushes	2.2	0.22	High
Shavers, Men's and Women's	2.5	1.02	High
Hair/Beard Trimmers	0.9	0.06	High
Hand Held Massagers	2.0	0.22	High
Home Care and Maintenance			
Cordless Hand Vacuums	1.7	0.32	High
Home Security and Protection			
Doorbells	2.2	0.70	High
Security Systems	12.0	0.68	33%
Garage Door Openers	6.0	1.41	High
Kitchen			
Microwaves	3.1	2.11	22%

A.4 Design Suggestion matrix – ECP

4.1 Design Suggestion Matrix - I Raw Material Extraction

Raw Material Extraction		
Design suggestion	**Further Instructions**	**Constraint**
1. Material choices :		
1.1 Choose a different material from the same material group	Check key elements: A) Material Price B) Production (embodied) energy required C) CO2 Emissions D) Trade off Issue: weight (density range)	**None**
1.2 Choose a different material from another material group		
1.3 Choose a renewable material source		
2. Mass of the product	Reduce the total mass of the product thus less material is required - Review of structural integrity and product requirements the weight can be reduced	**None**
	Use smart structural product design to enhance product stability/ rigidity by using less material	
3. Take the End-of Life scenario into account when choosing a raw material		**None**
3.1 Check if it is possible to improve EoL scenario	e.g. instead of landfill scenario evaluate Recycling of material/component options (If material can be recycled 3-4 times at end of life the environmental and financial impact is possibly reduced to 50%)	
3.1.2 Check "Embodied Energy" and possibility for energy recovery at EoL		
4. Increase the durability of the product	Increase of "Product Use Frequency" and "Average Life Cycle Length" (2.1)	**If either A07 <= 5 OR (A02xA03xA04) / 8760 <= 0.005**

4.1 Design Suggestion Matrix - II Manufacturing

Manufacturing		
Design suggestion	**Further Instructions**	**Constraint**
4. Application of DfM (Design for manufacture) principles		**None**
4.1 Design of product for easy of manufacturing	Is it possible to reduce the manufacturing steps (Review the product design and identify areas that are not	
	Review the possibility to carry out two manufacturing processes in one step	
	Review the ease of handling of the product during the manufacturing process;	
	Is it possible to reduce number of man hours required to produce one unit	
4.2 Reduce energy to manufacture the product		
4.3 Reduce the time to manufacture the product		
6. Re-use of components	Is it possible to plan for re-use of components from EoL stage being re-introduced at the manufacturing stage	**None**
2. Reduce the energy use on site	Apply an energy reduction scheme on site	**If Either one C02, C04, C06, C08 or C10 > 0**
2.1 Consider use of heating controls to switch of heating in areas where it is not essential		
2.2. Check the efficiency of heating system	Would it make sense to apply a more efficient heating system financially	
2.3 Check the efficiency of lighting system	Consider use high efficient light bulbs that consume less energy and have a longer life cycle	
2.4 Application of automation system	Tighten up processes by the use of an automation system; Is it possible to implement remote sensors to automatically switch of light in areas that are not in use (caution: keep health and safety aspect in mind)	
2.5 Use of waste heat	Is it possible to use waste heat of certain processes for various purposes	

4.1 Design Suggestion Matrix - II Manufacturing

Manufacturing		
Design suggestion	**Further Instructions**	**Constraint**
3. Maximise process efficiency	Reduce incoming material flow and energy flow during manufacturing stage	**If Either C12, C14, C16 > 0**
3.1 Reduce incoming material flow and energy flow during manufacturing stage	(e.g. how can water consumption be reduced?)	
3.2 Choose an incoming material with lower impact	Is it possible to use incoming material that has a lower economical and environmental impact?	
3.3 Reduce waste outflow from processes	Reduce Waste being produced during the manufacturing	
1. Reduce CO2 emissions produced from a process on site not inlcuding energy production	Check if those emission occur at all	**If C01 > 0**
1.1 Change certain machines and process steps	Is it possible to use alternative that does not generate any CO2 emissions	
1.2 Use filter system to reduce CO2 emissions on site	Evaluate suitability of mechanical or chemical filtration system	
5. Application of DfA (Design for assembly) principles		**If A10 > 20 OR A08 > 5**
5.1 Consider ease of assembly during product design		
5.2 Reduce the mix of materials in the components and the product as a whole		
5.3 Reduce the mix of fasteners	Reduction of different types of fasteners used	

4.1 Design Suggestion Matrix - III Transportation

Transportation		
Design suggestion	**Further Instructions**	**Constraint**
1. Transportation		
1.1 Evaluate to produce more parts on site instead of buying in from supplier		**If D01 > 70**
1.2 Review logistics and evaluate a different method of transportation from supplier and to distributors	Weigh delivery time issue against financial and environmental impact	**If D07 + D08 + D09+ D10 +D11 > 5000**
1.3 Set up a supplier network that is highly efficient	Is it possible to choose a supplier that is located closer to the prodcution facility. Reduction of component cost due to reduced trasnportation costs.	

4.1 Design Suggestion Matrix - III Transportation

Transportation		
Design suggestion	**Further Instructions**	**Constraint**
2. Packaging		**If D22 and D23 are > 0**
2.1 Consider the materials and designs you use		
2.2 Examine ways of eliminating or reducing your packaging requirement	Changes in product design, improved cleanliness, better handling, just-in-time delivery, bulk delivery, etc	
	Reduction of volume of packaging: If the product is displayed on a shelf for the final customer then the number of products on the shelf can be increased by a reduction of the packaging volume	
2.3 optimise your packaging use, ie match packaging to the level of protection needed.		
2.4. Increase ease of handling of the packaging (including the product)	It has appropriate handles for manual handling, access points for fork-lift trucks, attachment points for cranes, etc.	
	OR	
	Is of an appropriate shape that allows individual packaging units to be stacked one on top of the other (possibly with interlocks to stabilise the stacks) or to fit inside intermediate containers or racks.	
2.5 Identify main purposes of packaging used	Make product attractive for the customer	
	Protect product against contamination	
	Protect product against damage during transport (e.g. impact)	
2.6 Reduction of weight of packaging	Consider alternative materials which are lighter	
	Reduce amount of packaging material used	
2.7 Reduction of cost of packaging	Consider alternative material that costs less	
	Reduce amount of packaging	
	Make packaging less complex so less machines will be	

4.1 Design Suggestion Matrix - III Transportation

Transportation		
Design suggestion	**Further Instructions**	**Constraint**
2. Packaging		
2.8 Reduce cost of packaging disposal	Consider alternative material that is cheaper to dispose of	**If D24 > 0**
	Reduce amount of packaging that needs to be disposed of	
	Reduce number of materials used for packaging and thus less sorting if packaging is recycled	
2.9 Eliminate the packaging at the source: Product and packaging design	Include packaging design in the product design considerations	
2.10 Set up a Re-use system for the packaging		
2.11 Set up a Recycling scheme for the packaging	Collection system	

4.1 Design Suggestion Matrix - IV Use

Use		
Design suggestion	**Further Instructions**	**Constraint**
1. Application of DfS (Design for servicability, reliability and maintainability) principle	Take measures to increase the time between servicing	**None**
	Avoid or reduce amount of disposals and service consumables	
	Increase ease of access for areas that require servicing	
2. Reduce user impact	Design product for low energy consumption	**None**
	Reduce the risk of improper product use	
3. Reduce material inflow		**If E01 > 0**
3.1 Reduce material inflow during the use phase		
3.2 Choose a different material inflow with a lower financial and environmental impact		
4. Energy Inflow		**If Either one E07, E09, E11, E13, E15, E22 >0**
4.1 Active		
4.1.1 Reduce the active amount of energy required by efficiency increase measures		
4.1.2 Choose a different type of energy source and evaluate financial and environmental impact		
4.1.3 Evaluate if it is possible to reduce the energy consumption of the product during idle process	install automatic switch-off function or similar	
4.1.4 Take the Climate Change Levy into account and investigate impact on customer or product user	www.cclevy.com	

4.1 Design Suggestion Matrix - IV Use

Use		
Design suggestion	**Further Instructions**	**Constraint**
4.2 Passive	***Only if product has a standby function***	If E24 > 0
4.2.1 Is the relation of energy use during standby compared to switched-on status at a sensible level	e.g. it would not be sensible if the product consumes same amount of energy during standby as it does during	
4.2.2 Evaluate how much the user could save by designing out stand by function		
4.2.3 Measure energy use by switching product on and off	Does the product consume a great amount of energy when being switched on? Weigh switch off and on option against standby	
4.2.4 Consider user training (via manual, stickers on product, etc.) to assure that the product is switched off after use		
5. Consumables		If E25 > 0
5.1 Treat consumable as a product	Evaluate the Life Cycle Impact of a consumable by treating it as a regular product	
	Use matrix to find out what the biggest financial and environmental impact of the consumable is and at which (consumable) Life Cycle step it occurs	
	Investigate solutions to reduce the impact of the consumable during its Life Cycle step with the biggest impact	
5.2 What is the purpose of the consumable		
5.3 Can the consumable be designed out?	Is the consumable part of the products main function	
	If yes: Consumable cannot be designed out	
	If no: Is it possible to avoid use of consumable by using smart design	
5.5 Reduce Waste caused by Consumables	Some consumables create waste during their use	
	Re-use of consumable	
	Re-design consumables to avoid waste	

4.1 Design Suggestion Matrix - V End-of Life

End-of Life		
Design suggestion	**Further Instructions**	**Example**
I. For Joining a Take Back Scheme	1. Check if different take back schemes are available on the market and compare prices	
	2. Be aware of the legal background and your responsibilities as a producer if joining a Take Back Scheme	
II. Setting up a Take Back Scheme	1. Check if it is more cost effective to join an exisiting Take Back Scheme if these exists	
	2. Are you legally obliged to guarantee for Product Take Back from the customer	
	3. Be aware of foreign policies and legal ramifications if product is sold abroad also and Take Back Scheme has to be set up there also	
	4. Find Synergies with existing facilities and similar existing products	e.g. if a Take Back Scheme for a similar product group already exists then try to use it whilst setting up a Take Back Scheme
		If the producer of industrial equipment has to set up a Take Back Scheme it might be possible to use/ join in with Recycling Centres already in place
	5. Consider instead of selling the product just leasing/ lending it to the customer thus having more control over all Life Cycle Stages of the Product and thus finding the most cost efficient solution	

4.1 Design Suggestion Matrix - V End-of Life

End-of Life		
Design suggestion	**Further Instructions**	**Example**
III. If Product is not disassembled - Landfill	1. Is it more cost effective to consider a different EoL scenario for the product	
	2. Try to make the product biodegradable so landfill storage time is kept to a minimum	
	3. Identify the reason why the product is currently going to landfill and try to eliminate it	e.g. If a product is impossible to disassemble and thus goes to landfill then apply Design for Disassembly principle
		e.g If the consumer throws product in the regular waste bin then try to educate consumer or set up take back scheme
	4. Evaluate "real" costs from product going to landfill, investigate who is paying those and compare them to alternative EoL scenarios	
	5. Consider Upgradability and Modularization - Is it possible to upgrade product by exchanging certain parts? This would make it obsolete to throw the whole product away	
IV. If Product is not disassembled - Incineration	1. Reevaluate the products material and if they burn efficiently without causing toxicity	e.g. use materials mainly that are high in embodied energy and low in toxicity levels
	2. Use materials that cause a low or no Carbon Footprint over the product Life Cycle	e.g. wood has a negative Carbon Footprint during War Material Extraction (due to the fact that trees use the carbon in the air as building blocks) and thus this can eliminate the Carbon Footprint at EoL thus Incineration
	3. Apply the DfD (Design for disassembly principle) and evaluate if product disassembly is a more cost efficient scenario	
	4. Choose materials that produces more energy when being incinerated (higher embodied energy) or that can be incinerated more efficiently	

4.1 Design Suggestion Matrix - V End-of Life

End-of Life		
Design suggestion	**Further Instructions**	**Example**
V. If Product is disassembled	1. Apply the DfD (Design for disassembly) principle - Re-evaluate ways to dismantle a product quicker and more efficient	
	2. Review Fasteners used and try to use the following fastener types instead where possible: - Snap Fit - Threaded Fasteners	
	3. Apply the DfR (Design for Recycling) principle	Reduce the number of different materials used
		Avoid the use of composite materials
		Replace toxic materials with non-hazardous alternatives
		Reduce complexity of the product
		Promote infrastructures geared towards recycling
	4. Set up a framework so re-used parts and components can easily fed back into the spare part and used components market	

Appendix B: Advanced Concept Phase

Within the Appendix B the following information will be given:

B.1 – All the Input Information requested from the user at the Advanced Concept phase by the user interface are listed in the form of Excel Sheets. In the first three screenshots 35 different general input information parameters are displayed for a maximum number of six components. Screenshot four shows input information required regarding the fastener types used.

B.2 – Another input information type requested by the user interface is displayed in this screenshot. It collects all the information necessary to conduct a component necessity analysis for each of the six components.

B.3 – Here the whole TRIZ matrix integrated in the user interface including amendments is displayed. It was split into four different screenshots to provide a clearly readable format of the details.

B.4 – This section provides all the inventive principles used within the methodology and user interface. This covers the 40 original inventive principles and the 6 new principles developed during the course of this research.

B.5 – It provides a list with all the 30 component functions that the user can choose for the primary function of a component and secondary function also. Furthermore an Example is and the improving and worsening factors chosen from the TRIZ matrix in order to devise inventive principles for each of the functions.

B.6 – In the first two screenshots (8.3-A) the inventive principles generated by the modified TRIZ matrix for each of the component functions is shown. The next two screenshots show the inventive principle actually chosen for the methodology and user interface (black colour) and the ones rejected as unsuitable (grey colour).

B.7 – The screenshots of Excel sheets here show the list if the 46 inventive principles including further details on how to apply them to a product design as well as an example.

B.8 - Here all the equations are provided necessary to calculate the environmental and direct cost impact of a product. This is the cost impact for the Advanced Concept phase only. Similar to how this is conducted at the Early Concept Phase, the equations to evaluate the environmental and direct cost impact are divided into the following categories: Raw Material Extraction, Manufacturing, Transportation, Use and End-of Life. In the screenshots the equations are shown for component 1 only.

B.9 – This shows the suitability ranking of connection that was developed to rate the fasteners user and their suitability for the different life cycle stages.

B.10 – The various Excel sheets show all design suggestions that can be produced by the methodology in order to improve the component with the biggest impact.

B.1 Input from the user – ACP

7.1 Component Input Information

No.	Input	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6	Unit
(G)1	Name of component	N101	N201	N301	N401	N501	N601	n
(G)2	Internal component code	N102	N202	N302	N402	N502	N602	n
(G)3	Primary function of component	N103	N203	N303	N403	N503	N603	*(Choose from catalogue)*
(G)4	Secondary function 1 of component	N104	N204	N304	N404	N504	N604	*(Choose from catalogue)*
(G)5	Secondary function 2 of component	N105	N205	N305	N405	N505	N605	*(Choose from catalogue)*
(G)8	Total number of parts (est.) used for the component (from lowest hierarchy level)	N108	N208	N308	N408	N508	N608	n
(G)9	Number of materials (est.) used for the component (from lowest hierarchy level)	N109	N209	N309	N409	N509	N609	n
(G)10	Rate Re-use potential of component at EoL (10 [high] - 1 [not re-usable])	N110	N210	N310	N410	N510	N610	n
(G)11	Toxicity potential of component (10 [high risk of toxicity] - 1 [no risk of toxicity)	N111	N211	N311	N411	N511	N611	n
(G)12	EoL scenario of component	N112	N212	N312	N412	N512	N612	(Re-Use, recycling, incineration, landfill, hazardous waste landfill
(G)13	Main material of the component	N113	N213	N313	N413	N513	N613	catalogue
(G)14	Weight of component (est.)	N114	N214	N314	N414	N514	N614	kg

7.1 Component Input Information

No.	Input	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6	Unit
(G)16	%participation main material to total component weight	N116	N216	N316	N416	N516	N616	Yes/ No
(G)17	Is component manufactured on site	N117	N217	N317	N417	N517	N617	Yes/ No
(G)18	Additional raw material cost for component	N118	N218	N318	N418	N518	N618	£
(G)19	Does the component require packaging when delivered to assembly	N119	N219	N319	N419	N519	N619	Yes/ No
(G)20	Average weight of that incoming packaging per component	N120	N220	N320	N420	N520	N620	kg
(G) 21	Average cost of incoming component packaging (yearly)	N121	N221	N321	N421	N521	N621	£ / year
(G) 22	Average disposal cost of that incoming component packaging (yearly)	N122	N222	N322	N422	N522	N622	£ / year
(G) 23	Average cost of component if it is provided by the supplier	N123	N223	N323	N423	N523	N623	£
(G) 24	Does component rely on material inflow to function	N124	N224	N324	N424	N524	N624	Yes/ No
(G) 25	Does component create a material outflow	N125	N225	N325	N425	N525	N625	Yes/ No
(G) 26	Does component rely on energy inflow (such as LPG, etc.) to function	N126	N226	N326	N426	N526	N626	Yes/ No
(G) 27	Does component rely on electric energy inflow to function	N127	N227	N327	N427	N527	N627	Yes/ No
(G) 28	Number of components that require consumables to function	N128	N228	N328	N428	N528	N628	Yes/ No

7.1 Component Input Information

No.	Input	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6	Unit
(G) 29	Worst case EoL treatment costs (due to toxicity etc.)	N129	N229	N329	N429	N529	N629	£
(G) 30	Component treatment cost at EoL before it can be re-used	N130	N230	N330	N430	N530	N630	£ per component
(G) 31	Dismantling cost for the component	N131	N231	N331	N431	N531	N631	£ per component
(G) 32	Does the component move with respect to all the components already assembled	N132	N232	N332	N432	N532	N632	Yes/ No
(G) 33	Does the part has to be made of a different material with respect to all the other parts already assembled	N133	N233	N333	N433	N533	N633	Yes/ No
(G) 34	Is the part separate from all the other parts already assembled because necessary assembly or disassembly would otherwise be impossible	N134	N234	N334	N434	N534	N634	Yes/ No
(G) 35								
(G) 36	Importance Factor 1	N199	N299	N399	N499	N599	N699	[(N114 / A06) / 3] + [(N109 / A09) / 6] + [(N108 / A10) / 2] = N199

7.1 Input information - fasteners used (only between components)

Component	Connected to the following components	Connection method used	%
1	*e.g. 3,5,7*	Adhesives	*P01*
		Rivets or Staples	*P02*
		Snap Fit	*P03*
		Threaded Fasteners	*P04*
		Welding	*P05*
2		Adhesives	*P11*
		Rivets or Staples	*P12*
		Snap Fit	*P13*
		Threaded Fasteners	*P14*
		Welding	*P15*
3		Adhesives	*P21*
		Rivets or Staples	*P22*
		Snap Fit	*P23*
		Threaded Fasteners	*P24*
		Welding	*P25*
4		Adhesives	*P31*
		Rivets or Staples	*P32*
		Snap Fit	*P33*
		Threaded Fasteners	*P34*
		Welding	*P35*
5		Adhesives	*P41*
		Rivets or Staples	*P42*
		Snap Fit	*P43*
		Threaded Fasteners	*P44*
		Welding	*P45*
6		Adhesives	*P51*
		Rivets or Staples	*P52*
		Snap Fit	*P53*
		Threaded Fasteners	*P54*
		Welding	*P55*

B.2 Component Design Efficiency Analysis

7.2.1 Input - Component design efficiency analysis

Input	Unit	User Data
Component 1		
1.1 Does the component has a main function or secondary function?	Yes / No	R11
1.2 DFMA elimination criteria analysis		
1.2.1 The component moves with respect to all the parts already assembled	Yes / No	R12
1.2.2 The part has to be made of a different material with respect to all the other parts already assembled	Yes / No	R13
1.2.3 The part is separate from all the other parts already assembled because necessary assembly or disassembly would otherwise be impossible	Yes / No	R14

B.3 TRIZ matrix including amendments

	Worsening Feature / Improving Feature	Weight of moving object	Weight of stationary object	Length of moving object	Length of stationary object	Area of moving object	Area of stationary object	Volume of moving object	Volume of stationary object	Speed	Force (Intensity)	Stress or pressure	Shape	Stability of the object's composition	Strength	Duration of action of moving object	Duration of action of stationary object	Temperature	Illumination intensity	Use of energy by moving object	Use of energy by stationary object	Power	Loss of Energy	Loss of Substance
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	Weight of moving object	+	-	15, 8, 29,34	-	29, 17, 38, 34	-	29, 2, 40, 28	-	2, 8, 15, 38	8, 10, 18, 37	10, 36, 37, 40	10, 14, 35, 40	1, 35, 19, 39	28, 27, 18, 40	5, 34, 31, 35	-	6, 29, 45, 46	19, 1, 32	35, 12, 34, 31	-	12, 36, 18, 31	6, 2, 34, 19	5, 35, 3, 31
2	Weight of stationary object	-	+	-	10, 1, 29, 35	-	35, 30, 13, 2	-	5, 35, 14, 2	-	8, 10, 19, 35	13, 29, 10, 18	13, 10, 29, 14	26, 39, 1, 40	28, 2, 10, 27	-	2, 27, 19, 6	28, 19, 32, 22	19, 32, 35	-	18, 19, 28, 1	15, 19, 18, 22	18, 19, 28, 15	5, 8, 13, 30
3	Length of moving object	8, 15, 29, 34	-	+	-	15, 17, 4	-	7, 17, 4, 35	-	13, 4, 8	17, 10, 41, 44	41, 44, 1, 8	1, 8, 10, 29	1, 8, 15, 34	8, 35, 29, 34	19	-	10, 15, 41, 44	32	8, 35, 24	-	41, 44, 1, 35	7, 2, 35, 39	4, 29, 23, 10
4	Length of stationary object		35, 28, 40, 29	-	+	-	17, 7, 10, 40	-	35, 8, 2,14	-	44, 28, 10	1, 14, 44, 35	13, 14, 15, 7	39, 37, 35	15, 14, 28, 26	-	1, 10, 35	3, 35, 38, 18	3, 25	-		44, 12, 8	6, 28	10, 28, 24, 35
5	Area of moving object	2, 17, 29, 4	-	14, 15, 18, 4	-	+	-	7, 14, 17, 4		29, 30, 4, 34	19, 30, 35, 2	10, 15, 36, 28	5, 34, 29, 4	11, 2, 13, 39	3, 15, 40, 14	6, 3	-	2, 15, 41, 45	15, 32, 19, 13	45, 46, 19, 32	-	19, 10, 32, 18	15, 17, 30, 26	10, 35, 2, 39
6	Area of stationary object	-	30, 2, 14, 18	-	26, 7, 9, 39	-	+	-		-	1, 18, 35, 36	10, 15, 36, 37		2, 38	40	-	2, 10, 19, 30	35, 39, 44, 38		-		17, 32, 44	17, 7, 30	10, 14, 18, 39
7	Volume of moving object	2, 26, 29, 40	-	1, 7, 4, 35	-	1, 7, 4, 17	-	+	-	29, 4, 38, 34	15, 35, 36, 37	6, 35, 36, 37	1, 15, 29, 4	28, 10, 1, 39	9, 14, 15, 7	6, 35, 4	-	34, 39, 10, 18	2, 13, 10	35	-	35, 6, 13, 18	7, 15, 13, 16	36, 39, 34, 10
8	Volume of stationary object	-	35, 10, 19, 14	19, 14	35, 8, 2, 14	-		-	+	-	2, 18, 44, 37	44, 24, 35	7, 2, 35	34, 28, 35, 40	9, 14, 17, 15	-	35, 34, 38	44, 35, 6, 4		-		44, 30, 6		10, 39, 35, 34
9	Speed	2, 28, 13, 38	-	13, 14, 43, 8	-	29, 30, 34	-	7, 29, 34	-	+	13, 28, 44, 15	6, 18, 44, 38	35, 15, 18, 34	28, 33, 1, 18	8, 3, 26, 14	3, 19, 35, 5	-	28, 30, 45, 44	10, 13, 19	8, 15, 45, 46	-	19, 35, 38, 44	14, 20, 19, 35	10, 13, 28, 38
10	Force (Intensity)	8, 1, 37, 18	18, 13, 1, 28	17, 19, 9, 36	43, 28, 10	19, 10, 15	1, 18, 36, 37	15, 9, 12, 37	2, 36, 18, 37	13, 28, 15, 12	+	18, 21, 41, 44	10, 35, 40, 34	35, 10, 41, 43	35, 10, 14, 27	19, 2		35, 10, 41, 44	-	19, 17, 10	1, 16, 36, 37	19, 35, 18, 37	14, 15	8, 35, 40, 5
11	Stress or pressure	10, 36, 37, 40	13, 29, 10, 18	35, 10, 36	35, 1, 14, 16	10, 15, 36, 28	10, 15, 36, 37	6, 35, 10	35, 24	6, 35, 36	36, 35, 41, 45	+	35, 4, 15, 10	35, 33, 2, 40	9, 18, 3, 40	19, 3, 27		35, 39, 45, 19	-	14, 24, 10, 37	45	10, 35, 41, 14	2, 36, 45, 25	10, 36, 3, 37
12	Shape	8, 10, 29, 40	15, 10, 26, 3	29, 34, 5, 4	13, 14, 10, 7	5, 34, 4, 10		14, 4, 15, 22	7, 2, 35	35, 15, 34, 18	35, 10, 37, 40	34, 15, 10, 14	+	33, 1, 18, 4	30, 14, 46, 10	14, 26, 9, 25		22, 14, 45, 46	13, 15, 32	46, 2, 6, 34	45, 46	41, 4, 6, 2	45, 14	35, 29, 3, 5
13	Stability of the object's composition	21, 35, 45, 2	26, 39, 1, 40	13, 15, 1, 28	37, 43	2, 11, 13	39	28, 10, 19, 39	34, 28, 35, 40	33, 15, 28, 18	10, 35, 21, 45	2, 35, 45, 40	22, 1, 18, 4	+	17, 9, 43, 42	13, 27, 10, 35	39, 3, 35, 23	35, 1, 45, 32	32, 3, 27, 16	45, 13, 19	45, 27, 4, 29	32, 35, 27, 31	45, 14, 2, 39	2, 14, 30, 40
14	Strength	1, 8, 40, 15	40, 26, 27, 1	1, 15, 8, 35	15, 14, 28, 26	3, 34, 40, 29	9, 40, 28	10, 15, 14, 7	9, 14, 17, 15	8, 13, 26, 14	10, 18, 3, 14	10, 3, 18, 40	10, 30, 35, 40	13, 17, 41, 42	+	27, 3, 26		30, 10, 41, 40	35, 19	19, 35, 10	35	10, 26, 35, 28	42, 35	35, 28, 31, 40
15	Duration of action of moving object	19, 5, 34, 31	-	2, 19, 9	-	3, 17, 19	-	10, 2, 19, 30	-	3, 35, 5	19, 2, 41, 16	19, 3, 41, 27	14, 26, 28, 25	13, 3, 41, 35	27, 3, 41, 10	+	-	19, 35, 41, 39	2, 19, 4, 35	28, 6, 35, 18		19, 10, 35, 38		28, 27, 3, 18
16	Duration of action by stationary object	-	6, 27, 19, 16	-	1, 40, 35	-		-	35, 34, 38	-				39, 3, 35, 23		-	+	19, 18, 36, 40		-		16		27, 16, 18, 38
17	Temperature	36,22, 6, 38	22, 35, 32	15, 19, 9	15, 19, 9	3, 35, 39, 18	35, 38	34, 39, 40, 18	35, 6, 4	2, 28, 36, 30	35, 10, 3, 21	35, 39, 19, 2	14, 22, 19, 32	1, 35, 32	10, 30, 22, 40	19, 13, 39	19, 18, 36, 40	+	32, 30, 21, 16	19, 15, 3, 17	45	2, 14, 17, 25	21, 17, 35, 38	21, 36, 29, 31
18	Illumination intensity	19, 1, 32	2, 35, 32	19, 32, 16		19, 32, 26		2, 13, 10		10, 13, 19	26, 19, 6		46, 32, 30	32, 3, 27	46, 35, 19	2, 19, 6		32, 35, 46, 19	+	32, 1, 46, 19	32, 35, 46, 1	32	13, 16, 1, 6	13, 1
19	Use of energy by moving object	12,18, 28,31	-	12, 28	-	15, 19, 25	-	35, 13, 18	-	8, 35, 35	16, 26, 21, 2	23, 14, 41, 44	12, 2, 29	19, 13, 17, 24	5, 19, 9, 35	28, 35, 6, 18	-	19, 24, 3, 14	2, 15, 19	+	-	6, 19, 37, 18	12, 22, 15, 24	35, 24, 18, 5
20	Use of energy by stationary object	-	19, 9, 6, 27	-	43	-		-		-	44, 36, 37	44	43	27, 4, 29, 18	42, 35, 43			44	19, 2, 35, 32	-	+	44		28, 27, 18, 31
21	Power	8, 36, 38, 31	19, 26, 17, 27	1, 10, 35, 37	43	19, 38	17, 32, 13, 38	35, 6, 38	30, 6, 25	15, 35, 2	26, 2, 36, 35	22, 10, 41, 35	29, 14, 2, 40	35, 32, 15, 31	26, 10, 41, 28	19, 35, 10, 38	16	2, 14, 17, 25	16, 6, 19	16, 6, 19, 37		+	10, 35, 38	28, 27, 18, 38
22	Loss of Energy	15, 6, 19, 28	19, 6, 18, 9	7, 2, 6, 13	6, 38, 7, 43	15, 26, 17, 30	17, 7, 30, 18	7, 18, 23	7	16, 35, 38	41, 36, 38	41	43	14, 2, 39, 6	26, 41, 43			19, 38, 41, 7	1, 13, 32, 15			41, 3, 38	+	35, 27, 2, 37
23	Loss of substance	35, 6, 23, 40	35, 6, 22, 32	14, 29, 10, 39	43, 10, 28,24	35, 2, 10, 31	10, 18, 39, 31	1, 29, 30, 36	3, 39, 18, 31	10, 13, 28, 38	14, 15, 18, 40	3, 36, 37, 10	29, 35, 3, 5	2, 14, 30, 40	35, 28, 31, 40	28, 27, 3, 18	27, 16, 18, 38	21, 36, 39, 31	1, 6, 13	35, 18, 24, 5	28, 27, 12, 31	28, 27, 18, 38	35, 27, 2, 31	+

