DEVELOPMENT OF MULTI-OBJECTIVE OPTIMIZATION FOR HIGH RECYCLABILITY MATERIAL SELECTION IN PRODUCT DESIGN

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Development of Multi-Objective Optimization for High Recyclability Material Selection in Product Design

Abstract

This thesis presents the development of a multi-objective optimization for high recyclability material selection in product design. The aim of the research is to build up methodology that aid designers to improve product's recyclability that meet environmental legislative requirements. The research is motivated by low attention given on the high recyclability material selection in the literature review. There is also lack of study that developing an integrated method of recyclability assessment with material selection in product design specifically during conceptual design stage.

The research was conducted in three phases: the survey, exploratory study and the multi objective optimization for high recyclability material selection. The survey was done by distributing an open ended questionnaire to the designers to reveal the current practice of how a designer incorporates environmental issues into product design. The exploratory study was performed by conducting interviews to seek designer's existing practice specific for design of recycling and to determine what factors that significantly contribute to recyclability. The recyclability assessment using *Fuzzy Inference System* was employed in the High Recyclability Material Selection optimization model to minimize product's weight, as well as maximizing its function and recyclability.

Results from the survey showed that the awareness among designers in Malaysia to incorporate environmental concerns into the product design process were quite high but not properly implemented because lack of knowledge and management support. Five recyclability factors based on the recyclers' current practices have been identified from the exploratory study, namely profit, recycling infrastructure, material separation, material combination and joining type. The proposed method may support the product's recyclability which concurrently done during conceptual design stage. It is also resulted to an optimized set of design configurations that consider lightweight, functionality and recyclability. The report listed the significant factors that mostly influence product's recyclability in Malaysia. The research also provided a new methodology to assist designers in incorporating recyclability aspect during product design.

Pembangunan Pengoptimuman Pelbagai Objektif bagi Pemilihan Bahan dengan Kadar Kitar Semula Tertinggi pada Reka Bentuk Produk

Abstrak

Tesis ini melaporkan kajian pembangunan kaedah pengoptimuman pelbagai objektif bagi pemilihan bahan dengan kebolehan kitar semula yang tertinggi semasa reka bentuk produk. Matlamat penyelidikan ini ialah untuk membangunkan metodologi yang membantu pereka bentuk untuk meningkatkan tahap kitar semula produk supaya dapat memenuhi tuntutan undang-undang berkaitan alam sekitar. Penyelidikan ini sangat memandangkan perhatian yang kurang diberikan untuk pemilihan bahan yang memiliki kemampuan kitar semula di dalam kajian literatur. Integrasi penilaian kitar semula semasa reka bentuk produk dengan proses pemilihan bahan masih tiada wujud. Selain itu, kurangnya kajian yang dijalankan bagi mengenal pasti factor-faktor rekabentuk yang penting yang akan mempengaruhi kebolehan kitar semula produk bagi kegiatan aktiviti kitar semula pada masa kini.

Penyelidikan ini dijalankan dalam tiga fasa, kajian tinjauan, penyelidikan eksploratori dan pengoptimuman pelbagai objektif bagi pemilihan reka bentuk produk berdasarkan kadar tertinggi bahan kitar semula. Kajian tinjauan dibuat dengan mengagihkan borang soal selidik terbuka kepada pereka untuk mengetahui amalan mereka dalam menggabungkan isu persekitaran ke dalam reka bentuk produk. Penyelidikan eksploratori pula dijalankan dengan mengadakan temu bual untuk meninjau amalan terkini pereka bentuk semasa mereka bentuk bagi pengitaran semula dan untuk menentukan factor-faktor yang penting bagi pengitaran semula. Penilaian kebolehan mengitar semula menggunakan Fuzzy Inference System diintegrasikan dengan pemilihan bahan yang boleh dikitar semula untuk mengurangkan berat produk dan meningkatkan kegunaanya dan kebolehan mengitar semula.

Penemuan daripada kajian menunjukkan terdapat kesedaran di kalangan pereka bentuk di Malaysia untuk mengambil berat terhadap persekitaran semasa rekabentuk produk, namun kurang dilaksanakan dengan baik kerana kurangnya pengetahuan dan sokongan daripada pihak pengurusan. Lima faktor kebolehan mengitar semula dalam amalan terkini mengitar semula oleh pereka bentuk adalah: keuntungan, infrastuktur kitar semula, pengasingan bahan, gabungan bahan dan jenis gabungan bahan. Kaedah yang dicadangkan ini dipercayai dapat memberikan penyelesaian dan garis panduan untuk pereka bentuk dalam memilih bahan yang boleh dikitar semula.

Penemuan dalam penyelidikan ini menyajikan faktor-faktor signifikan dalam kebolehan kitaran semula di Malaysia. Penyelidikan ini juga menyumbangkan kaedah baru dalam membantu tugasan pereka untuk memilih bahan boleh kitar semula.

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List of Symbols and Abbreviations

A, B	linguistic constants
b	width, cm
CAD	computer aided design
CES	The Cambridge Engineering Selector
CI	consistency index
CR	consistency ratio
C_{diss}	cost for disassembly for part
C_{tran}	cost for transportation
C_{shrd}	shredding cost
C_{dps}	cost for disposal or landfill of unwanted substances
C_1	constant
C_m	cost/kg material
C_p	specific heat
DFE	design for environment
DFR	design for recycling
EWRQ	Environmentally Weighted Recycling Quote
F	notation of fuzzy sets
FIS	Fuzzy Inference System
GA	genetic algorithm
h_i	height of part I, cm
i	number of material
I	moment of area
jt	joining type score

LCA	Life Cycle Assessment
l_{diss}	labor cost per hour for disassembly activities
l_{shrd}	labor cost per hour for shredding activities
l_i	length of part I, cm
ms	material separation score
mc	material combination score
M_i	material type for part i
n	number of part
OECD	Organization of Economic Cooperation and Development
P_{rm}	price of reclaimed material for material
P_1	price of reclaimed material (first grade)
QWERTY	Quotes for Environmental Weighted Recyclability and Eco-Efficiency
REM	Recyclability Evaluation Methods
RI	random index
ri	recycling infrastructure score
R_{value}	recyclability index
R_c	recycling cost
$(R_p)_{add}$	recycling profit from additional valuable materials
S	desired stiffness
TEP	Toxic Equivalency Potential
t_{diss}	time for disassembly, hour
t_{shrd}	time for shredding, hour
t_i	thickness of part i, cm
W	weight vector
w	weight of material, g

WCED	World Commission on Environment and Development
X	universe of discourse
x	elements from universe of discourse

Greek letter

μ	membership function
β	degree of fulfillment
λ_{max}	maximum eigenvalue
δ	delta
ρ	density, kg/m^3
σ	yield strength, MPa
E	Young's Modulus, GN/m^2
λ	thermal conductivity
σ_y	elastic limit
ρ_e	electrical resistivity

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Over the last decade, the world's attention has shifted its focus on overcoming environmental problems such as global warming, resource depletion and waste disposal. Increasing concern for the future generation leads to the acceleration of research devoted on sustainability aimed at improving and preserving natural resources. Because of this motivation, the manufacturing road map that concerns more on environmental perspectives is applied intensively than before, since manufacturing activities is one of major contributor to environmental damage. As a result, manufacturing industries are encouraged to develop products and services that will lead to a sustainable environment.

Many current approaches adopted by manufacturing companies which dealt with environmental impacts are end–of-pipe solutions. However, design is the most strategic phase to control environmental impact during a product's life cycle (Graedel, 1995), from selection of materials, manufacturing processes, product usage and end-of-life treatment. Therefore, designers play a significant role in reducing environmental impact.

Design for Environment (DFE) is one of the established concepts that attempt to incorporate environmental impact during product design, with regards to product life cycle. Most research in DFE has been very fragmented, in which DFE research have been focused on Design for Disassembly, Design for Recycling, Design for Reuse, and Design for Remanufacture. In Design for Recycling, however, it has been shown that most of the existing approaches cannot be adopted easily in a company (Rose, 2000; Wongdeethai, 2006). In reality, Design for Recycling should involve different stakeholders such as designers, recyclers, policy makers and customers. Earlier research on Design for Recycling have not yet considered significant factors that influence product recyclability based on the real practice of recyclers. A structured methodology that assists designers' accounts recyclability aspects during design based on the recycling practices is very important to increase the efficiency of recycling process. In light of the above motivation, this study is aimed to develop a method that improves a product's recyclability during the product design stage, taking into account the recyclers' perspectives specifically in Malaysia. The development of a method for high recyclability material selection during product design is also proposed in this study as a novel contribution in Design for Recycling.

This study was carried out in two phases. The first phase involves a qualitative-quantitative approach to determine the important parameters in product recyclability from the recyclers' perspectives of view. The second phase involves developing a numerical experiment to optimize high recyclability material selection.

1.2 Research Aim and Objectives

The primary aim of this research is to develop a method that will facilitate designers in improving the product's recyclability that fulfill the requirements of environmental regulations.

In order to achieve this aim, the research objectives are set as follows:

1. To identify the current practices of product designers incorporating Design for Environment during product design
2. To identify recyclability factors from a recyclers' current practices
3. To develop a method using multi-objective optimization for high recyclability material selection in product design that can be integrate into CAD modeling environment

1.3 Scope of the Research

This research will focus on how to develop a method for improving a product's recyclability. An automotive product has been chosen to illustrate the effectiveness of the method proposed, mainly because of the well-established legislation which restricts recyclability levels. In addition, the automotive industry in Malaysia is recognized as one of the industries that foster economic growth.

This research is conducted in Malaysia in which reflect to the recyclability factors. For different countries, the legal system employed and recycling treatments available may affect the product's recyclability differently.

1.4 Outline of Thesis

This thesis comprises of nine chapters, and each chapter is associated with each stage of the research methodology, as shown in Figure 1.1.

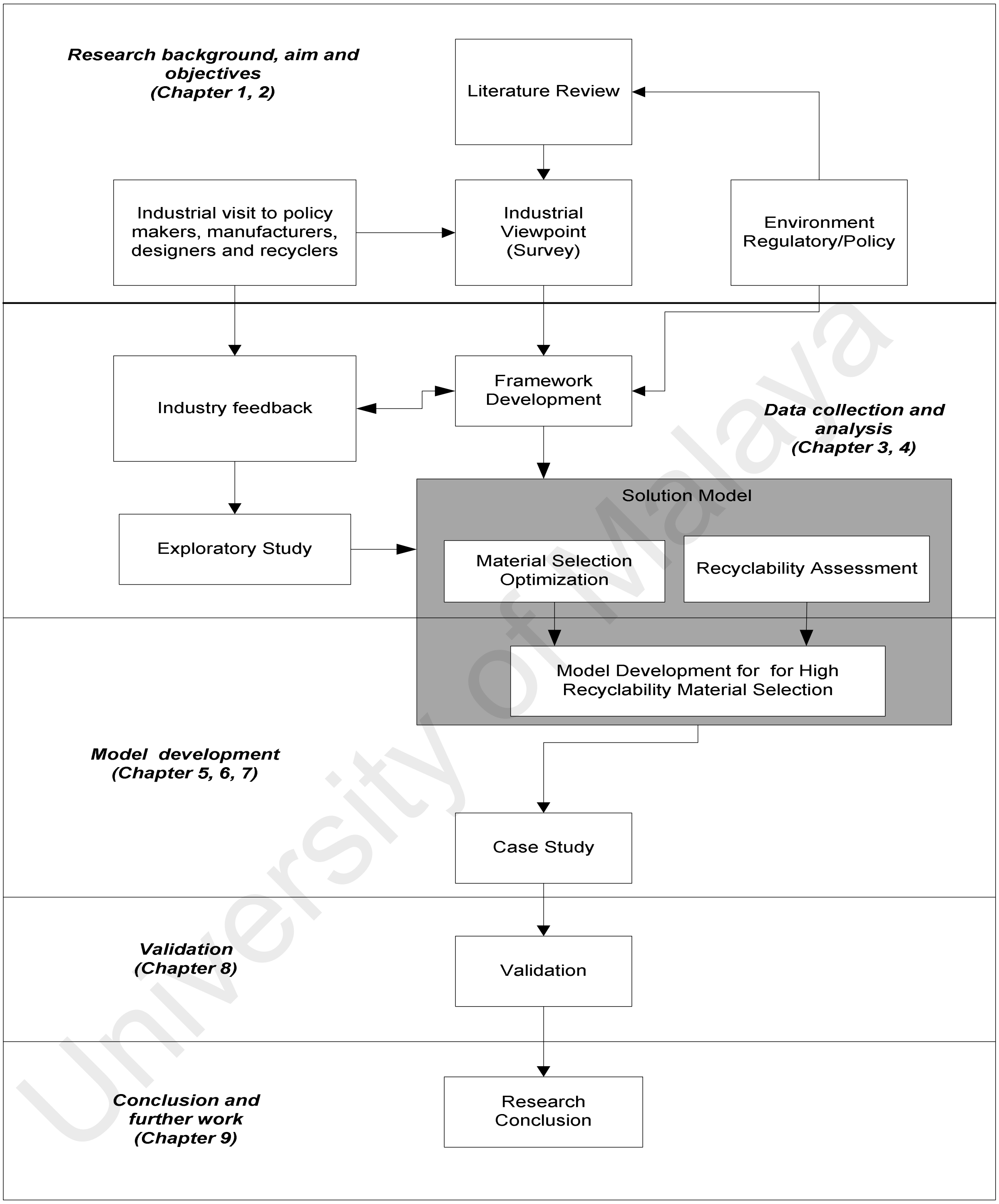


Figure 1.1 Research methodologies and associated thesis chapters.

A brief description of each chapter is given as follows:

Chapter 1

This chapter presents a background of the research, research problems, research aim, objectives, scope of the study and thesis structure.

Chapter 2

In this chapter, a review of significant literature relevant to the research domain is conducted. At the end of this chapter, the research gaps are identified and a conceptual framework is formulated.

Chapter 3

This chapter describes the methodology of this research. The approach used in the research design and strategies undertaken to answer the research questions are presented.

Chapter 4

This chapter reports on the results of the survey and exploratory study. The survey is undertaken to understand designers' current approach in incorporating environmental consideration during product design. The exploratory study provides an insight into the current approaches of evaluating a products' recyclability and the factors that influence.

Chapter 5

Chapter 5 describes the formulation of a recyclability assessment. This includes parameter setting, mathematical description of the problem, and fuzzy inference formulations. A numerical example of recyclability assessment is also presented in this chapter.

Chapter 6

A formulation for optimizing high recyclability material selection using mathematical model is presented in this chapter.

Chapter 7

The optimization model is implemented on two case studies of a typical problem in product design and the results are discussed in this chapter.

Chapter 8

This chapter presents validation of the proposed method. The validation technique, validation process and results are discussed.

Chapter 9

The conclusions of this research are presented succinctly in this chapter, as well as limitations of the research and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

For the past decades, it has been well accepted by academics and practitioners that environmental problems are crucial issues, which may affect economical and technical aspects of product development activities. The awareness of reducing environmental impact during product development stage creates various practices on sustainable product design. Selection of green materials, examination of product usage phase in order to reduce environmental impact, reduction on using hazardous and toxic substances and design for product end-of-life are some examples of those practices.

These following subsections provide a description of the driving force for environmental awareness in product design, current methods and practices, as well as initiatives taken in order to reduce environmental impact. A conceptual framework is highlighted and the research gaps are formulated at the end of this chapter. This chapter is aimed to review literature pertinent to the research topic.

2.2 Driving Force for Environmental Awareness

In 1987, the Brundtland Commission launched a sustainable development concept that emphasizes on developments that fulfill the needs of the present society without compromising the needs of future generations.

"Humanity has the ability to make development sustainable - to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs."
(*Brundtland Commision, 1987: p. 24*).

The World Commission on Environment and Development (WCED) also emphasized the need to sustain resources for future generations in 1987. It is stated that:

"The earth is one but the world is not. We all depend on one biosphere for sustaining our lives. Yet, each community, each country, strives for survival and prosperity with little regard for its impact on others. Some consume the Earth's resources at a rate that would leave little for future generations. Others, many more in numbers consume far too little and live with the prospects of hunger, squalor, disease and early death."

(WCED Report, 1998: Chapter 1)

Following the Brundtland report, the world's attention has shifted towards overcoming environmental problems such as global warming, resource depletion and waste disposal. Many milestones have been achieved, beginning with the Kyoto Protocol in 1997 where 37 industrialized countries committed themselves to reduce the production of greenhouse gases (GHG). The member countries committed themselves in reducing their collective greenhouse gas emissions by 5.2% from the 1990 level (UNFCC, 2006). This is followed by the Copenhagen meeting in 2009 where nations met to strengthen the previous commitment and showed great interest in developing a sustainable economy. There is also an increasing rate of voluntary participation from the industrial community (Fiksel, 2009; Seliger, 2007; Abele, 2005).

It is known that a large proportion of environmental problems are due to industrial activities. Industries contribute to natural resource depletion during mining or extraction; create CO_2 emissions and consume energy consumption during production and generate enormous waste, thus putting strain on the environment. Manufacturers failed to subscribe preventive actions to reduce waste which results in higher energy cost and time consumption for implementing corrective actions. Environmental damage has become prevalent due to past industrial practices and consequently results in the accumulation of a huge environmental burden. Unsustainable industrial activities will result in the production and consumption that exceed the limits of the world's natural resources. Production and consumption must be ecologically balanced so that it will not burden future generations. Lemos *et al.* (1998) identified five critical obstacles which hinder the attainment of industrial sustainability:

1. Tremendous increase in human population.
2. Reluctance to anticipate environmental damage.
3. Short-range assessment of opportunities.
4. Collapse with respect to natural systems.
5. Over confidence in technological innovation.

