Integrated Eco-design Decision Making for Sustainable Product Design

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This thesis is submitted in fulfilment of the requirement of the degree of

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DECLARATION AND STATEMENTS

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This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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To my family: Mama, Papa, Ibu, Ayah Li, Cik Mah,

my husband Normann Arbaq Abdul Rahman

beloved children: Ahmad Dhani and Aishah Dini,

my brothers: Abe Ewan and Yat,

for their love and support.

ABSTRACT

A major challenge for any manufacturer is including aspects of sustainable development in product design that are related to the social, environmental and economic impacts. Several methods and tools have been developed to facilitate sustainable product design, but they lack critical application of the ecological design (eco-design) process and economic costing, particularly during the conceptual design phase. This research overcomes these deficiencies by integrating eco-design approaches across all phases of product life cycle. These approaches were applied and tested in two case studies, which demonstrate that the tools developed can be used to reduce a product's environmental and economic impacts while fulfilling customer needs.

The integrated eco-design decision making (IEDM) methodology is proposed and developed in this study as a method for improving product sustainability. This is the principle contribution of this thesis to the field of sustainable product design. The IEDM applies environmental considerations across three stages of product development. The first stage is the life cycle assessment (LCA), which is used to identify critical areas in which the product's environmental performance can be improved. The results of the LCA are then analysed in the second stage using an eco-design process (Eco-Process) model. This model identifies environmental concerns relating to the manufacturing process, product use, and end-of-life (EOL) strategy. These concerns are then addressed within the third stage, which uses an ecological house of quality (Eco-HoQ) embedded in an ecological quality function deployment (Eco-QFD) process. The eco-design case-based reasoning (Eco-CBR) tool was also developed in this study to improve product design knowledge sharing.

The development of the Eco-HOQ, which is integrated into the Eco-QFD process and part of the broader IEDM, is the second major contribution of this work. The Eco-

HOQ is an extra "house" that can capture and manage sustainability considerations in a single place. This increases the relevance of the information used and produced in product design and encourages actions for improving sustainability at each phase of the Eco-QFD process. The Eco-QFD ensures that customer needs are incorporated within the context of sustainability.

The eco-design case-based reasoning (Eco-CBR) tool was developed on the premise that if experiences from the Eco-QFD process can be captured in some useful form, designers can refer to and learn from past experiences. The Eco-CBR is an intuitive decision support tool that complements the IEDM framework and proposes solutions related to the social, environmental, and economic impacts of the product.

The application of the entire IEDM framework, including the Eco-HoQ, Eco-QFD, and complementary Eco-CBR, is demonstrated in the case studies of single-use medical forceps and an office chair base. The case studies demonstrate the effectiveness of these tools when assessing a product's sustainability, even when its design is altered. In addition, this methodology provides a complete view of the environmental performance and economic cost of these products over their entire life cycles in conjunction with an assessment of customer requirements.

In summary, this thesis contributes significantly to the field of sustainable product design by proposing the integration of eco-design approaches at every stage of product development, including the critical conceptual phase. The approaches developed in this study will enable designers to improve product design, increase productivity, and reduce material usage and costs while meeting customer specifications.

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Journal articles:

Romli, A., Prickett, P., Setchi, R., and Soe, S., 2015. Integrated Eco-design Decision-Making for Sustainable Product Development. International Journal of Production Research, 53(2), 549–571.

Romli, A., Setchi, R., Prickett, P., and Miguel, P.D.L., 2015. Eco-CBR: Integration of Eco-QFD and CBR for Supporting Sustainable Product Design. Computers in Industry. (Submitted)

Conference proceedings:

Romli, A., Miguel, P.D.L, Setchi, R., Prickett, P., 2015. Eco-Case Based Reasoning (Eco-CBR) for Supporting Sustainable Product Design. In 2nd International Conference on Sustainable Design and Manufacturing. Seville. April 2015.

Romli, A., Prickett, P. Setchi, R., and Soe, S., 2014. Sensitivity Analysis of an Eco-Design House of Quality Model. In International Conference on Sustainable Design and Manufacturing. Cardiff, April 2014. pp 488-499.

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CHAPTER I

INTRODUCTION

'Design for Sustainability' has evolved since the 1990s; its focus is on sustainable product development by integrating the three main components of people, profit, and planet. These components have become fundamental to product innovation. Design for sustainability aims at making green products; it addresses the best way to meet consumers' needs in a sustainable way. In order to produce a more sustainable product, the implementation of sustainability considerations should be applied at the earliest possible stage of product design.

Product sustainability needs to be evaluated from both the environmental and economic perspectives; this requires careful consideration of customer needs, which must be met in the most economical way. To date, product designers normally focus on functionality, quality, and cost, which have long been the most important factors in product design. Sustainability has become ever more important in product design. This study advances the concept of ecological design (eco-design), as a system of strategies that aim to integrate environmental aspects throughout a product's lifecycle.

1.1 Research Motivation

As a result of the raised importance of sustainability, customers are becoming more environmentally conscious. Worldwide industrial product development trends have changed dramatically in recent years in order to produce more sustainable products to meet these customer needs. As society embraces higher levels of environmental awareness, new and established products need to evolve in order to meet the needs that are aligned with this particular demand. From a product development process perspective, this has placed greater emphasis on environmental parameters.

Legislation and related considerations from around the world place great emphasis on environmental matters. All phases in a product's lifecycle, including resource extraction, production, distribution, product use, and disposal, are increasingly dependent upon socio-ecological considerations to ensure sustainable development (Bevilacqua et al., 2007; Hare, 2010). The integration of environmental requirements into every stage of product development contributes to the establishment of a sustainable paradigm for manufacturing. Measurements such as carbon footprint (measuring kg. of CO_2), water eutrophication (kg. PO_4), air acidification (kg. SO_2), and total energy consumed (MJ) are now routinely considered in most design procedures. The need to include a sustainable and practical end-of-life (EOL) strategy requires considerations such as design for reuse, recycling, and disposal. A good practice should ensure that the product will not be 'eco-destructive' at the end of its life cycle (Kaebernick et al., 2003).

Those companies that emphasise and recognise the value in sustainability programmes often simultaneously target cost reductions, through reduced energy and usage of materials, as well as related environmental factors such as water, carbon footprint, waste, renewable materials, toxic substances, ecosystems, and habitats (Arnold et al., 2010; Ciroth, 2009; Zhou and Schoenung, 2007). A number of companies, however, view sustainability as a means to advancing their revenue. Such companies consider sustainability as the 'x-factor' in enhancing new growth that capitalises on the rising demand for environmentally friendly and energy-efficient products.

Many companies need support in developing products that meet customer requirements but that also exhibit superior environmental and social attributes. It is difficult to appraise the financial value of a product's sustainability attributes, because customers' precise sustainability needs may be intangible (Kim et al., 2014; Manmek, 2007). For example, the U.S. chemical company DuPont has a business-to-business customer base. Arnold et al. (2010) conducted a survey in April of 2010 involving nearly seven hundred DuPont customers. Their findings show that 89 percent of the respondents agreed that delivering products with environmental benefits represents a potential long-term market advantage. Although these results show that there are significant benefits in adopting customer-focussed approaches to sustainability in new product development, such approaches are often considered in a piecemeal (bit by bit) fashion.

Eco-design is now an established and critical factor during the early phases of product development. As such, enhancing customer satisfaction and providing innovative products have become crucial strategies for success. Sustainable product development and design must prudently maintain the equilibrium between social, economic, and environmental factors. The environmental and economic costs always occur early in the design phase. According to Turnbull (2014), the U.K. Design Council estimated that over four-fifths of materials and utilities costs are locked into the design stage. Another paper, by Weustink et al. (2000), emphasised that three-quarters of a product's costs are committed during the design process. As such, it is promising that by embedding eco-design into the new product design process, companies can make significant cutbacks in costs.

The optimal benefits of eco-design are achieved by reducing the environmental impact and cost for the product's entire life cycle. These processes can improve the design, increase productivity, and reduce material usage and costs. Eco-design strategies are also needed to allow manufacturers to turn the EOL process of a product into a profitable activity or business prospect.

1.2 Research Challenge

Sustainable product design represents a complex domain, in which past experiences are frequently used to solve new design problems. Product sustainability needs to be evaluated from both the environmental and economic perspectives. In reality, it is challenging to strike an appropriate balance between environmental elements while still keeping production costs as low as possible; for instance, using environmentally friendly materials may be more expensive than using more conventional materials. This challenge has led to the following research question:

> *How can past experience enable and support sustainable product development at an early design stage?*

The eco-design case-based reasoning (Eco-CBR) method introduced in this research study meets this challenge by storing and manipulating eco-design product knowledge within a case-base library. This is crucial to the continued innovation and application of the approach. It strengthens the value of the method by capturing and making available examples of good practise for re-use.

A comprehensive framework of the configuration design phase is undoubtedly needed to enable product designers to design and produce more sustainable products. Meeting these requirements will add to the understanding and practise of design in the following ways:

i. Providing a framework that will allow designers to collaborate with customers and gain insight for innovation and sustainable product design.
ii. The monetary value of a product’s sustainability attributes is difficult to quantify; indeed, the precise sustainability needs of customers can be elusive. Current product design activities generally focus on achieving high quality and profit at low cost. While environmental issues are all too often not integrated with existing activities in conventional product design procedures (they are only considered later, in the product development stage), ever more strenuous environmental requirements generate additional constraints and costs.
iii. Decision makers in industry, government, and non-governmental organisations (NGOs) have recently increased their interest in the development of methods to understand and address the wider impacts associated with their products. Several methods and tools have been developed for sustainable products, but they still lack critical knowledge of production and environmental costs during the conceptual

design. This research study aims to overcome these deficiencies by proposing the integration of eco-design tools. These are applied and tested with the intention that their application will be shown to provide reliable results in reducing a product's environmental impact.

1.3 Research Approach

This research study proposes an eco-design methodology, which is integrated into the innovation process using quality function deployment (QFD). This combination creates a new approach, in which aspects of sustainability are considered within the QFD process. The concept is represented by the inclusion of an ecological house of quality (Eco-HoQ) into the QFD process. The Eco-HoQ is an extra 'house' that can capture and manage sustainability considerations in a single place. This adds to the relevance of the information, and links attempts to improve sustainability to each phase of the design process.

The traditional form of QFD allows designers and customers to develop products that meet certain important criteria. It uses a four-phase process; each phase contributes to the design and manufacturing of a product. Phase I is the translation of the customer's requirements into measurable technical design requirements. Phase II is the translation of the technical design requirements into part deployment (i.e., the process of acquiring the necessary parts). Phase III translates part deployment into manufacturing requirements. Phase IV translates the manufacturing requirements into the production requirements to ensure that the product will fulfil customer needs.

Recent studies on QFD have identified the importance of design options that use environmentally conscious quality function deployment (ECQFD). ECQFD has been integrated with life cycle assessment (LCA) (Vinodh and Rathod, 2010; Wang et al., 2010) and correlated with the theory of inventive problem solving (TRIZ, from the Russian 'теория решения изобретательских задач', 'teoriya resheniya izobretatelskikh zadach') to select innovative design alternatives (Vinodh et al., 2013).

The concept of Eco-QFD has also been used to consider environmental concerns, formulated as a fuzzy multi-objective model (Kuo et al., 2009). An enhanced QFD method has been applied using a fuzzy analytic network process to calculate global warming and environmental protection (Lin et al., 2015). In extending QFD to include the environmental quality of a product, however, insufficient attention has been paid to the question of how to effectively and efficiently carry out an integrated Eco-QFD.

To date, QFD is not widely used (at least not all four phases of it), as it is difficult to manage the movement of (and access to) information. It is also challenging to re-use such information. The integrated eco-design decision making (IEDM) framework that is developed in this research is intended to address these limitations.

1.4 Research Aim and Objectives

Bringing together QFD and sustainability requires the configuration of a new framework. This is demonstrated in the current study by the use of case studies; the added dimension is the integration of these two elements. Integrating sustainability considerations in the design and manufacture of new products has become a leading priority for researchers and industries. The need to develop new models to quantify all of the sustainability aspects has thus become a major issue in sustainable product design.

The aim of this research is to develop an eco-design tool and methodology that can help the designer to evaluate economic and environmental impacts from the perspective of both customer requirements and product life cycles. The objectives of this thesis are as follows:

i. To develop a framework for integrating sustainability aspects into the product development process;
ii. To propose a conceptual model for integrating eco-design and economic viewpoints in the early phases of the design process;

iii. To develop a decision support tool to support the framework in the evaluation of product sustainability, and to propose solutions related to the social, environmental, and economic impacts of the product;

iv. To validate the practicality and the effectiveness of the framework through case studies.

1.5 Organisation of the Thesis

The thesis is divided into eight chapters.

Chapter 1 represents the introduction of the study, its motivation, challenge, research approach, and the aim and objectives of the research.

Chapter 2 reviews the relevant literature on sustainability, quality function deployment, life cycle assessment, and case-based reasoning. In addition, it considers the current state-of-the-art in decision-making tools that could contribute to the development of the IEDM model.

Chapter 3 provides a detailed overview of the integrated eco-design decision making (IEDM) framework by illustrating a step-by-step approach. This chapter describes and proposes the development of the IEDM framework for sustainable product design. The main research contribution made in the IEDM process is the integration of environmental considerations into each aspect of the product, which is then applied to the product’s entire life cycle.

Chapter 4 discusses the integration of the ecological house of quality (Eco-HoQ) method as a platform to be utilised in all phases in the ecological quality function deployment (Eco-QFD). This chapter introduces the IEDM framework and its three stages (life cycle assessment, the eco-design process model, and the Eco-QFD process), along with the ecological economic cost model. An application of the proposed approach is presented in the case study, which considers the redesign of single-use medical forceps.

Chapter 5 presents the eco-design case-based reasoning (Eco-CBR) method for sustainable product design. This method is described by following a step-by-step process of the Eco-CBR development tool. It also presents how the Eco-CBR library for the 72 types of single-use medical forceps was developed in this study.

Chapter 6 discusses a case study to demonstrate the use of the Eco-CBR method. The proposed approach is presented in the context of the development of a product design of a revised single-use medical forceps. All considerations in product sustainability are conducted within the Eco-CBR method. The process is based on identifying and utilising information related to the similarities within the existing cases in the library.

Chapter 7 describes a new case study to demonstrate the use of the IEDM tool. An application of the proposed approach is presented in the design of an office chair base. This chapter also discusses the sustainability of the product.

Chapter 8 summarises the main research contributions and conclusions. This chapter also identifies options for future research possibilities.

CHAPTER II

LITERATURE REVIEW

This chapter reviews the published work related to sustainable product design that forms the foundation of this research. As sustainable product design encompasses various approaches, the review covers a broad range of topics. This chapter is organised as follows: Section 2.1 discusses the concept of design for sustainability; Sections 2.2 and 2.3 discuss the eco-design strategies and the existing eco-design tools for sustainable product design; Section 2.4 highlights the research gaps and the establishment of research needs, while Section 2.5 provides a summary of the chapter.

2.1 The 'Design for Sustainability' Concept

Since the late 1980s and early 1990s, sustainability has become an enormous subject in environmental spheres. Initial sustainability efforts were focussed on improving pollution control ('end-of-pipe') technologies, which were designed to treat waste and polluted streams, and in creating pollution prevention strategies. According to the report *Our Common Future* (commonly known as 'The Brundtland Report'), the concept of sustainability should consider environmental, economic, and social aspects (Brundtland et al. 1987). This report was the first to focus on global sustainability. Although the term 'sustainability' is commonly used, the concept of sustainability is actively redesignated and redeveloped for particular purposes within different areas. In the World Commission on Environment and Development report, Brundtland et al. introduced a widely accepted definition of sustainable development, which is 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'.

Concepts such as cleaner production, pollution prevention, and eco-efficiency were implemented starting in the mid-1990s; production improvements were also considered (Clark et al., 2009). Cleaner production is an integrated approach to preventing environmental impacts. Often focussing on production efficiency, it encourages the ongoing analysis of material and energy flows and non-product/waste output. It is closely related to pollution prevention and source reduction, and is widely used in industry (Ehrenfeld, 1997; White et al., 2008).

Pollution prevention contributes to improving the design of products so that the result in less waste; it also considers how production processes can be improved to minimise the use of toxic chemicals as cleaners. Other aims of pollution prevention are to minimise the outflow releases from manufacturing processes, and to take steps to produce fewer hazards, both to society and to the environment (National Pollution Prevention Center, 1995; US EPA, 2015).

Through the work of the Organisation for Economic Co-operation and Development (OECD), the US President’s Council for Sustainable Development (PCSD), the European Commission (EC), and other governmental institutions, eco-efficiency has been established as a concept for macro-level policies. Eco-efficiency has been applied in industrialised countries as well as developing, emerging, and transitional economies (World Business Council for Sustainable Development, 2000). Eco-efficiency is important to companies in reducing the consumption of resources, reducing pollution, and saving on costs.

The focus next shifted towards product impacts via the concept of ‘eco-design’, which is also known as ‘Design for Environment’ (DfE). This field of design addresses the environmental concerns associated with production and consumption processes (Crul and Diehl, 2008). Many designers have applied it at early stages of product development phases, thus leading to improved design specifications (eg. Vinodh and Rathod 2010; Cerdan et al. 2009; Gehin et al. 2008). This process should include all drawings, dimensions, and documentation; environmental, ergonomic, and aesthetic factors; costs; and maintenance, quality, and safety requirements that describe the product. From the manufacturer's perspective, however, environmental considerations have often been linked to increases in costs. Thus, good plans and strategies needed to be implemented to ensure that the concept of design for sustainability would be achieved. Product sustainability is concerned with finding different ways of thinking and of making products. Figure 2.1 shows the shifting paradigm from traditional design to sustainable design.

Figure 2.1: The shift to sustainable design (White et al., 2008)

The protection of the environment now occupies an essential place in the manufacturing world. Various terms are used to represent design for the environment in manufacturing, such as environmentally conscious manufacturing, sustainable manufacturing, green manufacturing, design for sustainability, and sustainable product development (Ilgin et al., 2015). The concepts they share are similar, although the terms are presented using different nomenclatures.

In the context of manufacturing, 'sustainability' includes the consideration of environmental, social, regulatory, and economic factors for material and manufacturing processes, product use, and the end-of-life (EOL) treatment of products. Manufacturing has a significant influence on global development, as growth continues due to increased demand from consumers. Thus, manufacturing plays a critical role within modern socio-economic systems, and is a valuable contributor to wealth generation and job creation, especially in developing economies (Haapala et al., 2013). Manufacturing activities, however, also represent a negative impact on the environment. For example, in 2010, the US Department of Commerce published a report indicating that in 2006, the manufacturing sector in the United States was responsible for about one-fourth of total

CO2 emissions in the global environment (US DCESA, 2010). Figure 2.2 shows the distribution of CO2 emissions across seven industry sectors within the manufacturing sector. According to the figure, over half of all manufacturing-related CO2 emissions in 2006 came from petroleum products (21%), chemicals (20%), and primary metals industries (13%). Non-metallic mineral products also contributed significantly (11%) to CO2 emissions, mainly because of the production of cement and lime, which use energy-intensive processes.

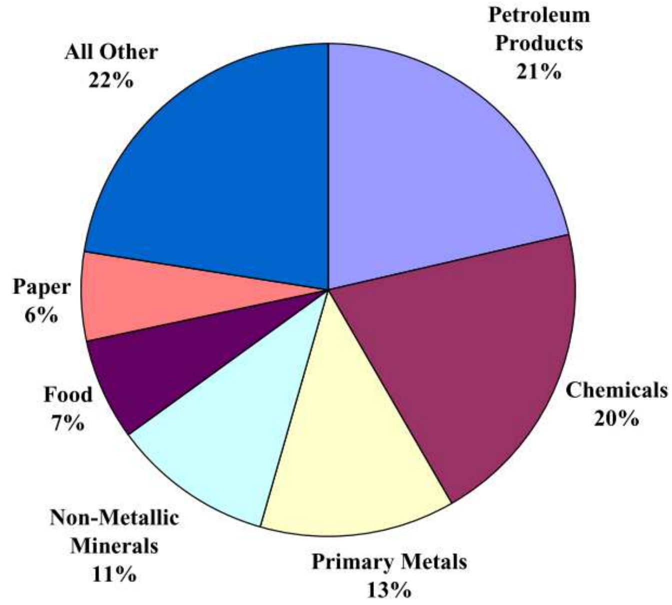


Figure 2.2: Distribution of total CO2 emissions within the manufacturing sector, 2006 (US DCESA, 2010)

Sustainability has become an important part of the entire innovation and new product development life cycle. In order to create innovation in sustainable product development, decisions are made throughout the new product’s development life cycle. The decisions made will have an impact on a product’s sustainability performance. The processes under which considerations may be made have been defined as:

i. Identifying the strategic areas and opportunities during innovation planning;
ii. Developing the ideas of sustainability factors;

iii. Identifying resource utilisation, materials selection and sourcing, production processes, and EOL products during the design stage of product development (https://www.sopheon.com).

According to Yan and Feng (2014), a sustainable product design method will blend all of the traditional design methodologies; the output will be a sustainable product. All of the objectives and outputs of the design methods will point towards the requirements of sustainable design. In addition, the idea of sustainable design requires considerations of the ‘closed-loop’ life cycle of a product.

Social sustainability is how communities, societies and individuals live; it is about equity and basic needs. It deals with working conditions, human rights, participation, fair wages and cultural diversity (Rajak and Vinodh 2015). The aim of social sustainability in this study is to enrich both manufacturer and customers in producing a more sustainable product. The factors of social sustainability for the manufacturer are as follows (Dillard et al. 2009): provide great place to work, ensure a safe, clean, injury-free workplace, and lastly, customer oriented. The manufacturer strives to listen and respond to the customers’ needs by clearly communicating mutual expectations, deliver innovative and competitive products and services, and excel at customer satisfaction.

2.2 Eco-design Strategies in Sustainable Product Design

The consideration of sustainability at the design stage requires dealing effectively with products’ functional and environmental impacts (Bereketli and Genevois, 2013; Remery et al., 2012). Functional product impact has previously been evaluated based on affordability, durability, reliability, and the aesthetic perspective. More recently, functional product impact has been evaluated together with eco-design aspects, including global warming / climate change, energy consumption reduction, and conducting end-of-product life cycle activities, such as reusing, recycling, and remanufacturing (Ljungberg, 2007; Yang et al., 2012).

Several important strategies should be considered when adapting eco-design in product development. The strategies that researchers have highlighted to optimise and redesign sustainable products include:

i. The product should be designed with the minimum amount of material without reducing its functionality. Heavy materials should be replaced by lighter materials, especially for products that will be transported. Materials that have a great impact on the environment should be exchanged for materials with less environmental impact. Recyclable materials should be used to maximise the sustainable use of renewable resources;

ii. Local suppliers should be used to minimise emissions from the transportation sector, and transport based on renewable resources is preferable;

iii. Waste from production processes should be reduced and, if possible, recycled. The usage of energy and other resources during the manufacturing process should be optimised;

iv. The product's useful life and efficiency during its usage phase should be extended and increased;

v. The product should be designed for remanufacturing so that the newer replacement product can be more efficiently manufactured;

vi. At products' EOL, they should be easy to disassemble for recycling, remanufacturing, and reuse (Allione et al., 2012; Byggeth et al., 2007; Knight and Jenkins, 2009; Ljungberg, 2007; Luttropp and Lagerstedt, 2006; Russo and Rizzi, 2014).

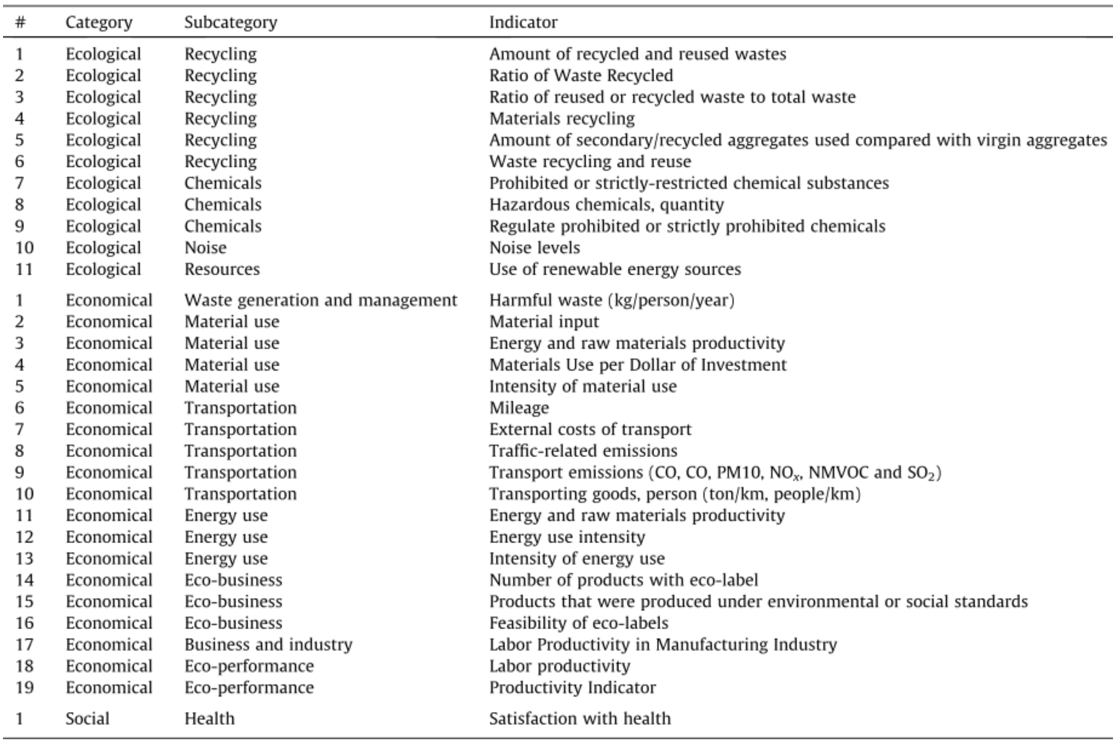
These strategies have been explored to better incorporate eco-design considerations into product development. Methods developed include the use of sustainability indicators to evaluate the impact of product design procedures (Adhitya et al., 2011; Cerdan et al., 2009; Heijungs et al., 2010).

Social sustainability is how communities, societies and individuals live; it is about equity and basic needs. It deals with working conditions, human rights, participation, fair wages and cultural diversity (Rajak and Vinodh 2015). The aim of social sustainability in this study is to enrich both manufacturer and customers in producing a more sustainable product. The factors of social sustainability for the manufacturer are as follows: provide great place to work, ensure a safe, clean, injury-free workplace, and lastly, customer oriented (Dillard et al. 2009). The manufacturer strives to listen and respond to the customers' needs by clearly communicating mutual expectations, deliver innovative and competitive products and services, and excel at customer satisfaction.

Environmental requirements will arise due to factors which include legislation and social pressure. Both manufacturers and customers will respond to these requirements. The role of the customer is key in democratic societies which operate market economies. Customers and manufacturers also play a role in creating the requirements that governments reflect in their legislation. The customer creates a demand for a product, manufacturers respond by trying to stimulate, encourage and feed the demand. Customers also can "punish" companies by boycotting their products if they disagree with their behaviour. Customers will increase their demand for a more sustainable life style and manufacturers will influence customers' needs by producing more sustainable products.

Sustainability indicators are an essential ingredient in the process of benchmarking, communication, and decision-making (Heijungs et al., 2010). The National Institute for Environmental Studies (NIES) in Japan reviewed several sustainable development indicators and developed a database of the types of indicators (NIES 2015). Table 2.1 shows the thirty-one sustainability indicators selected from the NIES database that relate to the development process of products. These indicators are categorised into three groups, considering ecological, economic, and social aspects (Inoue et al., 2012). In addition to mass and CO2 emissions, the current research includes further sustainability indicators and issues that have been considered and added to the evaluation of the case studies.

Table 2.1: Sustainability indicators related to the products' development processes (Inoue et al., 2012)



#	Category	Subcategory	Indicator
1	Ecological	Recycling	Amount of recycled and reused wastes
2	Ecological	Recycling	Ratio of Waste Recycled
3	Ecological	Recycling	Ratio of reused or recycled waste to total waste
4	Ecological	Recycling	Materials recycling
5	Ecological	Recycling	Amount of secondary/recycled aggregates used compared with virgin aggregates
6	Ecological	Recycling	Waste recycling and reuse
7	Ecological	Chemicals	Prohibited or strictly-restricted chemical substances
8	Ecological	Chemicals	Hazardous chemicals, quantity
9	Ecological	Chemicals	Regulate prohibited or strictly prohibited chemicals
10	Ecological	Noise	Noise levels
11	Ecological	Resources	Use of renewable energy sources
1	Economical	Waste generation and management	Harmful waste (kg/person/year)
2	Economical	Material use	Material input
3	Economical	Material use	Energy and raw materials productivity
4	Economical	Material use	Materials Use per Dollar of Investment
5	Economical	Material use	Intensity of material use
6	Economical	Transportation	Mileage
7	Economical	Transportation	External costs of transport
8	Economical	Transportation	Traffic-related emissions
9	Economical	Transportation	Transport emissions (CO, CO, PM10, NO_x, NMVOC and SO_2)
10	Economical	Transportation	Transporting goods, person (ton/km, people/km)
11	Economical	Energy use	Energy and raw materials productivity
12	Economical	Energy use	Energy use intensity
13	Economical	Energy use	Intensity of energy use
14	Economical	Eco-business	Number of products with eco-label
15	Economical	Eco-business	Products that were produced under environmental or social standards
16	Economical	Eco-business	Feasibility of eco-labels
17	Economical	Business and industry	Labor Productivity in Manufacturing Industry
18	Economical	Eco-performance	Labor productivity
19	Economical	Eco-performance	Productivity Indicator
1	Social	Health	Satisfaction with health

Strategies have also been formed to support the adoption of 'eco-materials' to lower the environmental impact of manufacturing and product usage (Allione et al., 2012; Bovea and Gallardo, 2006; Halada and Yamamoto, 2001). All production processes and products cause some environmental impact. This is assessed using factors such as carbon footprint, water eutrophication, air acidification, and total energy consumed. These impacts need to be assessed so that the product may be designed to be acceptable in the context of product sustainability. Zarandi et al. (2011) have provided guidelines to selecting materials for eco-design products, as shown in Table 2.2. In a fully integrated approach to providing product sustainability, material and resource selection are often the first and most critical points of intervention; the most eco-friendly materials should be considered alongside economic factors (Allione et al., 2012).

Table 2.2: Material selection for eco-design (Prendeville et al., 2014; Zarandi et al., 2011)

Rejection of toxic and harmful materials	Selection of renewable and bio-compatible materials
1. Avoid materials that emit toxic or harmful substances during pre-production 2. Avoid additives that emit toxic or harmful substances 3. Avoid toxic or harmful surface treatments 4. Avoid materials that emit toxic or hazardous substances during usage 5. Avoid materials that emit toxic or harmful substances during disposal 6. Avoid toxic substances, but use closed loops when necessary to do so 7. Avoid exhaustive materials	1. Use renewable materials 2. Use residual materials from production processes 3. Use retrieved components from disposed products 4. Use recycled materials, alone or combined with primary materials 5. Use biodegradable materials 6. Use few and unblended materials 7. Use non-hazardous, recyclable materials 8. Use materials with low energy consumption in extraction and transportation

The maximum benefits of eco-design are achieved by reducing the environmental impact and cost of the whole product lifecycle. Total product energy consumption is a useful environmental consideration, as operating a product with minimum energy consumption reduces the environmental impact and customer costs (Devanathan et al., 2010). These processes can improve the design, increase productivity, and reduce material usage and, ultimately, costs. Eco-design strategies may also allow manufacturers to turn the EOL process such as reusing, remanufacturing and recycling of a product into a profitable activity or business opportunity. They also support improved levels of recyclability and reduced EOL environmental impacts (Nguyen et al., 2005).

This review has identified that current eco-design strategies do not provide the in depth assessments required to improve designs. They lack quantitative information and do not provide direct guidance to product engineers.

2.3 Eco-design Tools for Sustainable Product Design

To date, a number of eco-design tools have been specially developed to support sustainable product design. Ramani et al. (2010) reviewed eco-design tools using three categories, namely tools based on checklists, quality function deployment (QFD), and life cycle assessment (LCA). Romli et al. (2015) later considered the case-based reasoning (CBR) method as another eco-design tool. These tools will be discussed below in terms of how they examine product sustainability.

2.3.1 Checklist-based Tools

Checklist-based tools are easy to implement among small and medium-sized companies, and do not require an experienced designer to evaluate them. Checklist tools evaluate a product's environmental impact through a series of questions to guide the sustainable design process; they highlight environmental awareness for the product (Knight and Jenkins, 2009; Luttropp and Lagerstedt, 2006). Table 2.3 shows an example of an eco-design requirements checklist for printed wiring board manufacturers (Adams, 2006).

The checklist is a tool that is easy to understand, and is often the first tool a company will use when considering various aspects of eco-design. The simplicity generally allows for both technical and non-technical personnel to understand the process (Adams, 2006). Some studies that have used checklist-based tools include:

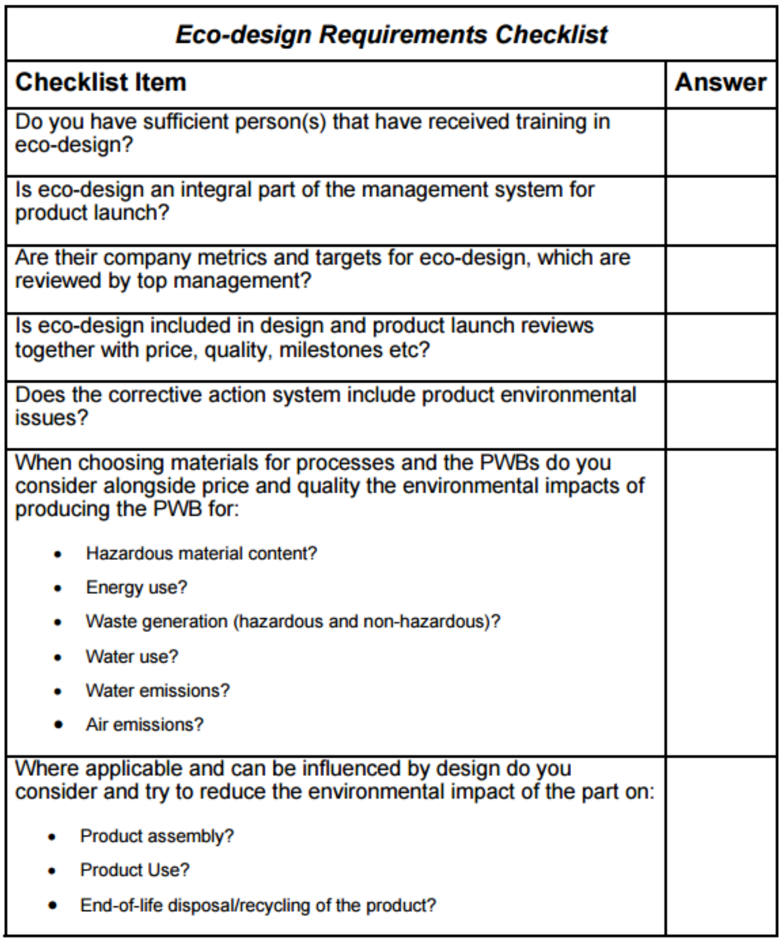
i. Bernstein et al. (2012) used checklists to discuss the possibility of using clean energy and recovering the latent heat of the phase transformation of water;

ii. Fernando and Souza (2006) proposed a set of indicators of sustainable product design that may be analysed by using a checklist of viability and performance that can be applied to a design process in general;

iii. Vezzoli and Sciama (2006) produced two handbooks of guidelines and checklists for the eco-efficient development of two types of vending machines. This checklist can become an essential supporting tool for the management of the products' development process.

Although checklist-based tools can suggest ways of modifying a product to improve its environmental performance, these methods fail to provide design details that may be directly linked with LCA assessment tools (Russo and Rizzi, 2014). The limitations of checklists are that they give a very simple picture, which can produce misleading results. They also do not document the process of arriving at a particular outcome. This makes it difficult both to investigate the results, and to use that data for future products.

Table 2.3: Eco-design checklist (Adams, 2006)



Eco-design Requirements Checklist	
Checklist Item	**Answer**
Do you have sufficient person(s) that have received training in eco-design?	
Is eco-design an integral part of the management system for product launch?	
Are their company metrics and targets for eco-design, which are reviewed by top management?	
Is eco-design included in design and product launch reviews together with price, quality, milestones etc?	
Does the corrective action system include product environmental issues?	
When choosing materials for processes and the PWBs do you consider alongside price and quality the environmental impacts of producing the PWB for: • Hazardous material content? • Energy use? • Waste generation (hazardous and non-hazardous)? • Water use? • Water emissions? • Air emissions?	
Where applicable and can be influenced by design do you consider and try to reduce the environmental impact of the part on: • Product assembly? • Product Use? • End-of-life disposal/recycling of the product?	

2.3.2 LCA-based Tools

LCA is a methodology used to analyse the life cycle of products or activities quantitatively, within the context of environmental impact (Goedkoop et al., 2013). The integration of LCA into product development enables designers to evaluate economic and environmental impacts, thus leading to more cost-effective and eco-friendly products. LCA has been applied to reduce resource use and environmental pollution during the product design and manufacture of thin-film-transistor liquid-crystal displays (TFT-LCDs) (Lin et al., 2015), diaper production (Adhitya et al., 2011), packaging material (Senthil et al., 2003), and engine filters (Zhang et al., 1999). With good design practise, the characteristics can be exploited to ensure environmental improvement throughout the product's life cycle.

Vinodh and Rathod (2014) proposed the integration of LCA and 'Monte Carlo' simulation to utilise the sustainable product design of rotary switches. The results from this integration showed that the model was capable of assessing the potential reusability of used products, while the use of simulation significantly increased the effectiveness of the model in addressing uncertainties.

Figure 2.3 shows the relationship between the phases of the LCA that make up British Standard's recommended four stages (*BS EN ISO 14040*, 2006a).

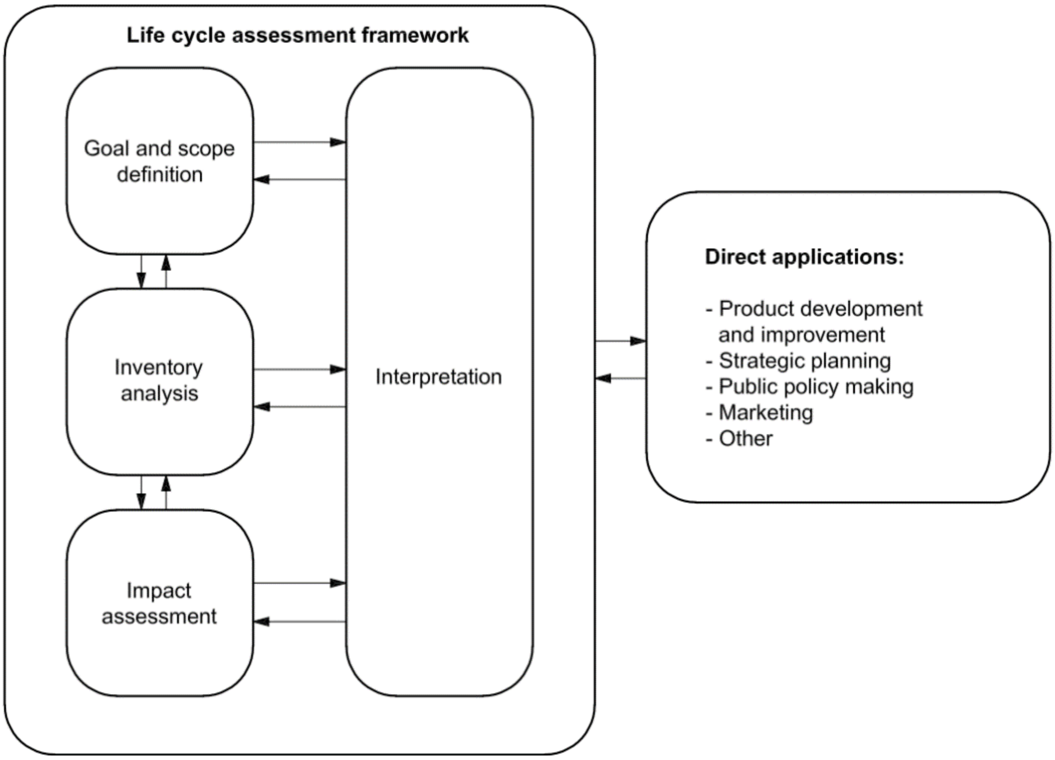


Figure 2.3: LCA phases (*BS EN ISO 14040*, 2006a)

i. The **goal and scope definition phase** defines the system boundary and level of detail of the study. This step is the most essential even mandatory part of the LCA study.

ii. The **life cycle inventory (LCI) phase** is a list of inputs and outputs related to the product. The inputs to the product process are energy and raw material, while the outputs are environmental releases of gas, liquid, and solid discharges. This stage includes the collection of the essential data to meet the goals of the defined study.

iii. The **life cycle impact assessment (LCIA) phase** is used to evaluate the environmental impacts of the product's lifecycle. This phase provides additional information to help assess a product system's LCI results in order to provide information on their environmental significance. Various LCIA methodologies can be applied, such as those of the Centre of Environmental Science (CML), the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI), Eco-indicator 99, and ReCiPe 2008 (European Commission, 2010).

Two of the most widely used impact category methodologies are CML (from the Dutch for Leiden University's 'Institute of Environmental Sciences') in European Union and TRACI in the United States. The CML and TRACI methodologies are elaborated upon in problem-oriented methods (midpoints) and damage-oriented methods (endpoints) (Frischknecht et al., 2007; VanDuinen and Deisl, 2009). Table 2.4 shows the different impact categories used in the CML and TRACI methods.

Eco-indicator 99 was extended from Eco-indicator 95 and is focussed on the weighting procedure to weight the different damage categories of human health, ecosystem quality, and resources (Baayen, 2000). ReCiPe 2008 comprises two sets of impact categories (midpoint approach and endpoint approach), with associated sets of midpoint approach characterisation factors, as in the ‘Handbook on LCA’ (Guinée et al., 2002), and the endpoint approach, as in Eco-indicator 99 (Baayen, 2000).

Table 2.4: Comparison of the CML and TRACI methods (VanDuinen and Deisl, 2009)

CML		**TRACI**	
Impact Categories	**Unit**	**Impact Categories**	**Unit**
Global Warming Potential (GWP)	kg CO_2	Global Warming Air	kg CO_2
Ozone Layer Depletion Potential (ODP)	kg R11	Ozone Depletion Air	kg CFC 11
Acidification Potential (AP)	kg SO_2	Acidification Air	Mol H+
Eutrophication Potential (EP)	kg PO_4	Eutrophication Air Eutrophication Water	kg N
Photochemical Ozone Creation Potential (POCP)	kg Ethene	Smog Air	kg NO_x
Human Toxicity Potential (HTP)	kg DCB	Human Health Cancer Air	kg Benzene
Freshwater Aquatic Ecotoxicity Potential (FAETP)	kg DCB	Ecotoxicity Air Ecotoxicity Water	kg 2,4 – Dichlorophenoxyace
Abiotic Depletion (ADP)	kg Sb	Human Health Criteria Air Point Source	kg PM2,5
		Human Health Non Cancer Air and Water	kg Toluene

iv. The **interpretation phase** summarises and discusses the numerous LCA results as a basis for conclusions, recommendations, and decision-making, according to the goal and scope definitions.

Several software tools have been developed for supporting and conducting LCA in particular fields. For instance, the Building for Environmental and Economic Sustainability (BEES), Eco-balance Assessment Tool (Eco-Bat), and Environmental Impact Estimator V3.02 were developed specifically for the construction industry (Lehtinen et al., 2011).

The BEES software, developed by the National Institute of Standards and Technology (NIST), measures the environmental performance of life cycle building products by using the LCA approach specified in the International Organization for Standardization (ISO) 14040 series of standards (Lippiatt, Greig and Lavappa, 2009).

Eco-Bat software is an independent tool that can model a building and perform a thorough life cycle impact assessment (http://www.eco-bat.ch/). The Environmental Impact Estimator V3.02 allows the user to input energy simulation results in order to calculate their operating effects alongside their embodied effects. The tool also provides flexibility for proposed designs and existing buildings (Athena Sustainable Materials Institute, 2015).

Another serious obstacle associated with applying LCA-based tools during early design lies in the fact that LCA is inherently not design-oriented (Devanathan et al., 2010). Instead, LCA was developed to analyse the environmental impacts of product structure, not the environmental costs associated with product functions based on customer requirements. Thus, to overcome this issue, several commercial software tools have been utilised and are available on the market, such as AutoCAD 2013, CES Educator, and SolidWorks 2013. They use simplified LCA with computer-aided design (CAD). The simplified LCA is used to measure environmental indicators over the life cycle of the product, which includes the extraction of raw materials, manufacturing, product transportation, use, and disposal. In the current study, SolidWorks has been chosen to be integrated with other eco-design methods in order to assess and produce a sustainable product.

SolidWorks Sustainability is appropriate CAD software for rapid design iteration. It adapts a simplified LCA that enables a designer to see and understand several impacts of design choices, at a modest cost. The environmental impacts of carbon footprints, air acidification, water eutrophication, and energy consumption are all examined (SolidWorks 2013).

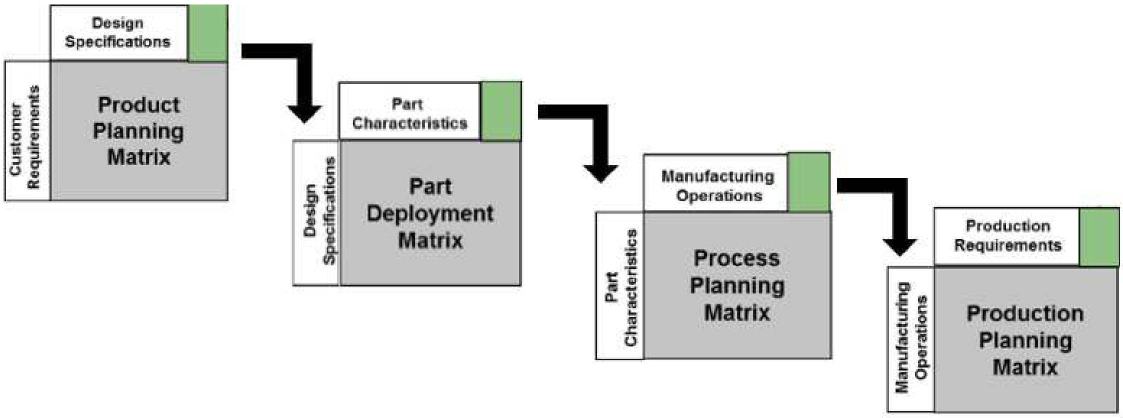
The assessment of current research has indicated that existing LCA tools provide valuable design information. They do not however provide guidance on how improvements can be achieved. They are not iterative and lack the required level of interaction to support designers with improvement strategies.

2.3.3 QFD-based Tools

The objectives of a traditional quality function deployment are to convert customers' needs into engineering characteristics, and to improve product quality. A vast amount of literature has been published in this field. QFD-based tools are significantly different from LCA-based tools, because the focus lies in the product specification development stage. Among these three types of eco-design tools (checklist, LCA, and QFD-based), QFD-based tools are the most suitable for early product development, when specifications are being established and concepts generated. Besides the traditional QFD, several approaches combine environmental issues into the QFD, such as green quality function deployment, eco-QFD, and quality function deployment for the environment. This review focusses on recent efforts in developing eco-design tools based upon the integration of LCA within QFD, with the goal of determining more objective design targets.

The first house in the QFD process is generally referred as the house of quality (HOQ) as shown in Figure 2.4. This review has established that current approaches can consider aspect of sustainability as and when they are identified by customers or designers. This process is however rather haphazard and is not a required element in QFD. What is required is a systematic consideration of sustainability in an organised manner. This lies at the heart of the method utilised in this thesis.

Figure 2.4: The traditional QFD approach



The traditional 'house of quality' (HoQ) is extended by directly adding environmental factors to customer requirements (Emzer et al., 2003). Zhou and Schoenung (2007) developed an 'Integrated Industrial Ecology Function Deployment'

(12-EFD) approach to assess the environmental behaviour of various technologies, with correlations to their performance and economic characteristics. The 12-EFD approach has been implemented in a case study of a computer display desktop. The results of this case study have been used to assess trade-offs among different objectives in product design.

Eco-QFD has been undertaken in the current study to identify innovative design alternatives using ‘environmentally conscious quality function deployment’ (ECQFD) and LCA, and has been correlated with the theory of inventive problem solving (TRIZ, from the Russian ‘теория решения изобретательских задач’, or ‘teoriya resheniya izobretatelskikh zadach’). Wang et al. (2010) and Vinodh and Rathod (2010) have proposed integration methods between ECQFD and LCA for ensuring sustainable product development in electronics switches (China) and rotary switches (India). Sakao used eco-design to reduce environmental impact throughout a product life cycle by combining LCA, ‘QFD for the environment’ (QFDE), and TRIZ, and applying the combination to a hair dryer to effectively support the product planning and conceptual design stages (Sakao, 2007). Very little attention has been paid to the question of how to carry out an eco-QFD effectively and efficiently, however.

The evolution of eco-QFD started from green QFD (GQFD) (Cristofari et al., 1996), which was used to evaluate products using QFD integrated with LCA. Later, the developments led to GQFD II, which integrates LCA, life cycle costing (LCC), and QFD into an efficient tool that deploys customer, environmental, and cost requirements throughout the entire product development process (Zhang et al., 1999). GQFD-II has several shortcomings, however, which makes it difficult to use: it depends on a detailed and time-consuming LCA that requires designers to have a comprehensive understanding of environmental science. To address these shortcomings, GQFD-III methodology was developed to integrate LCIA into the ‘Green House’, and the analytical hierarchy process (AHP) technique was used for selecting the best product concept. Mehta and Wang used the GQFD-III methodology to illustrate a case study of three coffee makers by comparing the quality, cost, and environmental performance of the products (Mehta and Wang, 2001).

In Japan, Masui et al. developed a QFDE tool to design an environmentally friendly product. QFDE is generally carried out in four phases (Masui et al. 2001, 2003). Phases I and II allow the user to identify environmentally significant components (parts and devices) of the product, while Phases III and IV allow the user to choose the most environmentally friendly design from alternative design proposals.

Ernzer et al. (2004), Kuo et al. (2009), and Utne (2009) presented Eco-QFD as an aid to a product design team in considering environmental concerns and as a proven quality systems tool to achieve total customer satisfaction. Bereketli and Genevois (2013) proposed a multi-aspect QFD for an environmental approach to identifying product improvement strategies. They did so by considering not only the end users' requirements, but also those raised by environmental stakeholders.

Hare (2010) believes that QFD for the environment would benefit environmental strategies by facilitating a more systematic and quantitative analysis of the requirements. Hare (2010) has also investigated how QFD for the environment should be included in the review of potential eco-innovation tools. This review can help the designer to improve the requirements of a product's specifications and integrate them with environmental considerations. QFD can translate product design requirements into engineering parameters, which will provide a useful tool for understanding design requirements; however, QFD cannot provide detailed information for the sustainability analysis (Miguel, 2013).

These studies have shown evidence of significant efforts in the development of environmental product design. Most of these studies, however, have not provided a precise sustainability framework. Researchers have suggested that QFD cannot provide the detailed information necessary for sustainability analysis. Thus, a sustainability framework for the relevant eco-design improvement strategies is needed as a basic conceptual structure for decision-makers in conducting eco-design with a multi-aspect approach (cost, quality, and environmental and social aspects). The proposed framework should include an integration of methods that could combine the required aspects.

2.3.4 Case-based Reasoning

Case-based reasoning (CBR) is an artificial intelligence (AI) tool and computational modelling technique used to solve design problems. Several studies have focussed on the application of CBR to support decisions in product design (Aamodt and Plaza, 1994; Belecheanu et al., 2003; Yang and Chen, 2011, 2012). The CBR method is used to find similarities to previous cases based on product features. These cases can then be retrieved and reused in a process that adapts the information and knowledge they contain to the new case.

The application of CBR to sustainable product development is a growing area of research. It includes the development of the Communication and Decision Support Environment for Managing Concurrent Engineering project (CODESCO) (Belecheanu et al., 2003). This is an application of CBR to new product development, which can be used as a decision support environment and practical communication tool for managing concurrent product development.

In other research, Takai (2009) implemented a CBR approach to storing information about various products in a knowledge base, and defined a new product concept. This involved retrieving a cluster of products and adapting the cost from existing cases to the new case. Kuo (2010) proposed a hybrid AHP-CBR method to determine recycling strategies for a product. Ghazalli and Murata, (2011) used the same hybrid method for evaluating remanufacturing processes to support the integration of economic and environmental cost models to determine the EOL strategies for a product.

A forecasting model to design eco-products based on the use of TRIZ and CBR evolution patterns has also been outlined (Yang and Chen 2012, 2011). Yang and Chen used these methods to accelerate the process and to help designers to reduce environmental impacts throughout the life cycle of their products. Jeong et al. (2013) proposed a solution to approximate LCA using CBR for the eco-design of products. Later, Germani et al. (2013) proposed a CBR approach that would allow designers to consider the indications given by the well-known eco-design guidelines in an efficient way.

Research on CBR was proposed recently by (Bejarano et al., 2014) by producing a recursive case-based reasoning (RCBR) method. They developed the RCBR method to guide design teams in system design by integrating industrial standards and existing CBR methodologies. They used this method to provide product requirements and solutions representation.

CBR product development methods have been deployed to include sustainability issues but not in an integrated manner. Individual approaches have considered environmental, economic and social aspects but not in a manner that enables the direct generation of design details which can be the basis of optimisation strategies. To achieve this, a level of iteration is required, allowing important parameters to be examined.

2.4 Research Gaps

The literature review presented in this chapter has identified several research gaps, as follows:

A framework for integrating technical, social, environmental, and economic aspects at the operational level is needed. The proposed framework will integrate existing LCA, Eco-QFD, and CBR methods that can be used to assess products. The new framework should be suitable for use as a guideline for evaluating an individual component and/or the reusability of a whole product. In this way, LCA results can be used to develop inputs that represent the environment and corresponding weightings.

Eco-QFD can then be used to establish relationships among consumers' stakeholders, environmental requirements, and product characteristics. An eco-design case-based reasoning (Eco-CBR) method is introduced in this framework to store all the product design knowledge in the library of cases and to help a designer to quickly evaluate the new product design case by finding similar cases in the library. The proposed framework will allow designers to collaborate with consumers, and will allow designers to gain insight and innovation for sustainable product design.

The intention of this framework is to enable and require a more detailed consideration of sustainability in each phase of the QFD process. The addition of the Eco-HOQ brings sustainability to the centre of the considerations in a manner which has not been previously deployed.**Environmental and economic aspects must be considered right from the beginning, as an integrative part of product design.** According to Turnbull (2014), the UK Design Council estimated that over four-fifths of material and utilities costs are locked into the design stage. Another paper, by Weustink et al. (2000), found that three-quarters of a product's costs are committed during the design process. As such, it is promising that by embedding eco-design into the new product design process, companies will be able to make crucial cost savings.

When enacted the Eco-HOQ will capture and make available important information. This information will be accessed using the tools developed by this research. By considering sustainability in all aspects of product design and manufacture, it should be possible to make more appropriate decisions regarding design requirements such that extra costs can be reduced or even removed. In this way, more sustainable products need not always be associated with higher costs.

The challenge in implementing eco-design is learning how to match product functionality with customer requirements. Designers should consider environmental factors from the earliest stage of conceptual design and through all subsequent product development. By introducing environmental impacts throughout a product's life cycle into Eco-QFDs as a new customer need, a set of eco-design tools will be developed for the current study. This research proposes an Eco-HoQ model as a platform of eco-design features that can be accessed by all QFD phases. This Eco-HoQ is to be embedded in the QFD process, and will be used to act as a practical guide to the assessment of the product.

The Eco-CBR method must be able to store information about product knowledge and quickly propose solutions for product design cases. Eco-CBR consists of eco-design features that are important in influencing design criteria during product development. This method facilitates well-informed decisions early in the product development process, and reduces the risk of costly and difficult changes during later phases. The Eco-CBR is developed in this study for a fast and efficient overview assessment of sustainability gaps for specific product categories.

2.5 Summary

This chapter presented the methodologies and tools for achieving sustainable products throughout the product development process. The basis of this process has been acknowledged by many researchers in the literature; the key point of consideration is the integration of the sustainability concept (along with the appropriate design tools) from the very start of the design process and at all stages thereafter. In this chapter, the eco-design strategies and existing eco-design support tools were discussed and classified into four types: checklist, LCA, QFD, and CBR tools. This approach has been practically implemented into the product development process for sustainable product design. The literature review has discussed the eco-design tools designed thus far, and has identified the research gaps in order to establish the fields of research needs.

CHAPTER III

CONCEPTUAL FRAMEWORK

This chapter addresses the first research objective of this thesis. It proposes a conceptual framework for an integrated ecological-design (eco-design) decision making approach to sustainable product development. The main research contribution relates to the integration of environmental considerations into every aspect of product use over its entire life cycle. A detailed description of the process involved for each stage of the framework is presented in sections 3.1 to 3.6. The operation of the proposed conceptual framework is then presented in section 3.7, which concludes this chapter.

3.1 Integrated Eco-design Decision Making Framework

This section describes the specifications of a conceptual framework that enables effective sustainable product development. A conceptual framework is proposed in this study as a method to be deployed in improving product sustainability. The integrated eco-design decision making (IEDM) framework proposed in this thesis applies environmental considerations across three stages of product development; LCA, Eco-Process and Eco-QFD. The framework was designed to embed sustainability within the QFD process. The intention was to add additional functions to the existing QFD process. The Eco-HOQ was engineered to add relevance to design considerations focused on product sustainability at each stage of QFD process.

The need to store and provide access to the information generated was seen to be vital. Following a review of potential approaches a CBR tool was identified as being most suited. The CBR method was therefore integrated into the framework with the aim of enabling information capture, re-use and optimisation. The resulting framework was designed to be intuitive and flexible in its application.

The resulting IEDM framework allows the attainment of identified eco-design objectives by including environmental considerations in every phase of the design process. The process starts with the inclusion of a sustainability performance evaluation among the criteria in the configuration design phase. The sustainability is central to considerations producing possible design alternatives of a product. The evaluation of the generated design alternatives includes reference to and use of sustainability criteria. The framework along with the supporting tools and methods will thus support a user-friendly evaluation approach that can be adopted in the working environment of product designers. This is demonstrated in the two case studies but is intended to be applicable across a wider sector of design activities. This approach, which is represented in Figure 3.1, applies environmental considerations using three linked stages contained within the IEDM framework.

Stage I is the completion of a life cycle assessment (LCA), which is used to identify critical areas where the environmental performance of the product can be improved. Stage II uses an eco-design process (Eco-Process) model to analyse the LCA results. This stage identifies environmental concerns related to the manufacturing informed by access to a knowledge base that links eco-design parameters to product characteristics. This access is formed around the use of the adapted ecological house of quality (Eco-HoQ). The framework also contains linkages to two self-contained but integrated models: the ecological economic cost (Eco-Economic Cost) model and the eco-design case-based reasoning (Eco-CBR) model.

The framework shown in Figure 3.1 allows the designer to establish and represent the environmental considerations arising from the meeting of user requirements in all design and manufacturing phases. All eco-design considerations and their influence on the resulting decisions are automatically embedded within this framework using a managed knowledge base located within the Eco-CBR model. This method can be accessed and updated when completing subsequent design tasks. This process is fully considered in Section 3.6. The Eco-Economic Cost model is a standalone

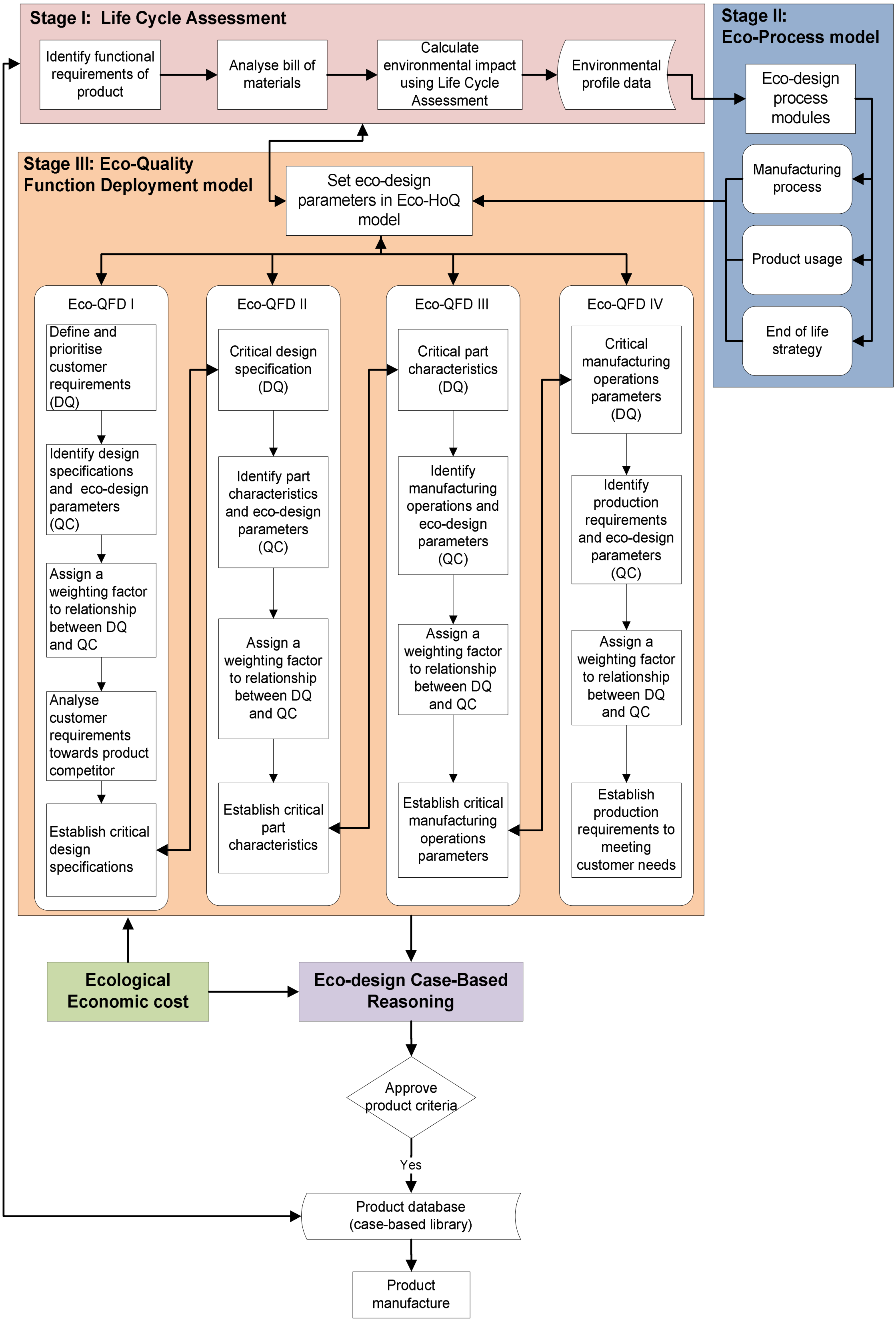


Figure 3.1: Integrated eco-design decision making (IEDM) framework for sustainable product development

cost model that can be used in conjunction with Eco-QFD and Eco-CBR. The IEDM framework is presented as an important contribution to sustainable product development and use.

3.2 Stage I: Life Cycle Assessment

LCA has been defined as the "compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle” (Guinee et al. 2011). Stage I includes a four-step LCA process, as indicated in Figure 3.1. These steps are the identification of the functional requirements of the product, the analysis of the bill of materials, the calculation of the environmental impact, and the provision of environmental profile data. These steps produce an environmental impact assessment using quantitative information and an objective analysis of the detailed product design. LCAs do not provide a practical basis for product design as they only highlight environmental aspects. Thus, the integration of the LCA within an Eco-QFD, as proposed in this methodology, is crucial because it allows designers to balance LCA recommendations with other design aspects to reach a feasible product design solution.

A functional requirement is a precise and detailed specification of a product’s functions and operational features. There are two types of functional requirements: operational functional requirements and general functional requirements Operational functional requirements provide parameters that the design must meet in order to satisfy the product’s intended function (Kamrani and Salhieh, 2002). General functional requirements are the criteria set by the designer that can be used to evaluate whether the resulting design meets the needs it was intended to meet. Once a design exists, it can be analysed and assessed using an LCA. The results will then be used as the basis of subsequent redesign and reassessment. Examples of typical operational functional requirements are diameter, radius, height, weight, transmission, etc. These criteria are critical to fulfilling the needs of customers and usually represent the most important attributes of the product's development. Therefore, the analysis of functional requirements must be linked to a product's Eco-QFD.

In the first scenario (case study of medical forceps) of this study, it is assumed that the aim is to improve an existing product. Initial details such as all computer aided design (CAD) drawings and product specifications are available for the existing product. These details can be analysed in Stage I and Stage II before design considerations are made in the Stage III. This means that these stages are linked, and a cycle is created.

A bill of materials is a list of the raw materials, sub-assemblies, components, and parts used in a product; it details the quantities of each of these required for the product (Jiao et al., 2000). It may be used in communication between manufacturing partners, or its use may be confined to a single manufacturing plant. There are three aspects that should be considered in producing a bill of materials:

i. A product will be formed from a number of items. An item might be a purchased part, raw material, subassembly, or a final product.

ii. It must provide details of the relationship between items in the form of a hierarchy, providing the full description of the composition of the product.

iii. It can be integrated with related business functions to enable product manufacture, sale, and operation.

A product's functional requirements and bill of materials can be jointly considered in the production of an environmental impact assessment, which uses quantitative information and objective analysis of the detailed product design as it exists at this stage.

In this study, the LCA serves as the environmental impact assessment of a product's design. The analysis of the LCA results considers a product's entire life and examines the associated environmental impacts. This analysis encompasses the costs arising from raw material extraction, material and manufacturing processes, product use, EOL disposal, and transportation. Raw material extraction includes material harvesting and transportation to material processing and manufacturing sites. Material and manufacturing processes are those which enable the manufacture of the product. These include manufacturing operations, including machining and/or processing costs, as well as costs arising from activities such as assembly and packaging. The analysis of product use includes consideration of the total energy and emissions produced during the product's life. This also necessitates consideration of required maintenance activities and any costs arising from product reuse. Lastly, the EOL assessment involves the calculation of the costs associated with recycling, landfill disposal, and incineration. Each of these considerations is supported by a relevant phase within the Eco-QFD process.

The operational process of LCA is considered in the ISO 14000 (environmental management) standards and is specifically addressed by ISO 14040:2006 (British Standard, 2006a) and 14044:2006 (British Standard, 2006b). The development of the IEDM framework is not intended to completely replace the LCA. Rather, it uses aspects of the LCA focusing specifically on critical elements of environmental impact which are carbon footprint, energy consumption, air acidification, and water eutrophication. These environmental impacts are importance to analyse a product's life cycle from cradle to cradle.

In this research, the LCA approach has been implemented using the SolidWorks Sustainability 2013 software package. This software is capable of supporting the integration of product design as part of the LCA. It is then possible to compare and analyse details associated with the different approaches to the manufacture of the product in terms of the material and manufacturing processes deployed. The Solidworks tool is able to link design decisions to the appropriate manufacturing strategy and provide an accurate assessment of the product's overall environmental impact (Solidworks, 2013). The application of LCA using SolidWorks Sustainability has been shown to be able to measure the environmental impact of a product (Hassan and Omar, 2012; Vinodh and Rathod, 2010).

In this study, the LCA is performed using the Centre of Environmental Science (CML) methodology. CML methodology was developed by the Institute of Environmental Sciences at the University of Leiden in the Netherlands. The CML impact assessment methodology is used in SolidWorks Sustainability to calculate the results of the LCA. It is the most widely-used methodology and is often considered the most complete methodology. The CML primarily uses European data to derive its impact factors. It groups the life cycle inventory (LCI) results into midpoint categories. The categories are human toxicity, air acidification, water eutrophication, carbon footprint, and energy consumption (European Commission, 2010). The process of LCA explained here is based upon the handbook of the GaBi EDU software package (VanDuinen and Deisl 2009). Figure 3.2 shows the conversion from emissions to impact potentials via classification and characterisation, which will be discussed in the next section.