Loss of Substance	Loss of Information	Loss of Time	Quantity of substance	Reliability	Measurement accuracy	Manufacturing precision	Object-affected harmful factors	Object-generated harmful factors	Ease of manufacture	Ease of operation	Ease of repair	Adaptability or versatility	Device complexity	Difficulty of detecting and measuring	Extent of automation	Productivity	Use of substance by moving object	Use of substance by stationary object	Ease of transportation	Frequency	Ease of re-use and recyling	Efficiency		Worsening Feature → Improving Feature ↓
23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45		
5, 35, 3, 31	10, 24, 35	10, 35, 20, 28	3, 26, 18, 31	1, 3, 11, 27	28, 27, 35, 26	28, 35, 26, 18	22, 21, 18, 27	22, 35, 31, 39	27, 28, 1, 36	35, 3, 2, 24	2, 27, 28, 11	29, 5, 15, 8	26, 30, 36, 34	28, 29, 26, 32	26, 35 18, 19	35, 3, 24, 37	42, 35, 34, 12	42	29, 41, 42, 46	44, 8, 18, 41	1, 42, 44, 46,	45, 2, 8, 43	1	Weight of moving object
5, 8, 13, 30	10, 15, 35	10, 20, 35, 26	19, 6, 18, 26	10, 28, 8, 3	18, 26, 28	10, 1, 35, 17	2, 19, 22, 37	35, 22, 1, 39	28, 1, 9	6, 13, 1, 32	2, 27, 28, 11	19, 15, 29	1, 10, 26, 39	25, 28, 17, 15	2, 26, 35	1, 28, 15, 35	42	42, 18, 35, 19	37, 45, 43, 42	44, 8, 19, 45	44, 30, 46, 1	5, 15	2	Weight of stationary object
4, 29, 23, 10	1, 24	15, 2, 29	44, 29, 35	10, 14, 29, 40	28, 32, 4	10, 28, 29, 37	1, 15, 17, 24	41, 44, 17, 15	1, 29, 17	15, 29, 35, 4	41, 1, 28, 10	14, 15, 1, 16	1, 19, 26, 24	35, 1, 26, 24	17, 24, 26, 16	14, 4, 28, 29	8, 35, 15	—	1, 41, 46, 4	44, 1, 46	44, 1, 5	1, 5, 7, 43	3	Length of moving object
10, 28, 24, 35	24, 26,	30, 29, 14	44	15, 29, 44, 28	32, 28, 3	2, 32, 10	1, 18	44	15, 17, 27	2, 25, 44	3	1, 35	1, 26	26		30, 14, 7, 26	1, 7	4, 17	1, 5, 7, 14	44, 35, 17, 43	7, 44, 1	43, 41, 1	4	Length of stationary object
10, 35, 2, 39	30, 26	26, 4	29, 30, 6, 13	41, 29, 44, 45	26, 28, 32, 3	41, 45, 2, 32	22, 33, 28, 1	17, 2, 18, 39	13, 1, 26, 24	15, 17, 13, 16	15, 13, 10, 1	15, 30	14, 1, 45, 13	2, 36, 26, 18	14, 30, 28, 23	10, 26, 34, 2	45, 46, 19	—	17, 41, 46, 14	44, 7, 4, 5	44, 46, 4	45, 14	5	Area of moving object
10, 14, 18, 39	30, 16	10, 35, 4, 18	2, 18, 40, 4	32, 35, 40, 4	26, 28, 32, 3	2, 29, 18, 36	27, 2, 39, 35	22, 1, 44, 40	40, 16	44, 16, 4	16	15, 16	1, 18, 36	2, 35, 30, 18	23	10, 15, 17, 7	—	14	4, 5	44, 4	44, 14, 30	46, 4	6	Area of stationary object
36, 39, 34, 10	2, 22	2, 6, 34, 10	29, 30, 44, 7	14, 1, 40, 11	25, 26, 28	25, 28, 2, 16	22, 21, 27, 35	17, 2, 40, 1	29, 1, 40	15, 13, 30, 12	41, 10	15, 29	26, 1	29, 26, 4	35, 34, 16, 24	10, 6, 2, 34	35	—	41, 4, 8, 45	13, 44, 7, 37	44, 7, 14, 17	77	7	Volume of moving object
10, 39, 35, 34		35, 16, 32 18	44, 35, 3	2, 35, 44, 16		35, 10, 25	34, 39, 19, 27	30, 18, 35, 4	35	44	1		1, 31	2, 17, 26		35, 37, 10, 2	—	4, 14, 17	46, 22, 37, 35	35, 33, 18, 44	14, 44, 35	7, 43, 41	8	Volume of stationary object
10, 13, 28, 38	13, 26		10, 19, 29, 44	11, 35, 45, 44	28, 32, 1, 24	10, 28, 32, 25	1, 28, 35, 23	2, 24, 35, 44	35, 13, 8, 1	32, 28, 13, 44	34, 2, 28, 27	15, 10, 26	10, 28, 4, 45	3, 34, 27, 16	10, 18, 45		43, 15, 45	—	11, 17, 41, 43	43, 44, 8, 19	44, 33, 44, 22	15, 5, 12, 22	9	Speed
8, 35, 40, 5		10, 37, 36	14, 29, 18, 36	3, 35, 13, 21	35, 10, 23, 24	28, 29, 41, 45	1, 35, 40, 18	13, 3, 36, 24	15, 37, 18, 1	1, 28, 3, 25	15, 1, 41, 11	15, 17, 18, 20	26, 35, 10, 18	36, 37, 10, 19	41, 2, 35	3, 28, 35, 37	43, 19, 10	1, 16, 45, 46	41, 43, 46	43, 44, 19, 18	44, 46, 2, 1	41, 43, 44, 6	10	Force (Intensity)
10, 36, 3, 37		37, 36, 4	10, 14, 36	10, 13, 19, 35	6, 28, 25	41, 45, 3, 35	22, 2, 37	2, 33, 27, 18	1, 35, 16	41, 11	41, 2	35	19, 1, 45, 35	2, 36, 37	41, 35, 24	10, 14, 35, 37	24, 45, 44	45, 46, 36	41, 11, 45, 46	8, 15, 30, 44	7, 30, 33	45, 1, 45, 43	11	Stress or pressure
35, 29, 3, 5		14, 10, 34, 17	36, 22	10, 40, 41, 45	28, 32, 1	32, 30, 41, 45	22, 1, 2, 35	35, 1, 41	1, 32, 17, 28	32, 15, 41, 43	41, 2, 13, 1	1, 15, 29	16, 29, 1, 28	15, 13, 39	15, 1, 41, 32	17, 26, 34, 10	43, 14, 6, 2	14, 45, 1	41, 43, 46	43, 4, 5	46, 7, 4, 14	45, 4, 44, 5	12	Shape
2, 14, 30, 40		35, 27	15, 32, 35, 42		13	45, 18	35, 24, 30, 18	35, 40, 27, 39	35, 19	32, 35, 43, 30	2, 35, 10, 16	35, 30, 34, 2	45, 2, 35, 22	35, 22, 39, 23	1, 8, 35	23, 35, 40, 3	42, 43	42, 27, 29	21, 14, 42, 43	43	1, 33, 22, 44	45, 7, 22, 11	13	Stability of the object's composition
35, 28, 31, 40		29, 3, 28, 10	29, 10, 42, 27	41, 11, 3	3, 27, 16	3, 27	18, 35, 37, 1	15, 35, 22, 2	11, 3, 10, 32	32, 40, 25, 2	27, 11, 41, 3	15, 3, 32	2, 13, 25, 28	27, 3, 15, 40	41, 15	29, 35, 10, 14	42, 43	42, 35	41, 22, 42, 43	43, 22, 29, 46	43, 44, 5, 1	46, 41, 1, 2	14	Strength
28, 27, 3, 18	10	20, 10, 28, 18	3, 35, 10, 40	11, 2, 41, 13	3	3, 27, 16, 40	22, 15, 33, 28	21, 39, 16, 22	27, 1, 4	41, 12, 27	29, 10, 41, 27	1, 35, 13	10, 4, 29, 15	19, 29, 39, 35	41, 6, 10	35, 17, 14, 19	46, 45, 41, 10	—	21, 26, 39, 41	19, 9, 10, 15	21, 19, 20,	41, 6, 25, 44	15	Duration of action of moving object
27, 16, 18, 38	10	28, 20, 10, 16	3, 35, 31	34, 27, 6, 40	10, 26, 24		17, 1, 40, 33	22	35, 10	1	1	2		25, 34, 6, 35	1	20, 10, 16, 38	—	7, 10, 19	10, 12, 20		18, 46	43, 44	16	Duration of action by stationary object
21, 36, 29, 31		35, 28, 21, 18	3, 17, 30, 39	19, 35, 3, 10	32, 19, 24	45, 24	22, 33, 35, 2	22, 35, 2, 24	26, 27	44, 26, 27	4, 10, 16	2, 18, 27	2, 17, 45, 16	3, 27, 35, 31	26, 2, 19, 16	15, 28, 35	19, 15, 42, 43	7, 10, 19, 35	22, 34, 37, 40	37, 44, 21, 22	44, 45, 43, 40	45, 21, 19	17	Temperature
13, 1	1, 6	19, 1, 26, 17	1, 19	46	11, 15, 32	3, 32	15, 19	35, 19, 32, 39	19, 35, 28, 26	28, 26, 19	15, 17, 13, 16	15, 1, 19	6, 32, 13	32, 15	2, 26, 10	2, 25, 16	43, 44, 46, 32	45, 43, 22, 32	46, 7, 19	32, 19, 41, 45	46	39, 32, 41, 45	18	Illumination intensity
35, 24, 18, 5		35, 38, 19, 18	34, 23, 16, 18	19, 21, 11, 27	3, 1, 32	41	1, 35, 6, 27	41, 44, 2, 35	28, 26, 30	41, 44, 19, 35	1, 15, 17, 28	15, 17, 13, 16	2, 29, 27, 28	35, 38	41, 32, 2	12, 28, 35	—	—	41, 46, 45	19, 18, 44, 13	44	43, 5, 6, 2	19	Use of energy by moving object
28, 27, 18, 31			3, 35, 42, 44	10, 36, 23, 44			10, 2, 22, 37	19, 22, 42, 44	1, 4	43, 44			43	19, 35, 16, 25		1, 6	42, 43	42	42, 43, 46, 45	43, 44	44		20	Use of energy by stationary object
28, 27, 18, 38	10, 19	35, 20, 10, 6	4, 34, 19	19, 24, 26, 31	32, 15, 2	41, 32, 2	19, 22, 31, 2	2, 35, 41, 18	26, 10, 34	26, 35, 41, 43	35, 2, 10, 34	19, 17, 34	20, 19, 30, 34	19, 35, 16	28, 2, 41, 17	28, 35, 34	43, 16, 6	—	7, 45, 41, 43	18, 8, 15, 43	10, 9, 12	10, 15, 17, 22	21	Power
35, 27, 2, 37	19, 10	10, 18, 32, 7	7, 18, 25	11, 10, 41, 35	32	41	21, 22, 35, 2	21, 35, 2, 22		35, 32, 41, 43	2, 19		43, 7, 23	35, 3, 15, 23	41, 2	28, 10, 29, 35	43	28, 27, 12, 31	45, 35, 41, 43	22, 44, 19	1, 30	29, 28, 38	22	Loss of Energy
+		15, 18, 35, 10	6, 3, 10, 24	10, 29, 39, 35	16, 34, 31, 28	35, 10, 24, 31	33, 22, 30, 40	10, 1, 34, 29	15, 34, 33	32, 28, 2, 24	2, 35, 34, 27	15, 10, 2	35, 10, 28, 24	35, 18, 10, 13	35, 10, 41, 18	28, 35, 10, 23	42, 43, 35, 18	42	41, 42, 43	30, 43, 2, 7	33, 30, 31, 46	31, 36, 39, 42	23	Loss of substance

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
24	**Loss of Information**	10, 24, 35	10, 35, 5	1, 26	26	30, 26	30, 16		2, 22	26, 32						10	10		19			10, 19	19, 10	
25	**Loss of Time**	10, 20, 37, 35	10, 20, 26, 5	15, 2, 29	30, 24, 14, 5	26, 4, 5, 16	10, 35, 17, 4	2, 5, 34, 10	35, 16, 32, 18		10, 37, 36,5	37, 36,4	4, 10, 34, 17	35, 3, 22, 5	29, 3, 28, 18	20, 10, 28, 18	28, 20, 10, 16	35, 29, 21, 18	1, 19, 26, 17	35, 38, 19, 18	1	35, 20, 10, 6	10, 5, 18, 32	35, 18, 10, 39
26	**Quantity of substance/the matter**	35, 6, 18, 31	27, 26, 18, 35	29, 14, 35, 18		15, 14, 29	2, 18, 40, 4	15, 20, 29		35, 29, 34, 28	35, 14, 44	10, 36, 44, 14	35, 14	15, 2, 17, 40	14, 35, 34, 10	3, 35, 10, 40	3, 35, 31	3, 17, 44		34, 29, 16, 18	3, 35, 42, 31	44, 35	7, 18, 25	6, 3, 10, 24
27	**Reliability**	3, 8, 10, 40	3, 10, 8, 28	15, 9, 14, 4	15, 29, 28, 11	17, 10, 14, 16	32, 35, 40, 4	3, 10, 14, 24	2, 35, 24	21, 35, 11, 28	8, 28, 10, 3	10, 24, 35, 19	35, 1, 16, 11		11, 28	2, 35, 3, 25	34, 27, 6, 40	3, 35, 10	11, 32, 13	21, 11, 27, 19	36, 23	21, 11, 26, 31	10, 11, 35	10, 35, 29, 39
28	**Measurement accuracy**	32, 35, 26, 28	28, 35, 25, 26	28, 26, 5, 16	32, 28, 3, 16	26, 28, 32, 3	26, 28, 32, 3	32, 13, 6		28, 13, 32, 24	32, 2	6, 28, 32	6, 28, 32	32, 35, 13	28, 6, 32	28, 6, 32	10, 26, 24	6, 19, 28, 24	6, 1, 32	3, 6, 32		3, 6, 32	26, 32, 27	10, 16, 31, 28
29	**Manufacturing precision**	28, 32, 13, 18	28, 35, 27, 9	10, 28, 29, 37	2, 32, 10	28, 33, 29, 32	2, 29, 18, 36	32, 23, 2	25, 10, 35	10, 28, 32	28, 19, 34, 36	3, 35	32, 30, 46, 40	30, 18	46, 3, 27	3, 27, 40		46, 19, 26	3, 32	46, 32, 2	46	32, 2	13, 32, 2	35, 31, 10, 24
30	**Object-affected harmful factors**	22, 21, 27, 39	2, 22, 13, 24	17, 1, 39, 4	1, 18	22, 1, 33, 28	27, 2, 39, 35	22, 23, 37, 35	34, 39, 19, 27	21, 22, 35, 28	13, 35, 39, 18	22, 2, 37	22, 1, 3, 35	35, 24, 30, 18	18, 35, 37, 1	22, 15, 33, 28	17, 1, 40, 33	22, 33, 35, 2	1, 19, 32, 13	1, 24, 6, 27	10, 2, 22, 37	19, 22, 31, 2	21, 22, 35, 2	33, 22, 19, 40
31	**Object-generated harmful factors**	19, 22, 15, 39	35, 22, 1, 39	17, 15, 16, 22		17, 2, 18, 39	22, 1, 40	17, 2, 40	30, 18, 35, 4	35, 28, 3, 23	35, 28, 1, 40	2, 33, 27, 18	35, 1	35, 40, 27, 39	15, 35, 22, 2	15, 22, 33, 31	21, 39, 16, 22	22, 35, 2, 24	19, 24, 39, 32	2, 35, 6	19, 22, 42, 18	2, 35, 44, 18	21, 35, 2, 22	10, 1, 34
32	**Ease of manufacture**	28, 29, 15, 16	1, 27, 36, 13	1, 29, 13, 17	15, 17, 27	13, 1, 26, 12	16, 40	13, 29, 1, 40	35	35, 13, 8, 1	35, 12	35, 19, 1, 37	1, 28, 13, 27	11, 13, 1	1, 3, 10, 32	27, 1, 4	35, 16	27, 26, 18	28, 24, 27, 1	28, 26, 27, 1	1, 4	27, 1, 12, 24	19, 35	15, 34, 33
33	**Ease of operation**	25, 2, 13, 15	6, 13, 1, 25	1, 17, 43, 13	43	1, 17, 13, 16	18, 16, 15, 39	1, 16, 35, 15	4, 18, 39, 31	18, 13, 34	28, 13, 41, 45	2, 32, 41, 45	15, 34, 29, 43	32, 35, 41, 43	32, 40, 43, 46	29, 3, 8, 25	1, 16, 25	26, 27, 41, 45	13, 17, 1, 24	1, 13, 24, 46	45, 46	35, 34, 2, 10	2, 19, 45, 13	28, 32, 2, 24
34	**Ease of repair**	2, 27 35, 11	2, 27, 35, 11	1, 28, 10, 25	3, 18, 31	15, 13, 32	16, 25	25, 2, 35, 11	1	34, 9	1, 11, 10	13	1, 13, 2, 46	2, 35	11, 1, 46, 2	11, 29, 28, 27	1	46, 4, 10	15, 1, 13	15, 1, 28, 16	46	15, 10, 32, 2	15, 1, 32, 19	2, 35, 34, 27
35	**Adaptability or versatility**	1, 6, 15, 8	19, 15, 29, 16	43, 35, 1, 29	1, 35, 43, 16	35, 30, 29, 7	15, 16	15, 35, 29		35, 10, 14	15, 17, 41, 20	41, 35, 44, 45	15, 37, 43, 1	35, 30, 41, 43	35, 3, 43, 32	13, 1, 35	2, 16	45, 27, 2, 44	6, 22, 26, 1	19, 35, 29, 13	45	19, 1, 41, 44	18, 15, 45, 1	15, 10, 2, 13
36	**Device complexity**	26, 30, 34, 36	2, 26, 35, 39	1, 19, 26, 24	26	14, 1, 13, 16	6, 36	34, 26, 6	1, 16	34, 10, 28	41, 26, 16	19, 1, 41, 35	29, 13, 28, 15	2, 22, 17, 19	2, 13, 41, 28	10, 4, 28, 15		2, 17, 46, 41	24, 17, 13	27, 2, 29, 28	46	20, 19, 30, 34	10, 35, 13, 2	35, 10, 28, 29
37	**Difficulty of detecting and measuring**	27, 26, 28, 13	6, 13, 28, 1	16, 17, 26, 24	26	2, 13, 18, 17	2, 39, 30, 16	29, 1, 4, 16	2, 18, 26, 31	3, 4, 16, 35	30, 28, 40, 19	35, 36, 37, 32	27, 13, 1, 39	11, 22, 39, 30	27, 3, 15, 28	19, 29, 39, 25	25, 34, 6, 35	3, 27, 35, 16	2, 24, 26	35, 38	19, 35, 16	18, 1, 16, 10	35, 3, 15, 19	1, 18, 10, 24
38	**Extent of automation**	28, 26, 18, 35	28, 26, 35, 10	14, 13, 17, 28	23	17, 14, 13		35, 13, 16		28, 10	2, 35	13, 35	15, 32, 1, 13	18, 1	25, 13	6, 9		26, 2, 19	8, 32, 19	2, 32, 13		28, 2, 27	23, 28	35, 10, 18, 5
39	**Productivity**	35, 26, 24, 37	28, 27, 15, 3	18, 4, 28, 38	30, 7, 14, 26	10, 26, 34, 31	10, 35, 17, 7	2, 6, 34, 10	35, 37, 10, 2		28, 15, 10, 36	10, 37, 44, 45	14, 10, 34, 40	35, 3, 22, 39	29, 28, 10, 18	35, 10, 2, 18	20, 10, 16, 38	35, 21, 45, 28	26, 17, 19, 1	35, 10, 38, 19	45, 1	35, 20, 44, 10	28, 10, 29, 35	28, 10, 35, 23
40	**Use of substance by moving object**	42, 12, 18, 2	42	43, 12, 28	43	15, 19, 25	—	35, 13, 18	—	21, 22	41, 4, 14	41, 4, 7	43, 7	41, 42, 43	41, 42	9, 10, 8, 21	—	41, 21, 19, 24	37, 32, 28, 35	—	42	41, 18, 6, 19	21, 25, 30, 12	25, 30, 35, 24
41	**Use of substance by stationary object**	42	42, 18, 35	—	43, 4, 17	—	14	—	17, 4, 14	—	44, 37, 1, 16	36, 45, 44	43, 14, 45	42, 27, 29	42, 35, 43	—	7, 10, 19	44, 7, 19	45, 43, 19, 21	—	42	—	28, 27	13, 18, 38, 27
42	**Ease of transportation**	42, 45, 35,2	42, 1, 45, 46	4, 1, 17	10, 14, 7	15, 13, 32	16, 25	29,13, 40, 1	4, 35, 39	1, 4, 43, 41	45, 35, 29, 2	45, 29, 32, 2	46, 43, 4, 17	42, 35	42, 46	—	35, 1	45, 46	—	45, 46	42, 45, 46	45, 7, 41	45, 35	45, 41, 46, 2
43	**Frequency**	8, 46, 45,	13, 43, 35	4, 30, 41, 44	43, 4	19, 38, 30	18, 14	38, 35, 46	6, 25	41, 44, 15, 13	44, 45, 41, 19	30 ,8, 19	46, 13, 41	44, 22, 8, 18	46, 8, 13, 15,	18, 19, 41, 22	—	46, 13, 22	32, 45, 46	46, 19, 8, 44	46, 30	8, 19, 18, 22	19, 22, 1, 21	45, 30, 1, 21
44	**Ease of re-use and recycling**	42, 1, 5, 8	42, 5, 1, 6	1, 4, 14, 33	1	—	—	30, 43, 2	46, 42	—	2, 33	33, 30, 22	4, 6, 14, 17	42, 33, 30, 14	42,14, 4, 33	33, 36, 39, 32	33, 44, 42, 32	36, 37, 21, 39	17, 15, 46, 24	—	42	2, 1, 33, 44	22, 2, 10, 9	3, 42, 7, 39
45	**Efficiency**	45, 15, 12, 1	5, 6, 43, 45	7, 43, 1, 3	43, 1	4, 14, 13	17	24, 26, 30, 29		21, 19, 20, 41	41, 44, 45, 5	9, 41, 44, 45	4, 43, 7, 14	41, 17, 13, 43	3, 41, 43	5, 25, 22, 15	41, 44, 6	45, 25, 41, 44	7, 41, 43, 44,	41, 45, 43, 2	12, 45	8,41, 44, 21	41, 10, 45	31, 30, 35, 39
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
	Worsening Feature → Improving Feature ↓	**Weight of moving object**	**Weight of stationary object**	**Length of moving object**	**Length of stationary object**	**Area of moving object**	**Area of stationary object**	**Volume of moving object**	**Volume of stationary object**	**Speed**	**Force (Intensity)**	**Stress or pressure**	**Shape**	**Stability of the object's composition**	**Strength**	**Duration of action of moving object**	**Duration of action of stationary object**	**Temperature**	**Illumination intensity**	**Use of energy by moving object**	**Use of energy by stationary object**	**Power**	**Loss of Energy**	**Loss of Substance**