Along with the rise of human population and higher quality of life, human demand on products and services will also increase. Consequently, industries must produce an ever increasing amount of products in order satisfy the demand. The products created have specific short and long-term environmental impacts during their life cycle. These problems, unless addressed, will significantly contribute to environmental damage and threat the survival of future generations and their quality of life. Thus, it is crucial for industries, governments and the general society to focus on minimizing the environmental damage produced (*O'Brien, 1999: p. 3)*:

> *"Industries must design, produce, distribute and dispose products in such a way that the associated environmental impacts and resource use levels are at least in line with the Earth's estimated carrying capacity."*

Manufacturing industries possess a strong potential as a motivating force to establish a sustainable society by designing and implementing sustainable practices. Changing the paradigm in conducting a sustainable business is now becoming essential (Maxwell *et al.*, 2006). In Malaysia specifically, sustainable development has become an important issue and should be aligned with the advancement of manufacturing technology. This includes public policy initiatives such as economic incentives, education, caps on resource consumption, impressive participatory management, conservation strategies and legislated limits on pollution (Johannesburg Summit Report, 2002). According to the Johannesburg Summit Report, the national concern for technology transfer in Malaysia is focused on three issues namely: (1) using limited public resources to support research and development directly; (2) encouraging the development and transfer of industrial process technologies that increase efficiency in input use and reduce the production of waste products; and (3) developing new financial incentives to achieve these two goals. In regards to the second issue, it is evident that Malaysia has put environmental perspective as an important national concern, especially in the utilization of natural resources. An example of the evidence is the implemented waste minimization program such as Malaysian Agenda for Waste Reduction (MAWAR) and Cleaner Production to educate industry in particular and the public in general on government efforts towards Integrated Waste Management (IWM) that guided by the National Environmental Policy (UNEP, 2012).

The ‘end-of-pipe’ concept implemented in early 1960s and 1970s has been quite successful for minimizing the environmental impact during industrial activities (Rose, 2000). However, Fiksel (2009) argued that in the long run, this concept is inefficient because remediation is taken after the damage has taken place. Successful solutions should be based on prevention strategies rather than remediation strategies. Avoiding problems before they arise are more beneficial, because it delimits the damage that may be produced during a product’s life cycle. An example of the prevention concept is the ‘polluter-pay-principles’ (OECD, 1992).However, this concept is problematic as it is difficult to determine who the ‘polluter’ is and who has to ‘pay’. The other concept called ‘producer pays’ which was introduced in 1990s as the concept of eco efficiency became the lexicon of environmental improvement. For many years, many companies were trying to practice eco efficiency as early as in the design stage by implementing eco design, design for environment, environmentally benign manufacturing, environmentally conscious design, in an attempt to reduce environmental impact. At a higher strategic level, a joint responsibility between consumers, policy makers, producers and other actors involved must be taken to minimize environmental impact. The involvement of stakeholders is the key to the success of a sustainable society (Abele *et al.*, 2005; Fiksel, 2009). Corporate initiatives to incorporate environmental aspects in their business practice began to grow phenomenally, as more and more companies recognized sustainability as an essential factor in their continued competitiveness (Fiksel, 2009). The following subsections outline a brief description of the factors which motivate companies to consider environmental issues during product development and manufacturing.

2.2.1 Consumer Awareness

Consumers' demands are the driver for each manufacturer's activities (Argument *et al.*, 1998). Global information on environmental issues has raised consumers' awareness to an extent that it has become a competitive value for manufacturers. Presently there is an increasing amount of consumers that demand green products. Green publicity will improve a company's image. With the pressure of consumers demand for green products, companies are challenged to include environmental considerations in their businesses in order to stay competitive. A number of companies have improved their image through communicating their green efforts by reporting product quality, initiating eco labeling, complying with environmental standards or publishing annual environment reports (Stancyzk, 1995).

2.2.2 Environmental Regulatory

Environmental regulations have been imposed since the 1970s (Rose, 2001), depending on specific environmental urgencies and concerns. Regulations, in a way can be an effective driver for manufacturers to increase environmental responsibilities during their activities. However, there may be circumstances whereby regulations are not fully implemented in order to give a satisfactory outcome. This is partly due to the failure of monitoring and weak law enforcement systems. The industry must not limit its response to environmental concerns by solely complying with regulations; environmental concerns should be taken as their social responsibility. Some regulatory actions include:

- European Union Waste Electronic and Electrical Equipment (WEEE).
- End-of-life Vehicles (ELV).
- Restricted of Hazardous Substances (RoHS).
- Energy using Product (EuP) directives.

Countries such as Japan, United States and others have also long embarked on regulatory as well as participatory measures to ensure that manufacturing sectors are concerned about the environment. Regulations can be considered as a constraint for designers and manufacturers in performing business competitiveness (Miemczyk, 2008).

The Malaysian government have also long attempted to create greater awareness and participation amongst Malaysian manufacturers towards caring for the environment and practice sustainable manufacturing processes. Malaysia established a legal and institutional framework for environmental protection mainly through the Environmental Quality Act 1974, in order to promote a sustainable manufacturing sector. The progress of EQA 1974 since then has shifted a regulatory control to a more proactive approach such as through the National Life Cycle Assessment (LCA) Project of Malaysia and the National Eco-Label Programme. Manufacturers are encouraged to consider environmental factors during the early product development stage through these approaches as more countries establish regulatory control that may restrict market penetration and compliance cost will be prohibitively expensive. This calls for manufacturers to adopt a more proactive strategy in order to remain competitive.

2.2.3 Business Value Driven

Industry is a business entity where environmental initiatives usually come after cost and quality. Profitability is still placed as a major factor in majority of industrial decision making activities, including product design. However, as natural resources become scarce, material cost also increases. In light of the increasing material cost, weight reduction is one of the tactics taken seriously by designers during product design in order to reduce manufacturing cost. Examination of the product’s end-of-life will give businesses many opportunities to reduce product cost and at the same time project a green image. The reduction of product cost will promote an increase in market share. The green image of a company is truly a good strategy to enhance market competitiveness. Many leading companies are now using environmental issues in marketing and have been quite successful in projecting a company’s brand image (Stevels, 2000). Thus, it can be concluded that environmental considerations have pivotal role in raising a company’s business value, and can serve as a competitive strategy.

2.3 Principles of Design for Environment

Product design is one of the most important activities in the manufacturing industry. Product design deals with the conversion of ideas into reality, from conceptual stage into a product prototype in order to fulfill human needs (Chitale and Gupta, 2007). According to Morris (2009), “*product design is concerned with the efficient, effective generation and development of ideas through a process that lead to a new product”*. From this definition, it is clear that product design can influence product characteristics and behaviour during its life cycle phases. Chitale and Gupta (2007) highlighted that a good product design process should include essential aspects such as customer requirements, physical realizability, economical benefits, optimality and morphology.

The design stage comprises of two levels, namely; primary stage and production-consumption cycle stage as shown in Figure 2.1. In the product design process, preliminary design is considered as an initial and crucial stage. It is the stage where product attributes are identified according to several criteria such as functions, costs, or environmental impacts. Selection of design properties need to be made carefully as the life cycle cost of a product is determined at this stage. The design choices will influence the life cycle of the product, beginning from the manufacturing process to its end-of-life.

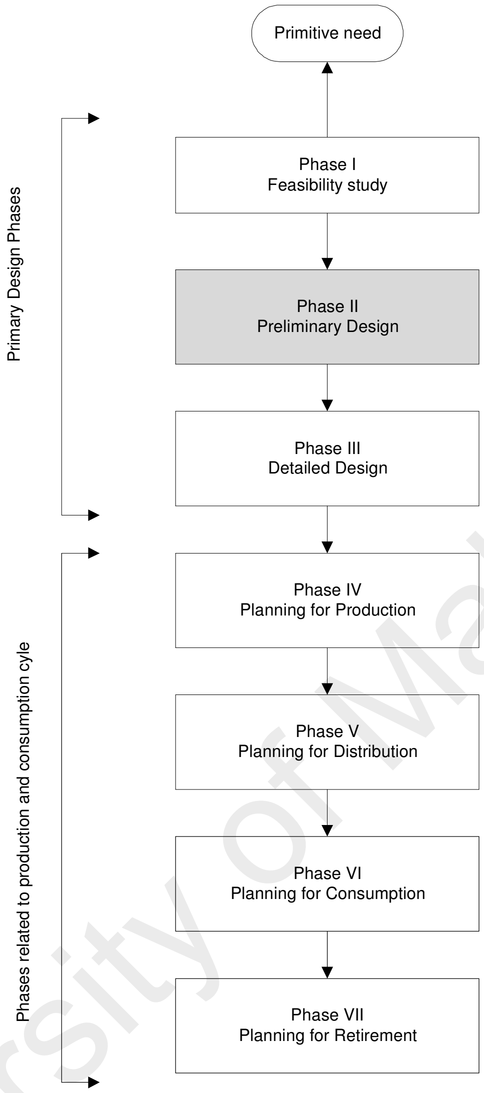


Figure 2.1 Design stages (Chitale and Gupta, 2007).

Each product has its own life cycle, beginning from the design and development of the product, production, consumption and finally its end-of-life activities (collection/sorting, reuse, recycle or waste disposal). Figure 2.2 illustrates the life of a product from the design phase to its disposal.

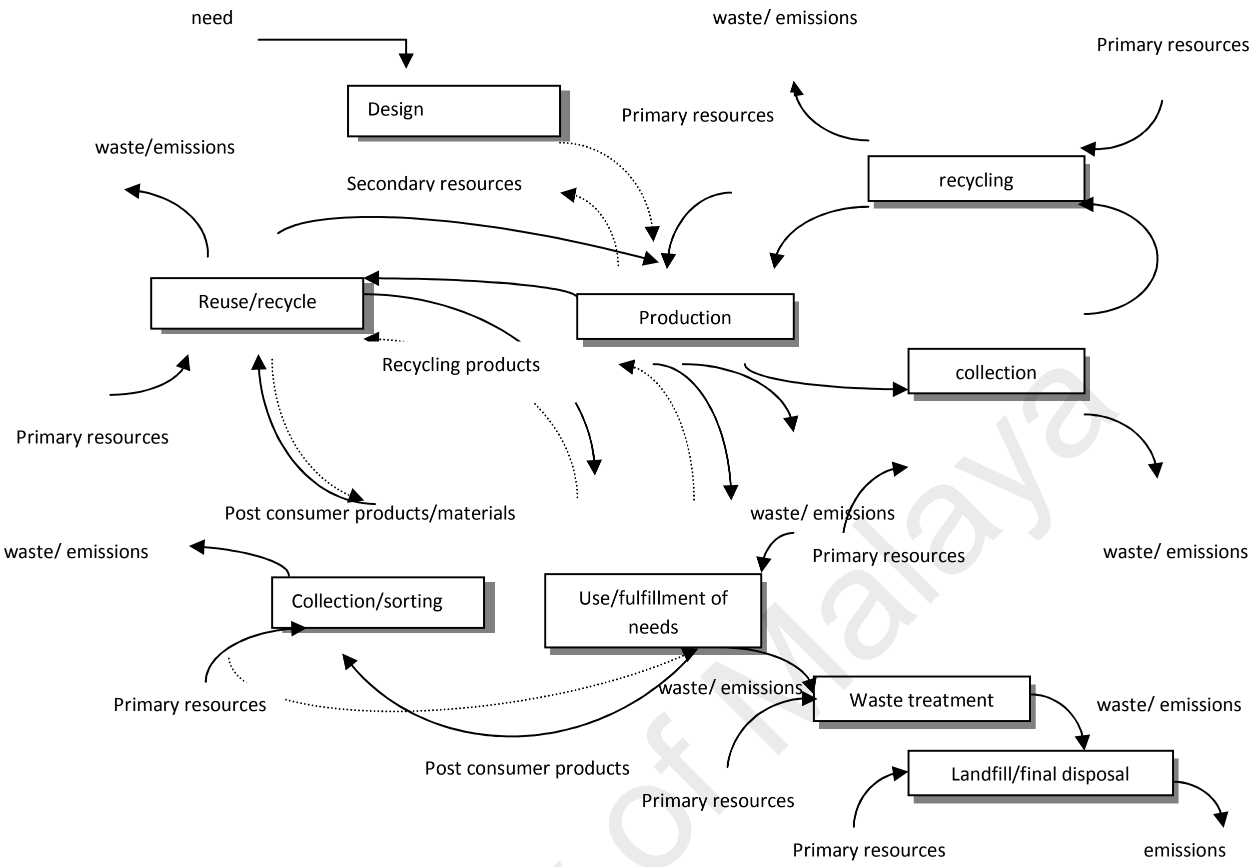


Figure 2.2 Generic life cycle of a product (Rebitzer *et al.*, 2000).

From the product life cycle viewpoint shown in Figure 2.2, Rebitzer *et al.* (2000) assumed that the design of a product strongly predetermines its behaviour in subsequent phases. Hallstedt (2008) explained that product development is a critical intervention for transforming society toward sustainability. Each product offers different environmental impacts during its end–of-life. Therefore, the product created should easily recovered by recycling, reusing, dismantling or disassembly at its end-of-life in order to reduce environmental impact.

In order to improve product recovery at the end of the product's life cycle, Mathieux *et al.* (2008) proposed two strategies that can be implemented by manufacturers:

1. Curative action, i.e. promoting technical and economical development and improvement in the recovery process of products at their end-of-life.
2. Preventive action, i.e. improving through better design.

However, preventive action through better design is generally preferable because environmentally design choices made during the early design phase will be more cost effective (Rose, 2000). Design problems which are discovered after the design stage is over will increase redesign cost and extend the time to market.

Recycling, disassembling, dismantling, remanufacturing, or reconditioning are methods that are intensively used in the industry to overcome environmental issues associated with product life cycle. However, these approaches are implemented after the product is discharge by the users. Hence, there is a large amount of waste to be treated at the end of products' life cycle. In order to improve the ability of a product for reusability and recyclability, the strategies must not only focus on curative actions, but also on preventive actions which can be carried out by designing better products (Johansson, 2002; Rose, 2000; Srinivasan *et al.*, 1997). One of these preventive actions is by introducing environmental requirements during the early design stage called Design for Environment (DFE). The process in which a product is designed has to address the minimum burden on the eco-system throughout its life cycle.

DFE is concerned with the impact of a product design on the environment. Fiksel (2009: p.83) stated that *"Design for Environment is the systematic consideration of design performance with respect to environmental, health, safety, and sustainability objectives* *over the full product and process life cycle".* Since DFE emphasizes the life cycle of a product, the DFE concept is disaggregated into specific approaches in each life cycle stage such as Design for Manufacturing, Design for Disassembly, Design for Recycling, Design for Dematerialization, and so forth (Fiksel, 2009). There are four levels of DFE or eco design implementation (Boks, 2006):

- No-DFE: Traditional design is used, where environmental criteria are considered in design only when necessary.
- Basic DFE: A system which consider the environmental attributes of products, primarily to ensure compliance with regulations. Environmental issues have lower priority than other design concerns.
- Cradle-to-Grave: A well developed eco design programme that considers multiple environmental factors throughout a product's life cycle. Effect on the environment is weighted as a significant design consideration.
- Cradle-to-cradle: A corporate focuses on environmental sustainability and is incorporated in product development. Design innovation, flexibility and prioritization of environmental performance are aimed to minimize a product's ecological footprint.

Researches in DFE have intensified and are especially focused on how to perform and how to integrate environmental aspects into product development. In practice, there are many available computer based tools or methods for assisting DFE, however most of these methods are not linked with the environmental requirements within the design process. This in turn, causes difficulties for designers to interpret. Thus it can be concluded that current DFE tools are less adapted to designers' practices, requirements and competencies (Lindahl, 2006; Mathieux *et al.*, 2008). Mizuki *et al.* (1996) found that the tools developed are currently useful, but they do not fulfill the requirements of the industry. In addition, Chang *et al.* (2004) stated that many DFE tools have been developed to support design engineers; however these tools are more focused on redesign or optimization of existing products and are less concerned with new product development. Building a DFE tool relies on metrics to calculate environmental performance, and one of the difficulties is the lack of reliable environmental data or information.

Companies must respond to societal expectations. However, catering the different requirements from all stakeholders is not as easy as harmonizing these requirements presents a great challenge. In order to overcome this challenge, DFE offers great potential in reducing environmental impact, fulfilling all stakeholder expectations as well as performing best practices in green design. The improvement of an end-of-life system performance greatly depends on the effectiveness in the manner of which stakeholders address their current practices. The involvement of stakeholders in the end-of-life performance will be described briefly in the following section.

2.3.1 Design for Recycling

There are many options in managing a product's end-of-life; however, each option emphasizes on reducing different types of environmental impact while simultaneously being economically feasible. Figure 2.3 shows the hierarchy of a product's end-of-life destination and Figure 2.4 illustrates the end-of-life options during a product's life cycle.