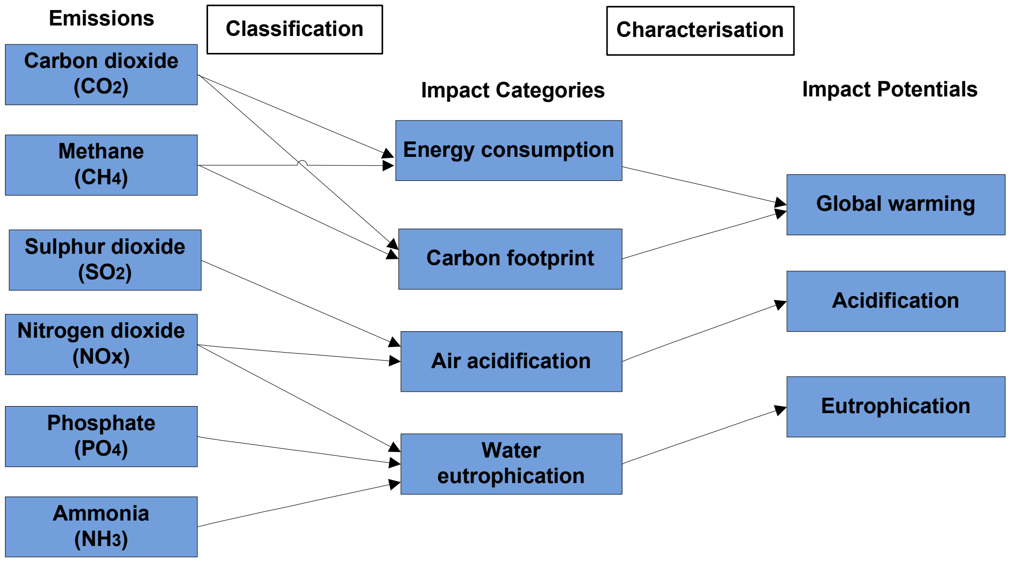


Figure 3.2: The classification and characterisation from emissions to impact potential (VanDuinen and Deisl, 2009)

The following seven key steps comprise a life cycle impact assessment (US EPA, 2006):

i. Selection and definition of impact categories. Identifying relevant environmental impact categories.
ii. Classification. Assigning LCI results to the impact categories.
iii. Characterisation. Modelling LCI impacts within impact categories using science-based conversion factors.
iv. Normalization. Expressing potential impacts in ways that can be compared.
v. Grouping. Sorting or ranking the indicators.
vi. Weighting. Emphasizing the most important potential impacts.
vii. Evaluating and reporting life cycle impact assessment (LCIA) results. Gaining a better understanding of the reliability of the LCIA results.

3.2.1 Step 1: Selecting and Defining Impact Categories

The first step in an LCA is to select the impact categories that will be considered in the overall process. The impact categories selected will depend on the goal of the study. In this case, these should cover the environmental effects of the analysed product system.

3.2.2 Step 2: Classification

The purpose of classification is to organise and possibly combine the emissions results into impact categories. The results of the LCI phase include many different emissions, as shown in Figure 3.2. The emissions identified here are carbon dioxide (CO_2), methane (CH_4), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), phosphate (PO_4), and ammonia (NH_3). These emissions are classified in one or more of the identified impact categories. If substances contribute to more than one impact category, they must be classified as contributors to all relevant categories. For example, CO_2 and CH_4 are both assigned to the impact categories “energy consumption” and “carbon footprint”. SO_2 and NO_2 are assigned to “air acidification”. NO_2, PO_4, and NH_3 are classified to the “water eutrophication” group and are characterised for their eutrophication potential. These impact categories are parallel mechanisms, and the flow will be correlated to potential impact.

3.2.3 Step 3: Characterisation

Impact characterisation uses science-based conversion factors, called characterisation factors, to convert and combine the LCI results into representative indicators of their impact on the environment. The characterisation factors are referred to as equivalency factors. Impact characterisation describes and quantifies the environmental impact of the analysed product system. Thus, after assigning the LCI results to the impact categories, characterisation factors must be defined.

The results of the LCI are converted into common units with characterisation factors. For example, the impact category "global warming potential" has "kg CO_2 equivalent" as the common unit. Thus, all emissions contributing to the global warming are converted into the unit "kg CO_2 equivalent" by a characterisation factor. Impact indicators are typically characterized using the following equation:

Inventory Value × Characterisation Factor = Impact Potential

The principle of characterisation can be described using the example of methane (CH_4) in Figure 3.3. CO_2 and CH_4 are listed under the "global warming potential" section. Global Warming Potentials (GWPs) are used to compare the impact of the emission of equivalent masses of different greenhouse gases relative to carbon dioxide. The conversion factors in Table 3.1 incorporate GWP values relevant to reporting under the United Nations Framework Convention on Climate Change (UNFCCC) (Defra, 2012).

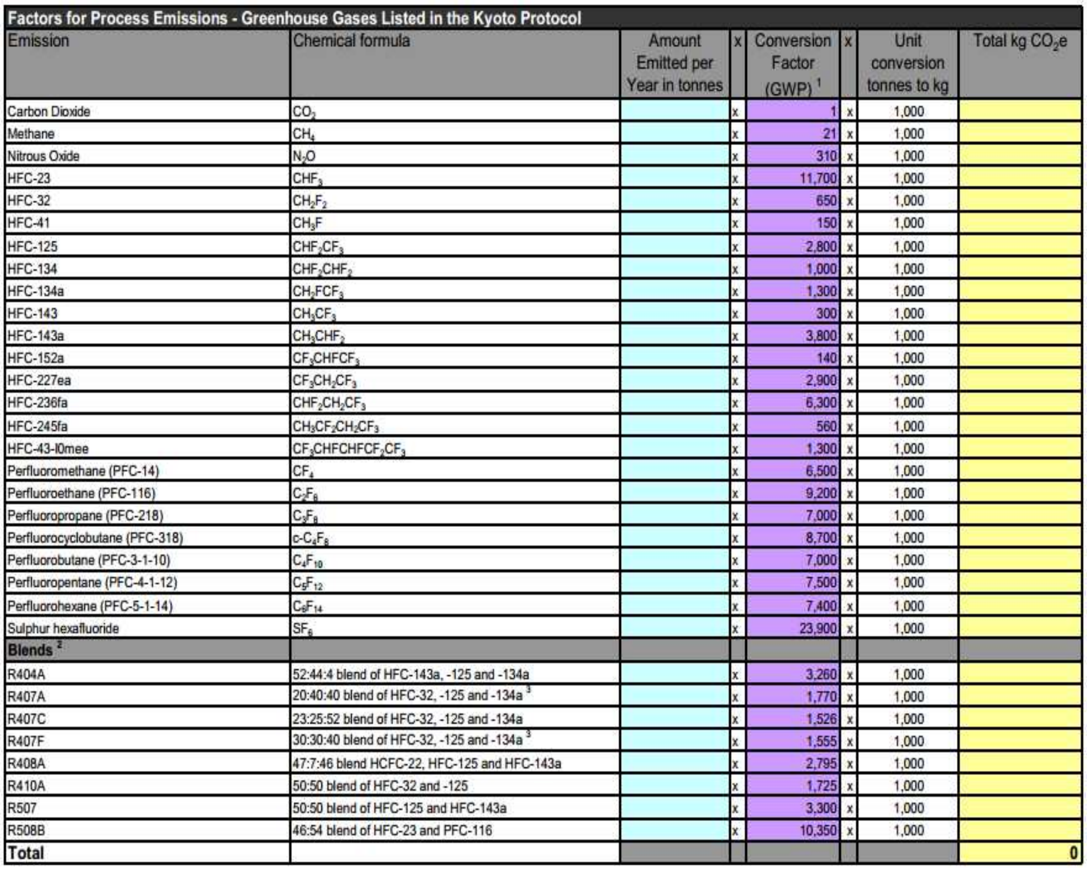
Figure 3.3 shows that the emission of 1 kilogram of CH_4 will have the same warming impact as 21 kilograms of CO_2. This means that CML has determined that CH_4 contributes 21 times more to potential global warming than CO_2. Therefore, the total impact potential for 30 kg CO_2 and 3 kg CH_4 is 93 kg CO_2. This total value will be used in the next step to calculate the normalisation factor, as shown in Figure 3.4.

Inventory value	x	GWP Factor	=	Impact potential
30 kg CO_2	x	1	=	30 kg CO_2
3 kg CH_4	x	21	=	63 kg CO_2
				====================
		Total	=	93 kg CO_2

*1 kg CH_4 is equivalent to the impact of 21 kg CO_2

Figure 3.3: The example of characterisation

Table 3.1: Global warming potentials (Defra, 2012)



Factors for Process Emissions - Greenhouse Gases Listed in the Kyoto Protocol

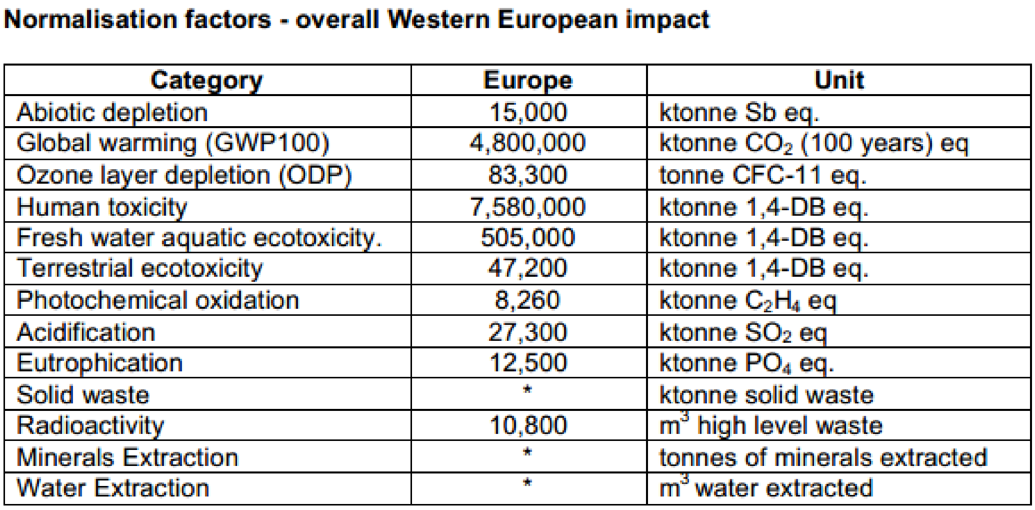
Emission	Chemical formula	Amount Emitted per Year in tonnes	x	Conversion Factor (GWP) [1]	x	Unit conversion tonnes to kg	Total kg CO_2e
Carbon Dioxide	CO_2		x	1	x	1,000	
Methane	CH_4		x	21	x	1,000	
Nitrous Oxide	N_2O		x	310	x	1,000	
HFC-23	CHF_3		x	11,700	x	1,000	
HFC-32	CH_2F_2		x	650	x	1,000	
HFC-41	CH_3F		x	150	x	1,000	
HFC-125	CHF_2CF_3		x	2,800	x	1,000	
HFC-134	CHF_2CHF_2		x	1,000	x	1,000	
HFC-134a	CH_2FCF_3		x	1,300	x	1,000	
HFC-143	CH_3CF_3		x	300	x	1,000	
HFC-143a	CH_3CHF_2		x	3,800	x	1,000	
HFC-152a	CF_3CHFCF_3		x	140	x	1,000	
HFC-227ea	$CF_3CH_2CF_3$		x	2,900	x	1,000	
HFC-236fa	$CHF_2CH_2CF_3$		x	6,300	x	1,000	
HFC-245fa	$CH_3CF_2CH_2CF_3$		x	560	x	1,000	
HFC-43-l0mee	$CF_3CHFCHFCF_2CF_3$		x	1,300	x	1,000	
Perfluoromethane (PFC-14)	CF_4		x	6,500	x	1,000	
Perfluoroethane (PFC-116)	C_2F_6		x	9,200	x	1,000	
Perfluoropropane (PFC-218)	C_3F_8		x	7,000	x	1,000	
Perfluorocyclobutane (PFC-318)	c-C_4F_8		x	8,700	x	1,000	
Perfluorobutane (PFC-3-1-10)	C_4F_{10}		x	7,000	x	1,000	
Perfluoropentane (PFC-4-1-12)	C_5F_{12}		x	7,500	x	1,000	
Perfluorohexane (PFC-5-1-14)	C_6F_{14}		x	7,400	x	1,000	
Sulphur hexafluoride	SF_6		x	23,900	x	1,000	
Blends [2]							
R404A	52:44:4 blend of HFC-143a, -125 and -134a		x	3,260	x	1,000	
R407A	20:40:40 blend of HFC-32, -125 and -134a [3]		x	1,770	x	1,000	
R407C	23:25:52 blend of HFC-32, -125 and -134a		x	1,526	x	1,000	
R407F	30:30:40 blend of HFC-32, -125 and -134a [3]		x	1,555	x	1,000	
R408A	47:7:46 blend HCFC-22, HFC-125 and HFC-143a		x	2,795	x	1,000	
R410A	50:50 blend of HFC-32 and -125		x	1,725	x	1,000	
R507	50:50 blend of HFC-125 and HFC-143a		x	3,300	x	1,000	
R508B	46:54 blend of HFC-23 and PFC-116		x	10,350	x	1,000	
Total							**0**

3.2.4 Step 4: Normalisation

Normalisation is an LCIA tool used to express impact indicator data that can be compared among impact categories. This procedure normalises the indicator results by dividing a selected reference value. This can be done for comparison with a reference system. Reference information over a given period of time could be an area (e.g., Germany, Europe, US, the world), a person (e.g., US citizen), or a product (e.g., the most frequently used product).

Table 3.2 shows the normalisation factors for impact on Western Europe. The goal of normalisation is to better understand the relative unit value of each indicator for the analysed product system. Normalisation is regarded as optional for simplified LCAs but mandatory for detailed LCAs.

Table 3.2: Normalisation factors (Huijbregts et al., 2005)



Normalisation factors - overall Western European impact

Category	Europe	Unit
Abiotic depletion	15,000	ktonne Sb eq.
Global warming (GWP100)	4,800,000	ktonne CO_2 (100 years) eq
Ozone layer depletion (ODP)	83,300	tonne CFC-11 eq.
Human toxicity	7,580,000	ktonne 1,4-DB eq.
Fresh water aquatic ecotoxicity.	505,000	ktonne 1,4-DB eq.
Terrestrial ecotoxicity	47,200	ktonne 1,4-DB eq.
Photochemical oxidation	8,260	ktonne C_2H_4 eq
Acidification	27,300	ktonne SO_2 eq
Eutrophication	12,500	ktonne PO_4 eq.
Solid waste	*	ktonne solid waste
Radioactivity	10,800	m^3 high level waste
Minerals Extraction	*	tonnes of minerals extracted
Water Extraction	*	m^3 water extracted

In the normalisation step, the relative contribution of each problem can be distinguished. Table 3.2 provides a reference for normalisation factors for European countries. Figure 3.4 shows an example of the calculation of the normalisation for GWP equal to 93 kg CO_2. The normalisation factor for GWP is 48E+8. This is used to normalise the GWP. The result for normalised GWP is 1.94E-8 kg CO_2.

Normalised GWP = GWP / Normalisation factor

Normalised GWP = 93 / 4, 800, 000, 00

Normalised GWP = 1.94E-8 kg CO2

Figure 3.4: Example of normalisation

3.2.5 Step 5: Grouping

Impact categories are grouped into one or more sets to better facilitate the interpretation of the results and their specific areas of concern. Grouping is the sorting and ranking of the impact categories. The following are two possible approaches used to group LCIA data:

i. Sorting indicators by characteristics such as inputs and outputs or global, regional, and local spatial scales.
ii. Sorting indicators by a ranking system, for example, as high, medium, or low priority. Ranking is based on value choices.

3.2.6 Step 6: Weighting

Weighting is done by aggregating indicator results across impact categories using numerical conversion factors, as shown in Table 3.3. Examples of bases for weighting factors are monetary values (willingness to pay, damage costs, and reduction costs) and panel methods (expert panels or non-expert panels). The following are two possible weighting methods:

i. Converting the indicator results or normalised results with selected weighting factors.
ii. Aggregating these converted indicator results or normalised results across impact categories.

The Eco-Indicator 99 (Baayen, 2000) method includes a weighting factor for three endpoints, which are human health, ecosystem quality, and resources, as shown in Table 3.3.

Table 3.3: Weighting factors for Eco-Indicator 99

Impact category	Weighting factor	Unit
Human Health	400	ECO 99 unit/DALY
Ecosystem Quality	400	ECO 99 unit/PDF m2 yr
Resources	200	ECO 99 unit/MJ

For example, if the results of the LCIA are as follows:

i. 10 person * years of human health for human beings (DALY)
ii. 25 PDF m2 * years potentially disappeared fraction species
iii. 8 MJ depleted resources

They can be presented using the following weighting factors in ECO 99 units:

i. Human health: 10 x 400 = 4 000 ECO 99 units
ii. Ecosystem quality: 25 x 400 = 10 000 ECO 99 units
iii. Resource depletion: 8 x 200 = 1 600 ECO 99 units.

The total impact is 15 600 ECO 99 units.

3.2.7 Step 7: Evaluating and Reporting LCIA Results

The goal of the evaluation is to enhance the reliability of the study. The results are checked and evaluated to ensure the goal and scope of the study are achieved. The results of the LCIA should be assembled into a comprehensive report that presents the results, data, and method in a clear, transparent, and structured manner.

Important results included in the report could be:

i. Inventory parameters like energy use, emissions, waste, etc.
ii. Impact category indicators like resource use, emissions, waste, etc.
iii. Essential contributions of life cycle stages to LCI or LCIA results such as individual unit processes or groups of processes like transportation and energy production.

After the LCA assessment has been made, the output will be stored and identified as environmental profile data. Figure 3.5 shows that the profile data contains environmental impact factors linked to several groups, which are transportation, material and manufacturing process, product usage, and EOL strategies for the product.

The transportation group consists of the manufacturing region, use region, types of transportation, and distance. Material and manufacturing process factors consist of material, weight, manufacturing process, recycle content, production volume, and material cost. Product usage factors consist of product durability and product life span. The last group is EOL strategies, which are used to consider options including reuse, remanufacturing, recycling, incineration, and landfill disposal. The outputs from Stage I are stored as environmental profile data and will form the inputs for the other stages in the IEDM framework.

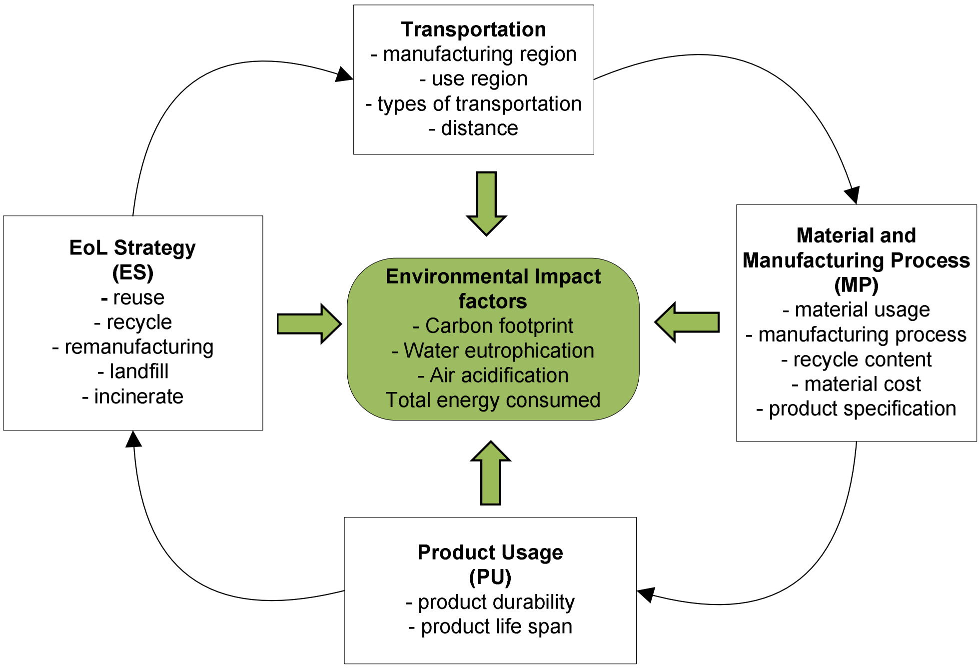
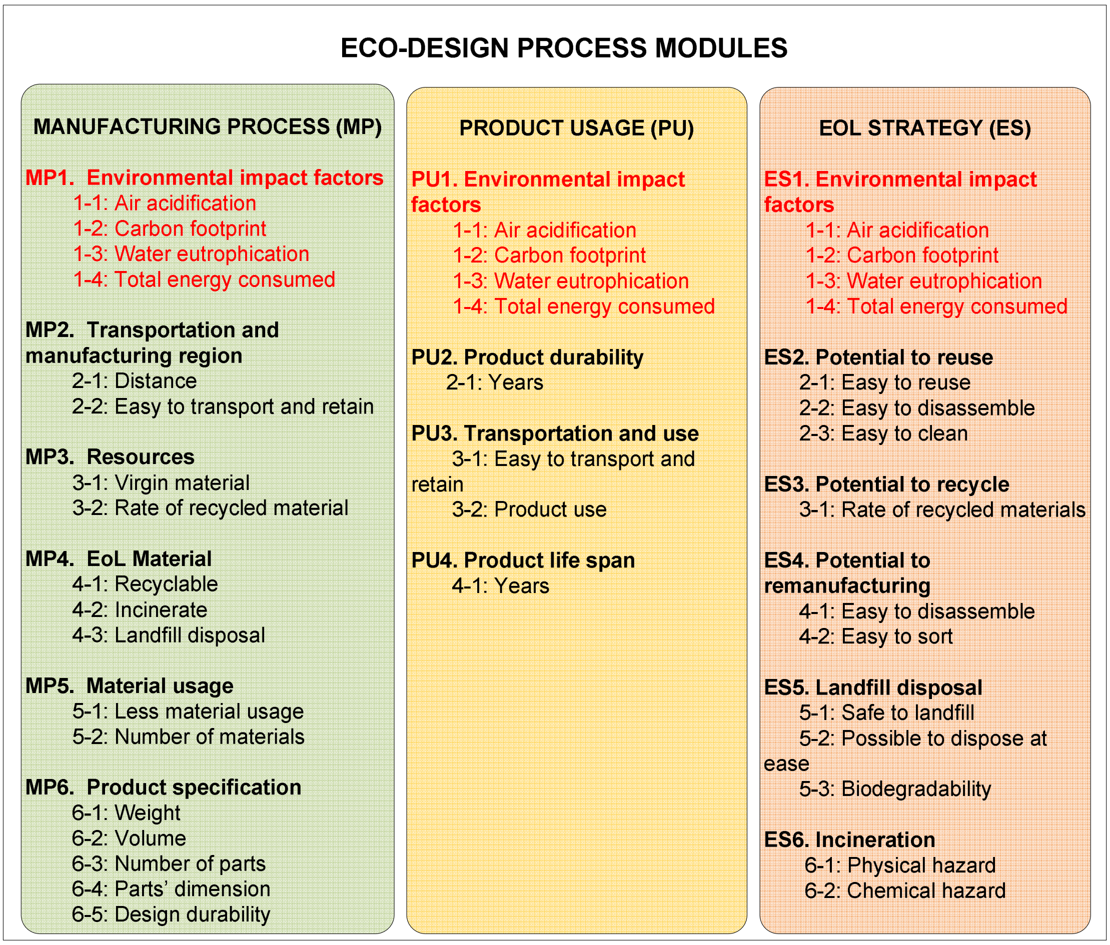


Figure 3.5: The environmental impacts on the product life cycle

3.3 Stage II: Eco-design Process Model

Stage II assesses the critical impact outputs from Stage I. These impacts will be aligned with the parameters of the Eco-Process model. The Eco-Process model depicted in Figure 3.6 is used as a guide to evaluate how the environmental impact factors contribute to the product life cycle.

The Eco-Process model uses three modules, shown in Figure 3.6, that relate to the manufacturing process, product usage, and EOL strategy. In addition to the environmental impact factors previously introduced and indicated in Figure 3.5, the Eco-Process modules include air acidification, carbon footprint, water eutrophication, and energy consumption. The information created in any individual design activity is stored within a knowledge base linked to these eco-design process (Eco-Process) modules; it is accessible for subsequent design tasks and can become a valuable eco-design resource. The designer can simplify and develop the relationship between these three modules and list the important parameters for assessment in the Eco-HoQ model.



ECO-DESIGN PROCESS MODULES

MANUFACTURING PROCESS (MP)

MP1. Environmental impact factors
- 1-1: Air acidification
- 1-2: Carbon footprint
- 1-3: Water eutrophication
- 1-4: Total energy consumed

MP2. Transportation and manufacturing region
- 2-1: Distance
- 2-2: Easy to transport and retain

MP3. Resources
- 3-1: Virgin material
- 3-2: Rate of recycled material

MP4. EoL Material
- 4-1: Recyclable
- 4-2: Incinerate
- 4-3: Landfill disposal

MP5. Material usage
- 5-1: Less material usage
- 5-2: Number of materials

MP6. Product specification
- 6-1: Weight
- 6-2: Volume
- 6-3: Number of parts
- 6-4: Parts' dimension
- 6-5: Design durability

PRODUCT USAGE (PU)

PU1. Environmental impact factors
- 1-1: Air acidification
- 1-2: Carbon footprint
- 1-3: Water eutrophication
- 1-4: Total energy consumed

PU2. Product durability
- 2-1: Years

PU3. Transportation and use
- 3-1: Easy to transport and retain
- 3-2: Product use

PU4. Product life span
- 4-1: Years

EOL STRATEGY (ES)

ES1. Environmental impact factors
- 1-1: Air acidification
- 1-2: Carbon footprint
- 1-3: Water eutrophication
- 1-4: Total energy consumed

ES2. Potential to reuse
- 2-1: Easy to reuse
- 2-2: Easy to disassemble
- 2-3: Easy to clean

ES3. Potential to recycle
- 3-1: Rate of recycled materials

ES4. Potential to remanufacturing
- 4-1: Easy to disassemble
- 4-2: Easy to sort

ES5. Landfill disposal
- 5-1: Safe to landfill
- 5-2: Possible to dispose at ease
- 5-3: Biodegradability

ES6. Incineration
- 6-1: Physical hazard
- 6-2: Chemical hazard

Figure 3.6: List of eco-design process parameters

Figure 3.7 shows an example of a relationship that has been created. The arrows represent links between the parameters for design durability within the manufacturing process group. The design durability (MP6-5) has a relationship to the product durability (PU2) and the potential for remanufacturing (ES4). In the case of a single-use medical device, for example, there is an issue to consider related to the product's life span. The issue will arise when the product made from a material with high durability is used for a product that has a short life span. Therefore, with this relationship, a designer will know what parameter to consider to solve this issue.

An EOL strategy is not developed separately but is included as part of the eco-design process, shown in Figure 3.6. By including these considerations into the information generated within the Eco-HoQ, it is possible to fully integrate EOL based decision into all aspects of the product development and manufacturing process as determined in the Eco-QFD process.This was seen as being the best way of integrating EOL into the IEDM framework.

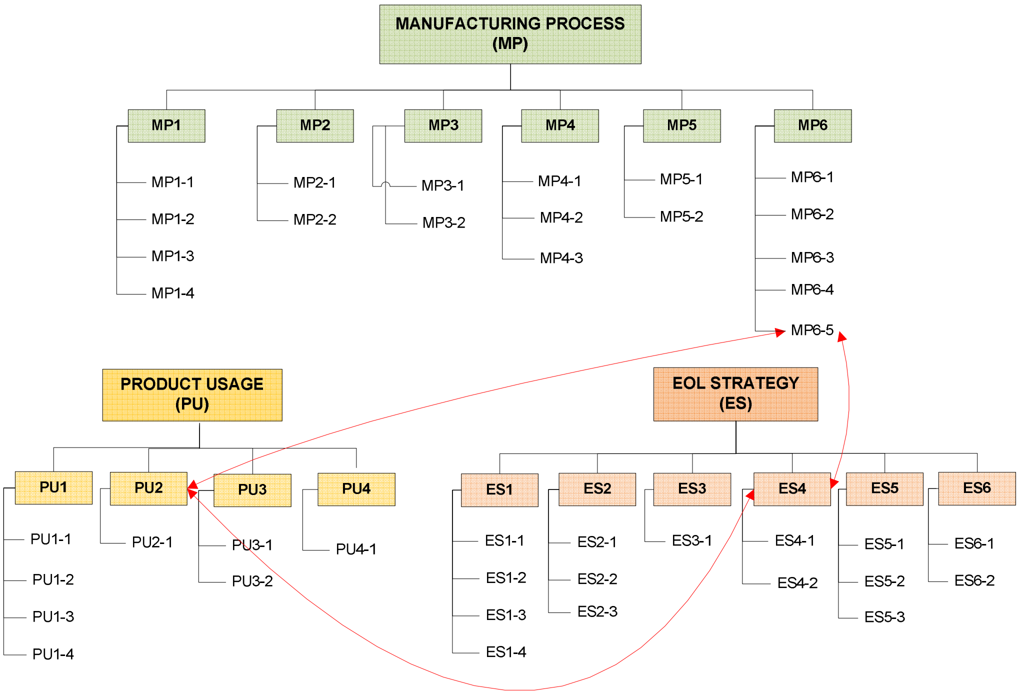


Figure 3.7: Eco-design process relationships

3.3.1 Manufacturing Process Module

The manufacturing process module considers the manufacturing phase, within which the selection of material is the most crucial parameter. It is used to identify and record the most important environmental features associated with the manufacture of a product from a selected material. Several parameters are used to characterise the environmental impact of the item being designed. This data can be used to establish a source of information in support of sustainable product development. In addition to the previously established environmental impact factors from the LCA analysis, the eco-design parameters included in this module are:

i. Transportation and manufacturing region. This factor relates to the distance from the manufacturing region to the region of use. It includes the types of transportation used to deliver products.

ii. Resources. This factor represents two main properties pertaining to the origin and critical state of the material, which are divided between the amount of virgin material used and the content of recycled material in the product.

iii. Material's EOL. This factor considers the EOL strategies, which are categorised as recycle, incinerate, and landfill disposal.

iv. Material usage. This factor focuses on considering the volume or level of material usage and the number of materials used in the product. It is proposed that by minimising the different types of material used and their weight in the product, it becomes simpler to process the product at the end of its life.

v. Product specification. This factor refers to the characteristics of the product such as the weight, volume, number of parts, dimensions, and design durability.

3.3.2 Product Usage Module

Products have limited lifetimes and will eventually be discarded. After an object is purchased and utilised, it will at some point lose its value or its desirability as a possession (Ko, Ramirez and Ward, 2011). The product usage module considers four important factors. Two of these factors (environmental impact and transportation) are discussed in the previous section. The remaining two are:

i. Product life span. This factor measures the length of time that the product remains relevant and can possibly be used.

ii. Product durability. This factor focuses on the product’s life cycle in terms of how long it can be sustained in terms of product functionality. For example, a single-use medical device has a limited lifetime and will be discarded due to contamination, even though the device could still feasibly be used. Therefore, it may be the case that for single-use products or those with short lifespans the designer should consider redesigning the product in a less durable or non-durable form.

Product durability is examined in greater depth in Chapter IV, which presents a case study of the application of single-use forceps where each product has a life span of one cycle.

3.3.3 End-of-Life Strategy Module

The EOL strategy module considers the options associated with product disposal using six factors, including the previously outlined environmental impact factors. The other factors are:

i. Potential to reuse. This assesses how easy it is to reuse all or some of the product’s parts. This includes conventional reuse, where the item is used again for the same function, and new-life reuse, where it is used for a different function. For example, the EOL of an automobile tyre can include reuse for household items, garden decorations, and toys for kids in playground.

ii. Potential to recycle. This identifies the benefits arising when the material can be recycled. The recycling process is the breaking down of the used item into raw materials, which are used to make new items. For example, tyres have been recycled into powder for the use of rubber mats, rubber racetracks, rubber tiles, and many other uses.

iii. Potential for remanufacturing. This considers whether it is possible and/or easy to disassemble and sort some of a product’s parts to be used again. For example, the tyre remanufacturing process will take the casing, inspect it, refurbish it, add a new sidewall and tread rubber, and then vulcanize the new rubber to the casing. After this process, the remanufactured tyre will look like a new tyre in every aspect (http://www.mobiusenviro.com/).

iv. Landfill disposal. This considers if disposal via landfill is safe to the "living environment". The nature of the material will determine whether it is easily disposed of. In this case, a tyre is not an appropriate item for landfill disposal because the material is not biodegradable. In terms of the living environment, water collects in scrap tyres, making them an excellent breeding ground for insects and vermin. A tyre becomes a significant fire risk; in fact, there have been quite a few dangerous fires in landfills in both Europe and the US (http://www.genan.eu/incineration-130.aspx).

v. Incineration. This considers whether it is possible or necessary to deploy a process of waste treatment that involves the combustion of organic substances contained in waste materials. For example, a tyre contains energy that can be released through incineration. Therefore, more and more scrap tyres end up as solid fuel. Tyres can be used as a replacement for coal in coal-burning power plants but are more frequently used in cement kilns. (http://www.genan.eu/incineration-130.aspx)

This module characterises the design in terms of appropriate EOL scenarios and aims to find the most suitable design options and assess their corresponding EOL impact. The Eco-Process module thus acts as a guideline in the IEDM methodology for producing a design tool based on the assessments or requirements from customers, recyclers, and manufacturers with the appropriate use of environmental parameters. These parameters are then used to inform the decision-making process based upon the Eco-HoQ matrix, outlined in Figure 3.1 as Stage III.

Table 3.4 describes the parameters of the Eco-Process modules. These descriptions are used as a reference for the development of Eco-QFD, which will be explained in section 3.4. The parameters are listed as the selected important eco-design features that should be considered in the development of a sustainable product.

3.4 Stage III: Eco-design Quality Function Deployment

The Eco-QFD is an enhanced method that represents an original contribution to the body of QFD knowledge and can be embedded within all of the QFD phases. No other QFD based methodology utilises such a centralised approach that focuses on eco-design consideration. This brings such considerations to the centre of all other activities, which is essential to achieve more sustainable products in the future. The Eco-QFD is a conceptual model for integrating eco-design and economic viewpoints in the early design phase. It generates eco-design parameters and integrates them into each of the QFD phases as shown in Figure 3.8. There are five linked elements: the four phases of QFD and the main Eco-HoQ.

Table 3.4: List of parameters for Eco-Process modules

List of parameters	Descriptions	Measurement / unit
Air acidification (AC)	The existence of contaminants in the air that interfere with human health and/or ecological systems	Gram (g)
Carbon footprint (CF)	The result of burning fossil fuels to supply materials to a factory for the manufacturing process	Gram (g)
Water eutrophication (WE)	Occurs when an overabundance of nutrients are added to a water ecosystem	Gram (g)
Total energy consumed (EC)	The cumulative amount of energy consumption in all the life cycle stages	Kilojoule (kJ)
Distance	Total distance for the transport type	Kilometre (km)
Easy to transport and retain	Ease of transport and retention in the logistics of shipping to retailers and reverse logistics from users	Kilometre (km)
Resources (material)	The amount of virgin material and recycled materials in the product	Gram (g)
Years material durability	Expected number of years a product will maintain its mechanical and physical properties	Years
Design durability	Whether a product can be easily re-used or redesigned into a new product	Product dimension, physical and characteristics of the product
Recyclable	Product or part which can be recycled	Part / components
Less material usage	Whether a product is lightweight	Gram (g)
Easy to process and assemble	Easy to process and assemble during manufacturing	Hours
Number of materials	The number of types of materials in the product	Number of materials per product
Weight	The weight of the product	Weight
Volume	Volume of the product	Quantity per production
Number of parts	The number of parts for the product	Number of parts per product
Product life span	Physical lifetime of the product	Year
Potential to reuse	Whether it is easy to reuse as a product or as a part and easy to disassemble in the maintenance stage during usage or in the EOL stage	Hours
Potential to remanufacturing	Easy to disassemble and sort parts at the EOL stage	Hours
Potential to recycle	Ratio of the product that can be recycled	Product ratio
Landfill disposal	Whether it is safe to living environment and possible to dispose of easily	Product ratio
Incineration	Whether the waste materials have combustible organic substances	Product ratio

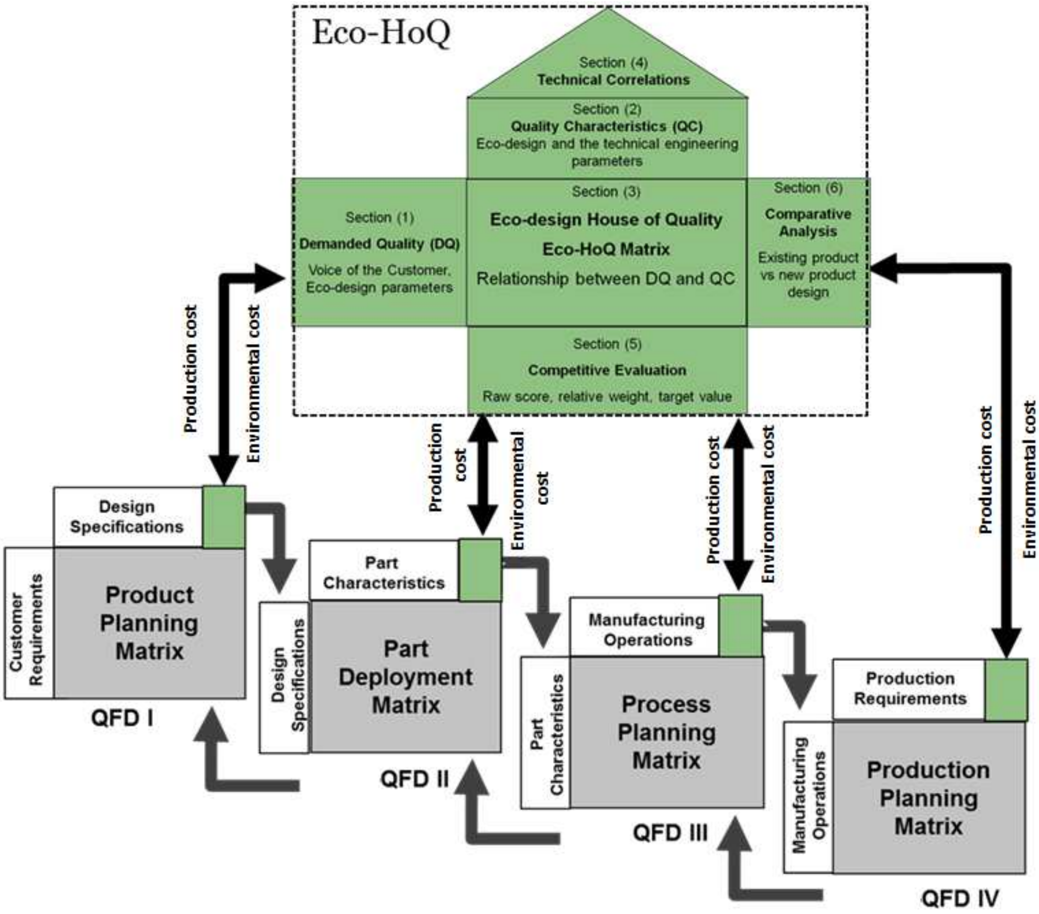


Figure 3.8: Conceptual model of Eco-HoQ with enhanced QFD process (Eco-QFD)

This new approach allows the Eco-HoQ to become the platform for managing eco-design and economic cost (production cost and environmental cost) considerations within all four QFD phases. The Eco-HoQ is an extra ‘house’ that can capture and manage sustainability considerations in a single place. This adds to the relevance of the information, and links attempts to improve sustainability to each phase of the design process. The main advantage of this approach is that it enables and encourages user feedback in each phase in an integrated manner. This means that inconsistencies arising and compromises made when applying eco-design considerations are detected and recorded, and their effects and resolution are analysed.

By accessing this information during preliminary and later Eco-QFD cycles, a coherent sustainability strategy can then be deployed. Organisations will continuously learn and develop their expertise from this approach and improve the process of sustainable product development. Examining sustainability along the entire product life cycle makes the goal of sustainable product development a feasible reality. The application of Eco-QFD to the case study of single-use forceps will be explained in detail in Chapter IV.

3.4.1 Eco-HoQ Model

This study propose that the Eco-HoQ model bridges the conceptual gap between the requirements of stakeholders (customers, recyclers, and manufacturers) and eco-design indicators by focusing on a product's life-cycle processes. The Eco-HoQ model deploys enhanced quality function concepts made up of "rooms" that allow the input of demanded quality (DQ) and quality characteristics (QCs). These requirements are mapped against each other using an interrelationship matrix and potential interactions, which are considered using a technical correlation matrix. Assessments are then supported via a competitive analysis tool with the results represented in a targets section. This assessment can then be used to highlight potential strengths and weaknesses in the proposed design. The use of information presented in this way is seen as supporting a systematic approach to eco-design, allowing greater information and expertise sharing. This is viewed as a concurrent process within which the Eco-HoQ can be utilised to indicate the perceived benefits, or drawbacks, of design proposals in an interactive way. The main Eco-HoQ model generates the environmental parameters and the combination of production cost and environmental cost used for all QFD phases shown in Figure 3.8. Figure 3.9 shows the development of the Eco-HoQ model. It consists of six sections.

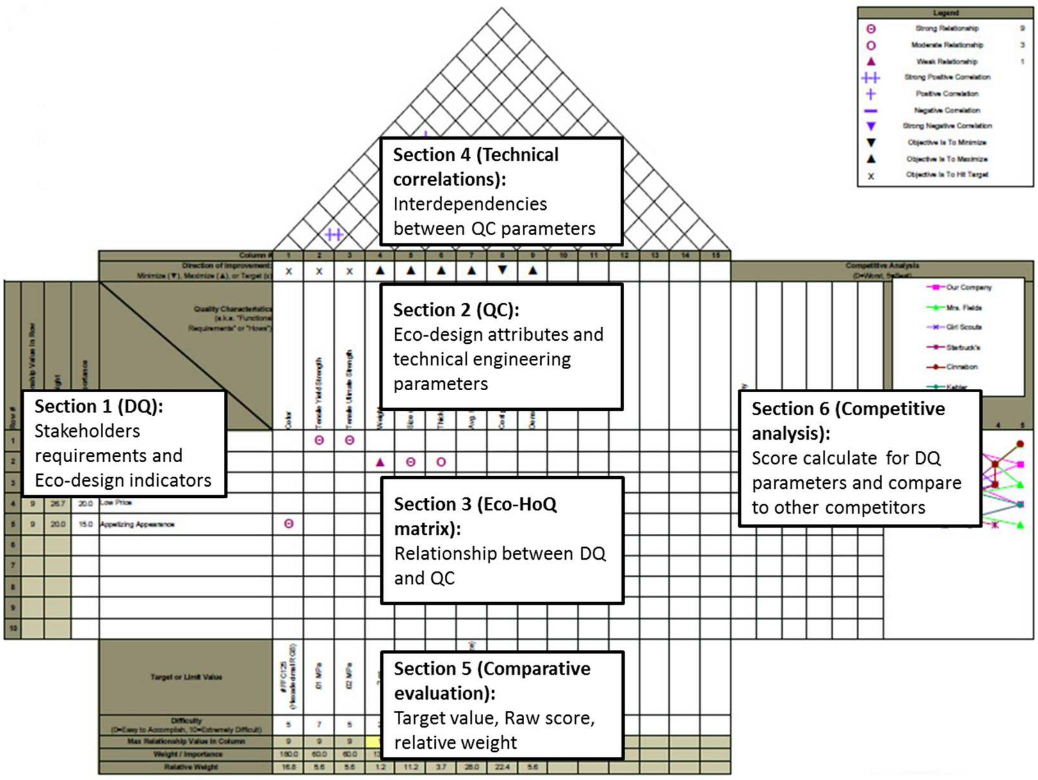


Figure 3.9: Eco-HoQ model

Section 1 contains the DQ requirements for the identified eco-design parameters. Section 2 provides the available QC as technical requirements and associated eco-design attributes. The Eco-HoQ Matrix, completed within Section 3, is used to build relationships between the DQ requirements and the QCs. It also maps the associated eco-design considerations within the processes proposed to engineer the product. This section has a critical function, as it demonstrates the results of any eco-design based proposals within each Eco-QFD phase, including, most importantly, the level of impact on customer satisfaction. This assessment is assured in this approach through the integration of the Eco-HoQ into a conventional QFD process. The critical point here is the use of a single Eco-HoQ, which means that all eco-design considerations can be referenced regardless of where they arise in the other QFD phases. This is supported by the analysis undertaken in the Eco-HoQ matrix in which the level of any relationship is mapped. This matrix effectively represents the eco-design considerations made and associates them with the attributes of the proposed design. This tool has been developed in Microsoft Excel.

The evaluation used in the Eco-HoQ is based on the raw score for each QC as assessed against the identified DQs. This process can be used to determine which parameters are important. The resulting information can then be employed across the QFD phases. The parameters have been weighted from 1 (very low) to 5 (very strong) to represent customer priorities within the DQs.

The degree of importance of each DQ has been analysed using the information and concepts identified by the developed LCA. The approach incorporated into the Eco-HoQ Matrix has utilised symbols consistent with those used in a traditional QFD process (Romli et al, 2014). The symbols have the following meanings and associated values:

● Strong positive relationship with a value of 9

▲ Marginally positive relationship with a value of 5

♦ Weak relationship with a value of 1

The raw score is the sum of relational strength multiplied by customer weighting for each column. The relative weight for each parameter has then been calculated by dividing each raw score by the total raw score. The values of relational strength have been provided to inform the decision-making process. The raw score and relative weight have been calculated using equations (3.1) and (3.2), respectively.

$$RS_i = \sum_{k=1}^{K} C_k * R_{i,k} \; (i = 1,2,\ldots.,I) \qquad (3.1)$$

$$W_i = \frac{RS_i}{\sum_{i=1}^{I} RS_i} \times 100, \qquad (3.2)$$

Where RS_i is the raw score of the i^{th} eco-design parameters for QC, C_k is the k^{th} importance weight for DQ, and $R_{i,k}$ is the relational strength of the i^{th} of QC to k^{th} of DQ. In equation (3.2), W_i is the relative weight of the i^{th} eco-design parameters in QC. *i* is the index number of the QC, and *k* is the index number of the DQ. The results of the analysis of the information presented in the matrix have been used to prioritize the environmental considerations for elements in each of the QFD phases that could potentially produce an improved product design.

The technical correlation in Section 4 forms the triangular matrix roof. It identifies how the technical requirements and associated eco-design considerations that characterise the product support or impede one another. This section performs an essential function in assessing the effect of any proposed changes using the negative and positive correlations between parameters at any stage of the design process. It maps the relationships between parameters so that the consequences of design changes are fully considered. These relationships have particular relevance when a change that provides a positive outcome in one phase may have a negative impact in another. The capture and analysis of the effect of any environmental consideration can thus be assured across the entire Eco-QFD process.

The comparative evaluation in Section 5, shown in Figure 3.9, summarises the conclusions drawn from the analysis of the matrix entries. This evaluation is used to demonstrate the result of any design changes and to compare post- and pre-design products. The competitive analysis in Section 6 allows comparison across and between existing and new attributes as rated by the consideration of DQ characteristics. Attributes are ranked in terms of their impact upon customer satisfaction, allowing decisions to be made regarding the efficacy of proposed design changes, including any environmental considerations.

To understand the structure and behaviour of functions within a product, it is essential to gather design requirements from the stakeholders involved. To meet this need, the Eco-QFD process integrates the Eco-HoQ and the four conventional QFD phases using the steps shown in Figure 3.10.

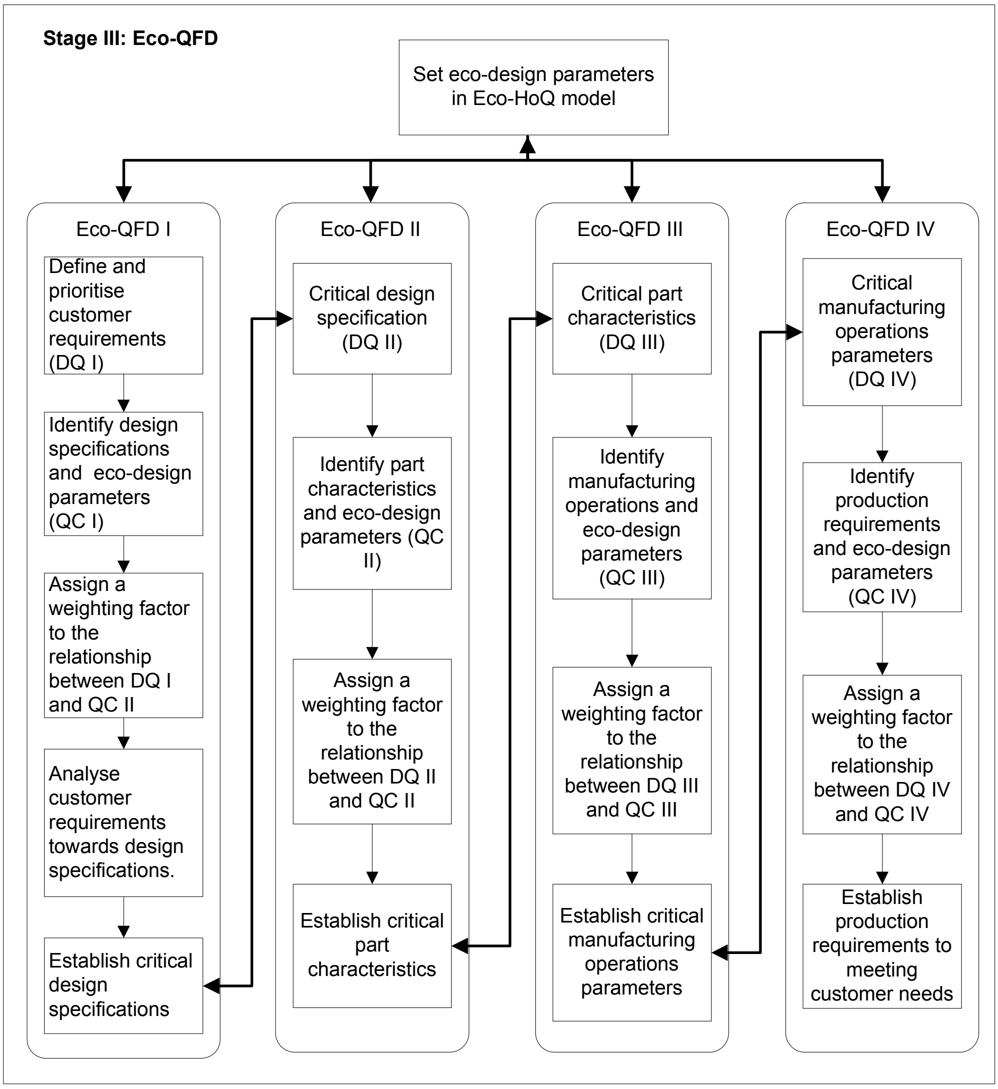


Figure 3.10: Relationship between phases in the Eco-QFD

The Eco-HoQ model acts as a platform to incorporate the analysis of sustainability aspects in product design. Social, environmental, and economic aspects are introduced into the evaluation process for Eco-QFD. These sustainability aspects are also related to the environmental considerations of the product's life cycle associated with the analysis of raw material, manufacturing processes, product usage, and EOL strategy. The concentration of environmental considerations in one place ensures that product sustainability is central to any design development and that the implications of any design change are fully identified and justified. It is helpful to consider how the assessment is achieved within each Eco-QFD phase.

3.4.2 Eco-QFD Phase I: Product Planning Matrix

In this phase, the designer defines and prioritises customer requirements and environmental requirements. This phase integrates the assessment of requirements from customers with the appropriate use of environmental factors to produce a sustainable product. This method utilises a matrix that provides a conceptual map for the design process as a means for understanding customer requirements and establishing priorities for design requirements (DQ I). These requirements will have relationships with technical characteristics and the eco-design process for the product (QC I). The key benefit of this phase is to ensure that the product focuses on customer requirements, developing factors to be used in rating concepts, selecting a product concept, and establishing product specifications. The process of identifying customer needs or preferences normally includes the following five steps:

i. Gathering raw data from customers (DQ I) through interview and discussion between product designer and customers enables both to contribute environmental considerations. This involves contact with customers and applying any experience with the product's use environment. Expert environmental inputs can be provided by designers and customers and discussed. Three methods are commonly used: interviews, focus groups, and observing the product in use.

ii. Interpreting the raw data in terms of customer needs based on the product attributes and eco-design product specifications. This provides the quality characteristics (QC I) for the product.

iii. Establishing the relative importance of the needs. The outcome of this step is a numerical importance weighting for a subset of the customer's needs. These weighting factors are values attributed to QC I for the product.

iv. Analysing customer requirements for design specification. This analysis is based on the relational strength of customers' needs (DQ I) towards quality characteristics (QC I) of the product.

v. Establishing critical design specifications. The most useful metrics are those that reflect as directly as possible the degree to which the product satisfies the customer needs. The relationship between needs and metrics is central to the entire concept and design specifications. These quality characteristics (QC I) will be used as inputs for the demanded quality (DQ II) in Phase II.

3.4.3 Eco-QFD Phase II: Part Deployment Matrix

This phase defines the relationship between design specifications (DQ II) and part characteristics (QC II). The key benefit of this phase is to translate design requirements into a satisfactory design solution, which is assessed on the level of part or component characteristics. There are four main steps involved in this phase:

i. Critical design specifications (DQ II) are acquired through the transfer of a list of design requirements together with weighting factors from the QC I in QFD Phase I.

ii. Part characteristics and eco-design parameters (QC II) are identified and defined. The design solution takes the form of part characteristics and eco-design parameters that best meet the measurable design requirements.

iii. The QFD process is used to assign a weighting factor to the relationship between the defined DQ II and QC II. This establishes the relative importance of the customers' needs. The outcome of this step is a numerical importance weighting for the part deployment parameters.

iv. Critical part characteristics (QC II) are then established. Parts that are determined to be most critical to meeting customer requirements are deployed in Phase III as the DQ III inputs.

3.4.4 Eco-QFD Phase III: Process Planning Matrix

In this phase, the part characteristics (QC II) from phase II are used to define manufacturing operations. There are four main steps involved in this phase:

i. The transfer of part characteristics together with weighting factors from Phase II. The part characteristics in this phase (DQ III) are analysed to identify the relevant manufacturing operations.

ii. Manufacturing operations (QC III) are considered with the aim of identifying the most appropriate operations and eco-design parameters to meet the measurable part requirements. These selected parameters form QC III for this phase.

iii. The weighting factors are used in the relationship between DQ III and QC III. These establish the relative importance of the customers' needs. The outcome of this step is a numerical importance weighting for the process planning parameters.

iv. The result of this process planning is that manufacturing focuses on the critical processes, dimensions, and characteristics that will have a significant effect on producing a product that meets customers' needs. These manufacturing operations (QC III) will be used as inputs for the demanded quality (DQ IV) in Phase IV.

3.4.5 Eco-QFD Phase IV: Production Planning Matrix

This phase produces performance indicators to monitor the production process used to manufacture the required number of products. There are four steps taken to find the critical parameters and establish production planning parameters.

i. The list of manufacturing operations (DQ IV) together with weighting factors in this phase are input from the QC III in Phase III.

ii. Product requirements and eco-design parameters (QC IV) are identified to determine the production planning needed to meet the measurable process planning requirements.

iii. A weighting factor is assigned to the relationship between DQ IV and QC IV. This establishes the relative importance of the customers' needs. The outcome of this step is a numerical importance weighting for the production planning parameters.

iv. This can be used to establish critical production planning parameters with the aim of ensuring that the production planning phase will deliver high quality products based on customer requirements.

Eco-QFD is a systematic means of ensuring that customer requirements are accurately translated into relevant technical descriptors and eco-design parameters throughout each stage of product development. Therefore, linking these phases provides a mechanism to ensure the customer's voice is present in process operations. Another benefit of Eco-QFD, as shown in Figure 3.10, is the traceability of requirements from each phase to the previous phase and to the original source of customer requirements.

3.5 The Ecological Economic Cost Model

The ecological economic cost (Eco-Economic Cost) model shown in Figure 3.11 is an approach used to summarise the development enabled by Eco-QFD and Eco-CBR in this framework. The Eco-Economic Cost is a stand-alone model that is used to calculate the costs of manufacturing, environmental impact, transportation, product use, and the product's EOL. It integrates consideration of environmental and production costs in each Eco-QFD phase and the single Eco-HoQ. The Eco-Economic Cost model will work iteratively to improve the accuracy of poor data. By accessing and combining the information generated in each of the Eco-QFD phases, a coherent strategy can then be deployed to improve the process of sustainable product development. The model allows data integrity to be continuously improved. Each stage can be re-considered as data is added. This process is used to support the calculation of the total life-cycle cost of a product from the time of purchase until the product's EOL as it is been assessed in the Eco-QFD process. In this study, the Eco-Economic Cost model is not fully developed. It has been deployed to illustrate how the method could be developed in the future. Evidence of how the information required can be produced has been considered in the two case studies.

By accessing and combining the information generated in each of the Eco-QFD phases, a coherent strategy can then be deployed to improve the process of sustainable product development. This process is used to support the calculation of the total life-cycle cost of a product from the time of purchase until the product's EOL as it is been assessed in the Eco-QFD process. In this study, the Eco-Economic Cost model is not fully developed. It has been highlighted to illustrate how the method could be developed in the future. A description of the elements used in this approach is shown in Table 3.5.

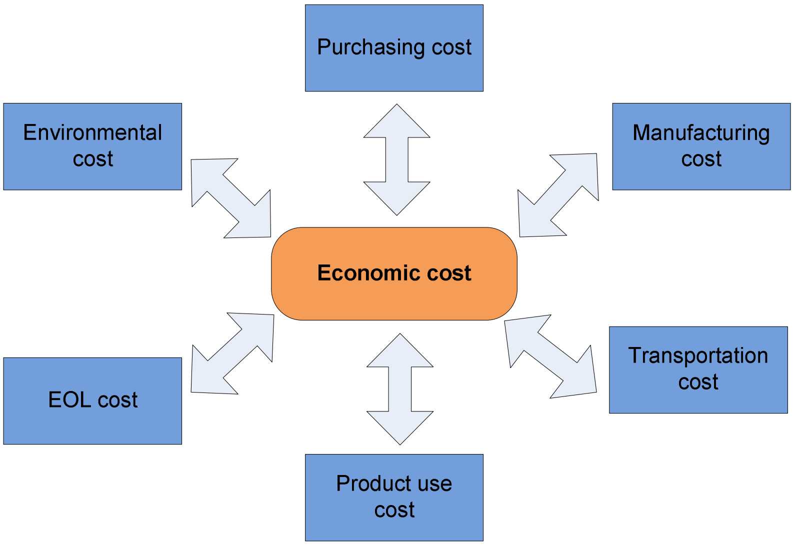


Figure 3.11: Eco-Economic cost model

In the Eco-Economic Cost model, life-cycle cost is assessed using the following equations:

Purchase cost of material, $Pc = Pc * W$ (3.3)

Where Pc is the purchase cost of materials (£/g) and *W* is the mass of the product (g).

Manufacturing cost, $Mc = Dc + Lc + Oc$ (3.4)

Where *Mc* is the manufacturing cost, *Dc* is direct cost, *Lc* is the labour cost, and *Oc* is the overhead cost.

Transportation cost, $Tc = \frac{\left\{\left\lceil\frac{Vol * W}{Box}\right\rceil \cdot Dc\right\}}{Vol}$ (3.5)

Where *Tc* is the transportation cost, *Vol* is the volume of production, *W* is the mass of product, *Box* is the box capacity, and *Dc* is the delivery cost.

Environmental cost, $ENc = CF + EC + AC + WE$ (3.6)

Where *ENc* is the environmental cost, *CF* is the carbon footprint cost, *EC* is the total energy consumed cost, *AC* is the acid acidification cost, and *WE* is the water eutrophication cost.

End-of-Life cost, $EOLc = (LFc + INc) - RV$ (3.7)

Where $EOLc$ is EOL cost, LFc *is* landfill cost, INc is the incineration cost, and RV is the recycle value.

Then, the economic cost is $ECOc = Pc + Mc + ENc + Tc + EOLc$ (3.8)

Table 3.5: Categories of cost solutions

Types of Cost	**Description**
Purchasing (Pc)	Purchasing cost for the material
Manufacturing (Mc)	Manufacturing cost for the product per unit and per production
Transportation (Tc)	Transportation cost is based on the types of transportation used from manufacturing region to use region.
Environmental (ENc)	The environmental cost is based on the calculation of environmental impact to product life cycle.
End of Life (EOLc)	EOL cost is based on the calculation of the EOL product for recycling, incineration, or landfill disposal.
Economic (ECOc)	The economic cost is the total cost of the product life cycle, including raw material, manufacturing, transportation, and EOL.

The information used when completing the assessment reported in this study was taken from an appropriate current LCA database (Vogtlander, 2011). This database has a quick reference guide to LCA data and eco-based materials selection.

The Eco-Economic Cost model should be used with the Eco-QFD model and the Eco-CBR model. In the Eco-QFD model, Eco-Economic Cost will calculate the total life-cycle cost from raw material extraction until the product's EOL. This means that the Eco-HoQ will be a platform to summarise the environmental and production costs. The approach will be demonstrated through the case study of single-use forceps in Chapter IV.

For the Eco-CBR model, an Eco-Economic Cost model will generate information by analysing the cost estimations to propose suitable solutions in the Eco-CBR output. The economic cost in the Eco-CBR will be presented in the form of a range and will be demonstrated through case studies in Chapter VI and Chapter VII.

3.6 Eco-design Case-based Reasoning Model

This section introduces the Eco-CBR model shown in Figure 3.12, which integrates CBR with eco-design factors. This study takes the CBR approach further with the development of the Eco-CBR tool. This uses the IEDM framework, which was previously engineered to ensure that product development embraces social, environmental, and economic considerations throughout a product's life cycle.

Figure 3.12 shows the proposed operation of the Eco-CBR model. The cycle starts with an initial description of a problem, which defines a new case without solutions. This new case is referring to the product design/redesign that is formed around a number of sustainability input features. These are used to retrieve similar cases from the Eco-CBR library. The retrieved cases are selected from data stored in the library within defined sustainability groups.

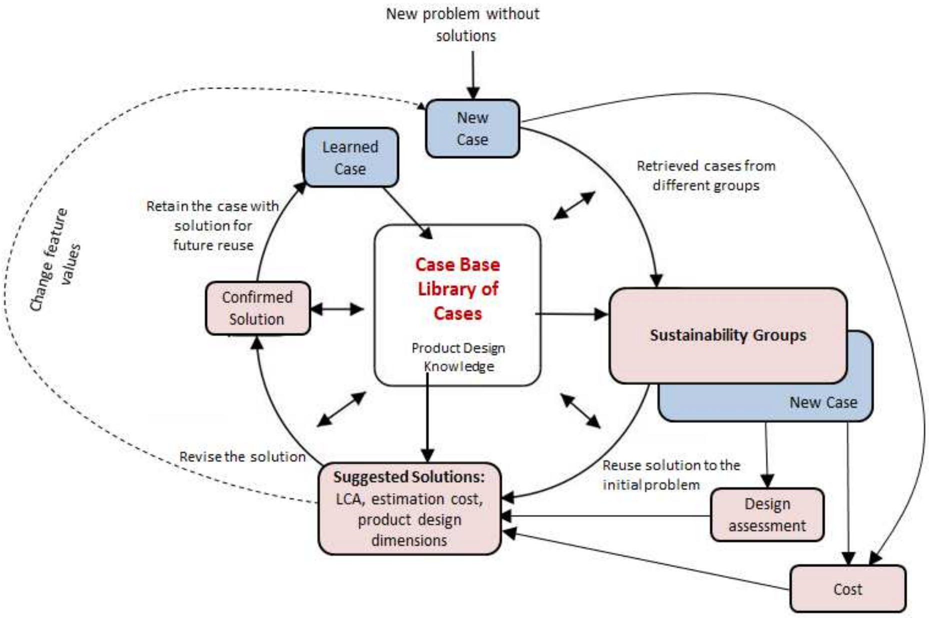


Figure 3.12: The Eco-CBR model

After retrieving similar cases, the designer can reuse the identified solutions to propose a solution for the new case. The suggested solutions will contain information about the LCA, estimations of the cost for product life cycle, and product design evaluations and will relate them to details such as new dimensional requirements. The solutions also relay critical information from the Eco-QFD phases, including customer requirements, environmental impact, and product design indicators. At this stage, the designers have two options:

ii. If the solutions are not valid, they can modify the feature values and run the process again in order to improve the product, or
iii. They can accept the solutions and revise and adapt them to the new case.

When a designer is satisfied with the solutions, the case will be retained, and the library is updated by storing the new case. This process will enlarge the case library, and the new case can be accessed in the future, allowing for the reuse of proven solutions. The details of the Eco-CBR method are explained further in Chapter V and are demonstrated through a case study in Chapter VI.

3.7 Summary

The IEDM framework has been designed to be easily and widely applicable. It allows the deployment of an enhanced QFD process and the incorporation of important eco-design considerations with a full assessment of their impact across the complete product design and manufacture process for the entire life cycle. The incorporation of information within the stages of the IEDM framework enables users with complementary knowledge to enter and access information in a timely and controlled manner. They are then able to contribute their expertise to help make decisions with the aim of delivering more sustainable products. The concentration of environmental considerations in the Eco-HoQ within the deployed QFD process and the integration with Eco-CBR ensures that product sustainability is always central to any design development. This, in turn, means that the implications of the changes are fully identified and, consequently, can be justified.

This framework can provide an organised design process, especially during the configuration design phase that allows designers to understand how a customer’s needs may be better defined in terms of the context of sustainability. It also allows them to evaluate product sustainability and to estimate the level of sustainability of different product parts or configurations. This can be used as a guideline in the product development process. In conclusion, the proposed framework provides a number of benefits and contributes to overcoming the research gaps in sustainable product development. The implementation of this framework for each model is presented in a case study in Chapter IV.

CHAPTER IV

ECO-DESIGN QUALITY FUNCTION DEPLOYMENT: CASE STUDY

This chapter addresses the second objective of this study by proposing a conceptual model for integrating eco-design and economic viewpoints in the early phases of the design process. It presents a case study that demonstrates the use of the ecological quality function deployment (Eco-QFD) through the integrated eco-design decision making (IEDM) framework. An application of the proposed approach is presented in the context of the redesign of single-use medical forceps. All product sustainability considerations are conducted within the ecological house of quality (Eco-HoQ) embedded in the Eco-QFD. This case study shows how the Eco-QFD has brought together the analysis of various factors relating to manufacturing processes, product usage, and end-of-life (EOL) strategy. It clearly demonstrates how the concentration of environmental considerations in one place ensures that sustainability remains central to any design development and the environmental implications of changes are fully identified and justified.

4.1 Case Study and Analysis

The Eco-QFD fits in the IEDM framework as a Stage III after the analysis of life cycle assessment (LCA) and eco-design process (Eco-Process) model. The application of the developed Eco-QFD model in the IEDM framework is demonstrated in the context of the redesign of medical forceps. This medical forceps is manufactured by a company, DTR Medical that designs single-use surgical instruments. These sterile single-use medical forceps are used primarily for ear, nose, and throat (ENT) surgery. In this case study, the customer’s requirements were based on discussions with the designer regarding the existing product range and with consultant engineers, including the author, who were considering the development of these products. These discussions produced the priorities for each requirement and these requirements were evaluated and ranked.

The material and manufacturing processes used to develop the forceps were reviewed in order to consider how the design could be improved to reduce the product's environmental impact. This product is currently manufactured in Pakistan; one of the manufacturer's considerations was whether to move the production into the UK, closer to the company. The intention was to explore the benefits of applying newly available material and manufacturing technologies to provide cost-effective and reliable volume production to meet the needs of the market.

The research contribution made in the development of Eco-HoQ embedded in the Eco-QFD process. This process is the continued presence of the voice of the customer and the integration of environmental consideration into each aspect of the product's life cycle. Moreover, the Eco-QFD model provides insight into the whole design and manufacturing operation (from concept to manufacture) and demonstrates possibilities for dramatically improving efficiency by resolving production problems early in the design phase.