24 Loss of Information	25 Loss of Time	26 Quantity of substance	27 Reliability	28 Measurement accuracy	29 Manufacturing precision	30 Object-affected harmful factors	31 Object-generated harmful factors	32 Ease of manufacture	33 Ease of operation	34 Ease of repair	35 Adaptability or versatility	36 Device complexity	37 Difficulty of detecting and measuring	38 Extent of automation	39 Productivity	40 Use of substance by moving object	41 Use of substance by stationary object	42 Ease of transportation	43 Frequency	44 Ease of re-use and recycling	45 Efficiency		
+	24, 26, 28, 32	24, 28, 35	10, 28, 23			22, 10, 1	10, 21, 22	32	27, 22				35, 33	35	13, 23, 15	—	—	7, 35, 17, 1		33, 22		24	Loss of Information
24, 26, 28, 32	+	35, 38, 18, 16	10, 30, 4	24, 34, 28, 32	24, 26, 28, 18	35, 18, 34	35, 22, 18, 39	35, 28, 34, 4	4, 28, 10, 34	32, 1, 10	35, 28	6, 29	18, 28, 32, 10	24, 28, 35, 30		35, 38, 18	1	43, 29	20, 16, 17	21, 20	21, 17	25	Loss of Time
24, 28, 35	35, 38, 18, 16	+	44, 18, 3, 28	13, 2, 28	33, 30	35, 33, 29, 31	44, 3, 35, 40	29, 1, 35, 27	44, 35, 29, 25	2, 32, 10, 25	15, 3, 29	3, 13, 27, 10	3, 27, 29, 18	8, 35	13, 29, 3, 27	42, 34, 29, 16	42, 35, 3	42, 43, 45, 5	44, 1, 41	44, 8, 41, 45	43, 44, 46	26	Quantity of substance/the matter
10, 28	10, 30, 4	21, 28, 40, 3	+	32, 3, 11, 23	11, 32, 1	27, 35, 2, 40	35, 2, 40, 26		27, 17, 40	1, 11	13, 35, 8, 24	13, 35, 1	27, 40, 28	11, 13, 27	1, 35, 29, 38	46, 11, 21, 1	36, 23, 20, 46	11, 9, 10, 39	23, 24, 11, 3	2, 22, 33, 44	23, 41, 25	27	Reliability
	24, 34, 28, 32	2, 6, 32	5, 11, 1, 23	+		28, 24, 22, 26	3, 33, 39, 10	6, 35, 25, 18	1, 13, 17, 34	1, 32, 13, 11	13, 35, 2	27, 35, 10, 34	26, 24, 32, 28	28, 2, 10, 34	10, 34, 28, 32	3, 6	—	28, 25, 21, 12	18, 26, 33	23, 25	46, 39, 33	28	Measurement accuracy
	32, 26, 28, 18	32, 30	11, 32, 46, 1		+	26, 28, 10, 36	4, 17, 34, 26		1, 32, 35, 23	25, 10		26, 2, 18		26, 28, 18, 23	10, 18, 32, 39	46, 32, 2	46	46, 13, 12	35, 35, 46, 1	24, 28, 35	9, 10, 15	29	Manufacturing precision
22, 10, 2	35, 18, 34	35, 33, 29, 31	27, 24, 2, 40	28, 33, 23, 26	26, 28, 10, 18	+		24, 35, 2	2, 25, 28, 39	35, 10, 2	35, 11, 22, 31	22, 19, 29, 40	22, 19, 29, 40	33, 3, 34	22, 35, 13, 24	42, 1, 24, 27	42, 10, 22	29, 28, 11	22, 41, 13,	2, 30	34, 6, 11, 15	30	Object-affected harmful factors
10, 21, 29	1, 22	3, 24, 39, 1	44, 24, 2, 40	3, 33, 26	4, 17, 34, 26		+		44			19, 1, 31	2, 21, 27, 1	2	22, 35, 18, 39	42, 4, 35	42, 19, 22, 18	42, 30, 35, 39	44, 22, 17, 21	44, 10, 9, 46	42, 43, 22	31	Object-generated harmful factors
32, 24, 18, 16	35, 28, 34, 4	35, 23, 1, 24		1, 35, 12, 18		24, 2		+	2, 5, 13, 16	35, 1, 11, 9	2, 13, 15	27, 26, 1	6, 28, 11, 1	8, 28, 1	35, 1, 10, 28	28, 26, 1	1, 4		44, 45, 1	1, 42, 33, 37	46, 1, 7, 10	32	Ease of manufacture
4, 10, 27, 22	4, 28, 10, 34	12, 35	17, 27, 46, 8	25, 13, 2, 34	1, 32, 35, 23	2, 25, 28, 39	41	2, 5, 12	+	12, 26, 1, 32	15, 34, 1, 16	32, 26, 12, 17		1, 34, 12, 3	15, 1, 28	43, 46, 1, 24	41, 43, 45, 46	41, 43, 46	46, 43, 8, 23	46, 8, 2, 22	45, 2, 25, 15	33	Ease of operation
	32, 1, 10, 25	2, 28, 10, 25	11, 10, 1, 16	10, 2, 13	25, 10	35, 10, 2, 16		1, 35, 11, 10	1, 12, 26, 15	+	7, 1, 4, 16	35, 1, 13, 11		34, 35, 7, 13	1, 32, 10	4, 15, 1, 28	46	46, 1, 7	1. 45. 32	46, 33, 25, 32	13, 12, 34,	34	Ease of repair
	35, 28	3, 35, 44, 15	35, 13, 8, 24	35, 5, 1, 10	41, 45	35, 11, 32, 31	41, 44	1, 13, 31	15, 34, 43, 44	1, 16, 7, 4	+	15, 29, 37, 43	1	27, 34, 41, 35	35, 28, 6, 37	43, 4, 35, 19	45	41, 43	15, 43, 41, 1	28, 37, 41	6, 45, 5, 12	35	Adaptability or versatility
	6, 29	13, 3, 27, 10	13, 35, 41, 46	2, 26, 10, 34	26, 24, 41, 32	22, 19, 29, 40	41, 19, 1	27, 26, 1, 13	27, 9, 26, 24	41, 1, 13	29, 15, 28, 37	+	15, 10, 37, 28	15, 1, 41, 24	12, 17, 28	27, 2, 29, 28	44, 46	41, 46	43, 44, 2, 5,	33, 44, 46	5, 7, 13, 28	36	Device complexity
35, 33, 27, 22	18, 28, 32, 9	3, 27, 29, 18	27, 40, 28, 8	26, 24, 32, 28		22, 19, 29, 28	2, 21	5, 28, 11, 29	2, 5	12, 26	1, 15	15, 10, 37, 28	+	34, 21	35, 18	46, 45, 39, 35	19, 35, 16		23, 13, 32	34, 32, 23	46, 44, 23	37	Difficulty of detecting and measuring
35, 33	24, 28, 35, 30	35, 13	11, 27, 32	28, 26, 10, 34	28, 26, 18, 23	2, 33	2	1, 26, 13	1, 12, 34, 3	1, 35, 13	27, 4, 1, 35	15, 24, 10	34, 27, 25	+	5, 12, 35, 26	41, 2, 32, 13	—	24, 23, 18, 29	45, 46, 8, 15	24, 16, 6, 13	25, 19, 15	38	Extent of automation
13, 15, 23		44, 35, 38	1, 35, 10, 38	1, 10, 34, 28	18, 10, 32, 1	22, 35, 13, 24	35, 22, 18, 39	35, 28, 2, 24	1, 28, 7, 10	1, 32, 10, 25	1, 35, 28, 37	12, 17, 28, 24	35, 18, 27, 2	5, 12, 35, 26	+	43, 24, 35, 10	43, 44, 45, 1	43, 45, 1	43, 44	44, 29, 46, 20	45, 8, 41, 39	39	Productivity
—	35, 38, 19	42, 34, 23	41, 3, 19, 11	23, 19, 21	41, 39	6, 35, 1	41, 42, 2	1, 28, 26	41, 43, 44	41, 1, 15, 32	4, 6, 15, 17	43, 5, 6, 35	23, 34, 35, 38	41, 32, 2	12, 28, 35	+	42	41, 42, 43	43, 13, 22	42, 1, 30, 33	44. 43. 2. 25	40	Use of substance by moving object
—	19, 20, 10	42, 44, 3, 35	9, 10, 44, 36	23, 39, 32	43, 46, 39	10, 2, 22	42, 37, 35, 22	21, 39, 42, 1	43, 44, 42	25, 42, 16, 12	41, 43, 46, 6	7, 33, 28, 41	46, 37, 19	15, 41, 10, 9	5,46, 42, 44	42	+	42, 43, 4, 1	45, 19, 15, 44	33, 42, 22, 2	43, 7, 12, 41	41	Use of substance by stationary object
	4, 28,35	42, 35, 2, 43	45, 46, 43, 29	43, 17	45	24, 2, 25	42, 41, 43	1, 7, 17, 43	41, 2, 43	1, 4, 29	41, 45, 17, 3	45, 1, 43, 5	23, 43, 45	29, 2, 41	41, 19, 24	42, 35, 46, 45	42, 45, 46	+	8, 45, 42	46, 1, 42, 33	45, 5, 41, 25	42	Ease of transportation
2, 23, 44, 45	21, 41, 10, 20	1, 44, 32, 15	15, 46, 13, 43	3, 22, 23, 32	2, 1, 45, 46	—	2, 8, 22, 19	1, 2, 16, 20	11, 21, 28, 29	25, 2, 21, 19	13, 15	41, 44, 5	23, 32, 45	18, 15, 44	46, 15, 35, 41	3, 15, 35	46, 15, 19, 22,	46	+	46	46, 15, 35, 41	43	Frequency
46, 32, 24, 23	10, 21, 15	33, 42, 35, 44	3, 43, 41, 35	—	1, 45, 39, 16	30, 22, 2, 1	33, 42	45, 40, 28, 12	5, 46, 41,	1, 34, 25, 43,	30, 3, 7, 6	33, 41,		10, 44, 34, 23	33, 44, 7	42, 38, 33, 22	42, 22, 2	31, 42, 43, 25	21, 18	+	33, 42, 2, 1	44	Ease of re-use and recycling
22, 46	5, 9, 10, 44	44, 2, 5, 16	15, 41, 44, 45	43, 6, 2	41, 45		41, 44	19 ,16, 20, 24	41, 10, 43, 44	1, 41, 7, 25	6, 15, 26	3, 43, 45, 5	23, 7, 32, 30	41, 5, 25, 15	44, 43, 25, 2	43, 24, 38, 19	45, 38, 2, 46	41, 11, 43, 45, 1	43, 44, 21	2 ,44, 46, 43	+	45	Efficiency

Worsening Feature →

Improving Feature ↓

B.4 40 + 6 inventive principles

The 40 Inventive Principles of TRIZ including the six new ones

1. Segmentation

a. Divide an object into independent parts

b. Make an object sectional

c. Increase the degree of an object's segmentation

Examples:

- Sectional furniture, modular computer components, folding wooden ruler
- Garden hoses can be joined together to form any length needed

2. Extraction

a. Extract (remove or separate) a "disturbing" part or property from an object, or

b. Extract only the necessary part or property

Example:

- To frighten birds away from the airport, use a tape recorder to reproduce the sound known to excite birds. (The sound is thus separated from the birds.)

3. Local Quality

a. Transition from a homogeneous structure of an object or outside environment/action to a heterogeneous structure

b. Have different parts of the object carry out different functions

c. Place each part of the object under conditions most favorable for its operation

Examples:

- To combat dust in coal mines, a fine mist of water in a conical form is applied to working parts of the drilling and loading machinery. The smaller the droplets, the greater the effect in combating dust, but fine mist hinders the work. The solution is to develop a layer of coarse mist around the cone of fine mist.
- A pencil and eraser in one unit.

4. Asymmetry

a. Replace a symmetrical form with an asymmetrical form.

b. If an object is already asymmetrical, increase the degree of asymmetry

Examples:

- Make one side of a tire stronger than the other to withstand impact with the curb
- While discharging wet sand through a symmetrical funnel, the sand forms an arch above the opening, causing irregular flow. A funnel of asymmetrical shape eliminates the arching effect.

5. Combining

a. Combine in space homogeneous objects or objects destined for contiguous operations

b. Combine in time homogeneous or contiguous operations

Example:

- The working element of a rotary excavator has special steam nozzles to defrost and soften the frozen ground

6. Universality

Have the object perform multiple functions, thereby eliminating the need for some other object(s)

Examples:

- Sofa which converts into a bed
- Minivan seat which adjusts to accommodate seating, sleeping or carrying cargo

7. Nesting

a. Contain the object inside another which, in turn, is placed inside a third object

b. Pass an object through a cavity of another object

Examples:

- Telescoping antenna
- Chairs which stack on top of each other for storage
- Mechanical pencil with lead stored inside

8. Counterweight

a. Compensate for the object's weight by joining with another object that has a lifting force

b. Compensate for the weight of an object by interaction with an environment providing aerodynamic or hydrodynamic forces

Examples:

- Boat with hydrofoils
- A rear wing in racing cars which increases pressure from the car to the ground

9. Prior counter-action

a. Perform a counter-action in advance

b. If the object is (or will be) under tension, provide anti-tension in advance

Examples:

- Reinforced concrete column or floor
- Reinforced shaft made from several pipes which have been previously twisted to some specified angle

10. Prior action

a. Carry out all or part of the required action in advance

b. Arrange objects so they can go into action in a timely matter and from a convenient position

Examples:

- Utility knife blade made with a groove allowing the dull part of the blade to be broken off, restoring sharpness
- Rubber cement in a bottle is difficult to apply neatly and uniformly. Instead, it is formed into a tape so that the proper amount can be more easily applied.

11. Cushion in advance

Compensate for the relatively low reliability of an object by countermeasures taken in advance

Example:

- Merchandise is magnetized to deter shoplifting.

12. Equipotentiality

Change the working conditions so that an object need not be raised or lowered.

Example:

- Automobile engine oil is changed by workers in a pit to avoid using expensive lifting equipment

13. Inversion

a. Instead of an action dictated by the specifications of the problem, implement an opposite action

b. Make a moving part of the object or the outside environment immovable and the non-moving part movable

c. Turn the object upside-down

Example:

- Abrasively cleaning parts by vibrating the parts instead of the abrasive

14. Spheroidality

a. Replace linear parts or flat surfaces with curved ones; replace cubical shapes with spherical shapes

b. Use rollers, balls spirals

c. Replace a linear motion with rotating movement; utilize a centrifugal force

Example:

- Computer mouse utilized ball construction to transfer linear two-axis motion into vector motion

15. Dynamicity

a. Make an object or its environment automatically adjust for optimal performance at each stage of operation

b. Divide an object into elements which can change position relative to each other

c. If an object is immovable, make it movable or interchangeable

Examples:

- A flashlight with a flexible gooseneck between the body and the lamp head
- A transport vessel with a cylindrical-shaped body. To reduce the draft or a vessel under full load, the body is comprised of two hinged, half-cylindrical parts which can be opened.

16. Partial or overdone action

If it is difficult to obtain 100% of a desired effect, achieve somewhat more or less to greatly simplify the problem

Examples:

- A cylinder is painted by dipping into paint, but contains more paint than desired. Excess paint is then removed by rapidly rotating the cylinder.
- To obtain uniform discharge of a metallic powder from a bin, the hopper has a special internal funnel which is continually overfilled to provide nearly constant pressure.

17. Moving to a new dimension

a. Remove problems with moving an object in a line by two-dimensional movement (i.e. along a plane)

b. Use a multi-layered assembly of objects instead of a single layer

c. Incline the object or turn it on its side

Example:

- A greenhouse which has a concave reflector on the northern part of the house to improve illumination of that part of the house by reflecting sunlight during the day.

18. Mechanical vibration

a. Set an object into oscillation

b. If oscillation exists, increase its frequency, even as far as ultrasonic

c. Use the resonant frequency

d. Instead of mechanical vibrations, use piezovibrators

e. Use ultrasonic vibrations in conjunction with an electromagnetic field

Examples:

- To remove a cast from the body without injuring the skin, a conventional hand saw was replaced with a vibrating knife
- Vibrate a casting mold while it is being filled to improve flow and structural properties

19. Periodic action

a. Replace a continuous action with a periodic (pulsed) one

b. If an action is already periodic, change its frequency

c. Use pulsed between impulses to provide additional action

Examples:

- An impact wrench loosens corroded nuts using impulses rather than continuous force
- A warning lamp flashes so that it is even more noticeable than when continuously lit

20. Continuity of a useful action

a. Carry out an action continuously (i.e. without pauses), where all parts of an object operate at full capacity

b. Remove idle and intermediate motions

Example:

- A drill with cutting edges which permit cutting in forward and reverse directions

21. Rushing through

Perform harmful or hazardous operations at very high speed

Example:

- A cutter for thin-walled plastic tubes prevents tube deformation during cutting by running at a very high speed (i.e. cuts before the tube has a chance to deform)

22. Convert harm into benefit

a. Utilize harmful factors or environmental effects to obtain a positive effect

b. Remove a harmful factor by combining it with another harmful factor

c. Increase the amount of harmful action until it ceases to be harmful

Examples:

- Sand or gravel freezes solid when transported through cold climates. Over-freezing (using liquid nitrogen) makes the ice brittle, permitting pouring.
- When using high frequency current to heat metal, only the outer layer became hot. This negative effect was later used for surface heat-treating.

23. Feedback

a. Introduce feedback

b. If feedback already exists, reverse it

Examples:

- Water pressure from a well is maintained by sensing output pressure and turning on a pump if pressure is too low
- Ice and water are measured separately but must combine to total a specific weight. Because ice is difficult to dispense precisely, it is measured first. The weight is then fed to the water control device, which precisely dispenses the needed amount.

24. Mediator

a. Use an intermediary object to transfer or carry out an action

b. Temporarily connect an object to another one that is easy to remove

Example:

- To reduce energy loss when applying current to a liquid metal, cooled electrodes and intermediate liquid metal with a lower melting temperature are used.

25. Self-service

a. Make the object service itself and carry out supplementary and repair operations

b. Make use of wasted material and energy

Examples:

- To prevent wear in a feeder which distributes an abrasive material, its surface is made from the abrasive material
- In an electric welding gun, the rod is advanced by a special device. To simplify the system, the rod is advanced by a solenoid controlled by the welding current.

26. Copying

a. Use a simple and inexpensive copy instead of an object which is complex, expensive, fragile or inconvenient to operate.

b. Replace an object by its optical copy or image. A scale can be used to reduce or enlarge the image.

c. If visible optical copies are used, replace them with infrared or ultraviolet copies

Example:

- The height of tall objects can be determined by measuring their shadows.

27. Inexpensive, short-lived object for expensive, durable one

Replace an expensive object by a collection of inexpensive ones, forgoing properties (e.g. longevity)

Examples:

- Disposable diapers

28. Replacement of a mechanical system

a. Replace a mechanical system by an optical, acoustical or olfactory (odor) system

b. Use an electrical, magnetic or electromagnetic field for interaction with the object

c. Replace fields

1. Stationary fields with moving fields

2. Fixed fields with those which change in time

3. Random fields with structured fields

d. Use a field in conjunction with ferromagnetic particles

Example:

- To increase the bond between metal coating and a thermoplastic material, the process is carried out inside an electromagnetic field which applies force to the metal

29. Pneumatic or hydraulic construction

Replace solid parts of an object by gas or liquid. These parts can use air or water for inflation, or use air or hydrostatic cushions

Examples:

- To increase the draft of an industrial chimney, a spiral pipe with nozzles was installed. When air flows through the nozzles, it creates an air-like wall, reducing drag.
- For shipping fragile products, air bubble envelopes or foam-like materials are used.

30. Flexible membranes or thin film

a. Replace traditional constructions with those made from flexible membranes or thin film

b. Isolate an object from its environment using flexible membranes or thin film

Example:

- To prevent water evaporation from plant leaves, polyethylene spray was applied. After a while, the polyethylene hardened and plant growth improved, because polyethylene film passes oxygen better than water vapor.

31. Use of porous material

a. Make an object porous or add porous elements (inserts, covers, etc.)

b. If an object is already porous, fill the pores in advance with some substance

Example:

- To avoid pumping coolant to a machine, some of its parts are filled with a porous material soaked in coolant liquid. The coolant evaporates when the machine is working, providing short-term uniform cooling.

32. Changing the color

a. Change the color of an object or its surroundings

b. Change the degree of translucency of an object or processes which are difficult to see

c. Use colored additives to observe objects or processes which are difficult to see

d. If such additives are already used, employ luminescent traces or tracer elements

Examples:

- A transparent bandage enabling a wound to be inspected without removing the dressing
- A water curtain used to protect steel mill workers from overheating blocked infrared rays but not the bright light from the melted steel. A coloring was added to the water to create a filter effect while preserving the transparency of the water.

33. Homogeneity

Make those objects which interact with a primary object out of the same material or material that is close to it in behavior.

Example:

- The surface of a feeder for abrasive grain is made of the same material that runs through the feeder, allowing a continuous restoration of the surface.

34. Rejecting and regenerating parts

a. After it has completed its function or become useless, reject or modify (e.g. discard, dissolve, evaporate) an element of an object

b. Immediately restore any part of an object which is exhausted or depleted

Examples:

- Bullet casings are ejected after the gun fires
- Rocket boosters separate after serving their function

35. Transformation of the physical and chemical states of an object

Change an object's aggregate state, density distribution, degree of flexibility, temperature

Example:

- In a system for brittle friable materials, the surface of the spiral feedscrew was made from an elastic material with two spiral springs. To control the process, the pitch of the screw could be changed remotely.

36. Phase transformation

Implement an effect developed during the phase transition of a substance. For instance, during the change of volume, liberation or absorption of heat.

Example:

- To control the expansion of ribbed pipes, they are filled with water and cooled to a freezing temperature

37. Thermal expansion

a. Use a material which expands or contracts with heat

b. Use various materials with different coefficients of heat expansion

Example:

- To control the opening of roof windows in a greenhouse, bimetallic plates are connected to the windows. A change in temperature bends the plates, causing the window to open or close.

38. Use strong oxidizers

a. Replace normal air with enriched air

b. Replace enriched air with oxygen

c. Treat an object in air or in oxygen with ionizing radiation

d. Use ionized oxygen

Example:

- To obtain more heat from a torch, oxygen is fed to the torch instead of atmospheric air

39. Inert environment

a. Replace the normal environment with an inert one

b. Carry out the process in a vacuum

Example:

- To prevent cotton from catching fire in a warehouse, it is treated with inert gas while being transported to the storage area.

40. Composite materials

Replace a homogeneous material with a composite one

Example:

- Military aircraft wings are made of composites of plastics and carbon fibers for high strength and low weight

41. Aligning of functions

Align two or more different functions to enhance and amplify the favoured result.

Example:

- (Aircraft) gas turbine engine use the torque and speed produced by the turbine to power a compressor that enhances the airflow through the system. Same for the turbocharger

42. Increase the re-usability and re-cyclability of substance, product or component

a. Change the material used
b. Remove the factor that keeps the substance or product from being re-used or recycled (e.g. toxicity)
c. Increase the financial value of the component or product

Example:

- Switching from plastic bags to paper bags increases the recyclability
- Removing led in soldering makes electronics easier to re-use (e.g. filler material)
- By putting a deposit on bottles and crates the re-use is increased

43. Compromise – between two already existing methods to create a solution for a specific case

a. Find similarities in the two existing methods and create a new solution based on those
b. Create a method that is made of parts of both existing ones – Use parts 1 and 3 from method a and parts 2 and 4 from method b.

Example:

- A Turbofan is a compromise between a Turboprop (low altitude) and a Turbojet (high altitude)
- An intermediate tyre is a compromise between a slick tyre and a rain tyre for the specific case of a half dry track condition

44. Use accumulative principle or "Rice-Chess-Board" principle to achieve a target

Find a way to initiate a self amplifying effect or make use of the exponential effects.