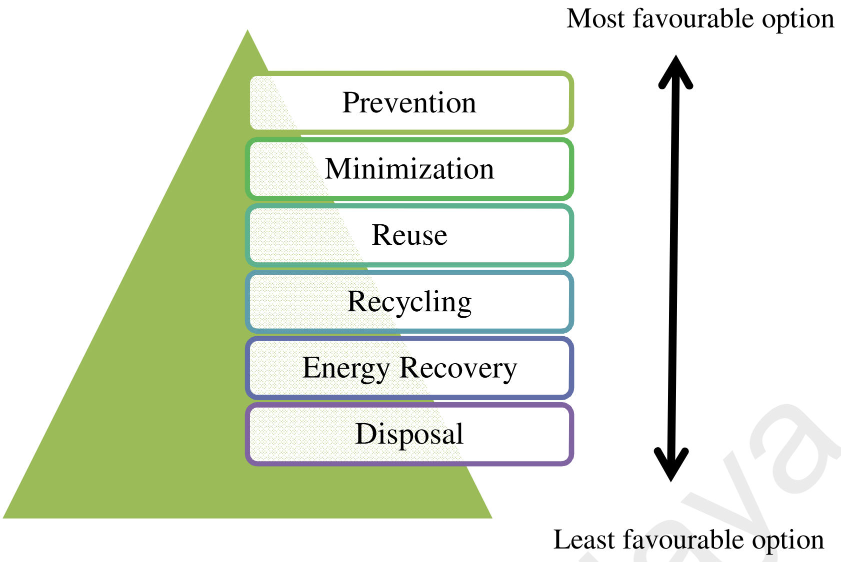


Figure 2.3 Waste Hierarchy (Gertsakis and Lewis, 2003).

Figure 2.3 shows the waste hierarchy and consists of six levels, namely, disposal, energy recovery, recycling, reuse, minimization and prevention. This hierarchy represents the end-of-life strategy from most favourable to least favourable options. There are various advantages offered by different strategies at different levels of the product's end-of-life. Reducing the environmental impact emphasizes on the pollution prevention as well as how to utilize materials when the product reaches its end-of-life. Extending lifespan and reuse is considered the best in the end-of-life strategy hierarchy. However, these strategies are not always easily implemented due to the requirement of strong material recovery infrastructure, support systems and regulations, which are currently unavailable in Malaysia.

Disposal is the least favourable end-of-life treatment. O'Brien (1999) emphasized the need for maximizing the use and reuse of recycled components and materials. Figure 2.4 denotes the role of recycling industries as a sub part of the original manufacturing systems.

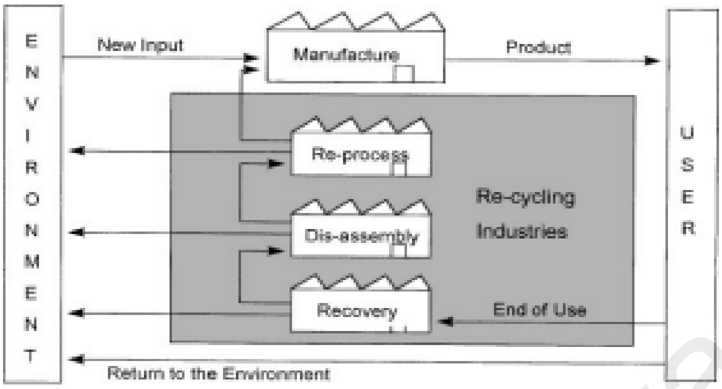


Figure 2.4 Role of recycling industries in manufacturing systems (O'Brien, 1999).

Recycling has a higher potential in creating new economic value by supplying secondary resources. Figure 2.5 demonstrates the output of recycling as secondary resources. It can be seen that recycling will create various potential secondary resources, thus it will generate economic value as well as prolonging material usage.

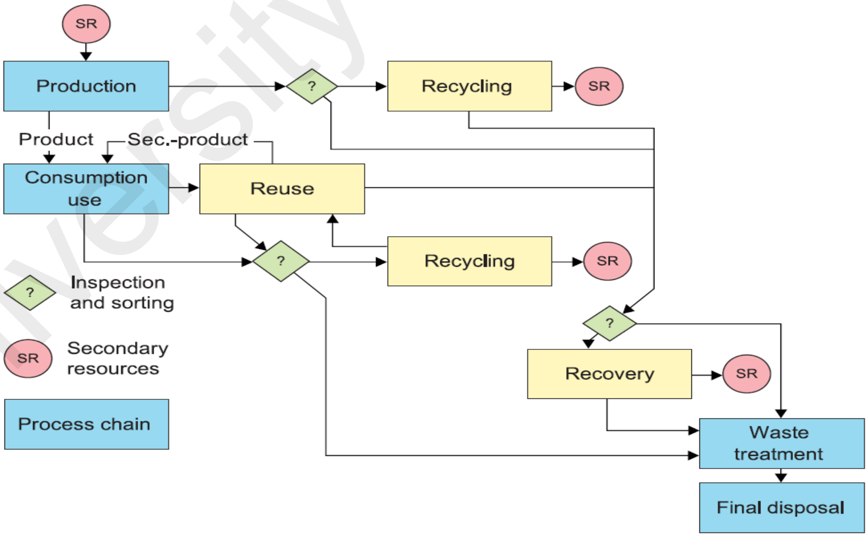


Figure 2.5 Option for material flow in a life cycle system (Seliger, 2009).

Recycling is the process of recovering materials after their primary use and is becoming increasingly important as industries respond to resource scarcity and environmental requirements. Furthermore, recycling activities will create an economical value during the product’s end-of-life chain. According to Tam and Tam (2006), recycling is believed as one of the important strategies to minimize waste and it offers three benefits:

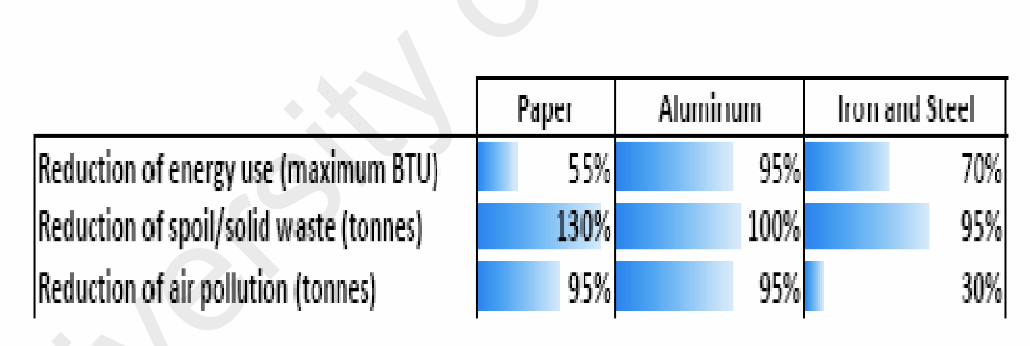
1. Reduces demand upon new resources.
2. Reduces transportation and energy costs.
3. Utilizes waste and reduces usage of landfill space.

Design for Recycling (DFR) is recognized as one of the specific areas covered in DFE. DFR is a design approach which incorporates recycling issues at the beginning of product development. Many researchers agree that DFR improves material recyclability and is an important approach to investigate (Coulter *et al.*, 1998; Rios *et al.* 2003).

The term ‘*recyclability*’ is widely used for assessing the recycling potential of a product. According to the EU Directive (2005), recyclability means the recycling potential of a component’s parts or materials diverted from an end-of life of a product. There are two approaches can be adopted by manufacturers in order to acquire good recyclability rate: (1) attain improved recycling strategies and technologies, (2) implement DFR (Liu *et al.*, 2002). However Seliger (2007) argued that existing recycling strategies and technologies have not been able to fulfill the need for social and sustainable development. This is primarily due to the fact that most companies emphasize more on developing new products and they neglect in the utilization of materials and waste of their existing products at the end-of-life. In the recycling context, waste may contain valuable materials. Unawareness of this potential will resulted in economical losses and lead to environmental problems, such as overflowing landfills. Therefore, there is a need for product design method that will make recycling processes more efficient.

Product recovery is highly influenced by the type of materials, complexity of material combinations and the manner in which parts are joined together for a particular product. Parts can be joined together by welding, adhesive bonding, alloying, layering, inserts, etc. According to Schaik *et al.* (2007), the use of materials in a product is not primarily determined by "in-use value" only, but by the possibility of returning these materials from their original application into the resource cycle after their end of life. It is a common situation nowadays for industries to incorporate recovered materials with their refined virgin material supply. Steel and aluminum are the leading examples of valuable materials that can be recycled up to 95% in advanced electric arc furnaces (Manouchehri, 2006). Table 2.1 shows an example of environmental savings from various recycled material such as paper, aluminium, iron and steel.

Table 2.1 Percentage savings per tonne of recycled materials (Chandler, 1986)



	Paper	Aluminium	Iron and Steel
Reduction of energy use (maximum BTU)	55%	95%	70%
Reduction of spoil/solid waste (tonnes)	130%	100%	95%
Reduction of air pollution (tonnes)	95%	95%	30%

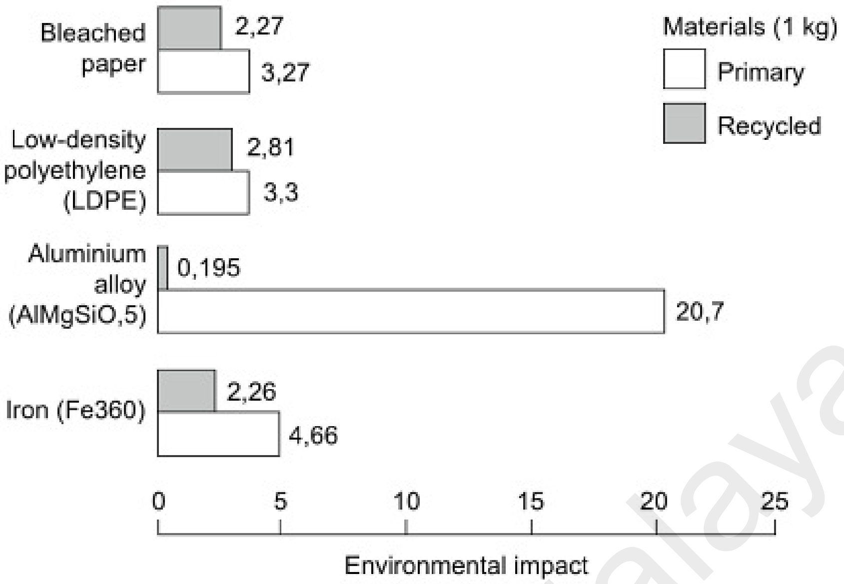


Figure 2.6 Comparison of environmental impact using primary and recycled materials (Vezolli and Manzini, 2008).

Figure 2.6 shows that using recycled materials will significantly reduce environmental impact. It is for this reason recycled materials are recommended as additional materials in a product at an acceptable level. The challenges faced by designers are to maintain and improve recyclability of the product either by using less materials, substituting with recyclable materials, or adopting other design approaches that will satisfy a certain recyclability level (Coulter and Bras, 1997). However, designers are also forced to balance environmental requirements and product functionality in terms of technical and cost specifications. For some reason, a design may not fulfill certain environmental requirements and often require modifications of an existing one. Modifying designs will extend the design cycle which will increase the product's time-to-market. Implementing DFR is also not easy since recycling is complicated and involves multi-criteria decision making (Williams *et al.*, 2007). Most designers mostly have insufficient knowledge on recycling. Consequently, there is missing information on the relevant aspects of recycling during product design, as depicted in Figure 2. 7.

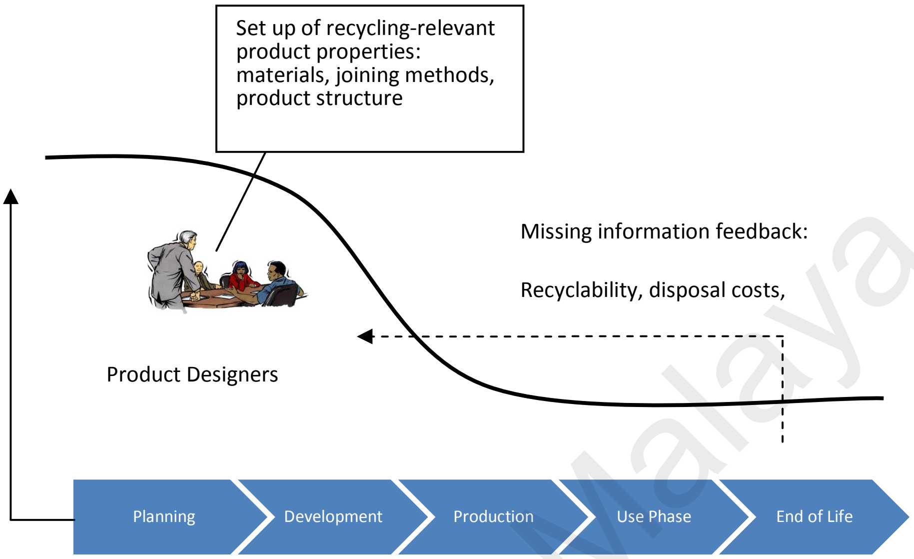


Figure 2.7 Importance of design for recycling (Hesselbach and Kuhn, 1998).

The missing information from the end-of-life cycle, particularly recycling, has not been widely considered in product design, since designers are not directly involved with any recycling activities (Seliger, 2007), creates a gap in the designers' competency for designing recyclability-oriented products. Feasible designs which incorporate recyclability aspects require knowledge on how recyclers will treat various subassemblies, parts, and materials in order to recover valuable waste (Seliger, 2007). Designers are responsible for many aspects of a product which include their economical, technical and environmental performance. Conflicting goals may arise when designers attempt to balance these three requirements as they are difficult to solve. Moreover, making wise decisions related to recycling cannot solely depend on designers' judgement and knowledge, but also requires input from recyclers, customers and policy makers (Huisman, 2003). Harmonizing product design with optimized recycling technology will minimize the loss of valuable materials and prevent creating unnecessary waste streams (Schaik, 2007). Figure 2.8 shows how the decisions of the stakeholders or players influence each other.

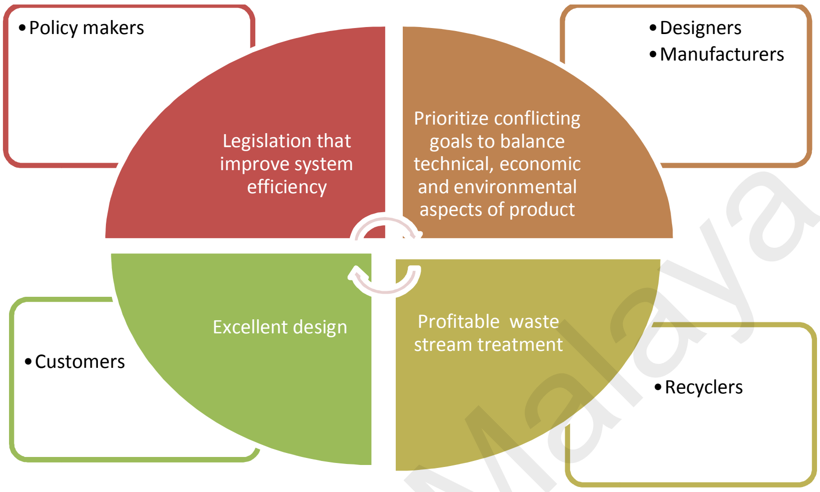


Figure 2.8 Relationship of decisions amongst stakeholders (adapted from Huisman (2003)).

For example, policy makers impose legislation to establish a sustainable economy and society. Customers generally demand for a lower cost product with higher quality and functionality. Recyclers make decisions to select profitable waste stream, infrastructure and technology in order to maximize the quality and quantity of the acquired waste. Thus designers need to understand how these players arrive at these decisions in order to improve design and maximize the recycling opportunities at the end of a product’s life. Coordination and knowledge sharing amongst these players is the key in developing best practices in DFR. Rose (2000) included science and technology as important stakeholder to improve a product’s end-of-life system performance. In the context of recycling, advancement in recycling technology will optimize the separation techniques and upgrading of secondary materials. The effectiveness of the system will depend on how well each stakeholder performs. Huisman (2003) enumerated the goals per stakeholder as follows:

1. The authorities should set meaningful environmental policies to foster system effectiveness.
2. The producers (including designers) should assess the effect of their products at end-of-life to recycling process efficiency.
3. Recyclers and secondary processors should be responsible for technology improvement and effective material utilization.
4. Consumers should examine sufficient environmental gains from their invested money.

Each stakeholder should not conduct improvements primarily for their own interests alone; rather they should aim to maximizing the overall system performance. Designers should pay attention to what recyclers require to improve their system performance. In conclusion, feedback of design-relevant information from stakeholders (in this case recyclers), can support end-of-life system performance and improve economical value within the system. Assigning designers in a more active role in retrieving information from recyclers is beneficial to ensure the effectiveness of recycling support systems.

2.3.2 Recycling Technology and Infrastructure

Recycling technology is essential to develop improved DFR methods. DFR should be implemented by taking the recycling process into account in order to optimize the entire system. The economical and valuable potential of recycling can be clearly identified by understanding the recycling process.

According to Vezolli and Manzini (2008), the stages of recycling can be distinguished as:

1. Collection and transportation

The first stage of recycling is the collection of valuable material from waste. In general, waste products are already gathered in certain locations. The bulky wastes are then transferred into recycling site for the next recycling stage.

2. Identification and separation

Material separation and identification are important in recycling in order to segregate metal and non-metal waste streams. At this stage, discarded products are sorted in order to retrieve valuable materials for the recycling process. During identification, the types of materials that can be recycled, the amount, and the types of materials be discarded are determined. Chrome, nickel, aluminium, steel, ABS, PC and thermoplastics are examples of materials that are considered to have high economical value once they are recycled (Rao, 2006). Material separation can be carried out manually or automatically, depending on the facilities available in the recycling yard.