4.2 IEDM Stage I: Product Requirements Using LCA

In Stage I, the features of the medical forceps were analysed. The product is currently manufactured from stainless steel using manual forging and machining processes. The designer proposed that a new product be made from polyether ether ketone (PEEK). Figure 4.1 shows that PEEK (circled) is a high performance thermoplastic. It has exceptionally high stiffness, strength, and resistance to heat. Peek can be injection moulded, extruded, and compression moulded. For the purposes of this case study, a manufacturing process using injection moulding was selected. The use of PEEK was intended to support and allow the following improvements in design and production:

i. Improved assembly

ii. Enhanced quality of final product compared to current design

iii. At a minimum, the same functionality as the existing forceps

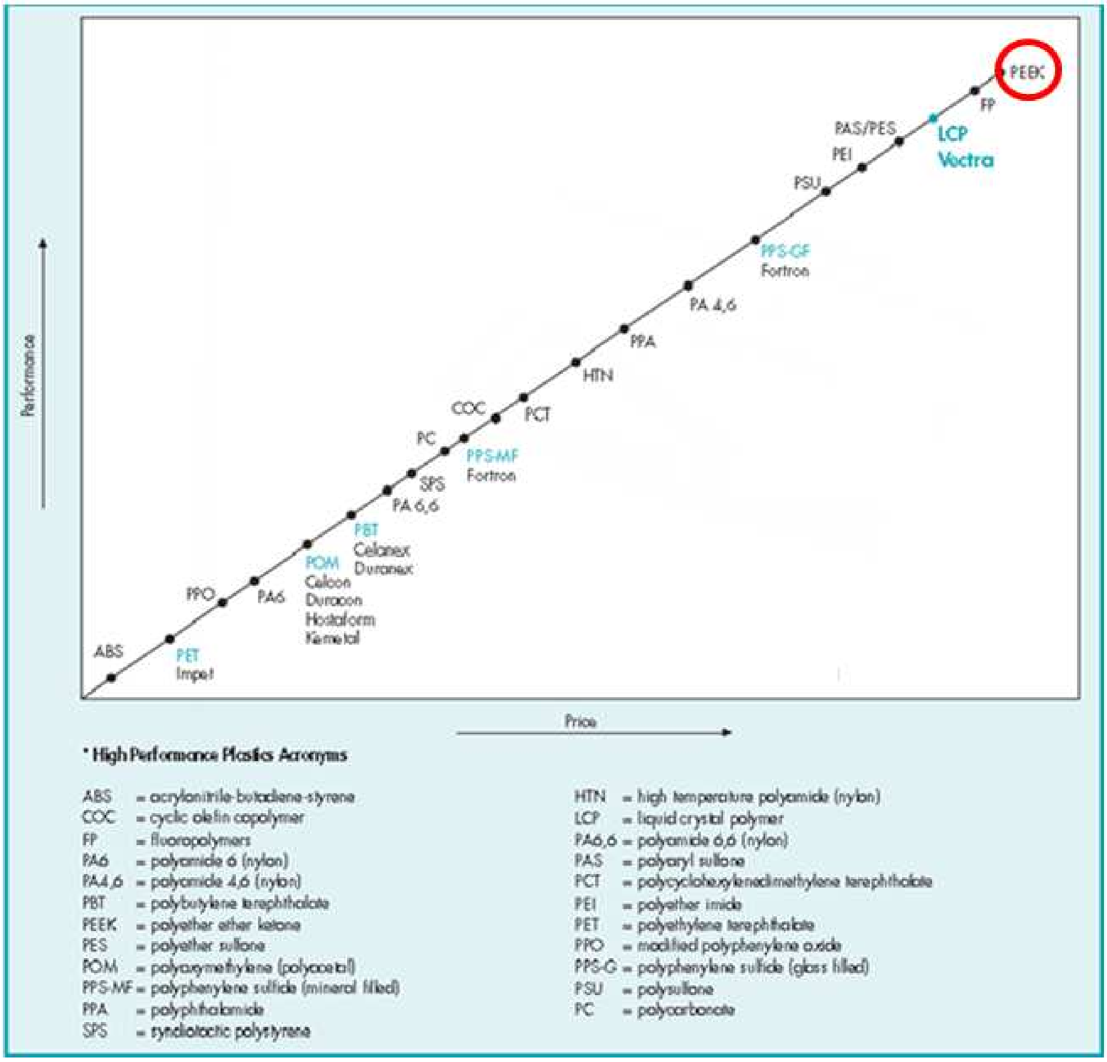


Figure 4.1: High performance polymers (Ashby and Johnson, 2002)

The functional requirements for the main parts of the existing design are as follows (also shown in Figure 4.2):

i. The grip/jaw, which is used for grasping and removing small objects. It should allow a movement of 5mm or less within ENT procedures.

ii. The top slider, which forms part of the linkage used for operating the grip/jaw. It is 80mm long.

iii. The fixed arm that provides the gripping motion has a thickness of 2.5mm.

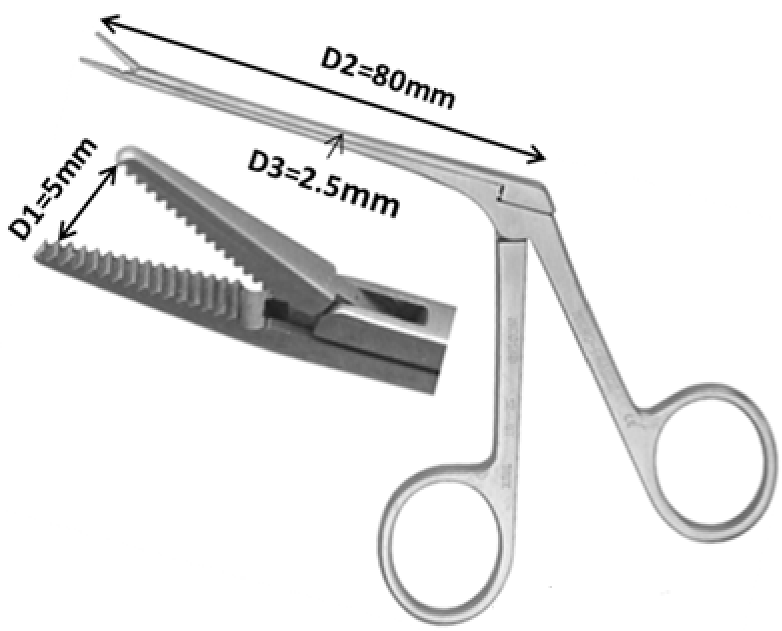
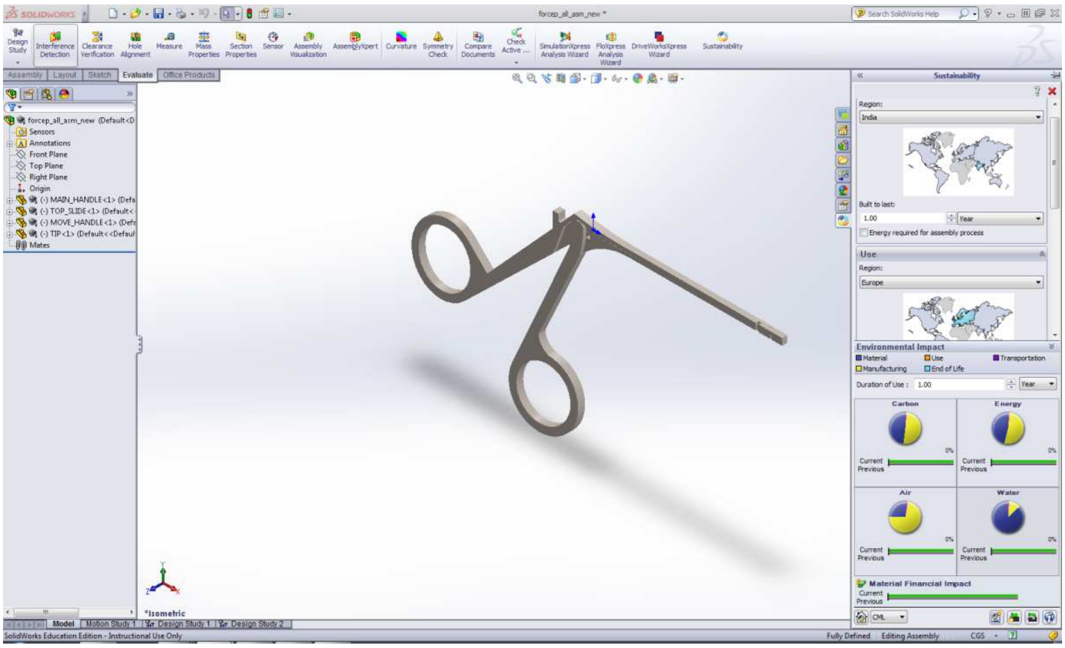


Figure 4.2: Existing design of medical forceps

In this case study, the LCA was initiated as part of the IEDM framework and focuses specifically on environmental impacts. LCA is used to determine and compare the attributes of the forceps manufactured using the two different materials, stainless steel and PEEK. The LCA procedure includes a number of widely used and accepted methods for environmental impact assessment (European Commission, 2010)

In this case study, the commercial Computer Aided Design (CAD) tool SolidWorks Sustainability was used to quantitatively assess the environmental impact of the forceps throughout their entire life cycle. SolidWorks, as shown in Figure 4.3, provides sustainability analysis that supports the completion of a detailed LCA over the product’s entire life, covering raw material extraction, material production, manufacturing, product use, EOL disposal, and transportation at each stage. The Centre of Environmental Science (CML) impact assessment methodology is implemented in SolidWorks Sustainability to calculate the LCA results. The CML methodology is discussed in Chapter III, section 3.2.



Region: India

Built to last: 1.00 Year

☐ Energy required for assembly process

Use

Region: Europe

Duration of Use : 1.00 Year

CML

Figure 4.3: SolidWorks sustainability software

SolidWorks Sustainability was used to measure environmental impact factors, including carbon footprint, energy consumption, air acidification, and water eutrophication (Solidworks, 2013). A product’s carbon footprint is produced from burning fossil fuels. Carbon gases accumulate in the atmosphere and, in turn, increase the earth’s average temperature. Carbon footprint is measured in kilograms of carbon dioxide (CO_2) equivalent. Total energy consumed is a measurement of the non-renewable energy sources associated with the product’s life cycle. It is measured in units of megajoules (MJ). This impact includes not only the electricity or fuels used during the product’s life cycle, but also the upstream energy required to obtain and process these fuels and the embodied energy of materials that would be released if burned. Total energy consumed represents the net calorific value of primary energy demand from non-renewable resources (e.g., petroleum, natural gas, etc.). Air acidification is typically measured in kilograms of sulphur dioxide (SO_2) equivalent. Water eutrophication occurs when an overabundance of nutrients are added to a water ecosystem. Nitrogen and phosphorous from wastewater and agricultural fertilizers cause damage to the water ecosystem. This impact is typically measured in either kilograms of phosphate (PO_4) equivalent or kilograms of nitrogen (N) equivalent. This software uses quantitative data for the LCA analysis. The inputs for the LCA process are assigned to the mass of a product or its parts, the type of material used, the manufacturing process, transportation used, and the type of energy needed during its use.

The SolidWorks Sustainability methodology is shown in Figure 4.4. It categorises information into three main groups: input, process, and output. The user has to enter the inputs, which are the type of material, manufacturing process, manufacturing region, transportation, and EOL strategy.

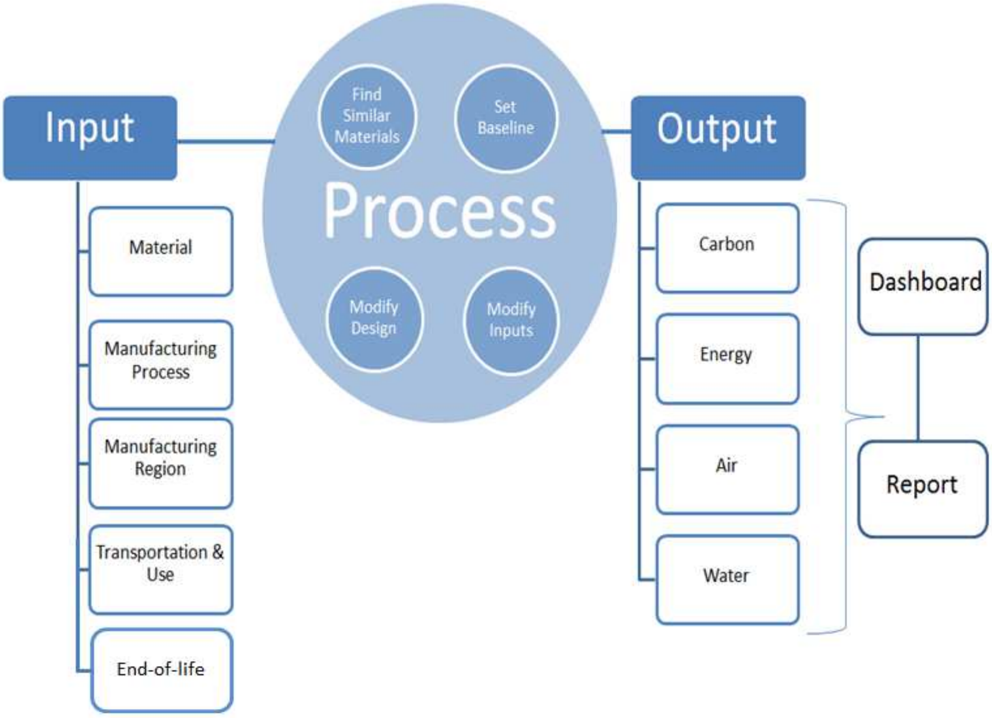


Figure 4.4: SolidWorks sustainability methodology

The steps for the input of material are:

i. Set the major class of material, for example, plastics.

ii. Choose the specific name for the specific material, for example, PEEK.

The steps for the input of manufacturing region are:

i. Set the region of manufacture, for example, Europe.

ii. Set the length of time the part will last, for example, 1 year.

The steps for the input of manufacturing process are:

i. Set a manufacturing process, for example, injection moulding.

ii. The total electricity and total natural gas usage is then shown for the manufacturing process selected. For example, electricity is 1.00 kWh for each part.

The steps for the input of transportation and use are:

i. Set the mode of transportation, for example, truck.

ii. Set the distance travelled from the manufacturing region to the use region, for example, 1,900 km.

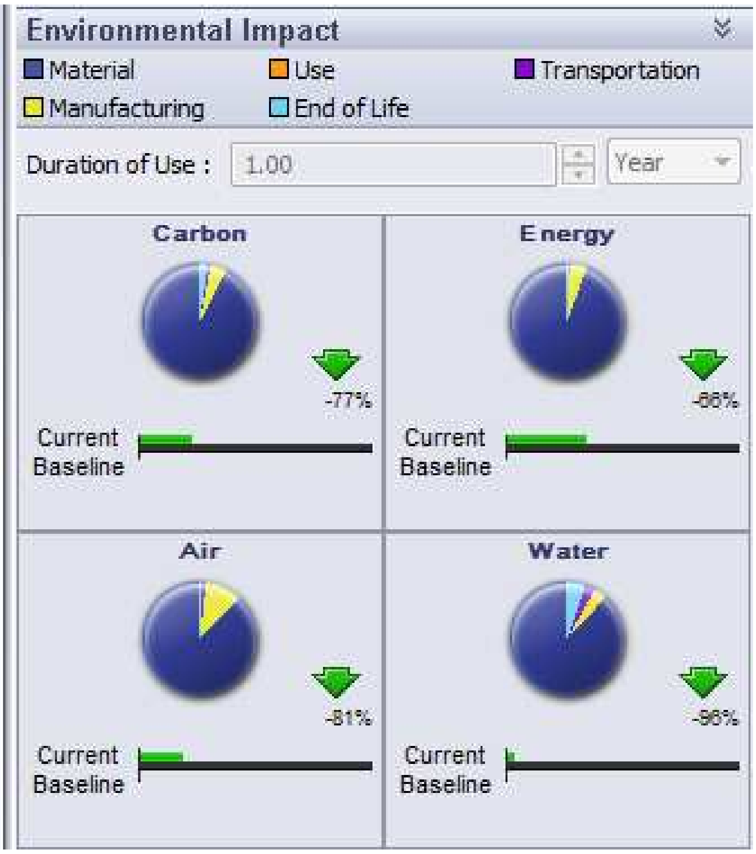
iii. Set the region where the product is transported to and used, for example, Europe.

The steps for the input of EOL are:

i. Set the percentage of the product that is recycled, incinerated, and disposed in a landfill, for example, recycled – 0%, incinerated – 50%, and landfill – 50%.

ii. Set the total of the values to 100%.

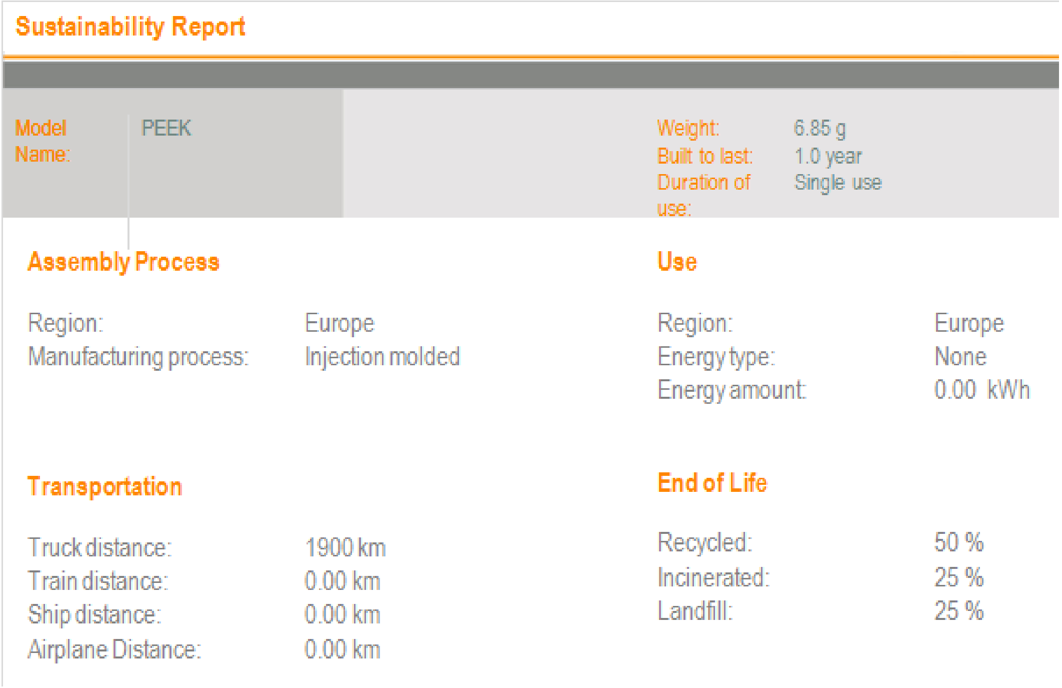
From the inputs that have been set, data will be processed to get the output of environmental impact for the product's life cycle. The graphical user interface is in the form of a dashboard and provides real-time feedback on environmental impact factors, as shown in Figure 4.5. Results appear in the dashboard, which updates dynamically with any changes. To perform a comparison between the two types of materials (PEEK and stainless steel), stainless steel has to be set as the baseline in the task pane. The baseline bar, referring to the stainless steel product, is the bottom bar below the pie charts and the current bar then refers to the PEEK product. The pie charts show that the PEEK product has a lower environmental impact than the stainless steel forceps.



Duration of Use : 1.00 Year

Figure 4.5: Dashboard for environmental impact

Figures 4.6 and 4.7 display the sustainability report and pie charts for the PEEK forceps. The report includes the absolute numerical values for each life-cycle stage (material extraction, manufacturing and assembly, transportation, product use, and EOL) broken down for each environmental indicator, as well as the total value for each indicator. The report, formatted in Microsoft Word, begins with a product overview, which outlines the basic assumptions of the environmental assessment. These include the time period over which the assumptions are being performed (duration of use), the manufacturing and use regions, and the weight of the product. These results use standard units for carbon footprint, water eutrophication, air acidification, and energy consumption. The standard units have been converted to grams (g) and kilojoules (kj) because the standard unit’s value was too small to account for the values. A detailed breakdown for these results can be seen in Table 4.1.



Sustainability Report

Model Name:	PEEK	Weight:	6.85 g
		Built to last:	1.0 year
		Duration of use:	Single use

Assembly Process

Region:	Europe
Manufacturing process:	Injection molded

Use

Region:	Europe
Energy type:	None
Energy amount:	0.00 kWh

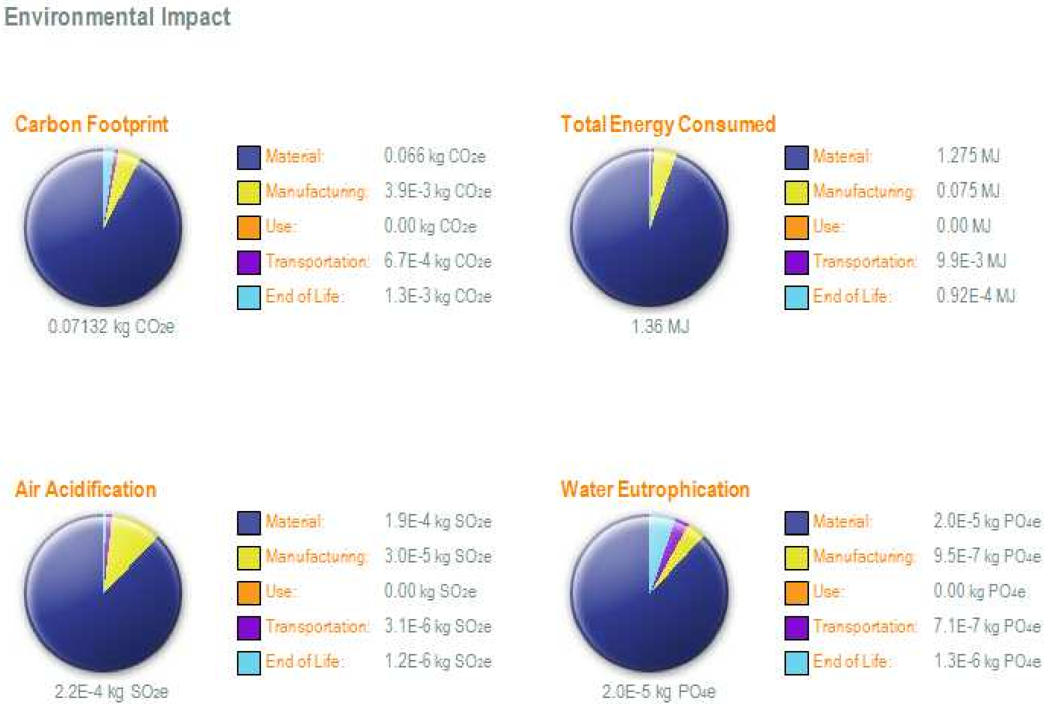
Transportation

Truck distance:	1900 km
Train distance:	0.00 km
Ship distance:	0.00 km
Airplane Distance:	0.00 km

End of Life

Recycled:	50 %
Incinerated:	25 %
Landfill:	25 %

Figure 4.6: Sustainability report (PEEK)



Environmental Impact

Carbon Footprint

Material:	0.066 kg CO_2e
Manufacturing:	3.9E-3 kg CO_2e
Use:	0.00 kg CO_2e
Transportation:	6.7E-4 kg CO_2e
End of Life:	1.3E-3 kg CO_2e

0.07132 kg CO_2e

Total Energy Consumed

Material:	1.275 MJ
Manufacturing:	0.075 MJ
Use:	0.00 MJ
Transportation:	9.9E-3 MJ
End of Life:	0.92E-4 MJ

1.36 MJ

Air Acidification

Material:	1.9E-4 kg SO_2e
Manufacturing:	3.0E-5 kg SO_2e
Use:	0.00 kg SO_2e
Transportation:	3.1E-6 kg SO_2e
End of Life:	1.2E-6 kg SO_2e

2.2E-4 kg SO_2e

Water Eutrophication

Material:	2.0E-5 kg PO_4e
Manufacturing:	9.5E-7 kg PO_4e
Use:	0.00 kg PO_4e
Transportation:	7.1E-7 kg PO_4e
End of Life:	1.3E-6 kg PO_4e

2.0E-5 kg PO_4e

Figure 4.7: Environmental impact report (PEEK)

Table 4.1: Environmental impact of medical forceps: stainless steel vs. PEEK

Criteria	Stainless Steel	PEEK
Material	Stainless steel	PEEK
Types of manufacturing process	Forging and machining	Injection moulding
Manufacturing region	Pakistan	Europe
Use region	Europe	Europe
Transportation	Plane	Truck
Weight (g)	22	6.85
Recycle content (material) in product (%)	0%	50%
Recycle rate at EOL product (%)	50%	50%
Carbon footprint	**Grams - CO_2**	**Grams - CO_2**
Material	100.00	65.45
Manufacturing	21.00	3.90
Use	0.00	0.00
Transportation	215.00	0.67
End-of-life	7.90	1.30
Total	**343.90**	**71.32**
Water Eutrophication	**Grams - PO_4**	**Grams - PO_4**
Material	0.42	0.02
Manufacturing	0.01	0.00
Use	0.00	0.00
Transportation	0.14	0.00
End-of-life	0.01	0.00
Total	**0.59**	**0.02**
Air Acidification	**Grams - SO_2**	**Grams - SO_2**
Material	0.37	0.19
Manufacturing	0.24	0.03
Use	0.00	0.00
Transportation	0.64	0.00
End-of-life	0.00	0.00
Total	**1.25**	**0.22**
Total Energy Consumed	**Kilojoules**	**Kilojoules**
Material	1100.00	1275.00
Manufacturing	235.00	75.00
Use	0.00	0.00
Transportation	3000.00	9.90
End-of-life	5.60	0.92
Total	**4340.60**	**1360.82**

4.2.1 Life Cycle Inventory Analysis

This section details the data and assumptions used to conduct a life cycle impact assessment (LCIA) for single-use medical forceps. The complete inventory is generated by combining the bill of activities (material composition, production requirements, use requirements, and transportation data) for the product with life cycle inventory (LCI) data from existing databases.

Whenever possible, data used in this study was obtained from existing sources accessed by the SolidWorks software. Table 4.1 represents the results of the environmental impact assessment. The results of the detailed life cycle analyses are summarised as follows:

i. PEEK has a lower carbon footprint compared to stainless steel at a ratio of 1:4.8. This gives PEEK a significant environmental advantage due to its lower global warming potential.
ii. The difference in water eutrophication is 0.59 g, with stainless steel having a greater impact on the environment compared to PEEK.
iii. Stainless steel has higher air acidification compared to PEEK. This shows that stainless steel is more likely to affect the acidic content of lakes and soil.
iv. Efficiencies in energy conversion such as power, heat, and steam are factors that contribute to the analysis of energy consumption. It would take 4340 kJ of energy to support stainless steel's life cycle. In comparison, PEEK requires 1360.82 kJ, which is 3.2 times lower energy consumption than stainless steel.

Table 4.2 illustrates the analysis of the environmental impact of the life cycle stages for four variations of forceps: two made from stainless steel and two using PEEK. Environmental factors have been quantified based on a single, functional product. The boundaries of this LCIA model are the product's material, manufacturing process, manufacturing region, use region, transportation, and EOL. A product's life cycle begins with the removal of raw materials and energy sources from the Earth. In the case of stainless steel, the two main types of production are from ore-based primary raw material or from recycled material. Different combinations of these materials are widely used, and it has been shown that there is a 32-33% reduction in carbon footprint and energy consumed when producing steel from recycled material (Johnson et al., 2007). Consideration of the percentage of recycled material used in production and at the EOL of the product has therefore been included in Table 4.2. The potential reduction of the carbon footprint and energy consumed when recycling PEEK is not yet fully understood; a 30% reduction was estimated to be suitable for both factors.

To allow a realistic representation of current practice, the hypothetical data has been used and discussed to the direct comparison of two forceps, SS (2) and PEEK (1). For SS (2), it is assumed that 50% of the stainless steel used in producing the forceps has been recycled and that 100% will be recycled at the end of its life. For PEEK (1), the analysis assumed that no recycled material was used to produce the forceps and that no material would be recycled after its use.

Table 4.2 presents a quantitative

d energy consumption were 84 grams and 918.5 kilojoules for SS (2) and 77 grams and 1500 kilojoules for PEEK (1). In the manufacturing phase, which considers how the material is transformed into the final product, the PEEK injection moulding process produces a carbon footprint of 3.9 grams and consumes 75 kilojoules. The values of the stainless steel forging and machine processes are 21 grams and 235 kilojoules.

The transportation phase assesses the energy impacts associated with transporting packaged medical forceps from the manufacturing region to the retail outlet. SS (2) produces a carbon footprint of 215 grams requiring 3000 kilojoules as compared to PEEK (1), which produces 0.67 grams of carbon footprint and consumes 9.9 kilojoules of energy. This information relates to the current stainless steel forceps manufactured in Pakistan, their air transportation costs, and their impact on the environment. Although it was not done here, it is possible to use this model to investigate the potential impacts of moving manufacture to another region.

Table 4.2: Environmental impact of medical forceps: stainless steel vs. PEEK

Criteria	**SS (1)**	**SS (2)**	**PEEK (1)**	**PEEK (2)**
Material	Stainless steel	Stainless steel	PEEK	PEEK
Types of manufacturing process	Forging and machining	Forging and machining	Injection moulding	Injection moulding
Manufacturing region	Pakistan	Pakistan	Europe	Europe
Use region	Europe	Europe	Europe	Europe
Transportation	Plane	Plane	Truck	Truck
Weight (g)	22	22	6.85	6.85
Recycle content (material) in product (%)	0%	50%	0%	50%
Recycle rate at EOL product (%)	50%	100%	0%	50%
Carbon footprint	**Grams - CO_2**	**Grams - CO_2**	**Grams - CO_2**	**Grams - CO_2**
Material	100.00	84.00	77.00	65.45
Manufacturing	21.00	21.00	3.90	3.90
Use	0.00	0.00	0.00	0.00
Transportation	215.00	215.00	0.67	0.67
End-of-life	7.90	0.00	2.60	1.30
Total	**343.90**	**320.00**	**84.17**	**71.32**
Water Eutrophication	**Grams - PO_4**	**Grams - PO_4**	**Grams - PO_4**	**Grams - PO_4**
Material	0.42	0.35	0.02	0.02
Manufacturing	0.01	0.01	0.00	0.00
Use	0.00	0.00	0.00	0.00
Transportation	0.14	0.14	0.00	0.00
End-of-life	0.01	0.00	0.00	0.00
Total	**0.59**	**0.50**	**0.02**	**0.02**
Air Acidification	**Grams - SO_2**	**Grams - SO_2**	**Grams - SO_2**	**Grams - SO_2**
Material	0.37	0.31	0.22	0.19
Manufacturing	0.24	0.24	0.03	0.03
Use	0.00	0.00	0.00	0.00
Transportation	0.64	0.64	0.00	0.00
End-of-life	0.00	0.00	0.00	0.00
Total	**1.25**	**1.19**	**0.25**	**0.22**
Energy Consumed	**Kilojoules**	**Kilojoules**	**Kilojoules**	**Kilojoules**
Material	1100.00	918.50	1500.00	1275.00
Manufacturing	235.00	235.00	75.00	75.00
Use	0.00	0.00	0.00	0.00
Transportation	3000.00	3000.00	9.90	9.90
End-of-life	5.60	0.00	1.8	0.92
Total	**4340.60**	**4153.50**	**1586.70**	**1360.82**

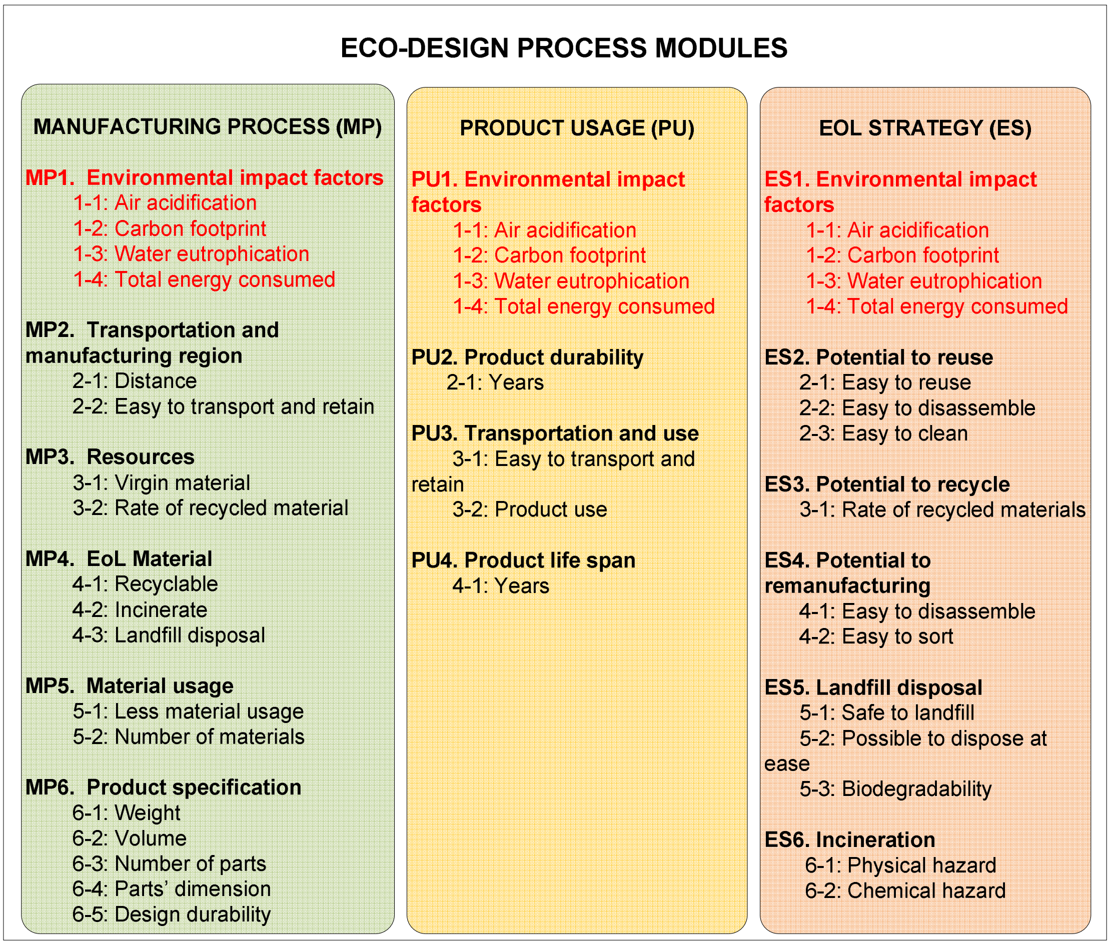
There is no carbon footprint or energy consumed in the product use phase because forceps do not require any electricity or gas energy to fulfil their function. Considerations at the EOL stage of the life cycle include any emissions associated with the disposal or recycling of the product. The main factors governing this phase are how recyclable the product is, its size and weight, and means of disposal. Here, SS (2) produces 0 grams of carbon footprint and does not consume any energy. This is because the recycle rate was set to 100% for the product's EOL. For PEEK (1), the carbon footprint is 2.6 grams and energy consumed is 1.8 kilojoules.

The overall LCA result shown in Table 4.2 indicates that replacing the SS (2) forceps with the PEEK (1) forceps will achieve a 74% reduction in the carbon footprint, a 94% drop in water eutrophication, a 79% fall in air acidification, and a 62% decline in total energy consumed. The assessments represented in this table also illustrate the benefits of increasing the recycling rate between the SS (1) and SS (2) forceps. This recycling rate enables reductions of 7% in the carbon footprint, 14% in water eutrophication, 5% in air acidification, and 4% in energy consumed. Table 4.2 also indicates the potential benefits associated with PEEK (2) in which 50% of the material used to manufacture the forceps is recycled and 50% of the material would be recycled at the EOL. It should be noted that the variations in recycling rate cited in the table have been selected from many possible combinations. All of the data generated and the associated information provided in this analysis has been stored within the Eco-Process modules and eco-design case-based reasoning (Eco-CBR) for subsequent reuse in future design activities.

4.3 IEDM Stage II: Integration with the Eco-Process Model

At this stage, the results obtained from the LCA have been incorporated into the Eco-Process model. This represents an innovation in the use of such information and allows designers to proceed with their efforts aimed at producing a more sustainable design. The eco-design parameters for the medical forceps have been selected based on the criteria and functional requirements of the product. Table 4.3 shows the list of parameters used in the Eco-Process modules. These modules are divided into three categories: manufacturing process, product usage, and EOL strategy. All modules have the following environmental impact factors: air acidification, carbon footprint, water eutrophication, and total energy consumed.

Table 4.3: List of Eco-Process parameters



ECO-DESIGN PROCESS MODULES

MANUFACTURING PROCESS (MP)

MP1. Environmental impact factors
- 1-1: Air acidification
- 1-2: Carbon footprint
- 1-3: Water eutrophication
- 1-4: Total energy consumed

MP2. Transportation and manufacturing region
- 2-1: Distance
- 2-2: Easy to transport and retain

MP3. Resources
- 3-1: Virgin material
- 3-2: Rate of recycled material

MP4. EoL Material
- 4-1: Recyclable
- 4-2: Incinerate
- 4-3: Landfill disposal

MP5. Material usage
- 5-1: Less material usage
- 5-2: Number of materials

MP6. Product specification
- 6-1: Weight
- 6-2: Volume
- 6-3: Number of parts
- 6-4: Parts' dimension
- 6-5: Design durability

PRODUCT USAGE (PU)

PU1. Environmental impact factors
- 1-1: Air acidification
- 1-2: Carbon footprint
- 1-3: Water eutrophication
- 1-4: Total energy consumed

PU2. Product durability
- 2-1: Years

PU3. Transportation and use
- 3-1: Easy to transport and retain
- 3-2: Product use

PU4. Product life span
- 4-1: Years

EOL STRATEGY (ES)

ES1. Environmental impact factors
- 1-1: Air acidification
- 1-2: Carbon footprint
- 1-3: Water eutrophication
- 1-4: Total energy consumed

ES2. Potential to reuse
- 2-1: Easy to reuse
- 2-2: Easy to disassemble
- 2-3: Easy to clean

ES3. Potential to recycle
- 3-1: Rate of recycled materials

ES4. Potential to remanufacturing
- 4-1: Easy to disassemble
- 4-2: Easy to sort

ES5. Landfill disposal
- 5-1: Safe to landfill
- 5-2: Possible to dispose at ease
- 5-3: Biodegradability

ES6. Incineration
- 6-1: Physical hazard
- 6-2: Chemical hazard

Figure 4.8 shows the links drawn between parameters within the different modules in this Eco-Process model. The relationships between eco-design parameters within these modules can be defined using this model. Detailed information related to the relationships between parameters can be represented and subsequently extracted, indicating how factors in the manufacturing process (MP), product usage (PU), and EOL strategy (ES) relate to each other. These relationships are established based on the considerations presented in Chapter II. It is important to develop the relationships between these features because the designer will then be able easily reuse the domain knowledge when redesigning a product in the future.

Figure 4.9 displays examples of the relationships for resources and product specification. Resources (MP3) represents two main properties pertaining to the origin and critical state of the material, which are divided between the amount of virgin material used (MP3-1) and the amount of recycled content used in the product (MP3-2). These properties will have relationships to product durability (PU2), product life span (PU3), and the potential rate of recycled materials at EOL (ES3-1). The PU2 and PU3 enable consideration of an EOL strategy (ES), which consists of six factors: environmental impact (ES1), potential to reuse (ES2), potential to recycle (ES3), potential to remanufacture (ES4), landfill disposal (ES5), and incineration (ES6). Here, the relationships enabling the consideration of MP3 are depicted as MP3 ↔ PU2, MP3 ↔ PU3, MP3 ↔ ES3, PU2 ↔ ES, and PU3 ↔ ES. This is one example of how the links between parameters can be represented in the Eco-Process model.

The next relationship focuses on product specification (MP6), which refers to a product’s characteristics such as weight (MP6-1), volume (MP6-2), number of parts (MP6-3), parts’ dimension (MP6-4), and design durability (MP6-5). These product characteristics will have relationships to the product usage (PU). PU consists of environmental impact factors (PU1), product durability (PU2), transportation and use (PU3), and product life span (PU4). The PU factors can have any relationship with the EOL strategy (ES). In Figure 4.9, the relationships are illustrated as MP6 ↔ PU and PU ↔ ES.

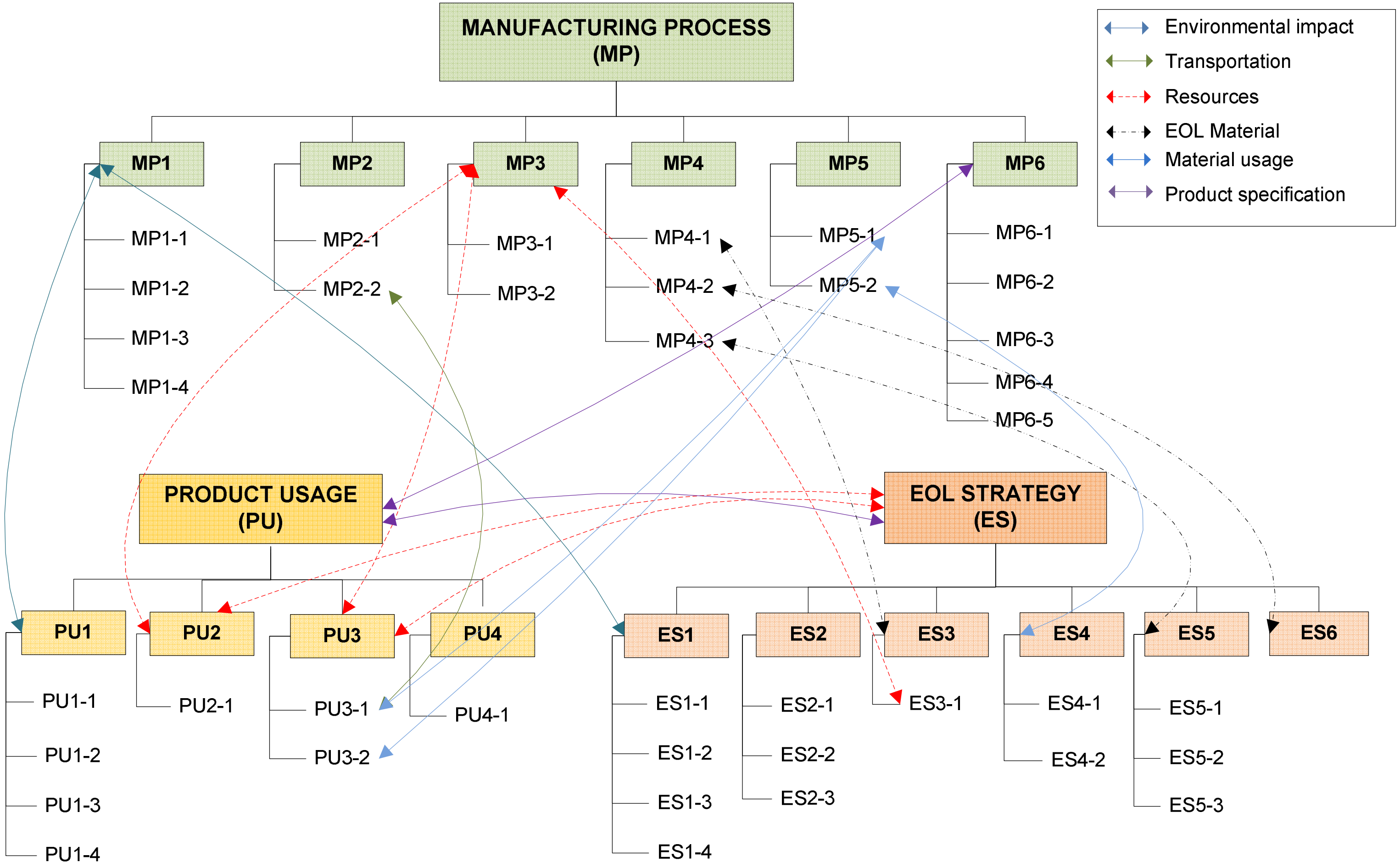


Figure 4.8: Complete relationship of Eco-Process model

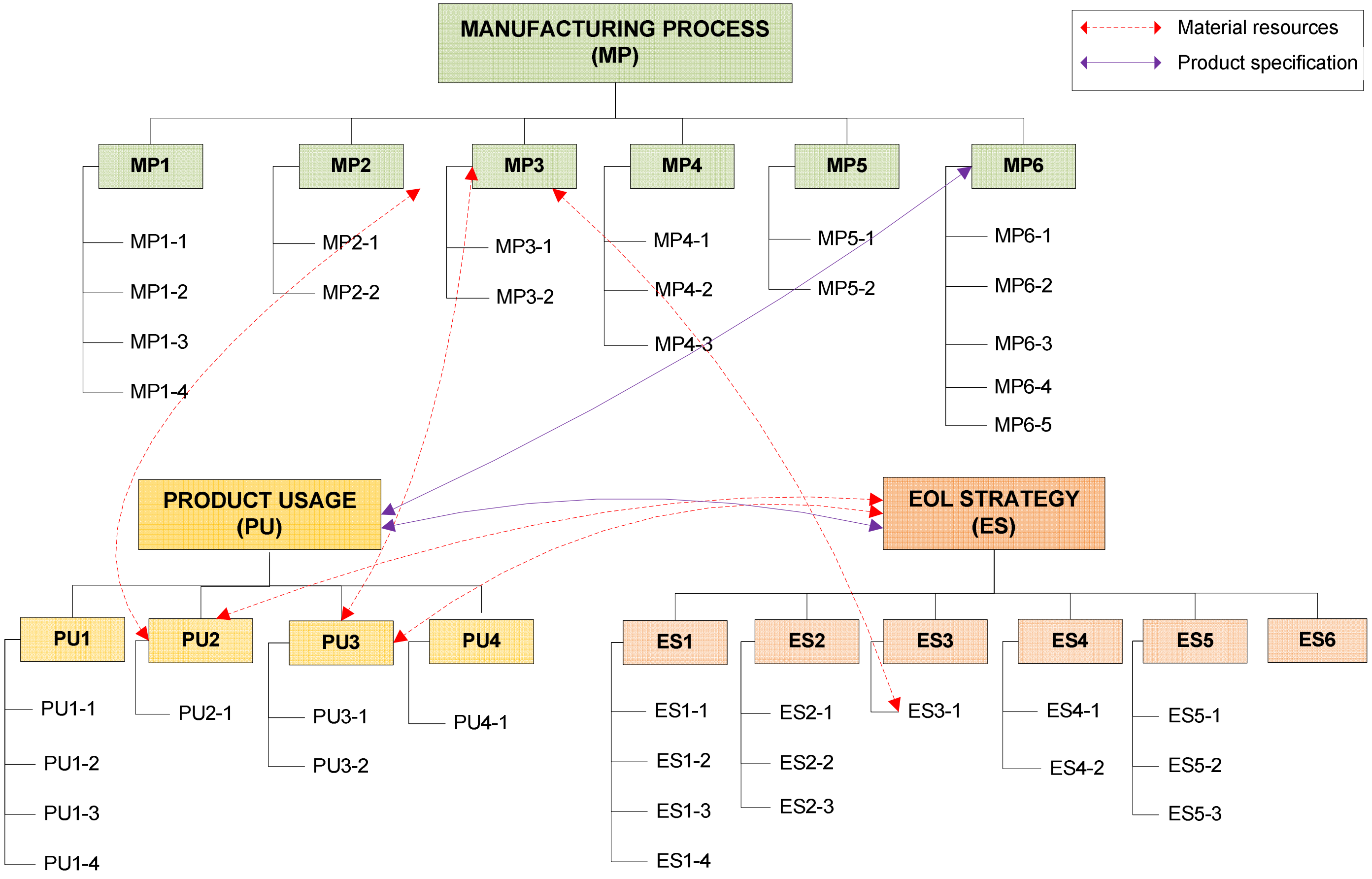


Figure 4.9: Eco-Process relationship

The parameters selected from the Eco-Process model in Figure 4.9 are used as core environmentally related inputs in the demanded qualities (DQs) and quality characteristics (QCs) in all subsequent Eco-HoQs. These parameters were defined in collaboration between the manufacturing company (DTR Medical) and the expert designers considering the product development. Table 4.4 and Table 4.5 show the inputs for the DQs and QCs with cross-referencing attributes from the Eco-Process model.

Table 4.4: List of Quality Characteristics (QCs)

Quality characteristics (QCs)	**Attributes**
Weight	PU3-1, PU3-2, ES2, ES3, ES4, ES5, ES6
Volume of product	PU3-1, PU3-2, ES2, ES3, ES4, ES5, ES6
Number of parts	PU2, PU4, ES2, ES3, ES4, ES5, ES6
Number of materials	ES2, ES3, ES4, ES5, ES6
Product durability	PU4, ES2, ES3, ES4, ES5, ES6
Product life span	PU2, ES2, ES3, ES4, ES5, ES6
Carbon footprint	MP2, MP3, MP4, MP5, MP6, ES2, ES3, ES4, ES5, ES6
Water eutrophication	MP2, MP3, MP4, MP5, MP6, ES2, ES3, ES4, ES5, ES6
Air acidification	MP2, MP3, MP4, MP5, MP6, ES2, ES3, ES4, ES5, ES6
Manufacturing region	MP2-1, MP2-2, PU3-1, PU3-2
Transportation	MP2-1, MP2-2, PU3-1, PU3-2
Rate of recycled materials	MP3-2, ES3-1
Total energy consumed	MP2, MP3, MP4, MP5, MP6, ES2, ES3, ES4, ES5, ES6

Table 4.5: List of demanded qualities (DQs)

Demanded Qualities (DQs)	**Attributes**
Less material usage	MP5-2, MP6-1, MP6-2, MP6-3, PU2, MP1, PU1, ES1, MP2-2, PU3-2, MP3-2, ES3-1
Meets laws and regulations	MP1, PU1, ES1, MP2-2, PU3-2
Easy to process and assemble	MP5-2, MP6-1, MP6-2, MP6-3, PU4, MP1, PU1, ES1, MP2-2, PU3-2, MP3-2, ES3-1
Easy to transport and retain	MP5-2, MP6-1, MP6-2, MP6-3, MP1, PU1, ES1, MP2-2, PU3-2,
Low environmental cost	MP5-2, MP6-1, MP6-2, MP6-3, PU2, PU4, MP1, PU1, ES1, MP2-2, PU3-2, MP3-2, ES3-1
Low production cost	MP5-2, MP6-1, MP6-2, MP6-3, PU2, PU4, MP2-2, PU3-2, MP3-2, ES3-1
Less carbon footprint	MP5-2, MP6-1, MP6-2, MP6-3, PU4, MP1-4, PU1-4, ES1-4
Less energy consumption	MP5-2, MP6-2, MP6-3, MP1-2, PU1-2, ES1-2, MP2, MP2-2, PU3-2
Less water eutrophication	MP1-3, PU1-3, ES1-3
Less air acidification	MP1-4, PU1-4, ES1-4
Potential to recycle	MP5-2, MP6-1, MP6-2, MP6-3, ES1, MP3-2, ES3-1
Potential to reuse	MP6-3, MP5-2
Potential to repair	MP6-3
Safe to landfill	MP6-3, MP5-2, ES1-2, ES1-1, ES1-3
Safe to incinerate	MP6-3, MP5-2, ES1-2, ES1-4

4.4 IEDM Stage III: Eco-QFD Relationship for Medical Forceps

The purpose of the third stage is to identify the best alternative design for the medical forceps using the conceptual model of Eco-QFD. This case study illustrates the process deployed in linking the Eco-HoQ model to the four QFD phases, as shown in Figure 4.10, to derive the importance ranking for sub-evaluation criteria. The analysis of the LCA has indicated that redesigning the forceps using PEEK offers great potential or engineering a more environmentally friendly medical product than the existing stainless steel one.

An Eco-QFD model is proposed and fits as a stage III in the IEDM framework. It provides indicators of the level of sustainability for each phase in the QFD. Figure 4.10 shows the Eco-HoQ model embedded in the QFD phases that used for the medical forceps case study.

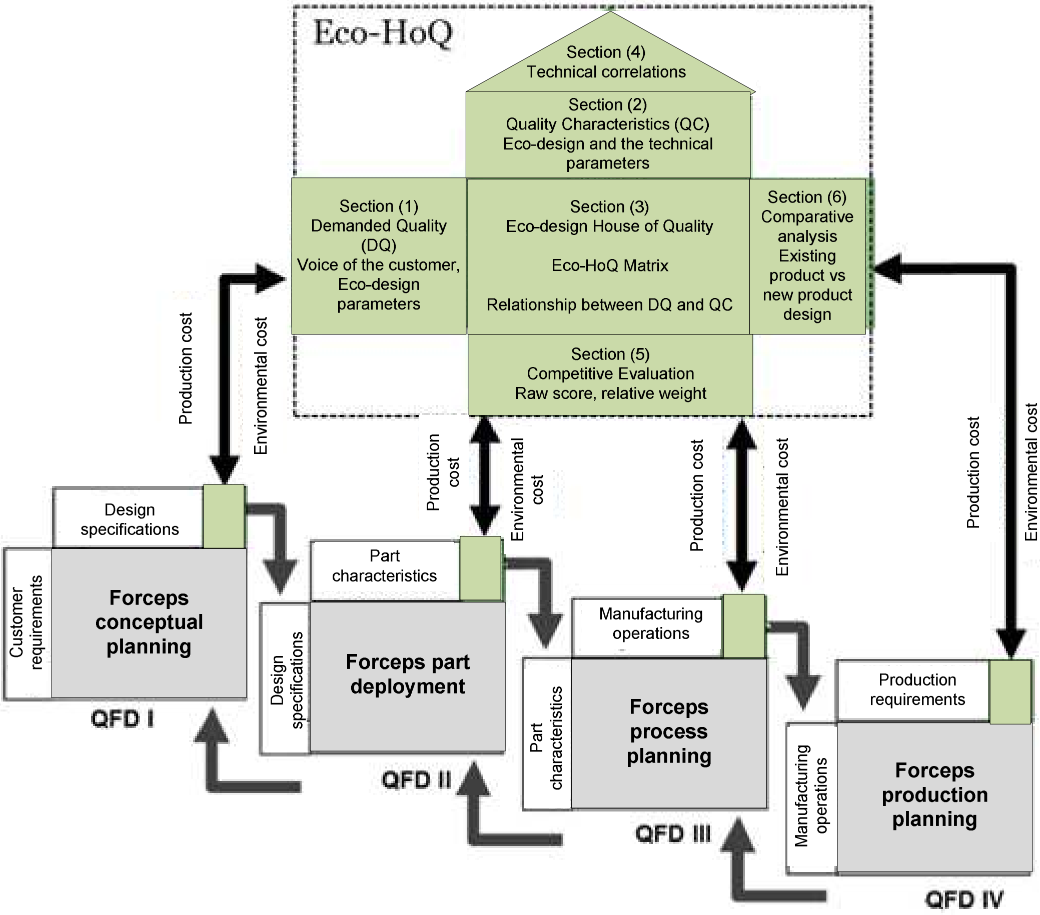
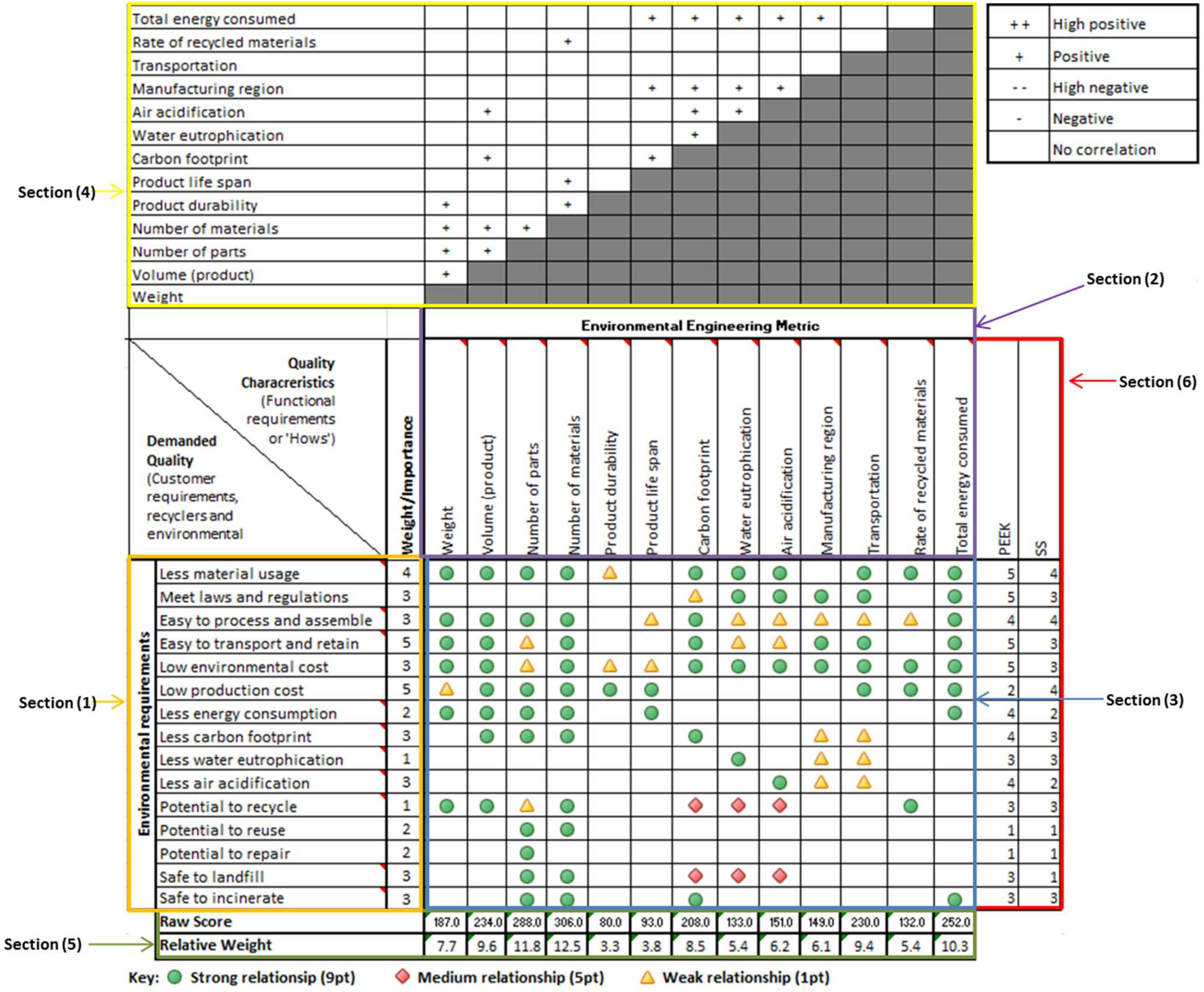


Figure 4.10: Conceptual model of Eco-HoQ with enhanced QFD process for forceps case study (Eco-QFD)

To continue the development of this reengineered product, the LCA results from Stage I and the eco-design parameter relationships from Stage II have been integrated into the Eco-HoQ, as shown in Figure 4.11. The Eco-HoQ matrix in Section (3) assesses the strength of the relationship between each DQ in Section (1) and the QCs in Section (2). It is important to note that both the DQ and QC parameters include environmental elements; this is a new innovation and an important feature of the Eco-HoQ.



	Weight	Volume (product)	Number of parts	Number of materials	Product durability	Product life span	Carbon footprint	Water eutrophication	Air acidification	Manufacturing region	Transportation	Rate of recycled materials	Total energy consumed
Total energy consumed						+	+	+	+	+			
Rate of recycled materials				+									
Transportation													
Manufacturing region						+	+	+	+				
Air acidification		+					+	+					
Water eutrophication							+						
Carbon footprint		+				+							
Product life span				+									
Product durability	+			+									
Number of materials	+	+	+										
Number of parts	+	+											
Volume (product)	+												
Weight													

++	High positive
+	Positive
--	High negative
-	Negative
	No correlation

Quality Characreristics (Functional requirements or 'Hows') Demanded Quality (Customer requirements, recyclers and environmental	Weight/Importance	Weight	Volume (product)	Number of parts	Number of materials	Product durability	Product life span	Carbon footprint	Water eutrophication	Air acidification	Manufacturing region	Transportation	Rate of recycled materials	Total energy consumed	PEEK	SS
Less material usage	4	●	●	●	●	△		●	●	●		●	●	●	5	4
Meet laws and regulations	3							△	●	●	●	●		●	5	3
Easy to process and assemble	3	●	●	●	●		△	●	△	△	△	△	△	●	4	4
Easy to transport and retain	5	●	●	△	●			●	△	△	●	●		●	5	3
Low environmental cost	3	●	●	△	●	△	△	●	●	●	●	●	●	●	5	3
Low production cost	5	△	●	●	●	●	●					●	●	●	2	4
Less energy consumption	2	●	●	●	●		●							●	4	2
Less carbon footprint	3		●	●	●			●			△	△			4	3
Less water eutrophication	1								●		△	△			3	3
Less air acidification	3									●	△	△			4	2
Potential to recycle	1	●	●	△	●			◆	◆	◆			●		3	3
Potential to reuse	2			●	●										1	1
Potential to repair	2			●											1	1
Safe to landfill	3			●	●			◆	◆	◆					3	1
Safe to incinerate	3			●	●			●						●	3	3
Raw Score		187.0	234.0	288.0	306.0	80.0	93.0	208.0	133.0	151.0	149.0	230.0	132.0	252.0		
Relative Weight		7.7	9.6	11.8	12.5	3.3	3.8	8.5	5.4	6.2	6.1	9.4	5.4	10.3		

Key: ● **Strong relationsip (9pt)** ◆ **Medium relationsip (5pt)** △ **Weak relationship (1pt)**

Figure 4.11: Eco-HoQ for the medical forceps

Establishing the actual numerical scores for each cell, and thereby for each QC, is obviously dependent upon the numerical values allocated to each of the three scale symbols. The assessment of the robustness of such a process, and the dependence of the solutions on the specific values used to convert the qualitative representation of relationships of the three symbols into these numerical values, is clearly very important (Romli et al., 2014). A value must be set for each symbol that represents the importance of those determining the level of such a relationship. The approach incorporated in the Eco-HoQ Matrix utilises symbols consistent with those used in traditional QFD processes. The symbols adopted in this study have the following meanings and associated values:

i. ● Strong positive relationship with a value of 9
ii. ▲ Marginally positive relationship with a value of 5
iii. ♦ Weak relationship with a value of 1

All of the eco-design parameters have been assigned a weighting factor to establish the relationship between the DQs and QCs. These weighting factors have been established through discussions between the manufacturer and the designer who developed the product. The discussion is took place at the DTR medical company. The results of their discussions were themselves discussed by the author with the designer. In each case, careful consideration was given. For example, the carbon footprint has a relationship with the following DQ parameters (with assigned weighting factor): less material usage (9), meets laws and regulations (5), easy to process and assemble (9), easy to transport and retain (9), low environmental cost (9), less carbon footprint (9), potential to recycle (1), safe to landfill (1), and safe to incinerate (1). By inserting these values into equations (3.1) and (3.2), the total weight or importance assigned to the carbon footprint has been shown as 208, giving a relative weight of 8.5.

$$RS_{CF} = (9*4) + (5*3) + (9*3) + (9*5) + (9*3) + (9*3) + (1*1) + (1*3) + (9*3) = 208$$

$$W_{CF} = \frac{208}{(187+234+288+306+80+93+208+133+151+149+230+132+252)} \times 100$$

$$W_{CF} = 8.5$$

This relative weight was calculated in Section (5) and has been used to establish critical design specifications and target values for the Eco-HoQ process. After the analysis was completed for all parameters, the results indicated that the five most influential environmental considerations with the highest impact on product sustainability were (with relative weight factor): number of materials (12.5), number of parts (11.8), total energy consumed (10.3), volume of product (9.6), and transportation (9.4). The result of setting these parameters was then considered in each of the QFD phases.

Section (6) in the Eco-HoQ model includes a comparative analysis between the redesigned medical forceps made with PEEK and the existing design made with stainless steel, with values ranging from 1 (weak) to 5 (very strong). The analysis is based on Stage I's LCA assessment shown in Tables 4.1 and 4.2. The analysis shows that medical forceps made from PEEK weigh less and have a lower environmental impact cost. The information generated by this assessment is used in QFD Phases I through IV.

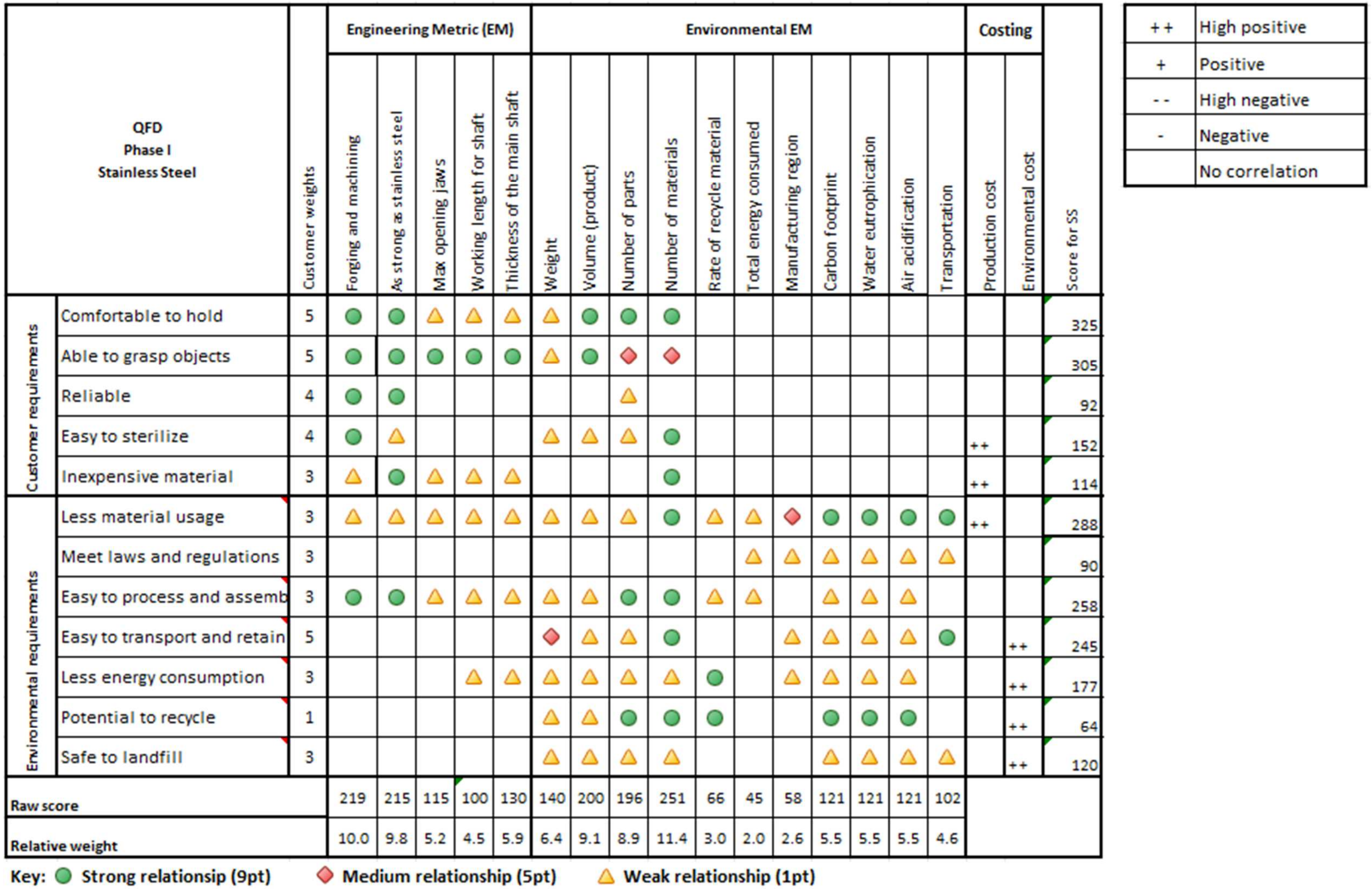
4.4.1 Eco-QFD Phase I

Eco-QFD Phase I uses the product planning matrix "conceptual forceps" as shown in Figure 4.10. In this phase, the DQ section consists of two categories: customer and environmental requirements. In this case study, the customer's requirements were based on discussions with the designer regarding the existing product range and with consultant engineers, including the author, who were considering the development of these products. These discussions produced the priorities for each requirement and these requirements were evaluated and ranked.