Example:

- Compound interest
- Nuclear reaction in a power plant
- Turbo Charger in a car

45. Use air or gas to create pressure difference or force

Find a way to contain a gas or air that has higher pressure than the surrounding to provide lifting.

Create a gas or air flow to create a useful force

Example:

- Hover Craft
- Air cushion packaging
- Helicopter
- Leaf Blower

46. Use an obsolete and out-of date principle in a new and inventive way

To generate an innovative approach review past solutions in the field and think about how re-invent them.

Example:

- Solar sail used for space travel (based on wind sail for sea travel)
- Vacuum Tubes are used again in amplifiers to produce a very distinct and warm sound even though they were considered obsolete at a time.

B.5 Component functions (Streamlining of contradiction matrix)

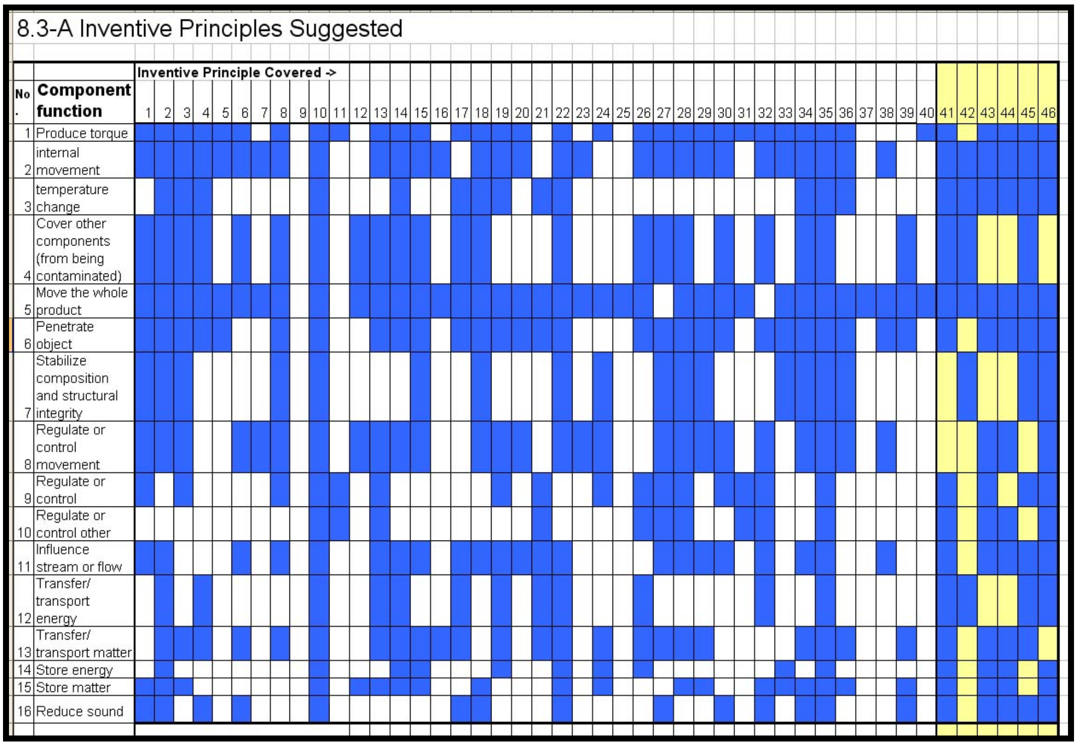
8.2 List of component functions

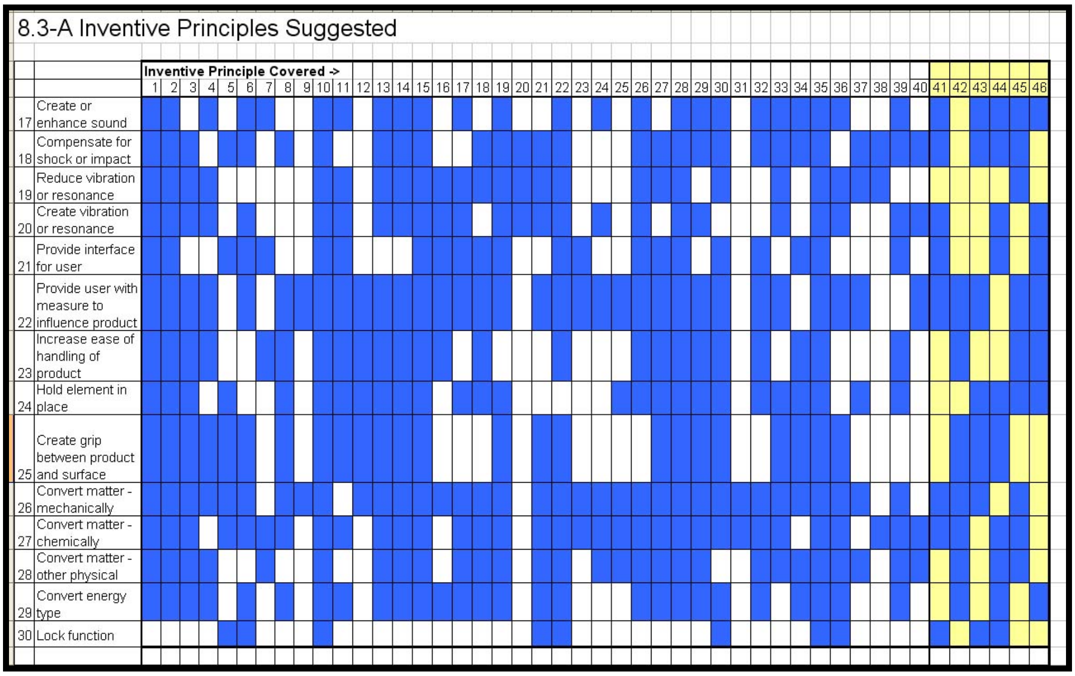
No.	Component function	Example	Improving Feature of TRIZ matrix	Worsening Feature of TRIZ matrix	Chosen Inventive Principle of those suggested
1	Produce torque	motor	1, 3, 9, 12, 21, 29, 33, 43, 45	11, 13, 15, 17, 22, 23, 27, 40, 41	1, 2, 3, 4, 5, 13, 14, 15, 18, 19, 28, 29, 34, 35, 41,43, 44, 45, 46
2	Produce internal movement	motor	9, 12, 21, 29, 42, 45	1, 3, 5, 7, 9, 11, 12, 15, 17, 19, 22, 41	1, 2, 3, 4, 5, 7, 10, 13, 14, 15, 18, 19, 20, 22, 28, 29, 34, 35, 36, 38, 41,42, 43, 44, 45, 46
3	Produce temperature change	heating element	12, 16, 17, 21, 41, 45	17, 22, 26, 42, 43	3, 4, 21, 22, 41, 42, 43, 44, 45
4	Cover other components (from being contaminated	engine hood	4, 6, 12, 13, 14, 45	10, 11, 15, 17, 21, 44	1, 2, 3, 4, 13, 17, 27, 28, 34, 43, 44, 46
5	Move the whole product	wheels	3, 7, 9, 13, 19, 41, 42	1, 12, 13, 17, 22, 23, 29, 40	1, 3, 4, 13, 14, 15, 28, 31, 34, 36, 37, 38, 39, 40, 41, 43, 44, 45, 46
6	Penetrate object	drill, cone strainer	9, 11, 12, 13, 14, 15, 21, 31, 40	1, 12, 13, 17, 22, 23, 29, 45	1, 3, 4, 5, 10, 13, 15, 17, 18, 19, 21, 22, 27, 33, 34, 35, 36, 41, 43, 44, 45, 46
7	Stabilize composition and structural integrity	beam,	12, 13, 14, 23, 27, 41	10, 11, 30, 44	1, 3, 14, 24, 35, 42, 45, 46
8	Regulate or control movement	clutch	9, 19, 21, 45	1, 3, 5, 7, 22, 23, 25, 28, 29, 30, 37, 43	6, 13, 14, 15, 18, 19, 20, 23, 28, 29, 43, 44
9	Regulate or control pressure	valve	27, 29, 41, 45	10, 11, 12, 17, 22, 23, 26, 28, 30, 41, 45	3, 13, 21, 28, 30, 35, 41, 43, 45, 46
10	Regulate or control other	light intensity sensor	27, 29, 41, 43	9, 22, 23, 24, 30, 45	13, 21, 28, 31, 32, 35, 41, 43, 44, 46
11	Influence stream or flow	car spoiler - air flow, regulating valve for fluid flow speed	9, 10, 12, 21, 45	3, 4, 5, 6, 11, 17, 22, 23	1, 2, 8, 13, 14, 15, 17, 18, 19, 20, 29, 38, 41, 43, 44, 45, 46
12	Transfer/ transport energy	cable	17, 21, 29, 42, 43, 45	17, 22, 31, 43	2, 13, 17, 19, 21, 22, 35, 41,42, 45, 46
13	Transfer/ transport matter	pipe, conveyor belt	11, 12, 17, 21,	1, 7, 9, 10, 15, 17, 19, 22, 23, 26	2, 3, 4, 8, 10, 13, 14, 17, 19, 24,35, 41, 43, 44, 45
14	Store energy	battery, flywheel	13, 21, 44, 45	9, 10, 22, 30, 44	19, 22, 29, 35, 41, 43, 44, 46
15	Store matter	fuel tank	4, 8, 12, 13, 33, 42, 43	9, 10, 11, 23, 26	1, 3, 15, 24, 30, 35, 41, 43, 44, 46

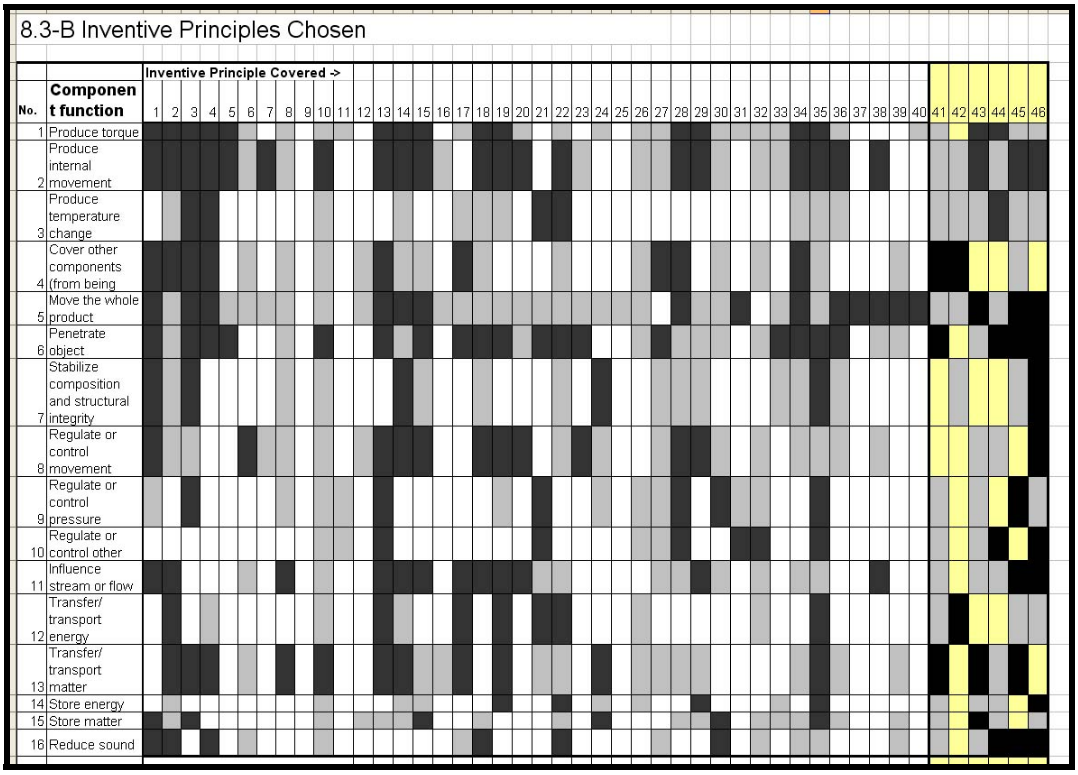
8.2 List of component functions

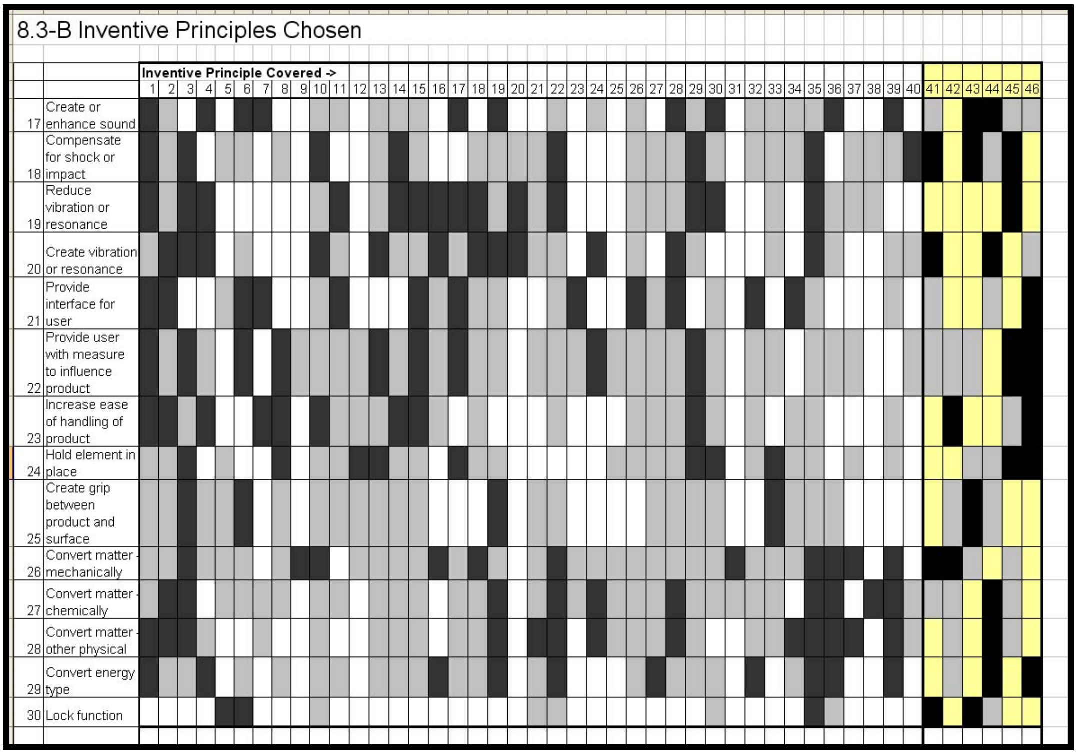
No.	Component function	Example	Improving Feature of TRIZ matrix	Worsening Feature of TRIZ matrix	Chosen Inventive Principle of those suggested
16	Reduce sound	hood	12, 6, 8, 43, 41	10, 21, 30, 45	1, 2, 4, 18, 22, 30, 41, 43, 44, 45, 46
17	Create or enhance sound	loudspeaker	5, 7, 10, 11, 12, 43, 42	9, 13, 17, 19, 21, 22, 24, 45	1, 4, 6, 7, 17, 19, 28, 30, 36, 39, 41, 43, 44, 45, 46
18	Compensate for shock or impact	spring in car suspension	12, 13, 14, 22, 25, 29, 41	1, 2, 9, 10, 11, 15, 16, 17, 43	1, 3, 10, 14, 22, 29, 35, 40, 41, 43, 44, 45
19	Reduce vibration or resonance	damper in car suspension	9, 20, 22, 25, 29, 35,	10, 13, 16, 30,	1, 3, 4, 11, 14, 15, 16, 17, 18, 20, 22, 29, 30, 35, 45
20	Create vibration or resonance	microwave,	9, 10, 12, 15, 17, 43	13, 21, 22, 26, 27, 31, 36, 45	2, 3, 4, 10, 13, 16, 18, 19, 20, 24, 28, 35, 41, 44, 46
21	Provide interface for user	computer screen, speedometer	6, 35,	9, 10, 17, 18, 21, 22, 24, 25, 28, 30, 38, 44	1, 2, 6, 7, 11, 15, 17, 23, 26, 28, 32, 34, 41, 44, 46
22	Provide user with measure to influence product	PC keyboard, switch	3, 10, 11, 12, 14, 27, 30, 33, 38, 39, 42, 44	1, 7, 9, 15, 25, 27, 31, 36	1, 3, 6, 8, 13, 15, 17, 24, 29, 1, 2, 4, 7, 8, 10, 14, 15, 29, 40, 41, 42, 43, 45, 46
23	Increase ease of handling of product	tennis racket grip, rubber grip inlets on water kettle	4, 6, 12, 33, 34, 42, 44	2, 8, 10, 11, 16, 17, 23, 26, 41	1, 5, 4, 7, 8, 10, 14, 15, 29, 42, 45, 46
24	Hold element in place	car seat, cavity of telephone handset charger	4, 6, 12, 14, 29, 32, 33, 34,	1, 3, 5, 10, 11, 13, 15, 43	3, 8, 12, 13, 17, 29, 30, 33, 43, 44, 45, 46
25	Create grip between product and surface	tires on a car, rubber pads under keyboard to keep it from sliding	1, 3, 5, 10, 11, 12, 17, 35, 41	9, 12, 13, 15, 17, 21, 30, 44	3, 6, 19, 33, 42, 43, 44
26	Convert matter - mechanically	injection moulding	10, 11, 15, 17, 29, 33, 38, 41, 42	1, 7, 9, 12, 13, 19, 23, 26, 37, 45	3, 9, 10, 16, 18, 22, 31, 35, 36, 37, 39, 41, 42, 43, 45
27	Convert matter - chemically	combustion engine	2, 6, 10, 11, 12, 15, 17, 29, 33, 35, 38, 41	1, 9, 13, 19, 22, 23, 27	2, 3, 19, 22, 24, 28, 35, 36, 38, 39, 41, 42, 44, 45
28	Convert matter - other physical	nuclear power plant	10, 12, 13, 15, 17, 21, 26, 29, 33, 43	11, 22, 30, 31, 37	1, 2, 3, 19, 21, 22, 24, 28, 34, 35, 36, 37, 39, 42, 44, 45
29	Convert energy type	light bulb changes electrical energy to light energy; industrial magnet changes electrical energy to magnetic field energy	10, 12, 13, 17, 18, 21, 27, 41, 43	10, 12, 16, 17, 18, 21, 22, 23, 44	1, 4, 16, 19, 22, 27, 32, 35, 36, 39, 42, 44, 46
30	Lock function	paddock lock, integrated lock	1, 12, 13, 14, 26, 29, 35, 45	11, 17, 23, 30, 43	5, 6, 35, 41, 43, 44

B.6 Allocation of inventive principles






8.3-B Inventive Principles Chosen
Inventive Principle Covered ->
No.
Component function
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46
1 Produce torque
2 Produce internal movement
3 Produce temperature change
4 Cover other components (from being
5 Move the whole product
6 Penetrate object
7 Stabilize composition and structural integrity
8 Regulate or control movement
9 Regulate or control pressure
10 Regulate or control other
11 Influence stream or flow
12 Transfer/ transport energy
13 Transfer/ transport matter
14 Store energy
15 Store matter
16 Reduce sound


8.3-B Inventive Principles Chosen
Inventive Principle Covered ->
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46
17 Create or enhance sound
18 Compensate for shock or impact
19 Reduce vibration or resonance
20 Create vibration or resonance
21 Provide interface for user
22 Provide user with measure to influence product
23 Increase ease of handling of product
24 Hold element in place
25 Create grip between product and surface
26 Convert matter - mechanically
27 Convert matter - chemically
28 Convert matter - other physical
29 Convert energy type
30 Lock function

B.7 List of design suggestions with examples (including additional features)

8.4 List of design suggestions with examples (including additional features)

No	Inventive Principle (TRIZ)	Further Detail	Example
1	**Segmentation**	a. Divide an object into independent parts b. Make an object sectional c. Increase the degree of an object's segmentation	• Sectional furniture, modular computer components, folding wooden ruler • Garden hoses can be joined together to form any length needed
2	**Taking out**	a. Extract (remove or separate) a "disturbing" part or property from an object, or b. Extract only the necessary part or property	• To frighten birds away from the airport, use a tape recorder to reproduce the sound known to excite birds. (The sound is thus separated from the birds.)
3	**Local quality**	a. Transition from a homogeneous structure of an object or outside environment/action to a heterogeneous structure b. Have different parts of the object carry out different functions c. Place each part of the object under conditions most favorable for its operation	• To combat dust in coal mines, a fine mist of water in a conical form is applied to working parts of the drilling and loading machinery. The smaller the droplets, the greater the effect in combating dust, but fine mist hinders the work. The solution is to develop a layer of coarse mist around the cone of fine mist. • A pencil and eraser in one unit.
4	**Asymmetry**	a. Replace a symmetrical form with an asymmetrical form. b. If an object is already asymmetrical, increase the degree of asymmetry	• Make one side of a tire stronger than the other to withstand impact with the curb • While discharging wet sand through a symmetrical funnel, the sand forms an arch above the opening, causing irregular flow. A funnel of asymmetrical shape eliminates the arching effect.
5	**Merging**	a. Combine in space homogeneous objects or objects destined for contiguous operations b. Combine in time homogeneous or contiguous operations	• The working element of a rotary excavator has special steam nozzles to defrost and soften the frozen ground
6	**Universality**	Have the object perform multiple functions, thereby eliminating the need for some other object(s)	• Sofa which converts into a bed • Minivan seat which adjusts to accommodate seating, sleeping or carrying cargo
7	**Nesting**	a. Contain the object inside another which, in turn, is placed inside a third object b. Pass an object through a cavity of another object	• Telescoping antenna • Chairs which stack on top of each other for storage

8.4 List of design suggestions with examples (including additional features)

No	Inventive Principle (TRIZ)	Further Detail	Example
8	**Anti-weight**	a. Compensate for the object's weight by joining with another object that has a lifting force b. Compensate for the weight of an object by interaction with an environment providing aerodynamic or hydrodynamic forces	• Boat with hydrofoils • A rear wing in racing cars which increases pressure from the car to the ground
9	**Preliminary anti-action**	a. Perform a counter-action in advance b. If the object is (or will be) under tension, provide anti-tension in advance	• Reinforced concrete column or floor • Reinforced shaft made from several pipes which have been previously twisted to some specified angle
10	**Preliminary action**	a. Carry out all or part of the required action in advance b. Arrange objects so they can go into action in a timely matter and from a convenient position	• Utility knife blade made with a groove allowing the dull part of the blade to be broken off, restoring sharpness • Rubber cement in a bottle is difficult to apply neatly and uniformly. Instead, it is formed into a tape so that the proper amount can be more easily applied.
11	**Beforehand cushioning**	Compensate for the relatively low reliability of an object by countermeasures taken in advance	• Merchandise is magnetized to deter shoplifting.
12	**Equipotentiality**	Change the working conditions so that an object need not be raised or lowered.	• Automobile engine oil is changed by workers in a pit to avoid using expensive lifting equipment
13	**Inversion - The other way round**	a. Instead of an action dictated by the specifications of the problem, implement an opposite action b. Make a moving part of the object or the outside environment immovable and the non-moving part movable c. Turn the object upside-down	• Abrasively cleaning parts by vibrating the parts instead of the abrasive
14	**Spheroidality - Curvature**	a. Replace linear parts or flat surfaces with curved ones; replace cubical shapes with spherical shapes b. Use rollers, balls spirals	• Computer mouse utilized ball construction to transfer linear two-axis motion into vector motion

8.4 List of design suggestions with examples (including additional features)

No	Inventive Principle (TRIZ)	Further Detail	Example
15	**Dynamics**	a. Make an object or its environment automatically adjust for optimal performance at each stage of operation b. Divide an object into elements which can change position relative to each other c. If an object is immovable, make it movable or interchangeable	• A flashlight with a flexible gooseneck between the body and the lamp head • A transport vessel with a cylindrical-shaped body. To reduce the draft or a vessel under full load, the body is comprised of two hinged, half-cylindrical parts which can be opened.
16	**Partial or excessive actions**	If it is difficult to obtain 100% of a desired effect, achieve somewhat more or less to greatly simplify the problem	• A cylinder is painted by dipping into paint, but contains more paint than desired. Excess paint is then removed by rapidly rotating the cylinder. • To obtain uniform discharge of a metallic powder from a bin, the hopper has a special internal funnel which is continually overfilled to provide nearly constant pressure.
17	**Another dimension**	a. Remove problems with moving an object in a line by two-dimensional movement (i.e. along a plane) b. Use a multi-layered assembly of objects instead of a single layer c. Incline the object or turn it on its side	• A greenhouse which has a concave reflector on the northern part of the house to improve illumination of that part of the house by reflecting sunlight during the day.
18	**Mechanical vibration**	a. Set an object into oscillation b. If oscillation exists, increase its frequency, even as far as ultrasonic c. Use the resonant frequency d. Instead of mechanical vibrations, use piezovibrators	• To remove a cast from the body without injuring the skin, a conventional hand saw was replaced with a vibrating knife • Vibrate a casting mold while it is being filled to improve flow and structural properties
19	**Periodic action**	a. Replace a continuous action with a periodic (pulsed) one	• An impact wrench loosens corroded nuts using impulses rather than continuous force

8.4 List of design suggestions with examples (including additional features)

No	Inventive Principle (TRIZ)	Further Detail	Example
20	**Continuity of useful action**	a. Carry out an action continuously (i.e. without pauses), where all parts of an object operate at full capacity b. Remove idle and intermediate motions	• A drill with cutting edges which permit cutting in forward and reverse directions
21	**Skipping/ Rushing through**	Perform harmful or hazardous operations at very high speed	• A cutter for thin-walled plastic tubes prevents tube deformation during cutting by running at a very high speed (i.e. cuts before the tube has a chance to deform)
22	**Convert harm into benefit/ Blessing in disguise**	a. Utilize harmful factors or environmental effects to obtain a positive effect b. Remove a harmful factor by combining it with another harmful factor c. Increase the amount of harmful action until it ceases to be harmful	• Sand or gravel freezes solid when transported through cold climates. Over-freezing (using liquid nitrogen) makes the ice brittle, permitting pouring. • When using high frequency current to heat metal, only the outer layer became hot. This negative effect was later used for surface heat-treating.
23	**Feedback**	a. Introduce feedback b. If feedback already exists, reverse it	• Water pressure from a well is maintained by sensing output pressure and turning on a pump if pressure is too low • Ice and water are measured separately but must combine to total a specific weight. Because ice is difficult to dispense precisely, it is measured first. The weight is then fed to the water control device, which precisely dispenses the needed amount.
24	**Intermediary**	a. Use an intermediary object to transfer or carry out an action b. Temporarily connect an object to another one that is easy to remove	• To reduce energy loss when applying current to a liquid metal, cooled electrodes and intermediate liquid metal with a lower melting temperature are used.
25	**Self-Service**	a. Make the object service itself and carry out supplementary and repair operations b. Make use of wasted material and energy	• To prevent wear in a feeder which distributes an abrasive material, its surface is made from the abrasive material • In an electric welding gun, the rod is advanced by a special device. To simplify the system, the rod is advanced by a solenoid controlled by the welding current.