3. Disassembly

The most important stage in recycling is disassembly (Desai and Mital, 2003). The materials have to be separated in order to remove different parts so that they are recycled properly. For example, removing two different types of plastic from a certain part will benefit the recycling process because some plastics have different melting temperatures and hence they cannot be recycled together. The disassembly process can be classified into two categories, namely: non-destructive disassembly (dismantling), and destructive disassembly (shredding). Dismantling is used when the possibility for removing parts and joining are higher, while shredding is employed if manual separation is not possible.

4. Cleaning/Washing

After disassembly, the wastes are cleaned thoroughly in order to achieve materials with high purity. Cleaning is also a method of removing toxic and dirty substances which contaminate the waste.

5. Pre production of secondary materials

The subsequent phase of recycling is the pre-production of secondary materials. In this case, the materials will be sent for thermal, chemical or physical processes depending on the material type. For instance, plastic-based waste is melted through some heat process and palletized. Copper waste, however, is treated by a chemical process with *sulphuric acid* to produce *copper sulphate*. *Copper sulphate* is then mixed with steel scrap to produce *ferrous sulphate*.

2.3.3 Factors Influencing Product Recyclability

According to the European Union Directive (2005), recyclability of a product refers to "*the potential of recycling for components or parts of materials diverted from end-of-life of a product*". Many countries are now attempting to set recyclability targets for a specific product. For example, there is an 85% recyclability target that needs to be met by 2015 for automotive producers in Europe (EU Directive, 2005). This means that there should be at least 85% of components or parts in an automotive product that must be recycled at the end of its product's life. This regulation has influenced other countries to set recyclability targets. In order to achieve the target, product design plays a vital role in making the target achievable. For example, designers should clearly indicate the important factors that influence recyclability in order to make recycling process more efficient. Designers should have knowledge of recycling process to determine the important factors of recyclability.

Therefore, information sharing between recyclers and designers are beneficial to make recycling process more efficient.

There are many recyclability factors that are written in the literature. Many literature confirmed that disassembly is one of the essential elements to make recycling more efficient (Desai and Mital, 2003). In the engineering context, Desai and Mital (2003) defined disassembly as "*an organized process of taking apart a systematically assembled product"*. The disassembly process can be differentiated into two categories based on the method used, i.e., non-destructive disassembly (dismantling) and destructive disassembly (shredding). In literature, disassembly may have different terms, such as removability, material separation, accessibility of components and disaggregation. Material communization (Coulter and Bras, 1997) and material compatibility (Feldmann, 2001) are also factors that influence recyclability. Seliger (2007) included materials, product structure and joining technology as the crucial factors for recyclability. A wide scope of factors have also been used by other researchers to evaluate recyclability, such as policy, technology, economical factors, and environmental benefits (Philis *et al.*, 2005; Qi *et al.*, 2005). Furthermore, Philis (2005) and Qi (2005) believed that cost is an important factor that determines a product's recyclability. The recyclability factors used by a number of researchers are summarized in Table 2.2.

Table 2.2 Recyclability factors found in the relevant literature.

Authors	Recyclability Factors Considered
Marco et. al (1994)	▪ Ease of disassembly ▪ Material selection
Newcomb (1996)	▪ Modularity ▪ Product architecture
Lee (1997)	▪ Sorting complexity ▪ Material complexity ▪ Disassembly complexity
Coulter and Bras (1997)	▪ Ease of material communization ▪ Effect on system recyclability ▪ Impact on other components
Feldmann (2001)	▪ Ease of disassembly ▪ Material compatibility ▪ Product structure
Phillis (2005)	▪ Policy ▪ Economic ▪ Technology ▪ Properties ▪ Environmental benefit
Qi (2005)	▪ Product properties ▪ Social factor ▪ Economical factor ▪ Technology factor ▪ Space factor
Oyasato (2006)	▪ Material compatibility ▪ Material degradation

It can be summarized from Table 2.2, the factors that influence recyclability are listed as follows:

1. Material separation
2. Material combination
3. Joining type
4. Recycling technology
5. Profit or economical factor

A detailed description is provided below in order to provide a better understanding and clarity of each recyclability factor:

Material Separation

In literature, material separation is associated with the term disassembly in which dependent to the joining type. Selection of joining types will influence the degree of disassembly difficulty. Schaik and Reuter (2007) highlighted the relationship between joining types and material liberation during recycling. For example, bolting and riveting have a higher of liberation degree compared to welding and adhesive bonding. Table 2.3 shows the joint or connection type corresponding with the specific liberation behaviour during material separation. The liberation behaviour of a product can be estimated from Table 2.3. It is important to select connection types that will give higher recyclability for a particular design. The efficiency of disassembly and recycling process is highly dependent on the product design; therefore, the designers' role in making a recycling process more successful is highly significant (Seliger, 2007).

Material separation can be operated mostly in two ways, i.e., dismantling or shredding depending on the joining types. Most dismantling operations are for Type B joining, whilst the remaining joining types use shredding. Intensive shredding is very costly and sometimes there are joining types that cannot be shredded. This situation worsened if it involves shredding a product that has complex shapes resulting in the product failure to be recycled. Seliger (2007) showed that poor material separation occurs subject to one of the following conditions:

- Great variety of materials and the use of insoluble composite materials
- Large number of small parts made of different material combinations
- Complex product structure
- Small, irregular shaped parts

Table 2.3 Liberation behaviour for different types of joining (Schaik and Reuter 2007).

Joint Type	Connection	Liberation characteristic	Liberation behaviour type
Type B	Bolting/riveting	High randomness	High
Type A	Adhesive bonding/gluing	Low randomness	Low
Type W	Welding	Medium randomness	Medium
Type I	Insertion	Medium randomness	Medium
Type S	Surface finish (coating/painting)	Low randomness	Low

Material Combination

Material combinations influence the recycling process, particularly during the material separation stage. Schaik and Reuter (2007) identified material combination types and their characteristics, as shown in Table 2.4.

Table 2.4 Defined material combination types.
Adapted from Schaik and Reuter (2007)

Material combination types	Characteristic
Combination 1	Single material, not connected
Combination type 2	2 materials connected
Combination type 2 or 3	2 or 3 materials connected
Combination type 3	3 materials connected

The quality of a recycled product is dependent on the liberation of materials during material separation. Therefore, material separation, selection of joining types, and selection of materials and material combinations in product design of a product are crucial to raise the recyclability level of a product. A product with complex shapes will make recycling and waste recovery difficult.

Joining Type

It has been mentioned previously that joining type contributes to recycling difficulties especially during material separation. Castro *et al.* (2005) classified joining types in automotive design. Table 2.5 illustrates the joining principles according to geometry and level of contact surface between two materials in a joint area. Figure 2.7 demonstrates the liberation of materials for specific joining types.

Table 2.5 Joining principles and classification.
Adapted from Castro *et al.* (2005)

Geometry	**Definition**	**Joining Principle**		**Application**
		Physical	Chemical	
Z	Particles are constituted by single material	-	-	No joint
P	Mechanical joining used as connection between components	1.		Bolts, screws, rivets, point fitting
L	Two materials in the component are jointed along a continuous line	2.	3.	Length fitting, weld, adhesive bonding
S	The whole surface of multi materials are jointed		4.	Weld, adhesive bonding, plating

In order to increase the efficiency of material separation, the VDI Guideline 2225 (2002) recommended that reducing the number of connections will result in ease of disassembly. Table 2.6 shows the correlations between value scales and magnitudes of selected parameters with the number of connections and parts. Figure 2.9 shows the possibilities of material liberation using different types of joining.

Table 2.6 Correlations between value scales and magnitudes of selected parameters. (VDI Guidelines 2225, 2002)

Value Scale		**Magnitude of Parameter**		
Points	Meaning	Number of parts	Number of connections	Number of different connection types
0	Unsatisfactory	>40	>9	>4
1	Just tolerable	30-40	7-9	4
2	Adequate	20-39	5-6	3
3	Good	10-19	2-4	2
4	ideal	<10	1	1

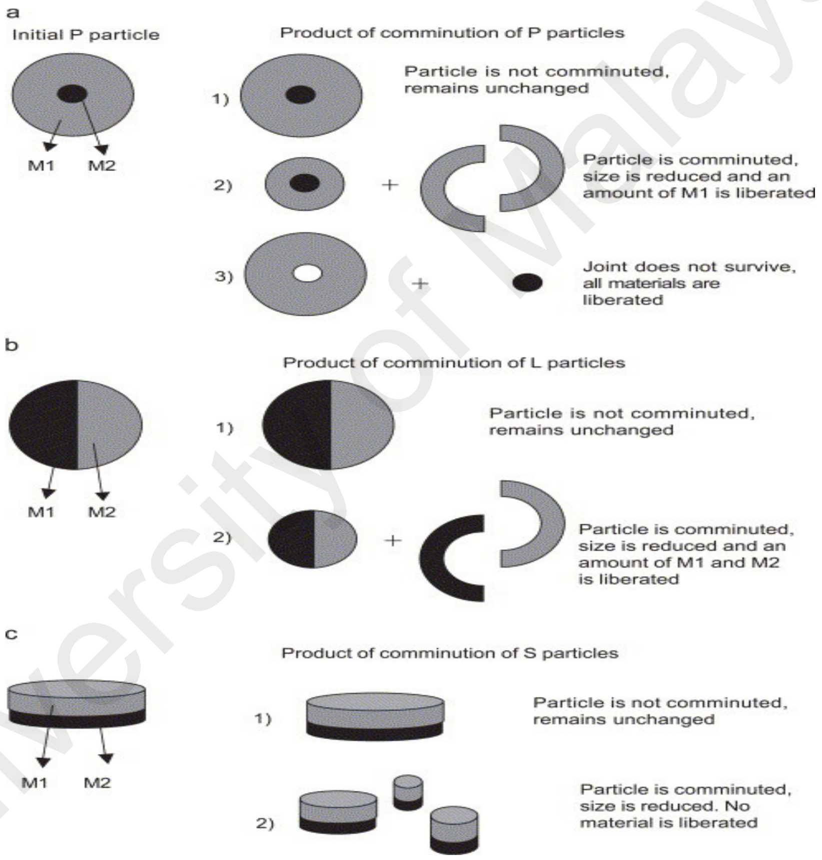


Figure 2.9 Comminution of particles based on joining types, (a) possibilities of material liberation for joining type P, (b) possibilities of material liberation for joining type L and (c) possibilities of material liberation for joining type S (Castro *et al.*, 2005).

Availability of Recycling Technology

The availability of recycling technology and infrastructure is important to ensure that recycling can be carried out effectively. Recycling technology and infrastructure have been discussed in Section 2.3.2. Recycling technology and infrastructure are dependent on the type of materials, for example, plastics require a different recycling process compared to metals, and therefore plastics require different technology and infrastructure.

Profit in Recycling

One of the major considerations in recycling is the profit gained from the process. Profit in recycling is dependent on the demand for recycled materials, volume and price of the reclaimed materials. Recycling activities cannot be carried out if there is no demand for recycled materials.

Although recyclability factors have been clearly highlighted, previous studies did not identified the factors which will significantly influence a recycling activity. Moreover, fewer studies have taken current recycling practices as the baseline of recyclability assessment. Therefore, it is deemed important to conduct a study that explores current recycling practices, examine the factors that influence recyclability and determine the relative weight of each factor.

Material selection plays an important role in product design. A design demands specific material properties in order to fulfill its functional requirements and to minimize its detrimental impact on the environment. Hence, much effort has been devoted to the recyclability of a product at the end of its life during product design. It is the responsibility of designers to incorporate recyclability considerations during product design to ensure that a certain level of recyclability is attained at the end of a product's life as imposed by legislation. According to Ishii (1994), material selection is one of the crucial factors that influence a product’s recyclability. Selection of materials will influence the ease of recycling in a product’s end-of-life. The type of materials has a direct influence on recyclability as it determines the profit of recycling and recycling infrastructure. It has been shown that material selection is never integrated with recyclability assessment, and material selection is conducted by solely considering functional requirements. There is an absence in the literature to develop methods that integrates material selection and recyclability assessment into a single entity. Therefore, solving material selection with respect to satisfying product recyclability is an area worthy of investigation.

2.3.4 Comparison of Methods for Recyclability Evaluation

Many researches in DFR have widely focused on developing an index using heuristic methods, e.g., (Kuo, 1996; Hiroshige, 2001; Huisman, 2003; Abele, 2005; Tsuji, 2006, Pomykala, 2007), guidelines, e.g., (Coulter, 2000; Seliger, 2007) and optimization approaches, e.g. (Feldmann *et al.*, 2001; Lee *et al.*, 2001; Liu *et al.*, 2002; Shih *et al.* ,2006) to evaluate recyclability during product design.

The term ‘recyclability index’ used in existing literature is parallel with the recyclability rate, which is defined as the weight of the recycled material divided by the overall product’s weight. Recyclability index mostly emphasizes on a product’s disassembly. Parts or components which are difficult to disassembly are intricate to recycle. Hiroshige (2001) defined recyclability index as Recyclability Evaluation Methods (REM). REM determines the product’s ease of recycling in advance, without the need to build complex product prototyping and experimentation. REM is based on a 100-point scale that indexes the ease of recycling and cost. Two variables employed in REM are recyclability evaluation score (E) for accessing design quality in terms of difficulty of recycling, and estimated recycling cost (K) for project recycling cost. Combining recycling expenses and recyclability target is very useful to guide design engineers in selecting materials. However, the method is rather rigid and does not offer the freedom to designers to make design modifications.

A method for recyclability evaluation called Recyclability and Toxicity Score was developed by Tsuji (2006). This method attempts to calculate the percentage of recyclability and the toxicity value of automobiles using toxic equivalency potential (TEP). This method is ineffective as it is not a preventive approach. Assessment is carried out after the product has been manufactured. Thus, recyclability is not incorporated during the product development phase and further complicates design corrections. Suitability for Recycling was developed by Pomykala (2007), which compares cost components arising from materials that are not recycled with costs that occur in the material recycling process chain. This method proposes an approach to optimize cost as well as the suitability of recycling derived from dismantling analysis.

Environmentally Weighted Recycling Quotes (EWRQ) was introduced by Huisman (2003), which is a new approach to calculate the recycling quota. The general idea of EWRQ is to replace conventional weight-based recyclability values that solely address weight factors for material fraction and do not represent the actual environmental value. In this method, recyclability is determined from environmental impact reflected by an eco-indicator. Eco-indicator is an indexing system that expresses the total environmental load of a product or process. Eco-indicator can be used to analyse the environmental load of a particular product or process. Huisman (2003) developed an advanced version of EWRQ called Quotes for Environmental Weighted Recyclability and Eco-Efficiency (QWERTY), which gives a more accurate recyclability index. QWERTY is a top-down Life Cycle Assessment (LCA) approach translated into a simple environmental score using a weightage calculation.

Recyclability index in terms of material monetary value was introduced by Villalba *et al.* (2004). The recyclability index represents the degree of recycled material usage, in which greater the difference between the virgin material price and secondary material price, the lower the recyclability index.

Guidelines for recyclability were also developed by Coulter (1997), which provides ratings for ease of material separation, effect of product recyclability and impact change of other components. The guidelines provide a checklist and a rating system to calculate the recyclability of the product. Seliger (2007) proposed a different approach in developing guidelines for DFR. The guideline is based on material and marking, product structure and joining techniques. The guideline combines multi criteria evaluation of a product's recycling potential. One of the well known methods for recycling guidelines is VDI 2243 (VDI Guideline, 2002). This is a German standard guideline for designing recycling-oriented products.

On the other hand, other researches in DFR are focused on optimization. Feldmann *et al.* (2001) systematically investigated the disassembly sequence and related operations in order to estimate disassembly cost that influences recycling. Several studies have incorporated both cost estimation and environmental impact estimation. Lee *et al.* (2001) attempted to optimize both profit and environmental impact and a coffee maker was taken as a case study. Liu *et al.* (2002) adopted a similar approach in solving optimization problems using neural networks, while other researchers have established decision support systems for product recycling strategies using case-based reasoning (Shih *et al.*, 2006).

A comparison of recyclability evaluation methods is shown in Table 2.7, Most of the recyclability evaluations are intended to estimate or predict the recycling rate at the product level. Researchers have implemented different approaches and parameters in order to fulfil the recycling index. Designers must take necessary actions once the recycling rate has been determined. Example, if the recycling rate is low, redesign which improves the recyclability of the product will be necessary. Figure 2.10 shows the generic approach for recyclability evaluation found in literature.

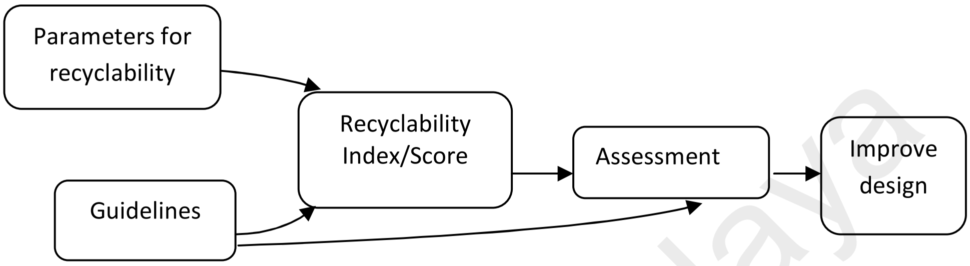


Figure 2.10 Generic approaches for recyclability evaluation.

The generic recyclability evaluation, however, emphasized more on recyclability evaluation and neglected the need to balance the stakeholders' viewpoints. This is due to the fact that DFR considerations are not dependent solely on designers, and these considerations rely on the efficient relationships between relevant stakeholders involving designers, recyclers, consumers and policy makers (Abele, 2005). Substantive information from the stakeholders should be taken into account prior to the implementation of new innovative processes such as DFR, so that the close loop information sharing between stakeholders can be improved effectively.