The QC inputs include those that were acquired from the design specification of the product and the eco-design parameters retrieved from the Eco-HoQ. The designer assessed the importance of these requirements with the customer, based on their priorities, using values from 1 (very low) to 5 (very high). The result of the analysis for the stainless steel medical forceps is shown in Figure 4.12. For example, the DQ customer requirement that the forceps be “comfortable to hold” has been set to priority 5. With weighting factors assigned to all QC parameters that have a relationship to this parameter, the total values have been summed. In this case, the parameters were forging and machining (9), as strong as stainless steel (9), maximum jaw opening (5), working length for shaft (5), thickness of the main shaft (5), weight (5), volume (9), number of parts (9) and number of materials (5). These values have been summed and multiplied by customer weightings that has been set to priority of (5) to give a score of 325.

Figure 4.13 shows the analysis of Eco-QFD Phase I for the PEEK (1) medical forceps. Most of the parameters used in this phase were the same for SS (2), except for the requirement that they be mouldable and machinable. For clarity, the same “comfortable to hold” parameter assessed in regard to the stainless steel forceps, as shown in Figure 4.12, is discussed. The DQ customer requirement that the forceps be “comfortable to hold” has been set to priority 5. With weighting factors assigned to all QC parameters that have a relationship to this parameter, the total values have been summed. In this case, the parameters were mouldable and machinable (9), as strong as stainless steel (9), maximum jaw opening (5), working length for shaft (5), thickness of the main shaft (5), weight (9), volume (9), number of parts (9) and number of materials (5). These values were summed and multiplied by customer weightings that has been set to priority of (5) to give a score of 345.

The scores for DQs and QCs can be used to compare the environmental impact results obtained for each design proposal. Analyses of SS (2) and PEEK (1) have been used for comparison. The comparative analysis between the two materials in each of the DQ and QC parameters is shown in Figure 4.14.

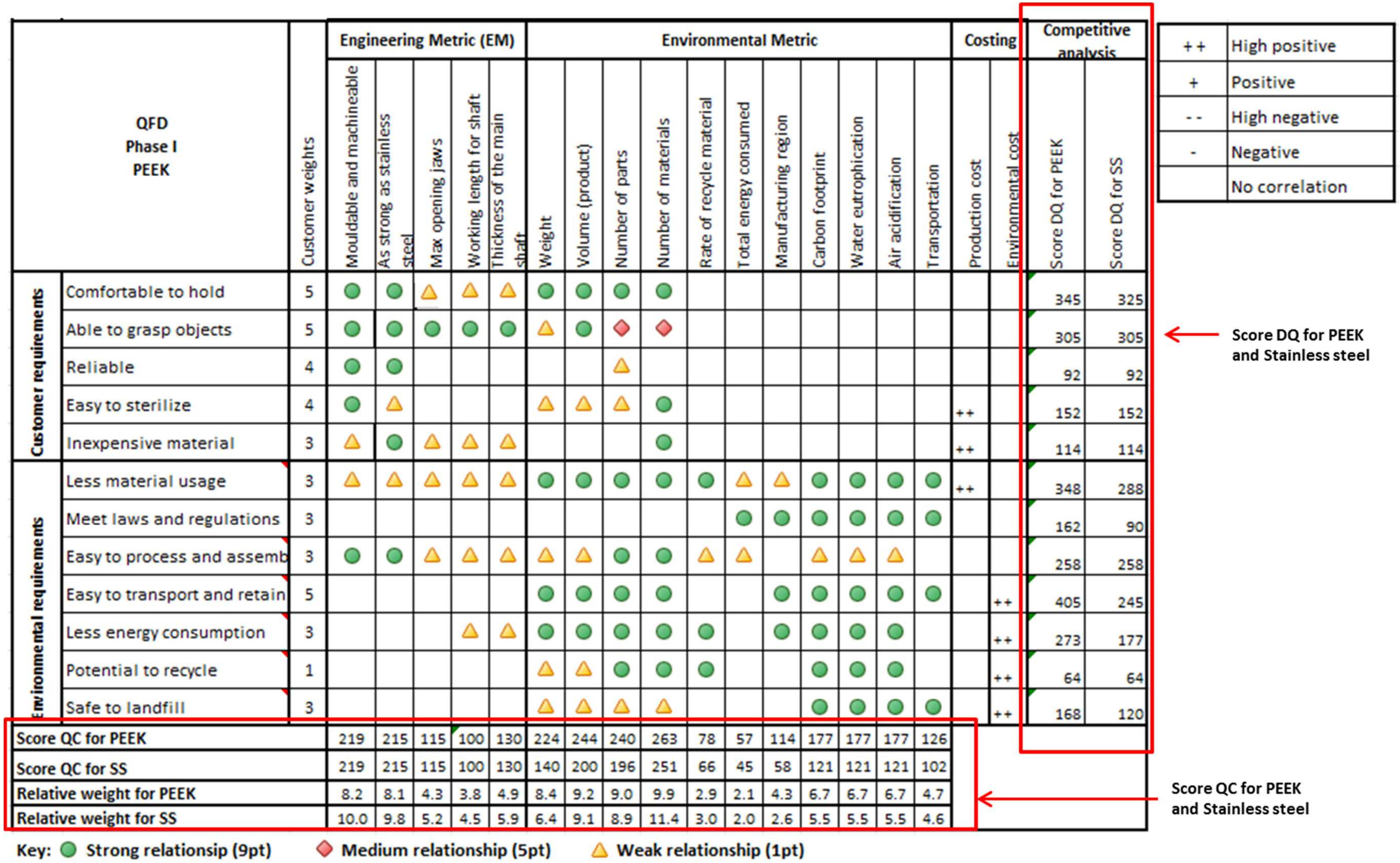


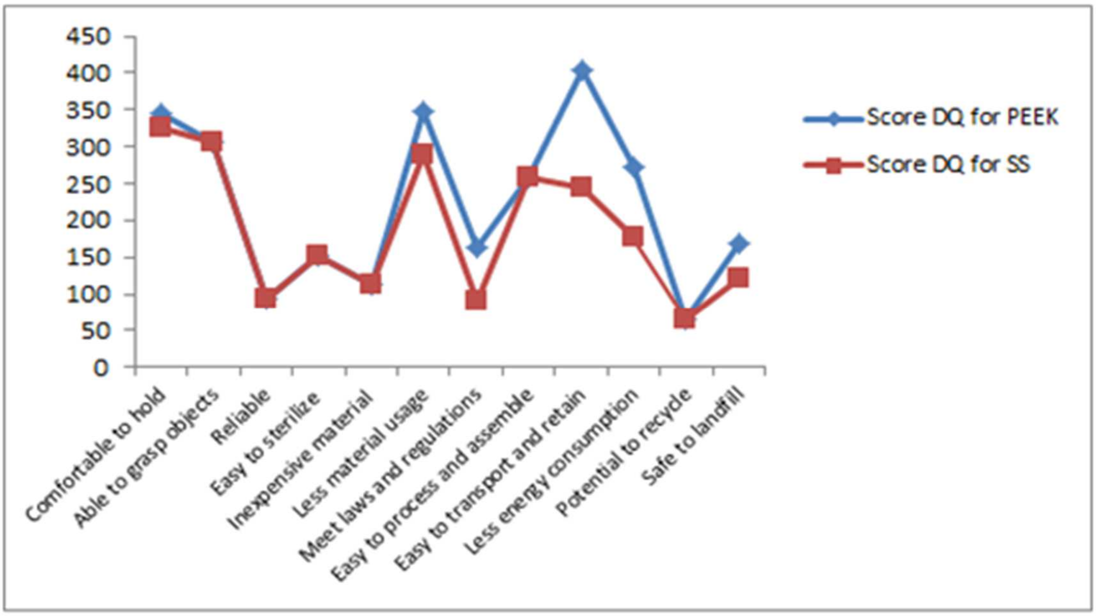
QFD Phase I Stainless Steel		Customer weights	Engineering Metric (EM)					Environmental EM											Costing		
			Forging and machining	As strong as stainless steel	Max opening jaws	Working length for shaft	Thickness of the main shaft	Weight	Volume (product)	Number of parts	Number of materials	Rate of recycle material	Total energy consumed	Manufacturing region	Carbon footprint	Water eutrophication	Air acidification	Transportation	Production cost	Environmental cost	Score for SS
Customer requirements	Comfortable to hold	5	●	●	△	△	△	△	●	●	●										325
	Able to grasp objects	5	●	●	●	●	●	△	●	◆	◆										305
	Reliable	4	●	●						△											92
	Easy to sterilize	4	●	△				△	△	△	●								++		152
	Inexpensive material	3	△	●	△	△	△				●								++		114
Environmental requirements	Less material usage	3	△	△	△	△	△	△	△	△	●	△	△	◆	●	●	●	●	++		288
	Meet laws and regulations	3											△	△	△	△	△	△			90
	Easy to process and assemb	3	●	●	△	△	△	△	△	●	●	△	△		△	△	△				258
	Easy to transport and retain	5						◆	△	△	●			△	△	△	△	●		++	245
	Less energy consumption	3				△	△	△	△	△	△	●		△	△	△	△			++	177
	Potential to recycle	1						△	△	●	●	●			●	●	●			++	64
	Safe to landfill	3						△	△	△	△				△	△	△	△		++	120
Raw score			219	215	115	100	130	140	200	196	251	66	45	58	121	121	121	102			
Relative weight			10.0	9.8	5.2	4.5	5.9	6.4	9.1	8.9	11.4	3.0	2.0	2.6	5.5	5.5	5.5	4.6			

+ +	High positive
+	Positive
- -	High negative
-	Negative
	No correlation

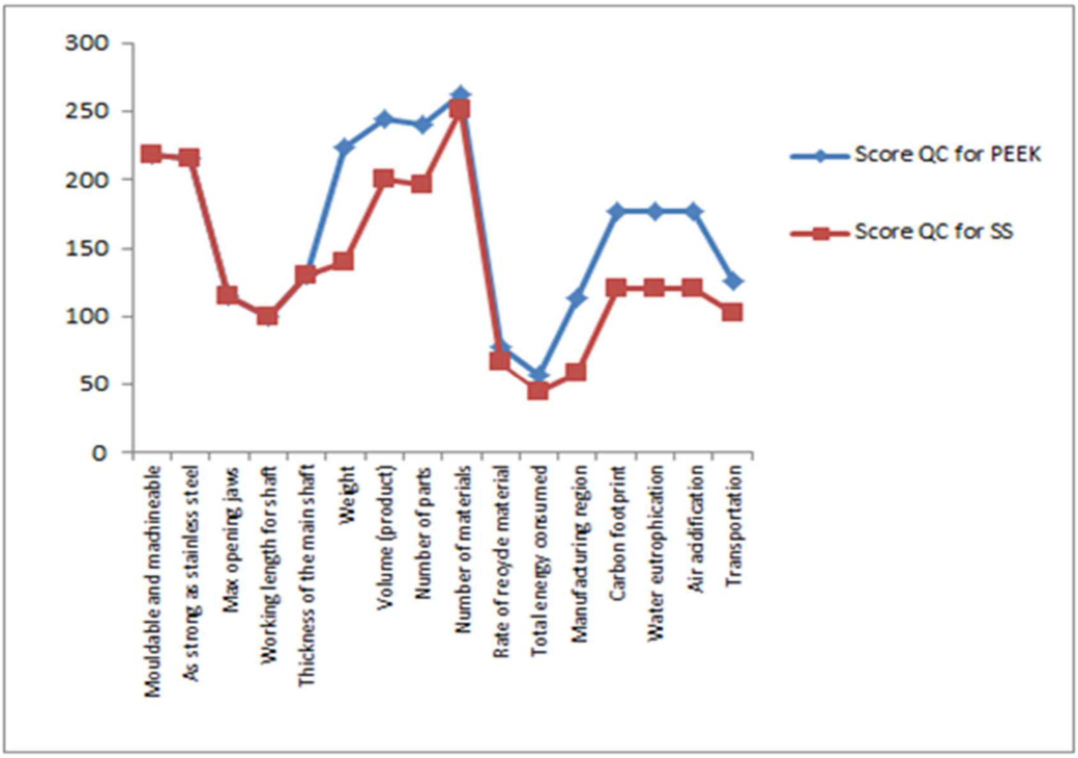
Key: ● **Strong relationsip (9pt)** ◆ **Medium relationship (5pt)** △ **Weak relationship (1pt)**

Figure 4.12: QFD Phase I for SS (2)





(a) Score for DQ



(b) Score for QC

Figure 4.14: Comparative analysis for DQs (a) and QCs (b) (from Figure 4.13) SS (2) vs PEEK (1)

Similar analyses were also undertaken for QC parameters, based on the columns in Figure 4.13. Here, “as strong as stainless steel” has relationships to the following DQ parameters: comfortable to hold (9), able to grasp object (9), reliable (9), easy to sterilise

(5), inexpensive material (9), less material usage (5) and easy to process and assemble (9).

Equations (3.1) and (3.2) have been used to calculate a raw score of 215 and relative weight of 8.1.

$$RS_{as\ strong\ as\ steel} = (9 * 5) + (9 * 5) + (9 * 4) + (5 * 4) + (9 * 3) + (5 * 3) + (9 * 3)$$

$$RS_{as\ strong\ as\ steel} = 219$$

$$W_{as\ strong\ as\ steel} = \frac{215}{(219+215+115+100+130+224+224+240+263+78+57+114+177+177+177+126)} \times 100$$

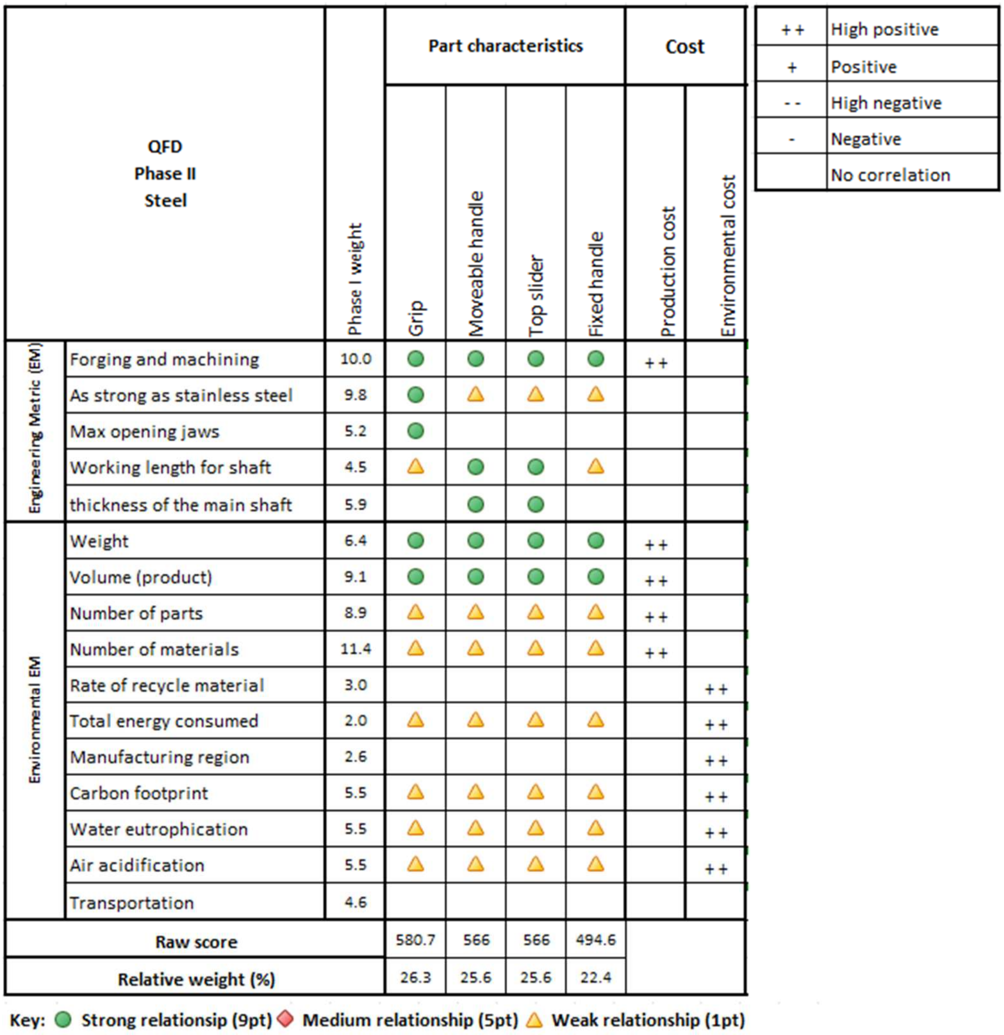
$$W_{as\ strong\ as\ steel} = 8.1.$$

From this analysis, the list of the most important QC parameters for SS (2) and their respective values in Figure 4.12 was established as: number of materials (11.4), forging and machining (10.0), volume of product (9.1), number of parts (8.9), and weight (6.4). For the PEEK (1) forceps, the most important QC parameters with respective values were number of materials (9.9), volume of product (9.2), number of parts (9.0), weight (8.4), and mouldable and machinable (8.2). These parameters were considered to be the key parameters and were further deployed in the priorities for DQ parameters in Eco-QFD Phase II.

The symbols “++” (high positive), “+” (positive), “- -” (high negative) and “-” (negative) were included in all Eco-QFD phases to indicate how the selected parameters contribute to the environmental and production costs. In Figures 4.12 and 4.13, the parameters involved in production cost were: easy to sterilise, inexpensive material, and less material usage. For environmental cost, the parameters were: easy to transport and retain, less energy consumption, potential to recycle, and safe to landfill. These parameters were considered in the Eco-Economic Costs model to calculate the total life-cycle cost of the product, as discussed in Section 4.5 and shown in Tables 4.6 and 4.5.

4.4.2 Eco-QFD Phase II

Figures 4.15 and 4.16 show Eco-QFD Phase II for PEEK (1) and SS (2) with the populated analysis. The DQ parameters in this phase have been retrieved from the QCs in QFD Phase I. The parameters were: forging and machining for PEEK (1) and mouldable and machinable for SS (2). The remaining parameters were shared in common: as strong as steel, maximum jaw opening, working length for shaft, thickness of the main shaft, weight, volume, number of parts, number of materials, rate of recycled materials, total energy consumed, manufacturing region, carbon footprint, water eutrophication, air acidification, and transportation. The relationship weighting factor between DQ and QC was then assigned by the designer.



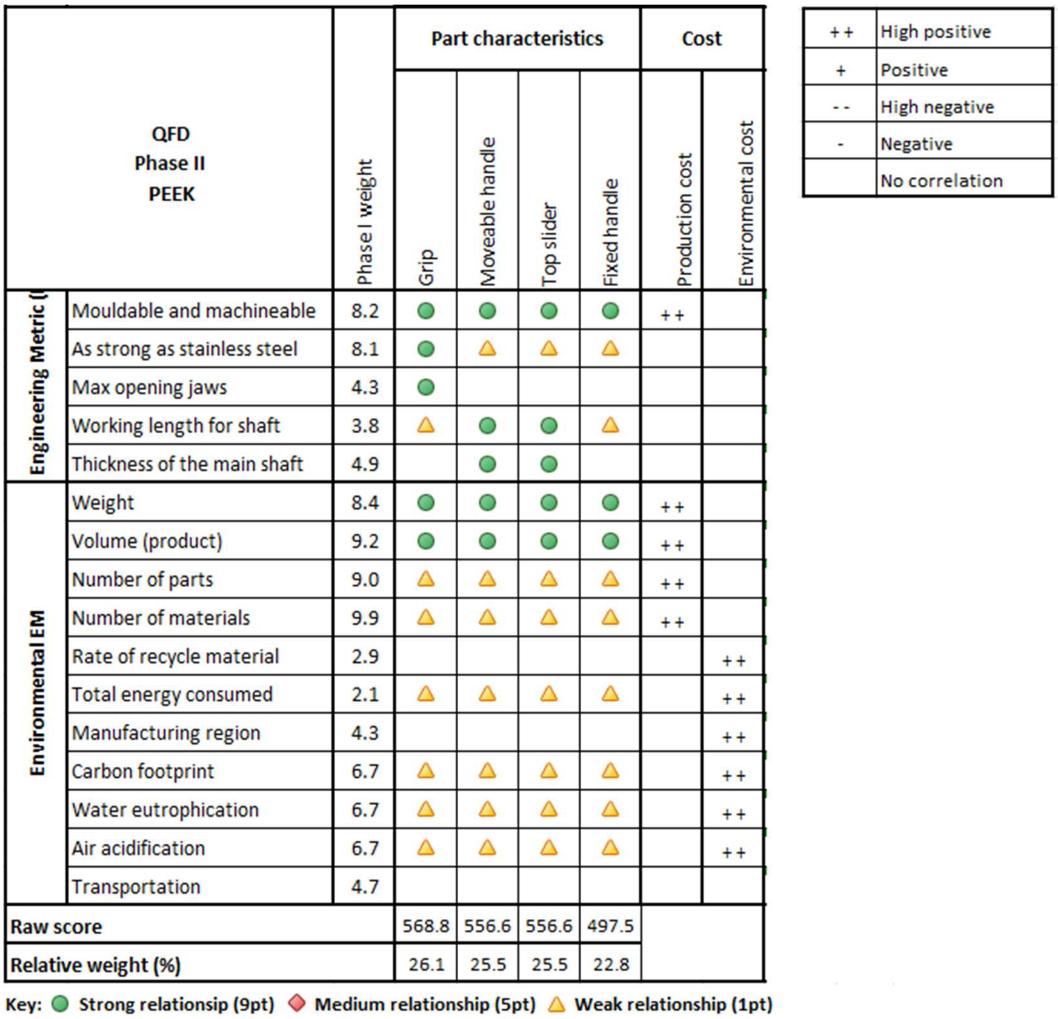
QFD Phase II Steel		Phase I weight	Part characteristics				Cost	
			Grip	Moveable handle	Top slider	Fixed handle	Production cost	Environmental cost
Engineering Metric (EM)	Forging and machining	10.0	●	●	●	●	++	
	As strong as stainless steel	9.8	●	△	△	△		
	Max opening jaws	5.2	●					
	Working length for shaft	4.5	△	●	●	△		
	thickness of the main shaft	5.9		●	●			
Environmental EM	Weight	6.4	●	●	●	●	++	
	Volume (product)	9.1	●	●	●	●	++	
	Number of parts	8.9	△	△	△	△	++	
	Number of materials	11.4	△	△	△	△	++	
	Rate of recycle material	3.0						++
	Total energy consumed	2.0	△	△	△	△		++
	Manufacturing region	2.6						++
	Carbon footprint	5.5	△	△	△	△		++
	Water eutrophication	5.5	△	△	△	△		++
	Air acidification	5.5	△	△	△	△		++
	Transportation	4.6						
Raw score			580.7	566	566	494.6		
Relative weight (%)			26.3	25.6	25.6	22.4		

+ +	High positive
+	Positive
- -	High negative
-	Negative
	No correlation

Key: ● Strong relationsip (9pt) ◆ Medium relationship (5pt) △ Weak relationship (1pt)

Figure 4.15: QFD Phase II for SS (2)

In Figure 4.15, the QC “grip” has a strong relationship to the DQ engineering metric parameters “forging and machining”, “as strong as stainless steel”, “maximum jaw opening”, and “working length for shaft”. It also has relationships with the following environmental metrics: weight, volume, number of parts, number of materials, carbon footprint, water eutrophication, and air acidification. The calculated raw score for this selected parameter was 580.7, and the relative weight was 26.3. For the PEEK (1) forceps shown in Figure 4.16, the raw score for “grip” was 568.8, and the relative weight was 26.1.



QFD Phase II PEEK		Phase I weight	Part characteristics				Cost	
			Grip	Moveable handle	Top slider	Fixed handle	Production cost	Environmental cost
Engineering Metric (	Mouldable and machineable	8.2	●	●	●	●	+ +	
	As strong as stainless steel	8.1	●	△	△	△		
	Max opening jaws	4.3	●					
	Working length for shaft	3.8	△	●	●	△		
	Thickness of the main shaft	4.9		●	●			
Environmental EM	Weight	8.4	●	●	●	●	+ +	
	Volume (product)	9.2	●	●	●	●	+ +	
	Number of parts	9.0	△	△	△	△	+ +	
	Number of materials	9.9	△	△	△	△	+ +	
	Rate of recycle material	2.9						+ +
	Total energy consumed	2.1	△	△	△	△		+ +
	Manufacturing region	4.3						+ +
	Carbon footprint	6.7	△	△	△	△		+ +
	Water eutrophication	6.7	△	△	△	△		+ +
	Air acidification	6.7	△	△	△	△		+ +
	Transportation	4.7						
Raw score			568.8	556.6	556.6	497.5		
Relative weight (%)			26.1	25.5	25.5	22.8		

+ +	High positive
+	Positive
- -	High negative
-	Negative
	No correlation

Key: ● Strong relationsip (9pt) ◆ Medium relationship (5pt) △ Weak relationship (1pt)

Figure 4.16: QFD Phase II for PEEK (1)

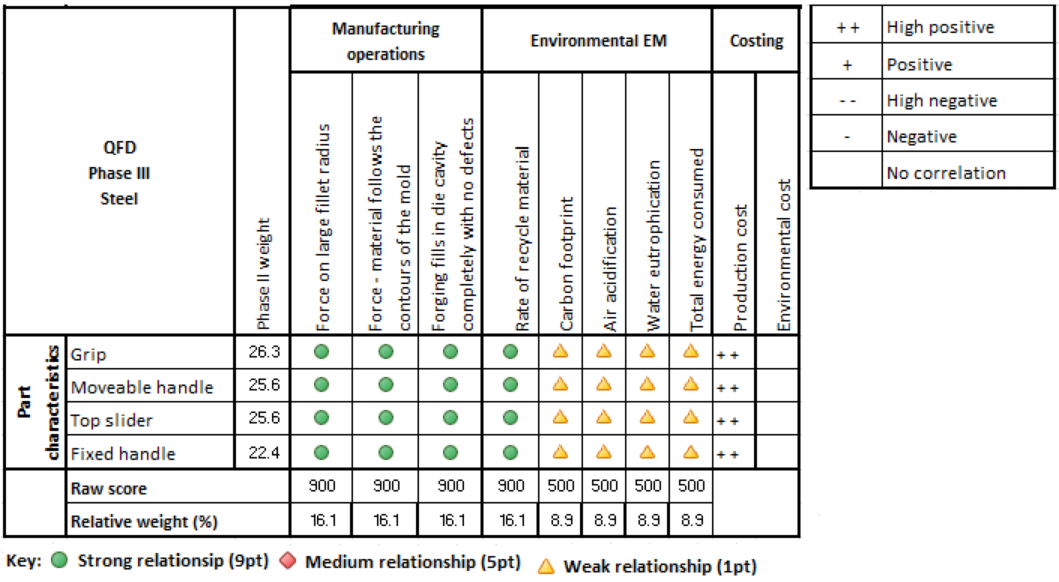
The results of this process show that the grip is the most critical part of the medical forceps, followed by the following parts: top slider, moveable handle, and fixed handle. This finding allows the designer to focus on the most important aspects of the product. This analysis can be continued by affirming that the forceps can be as strong as steel and can have a lower environmental impact.

Here, the parameters involved in production cost are: mouldable and machinable, weight, volume of parts, and number of materials. For environmental cost, the parameters are: rate of recycled material, product lifespan, manufacturing region, carbon footprint, water eutrophication, air acidification, and toxicity of materials. These parameters were considered in the Eco-Economic Costs model to calculate the total life-cycle cost of the product and will be outlined in Section 4.5.

4.4.3 Eco-QFD Phase III

Eco-QFD Phase III utilised the process planning matrix to consider the characteristics of parts (QFD Phase II) in relation to manufacturing operations (QFD Phase III). This is only presented here to demonstrate the method; a more in-depth analysis would be required to fully implement this approach. The product development path followed in this case study required the engineering of a manufacturing process using forging and machining for the stainless steel forceps and injection moulding and machining for the PEEK forceps. Figures 4.17 and 4.18 show the most important QC parameters for these materials, as evidenced in SS (2) and PEEK (1).

Figure 4.17 shows that the process of forging and machining gave high impact to the manufacturing operations with a respective value of 16.1. “Rate of recycled material” was the most important environmental parameter with the relative weight of 16.1. This was followed by: carbon footprint, air acidification, water eutrophication, and total energy consumed, all with the same respective value of 8.9.



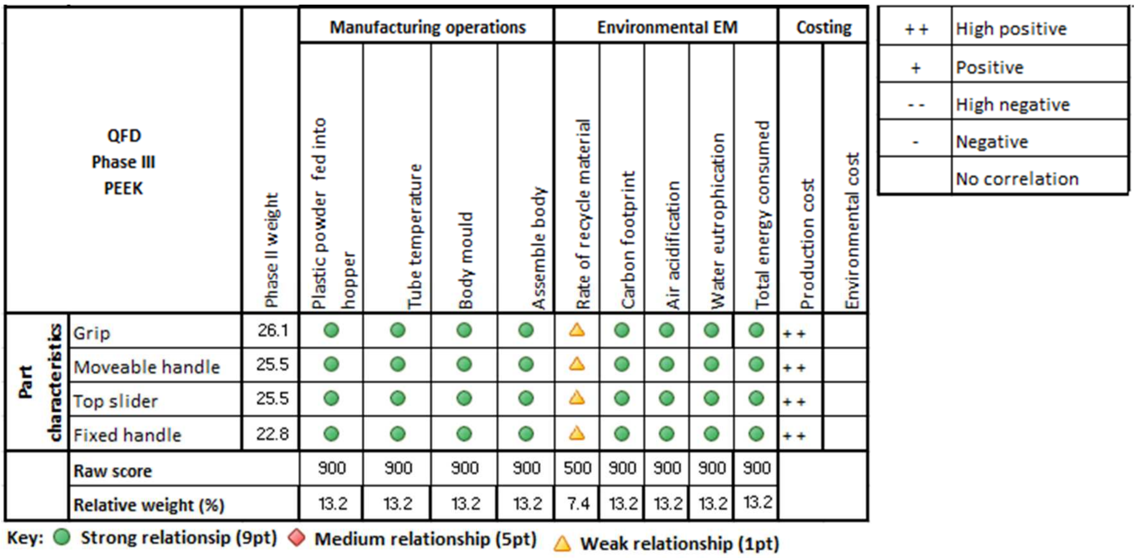
QFD Phase III Steel			Manufacturing operations			Environmental EM					Costing	
		Phase II weight	Force on large fillet radius	Force - material follows the contours of the mold	Forging fills in die cavity completely with no defects	Rate of recycle material	Carbon footprint	Air acidification	Water eutrophication	Total energy consumed	Production cost	Environmental cost
Part characteristics	Grip	26.3	●	●	●	●	△	△	△	△	+ +	
	Moveable handle	25.6	●	●	●	●	△	△	△	△	+ +	
	Top slider	25.6	●	●	●	●	△	△	△	△	+ +	
	Fixed handle	22.4	●	●	●	●	△	△	△	△	+ +	
	Raw score		900	900	900	900	500	500	500	500		
	Relative weight (%)		16.1	16.1	16.1	16.1	8.9	8.9	8.9	8.9		

+ +	High positive
+	Positive
- -	High negative
-	Negative
	No correlation

Key: ● Strong relationsip (9pt) ◆ Medium relationship (5pt) △ Weak relationship (1pt)

Figure 4.17: QFD Phase III for SS (2)

Figure 4.18 shows the resulting QC parameters for PEEK (1) forceps. All the following parameters had the same relative weight of 11.1: plastic powder fed into hopper, tube temperature, body mould, assembly body, rate of recycled material, carbon footprint, air acidification, water eutrophication, and total energy consumed. The rate of recycled material is an important environmental parameter; it was assumed here that PEEK can be 100% recycled. In fact, the process of recycling PEEK has not been fully developed, and this figure is conditional upon it being applied within an injection moulding context (McLauchlin, Ghita and Savage, 2014).



QFD Phase III PEEK			Manufacturing operations				Environmental EM					Costing	
		Phase II weight	Plastic powder fed into hopper	Tube temperature	Body mould	Assemble body	Rate of recycle material	Carbon footprint	Air acidification	Water eutrophication	Total energy consumed	Production cost	Environmental cost
Part characteristics	Grip	26.1	●	●	●	●	△	●	●	●	●	+ +	
	Moveable handle	25.5	●	●	●	●	△	●	●	●	●	+ +	
	Top slider	25.5	●	●	●	●	△	●	●	●	●	+ +	
	Fixed handle	22.8	●	●	●	●	△	●	●	●	●	+ +	
	Raw score		900	900	900	900	500	900	900	900	900		
	Relative weight (%)		13.2	13.2	13.2	13.2	7.4	13.2	13.2	13.2	13.2		

+ +	High positive
+	Positive
- -	High negative
-	Negative
	No correlation

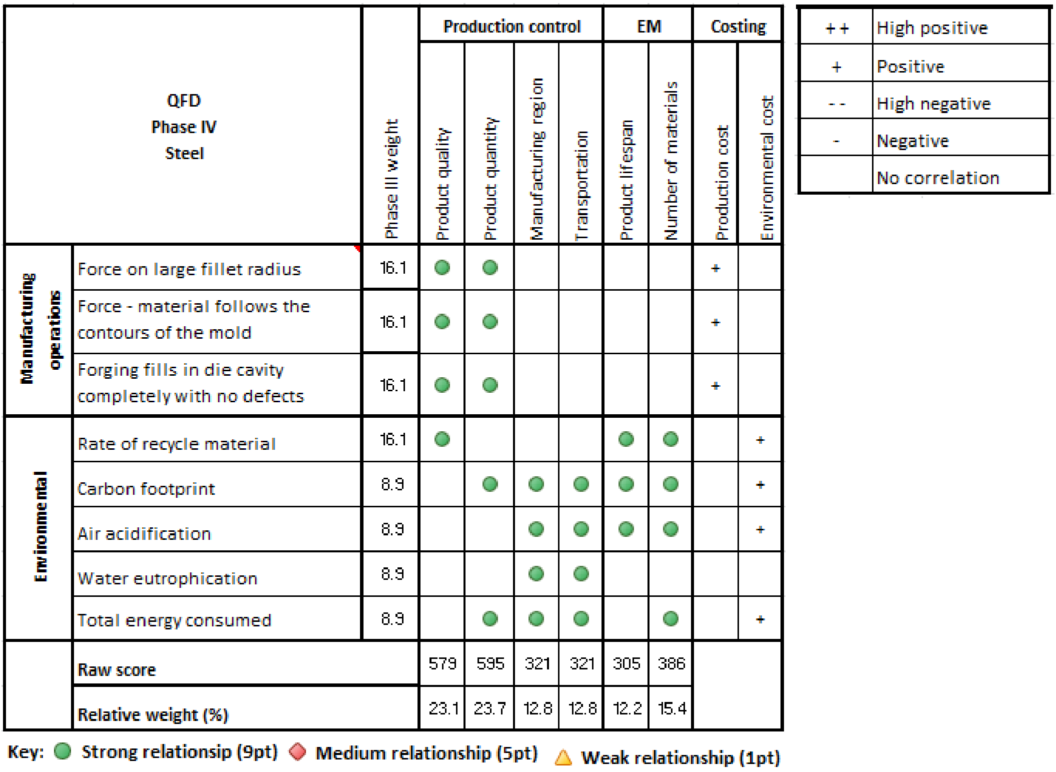
Key: ● Strong relationsip (9pt) ◆ Medium relationship (5pt) △ Weak relationship (1pt)

Figure 4.18: QFD Phase III for PEEK (1)

Inputs from all the part characteristics (grip, moveable handle, top slider, and fixed handle) can be measured in terms of production cost. In the next phase, the QC parameters considered above were used as the key parameters (and were further deployed within the priorities used) in Eco-QFD Phase IV.

4.4.4 Eco-QFD Phase IV

Eco-QFD Phase IV is the production planning stage that produces performance indicators between production requirements and manufacturing operations. The weighting factors for QCs have been assigned in this relationship matrix. Figure 4.19 shows the ranking QC parameters for SS (2) as follows: product quantity, product quality, number of materials, manufacturing region, transportation, and product lifespan.



QFD Phase IV Steel			Production control				EM		Costing	
		Phase III weight	Product quality	Product quantity	Manufacturing region	Transportation	Product lifespan	Number of materials	Production cost	Environmental cost
Manufacturing operations	Force on large fillet radius	16.1	●	●					+	
	Force - material follows the contours of the mold	16.1	●	●					+	
	Forging fills in die cavity completely with no defects	16.1	●	●					+	
Environmental	Rate of recycle material	16.1	●				●	●		+
	Carbon footprint	8.9		●	●	●	●	●		+
	Air acidification	8.9			●	●	●	●		+
	Water eutrophication	8.9			●	●				
	Total energy consumed	8.9		●	●	●		●		+
	Raw score		579	595	321	321	305	386		
	Relative weight (%)		23.1	23.7	12.8	12.8	12.2	15.4		

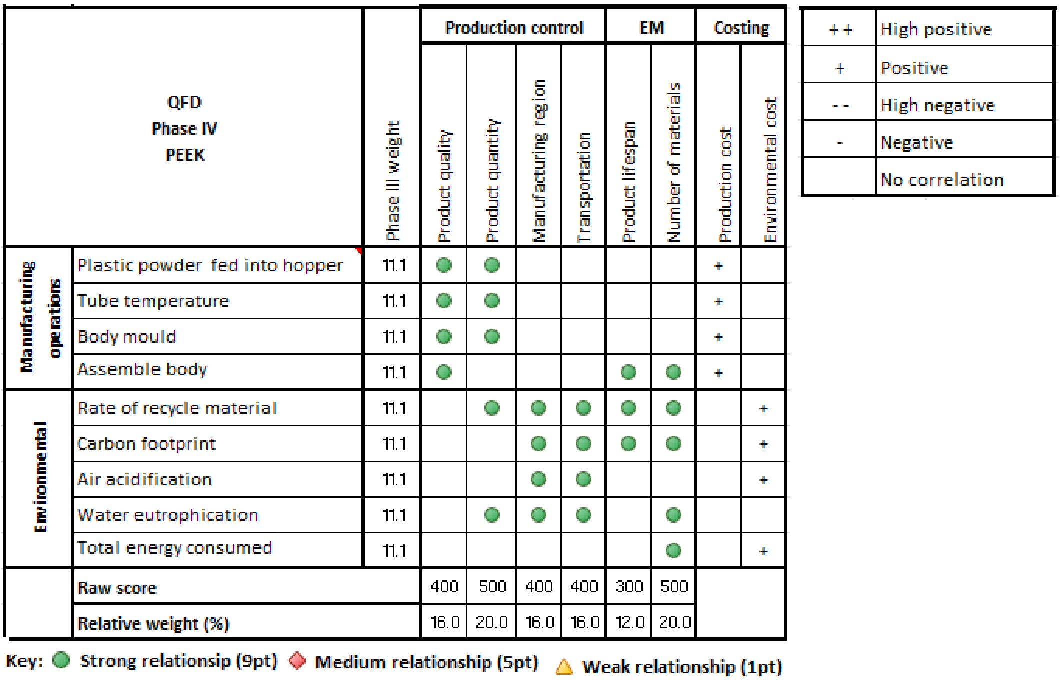
++	High positive
+	Positive
- -	High negative
-	Negative
	No correlation

Key: ● **Strong relationsip (9pt)** ◆ **Medium relationship (5pt)** △ **Weak relationship (1pt)**

Figure 4.19: QFD Phase IV for SS (2)

Figure 4.20 shows the ranking QC parameters for PEEK (1) forceps as follows: product quantity, product quality, manufacturing region, transportation, product lifespan, and number of materials. Again, the intention here is to demonstrate the approach; more detailed analysis would be required to develop the actual product.

In this phase, the parameters involved in production cost planning were: plastic powder fed into hopper, tube temperature, body mould, and assembly body. The parameters involved in environmental cost were: rate of recycled material, carbon footprint, air acidification, and water eutrophication. These parameters were extracted to the Eco-HoQ, Eco-Economic Costs model.



QFD Phase IV PEEK		Phase III weight	Production control				EM		Costing	
			Product quality	Product quantity	Manufacturing region	Transportation	Product lifespan	Number of materials	Production cost	Environmental cost
Manufacturing operations	Plastic powder fed into hopper	11.1	●	●					+	
	Tube temperature	11.1	●	●					+	
	Body mould	11.1	●	●					+	
	Assemble body	11.1	●				●	●	+	
Environmental	Rate of recycle material	11.1		●	●	●	●	●		+
	Carbon footprint	11.1			●	●	●	●		+
	Air acidification	11.1			●	●				+
	Water eutrophication	11.1		●	●	●		●		
	Total energy consumed	11.1						●		+
	Raw score		400	500	400	400	300	500		
	Relative weight (%)		16.0	20.0	16.0	16.0	12.0	20.0		

++	High positive
+	Positive
--	High negative
-	Negative
	No correlation

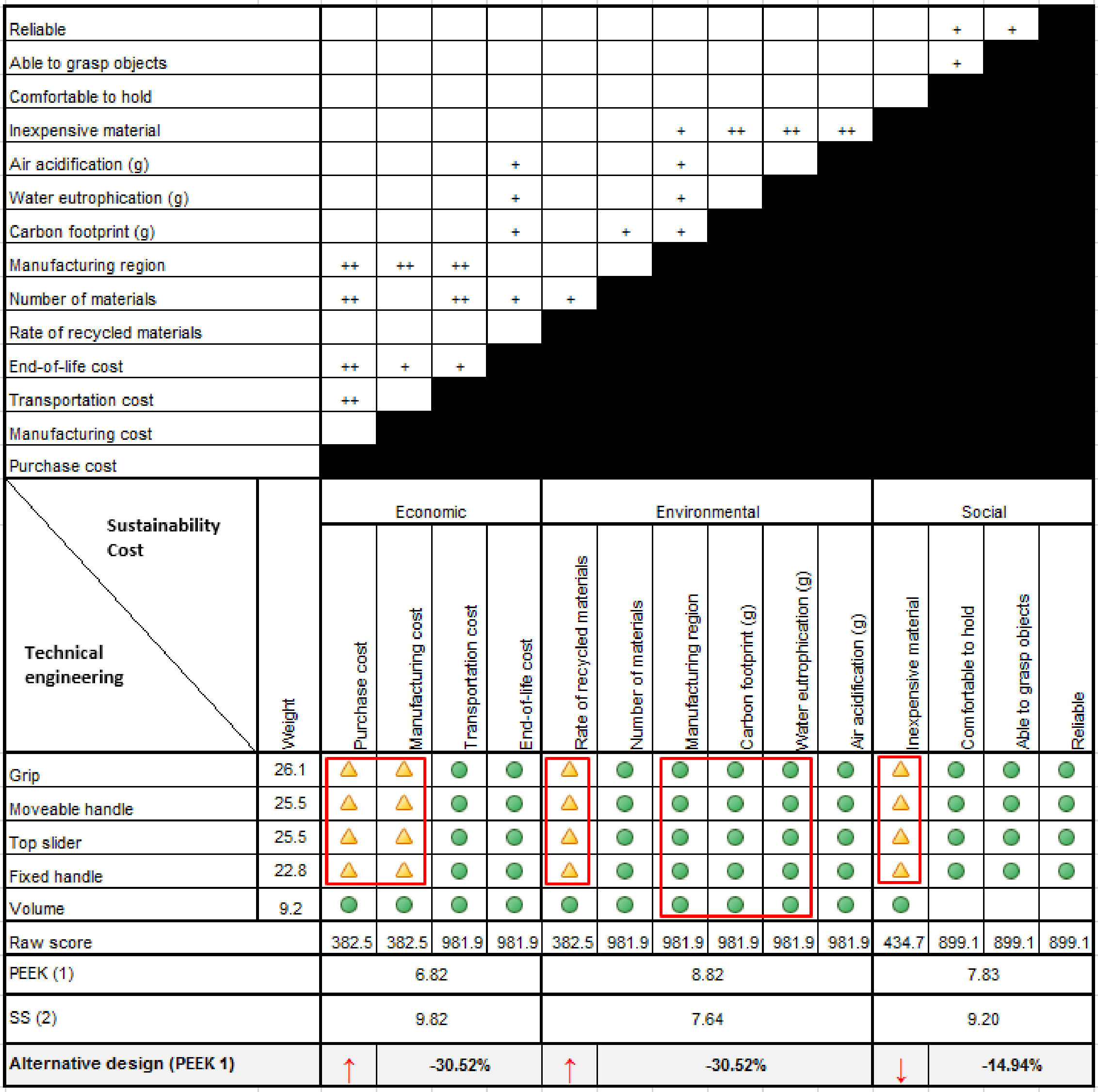
Key: ● **Strong relatiosnip (9pt)** ◆ **Medium relationship (5pt)** △ **Weak relationship (1pt)**

Figure 4.20: QFD Phase IV for PEEK (1)

4.5 Eco-Economic Costs embedded in the Eco-HoQ model

Figure 4.21 shows the Eco-Economic Costs model embedded in the Eco-HoQ model, which, as depicted in Figure 4.11, acts as a master platform to analyse the contributions of the sustainable product design parameters retrieved from the Eco-QFD phases for PEEK (1) and SS (2). Using the Eco-Economic Costs model, the designer can map correlations between QC parameters to identify the relative contributions of the highest costing components of a product. For instance, as shown in Figure 4.21, the transportation cost parameter has a positive correlation to EOL cost, number of materials, and manufacturing region. For the QC section, these parameters are divided into three main categories: economic, environmental, and social.

The parameters in the economic category were retrieved from Eco-QFD Phases II, III and IV; they are: purchase cost, manufacturing cost, transport cost, and end-of-life cost. The categories for the environmental category were derived from all four Eco-QFD phases; these are: rate of recycled materials, number of materials, manufacturing region, carbon footprint, water eutrophication, and air acidification. The last category is social, which had the following parameters: inexpensive material, comfortable to hold, able to grasp object, and reliability. These parameters were derived from the customer requirements retrieved in QFD Phase I.



	Purchase cost	Manufacturing cost	Transportation cost	End-of-life cost	Rate of recycled materials	Number of materials	Manufacturing region	Carbon footprint (g)	Water eutrophication (g)	Air acidification (g)	Inexpensive material	Comfortable to hold	Able to grasp objects	Reliable
Reliable												+	+	
Able to grasp objects												+		
Comfortable to hold														
Inexpensive material							+	++	++	++				
Air acidification (g)				+			+							
Water eutrophication (g)				+			+							
Carbon footprint (g)				+		+	+							
Manufacturing region	++	++	++											
Number of materials	++		++	+	+									
Rate of recycled materials														
End-of-life cost	++	+	+											
Transportation cost	++													
Manufacturing cost														
Purchase cost														

Sustainability Cost / **Technical engineering**	Weight	Economic				Environmental						Social			
		Purchase cost	Manufacturing cost	Transportation cost	End-of-life cost	Rate of recycled materials	Number of materials	Manufacturing region	Carbon footprint (g)	Water eutrophication (g)	Air acidification (g)	Inexpensive material	Comfortable to hold	Able to grasp objects	Reliable
Grip	26.1	△	△	●	●	△	●	●	●	●	●	△	●	●	●
Moveable handle	25.5	△	△	●	●	△	●	●	●	●	●	△	●	●	●
Top slider	25.5	△	△	●	●	△	●	●	●	●	●	△	●	●	●
Fixed handle	22.8	△	△	●	●	△	●	●	●	●	●	△	●	●	●
Volume	9.2	●	●	●	●	●	●	●	●	●	●	●			
Raw score		382.5	382.5	981.9	981.9	382.5	981.9	981.9	981.9	981.9	981.9	434.7	899.1	899.1	899.1
PEEK (1)		6.82				8.82						7.83			
SS (2)		9.82				7.64						9.20			
Alternative design (PEEK 1)		↑	**-30.52%**			↑	**-30.52%**					↓	**-14.94%**		

Figure 4.21: Eco-Economic cost for Eco-HoQ model

In populating the Eco-HoQ model shown in Figure 4.21, information was acquired and processed following the approach presented in Table 4.6, in which the parameters and allocated costs for the production and environmental requirements for PEEK (1) and SS

(2) are shown. The Eco-Economic Costs model was used to calculate a total life-cycle cost for the product based upon a functional unit of single forceps. The goals here were to minimise the product's total life-cycle cost and to minimise the environmental impact of the product. Table 4.6 shows that the direct cost for the components of a single forceps using PEEK (1) and SS (2) are £0.56 and £0.33, respectively. This cost has been calculated based on the bill of materials (BOM) of the product. The Eco-Economic Costs model can be used to calculate overhead costs, the purchase cost of material, the total manufacturing cost, and the cost of recycling the material.

In this case study, two different values were used to measure the EOL recycling cost for each material. The PEEK forceps were considered to have EOL recycling rates of 0% and 50%, while the recycling rates for stainless steel were input as 50% and 100%. The analyses of the environmental impact based on the different values of recycling rates are shown in Table 4.6. This data has been carried to Table 4.7 in order to evaluate the cost of manufacturing and sustainability. Table 4.7 shows the final life-cycle cost comparison. Based on the sustainability principles (Russo and Rizzi, 2014), reducing energy consumption and the amount of material used in product manufacture were considered priorities in this study. Table 4.6 indicates the total cost as the sum of the environmental and production costs for a single forceps. Formulas for life-cycle costs in equations (3.1), (3.2), and (3.3) discussed in Chapter III were used to quantify the production and environmental costs using the available data shown in Tables 4.2 and 4.4.

As an illustration, the mass of the PEEK forceps is 6.85 grams. The purchase cost of PEEK is £0.082 per gram, and the cost for recycling PEEK is £0.04 per gram (Ptiplastics 2014). The landfill costs were retrieved from the appropriate UK government website (HM Revenue and Customs, 2014). Using Equations (3.3), (3.4), (3.7), and (3.8) from Chapter III and the information from Tables 4.2 and 4.3 provides the following figures for a single PEEK forceps:

Table 4.6: Eco-Economic Cost parameters for medical forceps made with PEEK and Stainless Steel

	Product Cost			**Sustainability Cost (From table 1)**				
	Parameters	**PEEK**	**SS**	**Parameters**	**PEEK (1)**	**PEEK (2)**	**SS (1)**	**SS (2)**
QFD Phase I **Design specification**	Mouldable and machinable			Recycle rate at EOL product	0%	50%	50%	100%
	As strong as stainless steel			Product life span	single use	single use	single use	single use
	Weight (g)	6.85	22	Manufacturing region	Europe	Europe	Pakistan	Pakistan
	Volume	30000	10000	Manufacturing process	Injection moulding	Injection moulding	Forging and machining	Forging and machining
	Number of parts	4	4	Transportation and use	Truck-Europe	Truck-Europe	Plane-Europe	Plane-Europe
	Number of materials	1	1	Carbon footprint (g)	84.17	71.32	343.90	320.00
QFD Phase II **Part characteristics**	Grip			Water eutrophication (g)	0.02	0.02	0.59	0.50
	Moveable handle			Air acidification (g)	0.25	0.22	1.25	1.19
	Top slider			Total energy consumed (KJ)	1586.70	1360.82	4340.60	4153.50
	Fixed handle							
QFD Phase III **Manufacturing operations** **PEEK is using injection moulding while stainless steel is using machining and forging.**	Grip	0.05	0.02					
	Moveable handle	0.17	0.10					
	Top slider	0.05	0.03					
	Fixed handle	0.29	0.18					
	Plastic powder fed into the hopper	1kg						
	Labour cost (£/h)	20	7					
QFD Phase IV **Production control**	Product quality							
	Product quantity	30000	10000					
	Transportation (£/km)							
Total direct cost		**£0.56**	**£0.33**					

Table 4.7: Summary of total life cycle cost comparison

Production cost components per unit	**Quantity**	**Cost**	**PEEK**	**Stainless steel**
Grip	1	0.05	0.05	0.02
Moveable handle	1	0.17	0.17	0.10
Top slider	1	0.05	0.05	0.03
Fixed handle	1	0.29	0.29	0.18
Direct cost			**0.56**	**0.33**
Labour cost -£/hr (PEEK)	£20.00	1.2min	0.40	
Labour cost £/hr (Stainless steel)	£7.00	3min		0.35
Overhead cost	100%		0.96	0.68
Manufacturing cost (Mc)			**£1.92**	**£1.36**

Environmental cost per unit	**Eco-costs (£) per g**		**Eco-costs (£) forceps (g/unit)**			
	PEEK	**Stainles Steel**	**PEEK (1)**	**PEEK (2)**	**SS (1)**	**SS (2)**
Carbon footprint	1.81E-03	2.04E-04	1.53E-01	1.29E-01	7.02E-02	6.53E-02
Air acidification	4.53E-04	5.00E-05	9.06E-06	9.06E-06	6.25E-05	5.95E-05
Water eutrophication	2.00E-06	2.00E-05	4.00E-08	2.00E-07	1.18E-05	1.00E-05
Energy consumption	1.00E-05	3.50E-05	1.59E-02	1.36E-02	1.52E-01	1.45E-01
Environmental cost (Ec)			**£0.17**	**£0.14**	**£0.22**	**£0.21**

Economic cost	**PEEK**		**Economic cost**	**Stainless steel (SS)**	
	Cost (£/g)	**Life Cycle Cost (£) (g/unit)**		**Cost (£/g)**	**Life Cycle Cost (g/unit)**
Purchase cost of materials (Pc)	0.0420	0.29	Purchase cost of materials (Pc)	0.0060	0.13
Process cost of material	0.2803	1.92	Process cost of material	0.0618	1.36
Landfill (1 tonne - £110.00)	1.1E-04		Landfill (1 tonne - £110.00)	1.1E-04	
Recycle value PEEK (1) 0%	0.0210	0.00	Recycle value SS (1) 50%	0.0030	0.03
Landfill - PEEK (1) 100%		7.54E-04	Landfill - SS (1) 50%		1.21E-03
Recycle value PEEK (2) 50%	0.0210	0.07	Recycle value SS (2) - 100%	0.0030	0.07
Landfill - PEEK (2) 50%		3.77E-04	Landfill - SS (2) 0%		0.00
Total cost (Pc + Mc + Ec + EOL cost) EoL cost= Landfill cost - Recycle value	**PEEK (1)**	**£2.38**	**Total cost (Pc + Mc + Ec + EOL cost) EoL cost= Landfill cost - Recycle value**	**SS (1)**	**£1.68**
	PEEK (2)	**£2.28**		**SS (2)**	**£1.64**

- Purchase cost of materials, Pc = 0.042x6.85 = £0.29
- Manufacturing cost, M_C = 0.05+0.17+0.05+0.29+0.40+0.96 = £1.92
- *End-of-Life cost*$_{(PEEK1)}$= 2.26E-04 – 0 = £0.0002
- Total Economic cost, $ECOc$ = 2.09+0.29+0.0002 = £2.38

These costs were used in the summary of the total life-cycle cost shown in Table 4.7.

The percentage of recycled material used in the production of the forceps and at their EOL have been included in Table 4.7. The reduction of the carbon footprint and energy consumed associated with the recycling PEEK is not yet fully understood, and a 30% reduction of these factors was estimated to be suitable for both.

Table 4.7 also shows the environmental cost per unit for this product. The eco-costs values per kilogram have been obtained from the LCA database, Eco-cost 2007 (Vogtlander, 2011). These values have been used to calculate the environmental cost for the medical forceps and to find the total cost for both designs. The environmental cost for 0% and 50% recycled PEEK would be £0.17 and £0.14 per gram, respectively, and the stainless steel forceps with the recycled rate of 50% and 100% would be £0.22 and £0.21 per gram, respectively.

Table 4.7 also includes an analysis of the EOL alternatives for both PEEK and stainless steel. The recycling value for these materials has been set to 50% of the actual purchase cost; a PEEK recycling rate of 50% would generate £0.07 per unit. However, if PEEK is unable to be recycled, it would have to be transported to a landfill at a cost of £1.1E-04 per gram.

Finally, Table 4.6 indicates that this analysis has resulted in life cycle cost totals of £2.38 and £2.28 for PEEK (1) and PEEK (2), respectively. For stainless steel recycling rates at 50% and 100%, the LCC totals for SS (1) and SS (2) are £1.68 and £1.64. These findings show that recycling has a positive impact on product sustainability cost.

With IEDM-supported comprehensive eco-design considerations influencing the design process, the manufacture of medical forceps using PEEK has high potential to support improvements in most areas of environmental impact, including reduced material usage, reduced energy consumption, and safe emissions. Ultimately, however, the production cost of the PEEK-based forceps exceeds that of the existing stainless steel version.

4.6 Discussion

The results arising from the case study, as shown in Figure 4.21, demonstrate that the manufacture of medical forceps using PEEK can potentially support improvements and savings in most areas of environmental impact. However, as shown in the Table 4.7, the economic costs involved in supporting this process, including the labour and material costs required when switching to a product made from PEEK within the UK, have been found to be significantly higher than those of the existing stainless steel product manufactured in Pakistan. This analysis has been unable to support the proposed move; however, as the costs involved with manufacturing using PEEK (which is still a relatively expensive material) and with the manufacture of new injection moulding tools are reduced, then a move to PEEK-based production in the UK may be reconsidered using the existing IEDM model.

In this case study, the Eco-QFD stimulated the reconsideration of the first phase of the QFD design activity. Using this method, the designer was able to focus on important attributes of the product, reducing the effort spent on unrelated or unimportant product attributes. Here, these important attributes included the forceps' ergonomics and aesthetics, both of which ensure that the handles are comfortable. In this case, it would be possible to improve the existing design, as the comfort of the PEEK-based forceps could be enhanced by making the profiles more rounded. The design of the jaw and grip were assessed in order to ensure that the forceps can grasp the necessary objects and not break under the required loading.

The design analysis behind these improvements could equally be applied to the existing stainless steel forceps, confirming that the Eco-QFD approach can achieve incremental design improvements. Following the IEDM framework, the revision of part characteristics may be considered between Eco-QFD Phases I and II. The savings in the amount of material would have to be set against new tooling costs, which would be assessed between Eco-QFD Phases III and IV.

Following the review of the current design, it was clear that the existing stainless steel forceps can be improved. In terms of durability issue for the single use product, it can be assumed that the amount of material used can be reduced by 10% without reducing function, since the strength of the handles of the stainless steel forceps is greater than required. This factor relates to the life cycle of the product and how long it can be used. The redesign of the stainless steel forceps is illustrated using the Eco-CBR tool in Chapter VI.

4.7 Summary

The development of the Eco-HoQ tool within an enhanced Eco-QFD process and Eco-Economic Cost model included the important eco-design consideration and evaluation of a product’s life-cycle cost. Information has been incorporated within the IEDM framework in an easy-to-apply manner, using an enhanced Eco-QFD tool in a newly defined three-stage process. This process enables users with complementary knowledge to enter and access information in a timely and controlled manner. They are then able to contribute their expertise to influence design decisions and provide more sustainable products. The concentration of environmental considerations in the Eco-HoQ within the deployed Eco-QFD process ensures that product sustainability is always central to any design development. This means that the environmental implications of design changes are fully identified and can be justified. The generic nature of these considerations means that it is essential that the information produced is accessible for future usage.

Having proposed such significant design changes, the designer should ensure that new modes of failure do not arise and that functional performance is not affected throughout the product's useful life. Responses from customers and users of the existing and redesigned products can be incorporated into the data of each phase in the IEDM framework to better inform designers and manufacturers about the consequences of any actions taken. These responses may be quantitative or qualitative, but, in all cases, they can be associated with changes made within the Eco-QFD decision processes.

This study continues the development of a computer-based approach to product design, incorporating the Eco-QFD process and will be discussed in Chapter V and VI. This approach implements the Eco-CBR technique and it is based upon the hypothesis that if experiences from the Eco-QFD process can be captured in some useful form, then this experience can easily be referred to and leaned from in the future. In this case study, much of the eco-design considerations applied to the use of PEEK and stainless steel are generic. Information resulting from this process could be accessed and reused for the continuous improvement of the design of this or similar products, thus reducing the time and cost required for future work. Some of the features and output data from the Eco-QFD will be considered in the development of Eco-CBR and will be discussed in Chapters V and VI.

CHAPTER V

ECO-DESIGN CASE-BASED REASONING TOOL

This chapter addresses the third research objective by developing a decision support tool as part of the integrated eco-design decision making (IEDM) framework in the evaluation of product sustainability. A major challenge for any manufacturers is to include aspects of sustainable development in product design. Thus, this study aims at proposing solutions related to the social, environmental, and economic impacts of the product. This chapter is organised as follows: Section 5.1 introduces the eco-design case-based reasoning (Eco-CBR) tool within the IEDM framework; Section 5.2 discusses the process that is used in the Eco-CBR model; Section 5.3 introduces the development of the Eco-CBR tool for supporting sustainable product design, while Section 5.4 provides a summary of the chapter.

5.1 Eco-design Case-based Reasoning

Sustainable product design represents a complex domain, where past experiences are frequently used to solve new design problems. Product sustainability needs to be evaluated from social, environmental and economic perspectives. The maximum benefits of eco-design are achieved by reducing the environmental impact and cost for the entire product life cycle. In reality, it is a challenge to strike an appropriate balance in environmental elements while maintaining the production cost as low as possible. This challenge led to the following research question: how can past experience enables and supports sustainable product development at an early design stage? Hence, the Eco-CBR tool introduced in the IEDM framework answers this challenge by storing and manipulating eco-design product knowledge within an Eco-CBR library of cases.

The ‘eco-design case-based reasoning’ (Eco-CBR) tool embedded in the IEDM framework is considered as a significant contribution in this study. The aim of this tool is to produce an innovative, more sustainable product design process by finding similarities with previous cases stored in a case-based library. This process uses the experiences from similar cases to generate the ideal solution. The objective of developing the Eco-CBR tool is to support various design processes, and to add and maintain the library of cases in a more organised fashion. The integration of the ‘ecological quality function deployment’ (Eco-QFD) and ‘case-based reasoning’ (CBR) methods introduced in this study meets this challenge by storing and manipulating eco-design product knowledge within a case-based library. This uses the ‘integrated eco-design decision making’ (IEDM) framework, which was previously engineered to ensure that product development embraces environmental and economic considerations throughout the product’s life cycle.

The Eco-CBR tool is an intuitive decision support tool that complements the Eco-QFD method and proposes solutions related to customers' requirements and the environmental and economic impacts of the product. The Eco-QFD method ensures that customers' needs are considered within the context of product sustainability. The novelty of this study is in the development of the Eco-CBR tool which is based on the premise that if experiences from the Eco-QFD process can be captured in some useful form, designers can refer to and learn from them. This approach can help industrial decision-makers propose solutions by reusing solutions from similar cases and from their past experiences. The novelty is in the way the cases are structured around the Eco-QFD process and new cases are generated, using life cycle assessments (LCA), cost estimations and information about related manufacturing processes and means of transportation.

The IEDM framework takes the approach further with the development of the Eco-CBR tool. The developed Eco-CBR tool is used for the integration of Eco-QFD, LCA and Eco-Economic cost model as shown in the IEDM framework of Figure 5.1. Figure

5.1 illustrates that the input of the new case features for Eco-CBR is defined in Stage III (Eco-QFD). The features are divided under four sustainability input groups, namely transportation, material and manufacturing process, end-of-life (EOL) product, and design dimensions. The features of a particular problem from the groups are used to configure a product solution that has lower environmental impacts. The proposed solution within the Eco-CBR tool includes information contributed from Stage I (LCA), Stage III (Eco-QFD) and Eco-Economic Cost model. The intention is to aid designers in improving the quality of a product, while fulfilling the customer requirements by enabling them to choose optimal manufacturing and end-of-life strategies during the design stage.

This chapter describes the process and the development of the prototype system that applies the proposed artificial intelligence tool known as Eco-CBR. This tool facilitates a problem solving approach that relies on similar past cases to find solutions to specific problems of sustainable product design. The solution to the previous problem is then reused either completely for the new problem or as an initiating point for a new solution. This approach is presented as an important contribution to the practise of sustainable product design. Through this approach, it is possible to evaluate design decisions made at an early stage of a product life cycle based on the previous experience.

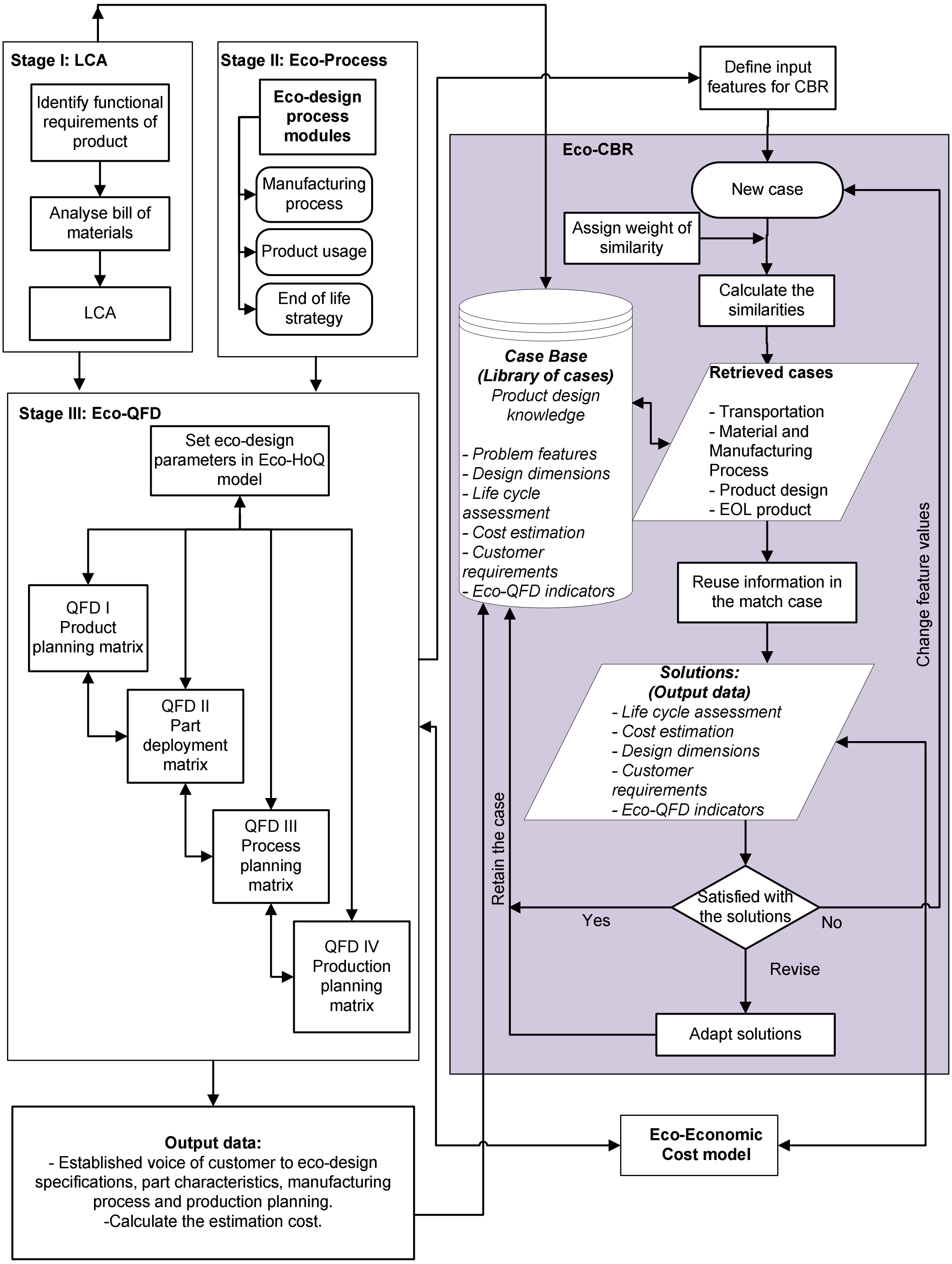


Figure 5.1: The Eco-CBR tool in the IEDM framework for sustainable product design

5.2 The Process of Eco-CBR model

The processes to produce Eco-CBR tool can be seen as a reflection of a particular type of human reasoning. In many situations, the problems that humans encounter are solved with a human equivalent of case-based reasoning. When a person encounters a new situation or problem, he or she will often refer to the past experience of a similar problem to find a solution. In a similar approach, Eco-CBR tool involves basic reasoning from previous experiences by retaining solutions of previous problems.

The Eco-CBR tool integrates CBR with eco-design factors, resulting in new product design process. Figure 5.2 shows the proposed processes of development of the Eco-CBR model. The platform of the Eco-CBR tool is the cases stored in the Eco-CBR library that are directly applied for product design knowledge. This library was initially developed to store the information related to the solutions of previous problems that have been assessed in the Stage I (LCA) and Stage III (Eco-QFD) as shown in Figure 5.1. The output data from Stage I for each case is kept in the Eco-CBR library. These outputs are stored in relation to the design dimensions of the product, manufacturer origin, destination use, types of transport, distance, types of material, manufacturing process, weight of product, recycle content of material, carbon footprint, energy consumption, air acidification, water eutrophication and end-of-life (EOL) product strategies (recycled, incinerated and landfill). The output data from Stage III (Eco-QFD) are also kept in the same Eco-CBR library. The outputs are stored with respect to requirements from the customers, production volume, material cost, purchasing cost, manufacturing cost, transportation cost, environmental cost, EOL cost and economic cost. During the development phase of Eco-CBR tool, it was necessary that the library to be populated prior to considering the design of a new case.