8.4 List of design suggestions with examples (including additional features)

No	Inventive Principle (TRIZ)	Further Detail	Example
26	**Copying**	a. Use a simple and inexpensive copy instead of an object which is complex, expensive, fragile or inconvenient to operate. b. Replace an object by its optical copy or image. A scale can be used to reduce or enlarge the image.	• The height of tall objects can be determined by measuring their shadows.
27	**Cheap short-living objects**	Replace an expensive object by a collection of inexpensive ones, forgoing properties (e.g. longevity)	• Disposable diapers
28	**Mechanics substitution**	a. Replace a mechanical system by an optical, acoustical or olfactory (odor) system b. Use an electrical, magnetic or electromagnetic field for interaction with the object c. Replace fields 1. Stationary fields with moving fields 2. Fixed fields with those which change in time 3. Random fields with structured fields d. Use a field in conjunction with ferromagnetic particles	• To increase the bond between metal coating and a thermoplastic material, the process is carried out inside an electromagnetic field which applies force to the metal
29	**Pneumatics and hydraulics**	Replace solid parts of an object by gas or liquid. These parts can use air or water for inflation, or use air or hydrostatic cushions	• To increase the draft of an industrial chimney, a spiral pipe with nozzles was installed. When air flows through the nozzles, it creates an air-like wall, reducing drag. • For shipping fragile products, air bubble envelopes or foam-like materials are used.
30	**Flexible shells and thin films**	a. Replace traditional constructions with those made from flexible membranes or thin film b. Isolate an object from its environment using flexible membranes or thin film	• To prevent water evaporation from plant leaves, polyethylene spray was applied. After a while, the polyethylene hardened and plant growth improved, because polyethylene film passes oxygen better than water vapor.
31	**Porous materials**	a. Make an object porous or add porous elements (inserts, covers, etc.) b. If an object is already porous, fill the pores in advance with some substance	• To avoid pumping coolant to a machine, some of its parts are filled with a porous material soaked in coolant liquid. The coolant evaporates when the machine is working, providing short-term uniform cooling.

8.4 List of design suggestions with examples (including additional features)

No	Inventive Principle (TRIZ)	Further Detail	Example
32	**Colour changes**	a. Change the color of an object or its surroundings b. Change the degree of translucency of an object or processes which are difficult to see c. Use colored additives to observe objects or processes which are difficult to see d. If such additives are already used, employ luminescent traces or tracer elements	• A transparent bandage enabling a wound to be inspected without removing the dressing • A water curtain used to protect steel mill workers from overheating blocked infrared rays but not the bright light from the melted steel. A coloring was added to the water to create a filter effect while preserving the transparency of the water.
33	**Homogeneity**	Make those objects which interact with a primary object out of the same material or material that is close to it in behavior.	• The surface of a feeder for abrasive grain is made of the same material that runs through the feeder, allowing a continuous restoration of the surface.
34	**Discarding and recovering**	a. After it has completed its function or become useless, reject or modify (e.g. discard, dissolve, evaporate) an element of an object b. Immediately restore any part of an object which is exhausted or depleted	• Bullet casings are ejected after the gun fires • Rocket boosters separate after serving their function
35	**Parameter changes**	Change an object's aggregate state, density distribution, degree of flexibility, temperature	• In a system for brittle friable materials, the surface of the spiral feedscrew was made from an elastic material with two spiral springs. To control the process, the pitch of the screw could be changed remotely.

8.4 List of design suggestions with examples (including additional features)

No	Inventive Principle (TRIZ)	Further Detail	Example
36	**Phase transitions**	Implement an effect developed during the phase transition of a substance. For instance, during the change of volume, liberation or absorption of heat.	• To control the expansion of ribbed pipes, they are filled with water and cooled to a freezing temperature
37	**Thermal expansion**	a. Use a material which expands or contracts with heat b. Use various materials with different coefficients of heat expansion	• To control the opening of roof windows in a greenhouse, bimetallic plates are connected to the windows. A change in temperature bends the plates, causing the window to open or close.
38	**Strong oxidants**	a. Replace normal air with enriched air b. Replace enriched air with oxygen c. Treat an object in air or in oxygen with ionizing radiation d. Use ionized oxygen	• To obtain more heat from a torch, oxygen is fed to the torch instead of atmospheric air
39	**Inert Atmosphere**	a. Replace the normal environment with an inert one b. Carry out the process in a vacuum	• To prevent cotton from catching fire in a warehouse, it is treated with inert gas while being transported to the storage area.
40	**Composite materials**	Replace a homogeneous material with a composite one	• Military aircraft wings are made of composites of plastics and carbon fibers for high strength and low weight

8.4 List of design suggestions with examples (including additional features)

No	Inventive Principle (TRIZ)	Further Detail	Example
41	**Aligning of functions**	Align two or more different functions to enhance and amplify the favoured result.	• (Aircraft) gas turbine engine use the torque and speed produced by the turbine to power a compressor that enhances the airflow through the system. Same for the turbocharger
42	**Increase the re-usability and re-cyclability (of substance, product or component)**	a. Change the material used b. Remove the factor that keeps the substance or product from being re-used or recycled (e.g. toxicity) c. Increase the financial value of the component or product	• Switching from plastic bags to paper bags increases the recyclability • Removing led in soldering makes electronics easier to re-use (e.g. filler material) • By putting a deposit on bottles and crates the re-use is increased
43	**Compromise (between two already existing methods to create a solution for a specific case)**	a. Find similarities in the two existing methods and create a new solution based on those b. Create a method that is made of parts of both existing ones – Use parts 1 and 3 from method A and parts 2 and 4 from method B.	• A Turbofan is a compromise between a Turboprop (low altitude) and a Turbojet (high altitude) • An intermediate tyre is a compromise between a slick tyre and a rain tyre for the specific case of a half dry track condition
44	**Use accumulative principle**	Find a way to initiate a self amplifying effect or make use of the exponential effects.	• Compound interest • Nuclear reaction in a power plant • Turbo Charger in a car
45	**Use air (or gas) to create pressure difference**	a. Find a way to contain a gas or air that has higher pressure than the surrounding to provide lifting. b. Create a gas or air flow to create a useful force	• Hover Craft • Air cushion packaging • Helicopter • Leaf Blower
46	**Use an obsolete and out-of date principle in a new and inventive way**	To generate an innovative approach review past solutions in the field and think about how re-invent them.	• Solar sail used for space travel (based on wind sail for sea travel) • Vacuum Tubes are used again in amplifiers to produce a very distinct and warm sound even though they were considered obsolete at a time.

B.8 Direct and environmental cost impact equations – ACP

9.1 Costs related to environmental impact - I		
Raw Material Extraction		
	Related Letter Formula	
	Direct Cost	Environmental Cost
Component 1:		
1.1 Energy Cost for mat. Prod.:		
m x % mat. x CES prod. energy x energy costs	N113 x N114 x database 3.1 (Averaged Embodied Energy) x C03	
+		
1.2 Climate Change Levy Costs		
m x % mat. X CES prod. energy x CCL Value		N113 x N114 x database 3.1 (Averaged Embodied Energy) x L01
+		
1.3 Other Material Cost	N118 / A01	
]		
Component 2:		
1.1 Energy Cost for mat. Prod.:		
m x % mat. x CES prod. energy x energy costs	N213 x N214 x database 3.1 x C03	
+		
1.2 Climate Change Levy Costs		
m x % mat. X CES prod. energy x CCL Value		N213 x N214 x database 3.1 x L01
+		
1.3 Other Material Cost	N218 / A01	
]		
Component 3:		
1.1 Energy Cost for mat. Prod.:		
m x % mat. x CES prod. energy x energy costs	N313 x N314 x database 3.1 x C03	
+		
1.2 Climate Change Levy Costs		
m x % mat. X CES prod. energy x CCL Value		N313 x N314 x database 3.1 x L01
+		
1.3 Other Material Cost	N318 / A01	
]		

9.1 Costs related to environmental impact - I		
Raw Material Extraction		
	Related Letter Formula	
	Direct Cost	Environmental Cost
Component 4:		
1.1 Energy Cost for mat. Prod.:		
m x % mat. x CES prod. energy x energy costs	N413 x N414 x database 3.1 x C03	
+		
1.2 Climate Change Levy Costs		
m x % mat. X CES prod. energy x CCL Value		N413 x N414 x database 3.1 x L01
+		
1.3 Other Material Cost	N418 / A01	
]		
Component 5:		
1.1 Energy Cost for mat. Prod.:		
m x % mat. x CES prod. energy x energy costs	N513 x N514 x database 3.1 x C03	
+		
1.2 Climate Change Levy Costs		
m x % mat. X CES prod. energy x CCL Value		N513 x N514 x database 3.1 x L01
+		
1.3 Other Material Cost	N518 / A01	
]		
Component 6:		
1.1 Energy Cost for mat. Prod.:		
m x % mat. x CES prod. energy x energy costs	N613 x N614 x database 3.1 x C03	
+		
1.2 Climate Change Levy Costs		
m x % mat. X CES prod. energy x CCL Value		N613 x N614 x database 3.1 x L01
+		
1.3 Other Material Cost	N618 / A01	
]		

9.1 Costs related to environmental impact - II		
Manufacturing		
	Related Letter Formula	
	Direct Cost	**Environmental Cost**
Component 1:		
1.1 Component is Manufactured on site (If N117 = Yes) - Use of following Importance Factor:		
[(N114 / A06) / 3] + [(N109 / A09) / 6] + [(N108 / A10) / 2] = N199		
1.1.1 On Site CO2 Emission Cost		
m (CO2 Emissions) / yearly production x CCL Value		N199 x C01 / A01 x L06
+		
1.1.2. Energy Cost for Production & Facility		
amount (kWh) / yearly production x [current energy costs + CCL value]	N199 x C02 / A01 x [C03] / 100	N199 x C02 / A01 x [L01]
+		
1.1.3. Material Inflow Cost		
1.1.3.1 Material for energy production *(e.g. LPG, gas, etc.)*		
amount / yearly production x [current mat. Cost + CCL]	N199 x {C04,C06,C08 or C10} / A01 x [C05,C07,C09 or C11]	N199 x {C04,C06,C08 or C10} / A01 x [L02, L03, L04 or L05]
1.1.3.2 Other material *(water, or other)*		
amount / yearly production x current mat. Cost	N199 x {C12, C14 or C16} / A01 x {C13, C15 or C17}	
+		
1.1.4. Material Outflow Cost		
amount / yearly production x [waste treatment + waste disposal costs]		N199 x C18 / A01 x C19
		N199 x C20 / A01 x [C21 + C22]
1.2 Component is Manufactured on site (If N117 = No)		
1.2.1 Component Cost charged by supplier	N123	

9.1 Costs related to environmental impact - III		
Transportation		
	Related Letter Formula	
	Direct Cost	**Environmental Cost**
Component 1:		
1.1 Component is Manufactured on site (If N117 = Yes):		
1.1.1 Outgoing Transportation		
(weight of component / overall product weight) x % Category (e.g. Regional) x average distance x Product weight x [cost of transportation per ton per distance + CO2 emission per ton per distance x CCL value]	(N114/A06) x (D12 to D16)/100 x (D17 to D21) x A06 / 1000 x [Table 2.5] / 100	(N114/ A06) x (D12 to D16) /100 x (D17 to D21) x A06 / 1000 x [Table 2.6] / 100
1.1.2 Packaging Waste - Outgoing		
Outgoing transportation costs due to packaging	(N114 / A06) x (D12 to D16)/100 x (D17 to D21) x [Table 2.5] / 100 x D22 / 1000	(N114 / A06) x (D12 to D16)/100 x (D17 to D21) x [Table 2.6] / 100 x D22 / 1000
+		
Cost of yearly packaging (yearly) / yearly production	(N114 / A06) x D23 / A01	
+		
Cost of packaging diposal (yearly) / yearly production		(N114 / A06) x D24 / A01

OR		
1.2 Component is Manufactured on site (If N117 = No) :- Use of following Importance Factor 2		
1.2.1 Incoming Transportation (for component)		
Weight of component x average distance x % Category (e.g. Regional) x [cost of transportation per ton per distance + (CO2 emission per ton per distance x CCL value)]	N114 / 1000 x {D01/100} x (D07 to D11) x (D02 to D06) / 100 x (Table 2.5) / 100	N114 / 1000 x {D01/100} x (D07 to D11) x (D02 to D06) / 100 x (Table 2.6) / 100
1.2.2 Outgoing Transportation		
(weight of component / overall product weight) x % Category (e.g. Regional) x average distance x Product weight x [cost of transportation per ton per distance + CO2 emission per ton per distance x CCL value]	(N114/ A06) x (D12 to D16) /100 x (D17 to D21) x A06 / 1000 x [Table 2.5] / 100	(N114/ A06) x (D12 to D16)/100 x (D17 to D21) x A06 / 1000 x [Table 2.6] / 100
1.2.3 Packaging Waste - Incoming (only of N119 = YES)		
Incoming transportation costs due to packaging	N120 / 1000 x {D01/100} x (D07 to D11) x (D02 to D06) / 100 x (Table 2.5) / 100	N120 / 1000 x {D01/100} x (D07 to D11) x (D02 to D06) / 100 x (Table 2.6) / 100
+		
Cost of yearly packaging (yearly) / yearly production	N121 / A01	
+		
Cost of packaging diposal (yearly) / yearly production		N122 / A01
1.2.4 Packaging Waste - Outgoing		
Outgoing transportation costs due to packaging	(N114 / A06) x (D12 to D16)/100 x (D17 to D21) x [Table 2.5] / 100 x D22 / 1000	(N114 / A06) x (D12 to D16) /100 x (D17 to D21) x [Table 2.6] / 100 x D22 / 1000
+		
Cost of yearly packaging (yearly) / yearly production	(N114 / A06) x D23 / A01	
+		
Cost of packaging diposal (yearly) / yearly production		(N114 / A06) x D24 / A01

9.1 Costs related to environmental impact - IV

Use

General calculations necessary

Number of components that consume material:

N124 + N224 + N324 + N424 + N524 + N624 [for all that are yes] = N724 (0 - 6)

Number of components that produce material outflow

N125 + N225 + N325 + N425 + N525 + N625 [for all that are yes] = N725 (0 - 6)

Number of components that require energy (in the form of LPG, etc.) to function

N126 + N226 + N326 + N426 + N526 + N626 [for all that are yes] = N726 (0 - 6)

Number of components that require electric energy to function

N127 + N227 + N327 + N427 + N527 + N627 [for all that are yes] = N727 (0 - 6)

Number of components that require consumables to function

N128 + N228 + N328 + N428 + N528 + N628 [for all that are yes] = N728 (0 - 6)

	Related Letter Formula	
	Direct Cost	**Environmental Cost**
Component 1:		
1.1 Component consumes material (If N124 = Yes):		
Material Inflow		
Mat. 1 x [m consumed / hour] x product use frequency x average life cycle length x cost] / **N724**	E01 x A02 x A03 x A04 x A07 x E02 / N724	
Mat. 2 x [m consumed / hour] x product use frequency x average life cycle length x cost] / **N724**	E03 x A02 x A03 x A04 x A07 x E04 / N724	
Mat. 3 x [m consumed / hour] x product use frequency x average life cycle length x cost] / **N724**	E05 x A02 x A03 x A04 x A07 x E06 / N724	
+		
1.2 Component creates material outflow (If N125 = Yes)		
Material Outflow		
Mat. 4 x product use frequency x average life cycle length x cost / **N725**		[E17 x E18 / 100] x A02 x A03 x A04 x A07 / N725
Mat. 5 x product use frequency x average life cycle length x cost / **N725**		[E19 x E20/ 100]x A02 x A03 x A04 x A07 / N725
+		
1.3 Component requires energy other than electricity (If N126 = Yes)		
Energy Inflow (For coal, gas, LPG, etc.)		
Energy material x price / **N726**	[(E07xE08) + (E09xE10) + (E11xE12) + (E13xE14) +(0.3 x E15xE16)] / 100 x A02 x A03 x A04 x A07 / N726	(E07xL03) + (E09xL02) + (E11xL04) + (E13xL05) +(0.7 x E15x E16/100) x A02 x A03 x A04 x A07 / N726
+		
1.4 Component requires electric energy (If N127 = Yes)		
Energy Inflow (For electricity)		
Active [energy amount (kWh/h) x use frequency (h/year) x average life cycle length (years) x [current average energy price + CCL tax value] / **N727**	E22/1000 x A02 x A03 x A04 x A07 / 100 x [A09] / N727	E22/1000 x A02 x A03 x A04 x A07 x [L01] / N727
+		
Stand by or Leakage [((365x24)h - use frequency) x Energy Amount (kWh/h) x average life cycle length (years) x [current average energy price + CCL tax value] / **N727**	[8760 - (A02 x A03 x A04)] x A07/100 x E24/1000 x [A09] / N727	[8760 - (A02 x A03 x A04)] x E24/ 1000 x A07 x [L01] / N727
+		
1.5 Does the component require consumables to function (If N128 = Yes)		
Consumables used		
No. used per day x product use frequency x [price of consumables + price of consumable disposal] / **N728**	E25 x [A03 x A02] x A07 / N728 x [E26] / 100	E25 x [A03 x A02] x A07 / N728 x [E27] / 100
+		
1.6 Further Eco-taxes that apply		E21 / N100 x A07

9.1 Costs related to environmental impact - V		
End of Life	***Related Letter Formula***	
	Direct Cost	**Environmental Cost**
Component 1:		
1.1 What is the most propable EoL scenario for component 1:		
Check N112		
1.2 EoL scenario: Landfill		
1.2.1 Transport costs x (average distance to landfill site) x (component weight / product weight)	2.37/100 x 200 x [N114] / 1000	0.0355/100 x 200 x [N114] / 1000
1.2.2 Landfill costs x (component weight / product weight)	(26) x [N114 / A06] / 1000	(24) x [N114 / A06] / 1000
1.3 EoL scenario: Hazardous Waste Landfill		
1.3.1 Transport costs x (average distance to treatment site x (component weight / product weight)	2.37/100 x 200 x [N114] / 1000	0.0355/100 x 200 x [N114] / 1000
1.3.2 Worst case scenario treatment cost of hazardous substances (probability N111 x N129)		N129 x (N111 - 1) / 9
1.3.3 Landfill cost after treatment x (component weight / product weight)	(26) x [N114 / A06] / 1000	(24) x [N114 / A06] / 1000
1.4 Incineration		
1.4.1 Transport costs (average distance to treatment site) x (component weight / product weight)	2.37/100 x 200 x [N114] / 1000	0.0355/100 x 200 x [N114] / 1000
1.4.2 Revenue from incineration	[-] 70 x N114/1000	32.75 x N114/1000
1.5 Re-Use		
1.5.1 Incoming + Outgoing transport costs (average distance to treatment site + distance from treatment site to spare part storage) x (component weight / product weight)	2.37/100 x 2 x 200 x [N114] / 1000	0.0355/100 x 200 x [N114] / 1000
1.5.2 Cost of component treatment (cleaning, etc.) before it can be re-used	N130	
1.5.3 Revenue from re-use	[-] (N110 -1 / 9) x (Total Results from I Raw Material Extr. & II. Manufacturing)	
1.6 Re-cycle		
1.6.1 Transport costs (average distance to treatment site) x (component weight / product weight)	2.37/100 x 200 x [N114] / 1000	0.0355/100 x 200 x [N114] / 1000
1.6.2 Revenue from sale of recyclates	[-] 46.5 x N114 / 1000	
1.7 If EoL of the component is different from the whole product		
Dissmantling & seperation costs	N131	

B.9 Connection method list

10.1 Connection Method List - Suitability Rating					
	Life Cycle Stage				
Fastening method	**Raw Material Extraction**	**Manufacturing**	**Transportation**	**Use & Servicing**	**End-of Life**
Adhesives	High	Low	High	Medium	Low
Reason for score	Usually a small amount of adhesives is required; Small impact on Raw Material Extraction (e.g. glue)	Long bonding time reduces productivity	Low weight improves transportation;	Difficult to disassemble components; putting back together can be tricky	Adhesives can inherit toxicity; diffcult to disassemble components
Rivets or Staples	Medium	High	Low	Low	Low
Reason for score	Average amount of raw material required for rivets	Quick and easy application	Relatively high weight of fastener	Very difficult to disassemble for servicing; difficult to re-assemble	Very difficult to disassemble for servicing; damage to component possible once disassembled
Snap Fit	Low	High	Low	High	High
Reason for score	Usually a large amount of raw material is required for snap fit solutions	Quick assembly time	High weight of this solution	Very quick disassembly and re-assemble	Components and part can easily be taken apart and re-assembled e.g. as spare parts
Threaded Fasteners	Low	Medium	Medium	High	High
Reason for score	Usually a large amount of raw material is required for threaded fasteners such as bolts and nuts	Medium level of time and effort required for assembly	medium weight of this solution	Easy disassembly and te-assembly; Ease of availability if fastener is destroyed	Components and part can easily be taken apart and re-assembled e.g. as spare parts
Welding	High	Low	Medium	Low	Medium
Reason for score	Medium amount of material required	long and difficult application if not automated	Low weight improves transportation;	Very difficult to disassemble for servicing; difficult to re-assemble	Difficult to disassemble components at the End of Life

B.10 Design suggestion matrix - ACP

11.2 Design Suggestion Matrix - I Raw Material Extraction

Raw Material Extraction		
Design suggestion	**Further Instructions**	**Examples**
1. Material choices :	review for the 30% of materials that are the main cost drivers	
1.1 Choose a different material from the same material group	Check key elements: A) Material Price B) Production (embodied) energy required C) CO2 Emissions D) Trade off Issue: weight (density range)	
1.2 Choose a different material from another material group		
1.3 Choose a renewable material source		Choose wood over plastic
2. Mass of the component	Reduce the total mass of the component thus less material is required - Review of structural integrity and component requirements the weight can be reduced	
	Use smart structural component design to enhance component stability/ rigidity by using less material	
3. Take the End-of Life scenario into account when choosing a raw material		
3.1 Check if it is possible to improve EoL scenario	e.g. instead of landfill scenario evaluate Recycling of material/component options (If material can be recycled 3-4 times at end of life the environmental and financial impact is possibly reduced to 50%)	
3.1.2 Check "Embodied Energy" and possibility for energy recovery at EoL		

11.2 Design Suggestion Matrix - II Manufacturing

Manufacturing		
Design suggestion	**Further Instructions**	**Examples**
1.1 Change certain machines and process steps used to manufacture component	Is it possible to use alternative that does not generate any CO2 emissions	
2. Reduce the energy use on component production site	Apply an energy reduction scheme on site	
2.1 Consider use of heating controls to switch of heating in areas where it is not essential		
2.2. Check the efficiency of heating system	Would it make sense to apply a more efficient heating system financially	E.g. switch from electric heating to gas heating
2.3 Check the efficiency of lighting system	Consider use high efficient light bulbs that consume less energy and have a longer life cycle	
2.4 Application of automation system	Tighten up processes by the use of an automation system; Is it possible to implement remote sensors to automatically switch of light in areas that are not in use (caution: keep health and safety aspect in mind)	
2.5 Use of waste heat	Is it possible to use waste heat of certain processes for various purposes	E.g. divert waste heat from large compressor to heat office spaces
3. Maximise process efficiency	Reduce incoming material flow and energy flow during manufacturing stage	
3.1 Reduce incoming material flow and energy flow during manufacturing stage	(e.g. how can water consumption be reduced?)	
3.2 Choose an incoming material with lower impact	Is it possible to use incoming material that has a lower economical and environmental impact?	E.g switch from coal for heating to LPG
3.3 Reduce waste outflow from processes	Reduce Waste being produced during the manufacturing	

11.2 Design Suggestion Matrix - II Manufacturing

Manufacturing

Design suggestion	Further Instructions	Examples
4. Application of DfM (Design for manufacture) principles		
4.1 Design component for easy of manufacturing	Is it possible to reduce the manufacturing steps (Review the component design and identify areas that are not	
	Review the possibility to carry out two manufacturing processes in one step	
	Review the ease of handling of the component during the manufacturing process;	
	Is it possible to reduce number of man hours required to produce one unit	
4.2 Reduce energy to manufacture the component		
4.3 Reduce the time to manufacture the component		
5. Application of DfA (Design for assembly) principles		
5.1 Consider ease of assembly during component design		
5.2 Reduce the mix of materials in the components and the component as a whole		
5.3 Reduce the mix of fasteners	Reduction of different types of fasteners used	
6. Re-use of components	Is it possible to plan for re-use of components from EoL stage being re-introduced at the manufacturing stage	

11.2 Design Suggestion Matrix - III Transportation

Transportation

Design suggestion	Further Instructions	Examples
1. Transportation		
1.1 Evaluate to produce component on site instead of buying in from supplier (if not already the case)		
1.2 Review logisitcs and evaluate a different method of transportation from supplier	Weigh delivery time issue against financial and environmental impact	E.g switch from plane to sea ship
1.3 Set up a supplier network that is highly efficient	Is it possible to choose a supplier that is located closer to the production facility. Reduction of component cost due to reduced transportation costs.	