Considering the recycling of complex products, existing recyclability evaluations seem insufficient because they imply poor understanding on the general context of recycling, which includes complex processes such as material separation and other technical factors. In addition, there seems to be a lack of studies that focus on enhancing integration of various methods and at the same time reducing design lead time. Various studies have been carried out on improving product recyclability; however, the methods developed in these studies emphasize more on recyclability evaluation and they neglect the need to improve designs on the early stage of product development. This is highlighted by Chang *et al.* (2004), as they observed that many DFE tools are focused on the assessment of existing products. Thus, it can be concluded that there is inadequate evidence on the design factors that significantly affect product recyclability. Furthermore, the critical parameters used to determine recyclability based on recyclers' current practices are not established. Designers rely on their knowledge and perception to address the environmental issues at the design stage. Most DFR approaches recommend what designers must do without proper understanding of the success factors and difficulties of the current practice faced by recyclers. Understanding the current issues and problems is one of the research opportunities in this area.

Table 2.7 Comparison of existing recyclability evaluation methods, advantages and limitations.

Methods	Placement of evaluation	Advantages	Limitations
Guidelines Coulter *et al*. (1997) Seliger (2007)	▪ Product level ▪ Product level	▪ Step by step guidelines for designer to improve design ▪ Designers can merely follow the guidelines	▪ Possibility of mismatch with designers' perspectives ▪ Designers work based on experience and creativity, and using strict guidelines will hinder the liberty of composing design parameters
Index/Score Kuo (1996) Hiroshige (2001) Huisman (2003) Abele (2005) Tsuji (2006) Pomykala (2007) Mat Saman (2010)	▪ Product level ▪ Product level ▪ Product level ▪ Product level ▪ Product level ▪ Product level ▪ Product level	▪ Estimate recyclability of a product when the product reaches its end-of-life	▪ Another action plan needs to be considered if the recyclability target is too low. In addition, essential information is not incorporated during the product development phase, which complicates design corrections ▪ Some models adopt end point score that uses subjective weighting steps. Therefore, detailed information on specific fractions of material to specific environmental problem is needed. ▪ To determine recyclability index, designers need to key in the associated recycling parameters, which will require knowledge in recycling domain for designers.
Optimization approach Feldmann *et al*. (2001) Lee et al. (2001) Liu et al. (2002) Shih et al. (2006)	▪ Product level	▪ Design parameters can be included as many as needed	▪ Different parameters will produce different results, and therefore, a decision making process in selecting the best design are needed.

Comparison of different recyclability assessments reveals that several researchers have proposing method to incorporate recyclability assessment of products during the conceptual stage of product design. However, it can be conclude that recyclability assessments at subassembly level are still lacking. Moreover, less of study giving attention on the recyclability assessment that can be linked to CAD environment, which can indirectly reduce design cycle time. Recyclability assessment that integrated with material selection method is not found in the literature. According to the above considerations, the following subsection presents the contextual literature on material selection in product design.

2.4 Material Selection in Product Design

Selection of materials is vital in the product design phase. From an engineering design viewpoint, material selection is the process which aims to identify the appropriate materials for manufacturing processes (Ermolaeva *et al.*, 2002). During the design phase, designers first need to identify functional requirements of a product. Each material possesses its own specific mechanical properties such as strength, density, corrosion resistance, thermal conductivity and so forth, and a design demands that the material properties should satisfy the product's functional requirements. The material properties determine the quality and performance of the product. Five steps for material selection have been proposed by Chinner (1988), namely: clarity of the design model, evaluation of material properties, selection of material candidates, evaluation and judgment for optimal solution and proof checks. Ashby (2009) recommended a strategy for material selection, which involves translating the design requirements, screening the materials using constraints, ranking the materials using the targeted objectives and supporting information, as illustrated in Figure 2.11.

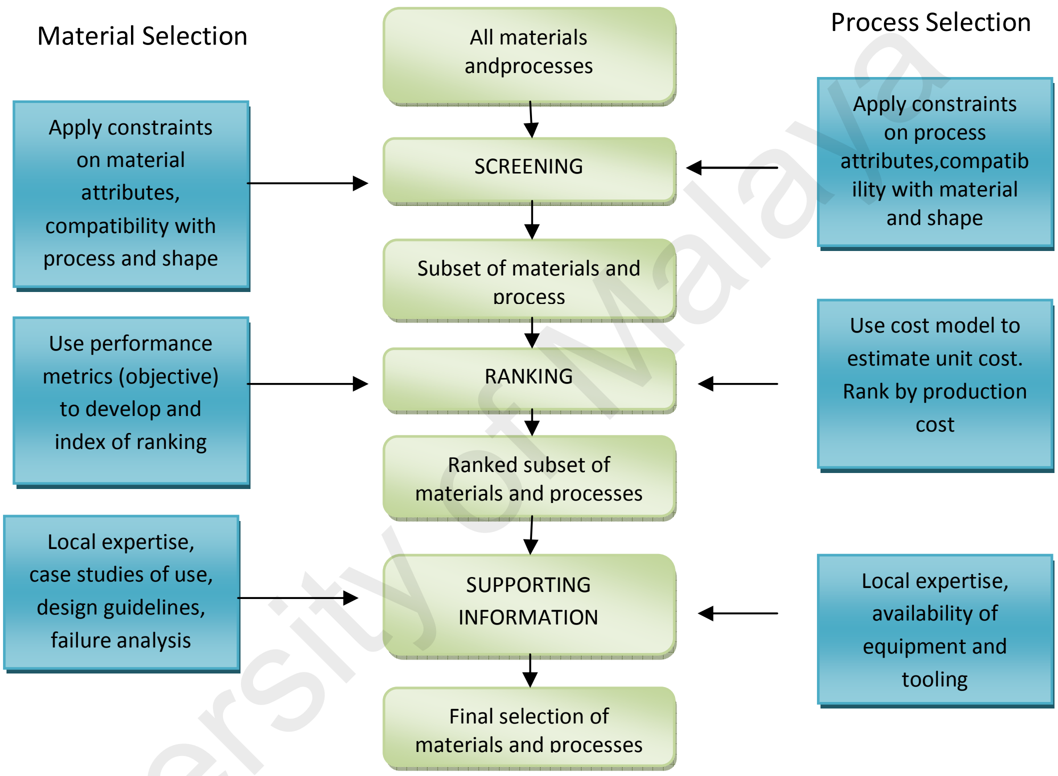


Figure 2.11 Different stages in material and process selection during product design (Ashby, 2004).

In order to develop good-quality design, designers should consider many factors such as mechanical properties, manufacturing properties, material costs, reliability, durability and other related factors. Currently, there is greater interest in designing sustainable products due to environmental regulations (Ashby, 2009). In sustainable product design, environmental impacts should also be considered during material selection. The complex relationships between different selection parameters increase the complexity of material selection and hence, material selection becomes a multi-criteria decision problem (Zhou *et al.*, 2009).

2.4.1 Approaches in Material Selection

Currently, there are many material selection strategies in the literature, Ashby (2004) classified selection strategies as free search, questionnaire-based and analogy. There are a number of free search methods. For example Ashby (2004) developed a graphical engineering selection method, in which database screening is used to evaluate material candidates. This method has been implemented in a software package called The Cambridge Engineering Selector (CES). CES provided an eco material selector that supports design with low environmental impact from the viewpoint of product life cycle, and less emphasizes on end-of-life issues, particularly recyclability.

Several researchers have performed the optimization using the free search method. However, optimization merely is limited to the structural shape of parts and certain types of materials. For example, a questionnaire-based selection strategy was proposed by Edwards (2005), whereby a structured set of questions were developed to improve the optimal design solution. The analogy selection strategy offers rapid development of a knowledge-based system material selection such as that developed by Sapuan (2001). The case-based reasoning method was developed by Zhou *et al.*(2009).

With regards to the material selection evaluation method, Deng *et al.* (2007) identified two of the most favourable methods, i.e. multi-criteria decision-making

(MCDM) and optimization methods. In the MCDM evaluation method, a wide range of MCDM methods have been used. Sharma (1993) developed an expert system based on the Technique of Ranking Preferences by Similarity to Ideal Solution (TOPSIS). A hybrid method was also proposed by Rao *et al.* (2008), in which a framework model for material selection using TOPSIS and Analytical Hierarchy Process (AHP) was proposed. Shanian *et al.* (2006) applied the ELECTRE method for bi-polar polymer material selection while Shanian *et al.* (2008) demonstrated the application of ELECTRE III for group material selection under vague weighting. The intelligent approach is also known as an effective method for solving engineering problems with high complexity. Jahan *et al.* (2010) reported that the intelligent approach is a powerful method to solve material selection problems. However, there are still limited studies devoted on the application of green or sustainable material selection.

In material selection, designers often face complex decisions while carrying out conflicting objectives such as minimizing material cost, maximizing performance and other preset objectives. In this case, optimization approach has been well accepted as a powerful method to solve complex problems. Several optimization methods have been used. Schiederjans *et al.* (2008) applied a goal programming approach to evaluate energetic materials. Genetic algorithm and neural network were introduced by Zhou *et al.* (2009) in order to optimize multi-objective material selection of drink containers which yields possible materials for drink containers. Using a similar approach on automotive structure, Ciu *et al.* (2008) proposed a method to determine the optimal design parameters for an automotive door assembly. Genetic algorithm was also implemented to select optimal material constituent compositions and microstructures (Chu *et al.*, 2009).

In order to develop a good-quality design, designers should consider many factors such as mechanical properties, manufacturing properties, material costs, reliability, durability and other related factors. Currently, there is greater interest in sustainable product design (Ashby, 2009) and Deng *et al.* (2007) highlighted that material selection for green design would be of great interest in the future. In sustainable product design, environmental impacts should be considered during material selection. Ashby *et al.* (2004) stated that the development of sustainable product design should incorporate environmental metrics into the material selection process. In this situation, product life cycle is regarded as an important parameter in the design stage. The complex relationships between different selection parameters increase the complexity of material selection and hence, material selection becomes a multi-criteria decision problem (Zhou *et al.*, 2009).

In the context of product life cycle, higher product recyclability will prolong the material's life. Recyclability refers to the potential of a product to be recycled at the end of its life (EU Directive, 2005). Prolonging a product's life will result in preservation of natural resources. In recent years, environmental regulations and policies are imposed higher levels of product recyclability, which aim to minimize natural resource depletion by using fewer materials, and creating products which are highly recyclable and easily disassembled. It is the responsibility of the manufacturers to incorporate recyclability features during product design to ensure that a certain level of product recyclability is attained at the end of the product's life. To date, very limited studies have been carried out in sustainable material selection. Owing to the significance of recycling, it is therefore imperative to develop a method that can guide designers to select high recyclability materials. Moreover, it is found that there is no research which integrates material selection and recyclability assessment.

A brief description of multi-objective optimization and genetic algorithm, which form the basis of the intelligent approach that will be used in this research, is given in the following section.

2.4.2 Intelligent Approaches in Material Selection

Intelligent approaches have been widely accepted as effective methods to solve engineering problems with high complexity. Jahan *et al.* (2010) reported that intelligent approaches are powerful methods for solving material selection problems. However, there are few studies which report the application of intelligent approaches.

2.5 Fuzzy Systems

The fact that humans can model complex tasks under uncertainty and incomplete information has inspired artificial intelligent controls and methodologies. One of the accepted methods in mimicking human brain capability when handling vague and imprecise data is fuzzy systems. Fuzzy systems is "*a static or dynamic system which makes use of fuzzy sets or fuzzy logic and of the corresponding mathematical framework*" (Babuska, 1996). A fuzzy system is chosen due to its capability in handling problems with incomplete and vague data. Conventional system theory relies on crisp mathematical models in which the physical parameters governing the system are well understood. However, in reality, a large number of practical problems are not easily modeled due to their complexity and uncertainty. Gathering an acceptable degree of knowledge needed for physical modeling is difficult, time consuming and costly. Portions of information in the system are extracted from human experts, engineers or designers and this knowledge cannot be expressed using mathematical functions. Nevertheless, there is an alternative method to express this knowledge by using natural (linguistic) language, in the form of if-then rules. Babuska (1996) highlighted that fuzzy systems are similar to expert systems.

According to Munakata (2008), fuzzy systems offer the following advantages and disadvantages:

Advantages

- Ease of application since it is based on the natural language.
- Takes into account the skills and knowledge of experts.
- It can model non-linear function.
- The membership function is designed to treat the vagueness of the natural language.
- The membership function standardizes the semantic meaning variables and makes the method easily applicable in different environments.

Disadvantages

- Difficult measurement, scaling and estimation of parameter values.
- Successful application depends on the proper definition of fuzzy sets.

A generic model of fuzzy logic is described as follows:

$$F = \{(x, \mu F(x)) | x \in X\} \quad (2.1)$$

where:

F = notation for fuzzy sets,

X = universe of discourse,

X = elements from universe of discourse,

$\mu F(x)$ = membership function from x (value between 0 and 1).

2.5.1 Rule Based Fuzzy Models

According to Babuska (1996), common fuzzy systems employ if-then rules, and are therefore known as rule-based system. In rule-based fuzzy systems, the relationship between variables is represented in the general form:

If *antecedent proposition (x* ***is*** *A)* **then** *consequent proposition*.

The antecedent always uses a fuzzy proposition that x is A where x is a linguistic variable and A is a linguistic constant. The two main types of rule-based fuzzy models are:

- Linguistic fuzzy model

  In this model, the antecedent and consequent are both fuzzy propositions.

This model was introduced by Mamdani (1977), and the if-then rule is constructed as follows:

$$\textbf{If } x \text{ is } A_i \textbf{ then } y \text{ is } B_i, \qquad i=1,2,\ldots,K$$

x is the input and y is the output of fuzzy model, whereas A_i and B_i are denoted as the linguistic terms (constant), which is expressed in linguistic language such as Small, Medium, High, Low, etc. The membership functions of the antecedent (consequent) fuzzy sets are then mapped as$\mu(x):X \rightarrow [01]$, $\mu(y):Y \rightarrow [0,1]$. The rule base and the set of A and B constitute the knowledge base of the linguistic model. The linguistic terms are defined by their membership functions, as depicted in Figure 2.12.

The Mamdani method is most commonly used for linguistic fuzzy models as it possesses the capability to analytically define membership functions, especially for small number of inputs. The Mamdani inference algorithm is listed down as follows:

a. Compute the degree of fulfillment by:

$$\beta_i = \max_{x} [\mu_{A'}(x) \wedge \mu_{Ai}(x)],\ 1 \leq i \leq K. \tag{2.2}$$

For a singleton fuzzy set ($\mu_{A'}(x) = 1$ for $x = x_0$ and $\mu_{A'}(x) = 0$ otherwise), the equation for β_i is simplified to $\beta_i = \mu_{Ai}(x_0)$.

b. Derive the output fuzzy sets B'_I :

$$\mu_{B'i}(y) = \beta_i) \wedge \mu_{Bi}(y),\ y \in Y,\ 1 \leq i \leq K. \tag{2.3}$$

c. Aggregate the output fuzzy sets B'_I :

$$\mu_{B'}(y) = \max\ 1 \le i \le K\ \mu_{B'i}(y),\ y \in Y \tag{2.4}$$

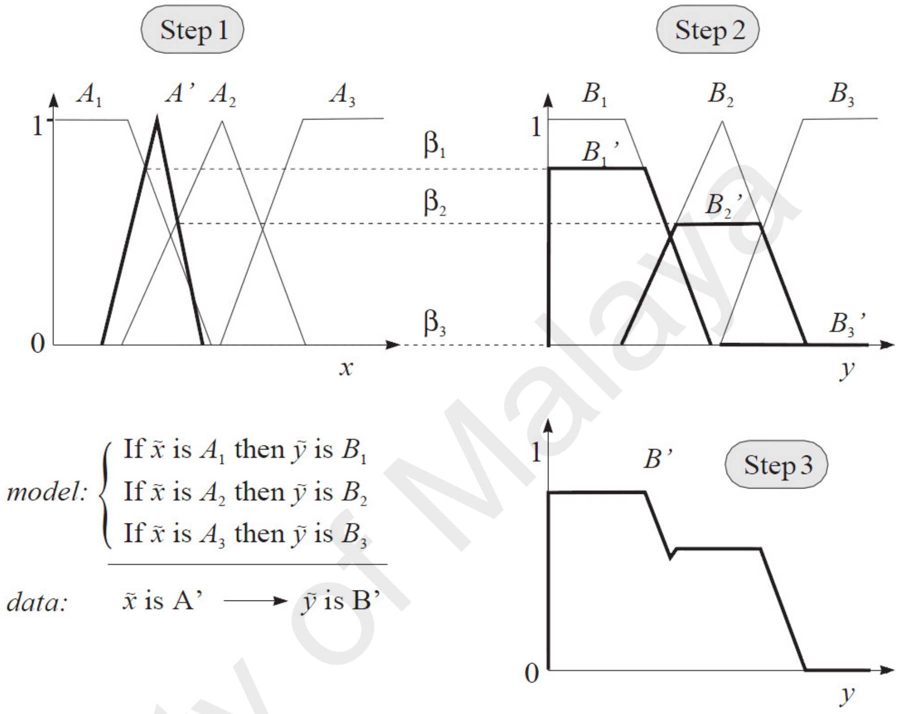


Figure 2.12 Schematic representation of the Mamdani inference system (Babuska, 1996).