The cycle shown in Figure 5.2 starts with an initial description of a problem, which defines a new case without solutions. The features for a new case are divided into four groups, namely transportation, material and manufacturing process, EOL and design dimensions. The details of the groups are as follow, i) transportation group: origin, destination, types of transport and distance; ii) material and manufacturing process: materials, weight, manufacturing process, recycle content, volume and material cost; iii) EOL product: recycle, incineration and landfill; and iv) design dimensions: classified into product specifications.

The Eco-CBR retrieval process is structured to assess the similarity rate of the new case features and existing cases in the Eco-CBR library. The input features of a case are those that are provided as part of its description and are typically represented using attribute-value pairs. In other applications of Eco-CBR, it is necessary to use derived features obtained from a case's description in the domain knowledge of the case-based library. Usually the retrieved cases are those with the highest similarity to the target problem. There are many ways of measuring similarity and different approaches are appropriate for different case representations. In this study, a local similarity measure is usually defined for each attribute and a global similarity measure is computed as a weighted average of the local similarities. The weights assigned to case attributes allow them to have varying degrees of importance and may be selected by a domain expert or user. The Eco-CBR tool retrieves the cases that are maximally similar to the new case by computing the similarity of the new case to every case in the case-based library.

These features are used to retrieve cases from the case-based library. During the process of retrieving cases, the weight for each feature has to be assigned. In this study, the weighting has values from 1 (less important attribute) to 5 (very importance attribute). The weight of each feature is not fixed, hence allowing the decision maker to assign their importance according to the characterisation of the studied product. Therefore, this criterion enables the searching process to be more efficient and adaptable to the requirements of the user.

During the search of similar cases, the weight of each feature is calculated using a local similarity technique. There are two types of local similarity techniques, namely:

i. Non numerical local similarity

ii. Numerical local similarity

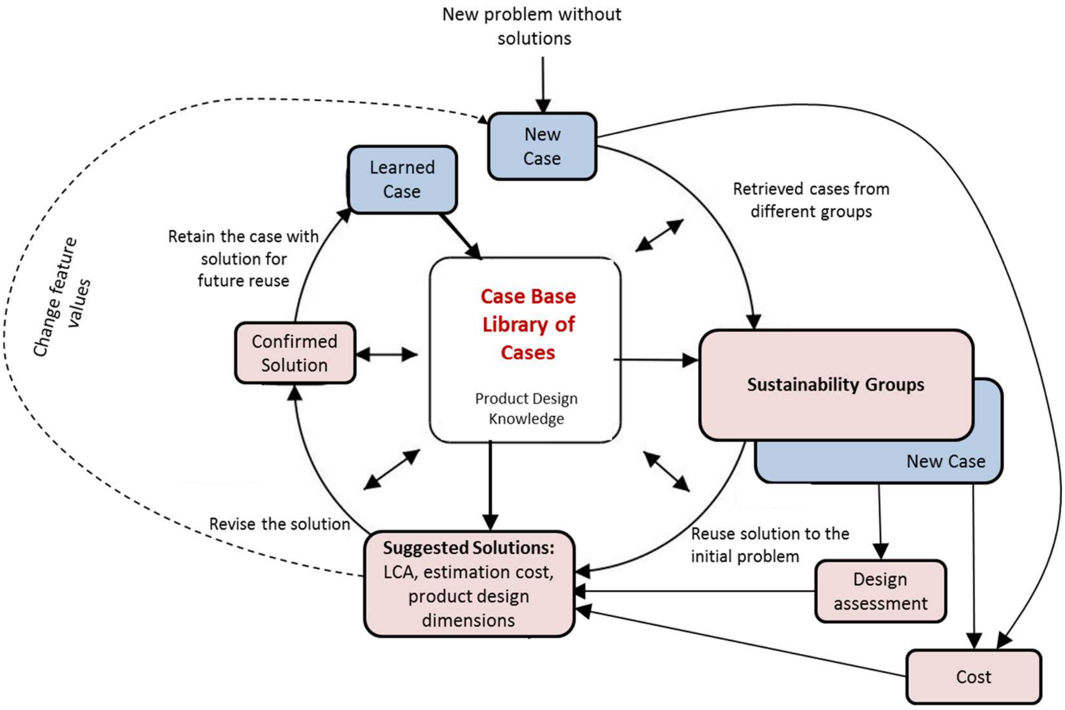


Figure 5.2: The process of Eco-CBR model

Equation (5.1) is used for features that contain non-numerical values, while equation (5.2) is used for numerical features. Equation (5.2) is used for the normalisation of the numerical features. Thereafter, a global similarity technique is used for the calculation of the total local similarities per group by using equation (5.3).

Non-numerical local similarity:

$$\text{IF NC} == \text{Lib}_\text{k} \quad \rightarrow \text{Local Similarity (LS)} = 1 \qquad (5.1)$$

$$\text{Else} \quad \rightarrow \text{Local Similarity (LS)} = 0$$

Numerical local similarity:

$$\text{s} = \frac{\min(\text{NC,Lib}_\text{k})}{\max(\text{NC,Lib}_\text{k})} \qquad (5.2)$$

If (NC == 0 & Lib_k == 0) then Local Similarity (LS) = 1

Where Lib_k is the k-case from the Eco-CBR library and NC is a new case. Equations 5.1 and 5.2 will be at feature level.

Global similarity (GS):

$$\mathrm{GS_i} = \frac{\sum_j \mathrm{w_{ij}} * \mathrm{LS_{jk}}}{\sum_j \mathrm{w_{ij}}} \quad \forall i \tag{5.3}$$

where i is a group of feature, j is a set of input features, LS is the local similarity for each feature and w_{ij} is a set of weights per group.

The global similarity function is used to find similarities between the new case and the existing cases in the Eco-CBR library, as shown in Figure 5.2. The existing cases with the highest similarities compared to the new case are then retrieved.

The existing cases that retrieved from the similarity process will provide solutions detailing the LCA, estimations of cost and product design dimensions. In order to reuse the information in the Eco-CBR library, the solution is first analysed based on the environmental impact to the product lifecycle of material, manufacturing process, transportation, product use and EOL. The environmental impact consists of carbon footprint, energy consumption, air acidification and water eutrophication. From the collective data in the Eco-CBR library, a process of translation from quantitative to qualitative data is performed. These data are measured based on one of the five rankings: 'very high' (5), 'high' (4), 'medium' (3), 'low' (2) and 'very low' (1). With this conversion, the interpretation of the LCA data by the designer is much clearer.

Next, the cost estimation of the solution is analysed. A range of economic cost will be presented, based on calculation of minimum and maximum cost for the new case (NC) and retrieved case (RC) from the Eco-CBR library, as shown in equation (5.4).

$$\text{Economic cost range} = [\min(NC, RC), \max(NC, RC)] \tag{5.4}$$

The differences between the limits of the range will be applied to evaluate whether the estimation of the costs is close to the actual costs. Multiple values for the cost estimation were collected from the different suppliers. The single value for each cost is obtained from the average of multiple values. Six categories of costs have been considered as follows:

i. Purchasing cost

ii. Manufacturing cost
iii. Transportation cost
iv. Environmental cost
v. End-of-life cost
vi. Economic cost

In real-life application, this process could be better underpinned by real data that will be available to a company, but could not be accessed at this stage.

In term of product dimensions as part of the solution, the design will be assessed by using the most similar case. The first task is to study and select the dimensions that are critical to the performance of the product. The collected data is then used to look for a most similar case. If the similarity is high enough, the design can be considered sustainable. However, if it is not suitable, then a list will be created that contains the sequence of dimensions from worst to best, which the designer will adapt to the new case. The solutions also relate to the critical information from the Eco-QFD phases, which are customer requirements, environmental impact and product design indicators, as shown in Figure 5.1.

At this stage, the designers have two options. If they are not satisfied with the solutions, they can modify the feature values and run the process again in order to improve the product. Otherwise, if they are satisfied with the solutions, the case will be retained, and the Eco-CBR library to be updated by storing a new learned case. Consequently, this process will increase the cases in the library that can be accessed in future, subsequently re-using solutions for the next new case. A detailed explanation regarding the proposed solutions will be discussed in the next section, which considers the development of the Eco-CBR tool.

5.3 The Development of Eco-CBR tool

This section introduces the Eco-CBR tool, which integrates CBR with eco-design factors into the new product design process. Figure 5.1 and Figure 5.2 show the processes related to the application of Eco-CBR tool. Herein, these processes have been implemented during the development phase of the Eco-CBR tool according to design flow shown in Figure 5.3.

Figure 5.3 represents the schematic of the Eco-CBR processes by showing stages and elements, labelled as ‘A’ to ‘H’. It starts with label ‘A’ that represents the entry of new case features, where a designer has to give a value for each feature. The new case acts as a problem, while the tool will find a suitable solution for this problem. Label ‘B’ represents the allocation of the weighing factor that has to be assigned for each feature. These weighs are used as an input to search the similarities between existing cases and the requirements of the new case from the Eco-CBR library. The retrieved cases will be shown at this stage as designated by Label ‘C’. After retrieving the cases, the solutions will be automatically shown with features assigned to the Labels ‘D’, ‘E’, ‘F’, ‘G’, and ‘H’.

In this study, a prototype system of an Eco-CBR tool has been developed in Microsoft Excel as shown in Figure 5.4. The Microsoft Excel sheet represents a template for the tool used in the investigation of sustainability product design problems. The processing of the information contained in the template is illustrated by using the same labels from ‘A’ to ‘H’, as shown in Figure 5.3. These labels exhibit the areas of the processes involved in this tool. This template is shown as a blank sheet that has to be filled by the designer to generate the solutions. The labels ‘A’ to ‘H’ shown in Figure 5.3 are in reference to the areas shown in Figure 5.4. In the following discussions, the contents of each area are considered without providing the inherent details. This discussion will be part of the case study.

5.3.1 New Case - Area A

This process starts with the problem that is defined as a new case according to the process flow in Figure 5.3, and areas with label ‘A’ in Figures 5.4 and 5.5. A designer will provide the input for each feature of the new product design, where the features are selected from the important parameters of the Eco-QFD process. The features for a new case are divided into four categories, namely transportation, material and manufacturing process, EOL and design dimensions. The details of the categories are as follow, i) transportation group: origin, destination, types of transport and distance; ii) material and manufacturing process: materials, weight, manufacturing process, recycle content, volume and material cost; iii) EOL product: recycle, incineration and landfill; and iv) design dimensions: classified into product specifications. The process of adding these inputs will be demonstrated in the case study as part of Chapter VI.

5.3.2 Weighting Factors – Area B

Area ‘B’ in Figure 5.4 and Figure 5.5 represents the weighting factors, which have to be assigned for the features in each group. Label ‘T’ in area ‘B’ represents the weighting factors for the transportation group, ‘M’ represents the material and manufacturing process group, ‘EOL’ represents the end-of-life group and ‘D’ represents the design group. These weights are used for the calculation of similarities between the new case and the existing cases in the library.

Usually, weights vary according to the product, and this immensely effects the similarity computation result. The searching process for similarity cases will be explained in the section 5.3.3. The information from the retrieved cases will be reused in the solutions entry of the new case.

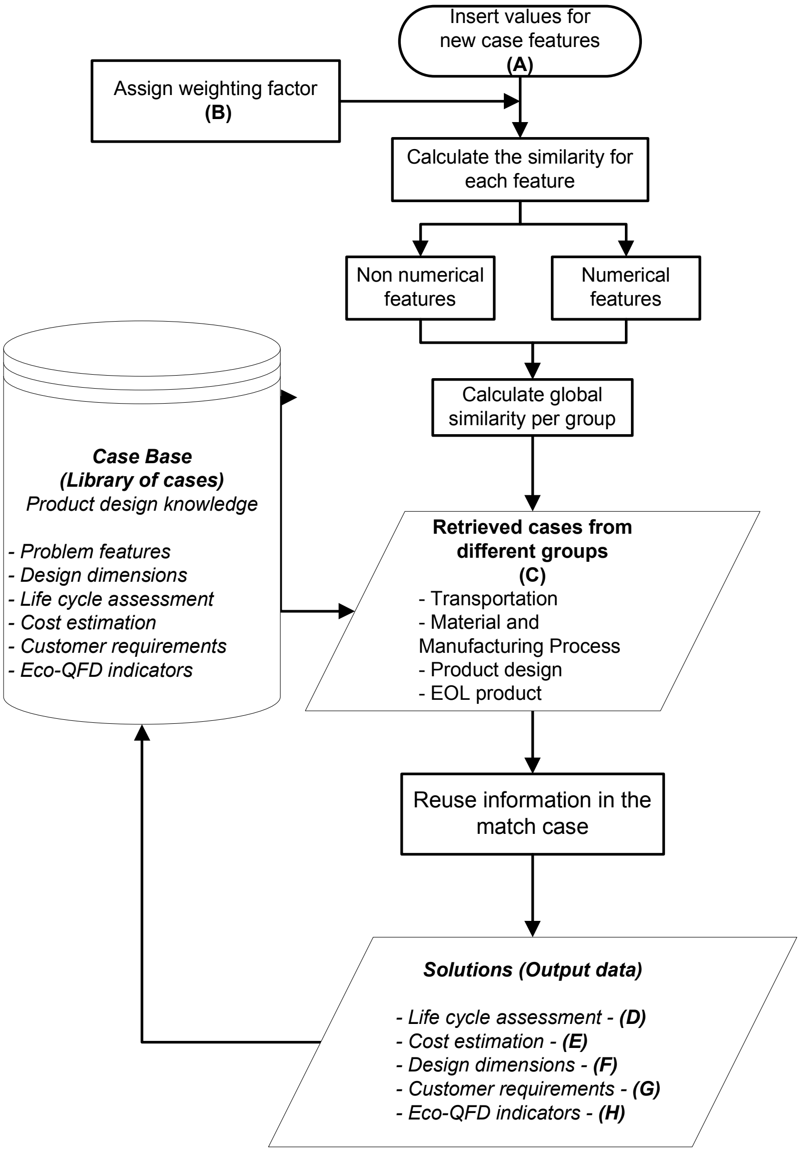


Figure 5.3: The schematic process of Eco-CBR tool

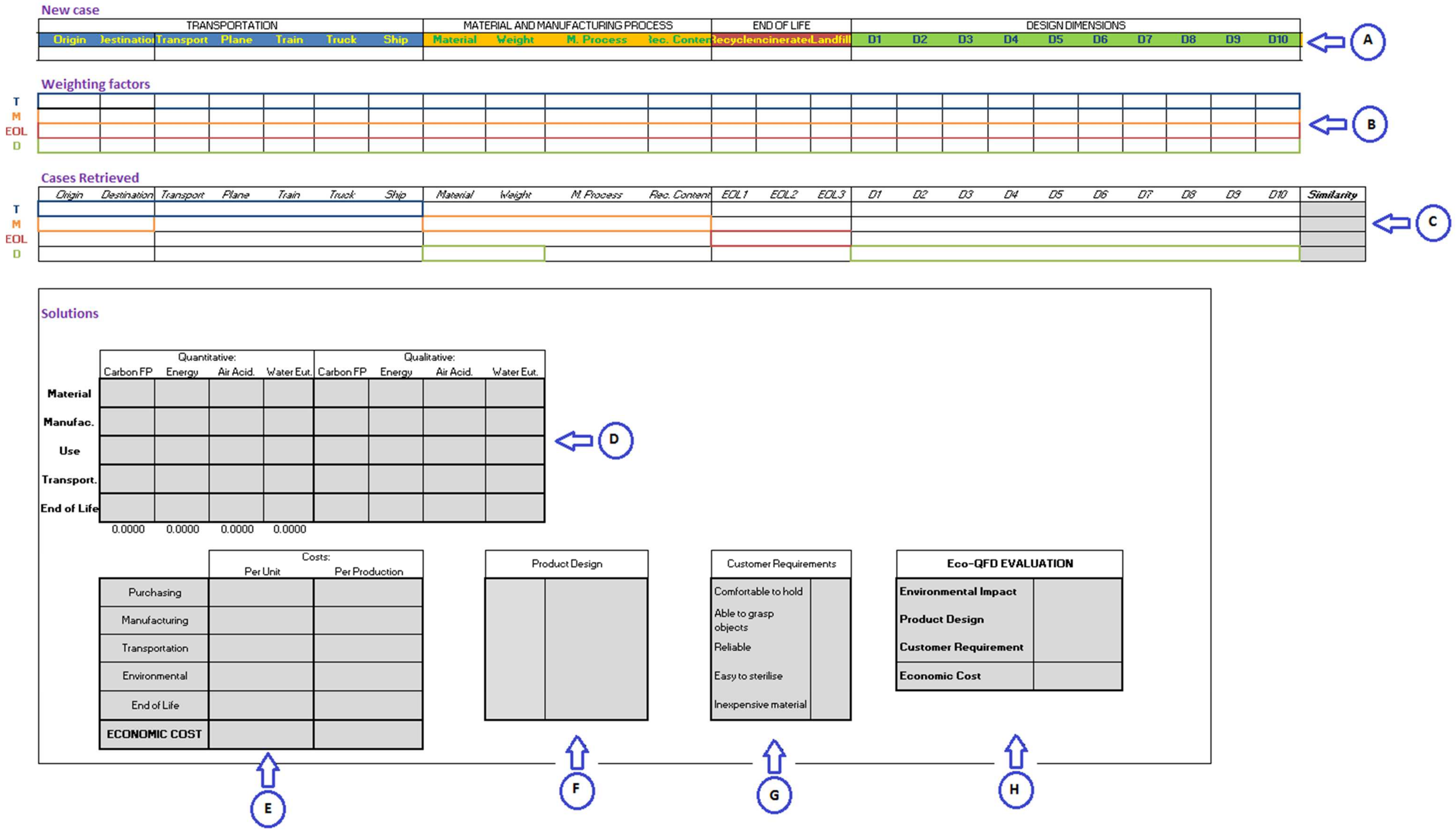
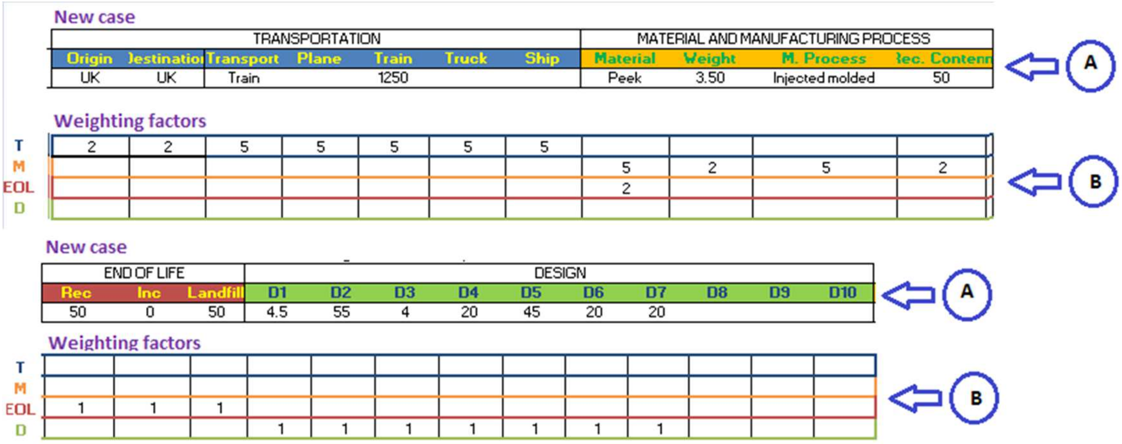


Figure 5.4: Eco-CBR tool interface screenshot


New case

TRANSPORTATION							MATERIAL AND MANUFACTURING PROCESS			
Origin	estinatio	Transport	Plane	Train	Truck	Ship	Material	Weight	M. Process	ec. Conten
UK	UK	Train		1250			Peek	3.50	Injected molded	50

Weighting factors

T	2	2	5	5	5	5	5				
M								5	2	5	2
EOL								2			
D											

New case

END OF LIFE			DESIGN									
Rec	Inc	Landfill	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
50	0	50	4.5	55	4	20	45	20	20			

Weighting factors

T													
M													
EOL	1	1	1										
D				1	1	1	1	1	1	1			

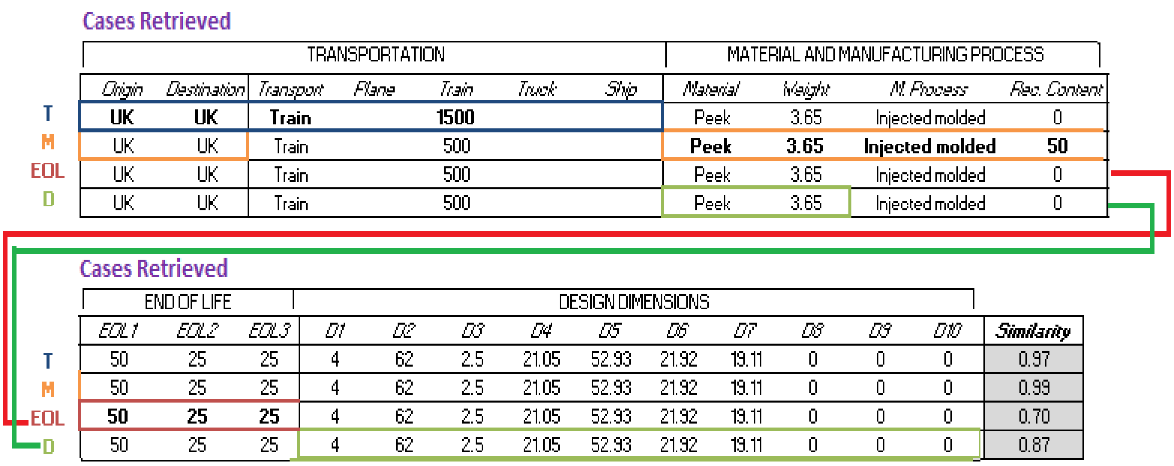
Figure 5.5: Screenshot of the areas labelled as ‘A’ and ‘B’

5.3.3 Searching Similarities Process - Area C

Area ‘C’ represents the retrieved cases from the process of searching for similarities. Figure 5.6 shows that the retrieval of cases are based on the highest similarity rate found in the searching process. The group of existing cases for transportation (T), material and manufacturing process (M), end-of-life (EOL) and design (D) are retrieved from the Eco-CBR library. Three of these groups are generic and are reused from the IEDM methodology. The exception is design dimensions. The features for the design dimensions group must always be specific to the product being designed, as illustrated by the case study.

For a new product design, the dimension based process should begin from the Stage I (LCA). It will continue in Stage II (Eco-Process parameters), and Stage III (Eco-QFD). The result from Stage III will be captured and be stored in the Eco-CBR library. The Eco-CBR method enables the design process and maintains an organised case-based library. Obviously dimension-related information can only be shared between similar products or components. It aids in solving product design problems by finding similarities with previous cases held in the case-based library. The experiences from these similar cases will be used to generate and assess design solutions. In this manner, a company can add and access information that relates specifically to their product range. During the searching process, the similarity techniques are performed based on calculations that used the equations (5.1), (5.2) and (5.3), as discussed in the section 5.2.

Depending upon the nature of the task, the non-numerical local similarity feature and numerical local similarity feature are calculated via equations (5.1) and (5.2), respectively. All the local similarity comparisons will be in the range of [0,1]. This helps in the setting of the weight. The global similarities for the groups are calculated using equation (5.3). As Figure 5.6 illustrates, the existing cases with the highest global similarity rating compared to the new case will be retrieved.



Cases Retrieved

	TRANSPORTATION							MATERIAL AND MANUFACTURING PROCESS			
	Origin	*Destination*	*Transport*	*Plane*	*Train*	*Truck*	*Ship*	*Material*	*Weight*	*M. Process*	*Rec. Content*
T	**UK**	**UK**	**Train**		**1500**			Peek	3.65	Injected molded	0
M	UK	UK	Train		500			**Peek**	**3.65**	**Injected molded**	**50**
EOL	UK	UK	Train		500			Peek	3.65	Injected molded	0
D	UK	UK	Train		500			Peek	3.65	Injected molded	0

Cases Retrieved

	END OF LIFE			DESIGN DIMENSIONS										
	EOL1	*EOL2*	*EOL3*	*D1*	*D2*	*D3*	*D4*	*D5*	*D6*	*D7*	*D8*	*D9*	*D10*	***Similarity***
T	50	25	25	4	62	2.5	21.05	52.93	21.92	19.11	0	0	0	0.97
M	50	25	25	4	62	2.5	21.05	52.93	21.92	19.11	0	0	0	0.99
EOL	**50**	**25**	**25**	4	62	2.5	21.05	52.93	21.92	19.11	0	0	0	0.70
D	50	25	25	4	62	2.5	21.05	52.93	21.92	19.11	0	0	0	0.87

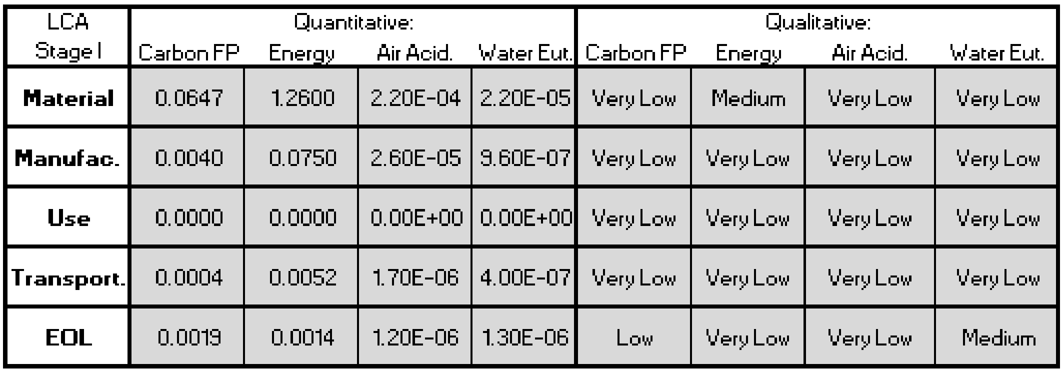
Figure 5.6: Screenshot of the retrieved cases (Area C)

The information from these retrieved cases will be reused in the solutions entry for the new case, within the solutions area that contains elements labelled ‘D’, ‘E’, ‘F’, ‘G’ and ‘H’. These solutions are retrieved from the Eco-CBR library by using the following methods.

5.3.4 Environmental Impact – Area D

The solution features for the LCA group, as represented by the area assigned with label ‘D’ are carbon footprint (Carbon FP), total energy consumed (Energy), air acidification (Air Acid) and water eutrophication (Water Eut). The LCA data is retrieved from the Stage

I (LCA) within IEDM framework. These features are used for the finding of the quantitative measurement for the environmental impact of the product lifecycle (material, manufacturing, use, transport and EOL). These data are set to one of the five rankings: 'very high (VH)', 'high (H)', 'medium (M)', 'low (L)' and 'very low (VL)'. With this conversion, the interpretation of the LCA data by the designer will be well supported. Figure 5.7 displays an example of the retrieved solution from the Eco-CBR library.

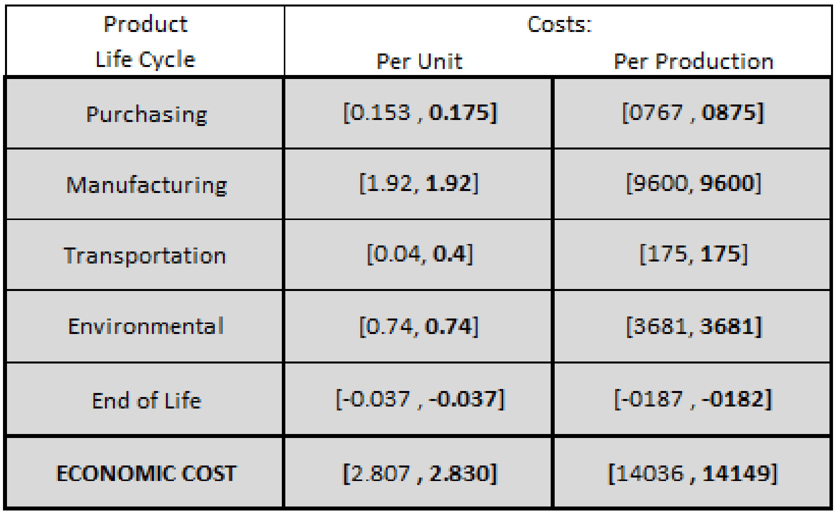


LCA	Quantitative:				Qualitative:			
Stage I	Carbon FP	Energy	Air Acid.	Water Eut.	Carbon FP	Energy	Air Acid.	Water Eut.
Material	0.0647	1.2600	2.20E-04	2.20E-05	Very Low	Medium	Very Low	Very Low
Manufac.	0.0040	0.0750	2.60E-05	9.60E-07	Very Low	Very Low	Very Low	Very Low
Use	0.0000	0.0000	0.00E+00	0.00E+00	Very Low	Very Low	Very Low	Very Low
Transport.	0.0004	0.0052	1.70E-06	4.00E-07	Very Low	Very Low	Very Low	Very Low
EOL	0.0019	0.0014	1.20E-06	1.30E-06	Low	Very Low	Very Low	Medium

Figure 5.7: Screenshot of the solution life cycle assessment (Area D)

5.3.5 Cost Estimation - Area E

As shown in Figure 5.8, Label ‘E’ represents the area that provides the solution group for cost estimation of the life cycle cost. The ecological economic cost (Eco-Economic Cost) model shown in Figure 3.1 in Chapter III is an approach used to summarise the development enabled by Eco-QFD and Eco-CBR in IEDM framework. The Eco-Economic Cost is a stand-alone model that is used to calculate the costs of manufacturing, environmental, transportation, product use and EOL of the product. It integrates the environmental and product costs considerations into each Eco-QFD phases of the single Eco-HoQ. Thus, these costs will be stored in the Eco-CBR library for the use of the Eco-CBR.



Product Life Cycle	Costs: Per Unit	Per Production
Purchasing	[0.153 , **0.175]**	[0767 , **0875]**
Manufacturing	[1.92, **1.92**]	[9600, **9600**]
Transportation	[0.04, **0.4**]	[175, **175**]
Environmental	[0.74, **0.74**]	[3681, **3681]**
End of Life	[-0.037 , **-0.037**]	[-0187 , **-0182]**
ECONOMIC COST	[2.807 , **2.830**]	[14036 , **14149**]

Figure 5.8: Screenshot of the solution for cost estimation (Area E)

The life cycle cost consists of the following features, purchasing cost (Pc), manufacturing cost (Mc), transportation cost (Tc), environmental cost (Ec), end-of-Life cost (EOLc) and economic cost (ECOc). This life cycle cost is assessed by using the equations (3.3), (3.5), (3.6), (3.7) and (3.8), as discussed in section 3.5. These equations will be demonstrated again in the case study within Chapter VI.

Figure 5.8 presents a screenshot example of the solution for cost estimation that had been retrieved from the Eco-CBR library. There are two types of costs, namely cost per unit and cost per production. The cost per production is the product function of the cost per unit and the production volume. In Figure 5.8, the costs printed in bold format refer to the estimated costs of the new cases and the costs printed in non-bold format are the retrieved cases. The economic cost is presented as a range, calculated as minimum and maximum costs for the new case.

5.3.6 Design Dimension Assessment – Area F

Label ‘F’ in Figure 5.4, indicates the area containing a suggested solution for the group of design dimension assessment. This solution is used to analyse the new design dimensions. The process of analysing design dimensions is shown in Figure 5.9.

First, the designer will be aware on the use of the minimum targeted similarity. The minimum similarity factor is used as a benchmark to compare with the global similarity factor of the design group to validate the new case. Normally, the minimum target similarity is set to 0.8 that close to the maximum target similarity which is 1.0, where the minimum similarity factor is set in a range of [0, 1]. ‘0’ represents the worst and ‘1’ represents the best. Through comparison of the existing and tested models in the Eco-CBR library, the new case is suggested as valid if it reaches a pre-established global similarity limit for the design group. However, there is still an alternative approach for the designer, which is saving this new design dimension, even if the global similarity rating is less than the minimum similarity rating.

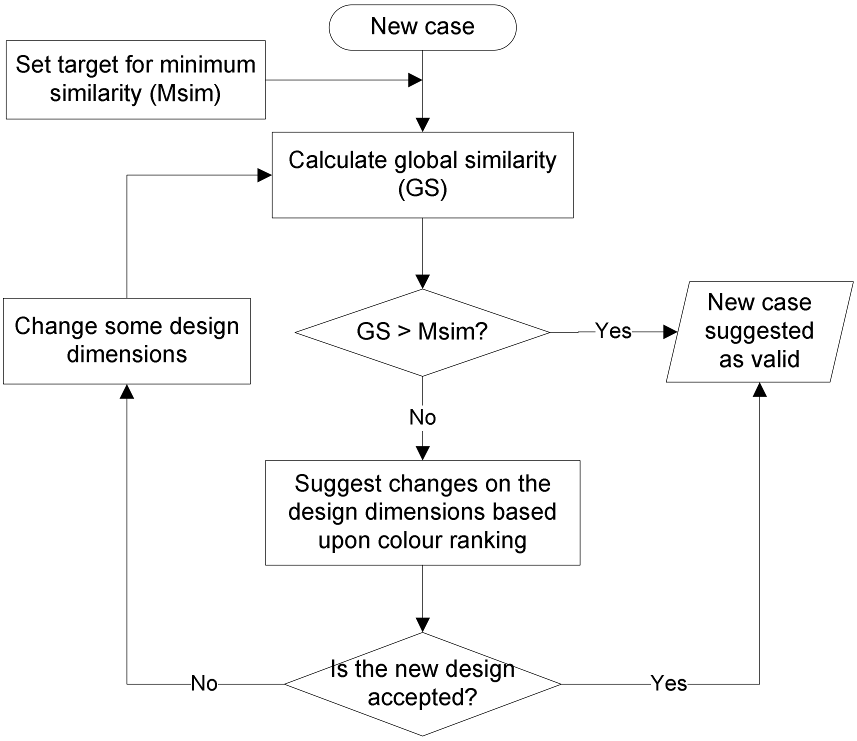
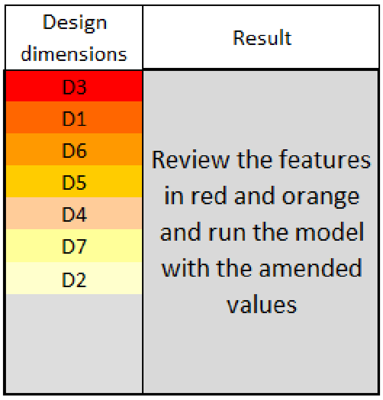


Figure 5.9: Flowchart of the design assessment

In the case of not being similar to the minimum similarity factor, the tool will show a colour scale referring to the dimensions, which suggests the need for change, as shown in Figure 5.10. The design dimensions are sorted according to the local similarity that has been calculated for each dimension. Figure 5.10 show that there are seven criteria of design dimensions (D1 - D7) that have to be analysed.



Design dimensions	Result
D3	Review the features in red and orange and run the model with the amended values
D1	
D6	
D5	
D4	
D7	
D2	

Figure 5.10: Screenshot for the solution design dimensions (Area F)

In this case, the red colour (D3) and the orange colour (D1) exhibit low local similarities compared to other dimensions. These colours show that the values for D3 and D1 should be amended; hence a new iteration of the design assessment will be calculated. Examples of the iteration process are illustrated as follows:

i. 1st iteration, GS = 0.7 and Msim = 0.9 (GS < Msim)

Result – Review the features in red and orange colours.

Action by the user:

a. Modify critical dimensions to increase the similarity or

b. Accept the new case design dimensions without any modification of values.

If the designer chooses action (a), the new design assessment will be processed as follow:

ii. 2nd iteration, GS = 0.92 and Msim = 0.9 (GS > Msim)

Result – Design dimensions are accepted as valid.

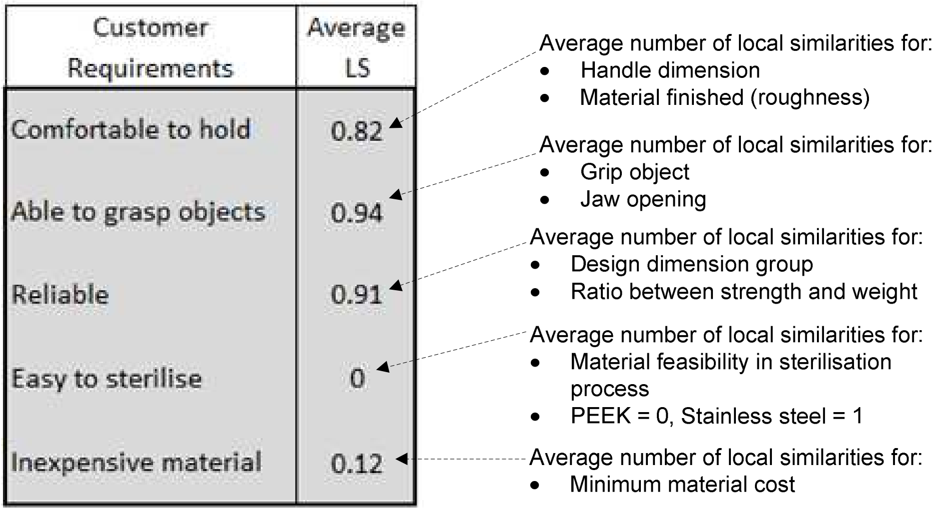
5.3.7 Customer Requirements – Area G

Area ‘G’ presents an assessment of the solution measured against customer requirements. Generally, these requirements are taken from the Eco-QFD in Phase I. Table 5.1 shows the application of this approach for the list of customer requirements and the rules used to measure the medical forceps taken from the case study in Chapter IV.

The criteria for each requirement are developed based on the characteristics of the product design in the Eco-CBR library. These criteria will be measured by calculating the average of local similarity for each requirement. The local similarity functions (discussed in section 5.2) will be considered in a range of [0, 1]. Here ‘0’ represents the worst criteria and ‘1’ represents the best criteria for product design to fulfil the requirements from the customer. Figure 5.11 displays the screenshot example of customer requirements with the average local similarity (LS) of product design.

Table 5.1: Input data of customer requirements

Customer Requirements (Eco-QFD Phase I)	**Criteria (Evaluation based on the cases in the Eco-CBR library)**
Comfortable to hold	• Find the similarities of handle dimensions (diameter for inside and outside) for medical forceps with a range of compound for all cases in the Eco-CBR library. • Find the similarity of finished (roughness) with same material cases in the Eco-CBR library.
Able to grasp objects	• Assign value for forceps if it can grip object (Yes = 1 , No = 0) • Find the similarity of jaw opening with all cases in Eco-CBR library.
Reliable	• Find similarity of design dimension group. • Find similarity in ratio Strength/Weight with all cases in the Eco-CBR library.
Easy to sterilise	• Pre-established material feasibility in sterilisation process, assign Peek = 0 and Stainless Steel = 1
Inexpensive material	• Find similarity with minimum Material Cost with all cases in the Eco-CBR library.



Customer Requirements	Average LS
Comfortable to hold	0.82
Able to grasp objects	0.94
Reliable	0.91
Easy to sterilise	0
Inexpensive material	0.12

Average number of local similarities for:
- Handle dimension
- Material finished (roughness)

Average number of local similarities for:
- Grip object
- Jaw opening

Average number of local similarities for:
- Design dimension group
- Ratio between strength and weight

Average number of local similarities for:
- Material feasibility in sterilisation process
- PEEK = 0, Stainless steel = 1

Average number of local similarities for:
- Minimum material cost

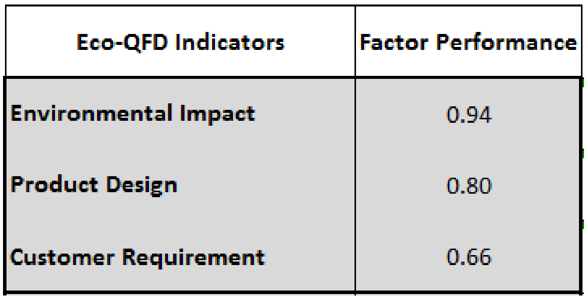
Figure 5.11: Screenshot for the solution customer requirements assessment (Area G)

After the assessment, the solutions have indicated that the three highest criteria values on customer requirements were ‘able to grasp object’ (0.94), ‘reliable’ (0.90) and ‘comfortable to hold’ (0.82). Detailed explanation regarding this calculation will be presented in Chapter VI for the Eco-CBR case study.

5.3.8 Eco-QFD Indicators – Area H

Area ‘H’, as shown in Figure 5.4, represents the summary indicators for an Eco-QFD evaluation for the three important factors in sustainable product design. The indicators comprise of environmental impact, product design and customer requirements.

These indicators exhibit the performance factor in a range of [0, 1], where ‘1’ is the best according to the data in the Eco-CBR library and ‘0’ is the worst. Referring to the IEDM framework, data for environmental impacts and product design dimensions for individual products are retrieved from Stage I (LCA). These data are then integrated into Stage III (Eco-QFD) process to corroborate with customer requirements, and subsequently stored into the Eco-CBR library. In order to calculate the performance factor for a new case, these indicators have to use normalised weights from the Eco-QFD to the Eco-CBR tool. The insights of the transformation indicators from Eco-QFD to the Eco-CBR tools will be discussed in the next section. Figure 5.12 illustrates the screenshot of the Eco-QFD solution indicators associated with this section.



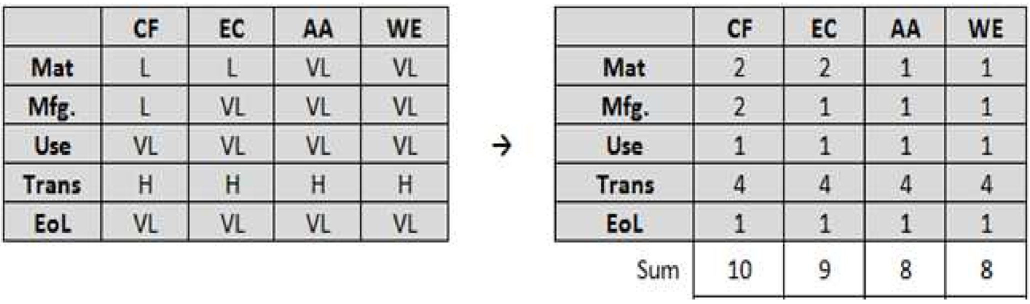
Eco-QFD Indicators	Factor Performance
Environmental Impact	0.94
Product Design	0.80
Customer Requirement	0.66

Figure 5.12: Screenshot of the Eco-QFD solution indicators (Area H)

5.3.8.1 Environmental Impact Indicator– Area H

In this study, there are various units of measurement in the inputs of the environmental impact indicator such as carbon footprint (kg CO_2), total energy consumed (MJ), air acidification (kg SO_2), and water eutrophication (kg PO_4). In order to solve this problem, the qualitative to quantitative conversion approach has been used by assigning score per value: very low (VL) - 1, low (L) - 2, medium (M) - 3, high (H) - 4 and very high (VH) - 5. Once the numerical conversion is done, the total score per environmental feature is calculated with the addition of all values, as shown in Table 5.2.

Table 5.2: Conversion environmental impact indicators



	CF	EC	AA	WE
Mat	L	L	VL	VL
Mfg.	L	VL	VL	VL
Use	VL	VL	VL	VL
Trans	H	H	H	H
EoL	VL	VL	VL	VL

→

	CF	EC	AA	WE
Mat	2	2	1	1
Mfg.	2	1	1	1
Use	1	1	1	1
Trans	4	4	4	4
EoL	1	1	1	1
Sum	10	9	8	8

Equation (5.5) is used to summarise these impacts into a single indicator via the weights that are retrieved from the Eco-QFD Phase I, as discussed in Section 4.4.1.

$$EI\ Ind(no\ norm) = \frac{\sum S_i * w_i}{\sum w_i} \tag{5.5}$$

where $EI\ Ind(no\ norm)$ is an environmental impact indicator of the total score S_i of the i^{th} environmental impact feature and w is the weight retrieved from the Eco-QFD.

Next, the $EI\ Ind(no\ norm)$ has to be normalised into the range of [0, 1]. In order to achieve this, a transformation function will be used. The value range for the non-normalised indicator is [5, 25], in which '25' represents the maximum number from 'worst possible value indicator' = [All Very High (5x5)] and '5' represents the minimum number from 'best possible value indicator' = [All Very Low (1x5)]. These values are then translated using the equation (5.6), where the line between two coordinates are (x1, y1 = 5, 1) and (x2, y2 = 25, 0). These coordinates are then calculated using equation (5.6).

$$\frac{x-x1}{x2-x1}=\frac{y-y1}{y2-y1} \tag{5.6}$$

$$\frac{x-5}{25-5}=\frac{y-1}{0-1}$$

The result of equation (5.6) is as follow:

$$y=1-\frac{x-5}{20} \quad = \quad EI\ Ind\ (Norm)=1-\frac{EI\ Ind\ (No\ norm)-5}{20} \tag{5.7}$$

Equation (5.7) is used to produce the attribute y, which represents the environmental impact indicator for normalisation and x is the environmental impact that has not been normalised. This result is an indicator that is weighted in a range of [0, 1], which gathers the important weight revealed in Eco-QFD phase I, hence allowing the comparison of results with other Eco-QFD indicators.

5.3.8.2 Product Design Indicator – Area H

Figure 5.13 displays the integration process between Eco-QFD and Eco-CBR tools for the product design indicator. The design dimensions are very critical to fulfil customer requirements. In the Eco-CBR library, there will be a range of possible solutions for the product design. A new case for product design is created by combining different variables and populating it into the Eco-CBR library. This product design indicator considers the main critical design dimensions and relative weights for a product from the process of Eco-QFD Phase I. The values of relational strength between design criteria and parts have been retrieved from the Eco-QFD Phase II. Thereafter, it will be integrated into the Eco-CBR process to analyse design indicator for a new case assigned in the Eco-CBR.

There will be a local similarity that is retrieved from the design group in the Eco-CBR process. The local similarity is calculated for each critical design dimension and will be used to weigh the values of relational strength. The following process would be the calculation of the raw score, where the sum of the modified relational strength will be multiplied by the weights (Eco-QFD phase I). The normalisation of each part is then calculated by dividing each raw score by its maximum possible score, which would be calculated by setting the feature similarity to 1. The raw score data is normalised in a range of [0, 1].

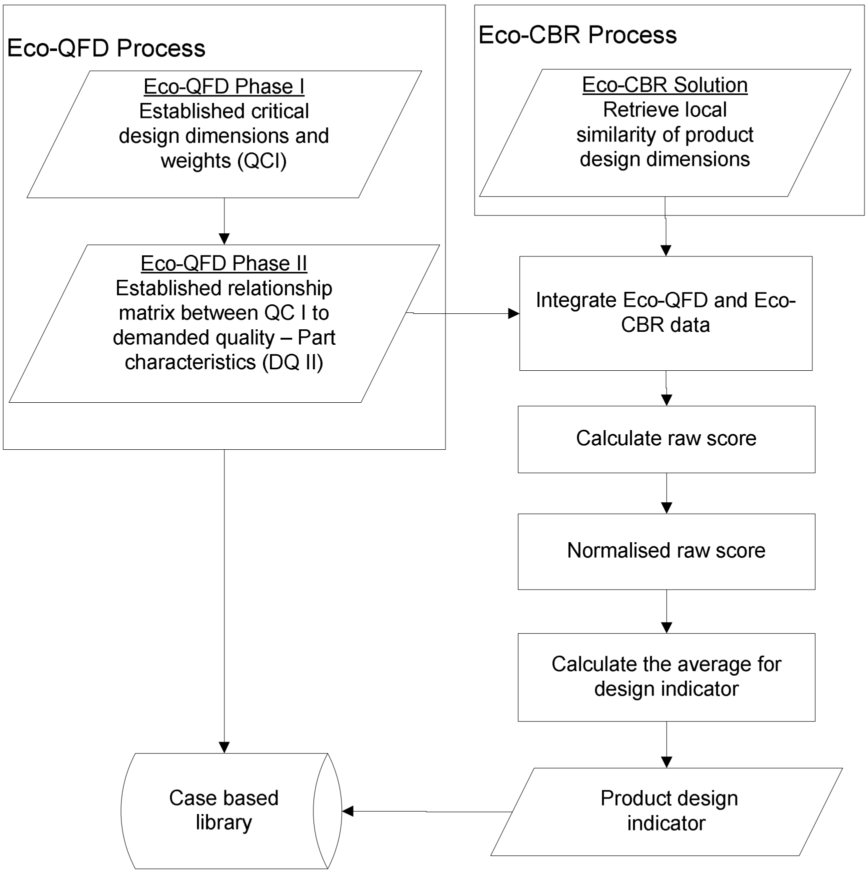


Figure 5.13: The integration process between Eco-QFD and Eco-CBR tool

Table 5.3 and 5.4 show the process of integration between the Eco-QFD and the Eco-CBR tool. In Table 5.3, local similarity is considered as '1' for each design criteria (max opening jaws, working length for shaft and thickness of the main shaft), and it is used to find the maximum score of each part (grip, moveable handle, top slider, fixed handle). The maximum score will be used as a reference to calculate the normalisation of the raw score. The weight for each design criteria is taken from Eco-QFD Phase I. The numbers of relational strength between design criteria and parts deployment are retrieved from the Eco-QFD Phase II.

The modifications of relational strength, raw score and normalisation have been calculated using equations (5.8), (5.9) and (5.10), respectively. The outcome of these equations is shown in Table 5.4.

$$MR_{ij} = R_{i,j} \cdot LS_i \quad \forall i,j \tag{5.8}$$

$$RS_j = \sum\nolimits_{j=1}^{n} p1w_i * MR_{i,j} \quad \forall i \tag{5.9}$$

$$NRS_j = \frac{RS_j}{RS\,Max_j} \quad \forall i \tag{5.10}$$

$$Design_{ind} = \frac{\sum_{j=i}^{n} NRS_j}{n} \tag{5.11}$$

where;

- $R_{i,j}$ is the relational strength of the i^{th} design criterion to j^{th} of parts deployment from Eco-QFD Phase II,
- LS_i is the local similarity of the i^{th} design criteria from Eco-CBR process,

MR_{ij} is the modified relational strength of the i^{th} design criteria to j^{th} of parts deployment,

- RS_j is the raw score of the j^{th} part deployment,
- $p1w_i$ is the weight of the Eco-QFD phase I for the i^{th} design criteria in the Eco-QFD Phase II,
- NRS_j is the normalised raw score of the j^{th} part deployment,
- $RSmax_j$ is the maximum raw score of the j^{th} part deployment and
- $Design_{ind}$ is the design indicator for average function of the total normalised score divided by the j^{th} part deployment.

Table 5.3: The integration of features selection between Eco-QFD and Eco-CBR process

Design Criteria's	**Eco-QFD Phase I (weight)**	**Parts Deployment**				**Eco-CBR Local Similarity (LS)**
		Grip	**Moveable Handle**	**Top Slider**	**Fixed Handle**	
Max opening jaws	4.3	9				1
Working length for shaft	3.8	5	9	9	5	1
Thickness of the main shaft	4.9		9	9		1
Maximum score (RSmax$_i$)		**57.7**	**78.3**	**78.3**	**19**	

Table 5.4: The average value for product design indicator

Design Criteria's	**Eco-QFD Phase I (weight)**	**Parts Deployment**				**Eco-CBR Local Similarity (LS)**
		Grip	**Moveable Handle**	**Top Slider**	**Fixed Handle**	
Max opening jaws	4.3	9				0.80
Working length for shaft	3.8	5	9	9	5	0.75
Thickness of the main shaft	4.9		9	9		0.90
Raw score (RS$_i$)		45.21	65.34	65.34	14.25	
Maximum score (RSMax$_i$)		57.70	78.30	78.30	19.00	
Normalised data (NRS$_i$)		0.78	0.83	0.83	0.75	
Design indicator		**0.80**				

Table 5.4 shows the next step in this process based on Table 5.3, which is used to calculate raw score and normalised data for parts deployment. The 'Eco-CBR local similarity' column shows the values that are recorded from the assessment in the design group. The values are recorded in conjunction with the critical design criteria from Eco-QFD Phase I and Phase II. The raw score and normalised data for parts deployment have been calculated. The design indicator summarises all normalised weight in one single indicator by using equation (5.11), as shown in Table 5.4. This result will help the designer to analyse the performance of the design integration with the evaluation made in Eco-QFD.

5.3.8.3 Customer Requirement Indicator – Area H

This indicator is particularly focuses on the customer requirements. It presents the relationship between features of customer requirements in Eco-QFD Phase I and input measurement in Eco-CBR's new case.

The process combines the data from customer solution, as shown in Table 5.1, with the weight assigned for each feature in the Eco-QFD process. Since the input data is in the range of [0, 1], thus no normalisation is needed. The indicator is calculated with the following expression:

$$CR\ Ind = \frac{\sum feat_i \cdot w_i}{\sum w_i} \tag{5.12}$$

where $CR\ Ind$ is the customer requirement indicator, $feat_i$ is the i^{th} feature data with [0,1] value from the new case for customer solution in Eco-CBR, and w_i is the weight for i^{th} features of customer requirements. This indicator summarises the performance of the new product from the perspective of end user.

5.4 Summary

The Eco-CBR tool has been designed to be easily and widely adoptable for sustainable product development. The retrieval concept applied in the Eco-CBR helps the designer to shorten the process of design by exploring similar cases in the Eco-CBR library.

This approach is intended to aid the industrial decision-makers to effectively propose solutions for new product design and feature requirements by reusing solutions from past experiences of similar cases. Information related to the solutions contains product details throughout its life cycle. These solutions also contain the cost estimations of the manufacturing, environmental, EOL and economic costs. Thereafter, these solutions will be summarised in the summary indicators for an Eco-QFD evaluation. The Eco-QFD indicators contain four important factors in sustainable product design, namely environmental impact, product design, customer requirements and economic cost.

This approach is demonstrated by continuing the development of the case study that considers the design of medical forceps. The case study will be further explained in Chapter VI.

CHAPTER VI

ECO-DESIGN CASE-BASED REASONING: CASE STUDY

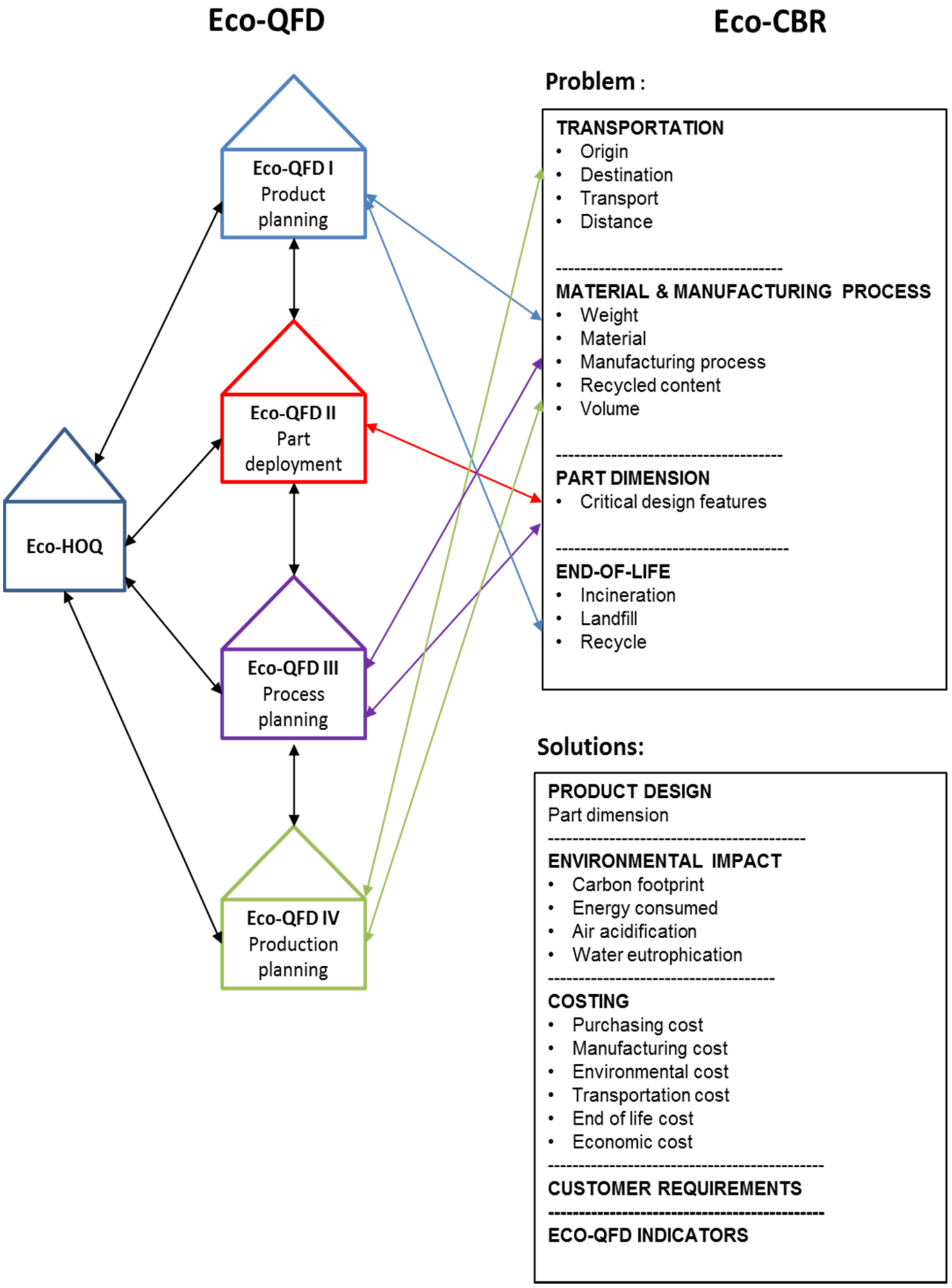
This chapter presents a case study to demonstrate the use of the eco-design case-based reasoning (Eco-CBR) method. An application of the proposed approach is presented in the context of product design and development for a revised single-use medical forceps. The entire product sustainability considerations are conducted within the Eco-CBR by further developing the case study in Chapter IV. The process is based on identifying and utilising information related to the similarities of the existing cases in the Eco-CBR library.

6.1 The Integration Process Eco-QFD and Eco-CBR

The aim of this study is to produce a new more sustainable product design by finding similarities with previous cases stored in the Eco-CBR library. This process using the experiences from the similar cases to generate the solution. The objective of developing the Eco-CBR tool is to support the processes of design, to add, and to maintain the library of cases in an organised approach. Figure 6.1 shows the relation between Eco-QFD and the Eco-CBR methods. The output from the Eco-QFD process is used to develop the knowledge required to generate the improved product design solution and to find the critical product features from the eco-design process. Figure 6.1 shows the relation between Eco-QFD and the Eco-CBR methods. The output from the Eco-QFD process is used to develop the knowledge required to generate the improved product design solution and to find the critical product features from the eco-design process.

Figure 6.1 illustrates the process adapted to link the Eco-HoQ model to the four Eco-QFD phases. The linking process is used to drive the important sub-evaluation criteria for ranking, and to establish critical design specifications and target values for the Eco-QFD process, as discussed in Chapter IV. In this case study, the important features in the Eco-QFD Phase I were weight, material, manufacturing process, recycled content, volume, incineration, landfill and recycle. From the Eco-QFD Phase II, the features adapted into Eco-CBR tool were critical design parts' dimensions. The features defined in Eco-QFD Phase III were material, manufacturing process, recycled content and critical design parts' dimensions. Finally, the features defined in Eco-QFD Phase IV were origin of manufacture, destination for product use, transportation, distance, volume, manufacturing process, material and recycled content. All of these important features are defined and used as features for the new case in the Eco-CBR process.

Figure 6.1: The relation between Eco-QFD and Eco-CBR features



The features of an existing case will be categorised into two sections, namely the problem and solutions as shown in Table 6.1 and Figure 6.1. The proposed solution will be using a process based on the calculation of similarity between the new case and the existing cases in the Eco-CBR library. Table 6.1 shows the recommendation and five categories of the solution features:

i. Life cycle assessment: Analyse the carbon footprint, air acidification, water eutrophication and energy consumed of the life cycle stages. This provides data indicating the overall environmental impact, with the goal being to reduce the environmental pollution during the product design stage.
ii. Cost: Life cycle cost for a product in terms of its purchasing cost, manufacturing cost, environmental cost, transportation cost, end-of-life (EOL) cost and economic cost.
iii. Product design: Assessment conducted based on the product dimensions.
iv. Customer requirements: Findings from the Eco-QFD Phase I and Phase II.
v. Eco-QFD indicators: The indicators unveil the environmental impact, product design and customer requirements.

6.2 Case Study: Medical forceps

The objective of this study is to demonstrate the use of the Eco-CBR tool in the creation and analysis of a new case for revised medical forceps. In response to the durability issue discussed in Section 4.6, it is identified that the handles of the current stainless steel forceps are solid. It is therefore assumed that the material reduction will be 10% without performance trade-off in the product. Figure 6.2 shows the revised design dimensions by reducing the length of the shaft and the thickness of the handles by 10%.

Table 6.1: Features of existing case

PROBLEM:

Transportation: Stage III (Eco-QFD)

Origin
Destination
Transport
Distance

Material and manufacturing process: Stage III (Eco-QFD)

Material
Weight
Manufacturing process
Material recycled content
Material cost
Production volume

EOL product: Stage III (Eco-QFD)

Recycled
Incinerated
Landfill

Design dimensions: Stage III (Eco-QFD)

Forceps design dimensions

SOLUTION:

Environmental Impact to product lifecycle: Stage I (LCA) & Stage III (Eco-QFD)

Carbon footprint
Total energy consumed
Water eutrophication
Air acidification

Life-cycle Cost: Stage III (Eco-QFD)

Purchasing cost
Manufacturing cost
Environmental cost
Transportation cost
EOL cost
Economic cost

Customer Requirements: Stage III (Eco-QFD)

Comfortable to hold
Able to grasp objects
Reliable
Easy to sterilize
Inexpensive material

Product Design Assessment: Stage III (Eco-QFD)

Eco-QFD indicators: Stage III (Eco-QFD)

Environmental impact
Product design
Customer requirements
Economic cost

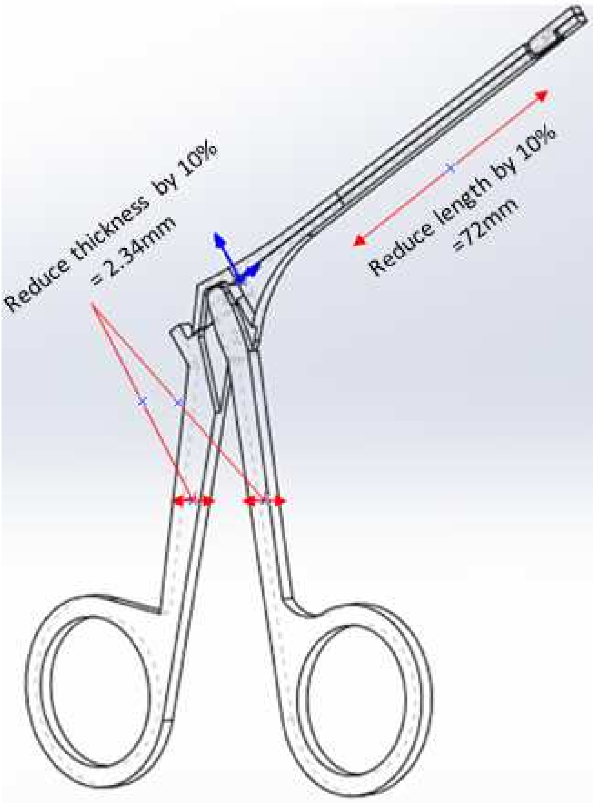


Figure 6.2: Revised design dimensions

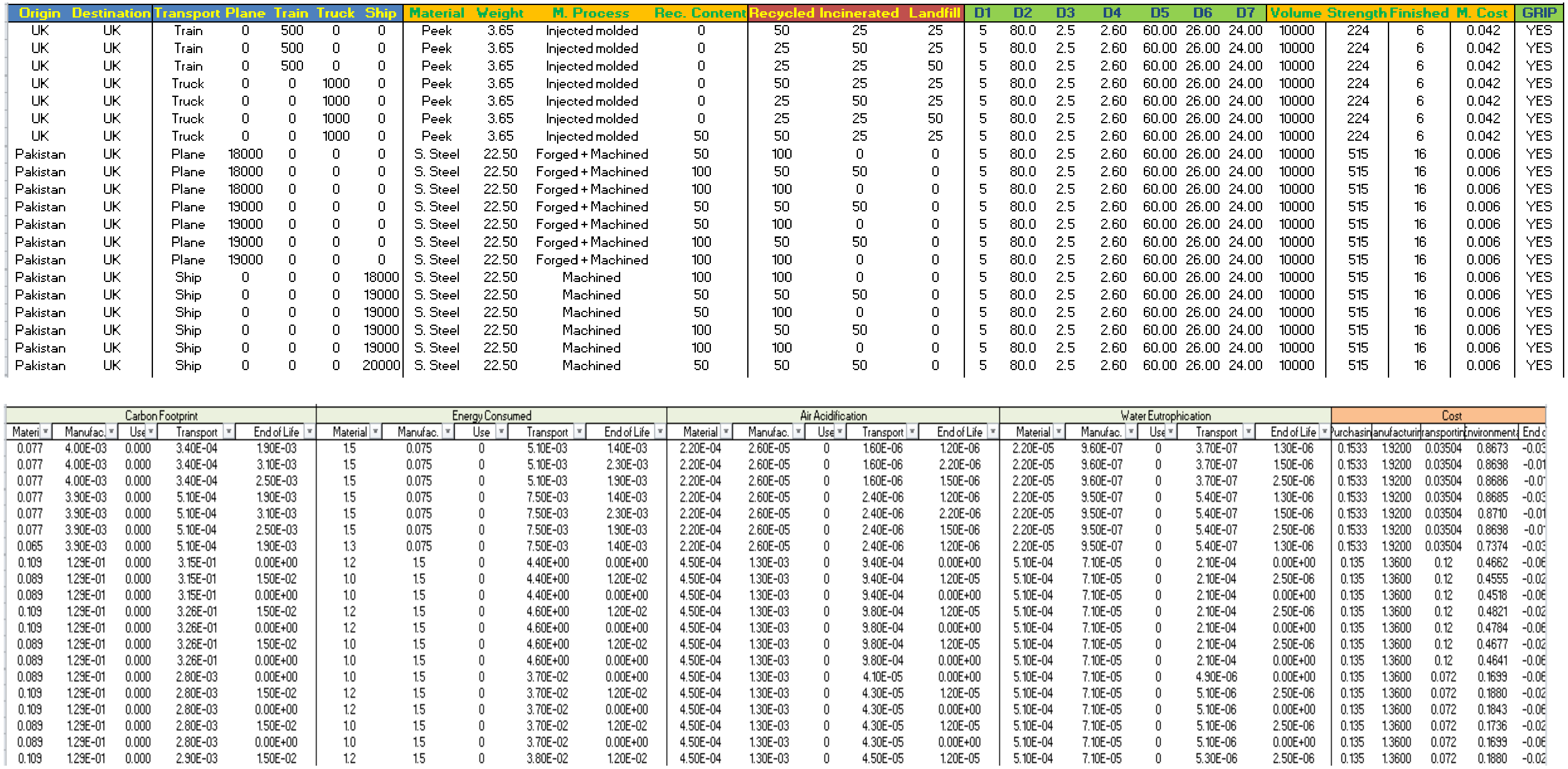
Table 6.2 presents a comparison between the new redesign product and existing product. The new design parameters is created from the experience of the designer. The information highlighted in bold under new design column indicates parameter changes for the new case, while non-bold indicates unchanged parameters. The transportation method is revised from a plane to a ship. The Eco-CBR tool will propose better solutions by moving towards a lower environmental impact and lower economic cost. Furthermore, the design still provides the same quality of performance and fulfils the customer requirements.

In order to illustrate the application of this process, the Eco-CBR library of the product design knowledge requires to be developed. The content and structure of the Eco-CBR library was discussed in Chapter V. Currently, this library contains 72 cases of product information for medical forceps. The Eco-CBR library is developed based on the information retrieved in Stage I (LCA) and Stage III (Eco-QFD). Table 6.3 shows an example of the data in the library. The full library of the cases is shown in Appendix A.