11.2 Design Suggestion Matrix - III Transportation

Transportation		
Design suggestion	**Further Instructions**	**Examples**
2. Packaging		
2.2 Examine ways of eliminating or reducing your packaging requirement of component	Changes in product design, improved cleanliness, better handling, just-in-time delivery, bulk delivery, etc	
2.3 optimise your packaging use, ie match packaging to the level of protection needed.		
2.4. Increase ease of handling of the packaging	It has appropriate handles for manual handling, access points for fork-lift trucks, attachment points for cranes, etc.	
	OR	
	Is of an appropriate shape that allows individual packaging units to be stacked one on top of the other (possibly with interlocks to stabilise the stacks) or to fit inside intermediate containers or racks.	
2.5 Identify main purposes of packaging used	Protect component against contamination	
	Protect component against damage during transport (e.g. impact)	
2.6 Reduction of weight of packaging	Consider alternative materials which are lighter	
	Reduce amount of packaging material used	
2.7 Reduction of cost of packaging	Consider alternative material that costs less	
	Reduce amount of packaging	
	Make packaging less complex so less machines will be required in order to package component	
2.8 Reduce cost of packaging disposal	Consider alternative material that is cheaper to dispose of	
	Reduce amount of packaging that needs to be disposed of	
	Reduce number of materials used for packaging and thus less sorting if packaging is recycled	
2.9 Set up a Re-use system for the packaging		
2.10 Set up a Recycling scheme for the packaging	Collection system	

11.2 Design Suggestion Matrix - IV Use

Use		
Design suggestion	**Further Instructions**	**Examples**
1. Application of DfS (Design for servicability, reliability and maintainability) principle	Take measures to increase the time between servicing	
	Avoid or reduce amount of disposals and service consumables	
	Increase ease of access of component	
2. Reduce user impact	Design component for low energy consumption	
	Reduce the risk of improper product use	
3. Reduce material inflow		
3.1 Reduce material inflow during the use phase		
3.2 Choose a different material inflow with a lower financial and environmental impact		
4. Energy Inflow		
4.1 Active		
4.1.1 Reduce the active amount of energy required by component		
4.1.2 Choose a different type of energy source and evaluate financial and environmental impact		E.g. Switch from diesel fuel to electricity (only valid in some cases)
4.1.3 Evaluate if it is possible to reduce the energy consumption of the component during idle process	install automatic switch-off function or similar	

11.2 Design Suggestion Matrix - IV Use

Use		
Design suggestion	**Further Instructions**	**Examples**
5. Consumables		
5.1 Treat consumable as a product	Evaluate the Life Cycle Impact of a consumable by treating it as a regular product	
	Use matrix to find out what the biggest financial and environmental impact of the consumable is and at which (consumable) Life Cycle step it occurs	
	Investigate solutions to reduce the impact of the consumable during its Life Cycle step with the biggest impact	
5.2 What is the purpose of the consumable		
5.3 Can the consumable be designed out?	Is the consumable part of the products main function	
	If yes: Consumable cannot be designed out	E.g. Vending machine - here the consumable cannot be designed out because it the main part of the component function
	If no: Is it possible to avoid use of consumable by using smart design	E.g. Dyson vacuum cleaner does not require filters
5.5 Reduce Waste caused by Consumables	Some consumables create waste during their use	
	Re-use of consumable	E.g. refill printer cartridges
	Re-design consumables to avoid waste	E.g. caseless ammunition
5.2 What is the purpose of the consumable		
5.3 Can the consumable be designed out?	Is the consumable part of the products main function	
	If yes: Consumable cannot be designed out	E.g. Vending machine - here the consumable cannot be designed out because it the main part of the component function
	If no: Is it possible to avoid use of consumable by using smart design	E.g. Dyson vacuum cleaner does not require filters
5.5 Reduce Waste caused by Consumables	Some consumables create waste during their use	
	Re-use of consumable	E.g. refill printer cartridges
	Re-design consumables to avoid waste	E.g. caseless ammunition

11.2 Design Suggestion Matrix - V End-of Life

Check N112 - N612 to select scenario

End-of Life		
Design suggestion	**Further Instructions**	**Examples**
I. For Re-Use	1. Evaluate the possibility of further disassembly of the component	
	2. Is it possible to set up a highly efficient re-sale of used components network	e.g. component is fed back into the spare part aftersale market
	3. Check the value of the component. If the value is rather low then consider another EoL scenario for it	
	4. Identify the cost drivers in the Re-Use chain of the component	e.g. are the disassembly plants working efficiently and thus cost effective, etc.
	5. Is the component sold for the right price when sold as a used component?	
	6. Apply the DfD (Design for disassembly) principle - Re-evaluate ways to dismantle a product quicker and more efficient	
	7. Review Fasteners used and try to use the following fastener types instead where possible: - Snap Fit - Threaded Fasteners	

11.2 Design Suggestion Matrix - V End-of Life

Check N112 - N612 to select scenario

End-of Life

Design suggestion	Further Instructions	Examples
II. Recycling	1. Consider another EoL scenario for the component and check if the Total Cost of the component can be further reduced	
	2. Use materials in the component that are easier to recycle and obtain for Re-Sale purposes then recycled materials	
	3. Reduce the number of the materials in the component to enhance Recycling efficiency	
	4. Consider Recycling fatigue rates(number of times materials can be recycled) for materials whilst chosing component material	
	5. Identify the cost drivers of the Recycling process	e.g. if the transport costs reduce the revenue from recycling try to find ways to shorten transportation distance - e.g. shorten distance between disassembly plant, recycling plant and potential buyer of recyclates
	6. Use recyclable materials only	
	7. Reduce contamination of recyclates	
	8. Apply the DfR (Design for Recycling) principle	e.g. reduce the number of different materials used
		e.g. avoid the use of composite materials
		e.g. replace toxic materials with non-hazardous alternatives
		e.g. reduce complexity of the component
		e.g. promote infrastructures geared towards recycling

11.2 Design Suggestion Matrix - V End-of Life

Check N112 - N612 to select scenario

End-of Life

Design suggestion	Further Instructions	Examples
III. Incineration	1. Reevaluate the components material and if they burn efficiently without causing toxicity	e.g. use materials mainly that are high in embodied energy and low in toxicity levels
	2. Use materials that cause a low or no Carbon Footprint over the product Life Cycle	e.g. wood has a negative Carbon Footprint during War Material Extraction (due to the fact that trees use the carbon in the air as building blocks) and thus this can eliminate the Carbon Footprint at EoL thus Incineration
	3. Apply the DfD (Design for disassembly principle) and evaluate if component disassembly is a more cost efficient scenario	
	4. Choose materials that produces more energy when being incinerated (higher embodied energy) or that can be incinerated more efficiently	

11.2 Design Suggestion Matrix - V End-of Life

Check N112 - N612 to select scenario

End-of Life

Design suggestion	Further Instructions	Examples
IV. Landfill	1. Is it more cost effective to consider a different EoL scenario for the product	
	2. Try to make the component biodegradable so landfill storage time is kept to a minimum	
	3. Identify the reason why the component is currently going to landfill and try to eliminate it	e.g. If a product is impossible to disassemble and thus goes to landfill then apply Design for Disassembly principle
		e.g If the consumer throws product in the regular waste bin then try to educate consumer or set up take back scheme
	4. Evaluate "real" costs from component going to landfill, investigate who is paying those and compare them to alternative EoL scenarios	At the moment 1 ton of General Household Waste going to landfill produces 2.1 tons of CO2 emissions equivalent. Furthermore it costs around £50 per ton of waste going to landfill based on landfill site contractor costs and landfill taxes.
	5. Consider Upgradability and Modularization - Is it possible to upgrade component by exchanging certain parts? This would increase the Life Cycle length of the product instead of sending it to landfill early	

11.2 Design Suggestion Matrix - V End-of Life

Check N112 - N612 to select scenario

End-of Life

Design suggestion	Further Instructions	Examples
V. Landfill - Hazardous Waste	1.Identify the hazardous materials within the component that are the reason for the component going to landfill	e.g. lead soldering in PCB (Printed Circuit Boards)
	2. Is it possible to replace the hazardous material with a non hazardous material	e.g. - replacing lead solder with tin/copper solder - replacing cadmium based coatings with zinc-bearing coatings
	3. Try to shift the End-of Life scenario to another scenario or at least to regular landfill in order to reduce costs	
	4. Find a way to remove the hazardous substance from the component before it is being send to landfill or alternative End-of Life scenario	

Appendix C: Detail Design Phase

Within the Appendix C the following information will be given:

C.1 – All the Input Information requested from the user at the Detail Design phase by the methodology are listed. Within the user interface the information is requested during two separate screens.

C.2 – The screenshots of Excel sheets here show the equations necessary to evaluate the direct cost and environmental cost impact for each of the maximum 10 parts.

C.3 – Various screenshots in section C.3.1 show the main issues that influence the direct cost and environmental cost of parts. It is shown all the parts main issues part of five main categories which are weight, complexity, material, energy, legislation and necessity. The various main issues are then judged to the life cycle stage they influence.

C.4 – This is the design suggestion matrix for the Detail Design phase broken down into each of the five life cycle steps. For each life cycle step the corresponding design suggestions are listed as internal code.

C.1 Input information from user – DDP

13.1 Input Information - Detail Design Phase - Component 1

Component Name: N101

Comment: Please list in hierarchical order. Hence subassembly and then all parts belonging to it before starting with the next subassembly

No.	Sub-component (if existent)	Parts	Weight (in kg)	No. of Materials	Material 1	% of part made of Material 1 (based on weight)	Material 2	% of part made of Material 2 (based on weight)	Material 3	% of part made of Material 3 (based on weight)	Internal Part Number (if available)	Main Fastener used	Manufacturing complexity of the part (no.of process steps, etc.) (1 - 10) 1 being very low and 10 being very high	Costs per unit (in £)	Toxicity potential in the part (1 - 10)	EoL scenario (pre selection based in material choices and Table 3.1)
1	TA000	TA001	TA002	TA003	TA004	TA005	TA006	TA007	TA008	TA009	TA010	TA011	TA012	TA013	TA014	TA015
2	TA100	TA101	TA102	TA103	TA104	TA105	TA106	TA107	TA108	TA109	TA110	TA111	TA112	TA113	TA114	TA115
3	TA200	TA201	TA202	TA203	TA204	TA205	TA206	TA207	TA208	TA209	TA210	TA211	TA212	TA213	TA214	TA215
4	TA300	TA301	TA302	TA303	TA304	TA305	TA306	TA307	TA308	TA309	TA310	TA311	TA312	TA313	TA314	TA315
5	TA400	TA401	TA402	TA403	TA404	TA405	TA406	TA407	TA408	TA409	TA410	TA411	TA412	TA413	TA414	TA415
6	TA500	TA501	TA502	TA503	TA504	TA505	TA506	TA507	TA508	TA509	TA510	TA511	TA512	TA513	TA514	TA515
7	TA600	TA601	TA602	TA603	TA604	TA605	TA606	TA607	TA608	TA609	TA610	TA611	TA612	TA613	TA614	TA615
8	TA700	TA701	TA702	TA703	TA704	TA705	TA706	TA707	TA708	TA709	TA710	TA711	TA712	TA713	TA714	TA715
9	TA800	TA801	TA802	TA803	TA804	TA805	TA806	TA807	TA808	TA809	TA810	TA811	TA812	TA813	TA814	TA815
10	TA900	TA901	TA902	TA903	TA904	TA905	TA906	TA907	TA908	TA909	TA910	TA911	TA912	TA913	TA914	TA915

C.2 Direct and environmental cost impact equations – DDP

14.2 Costs related to environmental impact - I - Detail Design

Raw Material Extraction	Related Letter Formula	
	Direct Cost	Environmental Cost
1.1 Energy Cost for mat. Prod.:	T02 x [{T04 CES database 3.1) x C03 / 100 x T05/100} + T02 x {T06 CES database 3.1) x C03 / 100 x T07/100} + T02 x {T08 CES database 3.1) x C03 / 100 x T09/100}	
1.2 Climate Change Levy Costs		T02 x [{T04 CES database 3.1) x L01 x T05/100} + {T06 CES database 3.1) x L01 x T07/100} + {T08 CES database 3.1) x L01 x T09/100}

14.2 Costs related to environmental impact - II - Detail Design

Manufacturing		
General calculations necessary		
Complexity Sum V01 = TA012 + TA112 + TA212 + TA312 +TA412 + TA512 +TA612 + TA712 + TA812 + TA912		
Number of Parts V02 = Number of Parts (Check TA001 to TA901 and assign 1 for every box that is filled out [1 -10])		
	Direct Cost	**Environmental Cost**
1.1 Direct Costs (per part)		
[Weight factor + complexity factor] / 2 x Direct Cost Component 1 -6 (corresponding one)	[(T02/A06) + (T12 x V02/V01)] / 2 x (frm31.txt05)	
1.2 Environmental Costs (per part)		
[Weight factor + complexity factor] / 2 x Environmental Cost Component 1 -6 (corresponding one)		[(T02/A06) + (T12 x V02/V01)] / 2 x (frm31.txt06)

14.2 Costs related to environmental impact - III - Detail Design

Transportation		
	Related Letter Formula	
	Direct Cost	**Environmental Cost**
1. Incoming Transportation (for each material)		
Part weight x average distance x % Category (e.g. Regional) x [cost of transportation per ton per distance + (CO2 emission per ton per distance x CCL value)]	T02 / 1000 x (D02 to D06) x (D07 to D11) x [Table 2.5] / 100	T02 / 1000 x (D02 to D06) x (D07 to D11) x [Table 2.6] / 100
2. Outgoing Transportation		
Part weight x average distance x Product weight x [cost of transportation per ton per distance + CO2 emission per ton per distance x CCL value]	T02 / 1000 x (D12 to D16) x (D17 to D21) x [Table 2.5] / 100	T02 / 1000 x (D12 to D16) x (D17 to D21) x [Table 2.6] / 100
3. Packaging Waste - Incoming {Proportionate}		
Incoming transportation costs due to packaging (proportionately to part weight)	D22 / 1000 x (T02/ A06) x (D07 to D11) x (D02 to D06) / 100 x (Table 2.5) / 100	D22 / 1000 x (T02/A06) x (D07 to D11) x (D02 to D06) / 100 x (Table 2.6) / 100
4. Packaging Waste - Outgoing		
Outgoing transportation costs due to packaging (proportionately to part weight)	D22 / 1000 x (T02/ A06) x (D12 to D16) x (D17 to D21) x (Table 2.5) / 100	D22 / 1000 x (T02/ A06) x (D12 to D16) x (D17 to D21) x (Table 2.6) / 100
+		
Cost of yearly packaging (yearly) / yearly production	(T02/A06) x (D23 / A01)	
+		
Cost of packaging diposal (yearly) / yearly production		(T02/A06) x (D24 / A01)
+		
Cost of packaging diposal (yearly) / yearly production		(T02/A06) x (D24 / A01)

14.2 Costs related to environmental impact - IV - Detail Design

Use		
General calculations necessary		
Complexity Sum		
V01 = TA012 + TA112 + TA212 + TA312 +TA412 + TA512 +TA612 + TA712 + TA812 + TA912		
Number of Parts		
V02 = Number of Parts (Check TA001 to TA901 and assign 1 for every box that is filled out [1 -10])		
	Related Letter Formula	
	Direct Cost	Environmental Cost
1.1 Direct Costs (per part)		
[Weight factor + complexity factor] / 2 x Direct Cost Component 1 -6 (corresponding one)	frm621.txt6210.Text / V02 x T02/A06	
1.2 Environmental Costs (per part)		
[Weight factor + complexity factor] / 2 x Environmental Cost Component 1 -6 (corresponding one)		frm621.txt621P.Text / V02 x T02/A06

14.2 Costs related to environmental impact - V - Detail Design

End-of Life	
General calculations necessary	
Complexity Sum	
V01 = TA012 + TA112 + TA212 + TA312 +TA412 + TA512 +TA612 + TA712 + TA812 + TA912	
Number of Parts	
V02 = Number of Parts (Check TA001 to TA901 and assign 1 for every box that is filled out [1 -10])	
1.1 What is the most propable EoL scenario for the part?:	
Check TA015, TA115, etc.	

End of Life	Related Letter Formula	
	Direct Cost	Environmental Cost
1. EoL scenario: Landfill		
1.1 Transport costs x (average distance to landfill site) x part weight	2.37/100 x 200 x T02 / 1000	0.0355/100 x 200 x T02 / 1000
1.2.2 Landfill costs x (part weight / product weight)	(26) x [T02 / A06] / 1000	(24) x [T02 / A06] / 1000
2. EoL scenario: Hazardous Waste Landfill		
2.1 Transport costs x (average distance to treatment site x (part weight / product weight)	2.37/100 x 200 x T02 / 1000	0.0355/100 x 200 x T02 / 1000
2.2 Worst case scenario treatment cost of hazardous substances		[(T02/A06) + (T12 x V02/V01)] / 2 x (N129 - N629) *(depending on which component the part is in)* x (T14 - 1) / 9
2.3 Landfill cost after treatment x (part weight / product weight)	(26) x [T02 / A06] / 1000	(24) x [T02 / A06] / 1000
3 Incineration		
3.1 Transport costs (average distance to treatment site) x (part weight / product weight)	2.37/100 x 200 x T02 / 1000	0.0355/100 x 200 x T02 / 1000
3.2 Revenue from incineration	[-] 70x T02/1000	32.75 x T02/1000

4. Re-Use		
4.1 Incoming + Outgoing transport costs (average distance to treatment site + distance from treatment site to spare part storage) x (part weight / product weight)	2.37/100 x 200 x T02 / 1000	0.0355/100 x 200 x T02 / 1000
4.3 Revenue from re-use	[-] [(T02 / (N114 t0 N614) *(depending on which component the part is in)*) + (T12 x V02/V01)] / 2 x ((N110 to N610) *(depending on which component the part is in)* -1 / 9) x (Total results from I Raw Material Extr. & II. Manufacturing)	
5. Recycle		
5.1 Transport costs (average distance to treatment site) x (part weight / product weight)	2.37/100 x 200 x T02 / 1000	0.0355/100 x 200 x T02 / 1000
5.2 Revenue from sale of recyclates *weight of material used x material group value table 3.3*		
5.2.1 Revenue from sale of recycled material 1	T02 x T04 x Averaged Cost in £ per kg (database 3.1)	
5.2.2 Revenue from sale of recycled material 2	T02 x T06 x Averaged Cost in £ per kg (database 3.1)	
5.2.3 Revenue from sale of recycled material 3	T02 x T08 x Averaged Cost in £ per kg (database 3.1)	
6. Legislative (environmental) Costs		F06 x T02 / A06 + (F07 x F08 / A01) x T02 / A06

C.3 Main issues of the parts

15.2 Main Issue of part Design - I Weight

Code	Weight Design suggestion	Further Instructions	Examples	Life Cycle Step(s) involved
Z01	**1. Material choices :**	Focus Issue: weight (density range)		
Z02	1.1 Choose a different material from the same material group			**All**
Z03	1.2 Choose a different material from another material group			**All**
Z04	**2. Mass of the part**			
Z05	2.1 Reduce the total mass of the part thus less material is required - Review of structural integrity and product requirements the weight can be reduced			**All**
Z06	2.2 Use smart structural product design to enhance product stability/ rigidity by using less material		Spaceframe of a car	**All**
Z07	2.3 Reduction of weight of packaging	Consider alternative materials which are lighter		**Transportation**
		Reduce amount of packaging material used		
Z08	2.4 Anti weight (TRIZ principle 8)	To compensate for the weight of an object merge with other objects that	Inject foaming agent into part	**Manufacturing, Transportation, Use, EoL**
			Use gas that is lighter than air to make balloon fly	
Z09	2.5 Flexible shells and thin film (TRIZ principle 30)	Use flexible shells and thin films instead of three dimensional structures (to save weight) of part	Use inflatable structure as winter covers on tennis courts	**Manufacturing, Transportation, Use, EoL**
Z10	2.6 Porous material (TRIZ principle 31)	Drill holes in the part in places of minimum stress to reduce weight of it	Beam used for buildings and structures has holes in the middle where minimum stress only occurs to save weight	**Manufacturing, Transportation, Use, EoL**
Z11	2.7 Composite materials (TRIZ principle 40)	Change the part from uniform to composite (multiple) materials	fiber golf club shafts are lighter, stronger and more flexible than	**Manufacturing, Transportation, Use, EoL**
Z12	2.8 Spheriodality - Curvature (TRIZ principle 14)	Change the shape of the part (from rectilinear to carvilinear) --> higher strength whilst less material is used hence lower weight		**Raw Material Extraction, Manufacturing, EoL**

15.2 Main Issue of part Design - II Complexity (& Processes)

Code	Complexity Design suggestion	Further Instructions	Examples	Life Cycle Step(s) involved
Z21	**3. Reduce the complexity of the part [Application of DfA (Design for assembly) principles] :**			**Manufacturing**
Z22	3.1 Consider ease of assembly during product design			**Manufacturing**
Z23	3.2 Reduce the mix of materials of the part			**Raw Material Extraction, Manufacturing, EoL**
Z24	3.3 Reduce the mix of fasteners	Reduction of different types of fasteners used		**Manufacturing, EoL**
Z25	3.4 Reduce the complexity of the geometrical shape of the part if possible	Easier to manufacture		**Manufacturing**
Z26	3.5 Merging (TRIZ principle 5)	Bring closer together or merge identical features of the part design thus making the part less complex		**Manufacturing**
Z27	**4. Application of DfM (Design for manufacture) principles**			**Manufacturing**
Z28	4.1 Design the part for easy of manufacturing	Is it possible to reduce the manufacturing steps (Review the part design and identify areas that are not essential)		**Manufacturing**
		Review the possibility to carry out two manufacturing processes in one step		
		Review the ease of handling of the part during the manufacturing process;		
		Is it possible to reduce time required to produce one unit		
Z29	4.2 Reduce energy to manufacture the part			**Manufacturing**
Z30	4.3 Reduce the time to manufacture the part			**Manufacturing**
Z31	**5. Evaluate to produce the part on site instead if it currently comes from a supplier**	Carry out a break even analysis and check if the yearly product units of the part actually justify this decision		**Manufacturing, Transportation**

15.2 Main Issue of part Design - III Material

Code	Design suggestion	Further Instructions	Examples	Life Cycle Step(s) involved
	Material			
Z40	**5. Take the End-of Life scenario into account when choosing a raw material**			**Raw Material Extraction, EoL**
Z41	5.1 Check if it is possible to improve EoL scenario of the part		e.g. instead of landfill scenario evaluate Recycling of material/part options (If material can be recycled 3-4 times at end of life the environmental and financial impact is possibly reduced to 50%)	**Raw Material Extraction, EoL**
Z42	5.1.2 Check "Embodied Energy" and possibility for energy recovery at EoL			**Raw Material Extraction, EoL**
Z43	**6. Maximise process efficiency to manufacture part**			**Manufacturing**
Z44	6.1 Reduce incoming material flow and energy flow during manufacturing stage			**Manufacturing**
Z45	6.2 Choose an incoming material (for the manufacturing of the part) with a lower impact	Is it possible to use incoming material that has a lower economical and environmental impact?	E.g switch from coal for heating to LPG	**Manufacturing**
Z46	6.3 Reduce waste outflow from processes	Reduce Waste being produced during the manufacturing processes		**Manufacturing**

15.2 Main Issue of part Design - III Material

Code	Design suggestion	Further Instructions	Examples	Life Cycle Step(s) involved
	Material			
Z47	**7. In case the part is a consumable**			**Use**
Z48	7.1 Treat the part that is the consumable as a product	Evaluate the Life Cycle Impact of a consumable by treating it as a		**Use**
		Use matrix to find out what the biggest financial and environmental impact of the consumable is and at which (consumable) Life Cycle step it occurs		**Use**
		Investigate solutions to reduce the impact of the consumable during its Life Cycle step with the biggest impact		**Use**
Z49	7.2 What is the purpose of the consumable part	Does it have one?		**Use**
Z50	7.3 Can the consumable be designed out?	Is the consumable part of the products main function		**Use**
		If yes: Consumable cannot be designed out	E.g. Vending machine - here the consumable cannot be designed out because it the main part of the product function	**Use**
		If no: Is it possible to avoid use of consumable by using smart design	E.g. Dyson vacuum cleaner does not require filters	**Use**
Z51	7.4 Reduce Waste caused by Consumables	Some consumables create waste during their use		**Use, EoL**
		Re-use of consumable	E.g. refill printer cartridges	**Use, EoL**
		Re-design consumables to avoid waste	E.g. caseless ammunition	**Use, EoL**

15.2 Main Issue of part Design - IV Energy

Code	Energy Design suggestion	Further Instructions	Examples	Life Cycle Step(s) involved
Z60	**8. Transportation**			Transportation
Z61	8.1 Review logistics and evaluate a different method of transportation from supplier and to distributors	Weigh delivery time issue against financial and environmental impact	E.g switch from plane to sea ship	Transportation
Z62	8.2 Set up a supplier network that is highly efficient	Is it possible to choose a supplier that is located closer to the prodcution facility. Reduction of component cost due to reduced transportation costs.		Transportation
Z63	**9. Application of DfS (Design for servicability, reliability and maintainability) principle**			Use
Z64	Take measures to increase the time between servicing		E.g. Two decades ago time between servicing for cars was appr. 10 000km; nowadays it is up to 25 000km or more.	Use
Z65	**10. Energy Inflow**			Use
Z66	**10.1 Active**	Reduce the active amount of energy required by the part and increase efficiency measures		Use
Z67	**10.2 Passive**			Use
		Design out the standby function of the component and the part		Use