- Takagi-Sugeno fuzzy model

This model is characterized by the crisp function in the consequent. The rule base in this model is:

$$\textbf{If } x \text{ is } A_i\ \textbf{then } y \text{ is } f_i\,(x), \qquad i=1,2,\ldots,K \tag{2.5}$$

Details of the model can be found in Takagi and Sugeno (1985).

In this thesis, the Mamdani's inference is selected to develop the recyclability assessment due to its capability to cater for a small number of inputs.

2.5.2 Structure and Parameter in Fuzzy Model

The structure of fuzzy models addresses the following options:

- Input and output variables
- Structure of the rules, involving the selection of model type (singleton, linguistic, Takagi-Sugeno)
- Number and type of membership function for each variable, involving the purpose of modeling and detail of available knowledge
- Type of inference mechanism, connective operator and defuzzification method

Parameters in a fuzzy model are the parameters of antecedent, consequent membership functions, and if-then rules.

2.6 Multi-Objective Optimization Method

According to Rao (2006), ”*optimization is the process of making something better or the act of obtaining the best results under given circumstances”*. Optimization deals with problems of minimizing or maximizing a function with certain parameters and variables, usually subject to equal or unequal constraints (Gen and Cheng, 2000).

When optimization problems use one objective function, the task of determining the optimal solution is called a single objective optimization. In engineering design, numerous problems have multiple-objectives, such as simultaneously minimizing material cost, maximizing performance, maximizing reliability and so on. For multiple-objective situations, the objectives often conflict one another, and therefore the optimization approach is deemed suitable to solve the complexity.

A general multi-objective design problem is expressed as:

$$\text{min/max}\, f_m(x) \quad m = 1,2,\ldots,M; \tag{2.6}$$

$$\text{Subject to } g_j(x) \geq 0, \quad j = 1,2,\ldots J; \tag{2.7}$$

$$h_k(x) = 0 \qquad j = 1,2,\ldots K; \tag{2.8}$$

$$x_i^{(L)} \leq x_i \leq x_i^{(U)}, \quad I = 1,2,\ldots,n \tag{2.9}$$

There are M objective functions in the equation. In the above formula, $g_j(x)$ and $h_k(x)$ are called constraints. Equation (2.9) is called variable bounds, which restrict each decision variable x_i within the lower $(x_i^{(L)})$ and upper bound $(x_i^{(U)})$. A solution, x, is a vector of n decision variables: $x = (x_1,x_2,\ldots,x_n)^T$.

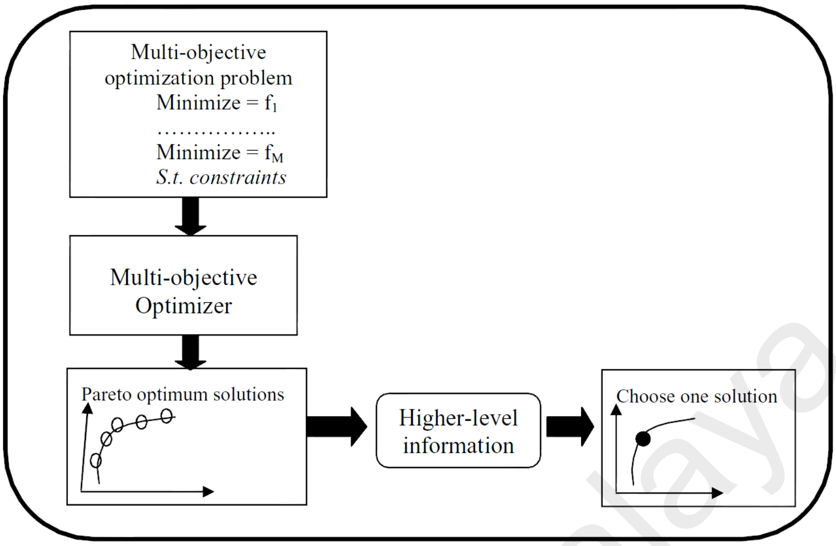


Figure 2.13 Schematic diagram for Multi-Objective Optimization Procedure (Deb, 2001).

2.6.1 Pareto Optimal Concept

In most of real problems, single-objective optimization on many variables results in an inaccurate solution. On the other hand, multi-objective computation that satisfies each objective is nearly impossible. The common approach is to investigate a set of solutions that satisfy objectives at an adequate level without being subjugated by any other solution (Konak et. al, 2006), which is often called a Pareto optimal solution. A Pareto optimal is set of solutions that are non-dominated with respect to each other's objectives. According to Andersson (2001), "*in a Pareto optimal solution, there would not exist any solutions that are better in all attributes*". Therefore, any ultimate design solution should preferably be a member of the Pareto optimal set.

2.6.2 Genetic Algorithm

Genetic Algorithm (GA) is one of the well-known multi-objective optimization methods that based on a population (Konak *et al.*, 2006). GA has the ability to simultaneously search different regions of the solution space. GA was inspired by the evolutionary theory of species origin and developed by Holland in the 1970s. In nature, weak and unfit species within their environment become extinct by natural selection. Random changes may occur in genes, and as a result new species will change from the previous one. Unsuccessful changes are eradicated by natural selection.

In GA, an individual is called a *chromosome*. Each chromosome is made up of discrete units called *genes* and correspond to a unique solution x in the solution space. A mapping mechanism called *encoding* is used to map the solution space of the *chromosomes*. A collection of *chromosomes* is called a *population.* GA uses *crossover* and *mutation* to generate new solutions. In the *crossover*, generally two chromosomes called parents are combined together to form new chromosomes. The parents are chosen amongst existing chromosomes in the population with preference towards fitness so that the offspring is expected to inherit good genes. By iterative crossover computation, good chromosomes are expected to emerge more numerously in the population, which will lead to an overall good solution. The mutation operator introduces random changes into the characteristics of the *chromosomes*. *Mutation* introduces genetic diversity back into the population and assists the search escape from local optima. GA is known as a well-suited method for multi-objective optimization due to its ability to attain the sets of Pareto optimal solutions in a single simulation (Deb *et al.*, 2002). Figure 2.14 highlights the basic steps involved in GA computation.

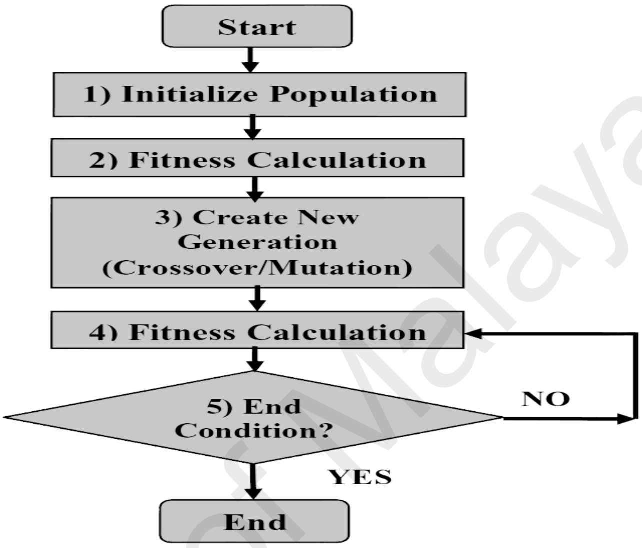


Figure 2. 14 Basic steps of Genetic Algorithm Process (Hossain, 2010).

Cheng and Gen (2000) identified the advantages of using GA as an optimization technique:

1. GAs operate on a coding set of variables and not with the variables themselves.
2. GAs do not require any auxiliary information except the objective value function.
3. GAs can handle varioustypes of functions and constraints.
4. GAs search for population of solutions rather than improving a single solution.

5. GAs are able to search for a global optima without requiring much supplied information.

A Pareto GA can search for a set of solutions by means of rank rather than by values of point. Disadvantages of using GA have been described by Manakata (2008), which are change-dependent outcomes and intensive computational time.

There are many variations of GA-based multi-objective optimization. Non-dominated Sorting GA (NSGA II) is widely applied because of its efficiency in catering discrete problems. NSGA-II is a ranking selection method which is used to achieve and maintain good points (Ciu *et al.*, 2008). The difference between classic GA and NSGA-II is the selection operation. Crossover and mutation remain the same. The basic steps of NSGA-II are described by Deb *et al.* (2002) and Lyu *et al.* (2005) as follows:

1. Create a random population *P* of *n* chromosomes.
2. Divide the number of populations into sub-populations according to an increasing level of non-domination. Store the chromosomes with rank 0 into set *O*, and create an empty sub-population *Q*.
3. Select two chromosomes c_i and c_j in *P* with a probability proportional to *n*-rank (c_i) and *n*-rank (c_j).
4. Crossover c_i and c_j to generate two new chromosomes c'_i and c'_j with a certain high probability.
5. Mutate c'_i and c'_j with a certain lower probability.
6. Evaluate the objective function values of c'_i and c'_j and store them in *Q*. If *Q* contains less that *n* new chromosomes, then go to step (3).
7. Let $P \leftarrow P \; U \; Q$ and empty *Q*. Rank each chromosome in *P* and remove *n* chromosomes with the lowest ranks from *P*.
8. Steps 2-7 are repeated until the termination condition is met.

2.6.3 Solution Approaches in MOO-Genetic Algorithm

Generally, the multi-objective optimization problem can be handled in four different modes depending on when the decision-maker articulates their preference concerning the different objectives (Hwang (1980) cited by Andersson (2001)). Figure 2.15 shows the different approaches of handling the optimization problem. There are four different types of multi-objective problems:

1. No articulation of preference information
2. Priori aggregation of preference information:

   In this approach, multi-objective optimization is performed with priori articulation of the decision-maker's preferences in the beginning. This means that before the actual optimization is conducted the different objectives have to be combined into one single objective function before the actual optimization is conducted. The most common priori method is the weighted sum method.

   The objective function is formulated as follows:

$$\left.\begin{array}{c} \text{Min } \sum \lambda_j f_j(x) \\ \\ \text{Subject to } x \in S \\ \\ \lambda \in R^k | \lambda_i > 0, \sum \lambda_i = 1 \end{array}\right\} \qquad (2.9)$$

   The preferred of decision makers is taken by putting weight λ_i for different objective functions. The objective function must be normalized for simplicity.

3. Progressive articulation of preference information

   These methods work according to the proposition that the decision-maker is unable to indicate preferences information 'a priori' due to the difficulty of the problem. However, as the search moves on and the decision-maker learns more about the problem, he or she can give directions to look for improvements. The advantages of these methods are:

   - There is no need for 'a priori' preference information,
   - Only local preference information is needed,

- It is a learning process where the decision-maker gets a better understanding of the problem,
- As the decision-maker takes an active part in the search it is more likely that he accepts the final solution.

The disadvantages are:

- The solution are based upon the decision-maker's capability to articulate his preferences.
- The decision-maker is highly involved in the whole search process.

4. Posteriori articulation of preference information

There are a number of techniques that allow searching the solution space for a set of Pareto optimal solutions and then present them to the decision-maker. The primary advantage of these methods is that the solutions are independent from the decision- maker's preferences. The analysis needs to be performed once, as the Pareto set would not change as long as the problem description remains unchanged. However, some of these methods suffer from a large computational burden. Another disadvantage may be that the decision-maker will have too many solutions to choose from.

In this study, the second and fourth approaches are chosen for handling the multi-objective problem.

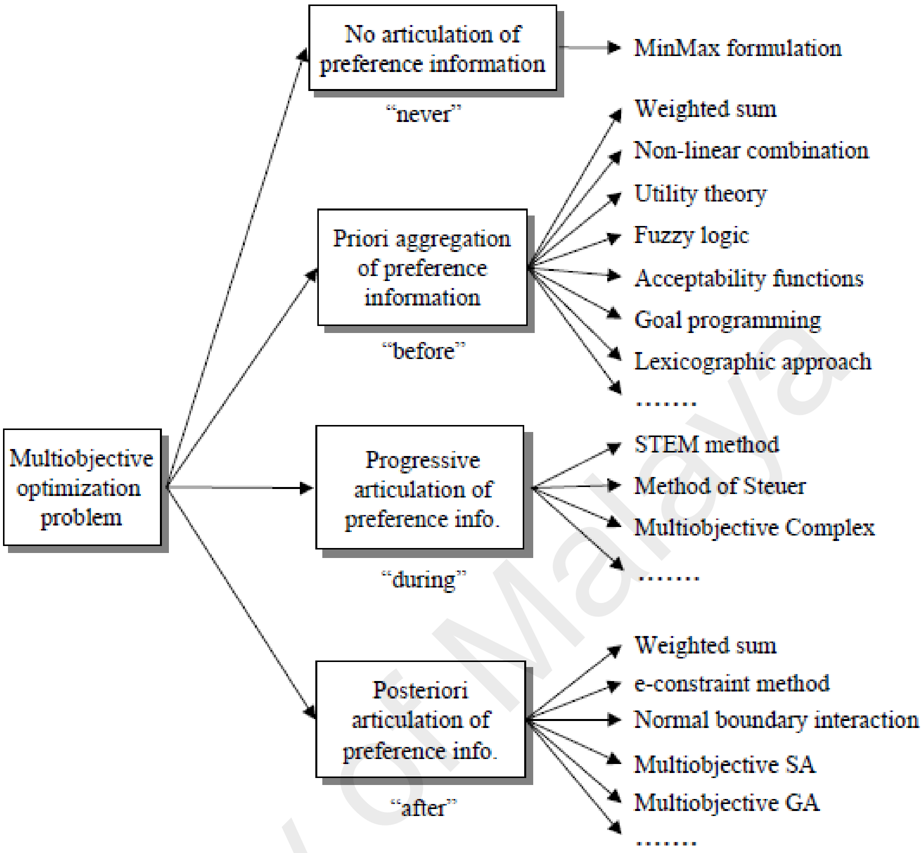
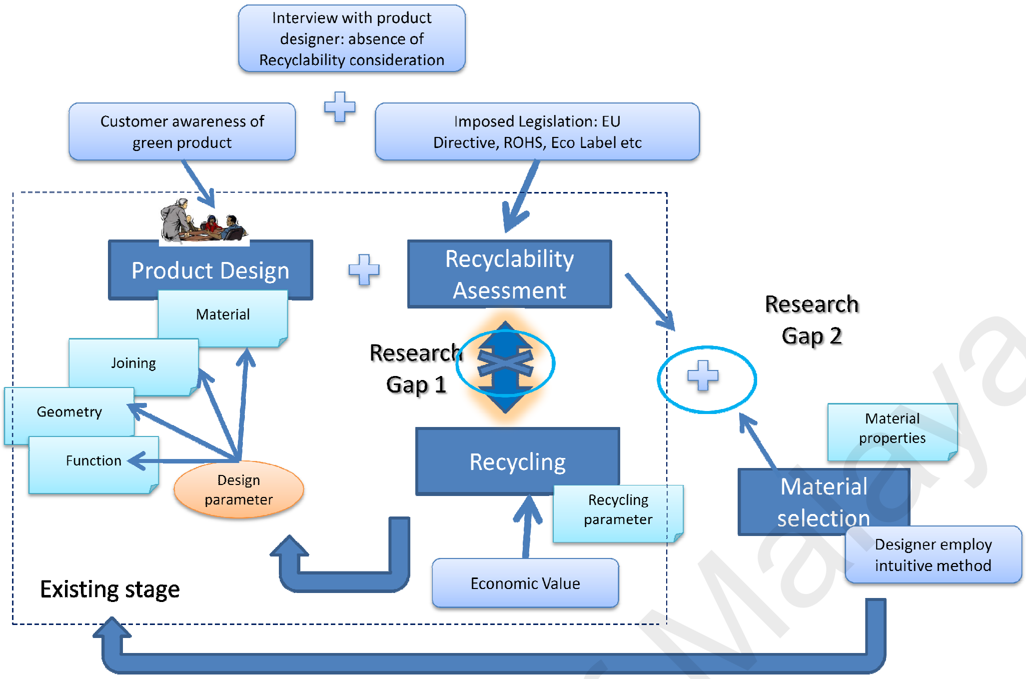


Figure 2. 15. Classification of multi-objective optimization.

2.7 Conceptual Framework and Research Gaps

Conceptual framework was defined by Miles and Huberman (1984) as "*the current version of the researcher*'s *map of the territory being investigated*". In this thesis, conceptual models are used to structure the research problems and link the proposed research framework with theory (Jonker and Pennink, 2010).

Following literature review, a conceptual framework is developed as shown in Figure 2.16.



Optimization of High Recyclability Material Selection

Figure 2.16. The conceptual framework for this research.

It is established from literature review that it is important to consider the stakeholders' views in order to obtain an efficient system for a product's end-of-life treatment. Figure 2.8 illustrates the influence stakeholders on product recyclability in which each stakeholder plays a unique role in enhancing a product's recyclability. Therefore, recyclers requirements need to be investigated. Product design is an important phase for achieving higher recyclability by providing a guideline and recycling-oriented assessment. In order to attain a higher degree of product recyclability, high recyclability material selection is introduced as a novel method that has never been researched before.

Thus it can be concluded that there are two research gaps as follows:

1. There is no evidence of the design factors that significantly influence recyclability based on recyclers' perspective
2. There are no studies on the optimization of high recyclability material selection carried out at the subassembly level which can be linked to a CAD modeling environment

To fill these research gaps, four research questions are generated:

1. *What is the current approach by designers to incorporate environmental issues at the product development stage?*
2. *What is the current approach by designers to incorporate product recycling during the design stage?*
3. *What is the significant design factors affecting recyclability based on the recycler's point of view?*
4. *How can high recyclability material selection be optimized?*

Based on the literature, research positioning has been formulated as shown on Table 2.8.