Table 6.2: Features to compare between existing forceps and revised forceps

Criteria	**Existing design – SS(2)**	**New design**
Material	Stainless steel	Stainless steel
Types of manufacturing process	Forging and machining	Forging and machining
Manufacturing region	Pakistan	Pakistan
Use region	Europe	Europe
Transportation	Plane	**Ship**
Distance(km)	17000	**18000**
Weight	**Gram**	**Gram**
Product (medical forceps)	22	**19.85**
Fixed handle + shaft	8.5	**7.65**
Moveable handle	8.5	**7.65**
Shaft	4.5	**4.05**
Jaw	0.5	0.5
Design dimension	**Millimetre**	**Millimetre**
Jaw (D1)	5	5
Length shaft (D2)	80	**72**
Thickness of the shaft (D3)	2.5	2.5
Thickness of the handle (D4)	2.6	**2.34**
Length of the handle (D5)	60	60
Handle outer diameter (D6)	26	26
Handle inner diameter (D7)	24	24

Table 6.3: Eco-CBR library



Origin	Destination	Transport	Plane	Train	Truck	Ship	Material	Weight	M. Process	Rec. Content	Recycled	Incinerated	Landfill	D1	D2	D3	D4	D5	D6	D7	Volume	Strength	Finished	M. Cost	GRIP
UK	UK	Train	0	500	0	0	Peek	3.65	Injected molded	0	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
UK	UK	Train	0	500	0	0	Peek	3.65	Injected molded	0	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
UK	UK	Train	0	500	0	0	Peek	3.65	Injected molded	0	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
UK	UK	Truck	0	0	1000	0	Peek	3.65	Injected molded	0	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
UK	UK	Truck	0	0	1000	0	Peek	3.65	Injected molded	0	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
UK	UK	Truck	0	0	1000	0	Peek	3.65	Injected molded	0	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
UK	UK	Truck	0	0	1000	0	Peek	3.65	Injected molded	50	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
Pakistan	UK	Plane	18000	0	0	0	S. Steel	22.50	Forged + Machined	50	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	515	16	0.006	YES
Pakistan	UK	Plane	18000	0	0	0	S. Steel	22.50	Forged + Machined	100	50	50	0	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	515	16	0.006	YES
Pakistan	UK	Plane	18000	0	0	0	S. Steel	22.50	Forged + Machined	100	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	515	16	0.006	YES
Pakistan	UK	Plane	19000	0	0	0	S. Steel	22.50	Forged + Machined	50	50	50	0	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	515	16	0.006	YES
Pakistan	UK	Plane	19000	0	0	0	S. Steel	22.50	Forged + Machined	50	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	515	16	0.006	YES
Pakistan	UK	Plane	19000	0	0	0	S. Steel	22.50	Forged + Machined	100	50	50	0	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	515	16	0.006	YES
Pakistan	UK	Plane	19000	0	0	0	S. Steel	22.50	Forged + Machined	100	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	515	16	0.006	YES
Pakistan	UK	Ship	0	0	0	18000	S. Steel	22.50	Machined	100	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	515	16	0.006	YES
Pakistan	UK	Ship	0	0	0	19000	S. Steel	22.50	Machined	50	50	50	0	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	515	16	0.006	YES
Pakistan	UK	Ship	0	0	0	19000	S. Steel	22.50	Machined	50	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	515	16	0.006	YES
Pakistan	UK	Ship	0	0	0	19000	S. Steel	22.50	Machined	100	50	50	0	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	515	16	0.006	YES
Pakistan	UK	Ship	0	0	0	19000	S. Steel	22.50	Machined	100	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	515	16	0.006	YES
Pakistan	UK	Ship	0	0	0	20000	S. Steel	22.50	Machined	50	50	50	0	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	515	16	0.006	YES

Carbon Footprint					Energy Consumed					Air Acidification					Water Eutrophication					Cost				
Materi	Manufac.	Use	Transport	End of Life	Material	Manufac.	Use	Transport	End of Life	Material	Manufac.	Use	Transport	End of Life	Material	Manufac.	Use	Transport	End of Life	Purchasin	anufacturin	ransportin	Environment	End
0.077	4.00E-03	0.000	3.40E-04	1.90E-03	1.5	0.075	0	5.10E-03	1.40E-03	2.20E-04	2.60E-05	0	1.60E-06	1.20E-06	2.20E-05	9.60E-07	0	3.70E-07	1.30E-06	0.1533	1.9200	0.03504	0.8673	-0.03
0.077	4.00E-03	0.000	3.40E-04	3.10E-03	1.5	0.075	0	5.10E-03	2.30E-03	2.20E-04	2.60E-05	0	1.60E-06	2.20E-06	2.20E-05	9.60E-07	0	3.70E-07	1.50E-06	0.1533	1.9200	0.03504	0.8698	-0.01
0.077	4.00E-03	0.000	3.40E-04	2.50E-03	1.5	0.075	0	5.10E-03	1.90E-03	2.20E-04	2.60E-05	0	1.60E-06	1.50E-06	2.20E-05	9.60E-07	0	3.70E-07	2.50E-06	0.1533	1.9200	0.03504	0.8686	-0.0
0.077	3.90E-03	0.000	5.10E-04	1.90E-03	1.5	0.075	0	7.50E-03	1.40E-03	2.20E-04	2.60E-05	0	2.40E-06	1.20E-06	2.20E-05	9.50E-07	0	5.40E-07	1.30E-06	0.1533	1.9200	0.03504	0.8685	-0.03
0.077	3.90E-03	0.000	5.10E-04	3.10E-03	1.5	0.075	0	7.50E-03	2.30E-03	2.20E-04	2.60E-05	0	2.40E-06	2.20E-06	2.20E-05	9.50E-07	0	5.40E-07	1.50E-06	0.1533	1.9200	0.03504	0.8710	-0.01
0.077	3.90E-03	0.000	5.10E-04	2.50E-03	1.5	0.075	0	7.50E-03	1.90E-03	2.20E-04	2.60E-05	0	2.40E-06	1.50E-06	2.20E-05	9.50E-07	0	5.40E-07	2.50E-06	0.1533	1.9200	0.03504	0.8698	-0.0
0.065	3.90E-03	0.000	5.10E-04	1.90E-03	1.3	0.075	0	7.50E-03	1.40E-03	2.20E-04	2.60E-05	0	2.40E-06	1.20E-06	2.20E-05	9.50E-07	0	5.40E-07	1.30E-06	0.1533	1.9200	0.03504	0.7374	-0.03
0.109	1.29E-01	0.000	3.15E-01	0.00E+00	1.2	1.5	0	4.40E+00	0.00E+00	4.50E-04	1.30E-03	0	9.40E-04	0.00E+00	5.10E-04	7.10E-05	0	2.10E-04	0.00E+00	0.135	1.3600	0.12	0.4662	-0.06
0.089	1.29E-01	0.000	3.15E-01	1.50E-02	1.0	1.5	0	4.40E+00	1.20E-02	4.50E-04	1.30E-03	0	9.40E-04	1.20E-05	5.10E-04	7.10E-05	0	2.10E-04	2.50E-06	0.135	1.3600	0.12	0.4555	-0.02
0.089	1.29E-01	0.000	3.15E-01	0.00E+00	1.0	1.5	0	4.40E+00	0.00E+00	4.50E-04	1.30E-03	0	9.40E-04	0.00E+00	5.10E-04	7.10E-05	0	2.10E-04	0.00E+00	0.135	1.3600	0.12	0.4518	-0.06
0.109	1.29E-01	0.000	3.26E-01	1.50E-02	1.2	1.5	0	4.60E+00	1.20E-02	4.50E-04	1.30E-03	0	9.80E-04	1.20E-05	5.10E-04	7.10E-05	0	2.10E-04	2.50E-06	0.135	1.3600	0.12	0.4821	-0.02
0.109	1.29E-01	0.000	3.26E-01	0.00E+00	1.2	1.5	0	4.60E+00	0.00E+00	4.50E-04	1.30E-03	0	9.80E-04	0.00E+00	5.10E-04	7.10E-05	0	2.10E-04	0.00E+00	0.135	1.3600	0.12	0.4784	-0.06
0.089	1.29E-01	0.000	3.26E-01	1.50E-02	1.0	1.5	0	4.60E+00	1.20E-02	4.50E-04	1.30E-03	0	9.80E-04	1.20E-05	5.10E-04	7.10E-05	0	2.10E-04	2.50E-06	0.135	1.3600	0.12	0.4677	-0.02
0.089	1.29E-01	0.000	3.26E-01	0.00E+00	1.0	1.5	0	4.60E+00	0.00E+00	4.50E-04	1.30E-03	0	9.80E-04	0.00E+00	5.10E-04	7.10E-05	0	2.10E-04	0.00E+00	0.135	1.3600	0.12	0.4641	-0.06
0.089	1.29E-01	0.000	2.80E-03	0.00E+00	1.0	1.5	0	3.70E-02	0.00E+00	4.50E-04	1.30E-03	0	4.10E-05	0.00E+00	5.10E-04	7.10E-05	0	4.90E-06	0.00E+00	0.135	1.3600	0.072	0.1699	-0.06
0.109	1.29E-01	0.000	2.80E-03	1.50E-02	1.2	1.5	0	3.70E-02	1.20E-02	4.50E-04	1.30E-03	0	4.30E-05	1.20E-05	5.10E-04	7.10E-05	0	5.10E-06	2.50E-06	0.135	1.3600	0.072	0.1880	-0.02
0.109	1.29E-01	0.000	2.80E-03	0.00E+00	1.2	1.5	0	3.70E-02	0.00E+00	4.50E-04	1.30E-03	0	4.30E-05	0.00E+00	5.10E-04	7.10E-05	0	5.10E-06	0.00E+00	0.135	1.3600	0.072	0.1843	-0.06
0.089	1.29E-01	0.000	2.80E-03	1.50E-02	1.0	1.5	0	3.70E-02	1.20E-02	4.50E-04	1.30E-03	0	4.30E-05	1.20E-05	5.10E-04	7.10E-05	0	5.10E-06	2.50E-06	0.135	1.3600	0.072	0.1736	-0.02
0.089	1.29E-01	0.000	2.80E-03	0.00E+00	1.0	1.5	0	3.70E-02	0.00E+00	4.50E-04	1.30E-03	0	4.30E-05	0.00E+00	5.10E-04	7.10E-05	0	5.10E-06	0.00E+00	0.135	1.3600	0.072	0.1699	-0.06
0.109	1.29E-01	0.000	2.90E-03	1.50E-02	1.2	1.5	0	3.80E-02	1.20E-02	4.50E-04	1.30E-03	0	4.50E-05	1.20E-05	5.10E-04	7.10E-05	0	5.30E-06	2.50E-06	0.135	1.3600	0.072	0.1880	-0.02

6.3 New Case – Area A

A new case consists of several features that describe a problem. Referring to Figure 5.3 and Figure 5.4 as discussed in Chapter V, area A is defined as a new case for a product design. Table 6.4 shows the input values for features and weights (w) assigned by the designer for the new case of medical forceps. This new case is segmented into four groups:

i. Transportation (origin from Pakistan, product usage in UK, transport used is ship with a distance of 18,000km).

vi. Material and manufacturing process (material is stainless steel, weight is 19.85g, manufactured (forged and machined), 50% recycling content is used in the product, production volume is 10000, material cost is £0.006 (per gram), strength is 515 Mpa and finished roughness is 16 µin.

vii. End-of-life product (recycling rate is 100%, incineration is 0% and landfill is 0%).

viii. Product dimensions (D1 is 5mm, D2 is 72mm, D3 is 2.5mm, D4 is 2.34mm, D5 is 60mm, D6 is 26mm and D7 is 24mm).

Table 6.4: Weights (w) assigned for a new case

Group Categories							
Transportation	**w**	**Material and manufacturing process**	**w**	**EOL product**	**w**	**Design dimensions (mm)**	**w**
Origin = **Pakistan**	4	Mat = **Stainless steel**	5	Rec= **100%**	5	D1 = **5**	5
Dest = **UK**	4	Weight = **19.85g**	5	Mat = **Stainless steel**	5	D2 = **72**	5
Trans = **Ship**	4	MP = **Forged and** M**achined**	5			D3 = **2.5**	5
Dist. Ship = **18000**	4					D4 = **2.34**	5
		RCT = **50%**	5			D5 = **60**	3
		Vol = **10000**				D6 = **26**	3
		MatC = **£0.006/g**				D7 = **24**	3
		Strength = **450 MPa**				Mat = **Stainless steel**	5
		Roughness = **16 µin**				Weight = **19.8g**	5

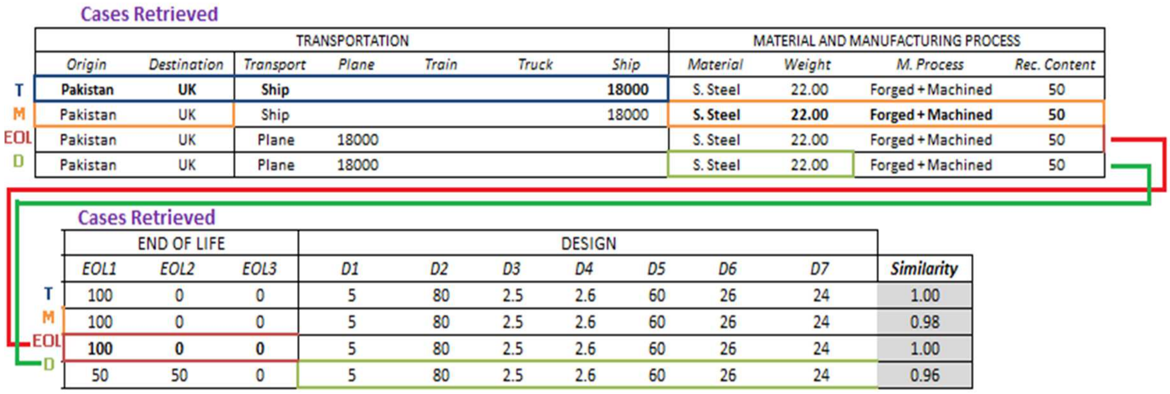
6.4 Weighting Factors – Area B

Referring to Figure 5.4 and 5.5 of Chapter V, Area ‘B’ is the location for the designer to assign the weights of the features in each group. In this study, a real number between 1 (a less important attribute) and 5 (a very important attribute) has been used as the weighting scale. These weights are not fixed, therefore allowing the designer to assign their importance according to the characterisation of the studied product.

Table 6.4 shows the input values for features and weights (w) assigned by the designer for the new medical forceps. Weights for volume, material cost, strength and roughness are not provided here because these parameters are not considered as part of the similarity values between existing cases and new cases. The material cost and production volume features will be used for the cost estimation calculation. On the other hand, the strength and roughness features are used to measure customer requirements that have been analysed in the Eco-QFD Phase I.

6.5 Searching Similarities Process - Area C

The next step is to carry out the similarity function between the new case and existing cases in the Eco-CBR library. Area ‘C’ represents the retrieved cases from the process of finding similarities. Figure 6.3 shows the retrieved cases that are based on the highest similarity found during the searching process. The group of existing cases that are retrieved from the Eco-CBR library will be rated in a range of [0, 1], where ‘0’ represents the lowest similarity and ‘1’ represents the highest similarity.



Cases Retrieved

	TRANSPORTATION							MATERIAL AND MANUFACTURING PROCESS			
	Origin	*Destination*	*Transport*	*Plane*	*Train*	*Truck*	*Ship*	*Material*	*Weight*	*M. Process*	*Rec. Content*
T	**Pakistan**	**UK**	**Ship**				**18000**	S. Steel	22.00	Forged + Machined	50
M	Pakistan	UK	Ship				18000	**S. Steel**	**22.00**	**Forged + Machined**	**50**
EOL	Pakistan	UK	Plane	18000				S. Steel	22.00	Forged + Machined	50
D	Pakistan	UK	Plane	18000				S. Steel	22.00	Forged + Machined	50

Cases Retrieved

	END OF LIFE			DESIGN							
	EOL1	*EOL2*	*EOL3*	*D1*	*D2*	*D3*	*D4*	*D5*	*D6*	*D7*	***Similarity***
T	100	0	0	5	80	2.5	2.6	60	26	24	1.00
M	100	0	0	5	80	2.5	2.6	60	26	24	0.98
EOL	**100**	**0**	**0**	5	80	2.5	2.6	60	26	24	1.00
D	50	50	0	5	80	2.5	2.6	60	26	24	0.96

Figure 6.3: Screenshot of the retrieved cases

The similarity based retrieval process is illustrated in Table 6.5 for the transportation group, while Table 6.6 illustrates for the material and manufacturing process group, Table 6.7 for the end-of-life group and Table 6.8 for the design dimensions group. These groups are showing the new case values, equations used, weight implied, local similarity, global similarity and the case retrieved from the Eco-CBR library. The global similarity shows the retrieved cases with the highest similarity compared to the new case. The solution obtained from this retrieved cases can be adapted into the new case.

The similarity process is calculated using the equations (5.1), (5.2) for local similarities and equation (5.3) for global similarity. These equations are illustrated here for the convenience of the readers.

Non-numerical local similarity:

$$\begin{array}{ll} \text{IF NC} == \text{Lib}_k & \rightarrow \text{LS} = 1 \\ \text{Else} & \rightarrow \text{LS} = 0 \end{array} \qquad (5.1)$$

Numerical local similarity:

$$\text{LS} = \frac{\min(\text{NC}, \text{Lib}_k)}{\max(\text{NC}, \text{Lib}_k)}$$

$$\text{If } (\text{NC} == 0 \ \& \ \text{Lib}_k == 0) \text{ then LS} = 1 \qquad (5.2)$$

Global similarity (GS) ≈Similarity:

$$\text{GS}_i = \frac{\sum_j w_{ij} * \text{LS}_{jk}}{\sum_j w_{ij}} \quad \forall i \qquad (5.3)$$

The illustration of the local similarity and global similarity calculations for the transportation group is shown below. Table 6.5 provides the summary of these calculations with the context of a case retrieved from the Eco-CBR library for the transportation group.

Non-numerical local similarity:

i. $NC_{origin}(Pakistan) == Lib_{origin}(Pakistan) \rightarrow LS = 1$

ii. $NC_{dest}(UK) == Lib_{dest}(UK) \rightarrow LS = 1$

iii. $NC_{trans}(Ship) == Lib_{trans}(Ship) \rightarrow LS = 1$

Numerical local similarity:

i. $\mathrm{LS}_{Dist.ship} = \frac{\min(\mathrm{NC}(18000),\mathrm{Lib}(18000))}{\max(\mathrm{NC}(18000),\mathrm{Lib}(18000))} = 1$

Global similarity (GS) ≈Similarity:

$$\mathrm{GS}_{\mathrm{transportation}} = \frac{(4*1)+(4*1)+(4*1)+(4*1)}{4+4+4+4} = \mathbf{1.00}$$

Table 6.5: Transportation group

New case features and values	Equation	Weight	Local similarity result	Eco-CBR library
Origin = Pakistan	Non-numerical	4	1	Pakistan
Dest = UK	Non-numerical	4	1	UK
Trans = Ship	Non-numerical	4	1	Ship
Dist. ship = 18000	Numerical	4	1	18000
Similarity = 1.00				

The illustration of the local similarities and global similarity calculations for the material and manufacturing group is shown below. Table 6.6 presents the summary of these calculations and the case retrieved from the Eco-CBR library for the material and manufacturing group.

Non-numerical local similarity:

i. $NC_{mat}(Stainless\ steel) == Lib_{mat}(Stainless\ steel) \rightarrow LS = 1$

ii. $NC_{MP}(ForgedMachined) == Lib_{MP}(ForgedMachined) \rightarrow LS = 1$

Numerical local similarity:

i. $\mathrm{LS}_{w} = \frac{\min(\mathrm{NC}(19.85),\mathrm{Lib}(22))}{\max(\mathrm{NC}(19.85),\mathrm{Lib}(22))} = 0.9$

ii. $\mathrm{LS}_{RCT} = \frac{\min(\mathrm{NC(50\%),Lib(50\%)})}{\max(\mathrm{NC(50\%),Lib(50\%)})} = 1$

Global similarity (GS) ≈Similarity:

$$\mathrm{GS}_{\mathrm{Mat\&Maf.Process}} = \frac{(5*1)+(5*0.9)+(5*1)+(5*1)}{5+5+5+5} = \mathbf{0.98}$$

Table 6.6: Material and manufacturing process group

New case features and values	Equation	Weight	Local similarity result	Eco-CBR library
Mat = Stainless steel	Non-numerical	5	1	Stainless steel
W = 19.85	Numerical	5	0.9	22
MP = Forged and Machined	Non-numerical	5	1	Forged and Machined
RCT = 50%	Numerical	5	1	50%
Similarity = 0.98				

The illustration of the local similarity and global similarity calculation for the end-of-life group is shown below. Table 6.7 presents the summary of these calculations and the case retrieved from the Eco-CBR library for the end-of-life group.

Non-numerical local similarity:

i. $NC_{mat}(Stainless\ steel) == Lib_{mat}(Stainless\ steel) \rightarrow LS = 1$

Numerical local similarity:

i. $\mathrm{LS}_{Rec} = \frac{\min(\mathrm{NC(100\%),Lib(100\%)})}{\max(\mathrm{NC(100\%),Lib(100\%)})} = 1$

Global similarity (GS) ≈Similarity

$$\mathrm{GS}_{\mathrm{EOL}} = \frac{(5*1)+(5*1)}{5+5} = 1.00$$

Table 6.7: End-of-Life group

New case features and values	Equation	Weight	Local similarity result	Eco-CBR library
Rec = 100%	Numerical	5	1	100%
Mat = Stainless steel	Non-numerical	5	1	Stainless steel
Similarity = 1.00				

The illustration of the local similarity calculation and global similarity for the design dimension group is shown below. Table 6.8 presents the summary of these calculations and the case retrieved from the Eco-CBR library for the design dimension group.

Non-numerical local similarity:

$NC_{mat}(Stainless\ steel) == Lib_{mat}(Stainless\ steel) \rightarrow LS = 1$

Numerical local similarity:

i. $\mathrm{LS}_{D1} = \frac{\min(\mathrm{NC}(5),\mathrm{Lib}(5))}{\max(\mathrm{NC}(5),\mathrm{Lib}(5))} = 1.00$

ii. $\mathrm{LS}_{D2} = \frac{\min(\mathrm{NC}(72),\mathrm{Lib}(80))}{\max(\mathrm{NC}(72),\mathrm{Lib}(80))} = 0.90$

iii. $\mathrm{LS}_{D3} = \frac{\min(\mathrm{NC}(2.5),\mathrm{Lib}(2.5))}{\max(\mathrm{NC}(2.5),\mathrm{Lib}(2.5))} = 1.00$

iv. $\mathrm{LS}_{D4} = \frac{\min(\mathrm{NC}(2.34),\mathrm{Lib}(2.6))}{\max(\mathrm{NC}(2.34),\mathrm{Lib}(2.6))} = 0.90$

v. $\mathrm{LS}_{D5} = \frac{\min(\mathrm{NC}(60),\mathrm{Lib}(60))}{\max(\mathrm{NC}(60),\mathrm{Lib}(60))} = 1.00$

vi. $\mathrm{LS}_{D6} = \frac{\min(\mathrm{NC}(26),\mathrm{Lib}(26))}{\max(\mathrm{NC}(26),\mathrm{Lib}(26))} = 1.00$

vii. $\mathrm{LS}_{D7} = \frac{\min(\mathrm{NC}(24),\mathrm{Lib}(24))}{\max(\mathrm{NC}(24),\mathrm{Lib}(24))} = 1.00$

viii. $\mathrm{LS}_{w} = \frac{\min\left(\mathrm{NC}(19.85),\mathrm{Lib}(22)\right)}{\max\left(\mathrm{NC}(19.85),\mathrm{Lib}(22)\right)} = 0.90$

Global similarity (GS) ≈Similarity:

$$\mathrm{GS}_{\mathrm{design}}$$

$$= \frac{(5*1)+(5*0.9)+(5*1)+(5*0.9)+(3*1)+(3*1)+(3*1)+(5*1)+(5*0.9)}{5+5+5+5+3+3+3+5+5}$$

$$\mathrm{GS}_{\mathrm{design}} = 0.96$$

Table 6.8: Design dimensions group

New case features and values	Equation	Weight	Local similarity result	Eco-CBR library
D1 = 5mm	Numerical	5	1.00	5mm
D2 = 72mm	Numerical	5	0.90	80mm
D3 = 2.5mm	Numerical	5	1.00	2.5mm
D4 = 2.34mm	Numerical	5	0.90	2.6mm
D5 = 60mm	Numerical	3	1.00	60mm
D6 = 26mm	Numerical	3	1.00	26mm
D7 = 24mm	Numerical	3	1.00	24mm
Mat = Stainless steel	Non-numerical	5	1.00	Stainless steel
W = 19.85	Numerical	5	0.90	22
Similarity = 0.96				

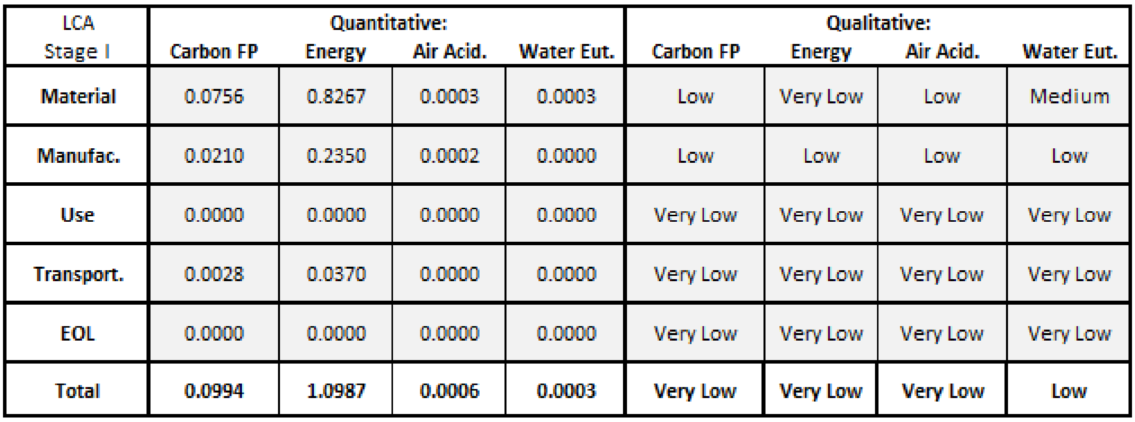
The next process is to reuse the previous experiences for a new case. If the new case possesses high similarity with the existing case in the Eco-CBR library, then the reuse process is to transfer the existing solution to the new case. However, if the proposed new case is slightly different from the existing cases, then the process of adaptation needs to be carried out. The recommended solutions from the Eco-CBR library need to be revised and altered to solve the case. In the Eco-CBR method, the process of adaptation represents an important step, as it translates the retrieved cases' solution into an appropriate solution for the current problem (new case), as mentioned in Table 6.4. The information from the retrieved cases will be reused as the entry for the new case in the solutions area.

6.6 Solution: Environmental Impact – Area D

Figure 6.4 shows the solution of the product life cycle to be analysed based on the associated environmental impact. The process of translation from quantitative to qualitative data is performed based on the data from the Eco-CBR library. These data results in one of the five rankings: 'Very High (VH)', 'High (H)', 'Medium (M)', 'Low (L)' and 'Very Low (VL)'.

By analysing the new case criteria relative to the retrieved case, the LCA result in the Figure 6.4 shows that carbon footprint, total energy consumed, air acidification and water eutrophication resulted in 99.4g, 1098.7kj, 0.6g and 0.3g respectively. The carbon footprint, total energy consumed, air acidification and water eutrophication provide 'Very Low' impacts to the product usage (because no energy required for operation), transportation via ship (origin in Pakistan and shipped to UK) and EOL product that is 100% product recycling.

Figure 6.4: Screenshot of the solution for life cycle assessment



LCA Stage I	Quantitative: Carbon FP	Energy	Air Acid.	Water Eut.	Qualitative: Carbon FP	Energy	Air Acid.	Water Eut.
Material	0.0756	0.8267	0.0003	0.0003	Low	Very Low	Low	Medium
Manufac.	0.0210	0.2350	0.0002	0.0000	Low	Low	Low	Low
Use	0.0000	0.0000	0.0000	0.0000	Very Low	Very Low	Very Low	Very Low
Transport.	0.0028	0.0370	0.0000	0.0000	Very Low	Very Low	Very Low	Very Low
EOL	0.0000	0.0000	0.0000	0.0000	Very Low	Very Low	Very Low	Very Low
Total	**0.0994**	**1.0987**	**0.0006**	**0.0003**	**Very Low**	**Very Low**	**Very Low**	**Low**

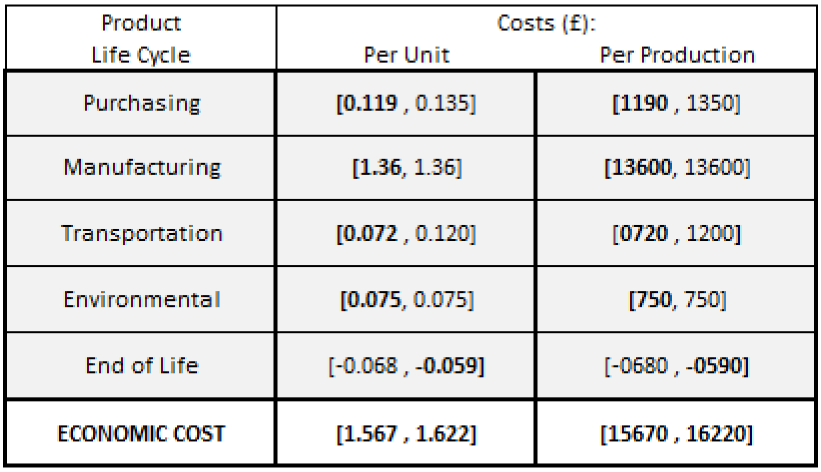
6.7 Solution: Cost Estimation - Area E

Label 'E' represents the area that provides the life cycle cost of the solution group for cost estimation. The ecological economic cost (Eco-Economic Cost) model is shown in Figure 3.1, which is an approach used to summarise the development enabled by the Eco-QFD and Eco-CBR in IEDM framework. Table 6.9 shows the information of the cost parameters used in this study.

Table 6.9: Cost parameters

Cost parameters	**Stainless steel (£)**
Direct cost (Dc)	0.33
Labour cost (Lc)	0.35
Overhead cost (Oc)	0.68
Carbon footprint (CF)	$2.04e^{-04}$ per gram
Air acidification (AA)	$5.00E^{-05}$ per gram
Water eutrophication (EU)	$2.00E^{-05}$ per gram
Energy consumption (EC)	$1.00E^{-05}$ per gram
Landfill cost (LFc)	$1.10E^{-04}$ per gram
Incineration cost (INc)	0.022 per gram
Recycle value (Rc)	50% of material cost

Figure 6.5 depicts the screenshot of the solution for cost estimation. It is calculated based on per unit and also per production (product volume). The costs parameters presented in bold, in Figure 6.5, refer to the estimated cost for the new case, while the non-bold parameters refer to the retrieved case. . The summary economic cost is presented in the form of a range, calculated as a minimum and maximum cost for the new case.



Product Life Cycle	Costs (£): Per Unit	Per Production
Purchasing	[**0.119** , 0.135]	[**1190** , 1350]
Manufacturing	[**1.36**, 1.36]	[**13600**, 13600]
Transportation	[**0.072** , 0.120]	[**0720** , 1200]
Environmental	[**0.075**, 0.075]	[**750**, 750]
End of Life	[-0.068 , **-0.059**]	[-0680 , **-0590**]
ECONOMIC COST	**[1.567 , 1.622]**	**[15670 , 16220]**

Figure 6.5: Screenshot for the cost estimation

The data presented in Figure 6.5 are auto generated by the Eco-CBR tool. Herein, the calculation for the new case is shown by using equations in the Eco-Economic cost model as discussed in Section 3.5.

i. Production cost per unit, $Pc = Pc * w$

$Pc = 0.006 * 19.85 = £0.119$

ii. Production cost per production,

$Pc = 0.119 * 10000 = £1190$

iii. Manufacturing cost per unit, $Mc = Dc + Lc + Oc$

$Mc = 0.33 + 0.35 + 0.68 = £1.36$

iv. Manufacturing cost per production,

$Mc = 1.36 * 10000 = £13600$

The calculation of transportation cost is divided into several steps. First, the capacity of a box is identified, where a box of forceps contains 1300 pieces. Then the logistic price to deliver a box from Pakistan to the UK is considered, where the price is £90.00 by ship based on the website of DPD (Dynamic Parcel Distribution, 2015). Next, the required volume in terms of number of boxes is calculated. Here the number is equal to 8 boxes, resulting in a total price of £720.00.

v. Transport cost per production, $Tc = \frac{\left\{\left\lceil\frac{Vol * W}{Box}\right\rceil \cdot Dc\right\}}{Vol}$

$Tc = 8 * 90.00 = £720.00$

vi. Transport cost per unit,

$Tc = 720/10000 = £0.072$

vii. Environmental cost per unit, $ENc = CF + EC + AC + WE$

$ENc = (99.4\mathrm{g} * 2.04\mathrm{E}^{-04}) + (1098.7\mathrm{g} * 5.00\mathrm{E}^{-05}) + (0.6\mathrm{g} * 2.00\mathrm{E}^{-05}) + (0.4\mathrm{g} * 1.00\mathrm{E}^{-05}) = £0.075$

viii. Environmental cost per production,

$ENc = 0.075 * 10000 = £750$

ix. End-of-Life cost per unit, $EOLc = (LFc + INc) - RV$

$EOLc = [(0.00011 * 0 * 19.85) + (0.022 * 0 * 19.85)] - (0.003 * 1 * 19.85)$

$EOLc = £ - 0.059$

x. End-of-Life cost per production,

$$EOLc\ = -0.079 * 10000 = \pounds - 590$$

xi. Economic cost per unit,

$$ECOc = 0.119 + 1.36 + 0.072 + 0.017 + (-0.059) = \pounds 1.567$$

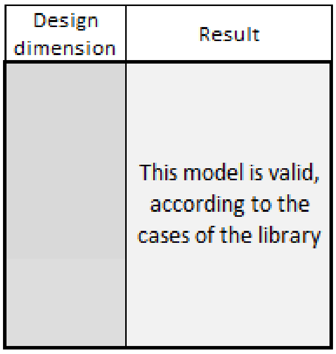
xii. Economic cost per production,

$$ECOc = 1.567 * 10000 = \pounds 15{,}670$$

For the economic cost per unit, the solution is £1.567 for minimum limit, and £1.622 for maximum limit. This approach is applied across the production volume of 10,000 forceps, where the minimum and maximum economic costs are between £15,670 and £16,220, respectively. During retaining a new case in the Eco-CBR library, the system will provide options to the designer either to save the cost based on the estimated cost or the retrieved cost, which depends on user preference.

6.8 Solution: Design Dimension Assessment – Area F

Figure 6.6 shows the proposed solution related to the product dimensions, with the message alert of '*This model is valid, according to the cases of the library*'. Here, it shows that the changes in design dimensions for a new case is valid based on the design assessment conducted on the existing cases in the Eco-CBR library.



Design dimension	Result
	This model is valid, according to the cases of the library

Figure 6.6: The solution for product design dimensions

6.9 Solution: Customer Requirements – Area G

Area 'G' presents an assessment of the solution measured against customer requirements. Generally, these requirements are taken from Eco-QFD Phase I. Table

6.10 presents the application of this approach with the list of customer requirements, and the criteria used to measure the medical forceps taken from the case study in Chapter IV.

In Table 6.10, the process starts with the calculation of the inputs. The similarities of the handles (D6 and D7) are calculated with a different method. For each dimension, a range between minimum and maximum values from the library can be combined by finding the average value.

Table 6.10: Customer requirements input calculation

Customer Requirements Features		Input new case	Eco-CBR library	Values
(i)	Comfortable to hold	Similarities of Handle dimension 1 (D6)	[26.0, 26.0]	$\frac{\min(\mathrm{NC}(26), \mathrm{Lib}(26))}{\max(\mathrm{NC}(26), \mathrm{Lib}(26))} = 1.00$
		Similarities of Handle dimension 2 (D7)	[24.0, 24.0]	$\frac{\min(\mathrm{NC}(24), \mathrm{Lib}(24))}{\max(\mathrm{NC}(24), \mathrm{Lib}(24))} = 1.00$
		Similarity of finished (roughness)	16	$\frac{\min(\mathrm{NC}(16), \mathrm{Lib}(16))}{\max(\mathrm{NC}(16), \mathrm{Lib}(16))} = 1.00$
(ii)	Able to grasp objects	Grip (Yes – 1, No – 0)	-	1
		Similarity of jaw opening (D1)	5	$\frac{\min(\mathrm{NC}(5), \mathrm{Lib}(5))}{\max(\mathrm{NC}(5), \mathrm{Lib}(5))} = 1.00$
(iii)	Reliable	Similarity of Design Group.	-	0.96
		Similarity in ratio Strength/Weight	$\frac{515}{22}$	$\frac{\min(\mathrm{NC}\frac{515}{19.85}, \mathrm{Lib}\ \frac{515}{22})}{\max(\mathrm{NC}\frac{515}{19.85}, \mathrm{Lib}\ \frac{515}{22})} = 0.90$
(iv)	Easy to sterilise	Material (Peek – 0, Stainless Steel – 1)	-	1
(v)	Inexpensive material	Similarity with minimum Material Cost	0.006	$\frac{\min(\mathrm{NC}(0.006), \mathrm{Lib}(\ 0.006)}{\max(\mathrm{NC}(0.006), \mathrm{Lib}(\ 0.006)} = 1.00$

The retrieved case from the Eco-CBR library shows that the dimension for the D6 = 26mm, D7=24mm, D1=5, strength (stainless steel) = 515mpa, roughness = 16 μin, weight = 22 and material cost (stainless steel) = £0.006 per gram. Meanwhile, for the new case design dimensions that have been assigned earlier in area ‘A’ were D6 =

26mm, D7=24mm, D1=5mm, strength (stainless steel) = 515mpa, roughness = 16 µin, weight = 19.85 and material cost (stainless steel) = £0.006 per gram.

As discussed in Section 5.3.8.3, equation (5.12) has been used to calculate the average value of the listed inputs for each customer requirement.

i. $CR(comfortable\ to\ hold) = \frac{1.00+1.00+1.oo}{3} = 1.00$

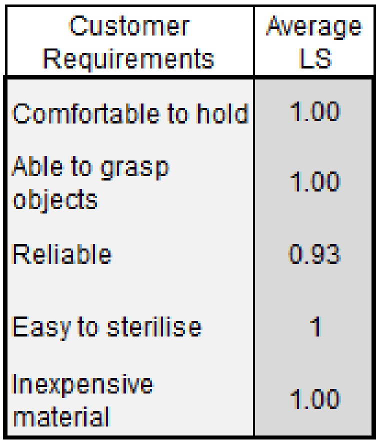
ii. $CR(able\ to\ grasp\ object) = \frac{1.00+1.00}{2} = 1.00$

iii. $CR(reliable) = \frac{0.96+0.90}{2} = 0.93$

iv. $CR(easy\ to\ sterillise) = 1$

v. $CR(inexpensive\ material) = 1.00$

Here, the calculation results in the average values of the features shown in Figure 6.7.



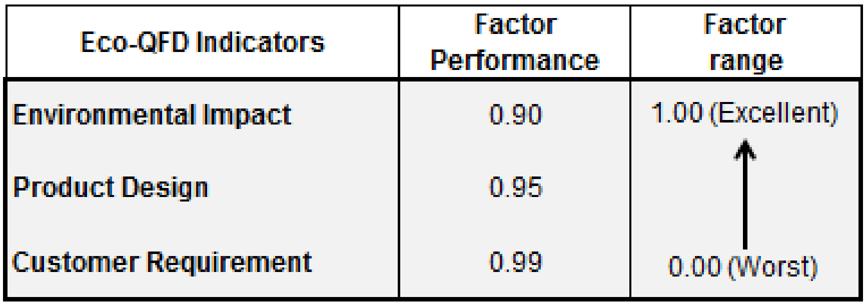
Customer Requirements	Average LS
Comfortable to hold	1.00
Able to grasp objects	1.00
Reliable	0.93
Easy to sterilise	1
Inexpensive material	1.00

Figure 6.7: Screenshot of the solution for customer requirements

6.10 Solution: Eco-QFD Indicators – Area H

The purpose of this solution is to summarise the performance of the product design assessment in three aspects (environmental impact, product design, and customer requirements). These indicators are given a single number based on the integration between the Eco-CBR solutions discussed in Section 6.6 (environmental impact), Section 6.8 (design dimension), and Section 6.9 (customer requirements) with the Eco-

QFD weighting factors. This solution will help industry decision makers propose solutions for new product design features by reusing solutions from similar cases and past experiences. Figure 6.8 depicts the screenshot of the solution for the Eco-QFD indicators.



Eco-QFD Indicators	Factor Performance	Factor range
Environmental Impact	0.90	1.00 (Excellent)
Product Design	0.95	↑
Customer Requirement	0.99	0.00 (Worst)

Figure 6.8: Screenshot of the solution for Eco-QFD indicators

In the next section, the result of factor performance for each indicator value are explained and illustrated in the Table 6.11 (environmental impact), Table 6.12 and Table 6.13 (product design) and Table 6.14 (customer requirements).

6.10.1 Environmental Impact Indicator– Area H

For the environmental impact indicator, the first step is to translate the qualitative data in Figure 6.4 into a numeric scale as shown in Table 6.11. The equation (5.7) in Chapter V is applied to calculate this indicator. The result shows that the indicator for the environmental impact is 0.90.

Table 6.11: Qualitative data to numeric scale for Environmental Impact indicator

Qualitative:			
CF	**EC**	**AA**	**WE**
L	VL	L	M
L	L	L	L
VL	VL	VL	VL
VL	VL	VL	VL
VL	VL	VL	VL

→

	Numeric:			
	CF	**EC**	**AA**	**WE**
	2	1	2	3
	2	2	2	2
	1	1	1	1
	1	1	1	1
	1	1	1	1
SUM:	7	6	7	8
Eco-QFD Phase I – stainless steel	5.5	2.0	5.5	5.5

$$EI\ Ind\ (No\ norm) = \frac{(7*5.5)+(6*2.0)+(7*5.5)+(8*5.5)}{5.5+2.0+5.5+5.5} = 7.2$$

$$EI\ Ind\ (Norm) = 1 - \frac{EI\ Ind\ (No\ norm) - 5}{20} \tag{5.7}$$

$$EI\ Ind\ (Norm) = 1 - \frac{7.2-5}{20} = 0.90$$

6.10.2 Product Design Indicator – Area H

For the product design indicator, Table 6.12 shows the integration process between Eco-QFD phase II and Eco-CBR local similarity (LS) data. The integration process has been discussed in Section 5.3.8.2. The selected design features in the Eco-QFD are the dimensions of D1 (max opening jaws), D2 (working length for the shaft) and D3 (thickness of the main shaft). These features of Eco-QFD will be integrated into Eco-CBR assessment under design dimension.

In Table 6.12, the 'Eco-CBR LS' column represents the local similarity (LS) for design features that have been assessed and discussed earlier in section 6.8. The local similarity is considered as '1' for each design criteria, and it is used to find the maximum score for each part. This maximum score will be used as a reference to calculate the normalisation for the raw score. The weight for each design feature is taken from the Eco-QFD Phase I. The numbers for relational strength between design features and parts deployment are retrieved from the Eco-QFD Phase II in Section 4.4.2.

Table 6.12: The integration of selection features between Eco-QFD Phase II and Eco-CBR process

Design Features	**Eco-QFD Phase I (weight)**	**Parts Deployment**				**Eco-CBR LS**
		Grip	**Moveable Handle**	**Top Slider**	**Fixed Handle**	
Max opening jaws (D1)	5.2	9				1
Working length of the shaft (D2)	4.5	5	9	9	5	1
The thickness of the main shaft (D3)	5.9		9	9		1
Maximum score ($RSmax_i$)		**69.3**	**93.6**	**93.6**	**22.5**	

The calculation of the maximum score for each part is as follows:

Maximum score ($RSmax_i$) = $\sum_{j=1}^{n} p1w_i * R_{i,j} * LS_i$

i. $RSmax_{grip} = (5.2 * 9 * 1) + (4.5 * 5 * 1) + (5.9 * 0 * 1) = 69.3$

ii. $RSmax_{moveable\ handle} = (5.2 * 0 * 1) + (4.5 * 9 * 1) + (5.9 * 9 * 1) = 93.6$

iii. $RSmax_{top\ slider} = (5.2 * 0 * 1) + (4.5 * 9 * 1) + (5.9 * 9 * 1) = 93.6$

iv. $RSmax_{fixed\ handle} = (5.2 * 0 * 1) + (4.5 * 5 * 1) + (5.9 * 0 * 1) = 22.5$

Table 6.13 illustrates the next process based on the data from Table 6.12. The process of the calculations of the raw score and weight normalisation for parts deployment are based on equations (5.9) and (5.10), while, the average score for the design indicator is calculated by equation (5.11).

Table 6.13: Process of calculation for design indicator

Design Features	**Eco-QFD Phase I (weight)**	**Parts Deployment**				**Eco-CBR Local Similarity (LS)**
		Grip	**Moveable Handle**	**Top Slider**	**Fixed Handle**	
Max opening jaws (D1)	5.2	9				1.00
Working length of the shaft (D2)	4.5	5	9	9	5	0.90
Thickness of the main shaft (D3)	5.9		9	9		1.00
Raw score (RS_i)		67.05	89.55	89.55	20.25	
Maximum score ($RSMax_i$)		**69.3**	**93.6**	**93.6**	**22.5**	
Normalised data (NRS_i)		0.97	0.96	0.96	0.90	
Design indicator		**0.95**				

The example of the calculation for a part (grip) is shown below.

i. $RS_{grip} = (5.2 * 9 * 1.00) + (4.5 * 5 * 0.90) + (5.9 * 0 * 1.00) = 67.05$

ii. $NRS_{grip} = \frac{67.05}{69.3}$=0.97

iii. $Design_{indicator} = \frac{0.97+0.96+0.96+0.90}{4}$ = 0.95

The results of raw scores for the grip, moveable handle, top slider and fixed handle are 67.05, 89.55, 89.55 and 20.25, respectively. Thereafter, these raw scores are normalised to new scores resulting in the values of 0.97 (grip), 0.96 (moveable handle), 0.96 (top slider) and 0.90 (fixed handle). The average value of the normalise scores is 0.95. This indicator will be used as a reference in the Eco-CBR solution for product improvement.

6.10.3 Customer Requirement Indicator – Area H

For the customer requirement indicator, the final result is calculated using the equation (5.12). Table 6.14 shows the process of assessing the relationship between the features of customer requirements in Eco-QFD Phase I and the input measurement of Eco-CBR. The Eco-CBR value is retrieved from the average value of the customer requirements, as shown in Figure 6.7. The weight of each feature in Table 6.14 is retrieved from the Eco-QFD process in Phase I. The result shows that customer requirement indicator resulted in 0.99, as shown in Figure 6.8.

Table 6.14: Eco-CBR customer solution value aligned with Eco-QFD Phase I

Customer Requirements	**Eco-CBR Value (*feat$_i$*)**	**Eco-QFD Phase I (w)**
Comfortable to hold	1.00	14.57
Able to grasp objects	1.00	13.68
Reliable	0.93	4.13
Easy to sterilize	1.00	6.82
Inexpensive material	1.00	5.11

$$CR\ Ind = \frac{\sum feat_i \cdot w_i}{\sum w_i} \tag{5.12}$$

$$CR.Ind = \frac{(1.00 * 14.57) + (1.00 * 13.68) + (0.93 * 4.13) + (1.00 * 6.82) + (1.00 * 5.11)}{14.57 + 13.68 + 4.13 + 6.82 + 5.11}$$

$$CR.Ind = 0.99$$

6.11 Retain the New Case into Eco-CBR Library

The new case as shown in Table 6.4 with the recommended solutions will be retained, and the Eco-CBR library is updated by storing the new case. This process will enlarge the case library, and the new case can be accessed in the future, allowing for the reuse of proven solutions.

6.12 Discussion

The proposed Eco-CBR tool is developed to integrate Eco-QFD, LCA and Eco-Economic costs model, as discussed in the IEDM framework of Chapter III. The features of a particular problem are used here to configure a product solution that has lower environmental impacts with a lower life cycle cost. Table 6.15 shows the improvement of the new medical forceps by comparing with the existing product as shown in Table 4.2

Table 6.15: Environmental impact of medical forceps: new design vs existing design

Criteria	Existing design SS(2)	New design	Result
Material	Stainless steel	Stainless steel	The transportation used is Ship. Weight of material is decreased by 10%
Types of manufacturing process	Forging and machining	Forging and machining	
Manufacturing region	Pakistan	Pakistan	
Use region	Europe	Europe	
Transportation	Plane	**Ship**	
Weight (g)	22g	**19.85g**	
Recycle content (material) in product (%)	50%	50%	
Recycle rate at EOL product (%)	100%	100%	
Economic cost (£)	1.817	1.567	↓ 14%
Carbon footprint	320g	99.4g	↓ 69%
Water Eutrophication	0.50g	0.30g	↓ 40%
Air Acidification	1.19g	0.60g	↓ 50%
Total Energy Consumed	4153.50kj	1098.65kj	↓ 74%

The solutions contained in the Eco-CBR tool include information contributed from Stage I (LCA), Stage III (Eco-QFD) and Eco-Economic Cost model. Figure 6.8 shows the summarisation of the solutions (environmental impacts, product design and customer requirements) resulted from the information integrating of Eco-QFD and Eco-CBR methods. The solutions show that the new case study of medical forceps with 10% weight reduction of the stainless steel material, and new design dimensions give lower environmental impact and economic cost to the product. This weight saving has a knock on effect in terms of profit for the company as there are not only material savings but an increase quantity of the product that can be transported for the same amount of fuel, hence increasing revenue.

Many improvements were observed from the combinations of the change of transportation mode of plane to ship, the reduction of material usage, environmental footprints and cost of the product improve. Some of the improvements are decreasing the carbon footprint (69%), water eutrophication (40%), air acidification (50%), and total energy consumed (74%). Additionally, the economic cost has also decreased by 14% due to the above changes.

The methodology outlined in this chapter has been considered in detail based on a step-by-step basis. In practice, the system operates interactively and automatically. The designer is able to make changes to the design features and importance of weighting factors and observe the consequences. This makes the Eco-CBR tool a user friendly and intuitive aid to the eco-design process.

The remaining concern regarding this method is the usefulness of the Eco-CBR library for a new design problem. The intention is that such solutions will help designers to improve the quality of the designed product, while fulfilling customer requirements by enabling them to choose both optimal manufacturing and end-of-life strategies during the design stage.

6.13 Summary

The Eco-CBR method has been designed to be easily and widely applicable to sustainable product development. The application of the Eco-CBR method using a case study relating to the design of a medical forceps has been proposed. The retrieval concept applied in the Eco-CBR method helps the designer to shorten the design process by exploring similar cases in the Eco-CBR library.

The next chapter will focus on the application of IEDM framework to demonstrate a new case study. All product sustainability considerations were conducted throughout all stages, including the LCA, Eco-QFD, and Eco-CBR processes. The Eco-CBR library will be developed to provide a solution to a new case. This process helps the designer to prioritise the product requirements and eco-design parameters that should be adopted to produce a more sustainable product.

CHAPTER VII

INTEGRATED ECO-DESIGN DECISION MAKING TOOL: CASE STUDY

This chapter presents a new case study to demonstrate the proposed framework of the integrated eco-design decision making (IEDM) tool. In this chapter, the IEDM tool is not intend to redesign the product but was applied to demonstrating the step-by-step method through a case study. All product sustainability considerations were conducted throughout all stages, including the life cycle assessment (LCA), eco-design process (Eco-Process), ecological house of quality (Eco-HoQ), and eco-design case-based reasoning (Eco-CBR) processes. The case study of an office chair base shows how the IEDM tool brings together the analysis of factors relating to manufacturing processes, product usage, and end-of-life (EOL) strategy.

7.1 Case Study and Analysis

The research contribution made in the development of IEDM tool is the integration of environmental considerations and economic costs into every aspect of the product's life cycle. These aspects can be seen with the development of the Eco-HoQ that is embedded into Quality Function Deployment (QFD), which is the third stage in the IEDM framework. The IEDM tool applies environmental considerations across three stages of product design, as shown in Figure 7.1. These stages are discussed in Chapter III and provide an output of product information that can be stored in the library of Eco-CBR, as discussed in Chapters V and VI. The Eco-CBR method enables the design process and maintains an organised case library. It aids in solving product design problems by finding similarities with previous cases held in the case-based library. The experiences from these similar cases will be used to generate and assess design solutions.

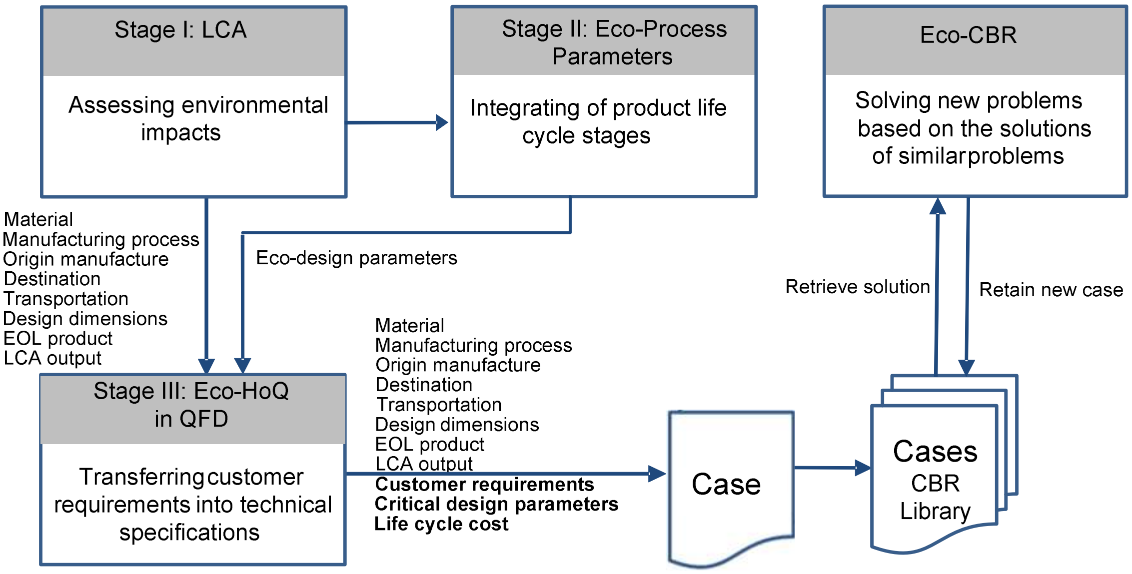


Figure 7.1: The integrated eco-design decision making (IEDM) tool

The IEDM tool is demonstrated in this case study with the design of an office chair base, as shown in Figure 7.2. The part selected was five-pointed office chair base made of nylon and aluminium alloy provided by Orangebox, a UK-based manufacturer. The design of office chair base is produced follows the specification for performance requirements and tests for office furniture based on the British standard *BS 5459-2:2000 +A2:2008* (British Standard, 2008)

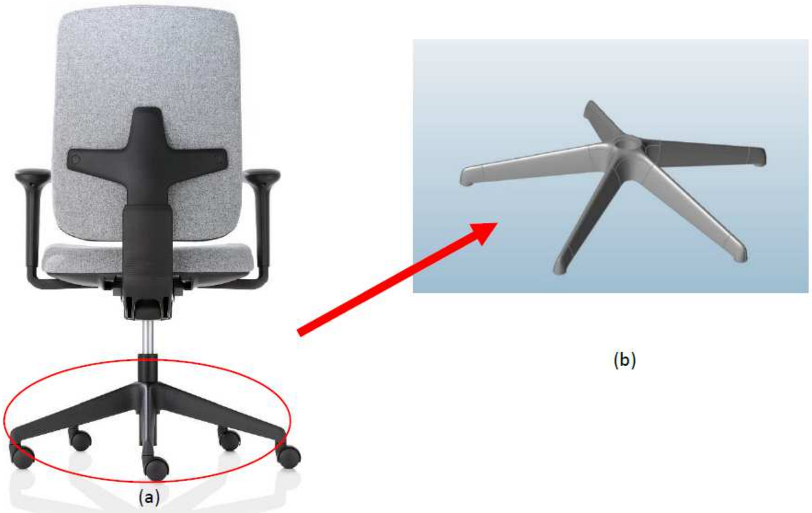


Figure 7.2: Office chair base (Orangebox, 2014)

The aim of this study was to show how effectively the IEDM tool can be implemented and demonstrated in the process of product design. Table 7.1 shows the current design of the office chair base. IEDM tool provides designers with quantitative measures (production cost, environmental cost, and transportation cost) to help them explore sustainable product design for materials, manufacturing processes, and transportation routes and means, as shown in Table 7.1.

Table 7.1: Product design knowledge

Design	Material	Manufacturing Process	Transportation
Office chair base	Nylon	Injection moulding	Material and product: UK – UK (Truck)
	Aluminium alloy	Die casting	Material and product: UK – UK (Truck)

7.2 Stage I: Product Requirements Using LCA

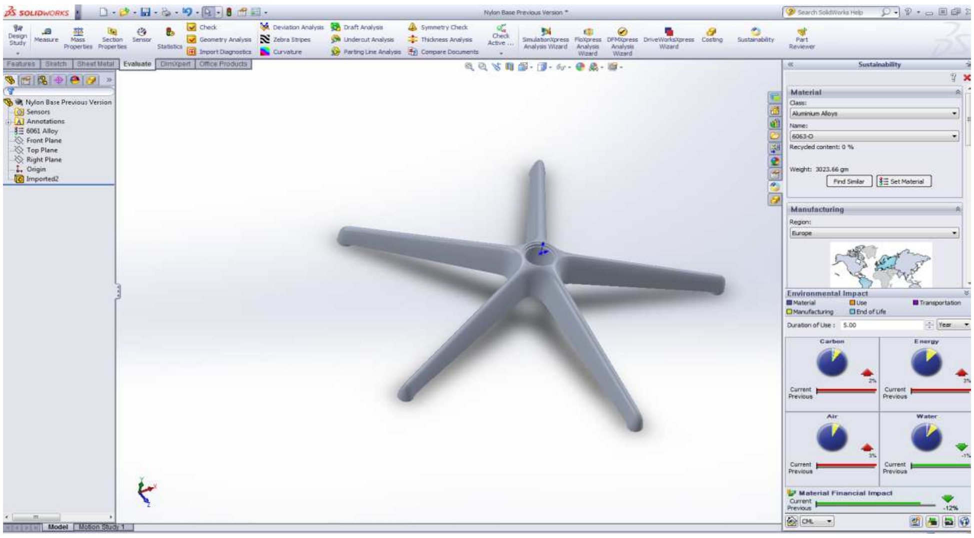
In Stage I, the features of the chair base were analysed. The products are currently manufactured from nylon using an injection moulding process or aluminium alloy using die casting. The functional requirements for this part are indicated in the product brochure (Orangebox, 2014) based on the *BS 5459-2:2000 +A2:2008* (British Standard, 2008):

i. A chair with a five-point legs (wide base) is needed for added stability. The *BS 5459-2:2000 +A2:2008* states that the chair should be able to withstand a maximum weight of 150kg for up to 24 hours of normal usage.

ii. The chair base must have a five-point unit with castors that will roll across carpeted floors. The castors should be large enough so it only takes a minimum effort to move the chair.

iii. The five-point base will measure not less than 570 mm across. The roller castors should be removable and capable of being replaced.

In this case study, the LCA as shown in Figure 7.1 was initiated as the first stage of the IEDM tool to determine and compare the attributes of the office chair base manufactured using two different materials, nylon and aluminium alloy. Figure 7.3 shows the SolidWorks software that provided the sustainability analysis of the detailed LCA that covered the product's entire life cycle. Table 7.2 presents the analysis of the two different materials for the office chair base with their associated environmental impacts.



Class: Aluminium Alloys
Name: 6063-O
Recycled content: 0 %
Weight: 3023.66 gm
Region: Europe
Duration of Use : 5.00 Year

Figure 7.3: SolidWorks Sustainability software

Figure 7.4 depicts the results of the LCA. These results use the standard units for the carbon footprint (kg CO_2), water eutrophication (kg PO_4), air acidification (kg SO_2), and total energy consumed (MJ). Measuring these impacts will help the designer to produce a better design for the environment. The difference between nylon to aluminium alloy, as shown in Figure 7.4, the environmental impact is high with an increase in carbon footprint (146%), air acidification (834%), water eutrophication (108.3), and total energy consumed (94%). The weight of a product or part is usually correlated to its environmental impact, and nylon has more potential to produce lighter products than aluminium alloy do. Table 7.2 shows the environmental impact of this material switch to the life cycle of the chair base.

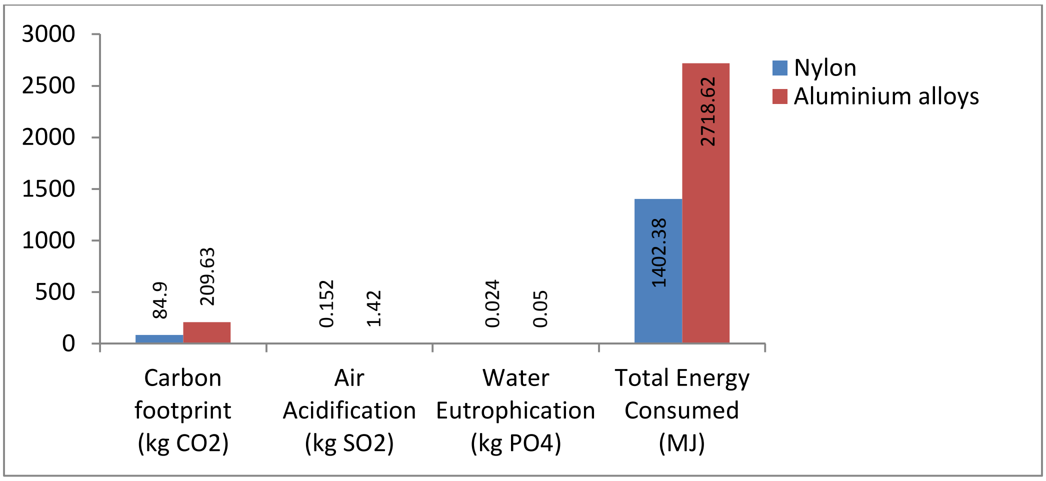


Figure 7.4: Results of the environmental impact

Table 7.2: Environmental impact of office chair base: nylon vs. aluminium alloy

Criteria	Nylon	Aluminium alloy
Material	Nylon 101	Alloy 1060
Type of manufacturing process	Injection moulding	Die casting
Manufacturing region	Europe	Europe
Use region	Europe	Europe
Transportation	Truck	Truck
Weight (kg)	1.287	3.023
Distance (km)	2000	2000
Recycle rate at EOL (%)	100%	100%
Carbon footprint	**kg CO_2**	**kg CO_2**
Material	77.43	192.06
Manufacturing	6.86	16.14
Use	0.00	0.00
Transportation	0.61	1.43
End-of-life	0.00	0.00
Total	**84.9**	**209.63**
Water eutrophication	**kg PO_4**	**kg PO_4**
Material	0.021	0.04
Manufacturing	0.002	0.01
Use	0.00	0.00
Transportation	0.001	0.00
End-of-life	0.00	0.00
Total	**0.024**	**0.05**
Air acidification	**kg SO_2**	**kg SO_2**
Material	0.103	1.30
Manufacturing	0.046	0.11
Use	0.00	0.00
Transportation	0.003	0.01
End-of-life	0.00	0.00
Total	**0.152**	**1.42**
Energy consumed	**MJ**	**MJ**
Material	1262.76	2389.99
Manufacturing	130.63	307.52
Use	0.00	0.00
Transportation	8.99	21.11
End-of-life	0.00	0.00
Total	**1402.38**	**2718.62**

7.3 Stage II: Integration of the Eco-Process Model

As shown in Figure 7.1, the results obtained from Stage I (LCA) were incorporated into Stage II (Eco-Process model), as discussed in Section 4.3 of Chapter IV. The parameters selected here were enhanced and modified based on the previous case study (medical forceps). Tables 7.3 and 7.4 show the input parameters that were used in the Eco-HoQ in Stage III (Eco-QFD). These parameters come together with cross-referencing attributes from the Eco-Process model, as shown in Figure 3.6 in Chapter III.

Table 7.3: List of parameters for the quality characteristics (QCs)

Quality characteristics (QCs)	Attributes
Weight	Material usage, product use, transport, EOL product
Volume of product	Transport, product use, potential to reuse, potential to recycle, potential for remanufacturing, landfill disposal, incineration
Number of parts	Product durability, product lifespan, potential to reuse, potential to recycle, potential for remanufacturing, landfill disposal, incineration
Number of materials	Potential to reuse, potential to recycle, potential for remanufacturing, landfill disposal, incineration
Product durability	Product lifespan, potential to reuse, potential to recycle, potential for remanufacturing, landfill disposal, incineration.
Product life span	Product durability, potential to reuse, potential to recycle, potential for remanufacturing, landfill disposal, incineration
Carbon footprint	Transportation and manufacturing region, resources, material usage, potential to reuse, potential to recycle, product usage, potential for remanufacturing, landfill disposal, incineration
Water eutrophication	
Air acidification	
Total energy consumed	
Manufacturing region	Easy to transport and retain, distance, product use
Transportation	
Rate of recycled materials	Number of materials, potential to recycle
Easy to disassemble	Number of parts, potential to reuse
Easy to clean	Number of parts, potential to reuse

Table 7.4: List of parameters for the demanded qualities (DQs)

Demanded Qualities (DQs)	Attributes
Less material usage	Number of materials, weight, number of parts, production volume, product durability, less environmental impact, transportation, rate of recycled material
Meets laws and regulations	Less environmental impact, transportation and manufacturing region, product lifespan
Easy to process and assemble	Production volume, number of materials, number of parts, product specifications, environmental impacts, transportation and manufacturing region, product lifespan
Easy to transport and retain	Weight, production volume, number of parts, parts' dimensions, less environmental impact
Low environmental cost	Less carbon footprint, less energy consumption, less water eutrophication, less air acidification, potential to reuse, potential to recycle, potential for remanufacturing
Low production cost	Weight of material usage, rate of virgin material, rate of recycled material, number of materials, production volume, design durability, product lifespan, potential to reuse, potential to recycle, potential for remanufacturing
Environmentally smarter	Lower carbon footprint, less energy consumption, less water eutrophication, less air acidification, potential to reuse, potential to recycle, potential for remanufacturing
Potential to recycle	Number of materials, number of parts, less environmental impact
Potential to reuse	Number of parts, easy to disassemble, easy to clean, less environmental impact
Safe to landfill	Weight, number of parts, number of materials, lower carbon footprint, air acidification, water eutrophication
Safe to incinerate	Weight, number of parts, number of materials, less total energy consumption

7.4 Stage III: Eco-QFD Relationship for the Office Chair Base

The objective of the third stage was to identify the best eco-design product for the chair base using the Eco-QFD model. Figure 7.5 illustrates the links between the Eco-HoQ model and the four QFD phases. In this case study, the focus was only on assessing the relationship between Eco-HoQ and Phases I and II of Eco-QFD. The assessment for the Eco-QFD has been done in consultation with the company (Orangebox) and design engineer, Dr Shwe Soe from Advanced Sustainable Manufacturing Technologies (ASTUTE).