15.2 Main Issue of part Design - IV Energy

Code	Energy Design suggestion	Further Instructions	Examples	Life Cycle Step(s) involved
Z68	**11. In the case the part is produced in site: Reduce CO2 emissions from a process on site not inlcuding energy production**			Manufacturing
Z69	11.1 Change certain machines and process steps	Is it possible to use alternative that does not generate any CO2 emissions		Manufacturing
Z70	11.2 Use filter system to reduce CO2 emissions on site	Evaluate suitability of mechanical or chemical filtration system		Manufacturing
Z71	**12. I Reduce the energy use on site**			Manufacturing
Z72	12.1 Consider use of heating controls to switch of heating in areas where it is not essential			Manufacturing
Z73	12.2. Check the efficiency of heating system	Would it make sense to apply a more	E.g. switch from electric heating to gas	Manufacturing
Z74	12.3 Check the efficiency of lighting system	Consider use high efficient light bulbs that consume less energy and have a longer life cycle		Manufacturing
Z75	12.4 Application of automation system	Tighten up processes by the use of an automation system; Is it possible to implement remote sensors to automatically switch of light in areas that are not in use (caution: keep health and safety aspect in mind)		Manufacturing
Z76	12.5 Use of waste heat	Is it possible to use waste heat of certain processes for various purposes	E.g. divert waste heat from large compressor to heat office spaces	Manufacturing
Z77	12.6 Apply an energy reduction scheme on site			Manufacturing

15.2 Main Issue of part Design - V Legislation

Legislation

Code	Design suggestion	Further Instructions	Examples	Life Cycle Step(s) involved
Z81	13. Re-use of parts	Is it possible to plan for re-use of parts from EoL stage being re-introduced at the manufacturing stage --> Change EoL scenario of the part	In case of producer take back schemes such as WEEE (Waste of Electrical and Electronic Equipment) or ELV (End-of Life Vehicle) Directive	EoL
Z82	14. Apply the DfR (Design for Recycling) principle	Ease of Recycling: Reduce the number of different materials used		EoL
		Ease of Recycling: Avoid the use of composite materials		EoL
		Replace toxic materials with non-hazardous alternatives	Directive in place e.g. RoHS (Restriction of Hazardous Substance) or ELV (End-of Life Vehicle) Directive banning e.g. lead	EoL
		Reduce complexity of the product		EoL
		Promote infrastructures geared towards recycling		EoL
Z83	15. Consider Upgradability and Modularization	Is it possible to upgrade product by exchanging certain parts? This would make it obsolete to throw the whole product away	E.g. Personal Computer, this has an impact on producer take back legislations (e.g. WEEE) since it extends the Life Cycle of the product	Use, EoL

15.2 Main Issue of part Design - VI Necessity

Necessity

Code	Design suggestion	Further Instructions	Examples	Life Cycle Step(s) involved
Z91	16. Re-evaluate if the part is necessary within the context of the component or product at all	Is it possible to do without the part, to design it out completely?		All
Z92	17. Merging (TRIZ principle 5)	Is it possible to merge the part with another (similar) part?		All
		Is it possible to use the same material for this part as for other parts within the component		All
Z93	18. Taking out (TRIZ principle 2)	Try to separate the part from the component and single out the only necessary parts of it	e.g locate a noisy compressor outside the building where compressed air is used.	All
Z94	19. Universality (TRIZ principle 6)	Is it possible to summarize several parts into one by making the one part perform multiple functions - thus making several parts obsolete?	Handle of toothbrush contains toothpaste	All
Z95	20. Aligning of functions ("new" TRIZ principle 41)	Align two or more different component functions to enhance and amplify the favoured results and by doing so reduce the number of parts used.		All

C.4 Design suggestion matrix – DDP

15.1 Design Suggestion Matrix - I Raw Material Extraction

Raw Material Extraction
Design suggestion (Code)
Z01
Z02
Z03
Z04
Z05
Z06
Z12
Z21
Z23
Z40
Z41
Z42
Z91
Z92

15.1 Design Suggestion Matrix - II Manufacturing

Manufacturing
Design suggestion (Code)
Z21
Z22
Z24
Z25
Z26
Z27
Z28
Z29
Z30
Z43
Z44
Z45
Z46
Z68
Z69
Z70
Z71
Z72
Z73
Z74
Z75
Z76
Z77
Z94
Z95

15.1 Design Suggestion Matrix - III Transportation

Transportation
Design suggestion (Code)
Z07
Z08
Z09
Z10
Z11
Z31
Z60
Z61
Z62

15.1 Design Suggestion Matrix - IV Use

Use
Design suggestion (Code)
Z11
Z12
Z47
Z48
Z49
Z50
Z51
Z63
Z64
Z65
Z66
Z67
Z83
Z93
Z94
Z95

15.1 Design Suggestion Matrix - V End-of Life

End-of Life
Design suggestion (Code)
Z21
Z23
Z24
Z40
Z42
Z50
Z51
Z81
Z82
Z83
Z94
Z95

Appendix D: Screenshots User Interface

Within the Appendix D screenshots of the user interface are provided. The order in which the screenshots are presented is the same order as if the user interface screen appears to the user if the go back option is not used at all. The screenshots shown contain preset input data and results for the case study 3 – Telehandler complete:

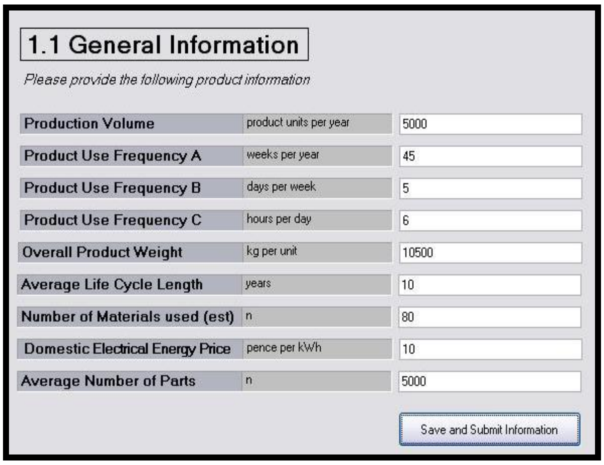
D.1.1 – These are the screenshots of the Early Concept phase only

D.1.2 – Here the screenshots of the Advanced Concept phase are shown

D.1.3 – This section shows the Detail Design phase screenshots of the user interface only

D.1 Telehandler complete case study

D.1.1 – Early Concept phase



1.2 Raw Material Extraction

Firstly choose the Material Class, then the Material Name and finally the % used (based on product weight)

	Material Name	% Used
Material 1	Low Carbon Steel	54
Material 2	Flexible Polymer Foam (MD)	0.001
Material 3	High Carbon Steel	10
Material 4	Cast Iron (ductile)	20
Material 5	Stainless Steel	4
Material 6	Copper Alloys	0.001
Material 7	Polyurethane	1
Material 8	ABS (Acrylonitrile Butadiene Styrene)	5
Material 9	PS (Polystyrene)	5
Material 10	PC (Polycarbonate)	0.002
		Total must be 100%

Additional Costs at Raw Material Extraction	£ per year	0

Go back to step 1.1 | Save and Submit Information

1.3.1 Manufacturing 1

Please provide the following product information - All figures are just regarding the manufacturing process

CO2 Emission (from Processes (not energy use)	t per year	0
Electrical Energy Use (per year)	kWh per year	20000000
Electrical Energy Price (Industrial)	pence per kWh	5
Natural Gas Use	kWh per year	15000000
Natural Gas Price (Industrial)	pence per kWh	1.7
Coal Use	t per year	0
Coal Price (Industrial)	pence per ton	0
LPG Use	cubic metres per year	0
LPG Price	pence per cubic metre	0
Diesel Fuel Use	cubic metres per year	0
Diesel Price (Industrial)	pence per cubic metre	0

Go back to step 1.2 | Save and Submit Information

1.3.2 Manufacturing 2

Please provide the following product information - All figures are just regarding the manufacturing process

Material 1 Inflow (not from Raw Material Extraction)	kg per year	0
Material 1 Price	pence per kg	0
Material 2 Inflow	kg per year	0
Material 2 Price	pence per kg	0
Water Use	cubic metres per year	500000
Water Price	pence per cubic metre	100

Water Outflow	cubic metres per year	450000
Cost of Effluent Water	pence per cubic metre	70
Toxic Substance Outflow	litres/ kg per year	0
Toxic Substance Treatment Costs	£ per litre / kg	0
Toxic Substance Disposal Costs	£ per litre / kg	0

Go back to step 1.3.1 | Save and Submit Information

1.4.1 Transportation 1

Please provide the following product information

Incoming Transportation

% of Parts Delivered by Suppliers (value can be anywhere between 0% and 100%)	n	90

% of All Parts Supplied - Total of all 5 must be 100%

% of Parts Delivered by Lorry	n	30
% of Parts Delivered by Train	n	20
% of Parts Delivered by Inland Ship	n	5
% of Parts Delivered by Sea Ship	n	40
% of Parts Delivered by Airplane	n	5

Average Distance of Incoming Transportation

by Lorry	km	350
by Train	km	400
by Inland Ship	km	200
by Sea Ship	km	8000
by Airplane	km	7000

Go back to step 1.3.2 | Save and Submit Information

1.4.2 Transportation 2

Please provide the following product information

Outgoing Transportation

% of All Parts Leaving Factory - Total of all 5 must be 100%

% of Parts Transported by Lorry	n	30
% of Parts Transported by Train	n	20
% of Parts Transported by Inland Ship	n	0
% of Parts Transported by Sea Ship	n	50
% of Parts Transported by Airplane	n	0

Average Distance of Outgoing Transportation

by Lorry	km	200
by Train	km	0
by Inland Ship	km	0
by Sea Ship	km	7000
by Airplane	km	0

Packaging

Average Mass of Product Packaging	kg per unit	120
Average Yearly Cost of Packaging	£ per year	100000
Average Cost of Packaging Disposal	£ per year	60000

Go back to step 1.4.1 | Save and Submit Information

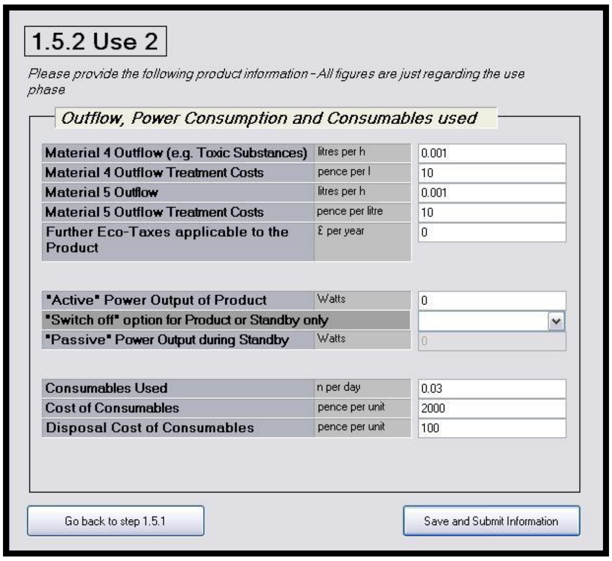
1.5.1 Use 1

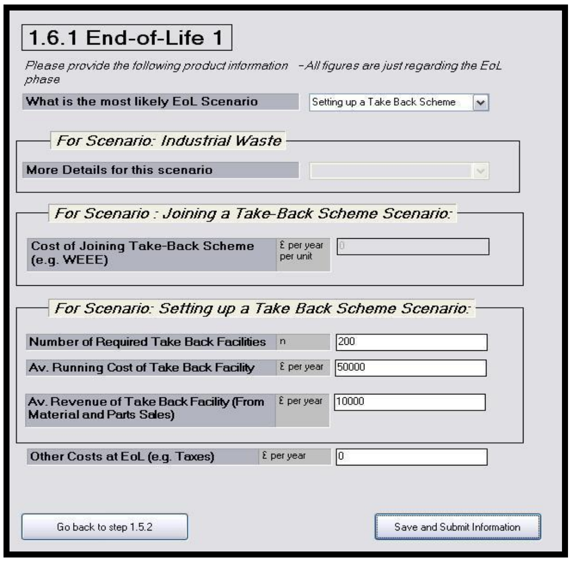
Please provide the following product information - All figures are just regarding the use phase

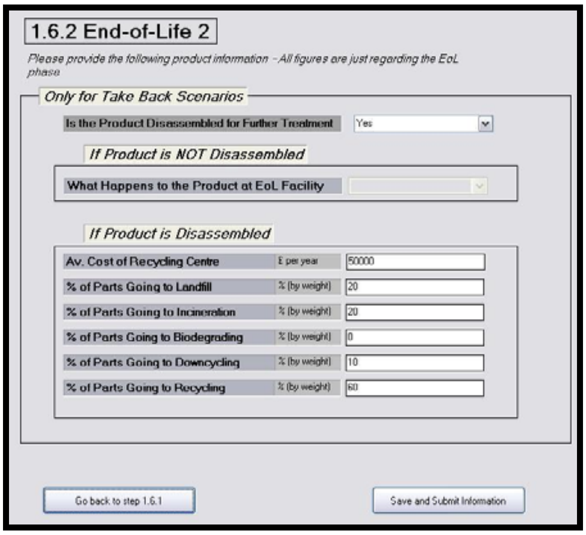
Inflow

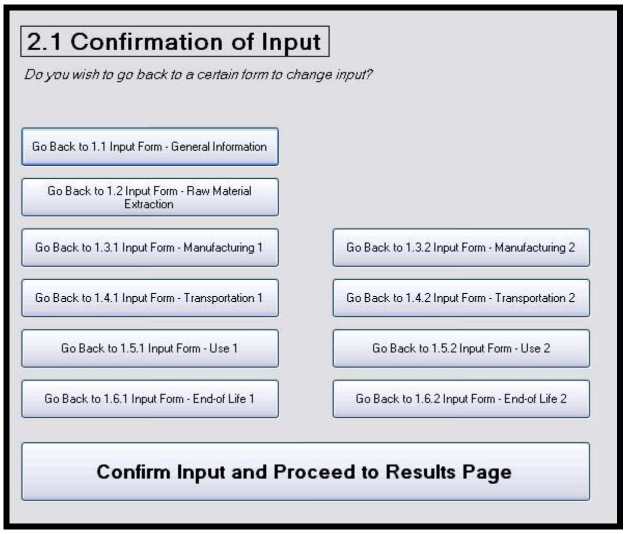
Material 1 Inflow (e.g. water)	litres per h	0.01
Material 1 Price	£ per litre	20
Material 2 Inflow	litres per h	0.01
Material 2 Price	£ per litre	10
Material 3 Inflow	litres per h	0
Material 3 Price	£ per litre	0
Natural Gas Use	kWh per h	0
Average Natural Gas Price	pence per kWh	0
Coal Use	g per h	0
Average Coal Price	pence per g	0
LPG Use	litres per h	0
LPG Price	pence per litre	0
Diesel Fuel Use	litres per h	10
Diesel Fuel Price	pence per litre	50
Petrol Fuel Use	litres per h	0
Petrol Fuel Price	pence per litre	0

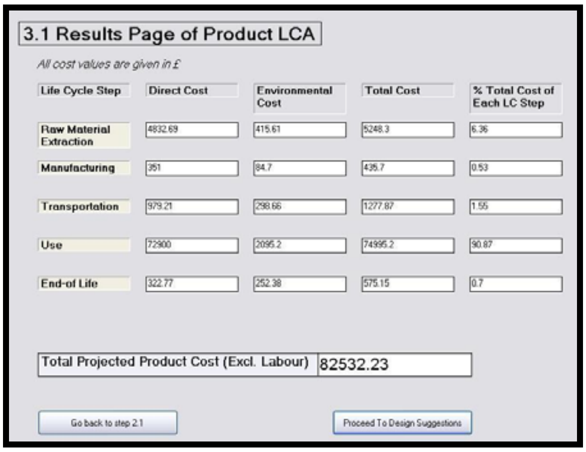
Go back to step 1.4.3 | Save and Submit Information

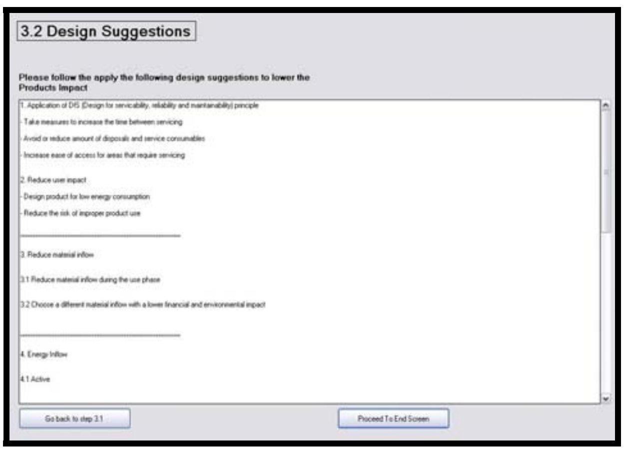

1.5.2 Use 2
Please provide the following product information - All figures are just regarding the use phase
Outflow, Power Consumption and Consumables used
Material 4 Outflow (e.g. Toxic Substances) litres per h 0.001
Material 4 Outflow Treatment Costs pence per l 10
Material 5 Outflow litres per h 0.001
Material 5 Outflow Treatment Costs pence per litre 10
Further Eco-Taxes applicable to the Product £ per year 0
"Active" Power Output of Product Watts 0
"Switch off" option for Product or Standby only
"Passive" Power Output during Standby Watts 0
Consumables Used n per day 0.03
Cost of Consumables pence per unit 2000
Disposal Cost of Consumables pence per unit 100
Go back to step 1.5.1
Save and Submit Information

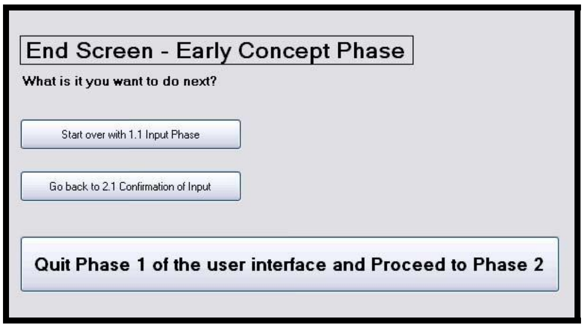

1.6.1 End-of-Life 1
Please provide the following product information - All figures are just regarding the EoL phase
What is the most likely EoL Scenario Setting up a Take Back Scheme
For Scenario: Industrial Waste
More Details for this scenario
For Scenario : Joining a Take-Back Scheme Scenario:
Cost of Joining Take-Back Scheme (e.g. WEEE) £ per year per unit 0
For Scenario: Setting up a Take Back Scheme Scenario:
Number of Required Take Back Facilities n 200
Av. Running Cost of Take Back Facility £ per year 50000
Av. Revenue of Take Back Facility (From Material and Parts Sales) £ per year 10000
Other Costs at EoL (e.g. Taxes) £ per year 0
Go back to step 1.5.2
Save and Submit Information


1.6.2 End-of-Life 2
Please provide the following product information - All figures are just regarding the EoL phase
Only for Take Back Scenarios
Is the Product Disassembled for Further Treatment Yes
If Product is NOT Disassembled
What Happens to the Product at EoL Facility
If Product is Disassembled
Av. Cost of Recycling Centre £ per year 50000
% of Parts Going to Landfill % (by weight) 20
% of Parts Going to Incineration % (by weight) 20
% of Parts Going to Biodegrading % (by weight) 0
% of Parts Going to Downcycling % (by weight) 10
% of Parts Going to Recycling % (by weight) 60
Go back to step 1.6.1
Save and Submit Information

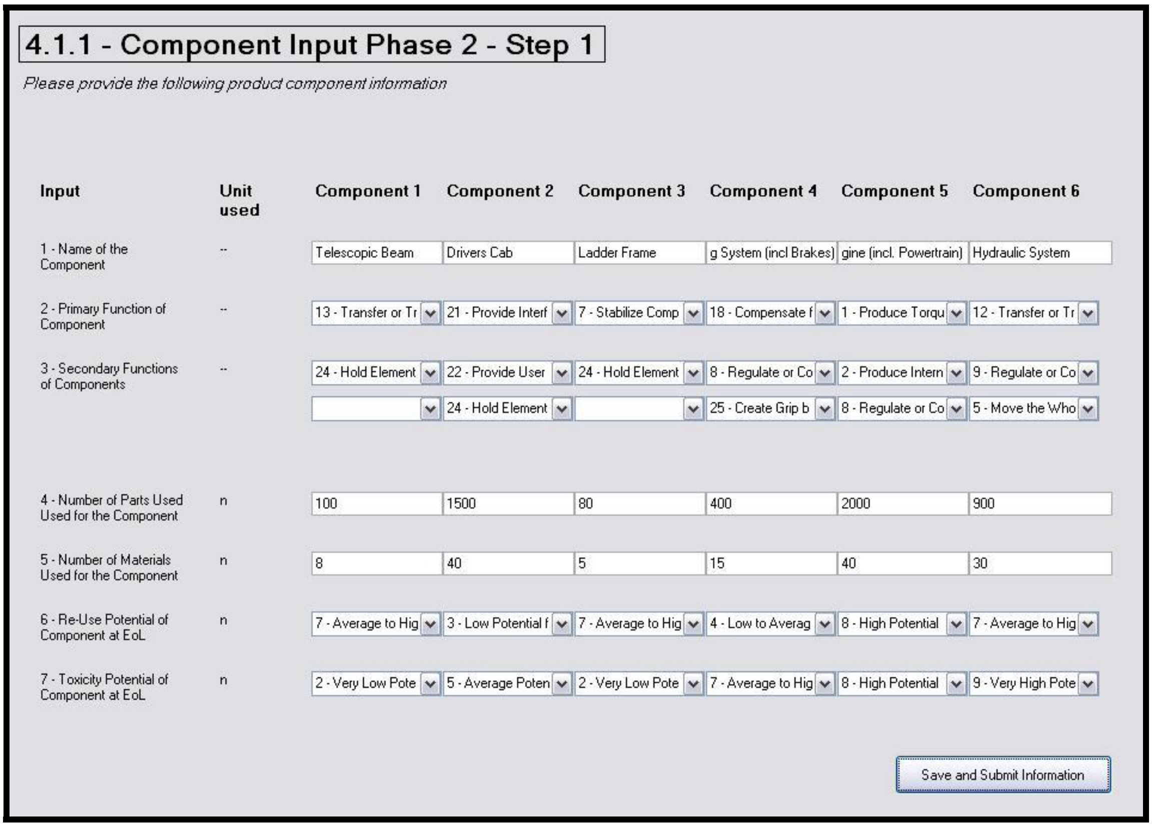

2.1 Confirmation of Input
Do you wish to go back to a certain form to change input?
Go Back to 1.1 Input Form - General Information
Go Back to 1.2 Input Form - Raw Material Extraction
Go Back to 1.3.1 Input Form - Manufacturing 1
Go Back to 1.3.2 Input Form - Manufacturing 2
Go Back to 1.4.1 Input Form - Transportation 1
Go Back to 1.4.2 Input Form - Transportation 2
Go Back to 1.5.1 Input Form - Use 1
Go Back to 1.5.2 Input Form - Use 2
Go Back to 1.6.1 Input Form - End-of Life 1
Go Back to 1.6.2 Input Form - End-of Life 2
Confirm Input and Proceed to Results Page


3.1 Results Page of Product LCA
All cost values are given in £
Life Cycle Step Direct Cost Environmental Cost Total Cost % Total Cost of Each LC Step
Raw Material Extraction 4832.69 415.61 5248.3 6.36
Manufacturing 351 84.7 435.7 0.53
Transportation 979.21 298.66 1277.87 1.55
Use 72900 2095.2 74995.2 90.87
End-of Life 322.77 252.38 575.15 0.7
Total Projected Product Cost (Excl. Labour) 82532.23
Go back to step 2.1
Proceed To Design Suggestions


3.2 Design Suggestions
Please follow the apply the following design suggestions to lower the Products Impact
1. Application of DfS (Design for servicability, reliability and maintainability) principle
- Take measures to increase the time between servicing
- Avoid or reduce amount of disposals and service consumables
- Increase ease of access for areas that require servicing
2. Reduce user impact
- Design product for low energy consumption
- Reduce the risk of improper product use
3. Reduce material inflow
3.1 Reduce material inflow during the use phase
3.2 Choose a different material inflow with a lower financial and environmental impact
4. Energy Inflow
4.1 Active
Go back to step 3.1
Proceed To End Screen



D.1.2 – Advanced Concept phase



4.1.2 - Component Input Phase 2 - Step 2

Please provide the following product component information

Input	Unit used	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6
8 - EoL Scenario of Component	--	Re-Use	Landfill	Re-Use	Landfill	Re-Use	Re-Use
9 - Main Material of the Component	--	Low Carbon Steel	Polyurethane	Low Carbon Steel	High Carbon Steel	Cast Iron (ductile)	High Carbon Steel
10 - Estimated Weight of Component	kg	1000	600	3000	1200	3500	1000
11 - Participation of main Material to Total Component Weight	% of total weight	6	2	20	40	50	50
12 - Is the Component Manufactured on Site	YES/ NO	YES	YES	YES	NO	NO	NO
13 - Additional Yearly Raw Material Cost for Component	£ / year	1500000	1000000	4000000	0	0	0
14 - Does the Component require Packaging when delivered to Assembly	YES/ NO	NO	NO	NO	YES	YES	YES
15 - Average Weight of that Packaging	kg per component	0	0	0	10	50	20
16 - Average Cost of the Incoming Component Packaging	£ / year	0	0	0	5	80	20
17 - Average Disposal Cost of that Incoming Packaging	£ / year	0	0	0	1	10	5