Table 2.8 Positioning of the research undertaken in comparison with relevant research available in the literature

	Recyclability Assessment					**Material Selection**		**CAD Interoperability**
	Guideline	**Index**	**Intelligent approach**	**Placement of assessment**		**Non-optimization**	**Optimization**	
				Assembly	**Sub-assembly**			
Coulter *et al.* (1997) Seliger (2007)	√			√				√
Kuo (1996) Hiroshige (2001) Huisman (2003) Abele (2005) Tsuji (2006) Pomykala (2007)		√		√				
Feldmann et al.(2001) Lee *et al*.(2001) Liu *et al*.(2002) Shih *et al.(*2006)			√					
Ashby (2004) Sapuan (2010) Zhou *et al.(*2009)						√		
Ciu et al. (2008) Ashby (2009) Schiederjans *et al*. (2008) Zhou *et al*. (2009) Chu *et al*. (2009)							√	
Sharma (1993) Rao (2008) Shanian *et al*.(2006) Shanian *et al*. (2008)						√		
Research Approach	√		√	√	√		√	√

Figure 2.17 shows the research gap and research questions that exhibit the novelty of this research.

The gap in knowledge :

1. There is no evidence of the design factors that significantly influence recyclability based on recyclers' perspective
2. Optimization for high recyclability material selection is has not been carried out

Research aim:

To develop methodologies that aid designers to improve product recyclability that meets the requirements of environmental legislative intentions.

Research objectives

1. To review related literature on product's end-of-life process, current driving force of legislative requirements and available methods/tools to improve product recyclability
2. To identify recyclability factors from recyclers' current practices
3. To develop multi-objective optimization for high recyclability material selection
4. To validate and demonstrate the method using appropriate case studies

Research questions:

RQ1a. What is the current approach used by designers to incorporate environmental issues during product development stage?(to fill Gap 1)

RQ1b. What is the current approach used by designers to incorporate product recycling during the design stage? (to fill Gap 1)

RQ2. What are the significant design factors affecting recyclability based on the recyclers' point of view? (to fill Gap 1)

RQ3. How to optimize high recyclability material selection? (to fill Gap 2)

Contribution to Knowledge:

- Optimization method to select high recyclability materials
- Recyclability parameters suitable for Malaysian industries

Figure 2.17 Research gaps and contribution to knowledge.

2.8 Summary

In this chapter a review of the relevant literature related to DFR, factors that influence recyclability, comparison of methods and tools used in current practices as well as valuable researches that have been undertaken is carried out. DFR is a challenging area where the effectiveness of the system depends on the knowledge extracted from recycling activities. Feedback of design-relevant information from the stakeholders will support the end-of-life performance and provide economic value along the chain.

It is found that there is less attention given on the selection of high recyclability materials. The integration of recyclability assessment during product design with material selection stage has never been carried out before. Two research gaps have been identified, as follows:

1. There is no evidence of the design factors that significantly influence recyclability based on the recyclers' perspective
2. Optimization of material selection combined with recyclability assessment has never been carried out, especially in the subassembly level of product design

The next chapter presents the research methodology chosen in order to carry out the research.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

According to Jonker and Pennink (2010), methodology is "*the way (or route) the researcher will need to take in order to achieve a certain result (knowledge, insight, design, intervention or solution)*". A methodology indicates the main routes taken by the researcher to arrive at his or her end destination. Each research has a different purpose, whether to explore, to describe or to explain a certain phenomenon. The purpose of research is dependent upon the research objective set. In this research, there are four research objectives and to achieve each objective a different research method is used.

This chapter describes the research approaches and strategies to answer the research questions and steps taken to accomplish the research. The rationale underlying the selection of the research methods is also presented. Conclusions are given at the end of this chapter to highlight the selected research methods.

3.2 Research Methods

According to Leedy (2012), *"research is defined as a procedure by which we attempt to find systematically, and with the support of a demonstrable fact, the answer to a question or the resolution of a problem"*. In this context, the result of the research is a new knowledge and the material that comes from research is evidence (Gillham, 2000). In research, evidence is important as it gives an understanding what has been going on and evidence provides scientific facts. Gillham (2000) classified that research evidence can be in the form of:

- Documents
- Records
- Interviews
- "Detached" observations
- Participant observations
- Physical artifacts

In this thesis, the evidence will be based on the company's documents, records from direct observations and interviews.

There are various research methods available for selection, depending on the complexity of the research. Research can be differentiated in many ways; however, research is commonly differentiated based on the type of research. Robson (2002) stated that quantitative research uses an empirical cycle that is deductive by nature, whereas qualitative research uses an inductive cycle rather than deductive cycle. In regards to data collection, quantitative data is based on numbers; whereas qualitative data is based on meaning expressed in words. Table 3.1 illustrates the differences between qualitative and quantitative research.

Table 3.1 Differences of quantitative and qualitative research

(adapted from Robson (2002)).

Research Type	**Fundamentals**	**Data Type**	**Research Strategy**
Quantitative	▪ The researcher formulates a theory about the reality he or she is going to examine ▪ The researcher is an expert regarding the subject as well as its content ▪ The researcher attempts to test the theoretical constructs as represented by the model he or she has developed	Data are always in the form of numbers	▪ *Experimental* The researcher actively and deliberately introduce some form of change in the situation, circumstances or experience of participants with a view to producing a resultant change in their behaviour ▪ *Non Experimental* The overall approach is the same as in the experimental strategy but the researcher does not attempt to change the situations, circumstances or experience of the participants
Qualitative	▪ Developing theory about the reality of a particular situation without interactions about this theory with the people who are part of the investigated reality is something the researcher will try to avoid as much as possible ▪ The researcher is not an expert but an”*explore”*’- he or she hopes to find ▪ The researcher attempts to develop insight into and understanding of actions and meanings within a certain social context while paying attention to time and process ▪ The researcher will act with respect for the phenomenon that he is examining, based on the assumption that the people involved attach meaning to the phenomenon	Data are usually in the form of words.	▪ *Case Study* Development of detailed, intensive knowledge about a single case, or of a small number of related cases ▪ *Ethnographic Study* Seeks to capture, interpret and explain how a group, organization or community live, experience and make sense of their lives and their world ▪ *Grounded Theory* To generate theory from data collected during the study

The most appropriate research methods can be chosen based on the research problems described in the previous section. The research methods are used to answer the research questions in order to achieve the research objectives. The research methods are formulated based on the following four objectives as follows:

- *Objective 1*: To review related literature on a product's end-of-life process, especially in the design of the recycling domain, current driving force of legislative requirements and available methods or tools to improve product recyclability.
- *Objective 2*: To identify recyclability factors from the recyclers' current practices. This objective seeks to determine how designers' current practice incorporate recyclability considerations during the design stage and understanding the significant design factors that may affect recyclability based on the recyclers' point of view. This problem can be solved using mixed methods by combining both quantitative and qualitative approaches.
- *Objective 3*: To develop multi-objective optimization of high recyclability material selection. To achieve this objective, a formulation for optimization of high recyclability material selection is developed. The formulation for optimization consists of two stages. The first stage involves developing recyclability assessment using *Fuzzy Inference System* (FIS), and the second stage involves formulating a genetic algorithm model for high recyclability material selection. The developed optimization model is computed using an Excel-based computer assisted software, i.e. Solve-XL.
- *Objective 4*: To validate and demonstrate the method using appropriate case studies. This objective can be achieved by comparing the existing methods with the proposed method.

Figure 3.1 shows the research methods chosen to achieve the research objectives. From Figure 3.1, it can be seen that there are two research phases that will be taken to achieve the research objectives. In the first phase, both quantitative and qualitative approaches are employed. In the quantitative approach, a survey is conducted as a preliminary study to understand the designers' current endeavors in incorporating environmental considerations. In the qualitative approach, an exploratory study is used to capture the design factors that influence recyclability based on the recyclers' experiences.

In the second phase, an optimization model is developed for selecting high recyclability materials. The following subsection will describe the research methods implemented in both research phases, inclusive of the data collection, data analysis, optimization method and validation method.

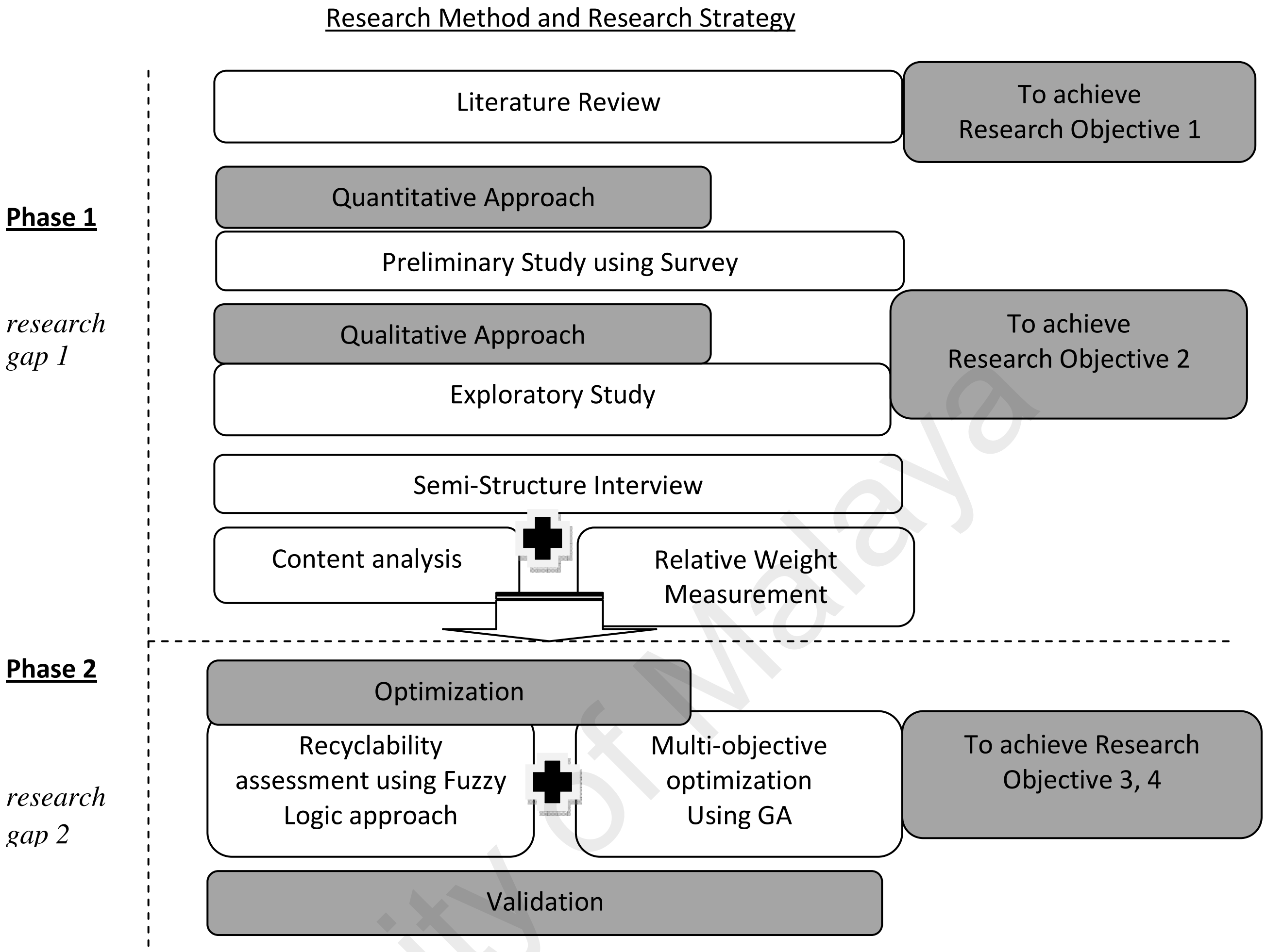


Figure 3.1 Research method and research strategies opted in this research.

3.3 Research Phase I

In research phase-I, a mix of quantitative and qualitative approaches is used. A mixed quantitative and qualitative approach provides a more comprehensive evidence for solving research problems (Creswell, 2009). The subsequent sections describe the selection of research methods for phase-I.

3.3.1 Quantitative Approach: A Preliminary Study

A quantitative approach is used in the first stage as a preliminary study of this research in the form of a survey. The aim of this survey is to understand the current situation of how designers incorporate environmental issues and existing DFE methods or tools used. This survey is conducted for a period of three month, starting from May 2008 to July 2008.

The next subsection outlines the quantitative data collection, quantitative data analysis, research instruments and reliability and validity selected for the survey.

3.3.1.1 Quantitative Data Collection

Prior to data collection, the sample size should be determined. There are two common methods in determining sample size, i.e. probability sampling and non-probability sampling. Probability sampling is taken when the population of the targeted subject is known, whereas non-probability sampling (purposive sampling) is selected when the population is unknown. Non-probability sampling is used to represent a particular group and reveal specific issues in depth, as stated by Ball (1990): *"in many cases of purposive sampling is used in order to access "knowledge people", i.e those who have in depth knowledge about particular issues, maybe by virtue of their professional role, power, access to networks, expertise or experience"*. It is also stressed by Mason (2002) that purposive sampling is meant to address specific issues in a specific group of people. Since the aim of the preliminary study is to capture the current situation of how designers incorporate environmental issues in product design, the purposive sampling method is selected in order to obtain deep insight of designers in respect to these issues.

According to Cohen et al. (2007), there are four key factors in sampling:

1. Sample size

   A total of 200 questionnaires with a mixed of open-ended and close ended questions are sent through electronic mail to designers in various manufacturing companies in

Malaysia and 32 questionnaires are returned. According to Cohen *et al.* (2007) a sample size of thirty is considered as the minimum sample size for researchers to use some form of a statistical analysis. An open-ended question is a type of question whereby respondent can answer the question based on their preferences (Brace, 2008). Open-ended questions posses many advantages such as the ability to tap the respondents' knowledge and understanding of the issues, the respondents are not forced to choose answers limited by the researchers' options these questions are useful for exploring new areas in which little is known (Bryman, 2008). Table 3.2 summarizes the data collection method, data analysis and research instrument for the survey.

2. Representative or sample parameters

   In data collection, the sample should represent the subject that the researcher wants to investigate. Product designers are selected as the subject of the sample in order to achieve the aim of the preliminary study.

3. Access to sample

   Access to sample is a key issue in data collection. In this research, access to the company is challenging. It is found that several companies are reluctant to participate in the survey when it is related to the company's strategy on incorporating environment issues. The companies are also extremely cautious in sharing the knowledge they have, and several companies retain the information as strictly confidential.

4. Sampling strategy

   Purposive sampling is selected in this research as the number of population for the designers cannot be accurately determined. Furthermore, the purpose of this preliminary study is to obtain in-depth knowledge of the designers.

Table 3.2 Data collection method for the survey.

Method of Data Collection	Number of Respondent	Source of Data	Research Instrument	Method of Analysis
Preliminary survey	32 designers	Questionnaire	Open and close ended questions	▪ Descriptive statistics ▪ Multi-response and Crosstab analysis ▪ Factor analysis

In the preliminary survey, questionnaire is used as the research instrument. A pilot study is conducted with fifteen post graduates students prior to distribution of the questionnaires. The questionnaire is then revised to get the desired results. An expert on survey method is also consulted to give comments on the questionnaire. The final version of questionnaire is then sent to the respondents to get their feedback. The questionnaire is attached in Appendix A.

3.3.1.2 Quantitative Data Analysis

The questionnaire comprises of three sections. Section A is focused on demographic information of the respondents. Section B consists of open-ended questions that are used to get a basic understanding of the designers' perspectives on DFE practices. Section C uses close-ended questions to determine the important factors that should be considered in developing an environmental-assisting tool for a designer. Each section is analyzed differently as described below:

1. Section A uses descriptive statistics to explain the demographic data of the respondents
2. Section B uses multi-response and crosstab analysis to explain the current practices of DFE
3. Section C uses factor analysis to determine the significant factors in the DFE methods used by the designers

Data analysis is performed using SPSS 20 software package.

3.3.1.3 Participants

There are two hundred participants identified and contacted through emails followed by telephone calls. A total of thirty-two participants returned the questionnaires and remaining respondents do not provide response. Participants who responded are product designers having at least five years of experience in the field and can be assumed to be experts in product design.

3.3.1.4 Reliability and Validity of Quantitative Approach

Research quality in quantitative approach is associated with the reliability and validity of the research. Reliability in quantitative research is defined by Joppe (2000) as *"the extent to which results are consistent over time and an accurate representation of total population under study is referred to as reliability and if the results of a study can be reproduced under a similar methodology, then the research instrument is considered to be reliable."* In this research, the reliability of each item in the survey questionnaire is tested to an accepted Cronbach-α value. A Cronbach-α of more than 0.7 is considered reliable (Berthoud, 2000).

According to Wainer and Braun (1998), validity means that the measurements taken are accurate and capture what is intended to be measured. In this context, validity is related to the accuracy of the research instruments used in the research. By asserting validity, the researcher is affirming that the data actually measures or reflects the specific observable fact stated. The research instrument used in the quantitative approach is a semi-structured questionnaire. The following steps are taken to confirm the validity of the data:

1. A pilot survey is conducted on fifteen postgraduate students in product design. This is to identify potential problems before the final survey is conducted, as well

as to obtain input on how the respondents interpret the questions. This step is suggested by Saris and Gallhofer (2007) to ensure the final questionnaire collects the intended data.