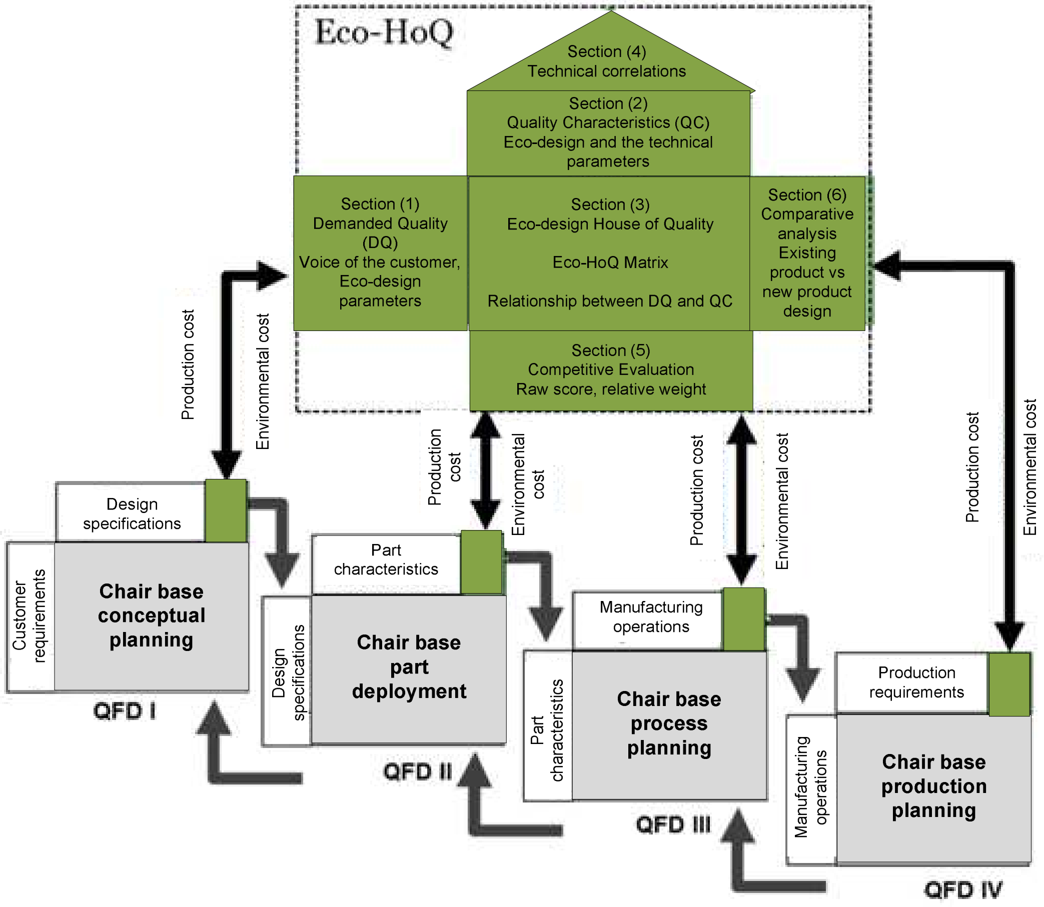
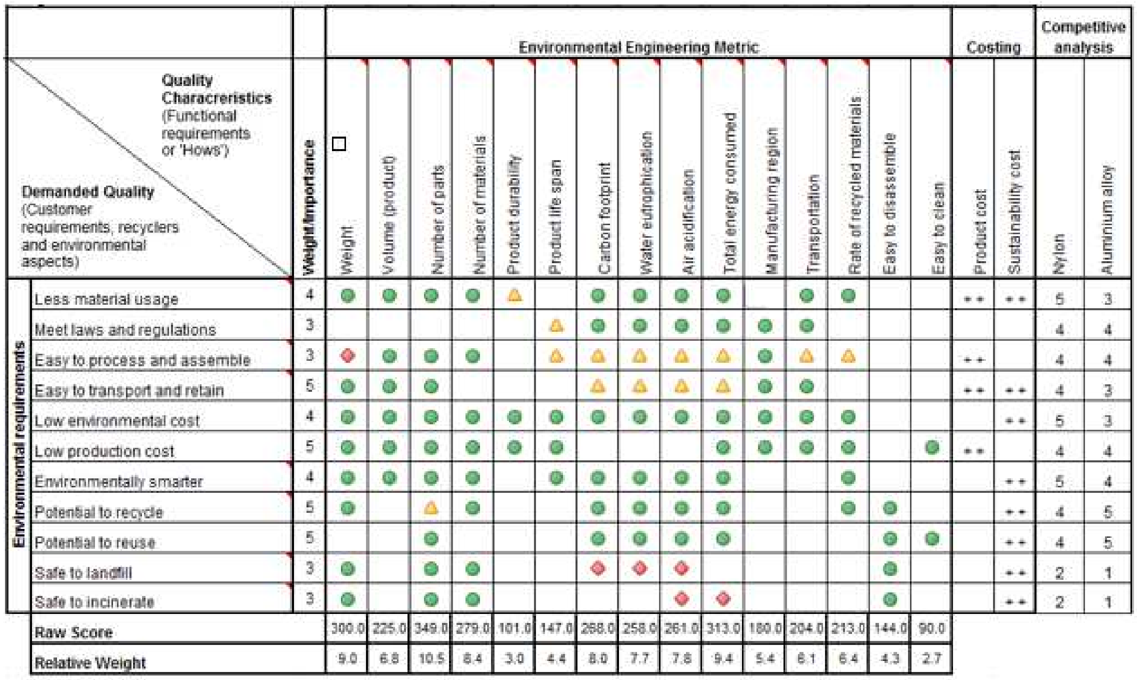


Figure 7.5: Conceptual model of EcoHoQ with enhanced QFD process (Eco-QFD)

To continue the development of this reengineered product, the LCA results from Stage I and the relationships between eco-design parameters in Stage II were integrated into the Eco-HoQ, as shown in Figure 7.6. All of the eco-design parameters were assigned a weighting factor to establish the relationship between demanded qualities (DQ) and quality characteristics (QC). The weighting factors for Eco-HoQ, and Eco-QFD (Phase I and II) were established with assigned values from Dr Shwe Soe as a design engineer of ASTUTE. The symbols adopted in this study have the following meanings and associated values:

i. ● Strong positive relationship with a value of 9
ii. ▲Marginally positive relationship with a value of 5
iii. ♦ Weak relationship with a value of 1

The competitive analysis columns in Figure 7.6 shows the competitive analysis between the chair base made with nylon and the one made with aluminium alloy. The analysis was executed based on the LCA assessment conducted in Stage I, which is shown in Table 7.2. The analysis shows that the chair base made from nylon produces less weight with a lower environmental cost. The information generated by this assessment was used in QFD Phases I and II.



				Environmental Engineering Metric													Costing		Competitive analysis	
	Demanded Quality (Customer requirements, recyclers and environmental aspects) / **Quality Characreristics** (Functional requirements or 'Hows')	**Weight/Importance**	☐ Weight	Volume (product)	Number of parts	Number of materials	Product durability	Product life span	Carbon footprint	Water eutrophication	Air acidification	Total energy consumed	Manufacturing region	Transportation	Rate of recycled materials	Easy to disassemble	Easy to clean	Product cost	Sustainability cost	Nylon	Aluminium alloy
Environmental requirements	Less material usage	4	●	●	●	●	△		●	●	●	●		●	●			++	++	5	3
	Meet laws and regulations	3						△	●	●	●	●	●	●						4	4
	Easy to process and assemble	3	◆	●	●	●		△	△	△	△	△	●	△	△			++		4	4
	Easy to transport and retain	5	●	●	●				△	△	△	△	●	●				++	++	4	3
	Low environmental cost	4	●	●	●	●	●	●	●	●	●	●	●	●	●				++	5	3
	Low production cost	5	●	●	●	●	●	●				●	●	●	●		●	++		4	4
	Environmentally smarter	4	●	●	●	●		●	●	●	●	●			●				++	5	4
	Potential to recycle	5	●		△	●			●	●	●	●			●	●			++	4	5
	Potential to reuse	5			●				●	●	●	●				●	●		++	4	5
	Safe to landfill	3	●		●	●			◆	◆	◆					●			++	2	1
	Safe to incinerate	3	●		●	●					◆	◆				●			++	2	1
	Raw Score		300.0	225.0	349.0	279.0	101.0	147.0	268.0	258.0	261.0	313.0	180.0	204.0	213.0	144.0	90.0				
	Relative Weight		9.0	6.8	10.5	8.4	3.0	4.4	8.0	7.7	7.8	9.4	5.4	6.1	6.4	4.3	2.7				

Figure 7.6: Eco-HoQ for the chair base

The relative weight was calculated and used to establish a critical environmental engineering metric for the Eco-HoQ process. After the analysis was completed for all parameters, the results indicated that the five most influential environmental considerations with the highest impact on product sustainability were (with relative weight factor): number of parts (10.5), total energy consumed (9.4), weight (9.0), number of materials (8.4), and carbon footprint (8.0). The importance ranking for the QCs provides a relative measure of each QC parameter in achieving the collective environmental requirements. This ranking can be useful in making trade-off decisions in situations that involve sacrificing one quality in order to gain another. The result generated by this assessment also will be used in QFD Phases I and II.

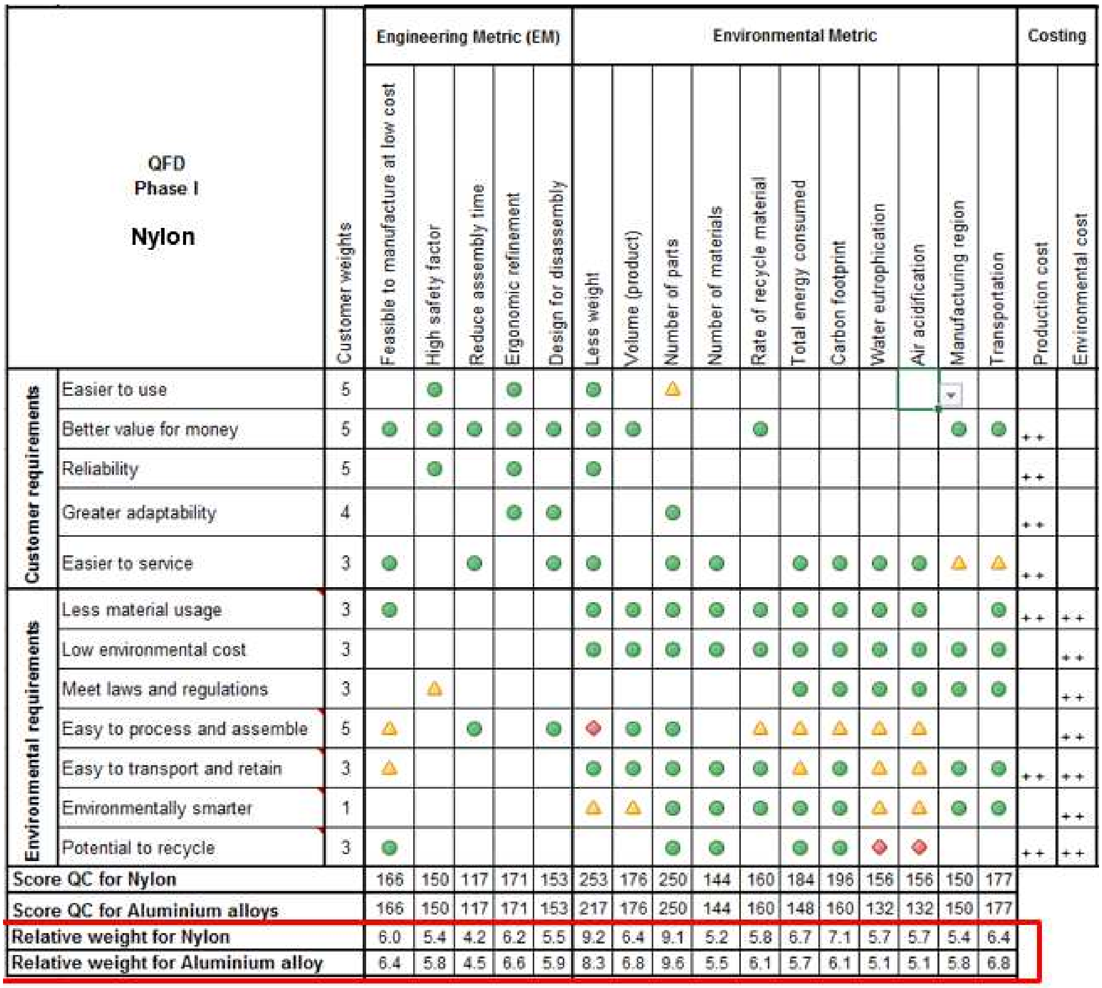
7.4.1 Eco-QFD Phase I

Figure 7.5 shows Eco-QFD Phase I for nylon and the results for both products (nylon and aluminium alloy) that are indicated in the red line. Eco-QFD Phase I uses the product planning matrix “chair base conceptual planning”, as shown in Figure 7.5. In this phase, the DQ section consists of two categories: customer and environmental requirements. The requirements from the customer were based on the study of the development for the office chair base product (Orangebox, 2014). The designer assesses the importance of these requirements alongside the customer’s DQ priorities, using values from 1 (not important) to 5 (very important).

The QC inputs in this phase include those that were acquired from the design specification of the product and the eco-design parameters retrieved from the Eco-HoQ. All of the eco-design parameters were assigned a weighting factor to establish the relationship between DQs and QCs. The relationship between DQs and QCs is central to the entire concept of design specification. The symbol ‘++’ in the costing columns represents parameters that contribute most to the environmental and production costs. The results of the analysis for the nylon and aluminium alloy chair bases are shown at the bottom of Figure 7.7 and are indicated with a red line.

The priority rankings for the QC parameters are divided to two categories: the engineering metric and the environmental metric, as shown in Figure 7.8. For the engineering metric, the priority rankings for the nylon and aluminium alloy products are the same in the following areas: ergonomic refinement, feasible to manufacture at low cost, design for disassembly, high safety factor, and reduced assembly time.

In the environmental metric of the product made with aluminium alloy, the ranking for the QC parameter is shown from the largest number to the smallest number in Figure 7.8. In the environmental metric for the nylon chair base, however, the ranking is slightly different than the aluminium alloy product.



QFD Phase I **Nylon**			Engineering Metric (EM)					Environmental Metric											Costing	
		Customer weights	Feasible to manufacture at low cost	High safety factor	Reduce assembly time	Ergonomic refinement	Design for disassembly	Less weight	Volume (product)	Number of parts	Number of materials	Rate of recycle material	Total energy consumed	Carbon footprint	Water eutrophication	Air acidification	Manufacturing region	Transportation	Production cost	Environmental cost
Customer requirements	Easier to use	5		●		●		●		△										
	Better value for money	5	●	●	●	●	●	●	●			●					●	●	+ +	
	Reliability	5		●		●		●											+ +	
	Greater adaptability	4				●	●			●									+ +	
	Easier to service	3	●		●		●	●		●	●		●	●	●	●	△	△	+ +	
Environmental requirements	Less material usage	3	●					●	●	●	●	●	●	●	●	●		●	+ +	+ +
	Low environmental cost	3						●	●	●	●	●	●	●	●	●	●	●		+ +
	Meet laws and regulations	3		△									●	●	●	●	●	●		+ +
	Easy to process and assemble	5	△		●		●	◆	●	●		△	△	△	△	△				+ +
	Easy to transport and retain	3	△					●	●	●	●	●	△	●	△	△	●	●	+ +	+ +
	Environmentally smarter	1						△	△	●	●	●	●	●	△	△	●	●		+ +
	Potential to recycle	3	●							●	●		●	●	◆	◆			+ +	+ +
Score QC for Nylon			166	150	117	171	153	253	176	250	144	160	184	196	156	156	150	177		
Score QC for Aluminium alloys			166	150	117	171	153	217	176	250	144	160	148	160	132	132	150	177		
Relative weight for Nylon			6.0	5.4	4.2	6.2	5.5	9.2	6.4	9.1	5.2	5.8	6.7	7.1	5.7	5.7	5.4	6.4		
Relative weight for Aluminium alloy			6.4	5.8	4.5	6.6	5.9	8.3	6.8	9.6	5.5	6.1	5.7	6.1	5.1	5.1	5.8	6.8		

Figure 7.7: QFD Phase I

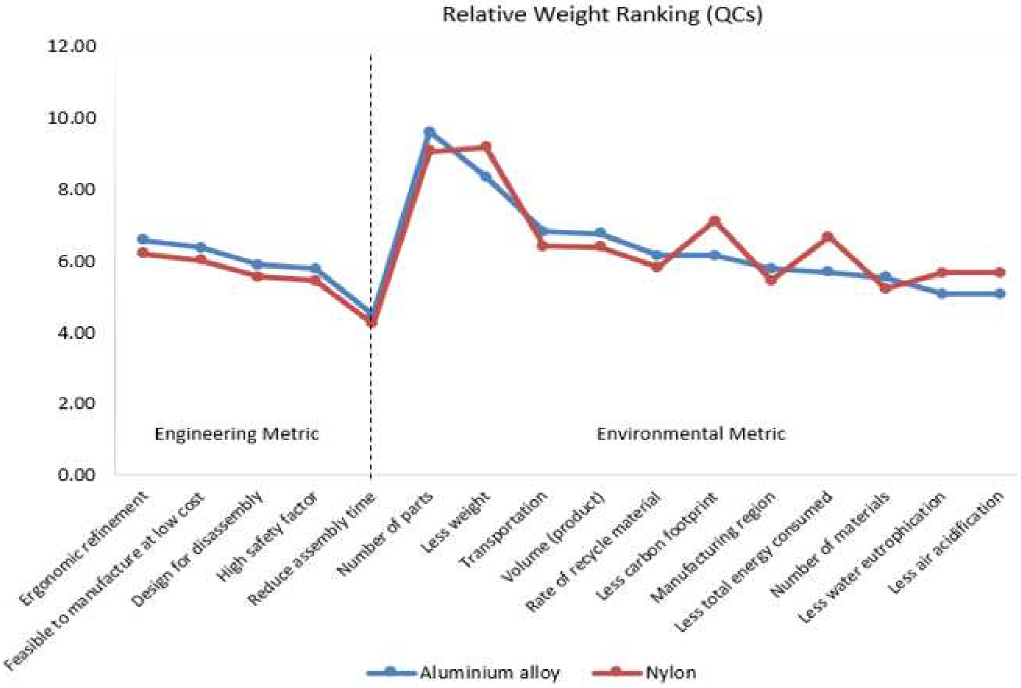
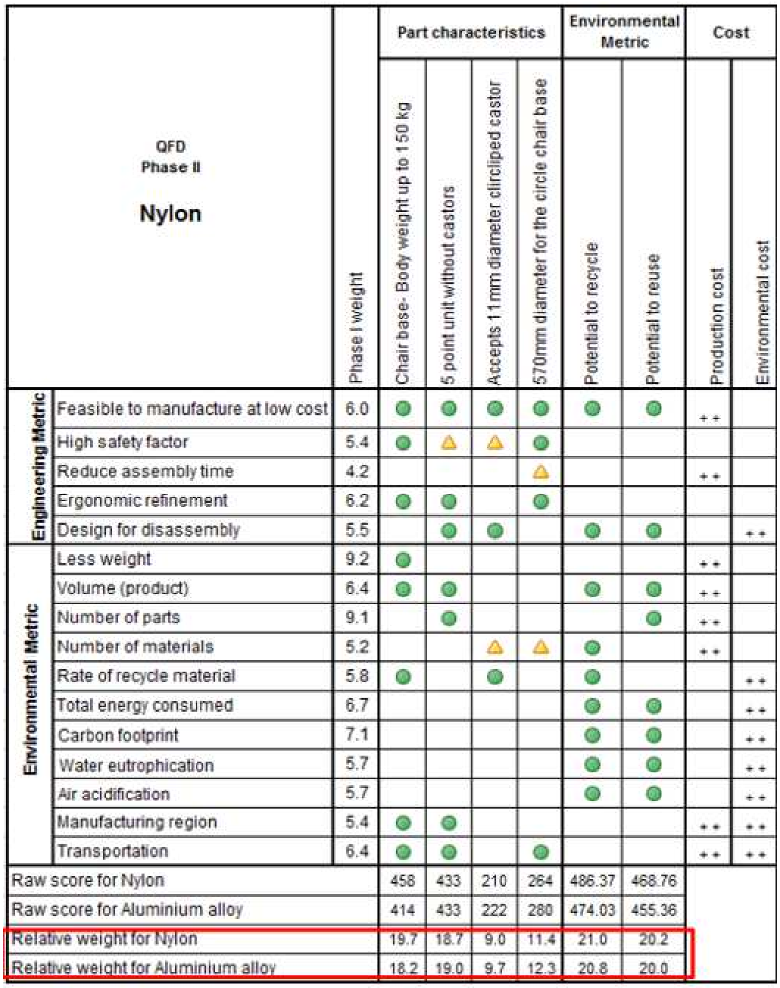


Figure 7.8: Comparison of the relative weight of QCs

The rankings for the nylon chair base were as follows: less weight (9.2), number of parts (9.1), carbon footprint (7.1), total energy consumed (6.7), volume (product) (6.4), transportation (6.4), rate of recycled material (5.8), water eutrophication (5.7), air acidification (5.7), manufacturing region (5.4) and number of materials (5.2). The relative weight for the QC parameters will help the designer identify the main parameters for consideration in conceptual planning for the chair base. The QC parameters with relative weights will be assessed to the next phase (Eco-QFD Phase II) and become as input parameters to the DQs.

7.4.2 Eco-QFD Phase II

Figure 7.9 shows Phase II of the Eco-QFD for nylon and the results for both products with the analysis section populated for part deployment. The DQ parameters with the weights in this phase were retrieved from the QCs in QFD Phase I.



QFD Phase II Nylon			Part characteristics				Environmental Metric		Cost	
		Phase I weight	Chair base- Body weight up to 150 kg	5 point unit without castors	Accepts 11mm diameter clirciped castor	570mm diameter for the circle chair base	Potential to recycle	Potential to reuse	Production cost	Environmental cost
Engineering Metric	Feasible to manufacture at low cost	6.0	●	●	●	●	●	●	++	
	High safety factor	5.4	●	△	△	●				
	Reduce assembly time	4.2				△			++	
	Ergonomic refinement	6.2	●	●		●				
	Design for disassembly	5.5		●	●		●	●		++
Environmental Metric	Less weight	9.2	●						++	
	Volume (product)	6.4	●	●			●	●	++	
	Number of parts	9.1		●				●	++	
	Number of materials	5.2			△	△	●		++	
	Rate of recycle material	5.8	●		●		●			++
	Total energy consumed	6.7					●	●		++
	Carbon footprint	7.1					●	●		++
	Water eutrophication	5.7					●	●		++
	Air acidification	5.7					●	●		++
	Manufacturing region	5.4	●	●					++	++
	Transportation	6.4	●	●		●			++	++
Raw score for Nylon			458	433	210	264	486.37	468.76		
Raw score for Aluminium alloy			414	433	222	280	474.03	455.36		
Relative weight for Nylon			19.7	18.7	9.0	11.4	21.0	20.2		
Relative weight for Aluminium alloy			18.2	19.0	9.7	12.3	20.8	20.0		

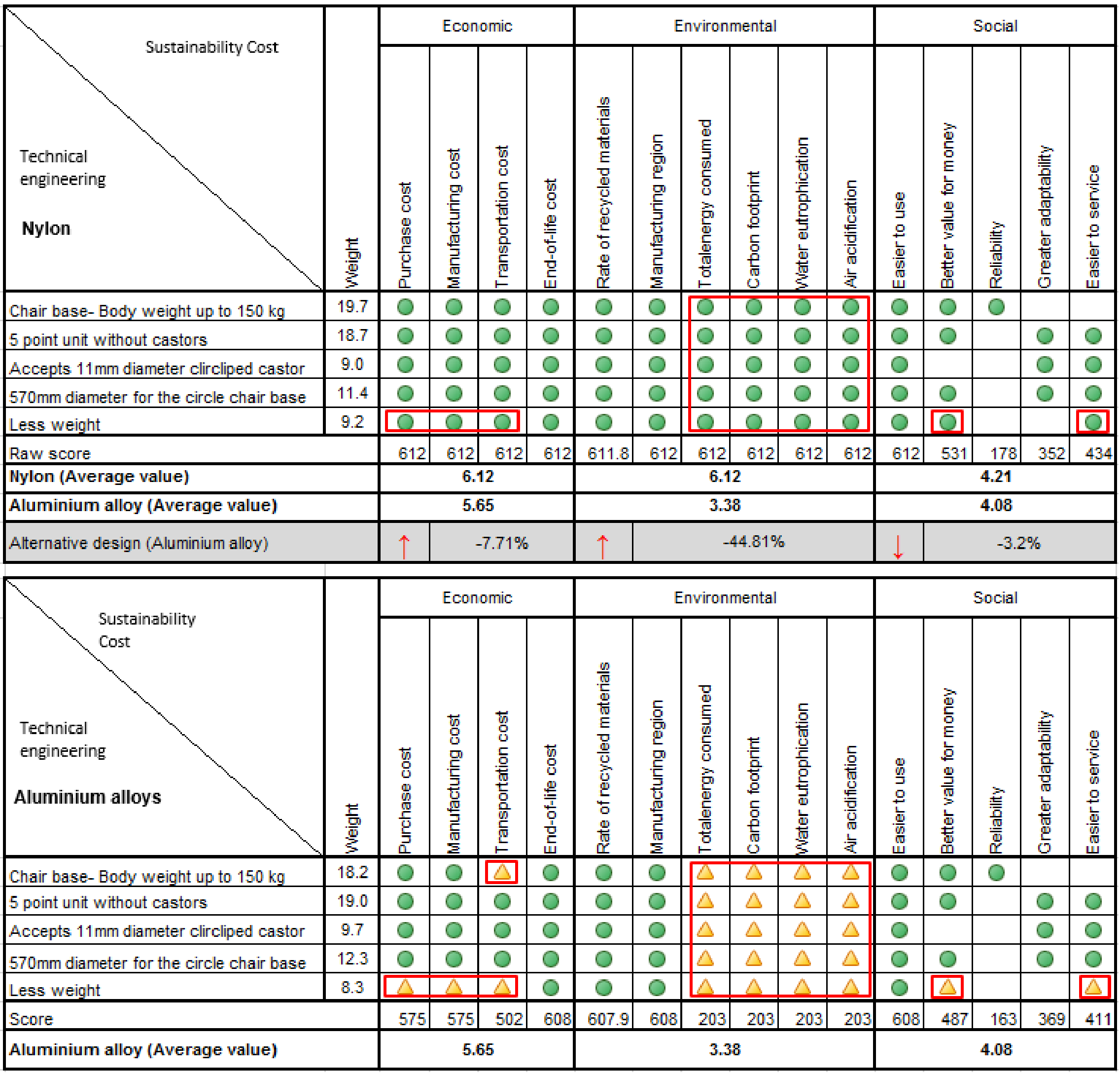
Figure 7.9: QFD Phase II

The results of this process show that the most critical feature of the chair base is its weight, which can accommodate safety loads up to 150 kilograms. This was followed by the following features: a five-point unit without castors, a 570 millimetre diameter for the chair base, and that it accepts 11 millimetre diameter clircliped castor. For the environmental metric category, the most important parameter was the potential to recycle the product followed by the potential to reuse it. This phase should allow the designer to focus on the most important aspects of the products. This analysis can then be continued by asserting that when made using nylon the chair base can have a lower environmental impact than the base made with aluminium alloy. The summary of the sustainability indicators, which are environmental impact, economic cost, and social factors (customer requirements), will be discussed in the Eco-HOQ model assessment in the next section.

7.4.3 Eco-HoQ: Summary Indicator

Figure 7.10 shows the Eco-HoQ model, which, as depicted in Figure 7.5, acts as a master platform for analysing the contributions of the sustainable product design parameters retrieved from the Eco-QFD phases.

The parameters in the economic category were: purchase cost, manufacturing cost, transportation cost, and end-of-life cost. They were retrieved from Eco-QFD Phases I and II. For the environmental category, the parameters were: rate of recycled materials, number of materials, manufacturing region, carbon footprint, water eutrophication, and air acidification; these were derived from the Eco-QFD phases. The last category is social (customer requirements), which had the following parameters: easier to use, better value for money, reliability, greater adaptability, and easier to service. All these parameters were derived from Eco-QFD Phase I.



Sustainability Cost Technical engineering **Nylon**		Economic				Environmental						Social				
	Weight	Purchase cost	Manufacturing cost	Transportation cost	End-of-life cost	Rate of recycled materials	Manufacturing region	Totalenergy consumed	Carbon footprint	Water eutrophication	Air acidification	Easier to use	Better value for money	Reliability	Greater adaptability	Easier to service
Chair base- Body weight up to 150 kg	19.7	●	●	●	●	●	●	●	●	●	●	●	●	●		
5 point unit without castors	18.7	●	●	●	●	●	●	●	●	●	●	●	●		●	●
Accepts 11mm diameter clircliped castor	9.0	●	●	●	●	●	●	●	●	●	●	●			●	●
570mm diameter for the circle chair base	11.4	●	●	●	●	●	●	●	●	●	●	●	●		●	●
Less weight	9.2	●	●	●	●	●	●	●	●	●	●	●	●			●
Raw score		612	612	612	612	611.8	612	612	612	612	612	612	531	178	352	434
Nylon (Average value)		**6.12**				**6.12**						**4.21**				
Aluminium alloy (Average value)		**5.65**				**3.38**						**4.08**				
Alternative design (Aluminium alloy)		↑	-7.71%			↑	-44.81%					↓	-3.2%			

Sustainability Cost Technical engineering **Aluminium alloys**		Economic				Environmental						Social				
	Weight	Purchase cost	Manufacturing cost	Transportation cost	End-of-life cost	Rate of recycled materials	Manufacturing region	Totalenergy consumed	Carbon footprint	Water eutrophication	Air acidification	Easier to use	Better value for money	Reliability	Greater adaptability	Easier to service
Chair base- Body weight up to 150 kg	18.2	●	●	⚠	●	●	●	⚠	⚠	⚠	⚠	●	●	●		
5 point unit without castors	19.0	●	●	●	●	●	●	⚠	⚠	⚠	⚠	●	●		●	●
Accepts 11mm diameter clircliped castor	9.7	●	●	●	●	●	●	⚠	⚠	⚠	⚠	●			●	●
570mm diameter for the circle chair base	12.3	●	●	●	●	●	●	⚠	⚠	⚠	⚠	●	●		●	●
Less weight	8.3	⚠	⚠	⚠	●	●	●	⚠	⚠	⚠	⚠	●	⚠			⚠
Score		575	575	502	608	607.9	608	203	203	203	203	608	487	163	369	411
Aluminium alloy (Average value)		**5.65**				**3.38**						**4.08**				

Figure 7.10: Eco-HoQ model summary: sustainability categories (nylon and aluminium alloy)

The different weighting factors in each group are highlighted with a red box in Figure 7.10. Negative values for the alternative design box show that economic cost and environmental cost bring out higher cost and for the social category means that it is lower cost than the other product. The analysis shows that the economic cost and environmental cost for the aluminium alloy product are higher than the chair base made with nylon, with respective values of -7.7% and -44.8%. Meanwhile, for the social (customer requirements) category, the chair base made with aluminium alloy received slightly low customer satisfaction (3.2%) than the one made with nylon.

7.5 Developing a Case in the Eco-CBR Tool

The output from the Eco-QFD process should be used to develop improved design solutions and to identify critical product features from the eco-design process. This process continues with the development of the Eco-CBR tool that stores all the existing cases in a case-based library. Figure 7.11 shows an example of the case of the nylon chair base. The case consists of two sections: the problem and the solution. The features used in this case are generic and have been discussed in Chapter VI.

Several types of materials were assessed; these are nylon 101, nylon 6/10, alloy 1060, and alloy 6061, selected on the basis of existing chair bases in the market (Caford NZ Ltd, 2013). The manufacturer (Orangebox company) confirms that these materials are 100% recyclable at its EOL. From this study, 24 cases were assessed and stored in the CBR library as part of the application of the Eco-CBR tool, as shown in the IEDM framework in Figure 7.1. This research used case-based reasoning references to search for design parameters in order to achieve sustainable solutions to design problems. Eco-QFD was expanded to guide the search of competitive products using Eco-CBR to meet quantitative targets and to increase knowledge of sustainable product designs. Figure 7.12 shows the existing cases in the Eco-CBR library.

7.6 Eco-CBR Tool

The objective of the Eco-CBR tool developed in this study was to support the process of product design knowledge and to add to and maintain the library of cases in an organised way. Eco-CBR was developed to generate solutions for new product designs by finding similarities with previous design cases held in the Eco-CBR library, which designers can learn from. This section poses solutions for a proposed new case of the redesigned chair base.

PROBLEM:

Transportation: Stage I (LCA) & Stage III (Eco-QFD)
Origin: Europe
Destination: Europe
Transport: Truck
Distance: 2000 km

Material and manufacturing process: Stage I (LCA) & Stage III (Eco-QFD)
Material: Nylon
Weight: 1287 gram
Manufacturing process: Injection moulding
Material recycled content: 0%
Material cost: £0.0036 per gram
Production volume: 50,000

EOL: Stage I (LCA) &Stage III (Eco-QFD)
Recycled: 100%
Incinerated: 0%
Landfill: 0%

Design dimensions: Stage I (LCA) & Stage III (Eco-QFD)
Diameter castor (D1): 11 mm
Height from the top base (D2): 130 mm
Diameter for the base (D3): 570 mm

SOLUTION:

Environmental impact of product life cycle: Stage I (LCA) & Stage III (Eco-QFD)
Carbon footprint (kg CO_2): 84.9
Total energy consumed (MJ): 1402.38
Water eutrophication (kg PO_4): 0.024
Air acidification (kg SO_2): 0.152

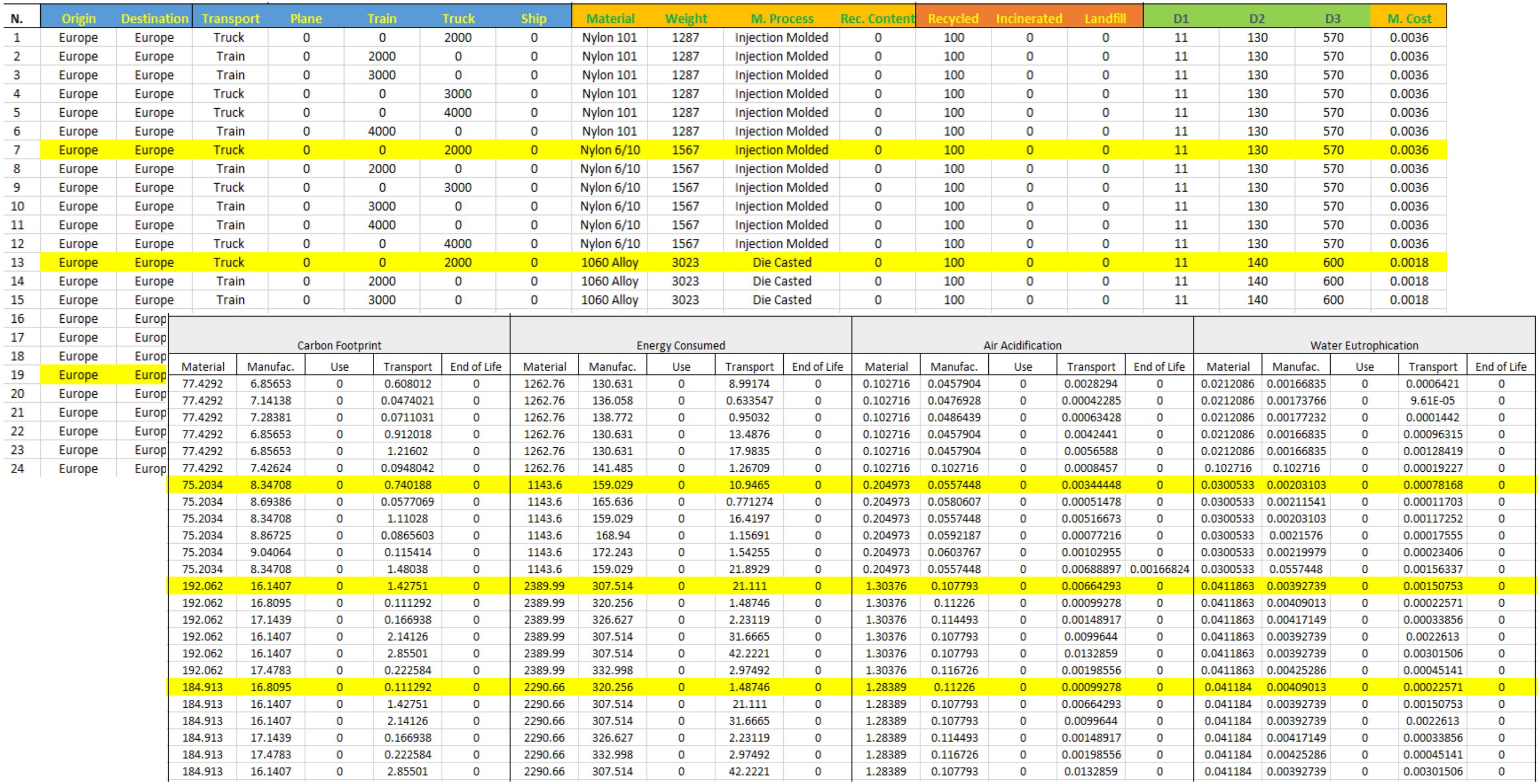
Life-cycle cost: Stage III (Eco-QFD)
Purchasing cost: £4.60 per unit
Environmental cost: £2.91 per unit
Transportation cost: £4.00 per unit
EOL cost: £-2.34
Economic cost: £9.17 per unit

Customer Requirements: Stage III (Eco-QFD)
Easier to use
Better value for money
Reliability
Greater adaptability
Easier to service

Product Design Assessment: Stage III (Eco-QFD)
Valid

Eco-QFD indicators: Stage III (Eco-QFD)
Environmental impact
Product design
Customer requirements

Figure 7.11: Product information for nylon product for the Eco-CBR tool



N.	Origin	Destination	Transport	Plane	Train	Truck	Ship	Material	Weight	M. Process	Rec. Content	Recycled	Incinerated	Landfill	D1	D2	D3	M. Cost
1	Europe	Europe	Truck	0	0	2000	0	Nylon 101	1287	Injection Molded	0	100	0	0	11	130	570	0.0036
2	Europe	Europe	Train	0	2000	0	0	Nylon 101	1287	Injection Molded	0	100	0	0	11	130	570	0.0036
3	Europe	Europe	Train	0	3000	0	0	Nylon 101	1287	Injection Molded	0	100	0	0	11	130	570	0.0036
4	Europe	Europe	Truck	0	0	3000	0	Nylon 101	1287	Injection Molded	0	100	0	0	11	130	570	0.0036
5	Europe	Europe	Truck	0	0	4000	0	Nylon 101	1287	Injection Molded	0	100	0	0	11	130	570	0.0036
6	Europe	Europe	Train	0	4000	0	0	Nylon 101	1287	Injection Molded	0	100	0	0	11	130	570	0.0036
7	Europe	Europe	Truck	0	0	2000	0	Nylon 6/10	1567	Injection Molded	0	100	0	0	11	130	570	0.0036
8	Europe	Europe	Train	0	2000	0	0	Nylon 6/10	1567	Injection Molded	0	100	0	0	11	130	570	0.0036
9	Europe	Europe	Truck	0	0	3000	0	Nylon 6/10	1567	Injection Molded	0	100	0	0	11	130	570	0.0036
10	Europe	Europe	Train	0	3000	0	0	Nylon 6/10	1567	Injection Molded	0	100	0	0	11	130	570	0.0036
11	Europe	Europe	Train	0	4000	0	0	Nylon 6/10	1567	Injection Molded	0	100	0	0	11	130	570	0.0036
12	Europe	Europe	Truck	0	0	4000	0	Nylon 6/10	1567	Injection Molded	0	100	0	0	11	130	570	0.0036
13	Europe	Europe	Truck	0	0	2000	0	1060 Alloy	3023	Die Casted	0	100	0	0	11	140	600	0.0018
14	Europe	Europe	Train	0	2000	0	0	1060 Alloy	3023	Die Casted	0	100	0	0	11	140	600	0.0018
15	Europe	Europe	Train	0	3000	0	0	1060 Alloy	3023	Die Casted	0	100	0	0	11	140	600	0.0018
16	Europe	Europ																
17	Europe	Europ																
18	Europe	Europ																
19	Europe	Europ																
20	Europe	Europ																
21	Europe	Europ																
22	Europe	Europ																
23	Europe	Europ																
24	Europe	Europ																

Carbon Footprint					Energy Consumed					Air Acidification					Water Eutrophication				
Material	Manufac.	Use	Transport	End of Life	Material	Manufac.	Use	Transport	End of Life	Material	Manufac.	Use	Transport	End of Life	Material	Manufac.	Use	Transport	End of Life
77.4292	6.85653	0	0.608012	0	1262.76	130.631	0	8.99174	0	0.102716	0.0457904	0	0.0028294	0	0.0212086	0.00166835	0	0.0006421	0
77.4292	7.14138	0	0.0474021	0	1262.76	136.058	0	0.633547	0	0.102716	0.0476928	0	0.00042285	0	0.0212086	0.00173766	0	9.61E-05	0
77.4292	7.28381	0	0.0711031	0	1262.76	138.772	0	0.95032	0	0.102716	0.0486439	0	0.00063428	0	0.0212086	0.00177232	0	0.0001442	0
77.4292	6.85653	0	0.912018	0	1262.76	130.631	0	13.4876	0	0.102716	0.0457904	0	0.0042441	0	0.0212086	0.00166835	0	0.00096315	0
77.4292	6.85653	0	1.21602	0	1262.76	130.631	0	17.9835	0	0.102716	0.0457904	0	0.0056588	0	0.0212086	0.00166835	0	0.00128419	0
77.4292	7.42624	0	0.0948042	0	1262.76	141.485	0	1.26709	0	0.102716	0.102716	0	0.0008457	0	0.102716	0.102716	0	0.00019227	0
75.2034	8.34708	0	0.740188	0	1143.6	159.029	0	10.9465	0	0.204973	0.0557448	0	0.00344448	0	0.0300533	0.00203103	0	0.00078168	0
75.2034	8.69386	0	0.0577069	0	1143.6	165.636	0	0.771274	0	0.204973	0.0580607	0	0.00051478	0	0.0300533	0.00211541	0	0.00011703	0
75.2034	8.34708	0	1.11028	0	1143.6	159.029	0	16.4197	0	0.204973	0.0557448	0	0.00516673	0	0.0300533	0.00203103	0	0.00117252	0
75.2034	8.86725	0	0.0865603	0	1143.6	168.94	0	1.15691	0	0.204973	0.0592187	0	0.00077216	0	0.0300533	0.0021576	0	0.00017555	0
75.2034	9.04064	0	0.115414	0	1143.6	172.243	0	1.54255	0	0.204973	0.0603767	0	0.00102955	0	0.0300533	0.00219979	0	0.00023406	0
75.2034	8.34708	0	1.48038	0	1143.6	159.029	0	21.8929	0	0.204973	0.0557448	0	0.00688897	0.00166824	0.0300533	0.0557448	0	0.00156337	0
192.062	16.1407	0	1.42751	0	2389.99	307.514	0	21.111	0	1.30376	0.107793	0	0.00664293	0	0.0411863	0.00392739	0	0.00150753	0
192.062	16.8095	0	0.111292	0	2389.99	320.256	0	1.48746	0	1.30376	0.11226	0	0.00099278	0	0.0411863	0.00409013	0	0.00022571	0
192.062	17.1439	0	0.166938	0	2389.99	326.627	0	2.23119	0	1.30376	0.114493	0	0.00148917	0	0.0411863	0.00417149	0	0.00033856	0
192.062	16.1407	0	2.14126	0	2389.99	307.514	0	31.6665	0	1.30376	0.107793	0	0.0099644	0	0.0411863	0.00392739	0	0.0022613	0
192.062	16.1407	0	2.85501	0	2389.99	307.514	0	42.2221	0	1.30376	0.107793	0	0.0132859	0	0.0411863	0.00392739	0	0.00301506	0
192.062	17.4783	0	0.222584	0	2389.99	332.998	0	2.97492	0	1.30376	0.116726	0	0.00198556	0	0.0411863	0.00425286	0	0.00045141	0
184.913	16.8095	0	0.111292	0	2290.66	320.256	0	1.48746	0	1.28389	0.11226	0	0.00099278	0	0.041184	0.00409013	0	0.00022571	0
184.913	16.1407	0	1.42751	0	2290.66	307.514	0	21.111	0	1.28389	0.107793	0	0.00664293	0	0.041184	0.00392739	0	0.00150753	0
184.913	16.1407	0	2.14126	0	2290.66	307.514	0	31.6665	0	1.28389	0.107793	0	0.0099644	0	0.041184	0.00392739	0	0.0022613	0
184.913	17.1439	0	0.166938	0	2290.66	326.627	0	2.23119	0	1.28389	0.114493	0	0.00148917	0	0.041184	0.00417149	0	0.00033856	0
184.913	17.4783	0	0.222584	0	2290.66	332.998	0	2.97492	0	1.28389	0.116726	0	0.00198556	0	0.041184	0.00425286	0	0.00045141	0
184.913	16.1407	0	2.85501	0	2290.66	307.514	0	42.2221	0	1.28389	0.107793	0	0.0132859	0	0.041184	0.00392739	0	0.00301506	0

Figure 7.12: Eco-CBR Library

7.6.1 New Case

A new case for Eco-CBR consists of several features that describe a problem in product design. The new case consists of information classified in four groups (transportation, material and manufacturing process, EOL, and design dimensions), as shown in Figure 7.11. These features are generic and are reused from the IEDM methodology, with the exception of the design dimensions as shown in Figure 7.12. The features for the design dimensions group was specifically designed for the case study of the chair base. The example for the existing case of the nylon chair base is shown in Figure 7.11.

The new case of redesigned chair base has been studied (Stephens et al., 2015). This new case has slightly different values than existing cases as follows: material recycled content is assumed 50% used in this new case to give same strength as existing product; material cost is reduced to £0.0026 per gram because the usage of recycled content; design dimensions is 5% decreased from current design; and weight is proposed 5% lighter than the existing product. This reduction material has been applied by reducing the thickness to a region towards the end of the leg as shown Figure 7.13. For the purposes of this study, the load was set as 2500 N in order to achieve the standard of office furniture: BS 5459-2:2000+A2:2008 (British Standard, 2008).

With these changes in the product’s design dimensions and other features, there is a need to find a solution to the new case. A search of similarities from existing cases in the Eco-CBR library would then be conducted. The process of retrieving and reusing solutions from existing cases would help the designer to revise and apply domain knowledge to the new case (problem). Figure 7.14 presents the input values and their correlating weight (w) assigned by the design engineer for the redesigned chair base, shown here without a solution.

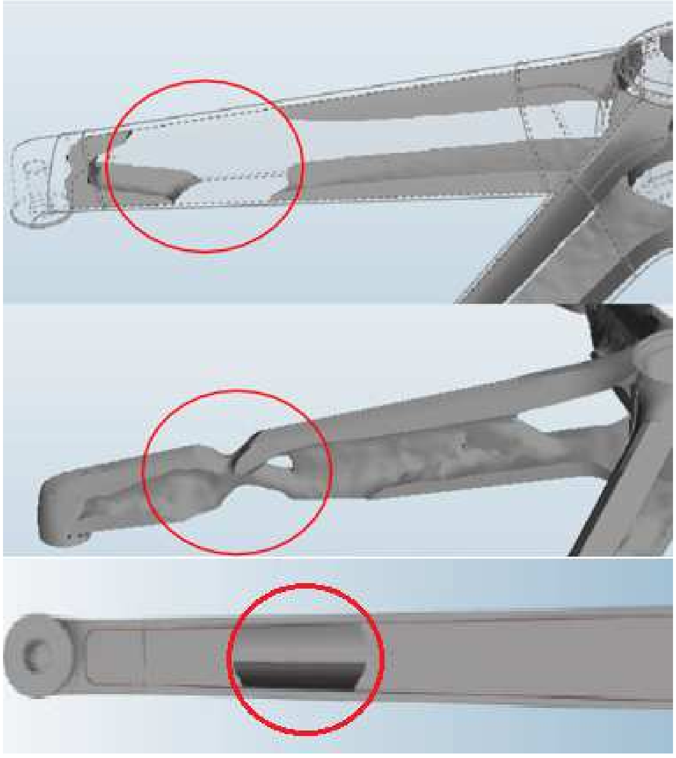


Figure 7.13: Highlighted region of reduced material (Stephens et al., 2015)

NEW CASE (PROBLEM):

Transportation

Origin: Europe (w = 3)
Destination: Europe (w = 3)
Transport: Truck (w = 3)
Distance: 2000 km (w = 3)

Material and manufacturing process

Material: Nylon 101 (w = 5)
Weight: 1223 gram (w = 5)
Manufacturing process: Injection moulded (w = 4)
Material recycled content: 50% (w = 5)
Material cost: £0.0026 per gram (w = 4)
Production volume: 50,000 (w = 4)

EOL

Recycled: 100% (w = 4)
Incinerated: 0 (w = 1)
Landfill: 0 (w = 1)

Design dimensions

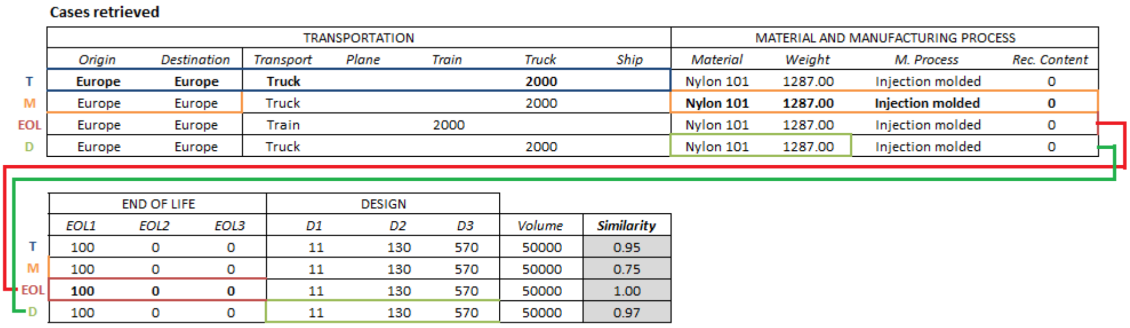
Diameter castor (D1): 11 mm (w = 5)
Height from the top base (D2): 130 mm (w = 5)
Diameter for the base (D3): 570 mm (w = 5)

SOLUTION: ?

Figure 7.14: Input values for the new case with weights (w) assigned

7.6.2 Process of Searching Similarities

The next step would be to search for similarities between the new case (Figure 7.14) and existing cases in the library. Figure 7.15 shows the retrieved cases from the Eco-CBR library that were matched to the new case.



Cases retrieved

	TRANSPORTATION							MATERIAL AND MANUFACTURING PROCESS			
	Origin	*Destination*	*Transport*	*Plane*	*Train*	*Truck*	*Ship*	*Material*	*Weight*	*M. Process*	*Rec. Content*
T	**Europe**	**Europe**	**Truck**			**2000**		Nylon 101	1287.00	Injection molded	0
M	Europe	Europe	Truck			2000		**Nylon 101**	**1287.00**	**Injection molded**	**0**
EOL	Europe	Europe	Train		2000			Nylon 101	1287.00	Injection molded	0
D	Europe	Europe	Truck			2000		Nylon 101	1287.00	Injection molded	0

	END OF LIFE			DESIGN				
	EOL1	*EOL2*	*EOL3*	*D1*	*D2*	*D3*	*Volume*	***Similarity***
T	100	0	0	11	130	570	50000	0.95
M	100	0	0	11	130	570	50000	0.75
EOL	**100**	**0**	**0**	11	130	570	50000	1.00
D	100	0	0	11	130	570	50000	0.97

Figure 7.15: Screenshot of the retrieved cases

The results were based on the highest similarities found in the search process, with similarity “0.95” for the transportation group, “0.75” for the material and manufacturing group, “1.00” for the EOL group, and “0.97” for the design group.

The next stage is applying previous experiences to the new case. If the new case is exactly like the existing case in the library, then the reuse process is simple; the existing solution is copied to the new case. However, if the new case is slightly different than existing cases, then the previous case or cases must be adapted. The recommended solutions from the Eco-CBR library need to be revised and adjusted to solve the new case. In the Eco-CBR method, the process of adaptation is an important step, as it translates the retrieved solutions for the current problem (new case). The information from retrieved cases would be reused in the “Solution” entry for the new case.

7.6.3 Solutions for the New Case

Five categories of solutions that retrieved from the Eco-CBR library were recommended for the new case; these are presented in Figure 7.14.

i. Environmental impact

ii. Cost estimation

iii. Design dimension assessment

iv. Customer requirements

v. Eco-QFD indicators

7.6.3.1 Environmental Impact

Table 7.5 shows the analysis of the solution based on its environmental impact to the product's life cycle. Quantitative data was translated to qualitative data using data from the library as discussed in Section 6.6. These data were set to one of the five rankings: "Very High" (VH), "High" (H), "Medium" (M), "Low" (L), and "Very Low" (VL). By analysing the new case criteria and matching it with the retrieved case, the LCA results in Table 7.5 shows that the values for the retrieved solution were the following for carbon footprint, total energy consumed, air acidification, and water eutrophication, respectively: 84.90 kg CO_2, 1402.38 MJ, 0.1520 kg SO_2, and 0.0240 kg PO_4.

Table 7.5: Screenshot of the solution's LCA

LCA Stage I	**Quantitative:**				**Qualitative:**			
	Carbon FP (kg)	**Energy (kg)**	**Air Acid.(kg)**	**Water Eut.(kg)**	**Carbon FP**	**Energy**	**Air Acid.**	**Water Eut.**
Material	77.4300	1262.76	0.1030	0.0210	Very Low	Very Low	Very Low	Very Low
Manufac.	6.8600	130.63	0.0460	0.0020	Very Low	Very Low	Very Low	Very Low
Use	0.0000	0.0000	0.0000	0.0000	Very Low	Very Low	Very Low	Very Low
Transport.	0.6100	8.99	0.0030	0.0010	Low	Low	Low	Low
EOL	0.0000	0.0000	0.0000	0.0000	Very Low	Very Low	Very Low	Very Low
Total	**84.9000**	**1402.38**	**0.1520**	**0.0240**	**Very Low**	**Very Low**	**Very Low**	**Very Low**

It is worth noting that this solution was retrieved from an existing case that has 0% recycled content. In the new case, the recycled content for the material is 50%. Therefore, the designer must revise this retrieved data by reducing values for the carbon footprint, energy, air acidification, and water eutrophication for the product's material by 50%. Figure 7.16 shows the new environmental impact values after making the necessary revisions.

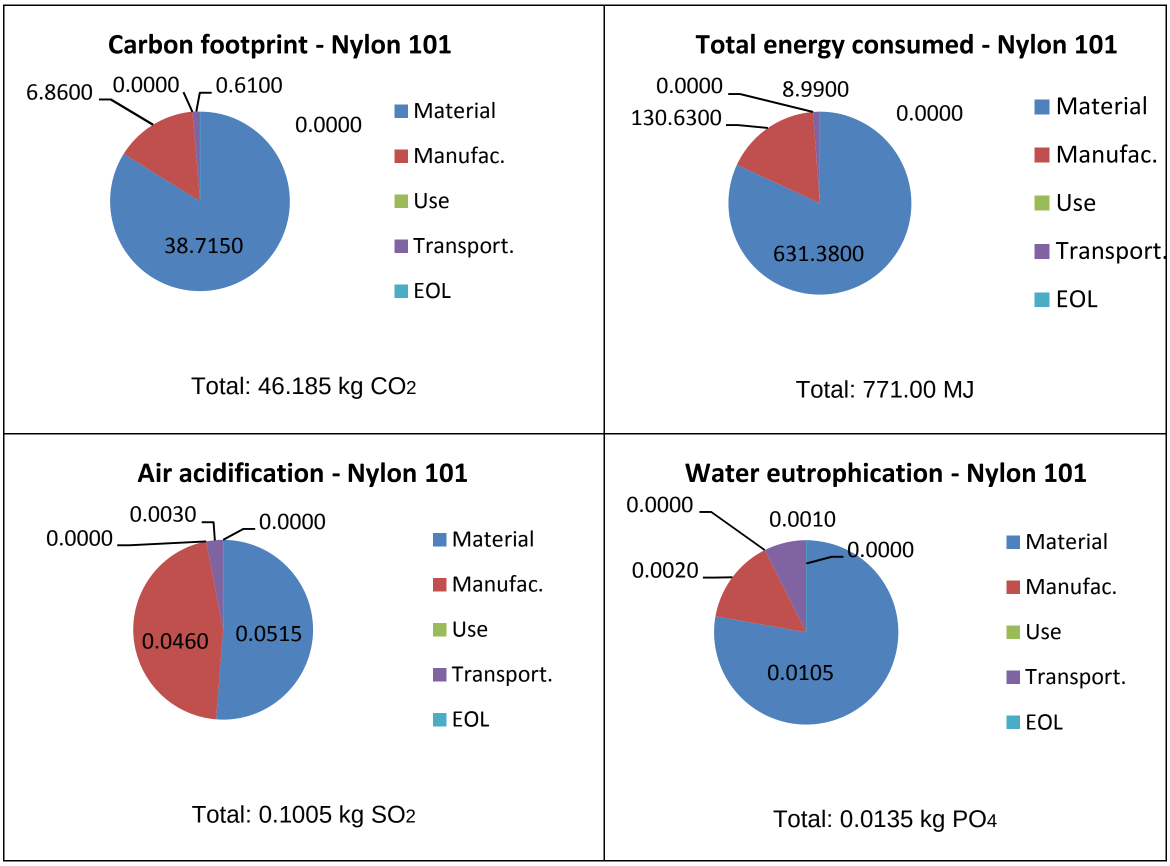


Figure 7.16: Life Cycle Assessment

The new values for this assessment of the environmental impact of the product's material were reduced, becoming 38.715 kg CO_2 (carbon footprint), 0.4133 MJ (energy consumed), 0.0515 kg SO_2 (air acidification), and 0.0105 kg PO_4 (water eutrophication). The designer would appropriate this new solution in the design of the new case and stored in the Eco-CBR library.

7.6.3.2 Cost Estimation

The ecological economic cost (Eco-Economic Cost) model has been used to summarise the developments enabled by the Eco-QFD and Eco-CBR in the IEDM framework. This is discussed in Section 3.5 of Chapter III as a means of implementing the Eco-CBR tool. Table 7.6 shows the cost parameters that used to solve the new case (Figure 7.14) in this study. Purchasing cost of the existing case is received from the manufacturer (Orangebox) without knowing the detail of manufacturing cost (labour cost, overhead cost, and machine cost).

Table 7.6: Cost parameters

Cost parameters	**Nylon 101 (£)**
Purchasing cost (Pc)	4.60
Carbon footprint (CF)	0.018 per kg CO_2
Air acidification (AA)	0.045 per kg SO_2
Water eutrophication (EU)	0.002 per kg PO_4
Energy consumption (EC)	0.001 per MJ
Landfill cost (LFc)	0.110 per kg
Incineration cost (INc)	22 per kg
Recycle value (Rv)	50% of material cost

Table 7.7 shows a screenshot of the solution's cost estimation. It is calculated per unit and also per production (production volume = 50,000). The transportation cost is indicated based on the survey market online for the chair base per unit. The approximate value for the big volume is just considered by times of the production volume.

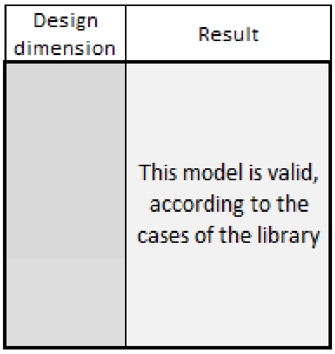
The costs presented in bold in this solution are the estimated costs for the new case, while the non-bold costs refer to the retrieved case from the Eco-CBR library. The summary economic cost is presented in the form of a range, calculated as a minimum and maximum cost for the new case. The economic cost per unit ranged from £6.56, which is the minimum limit, to £9.26, which represents the maximum limit. During the entry of a new case in the library, the system will offer options to the designer either to save the estimated cost or the retrieved cost, based on the user preference.

Table 7.7: Screenshot for the cost estimation

Product life cycle	Cost (£)	
	Per unit	Per production (50,000)
Purchasing	[4.63, **3.18**]	[231 500, **159 000**]
Transportation	[4.00, **4.00**]	[200 000, **200 000**]
Environmental	[2.94, **2.94**]	[147 000, **147 000**]
End-of-Life	[-1.68, **-1.60**]	[-84 000, **-80 000**]
ECONOMIC COST	**[8.44 - 9.97]**	**[422 000 - 498 500]**

7.6.3.3 Design Dimension Assessment

Figure 7.17 shows the solution for the product dimensions. It was proposed with the message alert *“This model is valid, according to the cases of the library”*. Here, it shows that changes in the design dimensions for the new case were valid based on the design assessment of the library cases.



Design dimension	Result
	This model is valid, according to the cases of the library

Figure 7.17: The solution for product design dimensions

7.6.3.4 Customer Requirements

Table 7.8 shows the list of customer requirements taken from Eco-QFD Phase I. The local similarity functions (discussed in Section 5.2 of Chapter V) are considered in a range of [0, 1]. Here “0” represents the worst and “1” represents the best product design criteria for fulfilling the requirements of the customer.

Table 7.8: Screenshot of the customer requirements solution

Customer Requirements	Local Similarity
Easier to use	0.95
Better value for money	1.00
Reliability	0.94
Greater adaptability	1.00
Easier to service	1.00

The solutions indicated that the three highest criteria values for customer requirements were: easier to service (1.00), better value for money (1.00), and reliability (1.00). This solution shows that the new case is able to fulfil the list of customer’s requirements.

7.6.3.5 Eco-QFD Indicators

Table 7.9 represents the Eco-QFD indicators solution for the product's environmental impact, design, and customer requirements. The purpose of this solution is to summarise the performance of the product design assessment in three aspects (environmental impact, product design, and customer requirements). These indicators are given a single number based on the integration between the solutions discussed in Section 7.6.3.1 (environmental impact), Section 7.6.3.3 (design dimension), and 7.6.3.4 (customer requirements) with the Eco-QFD weighting factors. This solution is intended to be used to help industry decision makers propose solutions for new product design features by reusing solutions from similar cases and past experiences.

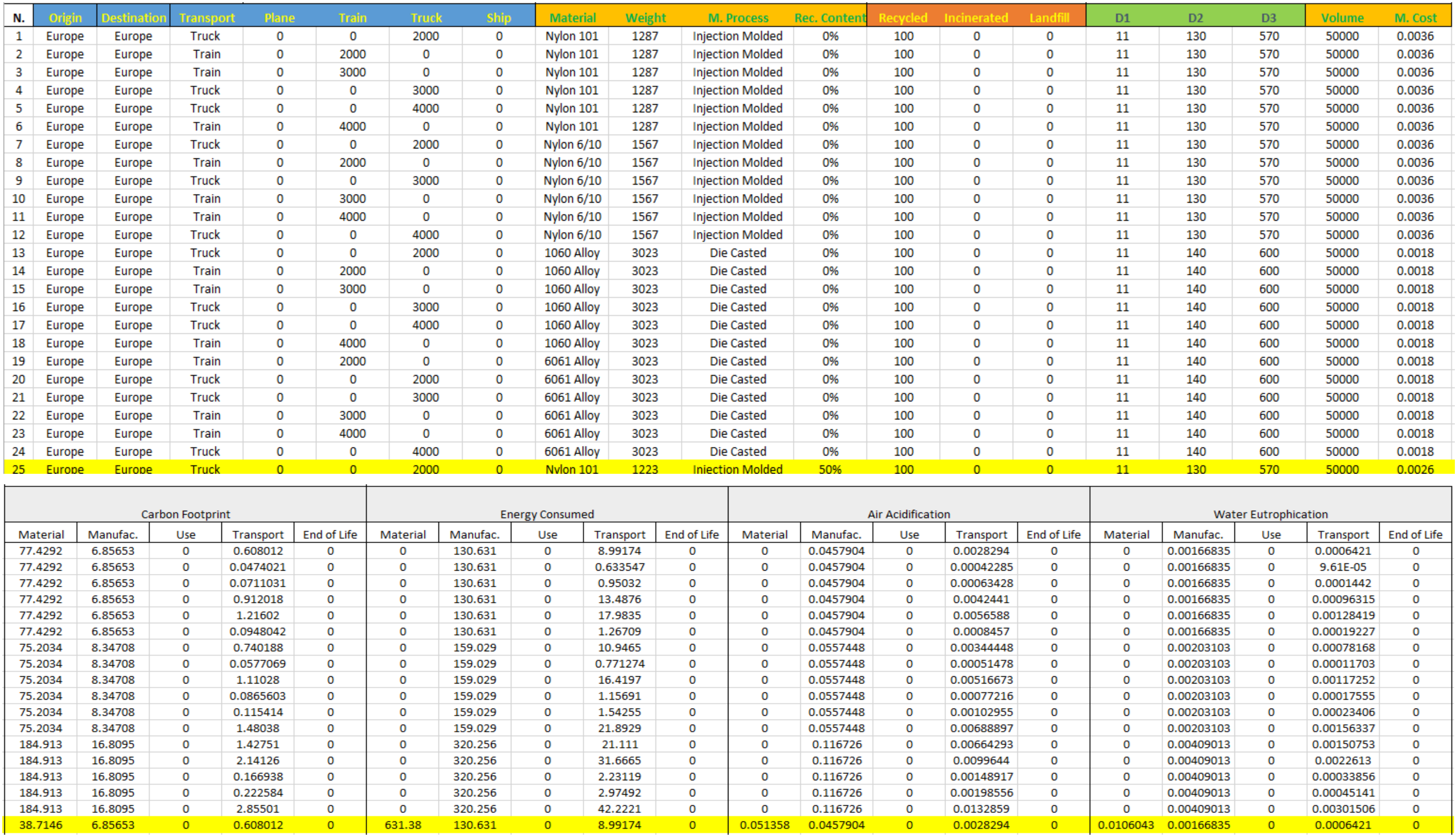
The factor performance in Table 7.9 shows the Eco-QFD scores that were evaluated and integrated into the Eco-CBR method, as discussed in Section 6.10 of Chapter VI. The solution proposed for the new case indicates that the environmental impact has an excellent performance, valued at 1.00, with product design and customer requirements valued at 0.95 and 0.99, respectively.

Table 7.9: Screenshot for the solution Eco-QFD indicators

Eco-QFD Indicators	**Factor Performance**	**Factor Range**
Environmental Impact	1.00	1.00 (Excellent) ↑ 0.00 (Worst)
Product Design	0.95	
Customer Requirements	0.99	

7.6.4 Retain the New Case into Eco-CBR Library

When a designer is satisfied with the solutions, the case will be retained, and the library is updated by storing the new case (number 25) as shown in Figure 7.18. This process will enlarge the case library, and the new case can be accessed in the future, allowing for the reuse of proven solutions. In this way, during future redesign of similar products, the designer will have a quantitative result for the application of each particular choice.