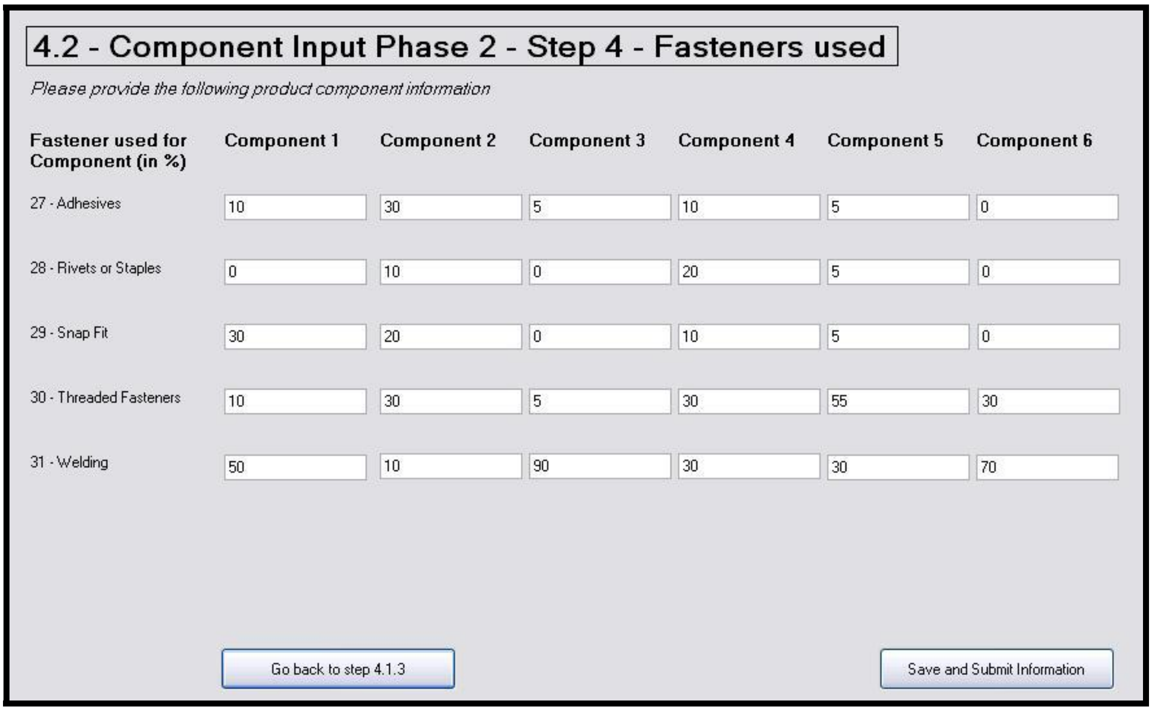
Go back to step 4.1.1 | Save and Submit Information

4.1.3 - Component Input Phase 2 - Step 3

Please provide the following product component information

Input	Unit used	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6
18 - Cost of Component if Purchased from Supplier	£ per Component	0	0	0	2500	8000	1200
19 - Does the Component Rely on Material Inflow to Function?	YES / NO	NO	NO	NO	NO	YES	YES
20 - Does the Component Create a Material Outflow ?	YES / NO	NO	NO	NO	NO	YES	YES
21 - Does the Component Rely on Energy Inflow (such as LPG) ?	YES / NO	NO	NO	NO	NO	YES	NO
22 - Does the Component Rely on Electric Energy Inflow ?	YES / NO	NO	YES	NO	NO	NO	NO
23 - Does the Component Rely on Consumables	YES / NO	NO	NO	NO	NO	YES	NO
24 - Maximum EoL Treatment Cost of Component (e.g. due to toxicity)	£ per Component	0	30	10	80	200	200
25 - Component Treatment Cost if Component is Re-used (e.g. Cleaning)	£ per Component	10	70	10	15	500	300
26 - Dismantling Costs of Component	£ per Component	30	200	30	30	700	300

Go back to step 4.1.2 | Save and Submit Information



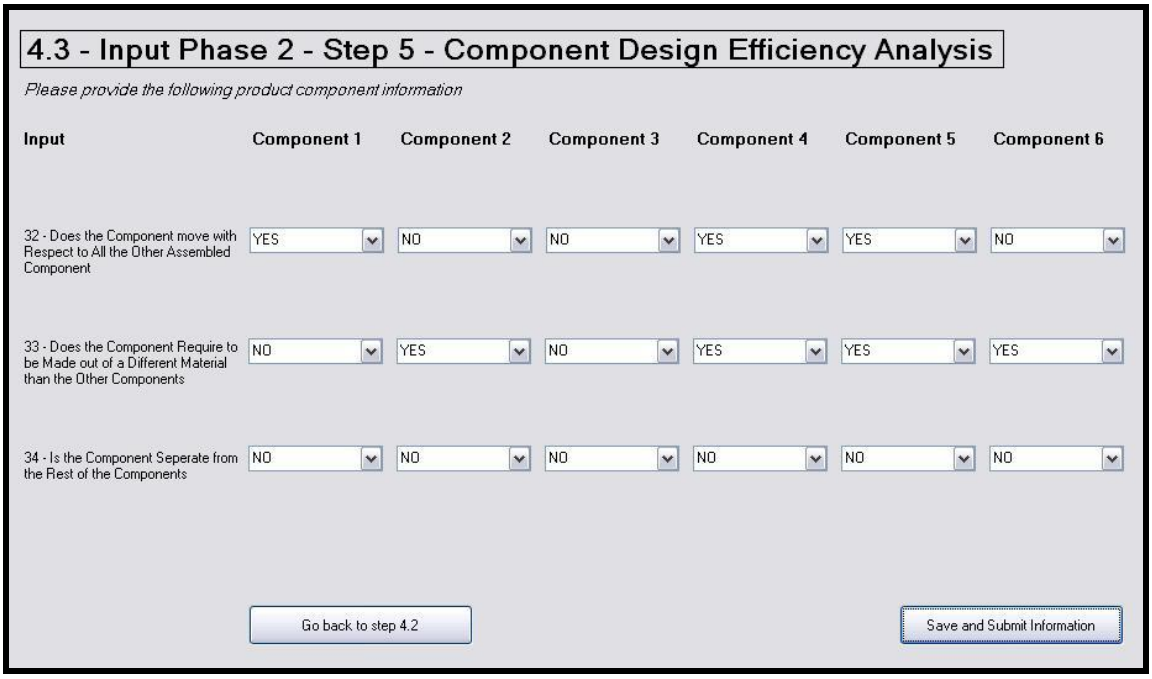
4.2 - Component Input Phase 2 - Step 4 - Fasteners used

Please provide the following product component information

Fastener used for Component (in %)	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6
27 - Adhesives	10	30	5	10	5	0
28 - Rivets or Staples	0	10	0	20	5	0
29 - Snap Fit	30	20	0	10	5	0
30 - Threaded Fasteners	10	30	5	30	55	30
31 - Welding	50	10	90	30	30	70

Go back to step 4.1.3

Save and Submit Information



4.3 - Input Phase 2 - Step 5 - Component Design Efficiency Analysis

Please provide the following product component information

Input	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6
32 - Does the Component move with Respect to All the Other Assembled Component	YES	NO	NO	YES	YES	NO
33 - Does the Component Require to be Made out of a Different Material than the Other Components	NO	YES	NO	YES	YES	YES
34 - Is the Component Seperate from the Rest of the Components	NO	NO	NO	NO	NO	NO

Go back to step 4.2

Save and Submit Information

5.1 Confirmation of Input - Phase 2

Do you wish to go back to a certain form to change input?

Go Back to 4.1.1 Input Form

Go Back to 4.1.2 Input Form

Go Back to 4.1.3 Input Form

Go Back to 4.2 Input Form

Go Back to 4.3 Input Form

Confirm Input and Proceed to Results Page of Phase 2

6.1 Results Page of Components Impact

	Impact Ranking of Components (1 = Component w highest Impact)	% Share of Total Product Costs	Total Cost Combined Environmental and Direct Cost (in £)	Direct Cost in £	Environmental Cost in £
Component 1		0.11	86.51	84.19	2.32
Component 2		1.93	1554.69	1473.85	80.84
Component 3		0.22	179.53	172.58	6.96
Component 4		4.14	3336.25	3020.35	315.89
Component 5	1	90.23	72636.51	72351.34	285.18
Component 6		3.37	2709.57	2704.26	5.31

Go back to 5.1 Confirmation of Input Page

Proceed to 6.2.1 Impact Result

6.2.1 Results Page - Component w biggest Impact

Component Name: *Engine (incl. Powertrain)*

The Life Cycle that Causes the Biggest Impact: Use

Life Cycle Step	Direct Cost	Environmental Cost	Total Cost	% Total Cost of Each LC Step
Raw Material Extraction	0	7.27	7.27	0.01
Manufacturing	8000	984	8984	12.37
Transportation	259.75	11.34	271.09	0.37
Use	70875	271.35	71146.35	97.95
End-of Life	-6783.41	-988.78	-7772.19	-10.7

Total Projected Component Cost (Excl. Labour): 72636.51

Go back to 6.1 Results of Components

Proceed to 6.2.2.1 - Design Suggestions 1

6.2.2.1 Design Suggestions - Component w biggest Impact

Please follow the apply the following design suggestions to lower the Components Impact

Component Name: *Engine (incl. Powertrain)*

1. Component Necessity Analysis Results

The component appears to be a vital part of the whole product and cannot be designed out

2. LCA based Design Suggestions

1. Application of DfS (Design for servicability, reliability and maintainability) principle

- Take measures to increase the time between servicing

- Avoid or reduce amount of disposals and service consumables

- Increase ease of access for areas that require servicing

2. Reduce user impact

- Design Component for low energy consumption

3. Fastener Design Suggestion

The following fastener methods are optimal/ideal
for the Life Cycle Raw Material Extraction:

1) Snap Fit - Very quick disassembly and re-assemble

[Go back to 6.2.1 - Results Impact] [Proceed to 6.2.2.2 - Design Suggestions 2]

6.2.2.2 Design Suggestions - Component w biggest Impact

Please follow the apply the following design suggestions to lower the Components Impact

Component Name: *Engine (incl. Powertrain)*

3. Function based Design Suggestions

INVERSION - The other way round

a. Instead of an action dictated by the specifications of the problem, implement an opposite action

b. Make a moving part of the object or the outside environment immovable and the non-moving part movable

c. Turn the object upside-down

Examples

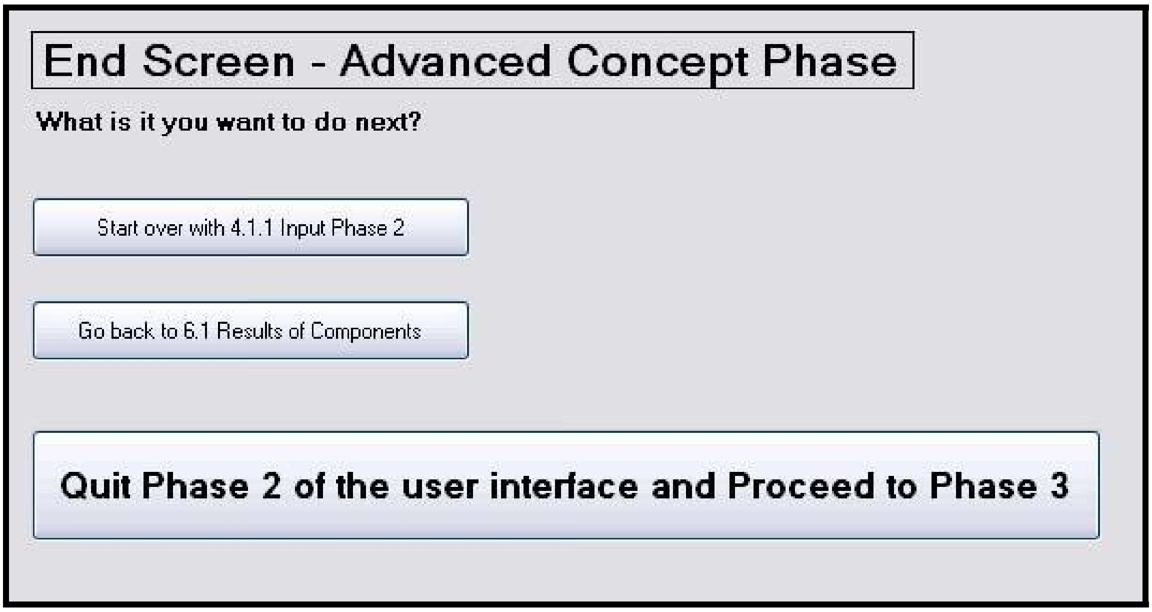
- Abrasively cleaning parts by vibrating the parts instead of the abrasive

SPHERIODALITY - Curvature

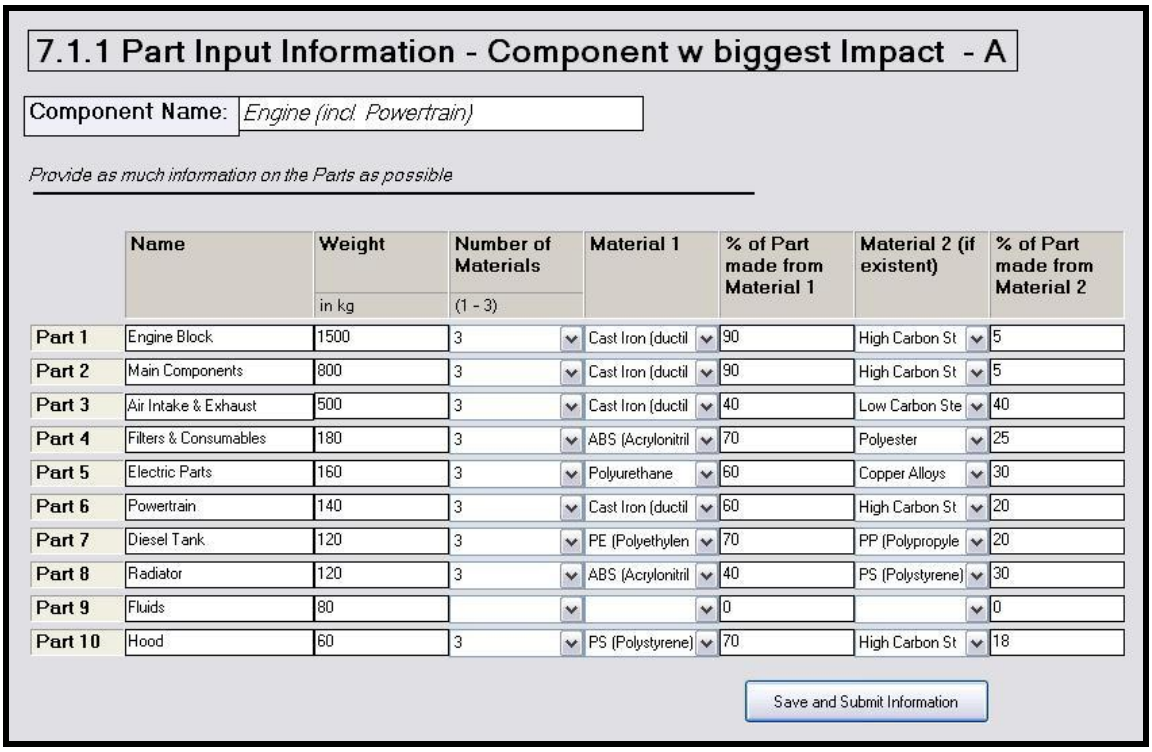
a. Replace linear parts or flat surfaces with curved ones; replace cubical shapes with spherical shapes

b. Use rollers, balls spirals
c. Replace a linear motion with rotating movement; utilize a centrifugal force

[Go back to 6.2.2.1 - Design Suggestions 1] [Proceed to 6.3.1 - Results Impact]



D.1.3 – Detail Design phase



7.1.1 Part Input Information - Component w biggest Impact - A

Component Name: *Engine (incl. Powertrain)*

Provide as much information on the Parts as possible

	Name	Weight in kg	Number of Materials (1 - 3)	Material 1	% of Part made from Material 1	Material 2 (if existent)	% of Part made from Material 2
Part 1	Engine Block	1500	3	Cast Iron (ductil	90	High Carbon St	5
Part 2	Main Components	800	3	Cast Iron (ductil	90	High Carbon St	5
Part 3	Air Intake & Exhaust	500	3	Cast Iron (ductil	40	Low Carbon Ste	40
Part 4	Filters & Consumables	180	3	ABS (Acrylonitril	70	Polyester	25
Part 5	Electric Parts	160	3	Polyurethane	60	Copper Alloys	30
Part 6	Powertrain	140	3	Cast Iron (ductil	60	High Carbon St	20
Part 7	Diesel Tank	120	3	PE (Polyethylen	70	PP (Polypropyle	20
Part 8	Radiator	120	3	ABS (Acrylonitril	40	PS (Polystyrene)	30
Part 9	Fluids	80			0		0
Part 10	Hood	60	3	PS (Polystyrene)	70	High Carbon St	18

Save and Submit Information

7.1.2 Part Input Information - Component 1 w biggest Impact - B

Component Name: *Engine (incl. Powertrain)*

Provide as much information on the Parts as possible

	Material 3 (if existent)	% of Part made from Material 3	Internal Part Number (if available)	Main Fastener used	Manufacturing Complexity of the Part 1 (= very low) to 10 (=very high)	Toxicity Potential 1 (= very low) to 10 (= very high)	EoL Scenario of the Part
Part 1	Stainless Steel	5		Welding	8	6	Re-Use
Part 2	Stainless Steel	5		Threaded Faste	7	5	Recycling
Part 3	Stainless Steel	20		Welding	7	5	Recycling
Part 4	Flexible Polymer	5		Threaded Faste	6	7	Hazardous Was
Part 5	Cast Iron (ductil	10		Adhesives	8	8	Hazardous Was
Part 6	Low Carbon Ste	20		Welding	5	4	Recycling
Part 7	Stainless Steel	10		Adhesives	5	9	Hazardous Was
Part 8	Low Carbon Ste	30		Threaded Faste	5	4	Landfill
Part 9		0				10 (very high)	Hazardous Was
Part 10	Flexible Polymer	6	1967452	Threaded Faste	5	4	Recycling

Go back to step 7.1.1

Save and Submit Information

8.1 Confirmation of Input - Phase 3

Do you wish to go back to a certain form to change input?

Go Back to 7.1.1 Input Form

Go Back to 7.1.2 Input Form

Confirm Input and Proceed to Results Page of Phase 3

9.1 Results - Combined Life Cycles

	Direct Cost	Environmental Cost	Total Cost	% Share of Part towards Total Component Costs	Impact Ranking (1 = Part w highest Impact)
Part 1	6189.1	27.43	6216.53	11.12	
Part 2	8869.91	697.75	9567.65	17.11	1
Part 3	7398.82	657.32	8056.14	14.41	
Part 4	5335.89	560.63	5896.52	10.54	
Part 5	6641	718.9	7359.9	13.16	
Part 6	4235.3	451.79	4687.09	8.38	
Part 7	4250.63	459.65	4710.28	8.42	
Part 8	4232.45	457.98	4690.43	8.39	
Part 9	360.6	5.21	365.82	0.65	
Part 10	3919.57	449.05	4368.62	7.81	

Go back to 8.1 - Confirmation of Results

Proceed to 9.2 - Results - Part w biggest Impact

9.2 Results Page - Part w biggest impact

Part Name:	*Main Components*

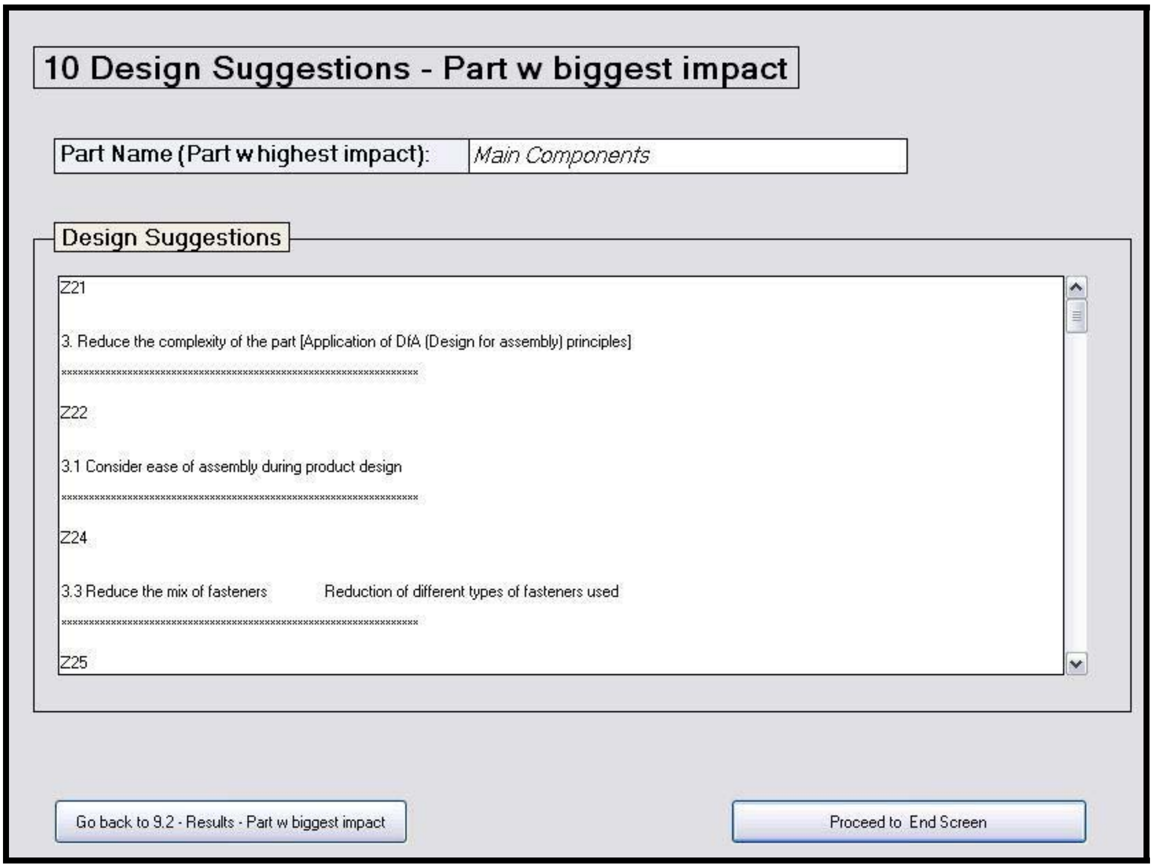
The Life Cycle that Causes the Biggest Impact for this Part	Manufacturing

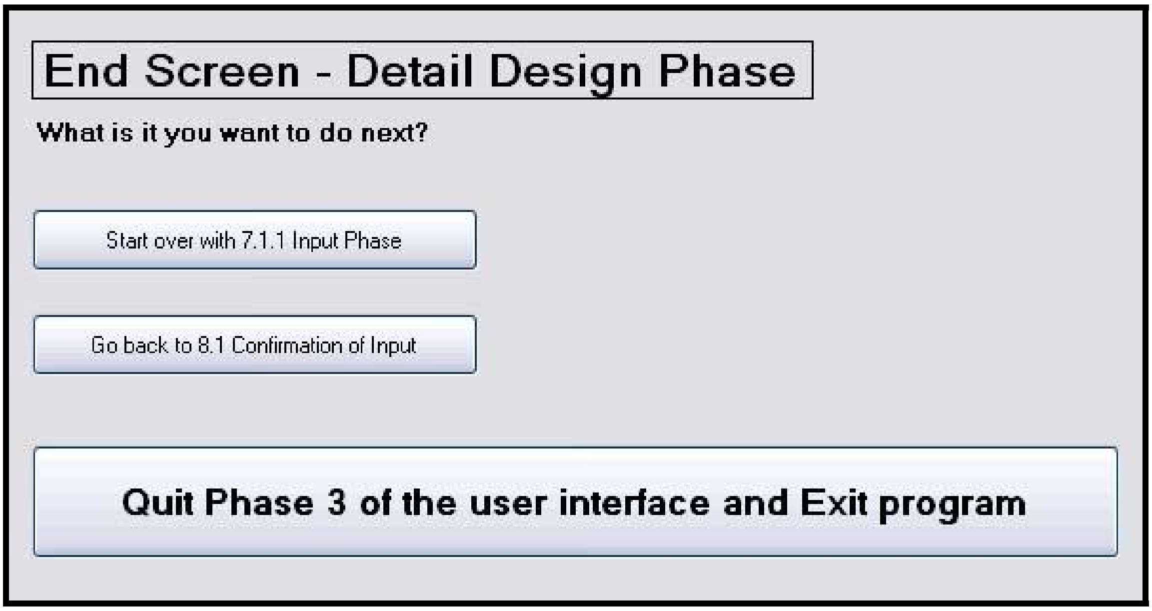
Life Cycle Step	Direct Cost	Environmental Cost	Total Cost	% Total Cost of Each LC Step
Raw Material Extraction	301.08	30.62	331.7	3.47
Manufacturing	5304.76	652.49	5957.25	62.26
Transportation	57.47	1.66	59.14	0.62
Use	3240	12.4	3252.4	33.99
End-of Life	-33.41	0.57	-32.84	-0.34

Total Projected Part Cost (Excl. Labour)	9567.65

Go back to 9.1 - Results Combined Life Cycles

Proceed to 10 - Design Suggestions


10 Design Suggestions - Part w biggest impact
Part Name (Part w highest impact):
Main Components
Design Suggestions
Z21
3. Reduce the complexity of the part [Application of DfA (Design for assembly) principles]
Z22
3.1 Consider ease of assembly during product design
Z24
3.3 Reduce the mix of fasteners
Reduction of different types of fasteners used
Z25
Go back to 9.2 - Results - Part w biggest impact
Proceed to End Screen


End Screen - Detail Design Phase
What is it you want to do next?
Start over with 7.1.1 Input Phase
Go back to 8.1 Confirmation of Input
Quit Phase 3 of the user interface and Exit program