N.	Origin	Destination	Transport	Plane	Train	Truck	Ship	Material	Weight	M. Process	Rec. Content	Recycled	Incinerated	Landfill	D1	D2	D3	Volume	M. Cost
1	Europe	Europe	Truck	0	0	2000	0	Nylon 101	1287	Injection Molded	0%	100	0	0	11	130	570	50000	0.0036
2	Europe	Europe	Train	0	2000	0	0	Nylon 101	1287	Injection Molded	0%	100	0	0	11	130	570	50000	0.0036
3	Europe	Europe	Train	0	3000	0	0	Nylon 101	1287	Injection Molded	0%	100	0	0	11	130	570	50000	0.0036
4	Europe	Europe	Truck	0	0	3000	0	Nylon 101	1287	Injection Molded	0%	100	0	0	11	130	570	50000	0.0036
5	Europe	Europe	Truck	0	0	4000	0	Nylon 101	1287	Injection Molded	0%	100	0	0	11	130	570	50000	0.0036
6	Europe	Europe	Train	0	4000	0	0	Nylon 101	1287	Injection Molded	0%	100	0	0	11	130	570	50000	0.0036
7	Europe	Europe	Truck	0	0	2000	0	Nylon 6/10	1567	Injection Molded	0%	100	0	0	11	130	570	50000	0.0036
8	Europe	Europe	Train	0	2000	0	0	Nylon 6/10	1567	Injection Molded	0%	100	0	0	11	130	570	50000	0.0036
9	Europe	Europe	Truck	0	0	3000	0	Nylon 6/10	1567	Injection Molded	0%	100	0	0	11	130	570	50000	0.0036
10	Europe	Europe	Train	0	3000	0	0	Nylon 6/10	1567	Injection Molded	0%	100	0	0	11	130	570	50000	0.0036
11	Europe	Europe	Train	0	4000	0	0	Nylon 6/10	1567	Injection Molded	0%	100	0	0	11	130	570	50000	0.0036
12	Europe	Europe	Truck	0	0	4000	0	Nylon 6/10	1567	Injection Molded	0%	100	0	0	11	130	570	50000	0.0036
13	Europe	Europe	Truck	0	0	2000	0	1060 Alloy	3023	Die Casted	0%	100	0	0	11	140	600	50000	0.0018
14	Europe	Europe	Train	0	2000	0	0	1060 Alloy	3023	Die Casted	0%	100	0	0	11	140	600	50000	0.0018
15	Europe	Europe	Train	0	3000	0	0	1060 Alloy	3023	Die Casted	0%	100	0	0	11	140	600	50000	0.0018
16	Europe	Europe	Truck	0	0	3000	0	1060 Alloy	3023	Die Casted	0%	100	0	0	11	140	600	50000	0.0018
17	Europe	Europe	Truck	0	0	4000	0	1060 Alloy	3023	Die Casted	0%	100	0	0	11	140	600	50000	0.0018
18	Europe	Europe	Train	0	4000	0	0	1060 Alloy	3023	Die Casted	0%	100	0	0	11	140	600	50000	0.0018
19	Europe	Europe	Train	0	2000	0	0	6061 Alloy	3023	Die Casted	0%	100	0	0	11	140	600	50000	0.0018
20	Europe	Europe	Truck	0	0	2000	0	6061 Alloy	3023	Die Casted	0%	100	0	0	11	140	600	50000	0.0018
21	Europe	Europe	Truck	0	0	3000	0	6061 Alloy	3023	Die Casted	0%	100	0	0	11	140	600	50000	0.0018
22	Europe	Europe	Train	0	3000	0	0	6061 Alloy	3023	Die Casted	0%	100	0	0	11	140	600	50000	0.0018
23	Europe	Europe	Train	0	4000	0	0	6061 Alloy	3023	Die Casted	0%	100	0	0	11	140	600	50000	0.0018
24	Europe	Europe	Truck	0	0	4000	0	6061 Alloy	3023	Die Casted	0%	100	0	0	11	140	600	50000	0.0018
25	Europe	Europe	Truck	0	0	2000	0	Nylon 101	1223	Injection Molded	50%	100	0	0	11	130	570	50000	0.0026

Carbon Footprint					Energy Consumed					Air Acidification					Water Eutrophication				
Material	Manufac.	Use	Transport	End of Life	Material	Manufac.	Use	Transport	End of Life	Material	Manufac.	Use	Transport	End of Life	Material	Manufac.	Use	Transport	End of Life
77.4292	6.85653	0	0.608012	0	0	130.631	0	8.99174	0	0	0.0457904	0	0.0028294	0	0	0.00166835	0	0.0006421	0
77.4292	6.85653	0	0.0474021	0	0	130.631	0	0.633547	0	0	0.0457904	0	0.00042285	0	0	0.00166835	0	9.61E-05	0
77.4292	6.85653	0	0.0711031	0	0	130.631	0	0.95032	0	0	0.0457904	0	0.00063428	0	0	0.00166835	0	0.0001442	0
77.4292	6.85653	0	0.912018	0	0	130.631	0	13.4876	0	0	0.0457904	0	0.0042441	0	0	0.00166835	0	0.00096315	0
77.4292	6.85653	0	1.21602	0	0	130.631	0	17.9835	0	0	0.0457904	0	0.0056588	0	0	0.00166835	0	0.00128419	0
77.4292	6.85653	0	0.0948042	0	0	130.631	0	1.26709	0	0	0.0457904	0	0.0008457	0	0	0.00166835	0	0.00019227	0
75.2034	8.34708	0	0.740188	0	0	159.029	0	10.9465	0	0	0.0557448	0	0.00344448	0	0	0.00203103	0	0.00078168	0
75.2034	8.34708	0	0.0577069	0	0	159.029	0	0.771274	0	0	0.0557448	0	0.00051478	0	0	0.00203103	0	0.00011703	0
75.2034	8.34708	0	1.11028	0	0	159.029	0	16.4197	0	0	0.0557448	0	0.00516673	0	0	0.00203103	0	0.00117252	0
75.2034	8.34708	0	0.0865603	0	0	159.029	0	1.15691	0	0	0.0557448	0	0.00077216	0	0	0.00203103	0	0.00017555	0
75.2034	8.34708	0	0.115414	0	0	159.029	0	1.54255	0	0	0.0557448	0	0.00102955	0	0	0.00203103	0	0.00023406	0
75.2034	8.34708	0	1.48038	0	0	159.029	0	21.8929	0	0	0.0557448	0	0.00688897	0	0	0.00203103	0	0.00156337	0
184.913	16.8095	0	1.42751	0	0	320.256	0	21.111	0	0	0.116726	0	0.00664293	0	0	0.00409013	0	0.00150753	0
184.913	16.8095	0	2.14126	0	0	320.256	0	31.6665	0	0	0.116726	0	0.0099644	0	0	0.00409013	0	0.0022613	0
184.913	16.8095	0	0.166938	0	0	320.256	0	2.23119	0	0	0.116726	0	0.00148917	0	0	0.00409013	0	0.00033856	0
184.913	16.8095	0	0.222584	0	0	320.256	0	2.97492	0	0	0.116726	0	0.00198556	0	0	0.00409013	0	0.00045141	0
184.913	16.8095	0	2.85501	0	0	320.256	0	42.2221	0	0	0.116726	0	0.0132859	0	0	0.00409013	0	0.00301506	0
38.7146	6.85653	0	0.608012	0	631.38	130.631	0	8.99174	0	0.051358	0.0457904	0	0.0028294	0	0.0106043	0.00166835	0	0.0006421	0

Figure 7.18: Insertion of new case into Eco-CBR library (yellow colour)

7.7 Validation for Life Cycle Assessment using Solidworks Software

In order to provide validation of results generated by the Eco-CBR tool, an LCA approach was carried out using the SolidWorks Sustainability 2013 software package. This software is capable of performing an LCA of parts or assemblies directly from the design platform. Comparison of the results obtained by SolidWorks Sustainability with those obtained by Eco-CBR tool was carried out in the context of the life cycle assessment of the redesigned chair base. A summary of the comparison is presented in Table 7.10. This draws data from the comparison, the solution summarised in Table 7.5 and Figure 7.16. The difference highlighted relates to the 50% recycled material content. This option is not available within Solidworks software.

7.8 Discussion

The Eco-CBR developed for this study integrates the LCA, Eco-QFD, and Eco-Economic Costs models as discussed in the IEDM framework in Chapter III. The features for a particular problem are used to configure a product solution using the Eco-CBR tool. The solutions relate a product's environmental impact, economic cost, and inclusion of customer requirements.

The sustainability considerations in this study consist of 32 sustainability metrics that cover a product's environmental, economic, and social aspects throughout its entire life cycle. These sustainability metrics were used as the sustainability criteria in the Eco-Process model and the Eco-HoQ. Certain costs such as overhead costs, labour costs, and machine costs that use quantitative measurements are sometimes unknown. In this case, cost have been approximated as indicated. Approximation enables the evaluation process to proceed even if some information cannot be found.

Table 7.10: Summary of the LCA by SolidWorks and Eco-CBR tool

Criteria	**Solidworks**	**Eco-CBR**
Material	Nylon 101	Nylon 101
Types of manufacturing process	Injection moulding	Injection moulding
Manufacturing region	Europe	Europe
Use region	Europe	Europe
Transportation	Truck	Truck
Weight (g)	1.287	1.223
Recycle content (material) in product (%)	0%	**50%**
Recycle rate at EOL product (%)	100%	100%
Carbon footprint	**kg CO_2**	**kg CO_2**
Material	77.43	**38.71**
Manufacturing	6.86	6.86
Use	0.00	0.00
Transportation	0.61	0.61
End-of-life	0.00	0.00
Total	**84.90**	**46.19**
Water Eutrophication	**kg PO_4**	**kg PO_4**
Material	0.02	**0.01**
Manufacturing	0.00	0.00
Use	0.00	0.00
Transportation	0.00	0.00
End-of-life	0.00	0.00
Total	**0.02**	**0.01**
Air Acidification	**kg SO_2**	**kg SO_2**
Material	0.10	**0.05**
Manufacturing	0.05	0.05
Use	0.00	0.00
Transportation	0.00	0.00
End-of-life	0.00	0.00
Total	**0.15**	**0.10**
Total Energy Consumed	**MJ**	**MJ**
Material	1262.76	**631.38**
Manufacturing	130.63	130.63
Use	0.00	0.00
Transportation	8.99	8.99
End-of-life	0.00	0.00
Total	**1402.38**	**771.00**

Table 7.11 shows the improvement of the new chair base by comparing with the existing product. Many improvements were observed from the changes of the reduction of material usage, and the use of material recycled content. Some of the improvements are decreasing the carbon footprint (84%), water eutrophication (43%), air acidification (50%), and total energy consumed (82%). Additionally, the economic cost has also decreased by 41% due to the above changes.

In this study, the results of the environmental evaluation were analysed using SolidWorks Sustainability, which conducts an LCA. The aim was to analyse a product's environmental impact and select the most environmentally friendly material, manufacturing process, and transportation means to minimise environmental impact.

Table 7.11: Environmental impact of medical forceps: new design vs existing design (per unit)

Criteria	**Existing design Nylon 101**	**New design**	**Result**
Material	Nylon 101	Nylon 101	Weight of material is decreased by 5%. The design dimension for the D1, D2, and D3 remain the same as the existing design. This thickness of the end legs of the chair base also been reduced to the 5% from the existing design.
Types of manufacturing process	Injection moulding	Injection moulding	
Manufacturing region	Europe	Europe	
Use region	Europe	Europe	
Transportation	Truck	Truck	
Weight (gram)	1287	**1223**	
Recycle content (material) in product (%)	0%	**50%**	
Recycle rate at EOL product (%)	100%	100%	
Economic cost (£)	9.26	6.56	↓ 41%
Carbon footprint (kg CO_2)	84.90	**46.16**	↓ 84%
Water Eutrophication (kg PO_4)	0.02	**0.014**	↓ 43%
Air Acidification (kg SO_2)	0.15	**0.10**	↓ 50%
Total Energy Consumed (MJ)	1402.38	**771.00**	↓ 82%

7.9 Summary

This chapter contributes to research in the field of sustainable product design by applying the IEDM tool to the office chair base case study. This tool can assist product designers to measure environmental impact and eco-design parameters at early design stages and inform decision making. This chapter has demonstrated a sustainability evaluation of the office chair base at the design stage in order to validate the practicability of the proposed IEDM framework and the application of the integration eco-design tools (Eco-QFD and Eco-CBR).

The outcomes of this work are the integration of the IEDM framework with the LCA, the embedding of the Eco-HoQ model in the QFD process, and the application of the Eco-CBR method, which plays an important role in product assessment with regards to sustainability considerations. The aim of this research was to develop an eco-design tool that can help the designer evaluate economic and environmental impacts from the perspective of both customer requirements and product life cycles. Therefore, the IEDM tool was developed in order to establish relationships between customer requirements and eco-design principles in terms of material used, manufacturing process, transportation, EOL strategies, and economic costs. Based on this general information, a product's sustainability performance can be evaluated.

CHAPTER VIII

CONTRIBUTIONS, CONCLUSIONS AND FUTURE WORK

This chapter concludes this thesis. Section 8.1 lists the main contributions of this research. Section 8.2 outlines the conclusions from the research. Section 8.3 presents recommendations for future work.

8.1 Contributions

The main research contribution made in the process relates to the integration of environmental consideration into each aspect of product design, manufacture and use over the entire life cycle. The proposed framework and the tools fill important research gaps in the field of sustainable product development. The IEDM framework can contributes to the body of knowledge in the field by facilitating the application of sustainability criteria in the early design phase. It makes considerations of sustainability available to designers at this early stage and presents these considerations in a context with which they are familiar. This will make such consideration more understandable and relevant. This is particularly true in real-life applications were such a process will be related to specific products with which designers are familiar. This meets the need for such strategies cited in Section 2.2.

As part of the IEDM framework, the integration of the ecological house of quality (Eco-HoQ) model in the quality function deployment (QFD) process is proposed as a means to bridge the conceptual gap between the requirements of stakeholders (customer, recycler and manufacturer) and eco-design indicators. This can increase the awareness of all concerned in how they can contribute to improving sustainability. Better products will result from such a process. This is based on better access to more accurate data within the Eco-QFD related process. The Eco-HoQ model developed in this thesis research is novel and provides a solution for estimating a product's sustainability in the early design phase. The central Eco-HoQ model generates and records the environmental parameters used to assess a product's environmental impact and cost. In addition, it centralises the production and environmental cost of the product for use in all QFD phases. The information collected in this model can be used to support a systematic approach to eco-design that allows for greater information and expertise sharing through ecological case-based reasoning (Eco-CBR) method. This can provide guidance on how strategies can be supported as previously identified in Section 2.3.3. The implementation of Eco-QFD process focuses on every stage of a product's life cycle through the five houses of Eco-QFD.

The eco-design case-based reasoning (Eco-CBR) tool has been developed meet the requirement of the poor data storage in the QFD process. The result from the assessment in the Eco-QFD process can be re-used and retrieved in a simple way by using the Eco-CBR tool. This was identified as a current deficiency in Section 2.3.1. The Eco-CBR tool developed in this thesis will assist product designers in using quantitative measures (production cost, environmental cost, and transportation cost) to explore product design alternative materials, manufacturing processes, and logistics. The Eco-CBR tool is not designed to replace the life cycle assessment (LCA) but rather facilitates focused attention on specific areas of concern in the product's life cycle. The Eco-CBR tool enables the cost-effective assessment of the product design based on the customer requirements. The nature of the integrated process resulting from the research will mean the tools will become increasingly improved and relevant as more information is added. This will make all aspects of the process more rewarding for the participants and increase considerations of sustainability as part of the integrated process. This brings LCA into wider use by meeting the need for such information identified early in this thesis as discussed in Section 2.3.2.

The research presented in this thesis is intended to provide a method that assists designers in conducting sustainable product design analyses. This will ensure that products are designed using sustainability considerations and will have positive environmental, economic, and social impacts whilst meeting customer requirements.

8.2 Conclusions

In conclusion, the objectives of the research has been successfully achieved. For the first objective of this research was to develop the IEDM framework for the design phase. The IEDM framework was designed to be easily and widely applicable. The mechanism for inputting information (LCA, eco-design parameters, customer requirements) at every stage of the IEDM framework enables users with complementary knowledge to enter and access information in a timely and controlled manner.

For the second objective which is to propose a conceptual model for integrating eco-design and economic viewpoints has been met. The development of the Eco-HOQ model as an extra “house” that can capture and manage sustainability considerations in a single place has increased the relevance of the information used and produced in the early product design. The Eco-HoQ model is developed by integrating into QFD process has encourage actions for improving sustainability of entire product life cycle. The Eco-QFD was developed to understand how customer needs may be better defined within the context of sustainability.

The third objective was to develop decision support tool to support the framework in the evaluation of product sustainability. The Eco-CBR has been successfully developed as an intuitive decision support tool, which complements the IEDM framework for evaluating a product’s sustainability and proposing solutions related to the social, environmental, and economic impacts of the product. The Eco-CBR tool is crucial for the continued innovation and application of the IEDM approach. It strengthens the value of this method by capturing and making available examples of good practise for reuse. The system operates interactively and automatically. The designer is able to make changes to design features and weighting factors and observe the consequences. This makes the Eco-CBR tool a user friendly and intuitive aid to the eco-design process.

Finally, for the last objective which is to validate the practicality and the effectiveness of the IEDM framework has been met by examining through the case studies of medical forceps and an office chair base. The case study results showed the effectiveness of this approach for assessing the sustainability of a product when its design was altered. In addition, the sustainability evaluation provided a complete view of the environmental performance and economic cost of these products' entire life cycles in conjunction with the assessment of customer requirements.

8.3 Future Work

It is recommended that further research should be undertaken to overcome the limitations of the research in the areas outlined below.

There are 32 sustainability criteria that were identified in the development of the Eco-Process modules and used in the Eco-QFD model. These criteria were used to provide information on the environmental, economic, and social aspects of the entire product life cycle. However, information on some of these criteria is difficult to obtain such as material cost, labour cost, production cost, recycling cost, remanufacturing cost, and environmental cost. Therefore, there is a need to develop a database to store sustainability criteria and product information, which can be used to improve the accuracy of the product design assessments.

The simply LCA concept used in this research is based on the conversion from emissions to impact potentials via classification and characterisation. The emissions identified here are carbon dioxide (CO_2), methane (CH_4), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), phosphate (PO_4), and ammonia (NH_3). These emissions are classified to the impact categories of carbon footprint, energy consumption, air acidification, and water eutrophication. The integration of complete / full LCA and the law and regulations are recommended for the future research to ensure that manufacturers will produce a sustainable product based on the environmental standard.

The Eco-CBR tool was developed to collect information on a single product or part that uses one type of material. It would be desirable to extend this capacity to capture more complex products. The library of the case-based reasoning tool has been shown to be reliable in terms of the accuracy of the solution retrieved. The Eco-CBR tool proposed here can also be integrated with the other systems to support a business process such as management processes, operational processes and supporting processes.

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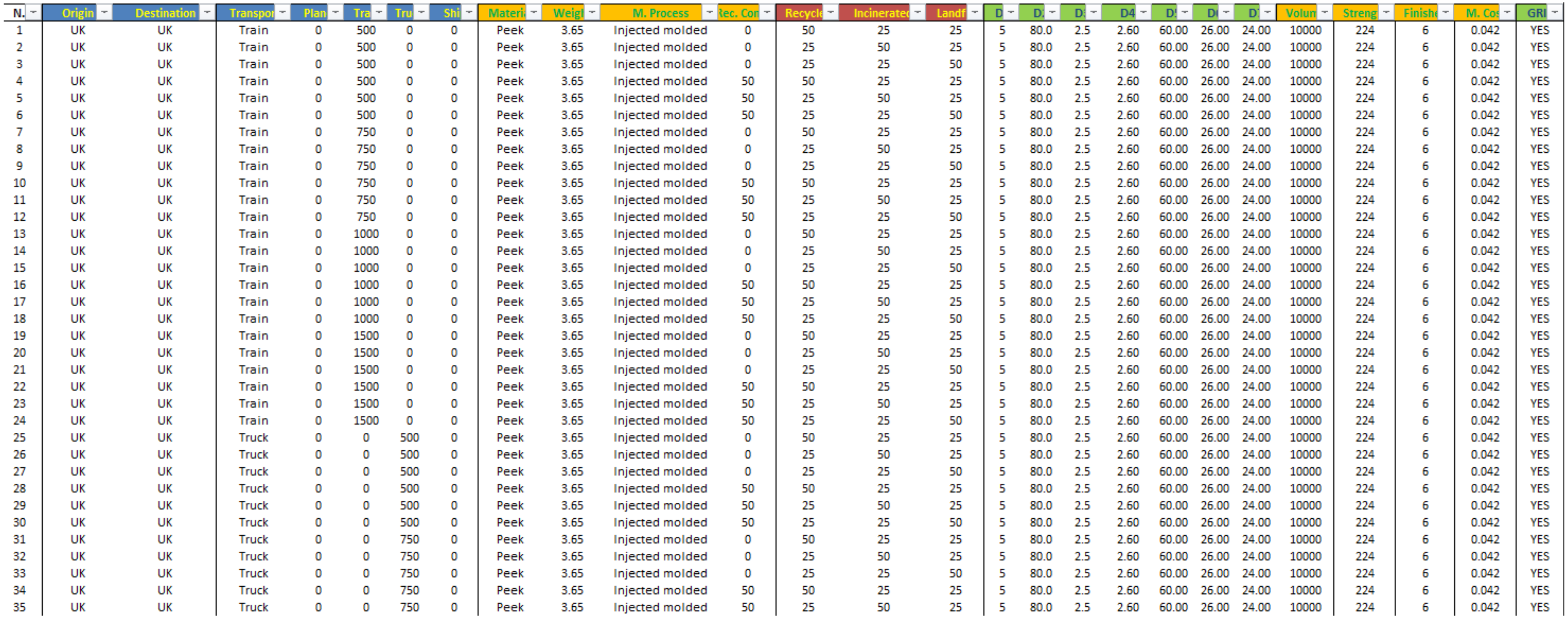
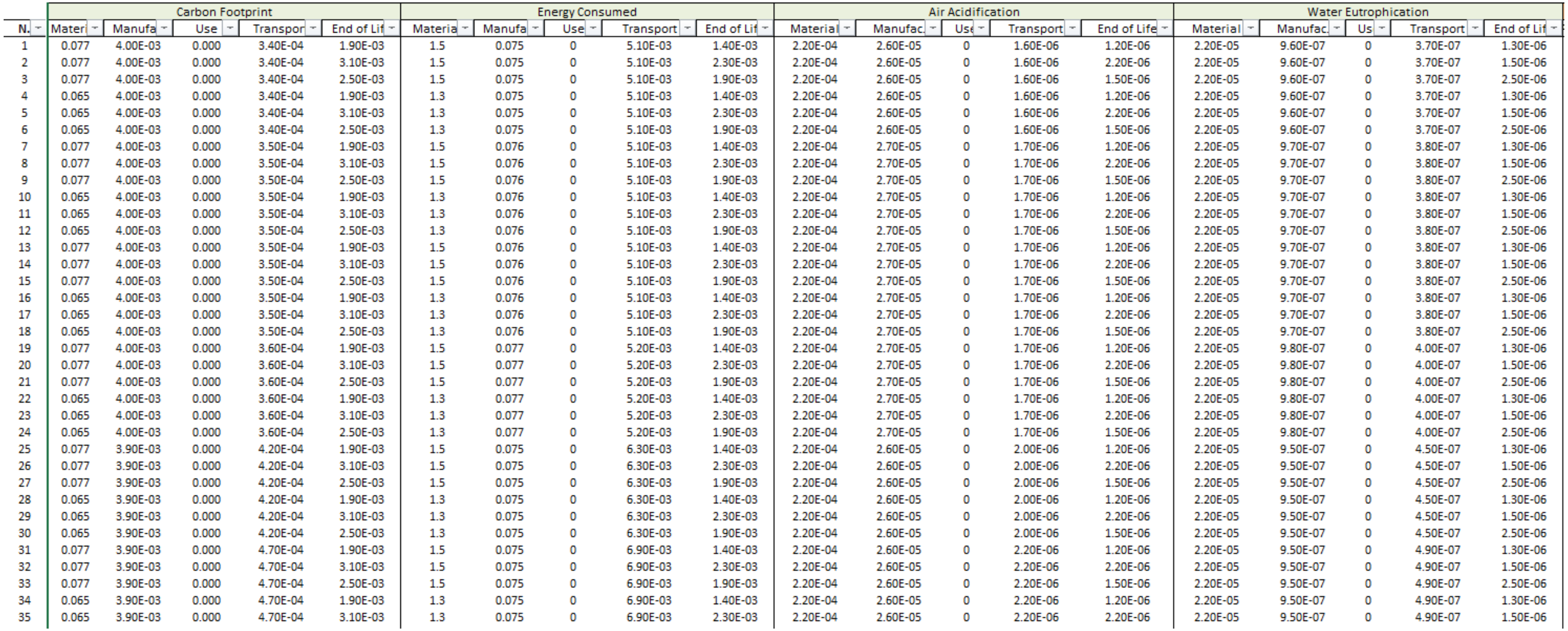
APPENDIX A

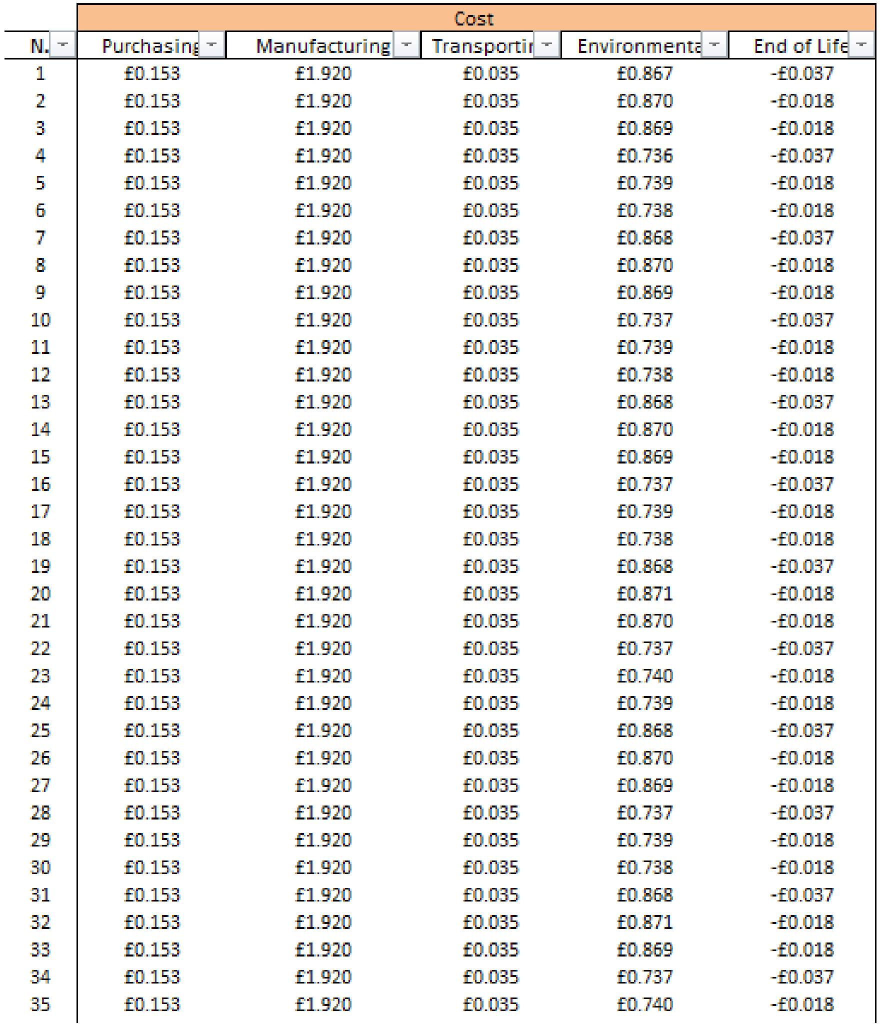
Eco-CBR library for the medical forceps.



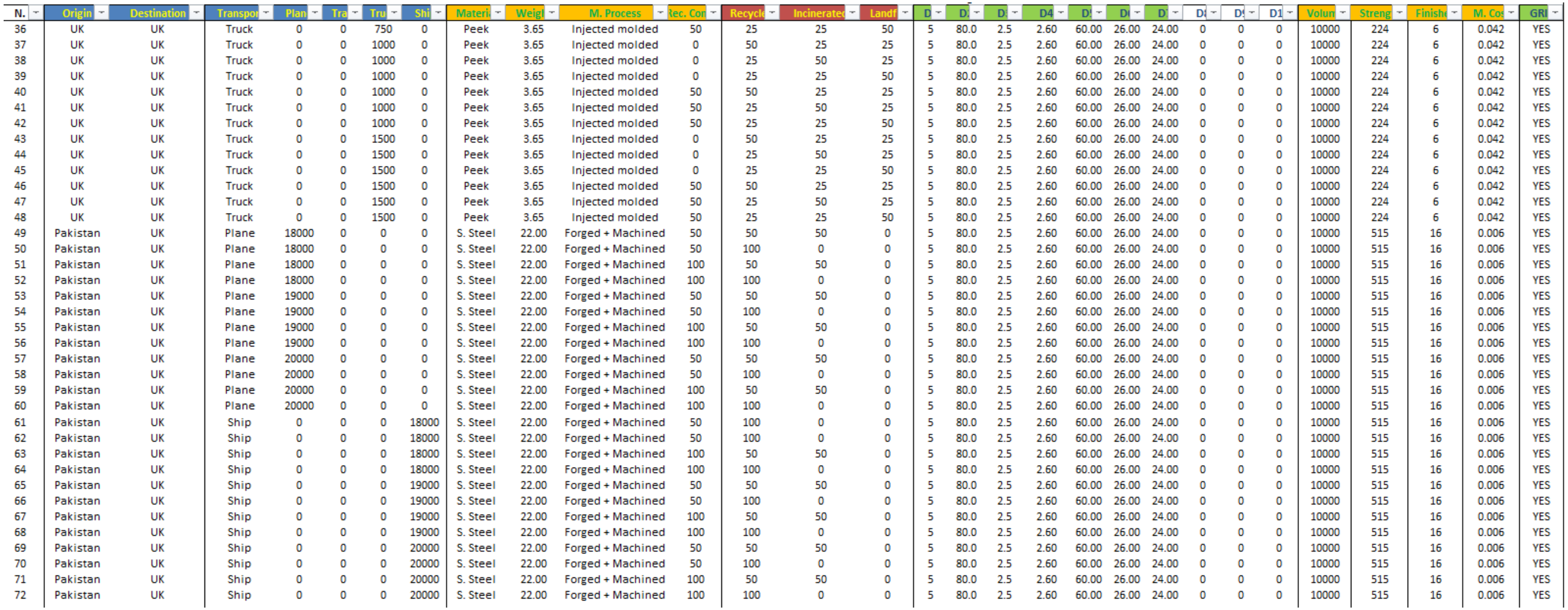
N.	Origin	Destination	Transpor	Plan	Tra	Tru	Shi	Materi	Weigl	M. Process	Rec. Con	Recycle	Incinerated	Landf	D	D	D	D4	D	D	D	Volun	Streng	Finishe	M. Cos	GRI
1	UK	UK	Train	0	500	0	0	Peek	3.65	Injected molded	0	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
2	UK	UK	Train	0	500	0	0	Peek	3.65	Injected molded	0	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
3	UK	UK	Train	0	500	0	0	Peek	3.65	Injected molded	0	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
4	UK	UK	Train	0	500	0	0	Peek	3.65	Injected molded	50	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
5	UK	UK	Train	0	500	0	0	Peek	3.65	Injected molded	50	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
6	UK	UK	Train	0	500	0	0	Peek	3.65	Injected molded	50	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
7	UK	UK	Train	0	750	0	0	Peek	3.65	Injected molded	0	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
8	UK	UK	Train	0	750	0	0	Peek	3.65	Injected molded	0	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
9	UK	UK	Train	0	750	0	0	Peek	3.65	Injected molded	0	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
10	UK	UK	Train	0	750	0	0	Peek	3.65	Injected molded	50	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
11	UK	UK	Train	0	750	0	0	Peek	3.65	Injected molded	50	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
12	UK	UK	Train	0	750	0	0	Peek	3.65	Injected molded	50	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
13	UK	UK	Train	0	1000	0	0	Peek	3.65	Injected molded	0	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
14	UK	UK	Train	0	1000	0	0	Peek	3.65	Injected molded	0	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
15	UK	UK	Train	0	1000	0	0	Peek	3.65	Injected molded	0	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
16	UK	UK	Train	0	1000	0	0	Peek	3.65	Injected molded	50	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
17	UK	UK	Train	0	1000	0	0	Peek	3.65	Injected molded	50	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
18	UK	UK	Train	0	1000	0	0	Peek	3.65	Injected molded	50	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
19	UK	UK	Train	0	1500	0	0	Peek	3.65	Injected molded	0	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
20	UK	UK	Train	0	1500	0	0	Peek	3.65	Injected molded	0	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
21	UK	UK	Train	0	1500	0	0	Peek	3.65	Injected molded	0	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
22	UK	UK	Train	0	1500	0	0	Peek	3.65	Injected molded	50	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
23	UK	UK	Train	0	1500	0	0	Peek	3.65	Injected molded	50	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
24	UK	UK	Train	0	1500	0	0	Peek	3.65	Injected molded	50	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
25	UK	UK	Truck	0	0	500	0	Peek	3.65	Injected molded	0	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
26	UK	UK	Truck	0	0	500	0	Peek	3.65	Injected molded	0	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
27	UK	UK	Truck	0	0	500	0	Peek	3.65	Injected molded	0	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
28	UK	UK	Truck	0	0	500	0	Peek	3.65	Injected molded	50	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
29	UK	UK	Truck	0	0	500	0	Peek	3.65	Injected molded	50	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
30	UK	UK	Truck	0	0	500	0	Peek	3.65	Injected molded	50	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
31	UK	UK	Truck	0	0	750	0	Peek	3.65	Injected molded	0	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
32	UK	UK	Truck	0	0	750	0	Peek	3.65	Injected molded	0	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
33	UK	UK	Truck	0	0	750	0	Peek	3.65	Injected molded	0	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
34	UK	UK	Truck	0	0	750	0	Peek	3.65	Injected molded	50	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES
35	UK	UK	Truck	0	0	750	0	Peek	3.65	Injected molded	50	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	10000	224	6	0.042	YES



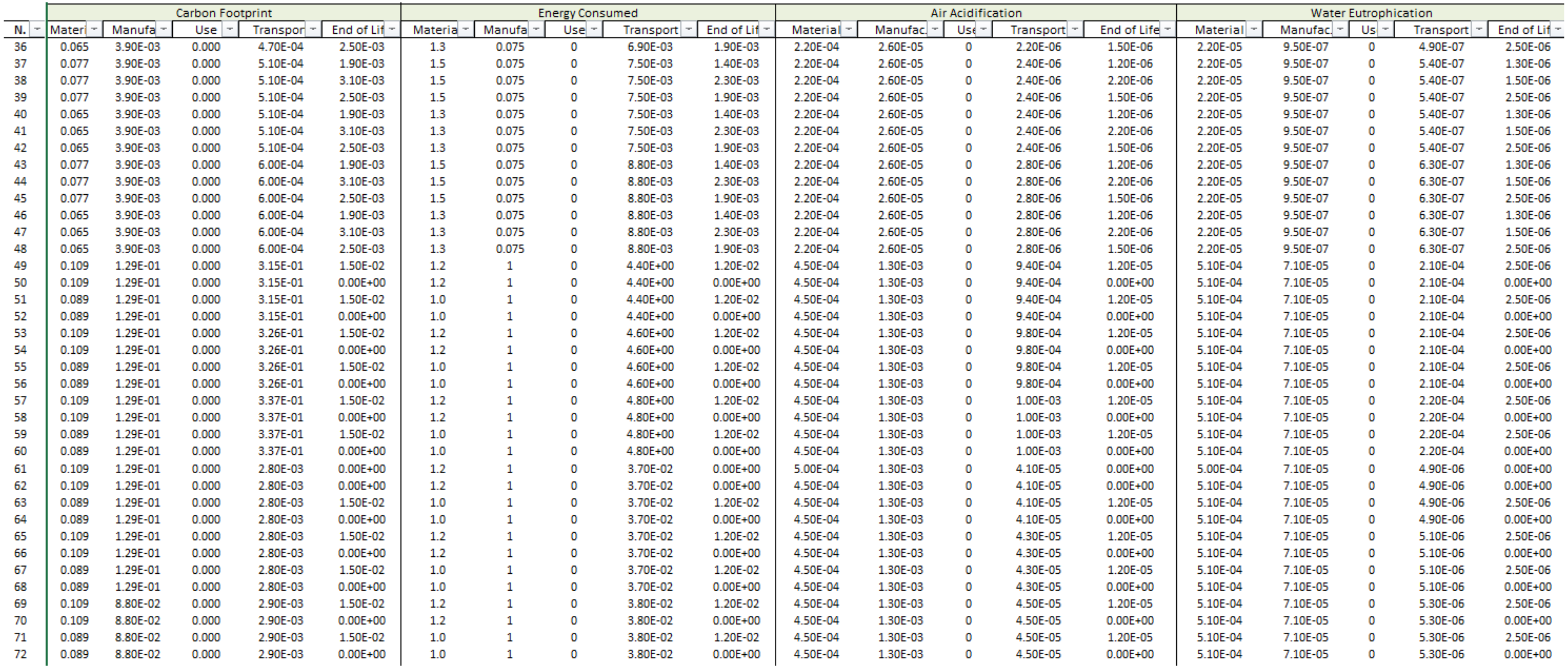
N.	Carbon Footprint					Energy Consumed					Air Acidification					Water Eutrophication				
	Materi	Manufa	Use	Transpor	End of Lif	Materia	Manufa	Use	Transport	End of Lif	Material	Manufac.	Use	Transport	End of Life	Material	Manufac.	Us	Transport	End of Lif
1	0.077	4.00E-03	0.000	3.40E-04	1.90E-03	1.5	0.075	0	5.10E-03	1.40E-03	2.20E-04	2.60E-05	0	1.60E-06	1.20E-06	2.20E-05	9.60E-07	0	3.70E-07	1.30E-06
2	0.077	4.00E-03	0.000	3.40E-04	3.10E-03	1.5	0.075	0	5.10E-03	2.30E-03	2.20E-04	2.60E-05	0	1.60E-06	2.20E-06	2.20E-05	9.60E-07	0	3.70E-07	1.50E-06
3	0.077	4.00E-03	0.000	3.40E-04	2.50E-03	1.5	0.075	0	5.10E-03	1.90E-03	2.20E-04	2.60E-05	0	1.60E-06	1.50E-06	2.20E-05	9.60E-07	0	3.70E-07	2.50E-06
4	0.065	4.00E-03	0.000	3.40E-04	1.90E-03	1.3	0.075	0	5.10E-03	1.40E-03	2.20E-04	2.60E-05	0	1.60E-06	1.20E-06	2.20E-05	9.60E-07	0	3.70E-07	1.30E-06
5	0.065	4.00E-03	0.000	3.40E-04	3.10E-03	1.3	0.075	0	5.10E-03	2.30E-03	2.20E-04	2.60E-05	0	1.60E-06	2.20E-06	2.20E-05	9.60E-07	0	3.70E-07	1.50E-06
6	0.065	4.00E-03	0.000	3.40E-04	2.50E-03	1.3	0.075	0	5.10E-03	1.90E-03	2.20E-04	2.60E-05	0	1.60E-06	1.50E-06	2.20E-05	9.60E-07	0	3.70E-07	2.50E-06
7	0.077	4.00E-03	0.000	3.50E-04	1.90E-03	1.5	0.076	0	5.10E-03	1.40E-03	2.20E-04	2.70E-05	0	1.70E-06	1.20E-06	2.20E-05	9.70E-07	0	3.80E-07	1.30E-06
8	0.077	4.00E-03	0.000	3.50E-04	3.10E-03	1.5	0.076	0	5.10E-03	2.30E-03	2.20E-04	2.70E-05	0	1.70E-06	2.20E-06	2.20E-05	9.70E-07	0	3.80E-07	1.50E-06
9	0.077	4.00E-03	0.000	3.50E-04	2.50E-03	1.5	0.076	0	5.10E-03	1.90E-03	2.20E-04	2.70E-05	0	1.70E-06	1.50E-06	2.20E-05	9.70E-07	0	3.80E-07	2.50E-06
10	0.065	4.00E-03	0.000	3.50E-04	1.90E-03	1.3	0.076	0	5.10E-03	1.40E-03	2.20E-04	2.70E-05	0	1.70E-06	1.20E-06	2.20E-05	9.70E-07	0	3.80E-07	1.30E-06
11	0.065	4.00E-03	0.000	3.50E-04	3.10E-03	1.3	0.076	0	5.10E-03	2.30E-03	2.20E-04	2.70E-05	0	1.70E-06	2.20E-06	2.20E-05	9.70E-07	0	3.80E-07	1.50E-06
12	0.065	4.00E-03	0.000	3.50E-04	2.50E-03	1.3	0.076	0	5.10E-03	1.90E-03	2.20E-04	2.70E-05	0	1.70E-06	1.50E-06	2.20E-05	9.70E-07	0	3.80E-07	2.50E-06
13	0.077	4.00E-03	0.000	3.50E-04	1.90E-03	1.5	0.076	0	5.10E-03	1.40E-03	2.20E-04	2.70E-05	0	1.70E-06	1.20E-06	2.20E-05	9.70E-07	0	3.80E-07	1.30E-06
14	0.077	4.00E-03	0.000	3.50E-04	3.10E-03	1.5	0.076	0	5.10E-03	2.30E-03	2.20E-04	2.70E-05	0	1.70E-06	2.20E-06	2.20E-05	9.70E-07	0	3.80E-07	1.50E-06
15	0.077	4.00E-03	0.000	3.50E-04	2.50E-03	1.5	0.076	0	5.10E-03	1.90E-03	2.20E-04	2.70E-05	0	1.70E-06	1.50E-06	2.20E-05	9.70E-07	0	3.80E-07	2.50E-06
16	0.065	4.00E-03	0.000	3.50E-04	1.90E-03	1.3	0.076	0	5.10E-03	1.40E-03	2.20E-04	2.70E-05	0	1.70E-06	1.20E-06	2.20E-05	9.70E-07	0	3.80E-07	1.30E-06
17	0.065	4.00E-03	0.000	3.50E-04	3.10E-03	1.3	0.076	0	5.10E-03	2.30E-03	2.20E-04	2.70E-05	0	1.70E-06	2.20E-06	2.20E-05	9.70E-07	0	3.80E-07	1.50E-06
18	0.065	4.00E-03	0.000	3.50E-04	2.50E-03	1.3	0.076	0	5.10E-03	1.90E-03	2.20E-04	2.70E-05	0	1.70E-06	1.50E-06	2.20E-05	9.70E-07	0	3.80E-07	2.50E-06
19	0.077	4.00E-03	0.000	3.60E-04	1.90E-03	1.5	0.077	0	5.20E-03	1.40E-03	2.20E-04	2.70E-05	0	1.70E-06	1.20E-06	2.20E-05	9.80E-07	0	4.00E-07	1.30E-06
20	0.077	4.00E-03	0.000	3.60E-04	3.10E-03	1.5	0.077	0	5.20E-03	2.30E-03	2.20E-04	2.70E-05	0	1.70E-06	2.20E-06	2.20E-05	9.80E-07	0	4.00E-07	1.50E-06
21	0.077	4.00E-03	0.000	3.60E-04	2.50E-03	1.5	0.077	0	5.20E-03	1.90E-03	2.20E-04	2.70E-05	0	1.70E-06	1.50E-06	2.20E-05	9.80E-07	0	4.00E-07	2.50E-06
22	0.065	4.00E-03	0.000	3.60E-04	1.90E-03	1.3	0.077	0	5.20E-03	1.40E-03	2.20E-04	2.70E-05	0	1.70E-06	1.20E-06	2.20E-05	9.80E-07	0	4.00E-07	1.30E-06
23	0.065	4.00E-03	0.000	3.60E-04	3.10E-03	1.3	0.077	0	5.20E-03	2.30E-03	2.20E-04	2.70E-05	0	1.70E-06	2.20E-06	2.20E-05	9.80E-07	0	4.00E-07	1.50E-06
24	0.065	4.00E-03	0.000	3.60E-04	2.50E-03	1.3	0.077	0	5.20E-03	1.90E-03	2.20E-04	2.70E-05	0	1.70E-06	1.50E-06	2.20E-05	9.80E-07	0	4.00E-07	2.50E-06
25	0.077	3.90E-03	0.000	4.20E-04	1.90E-03	1.5	0.075	0	6.30E-03	1.40E-03	2.20E-04	2.60E-05	0	2.00E-06	1.20E-06	2.20E-05	9.50E-07	0	4.50E-07	1.30E-06
26	0.077	3.90E-03	0.000	4.20E-04	3.10E-03	1.5	0.075	0	6.30E-03	2.30E-03	2.20E-04	2.60E-05	0	2.00E-06	2.20E-06	2.20E-05	9.50E-07	0	4.50E-07	1.50E-06
27	0.077	3.90E-03	0.000	4.20E-04	2.50E-03	1.5	0.075	0	6.30E-03	1.90E-03	2.20E-04	2.60E-05	0	2.00E-06	1.50E-06	2.20E-05	9.50E-07	0	4.50E-07	2.50E-06
28	0.065	3.90E-03	0.000	4.20E-04	1.90E-03	1.3	0.075	0	6.30E-03	1.40E-03	2.20E-04	2.60E-05	0	2.00E-06	1.20E-06	2.20E-05	9.50E-07	0	4.50E-07	1.30E-06
29	0.065	3.90E-03	0.000	4.20E-04	3.10E-03	1.3	0.075	0	6.30E-03	2.30E-03	2.20E-04	2.60E-05	0	2.00E-06	2.20E-06	2.20E-05	9.50E-07	0	4.50E-07	1.50E-06
30	0.065	3.90E-03	0.000	4.20E-04	2.50E-03	1.3	0.075	0	6.30E-03	1.90E-03	2.20E-04	2.60E-05	0	2.00E-06	1.50E-06	2.20E-05	9.50E-07	0	4.50E-07	2.50E-06
31	0.077	3.90E-03	0.000	4.70E-04	1.90E-03	1.5	0.075	0	6.90E-03	1.40E-03	2.20E-04	2.60E-05	0	2.20E-06	1.20E-06	2.20E-05	9.50E-07	0	4.90E-07	1.30E-06
32	0.077	3.90E-03	0.000	4.70E-04	3.10E-03	1.5	0.075	0	6.90E-03	2.30E-03	2.20E-04	2.60E-05	0	2.20E-06	2.20E-06	2.20E-05	9.50E-07	0	4.90E-07	1.50E-06
33	0.077	3.90E-03	0.000	4.70E-04	2.50E-03	1.5	0.075	0	6.90E-03	1.90E-03	2.20E-04	2.60E-05	0	2.20E-06	1.50E-06	2.20E-05	9.50E-07	0	4.90E-07	2.50E-06
34	0.065	3.90E-03	0.000	4.70E-04	1.90E-03	1.3	0.075	0	6.90E-03	1.40E-03	2.20E-04	2.60E-05	0	2.20E-06	1.20E-06	2.20E-05	9.50E-07	0	4.90E-07	1.30E-06
35	0.065	3.90E-03	0.000	4.70E-04	3.10E-03	1.3	0.075	0	6.90E-03	2.30E-03	2.20E-04	2.60E-05	0	2.20E-06	2.20E-06	2.20E-05	9.50E-07	0	4.90E-07	1.50E-06



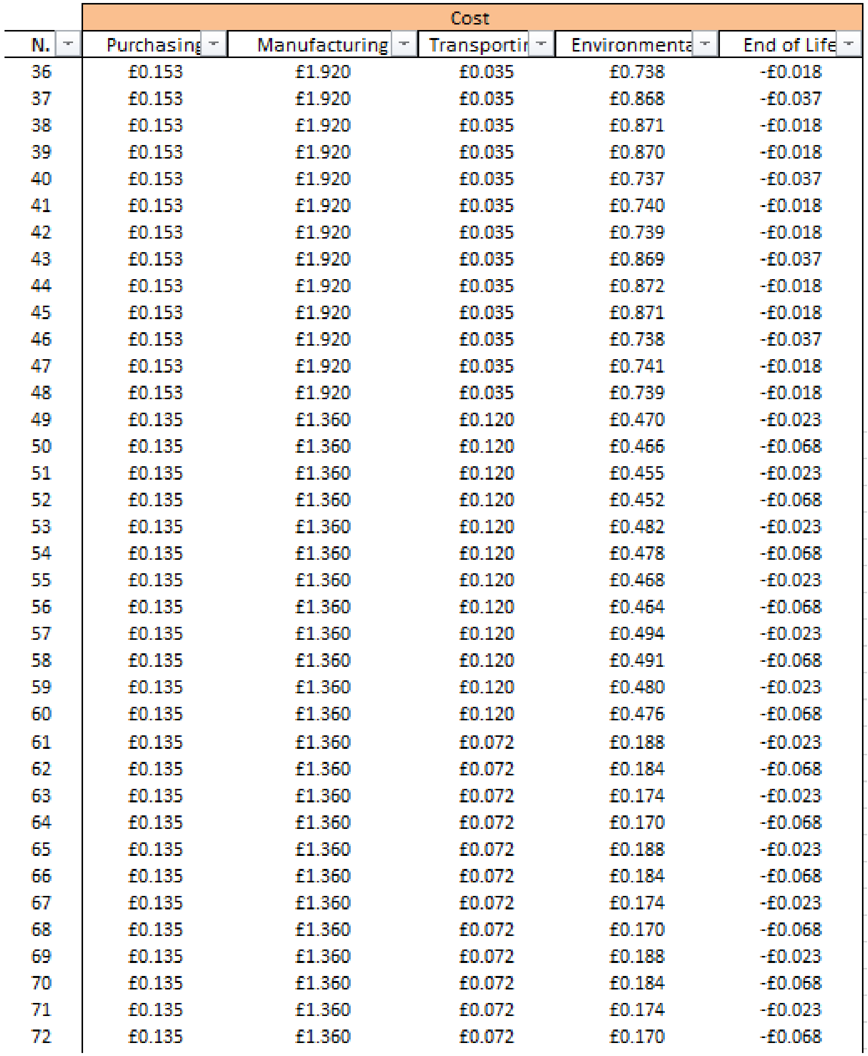
	Cost				
N.	Purchasin	Manufacturing	Transporti	Environmenta	End of Life
1	£0.153	£1.920	£0.035	£0.867	-£0.037
2	£0.153	£1.920	£0.035	£0.870	-£0.018
3	£0.153	£1.920	£0.035	£0.869	-£0.018
4	£0.153	£1.920	£0.035	£0.736	-£0.037
5	£0.153	£1.920	£0.035	£0.739	-£0.018
6	£0.153	£1.920	£0.035	£0.738	-£0.018
7	£0.153	£1.920	£0.035	£0.868	-£0.037
8	£0.153	£1.920	£0.035	£0.870	-£0.018
9	£0.153	£1.920	£0.035	£0.869	-£0.018
10	£0.153	£1.920	£0.035	£0.737	-£0.037
11	£0.153	£1.920	£0.035	£0.739	-£0.018
12	£0.153	£1.920	£0.035	£0.738	-£0.018
13	£0.153	£1.920	£0.035	£0.868	-£0.037
14	£0.153	£1.920	£0.035	£0.870	-£0.018
15	£0.153	£1.920	£0.035	£0.869	-£0.018
16	£0.153	£1.920	£0.035	£0.737	-£0.037
17	£0.153	£1.920	£0.035	£0.739	-£0.018
18	£0.153	£1.920	£0.035	£0.738	-£0.018
19	£0.153	£1.920	£0.035	£0.868	-£0.037
20	£0.153	£1.920	£0.035	£0.871	-£0.018
21	£0.153	£1.920	£0.035	£0.870	-£0.018
22	£0.153	£1.920	£0.035	£0.737	-£0.037
23	£0.153	£1.920	£0.035	£0.740	-£0.018
24	£0.153	£1.920	£0.035	£0.739	-£0.018
25	£0.153	£1.920	£0.035	£0.868	-£0.037
26	£0.153	£1.920	£0.035	£0.870	-£0.018
27	£0.153	£1.920	£0.035	£0.869	-£0.018
28	£0.153	£1.920	£0.035	£0.737	-£0.037
29	£0.153	£1.920	£0.035	£0.739	-£0.018
30	£0.153	£1.920	£0.035	£0.738	-£0.018
31	£0.153	£1.920	£0.035	£0.868	-£0.037
32	£0.153	£1.920	£0.035	£0.871	-£0.018
33	£0.153	£1.920	£0.035	£0.869	-£0.018
34	£0.153	£1.920	£0.035	£0.737	-£0.037
35	£0.153	£1.920	£0.035	£0.740	-£0.018



N.	Origin	Destination	Transpor	Plan	Tra	Tru	Shi	Materi	Weigl	M. Process	Rec. Con	Recycle	Incinerated	Landf	D	D	D	D4	D	D	D	D	D	D1	Volum	Streng	Finish	M. Cos	GRI
36	UK	UK	Truck	0	0	750	0	Peek	3.65	Injected molded	50	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	224	6	0.042	YES
37	UK	UK	Truck	0	0	1000	0	Peek	3.65	Injected molded	0	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	224	6	0.042	YES
38	UK	UK	Truck	0	0	1000	0	Peek	3.65	Injected molded	0	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	224	6	0.042	YES
39	UK	UK	Truck	0	0	1000	0	Peek	3.65	Injected molded	0	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	224	6	0.042	YES
40	UK	UK	Truck	0	0	1000	0	Peek	3.65	Injected molded	50	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	224	6	0.042	YES
41	UK	UK	Truck	0	0	1000	0	Peek	3.65	Injected molded	50	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	224	6	0.042	YES
42	UK	UK	Truck	0	0	1000	0	Peek	3.65	Injected molded	50	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	224	6	0.042	YES
43	UK	UK	Truck	0	0	1500	0	Peek	3.65	Injected molded	0	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	224	6	0.042	YES
44	UK	UK	Truck	0	0	1500	0	Peek	3.65	Injected molded	0	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	224	6	0.042	YES
45	UK	UK	Truck	0	0	1500	0	Peek	3.65	Injected molded	0	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	224	6	0.042	YES
46	UK	UK	Truck	0	0	1500	0	Peek	3.65	Injected molded	50	50	25	25	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	224	6	0.042	YES
47	UK	UK	Truck	0	0	1500	0	Peek	3.65	Injected molded	50	25	50	25	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	224	6	0.042	YES
48	UK	UK	Truck	0	0	1500	0	Peek	3.65	Injected molded	50	25	25	50	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	224	6	0.042	YES
49	Pakistan	UK	Plane	18000	0	0	0	S. Steel	22.00	Forged + Machined	50	50	50	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
50	Pakistan	UK	Plane	18000	0	0	0	S. Steel	22.00	Forged + Machined	50	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
51	Pakistan	UK	Plane	18000	0	0	0	S. Steel	22.00	Forged + Machined	100	50	50	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
52	Pakistan	UK	Plane	18000	0	0	0	S. Steel	22.00	Forged + Machined	100	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
53	Pakistan	UK	Plane	19000	0	0	0	S. Steel	22.00	Forged + Machined	50	50	50	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
54	Pakistan	UK	Plane	19000	0	0	0	S. Steel	22.00	Forged + Machined	50	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
55	Pakistan	UK	Plane	19000	0	0	0	S. Steel	22.00	Forged + Machined	100	50	50	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
56	Pakistan	UK	Plane	19000	0	0	0	S. Steel	22.00	Forged + Machined	100	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
57	Pakistan	UK	Plane	20000	0	0	0	S. Steel	22.00	Forged + Machined	50	50	50	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
58	Pakistan	UK	Plane	20000	0	0	0	S. Steel	22.00	Forged + Machined	50	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
59	Pakistan	UK	Plane	20000	0	0	0	S. Steel	22.00	Forged + Machined	100	50	50	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
60	Pakistan	UK	Plane	20000	0	0	0	S. Steel	22.00	Forged + Machined	100	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
61	Pakistan	UK	Ship	0	0	0	18000	S. Steel	22.00	Forged + Machined	50	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
62	Pakistan	UK	Ship	0	0	0	18000	S. Steel	22.00	Forged + Machined	50	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
63	Pakistan	UK	Ship	0	0	0	18000	S. Steel	22.00	Forged + Machined	100	50	50	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
64	Pakistan	UK	Ship	0	0	0	18000	S. Steel	22.00	Forged + Machined	100	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
65	Pakistan	UK	Ship	0	0	0	19000	S. Steel	22.00	Forged + Machined	50	50	50	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
66	Pakistan	UK	Ship	0	0	0	19000	S. Steel	22.00	Forged + Machined	50	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
67	Pakistan	UK	Ship	0	0	0	19000	S. Steel	22.00	Forged + Machined	100	50	50	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
68	Pakistan	UK	Ship	0	0	0	19000	S. Steel	22.00	Forged + Machined	100	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
69	Pakistan	UK	Ship	0	0	0	20000	S. Steel	22.00	Forged + Machined	50	50	50	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
70	Pakistan	UK	Ship	0	0	0	20000	S. Steel	22.00	Forged + Machined	50	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
71	Pakistan	UK	Ship	0	0	0	20000	S. Steel	22.00	Forged + Machined	100	50	50	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES
72	Pakistan	UK	Ship	0	0	0	20000	S. Steel	22.00	Forged + Machined	100	100	0	0	5	80.0	2.5	2.60	60.00	26.00	24.00	0	0	0	10000	515	16	0.006	YES



	Carbon Footprint					Energy Consumed					Air Acidification					Water Eutrophication				
N.	Materi	Manufa	Use	Transpor	End of Lif	Materia	Manufa	Use	Transport	End of Lif	Material	Manufac.	Use	Transport	End of Life	Material	Manufac.	Us	Transport	End of Lif
36	0.065	3.90E-03	0.000	4.70E-04	2.50E-03	1.3	0.075	0	6.90E-03	1.90E-03	2.20E-04	2.60E-05	0	2.20E-06	1.50E-06	2.20E-05	9.50E-07	0	4.90E-07	2.50E-06
37	0.077	3.90E-03	0.000	5.10E-04	1.90E-03	1.5	0.075	0	7.50E-03	1.40E-03	2.20E-04	2.60E-05	0	2.40E-06	1.20E-06	2.20E-05	9.50E-07	0	5.40E-07	1.30E-06
38	0.077	3.90E-03	0.000	5.10E-04	3.10E-03	1.5	0.075	0	7.50E-03	2.30E-03	2.20E-04	2.60E-05	0	2.40E-06	2.20E-06	2.20E-05	9.50E-07	0	5.40E-07	1.50E-06
39	0.077	3.90E-03	0.000	5.10E-04	2.50E-03	1.5	0.075	0	7.50E-03	1.90E-03	2.20E-04	2.60E-05	0	2.40E-06	1.50E-06	2.20E-05	9.50E-07	0	5.40E-07	2.50E-06
40	0.065	3.90E-03	0.000	5.10E-04	1.90E-03	1.3	0.075	0	7.50E-03	1.40E-03	2.20E-04	2.60E-05	0	2.40E-06	1.20E-06	2.20E-05	9.50E-07	0	5.40E-07	1.30E-06
41	0.065	3.90E-03	0.000	5.10E-04	3.10E-03	1.3	0.075	0	7.50E-03	2.30E-03	2.20E-04	2.60E-05	0	2.40E-06	2.20E-06	2.20E-05	9.50E-07	0	5.40E-07	1.50E-06
42	0.065	3.90E-03	0.000	5.10E-04	2.50E-03	1.3	0.075	0	7.50E-03	1.90E-03	2.20E-04	2.60E-05	0	2.40E-06	1.50E-06	2.20E-05	9.50E-07	0	5.40E-07	2.50E-06
43	0.077	3.90E-03	0.000	6.00E-04	1.90E-03	1.5	0.075	0	8.80E-03	1.40E-03	2.20E-04	2.60E-05	0	2.80E-06	1.20E-06	2.20E-05	9.50E-07	0	6.30E-07	1.30E-06
44	0.077	3.90E-03	0.000	6.00E-04	3.10E-03	1.5	0.075	0	8.80E-03	2.30E-03	2.20E-04	2.60E-05	0	2.80E-06	2.20E-06	2.20E-05	9.50E-07	0	6.30E-07	1.50E-06
45	0.077	3.90E-03	0.000	6.00E-04	2.50E-03	1.5	0.075	0	8.80E-03	1.90E-03	2.20E-04	2.60E-05	0	2.80E-06	1.50E-06	2.20E-05	9.50E-07	0	6.30E-07	2.50E-06
46	0.065	3.90E-03	0.000	6.00E-04	1.90E-03	1.3	0.075	0	8.80E-03	1.40E-03	2.20E-04	2.60E-05	0	2.80E-06	1.20E-06	2.20E-05	9.50E-07	0	6.30E-07	1.30E-06
47	0.065	3.90E-03	0.000	6.00E-04	3.10E-03	1.3	0.075	0	8.80E-03	2.30E-03	2.20E-04	2.60E-05	0	2.80E-06	2.20E-06	2.20E-05	9.50E-07	0	6.30E-07	1.50E-06
48	0.065	3.90E-03	0.000	6.00E-04	2.50E-03	1.3	0.075	0	8.80E-03	1.90E-03	2.20E-04	2.60E-05	0	2.80E-06	1.50E-06	2.20E-05	9.50E-07	0	6.30E-07	2.50E-06
49	0.109	1.29E-01	0.000	3.15E-01	1.50E-02	1.2	1	0	4.40E+00	1.20E-02	4.50E-04	1.30E-03	0	9.40E-04	1.20E-05	5.10E-04	7.10E-05	0	2.10E-04	2.50E-06
50	0.109	1.29E-01	0.000	3.15E-01	0.00E+00	1.2	1	0	4.40E+00	0.00E+00	4.50E-04	1.30E-03	0	9.40E-04	0.00E+00	5.10E-04	7.10E-05	0	2.10E-04	0.00E+00
51	0.089	1.29E-01	0.000	3.15E-01	1.50E-02	1.0	1	0	4.40E+00	1.20E-02	4.50E-04	1.30E-03	0	9.40E-04	1.20E-05	5.10E-04	7.10E-05	0	2.10E-04	2.50E-06
52	0.089	1.29E-01	0.000	3.15E-01	0.00E+00	1.0	1	0	4.40E+00	0.00E+00	4.50E-04	1.30E-03	0	9.40E-04	0.00E+00	5.10E-04	7.10E-05	0	2.10E-04	0.00E+00
53	0.109	1.29E-01	0.000	3.26E-01	1.50E-02	1.2	1	0	4.60E+00	1.20E-02	4.50E-04	1.30E-03	0	9.80E-04	1.20E-05	5.10E-04	7.10E-05	0	2.10E-04	2.50E-06
54	0.109	1.29E-01	0.000	3.26E-01	0.00E+00	1.2	1	0	4.60E+00	0.00E+00	4.50E-04	1.30E-03	0	9.80E-04	0.00E+00	5.10E-04	7.10E-05	0	2.10E-04	0.00E+00
55	0.089	1.29E-01	0.000	3.26E-01	1.50E-02	1.0	1	0	4.60E+00	1.20E-02	4.50E-04	1.30E-03	0	9.80E-04	1.20E-05	5.10E-04	7.10E-05	0	2.10E-04	2.50E-06
56	0.089	1.29E-01	0.000	3.26E-01	0.00E+00	1.0	1	0	4.60E+00	0.00E+00	4.50E-04	1.30E-03	0	9.80E-04	0.00E+00	5.10E-04	7.10E-05	0	2.10E-04	0.00E+00
57	0.109	1.29E-01	0.000	3.37E-01	1.50E-02	1.2	1	0	4.80E+00	1.20E-02	4.50E-04	1.30E-03	0	1.00E-03	1.20E-05	5.10E-04	7.10E-05	0	2.20E-04	2.50E-06
58	0.109	1.29E-01	0.000	3.37E-01	0.00E+00	1.2	1	0	4.80E+00	0.00E+00	4.50E-04	1.30E-03	0	1.00E-03	0.00E+00	5.10E-04	7.10E-05	0	2.20E-04	0.00E+00
59	0.089	1.29E-01	0.000	3.37E-01	1.50E-02	1.0	1	0	4.80E+00	1.20E-02	4.50E-04	1.30E-03	0	1.00E-03	1.20E-05	5.10E-04	7.10E-05	0	2.20E-04	2.50E-06
60	0.089	1.29E-01	0.000	3.37E-01	0.00E+00	1.0	1	0	4.80E+00	0.00E+00	4.50E-04	1.30E-03	0	1.00E-03	0.00E+00	5.10E-04	7.10E-05	0	2.20E-04	0.00E+00
61	0.109	1.29E-01	0.000	2.80E-03	0.00E+00	1.2	1	0	3.70E-02	0.00E+00	5.00E-04	1.30E-03	0	4.10E-05	0.00E+00	5.00E-04	7.10E-05	0	4.90E-06	0.00E+00
62	0.109	1.29E-01	0.000	2.80E-03	0.00E+00	1.2	1	0	3.70E-02	0.00E+00	4.50E-04	1.30E-03	0	4.10E-05	0.00E+00	5.10E-04	7.10E-05	0	4.90E-06	0.00E+00
63	0.089	1.29E-01	0.000	2.80E-03	1.50E-02	1.0	1	0	3.70E-02	1.20E-02	4.50E-04	1.30E-03	0	4.10E-05	1.20E-05	5.10E-04	7.10E-05	0	4.90E-06	2.50E-06
64	0.089	1.29E-01	0.000	2.80E-03	0.00E+00	1.0	1	0	3.70E-02	0.00E+00	4.50E-04	1.30E-03	0	4.10E-05	0.00E+00	5.10E-04	7.10E-05	0	4.90E-06	0.00E+00
65	0.109	1.29E-01	0.000	2.80E-03	1.50E-02	1.2	1	0	3.70E-02	1.20E-02	4.50E-04	1.30E-03	0	4.30E-05	1.20E-05	5.10E-04	7.10E-05	0	5.10E-06	2.50E-06
66	0.109	1.29E-01	0.000	2.80E-03	0.00E+00	1.2	1	0	3.70E-02	0.00E+00	4.50E-04	1.30E-03	0	4.30E-05	0.00E+00	5.10E-04	7.10E-05	0	5.10E-06	0.00E+00
67	0.089	1.29E-01	0.000	2.80E-03	1.50E-02	1.0	1	0	3.70E-02	1.20E-02	4.50E-04	1.30E-03	0	4.30E-05	1.20E-05	5.10E-04	7.10E-05	0	5.10E-06	2.50E-06
68	0.089	1.29E-01	0.000	2.80E-03	0.00E+00	1.0	1	0	3.70E-02	0.00E+00	4.50E-04	1.30E-03	0	4.30E-05	0.00E+00	5.10E-04	7.10E-05	0	5.10E-06	0.00E+00
69	0.109	8.80E-02	0.000	2.90E-03	1.50E-02	1.2	1	0	3.80E-02	1.20E-02	4.50E-04	1.30E-03	0	4.50E-05	1.20E-05	5.10E-04	7.10E-05	0	5.30E-06	2.50E-06
70	0.109	8.80E-02	0.000	2.90E-03	0.00E+00	1.2	1	0	3.80E-02	0.00E+00	4.50E-04	1.30E-03	0	4.50E-05	0.00E+00	5.10E-04	7.10E-05	0	5.30E-06	0.00E+00
71	0.089	8.80E-02	0.000	2.90E-03	1.50E-02	1.0	1	0	3.80E-02	1.20E-02	4.50E-04	1.30E-03	0	4.50E-05	1.20E-05	5.10E-04	7.10E-05	0	5.30E-06	2.50E-06
72	0.089	8.80E-02	0.000	2.90E-03	0.00E+00	1.0	1	0	3.80E-02	0.00E+00	4.50E-04	1.30E-03	0	4.50E-05	0.00E+00	5.10E-04	7.10E-05	0	5.30E-06	0.00E+00



	Cost				
N.	Purchasin	Manufacturing	Transporti	Environmenta	End of Life
36	£0.153	£1.920	£0.035	£0.738	-£0.018
37	£0.153	£1.920	£0.035	£0.868	-£0.037
38	£0.153	£1.920	£0.035	£0.871	-£0.018
39	£0.153	£1.920	£0.035	£0.870	-£0.018
40	£0.153	£1.920	£0.035	£0.737	-£0.037
41	£0.153	£1.920	£0.035	£0.740	-£0.018
42	£0.153	£1.920	£0.035	£0.739	-£0.018
43	£0.153	£1.920	£0.035	£0.869	-£0.037
44	£0.153	£1.920	£0.035	£0.872	-£0.018
45	£0.153	£1.920	£0.035	£0.871	-£0.018
46	£0.153	£1.920	£0.035	£0.738	-£0.037
47	£0.153	£1.920	£0.035	£0.741	-£0.018
48	£0.153	£1.920	£0.035	£0.739	-£0.018
49	£0.135	£1.360	£0.120	£0.470	-£0.023
50	£0.135	£1.360	£0.120	£0.466	-£0.068
51	£0.135	£1.360	£0.120	£0.455	-£0.023
52	£0.135	£1.360	£0.120	£0.452	-£0.068
53	£0.135	£1.360	£0.120	£0.482	-£0.023
54	£0.135	£1.360	£0.120	£0.478	-£0.068
55	£0.135	£1.360	£0.120	£0.468	-£0.023
56	£0.135	£1.360	£0.120	£0.464	-£0.068
57	£0.135	£1.360	£0.120	£0.494	-£0.023
58	£0.135	£1.360	£0.120	£0.491	-£0.068
59	£0.135	£1.360	£0.120	£0.480	-£0.023
60	£0.135	£1.360	£0.120	£0.476	-£0.068
61	£0.135	£1.360	£0.072	£0.188	-£0.023
62	£0.135	£1.360	£0.072	£0.184	-£0.068
63	£0.135	£1.360	£0.072	£0.174	-£0.023
64	£0.135	£1.360	£0.072	£0.170	-£0.068
65	£0.135	£1.360	£0.072	£0.188	-£0.023
66	£0.135	£1.360	£0.072	£0.184	-£0.068
67	£0.135	£1.360	£0.072	£0.174	-£0.023
68	£0.135	£1.360	£0.072	£0.170	-£0.068
69	£0.135	£1.360	£0.072	£0.188	-£0.023
70	£0.135	£1.360	£0.072	£0.184	-£0.068
71	£0.135	£1.360	£0.072	£0.174	-£0.023
72	£0.135	£1.360	£0.072	£0.170	-£0.068