2. Following the pilot survey, the questionnaire is restructured after which two experts are consulted to give comments on the questionnaire. The questionnaire is refined according to expert’s comments before distribution to the respondents.

3.3.2. Qualitative Approach: Exploratory Study

A qualitative method is initially used at the second initial stage of the research in order to elicit information on the existing scenario through the subjects’ experiences. According to Robson (2002), qualitative approach is suitable to investigate situations where little is known. Robson (2002) classified the qualitative approach into four types, namely: exploratory, explanatory, emancipatory and descriptive. Exploratory research is used to seek for insight, explanatory research is used to search for explanation of certain phenomena, emancipator research is used to demonstrate social engagement and descriptive research is used to describe a situation. Since there is not much known regarding DFR issues in Malaysia, exploratory study is chosen to understand the scenario for current recycling practices.

Robson (2002) listed research strategies in qualitative approach as experiments, surveys and case studies. In this thesis, case study is the most suitable strategy as it involves an empirical investigation of a specific contemporary phenomenon within its real life context using multiple sources of evidence (Yin, 1981). Case studies can develop detailed and intensive knowledge of a single case or a small number of related cases. Since this research is concerned with DFR, recyclers’ and designers’ experience have to be captured.

3.3.2.1 Qualitative Data Collection

Research tactics refer to the selection of appropriate research methods to obtain answers from research questions. Various research tactics can be used such as interviews, surveys, observations, questionnaires or documentary analysis, especially when searching for supplementary evidence.

The instrument used in this exploratory study is a semi-structured interview. Semi-structured interviews are conducted to obtain the designers' and recyclers' insight when dealing with DFR issues. Interviews are fundamental sources in case study information (Yin, 1994). A semi-structured interview possesses the flexibility of the given topic and amount of time. The interviewer asks predetermined questions and questions can be modified during the interview based upon the interviewer's perception of what seems most suitable in relation to the research objectives.

Either face-to-face or focus group interview is conducted to collect primary data from designers and recyclers. Focus group is a method of interviewing participants and it involves more than one interviewee. Focus group interviews consist of a very small group of people (1-3 persons), typically last for one to several hours (Robson, 2002). Focus group emphasize on specific issues that are explored in depth (Bryman, 2008). In a focus group interview, participants can bring forward a topic that they perceive as important. Focus group interview is more efficient for qualitative data collection since data is collected from several sources at once and it allows the researcher to develop an understanding regarding the participants' experience and knowledge. The purpose of this activity is to explore the industrial view point on recyclability issues. An industrial visit is also carried out to obtain an insight on the recycling process. Table 3.4 summarizes the data collection method for the exploratory study.

Table 3.3 Data collection method for exploratory study.

Method of Data Collection	Number of Respondent	Source of Data	Research Instrument	Method of Analysis
Industrial Visit	12 recycling, remanufacturing and refurbishing companies	Company data	Recording video, audio, picture	Direct observation
Case Study	6 recyclers	Interview	Open-ended pre written questions	Content Analysis
Case Study	5 designers	Interview	Open-ended pre written questions	Content Analysis
Industrial expert meeting	6 recyclers	Questionnaire	Pair-wise comparison Questionnaire	Relative weight measurement

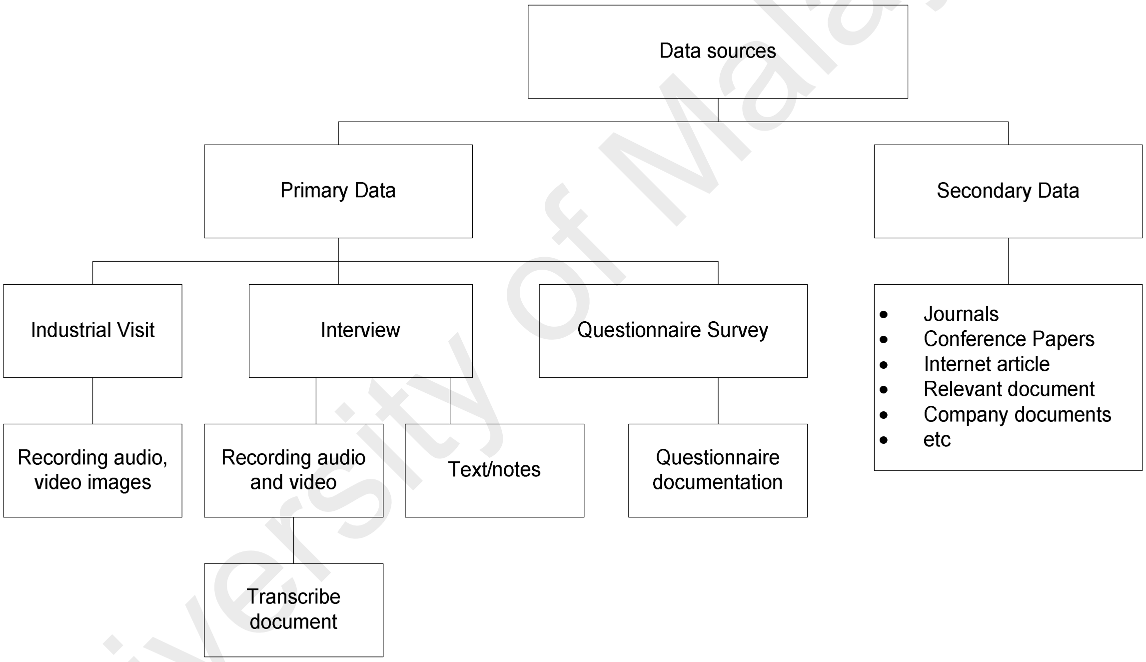


Figure 3.2 Sources of data used for preliminary and exploratory study.

3.3.2.2 Unit of Analysis

One of the purposes of this research is to study the current practices of designers in incorporating environmental issues, particularly in recycling. In addition, there is a need to understand the factors related to design that contribute significantly to the effectiveness of recycling based on the recyclers' point of view. According to Babbie (2010), the unit of analysis is defined as what or whom that is being studied. It can be a group of people, organization or individual depending on what the researcher intends to explore. Therefore, the unit analyses in this study are experts in product design and experts in recycling process (recyclers).

3.3.2.3 Participants

The participants of the exploratory study are designers and recyclers. The participants are divided as follows:

1. Designers

A total of 32 respondents participate in the preliminary study are invited to two workshop sessions on DFE. This activity is aimed to gather a deeper understanding on DFR from the designers' perspective and to get a closer view of the designers' current practices. An exploratory study is carried out, following these workshops. The availability of the respondents for further interviews is ascertained, in order to explore further the designers' perspective on the DFE related issues.

Five designers from different companies are chosen to give further insight into DFE practices. Recruitment is based on the designers' work experience to ensure that the interviewee has sufficient knowledge and experience in a particular area. Each interview last between 1-3 hours. Semi-structured interviews with open-ended and close-ended questions are used.

2. Recyclers

Although there are many listed recycling companies, only twenty companies are selected based on the credibility of the company, particularly the amount of experience the company has in running the business. The number of recyclers is further reduced to six following six interviews and 12 industrial visits to recycling, refurbishing and remanufacturing companies (Appendix B). Eisenhardt (1989) suggested that a number between 4 and 10 respondents is sufficient for case study research.

3.3.2.4 Qualitative Data Analysis

For the case study, the data collected is analyzed using content analysis. Content analysis is a data analysis technique used to make replicable and valid inferences from texts or other meaningful matter such as pictures, videos, and recorded interview to the context of its use (Krippendorff, 2004). Content analysis is capable of providing new insight and strengthens the researcher's understanding of a certain phenomenon and information of practical actions. Interview and focus group data are usually subject to content analysis.

Content analysis is generally used to identify significant content in documents, such as words that frequently occur in documents which reflect tendencies or important evidence, themes and disposition of particular documents. Coding is the most important element of content analysis, which consists of designing coding schedule and coding manual. According to Bryman (2008: p. 283) coding schedule is "*a form onto which all the data relating to an item being coded will be entered*". A coding manual is a statement of instruction to the coder, such as a list of categories, numbers corresponding to each category, etc. Factors for recyclability are coded as RF1, RF2, and so on. A coding example is given in Appendix C.

The tendencies for recyclability factors selected by the interviewees are then calculated. The results of the interviews are clarified and the categories refined based on the frequencies of words stressed by interviewees. A relative weight measurement is applied in order to identify the ranks of each recyclability factor.

3.3.2.5 Relative Weight Measurement

In order to identify the significant factors that influence recyclability, a questionnaire is distributed to the recyclers following the interview session and the resulting qualitative data are analyzed. The questionnaire is provided in the Appendix D.

From the questionnaire, the recyclers are requested to make pair-wise comparison of each factor. The results of the pair-wise comparison are then used to compute relative weight measurements based on the Analytical Hierarchy Process (AHP) approach. The idea of using the AHP approach is to determine the trade-off weights between recyclability factors. The result is a list of ranks for each factor that contribute to recyclability. The following steps are used in relative weight computation:

Step 1. Define the recyclability factors taken from qualitative data collection

A list of recyclability factors is constructed. The relative weights are measured from the list in order to understand the importance of each factor from the recyclers' view point.

Step 2. Establish each factor's pair-wise comparison matrix

In this step, the factors are compared pair-wise. A judgement matrix is formed and used to calculate the priorities for each factor. The judgement matrix, denoted as A, will be used for comparison. Let $A_1, A_2, \ldots, A_n$ be the set of stimuli. The quantified judgement on a pair of stimuli Ai, Aj, is represented by:

$$A = [aij], \quad i, j = 1,2,\ldots,n. \tag{3.1}$$

A comparison of two factors F_i and F_j with respect to the goal is made to determine the level of importance between these factors. Table 3.4 shows the relative scale of importance using a 9-point scale suggested by Saaty (1980).

Table 3.4 Pair-wise comparison scale (Saaty, 1980).

Intensity of importance	Definition
1	Equally important
3	Weak importance one element over another
5	Essential or strong importance one element over another
7	Demonstrated importance one element over another
9	Absolute importance one element over another
2, 4, 6, 8	Intermediate value between two adjacent judgements

Step 3. Calculate eigenvalues and eigenvectors

After the comparison values are solicited from the experts, the following step involves calculating eigenvalues and eigenvectors. Let a_{ij} is the numerical judgement and the weight vector W=($W_1, W_2,...,W_n$), which is matrix of judgements is then given as:

$$\begin{bmatrix} a11 & a12 \ldots a1n \\ a21 & a22 \ldots a2n \\ . & . \;\cdots\; . \\ . & . \;\cdots\; . \\ an1 & an2 \;\ldots\; ann \end{bmatrix} \simeq \begin{bmatrix} W1/W1 & W1/W2 \ldots W1/Wn \\ W2/W1 & W2/W2 \ldots W2/Wn \\ . & . \;\cdots\; . \\ . & . \;\cdots\; . \\ Wn/W1 & Wn/W2 \;\ldots\; Wn/Wn \end{bmatrix} \tag{3.2}$$

Multiplying matrix A with the weight vector in Equation (3.2) results in:

$$AW = nW \tag{3.3}$$

According to Saaty (1980), n is the eigenvalue of A, therefore:

$$AW = \lambda_{max} W \tag{3.4}$$

with λ_{max} as the eigenvalue of matrix A.

Step 4. Perform consistency test

The eigenvector will be used to calculate the consistency index where:

$CI = (\lambda_{max} - n)/(n-1)$, (3.5)

λ_{max} is the maximum eigenvalue, and n is the number of factors in the judgement matrix. Accordingly, Saaty (1980) defined the consistency ratio (CR)as:

$CR = CI/RI$, (3.6)

For each size of matrix size n, random matrices are generated and their mean CI value is defined as the random index (RI). RI represents the average consistency index over numerous random entries of the same order reciprocal matrices. A value of $CR \leq 0.1$ is considered acceptable. Larger values of CR oblige the decision maker to amend his or her judgments until CR is in the acceptable limit.

Step 5. Calculate the rank of recyclability factors

When the CR value is acceptable, a list of weights for each recyclability factor is determined.

3.3.2.6 Research Quality in Qualitative Approach

Research quality is an interesting issue in most qualitative approaches. Research quality in qualitative research is very important to ensure that the research is trustworthy. The common criteria of evaluating research quality in qualitative research are credibility and dependability which are equivalent to validity and reliability in quantitative approach (Miles and Huberman, 1994).

According to Bryman (2008), in qualitative research, credibility means that research is carried out carefully, so that the finding can be accepted as scientific evidence. In this context, the research instruments should produce consistent results during the research process and that the researcher has demonstrated a thorough, careful and honest research. The well known techniques used to ensure credibility are triangulation, peer debriefing and support, member checking and audit trail. In this research, audit trail and triangulation are used to ensure lack of credibility. An audit trail is a research trait of keeping a full record of research activities. This includes keeping all raw data, audio tape interviews, field notes, etc. Triangulation uses more than one method or sources of data to seek convergence in the research findings (Creswell, 1994). The following steps are taken in order to ensure validity of the research:

- Triangulation principles are employed during data collection by using multiple sources of data and collection techniques, namely literature review, direct observation and interview as seen in Figure 3.3. A report of the research results is sent to the interviewees to obtain their feedback. The research findings are also cross-checked with literature. Direct observation on site was also conducted to understand the complex relationship between related elements that may influence particular subject. In this research, direct observation is undertaken to study an event, facility, or process in its natural setting, in which by using this approach, a richer understanding of recyclers' practices can be obtain.

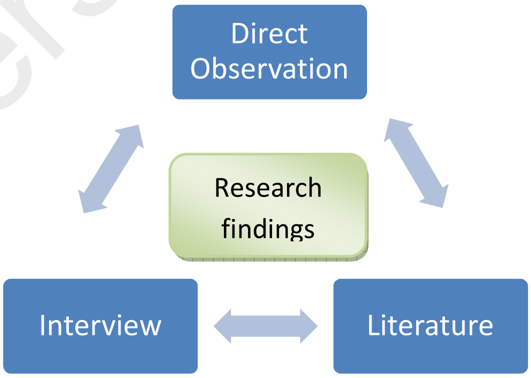


Figure 3.3 Triangulation used in this research.

- The findings from the collected data collection are reviewed and approved by the interviewees. The responses from the interviewees are included in the construction of the final findings.

Dependability or reliability stands for the accuracy of the research process. Robson (2002) suggested that to ensure the validity of a qualitative study, an audio taping should be carried out whenever possible. In this research, an audit trail is implemented. An audit trail is a detailed account of the methods, procedures and decision points while carrying out the study (Merriam, 2009). The purpose of an audit trail is to provide a transparent data collection process that exhibits the steps taken by the researcher and for others to confirm the findings based on the documents provided (Lincoln and Guba, 1985). In this research, the research findings are documented in the form of audio tape interviews, notes and videos from direct observations, research questionnaires, industrial visits schedule, email communication and interviews, as well as list of designers and recyclers.

Table 3.5 summarizes the strategies adopted to reduce the threats that will influence the credibility and dependability of the research.

Table 3.5 Strategies opted to ensure research quality.

Evaluation Criteria	Qualitative Approach
Credibility	▪ All interviews are taped ▪ Optimization model is developed during data collection and data analysis ▪ Triangulation using multiple source of data ▪ Findings from the interviews are shown to the interviewees for feedback
Dependability	▪ Audit trail is used

3.4 Research Phase II: Optimization Method

The data from the first phase are used as inputs for the optimization of high recyclability material selection. Two stages of methods are taken to optimize the selection of high recyclability materials. In the first stage, a recyclability assessment model is developed based on recyclers' recommendations. In the second stage, a list of materials that can satisfy recycling possibility, function and cost is drawn up. The method used for optimizing high recyclability material selection is described in the following section.

3.4.1 Recyclability Assessment using Fuzzy Logic

Recyclability assessment is crucial to evaluate the recycling potential of a product. However, recyclability evaluation usually deals with vague and imprecise data. In most recycling problems, the data do not have clearly defined boundaries. To address this problem, a fuzzy logic approach is employed in this study to estimate the recyclability level of a particular component. Here, recyclability factors are the inputs for fuzzy computation while the recyclability value (R_{value}) is the output of the computation. The R_{value} is an estimated value of the recyclability level of a particular design model.

The procedure used for the fuzzy logic based recyclability assessment is illustrated in Figure 3.4.

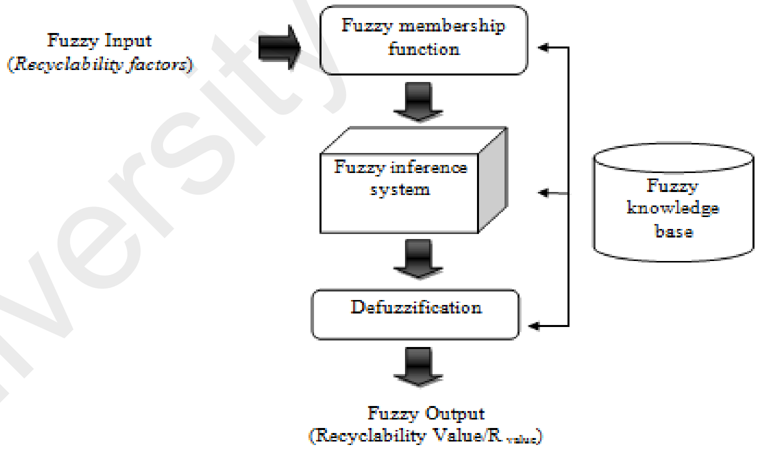


Figure 3.4 Fuzzy based recyclability assessment.

3.4.2 Multi-Objective Optimization using Genetic Algorithm

Figure 3.5 shows the optimization model for the selection of high recyclability materials.

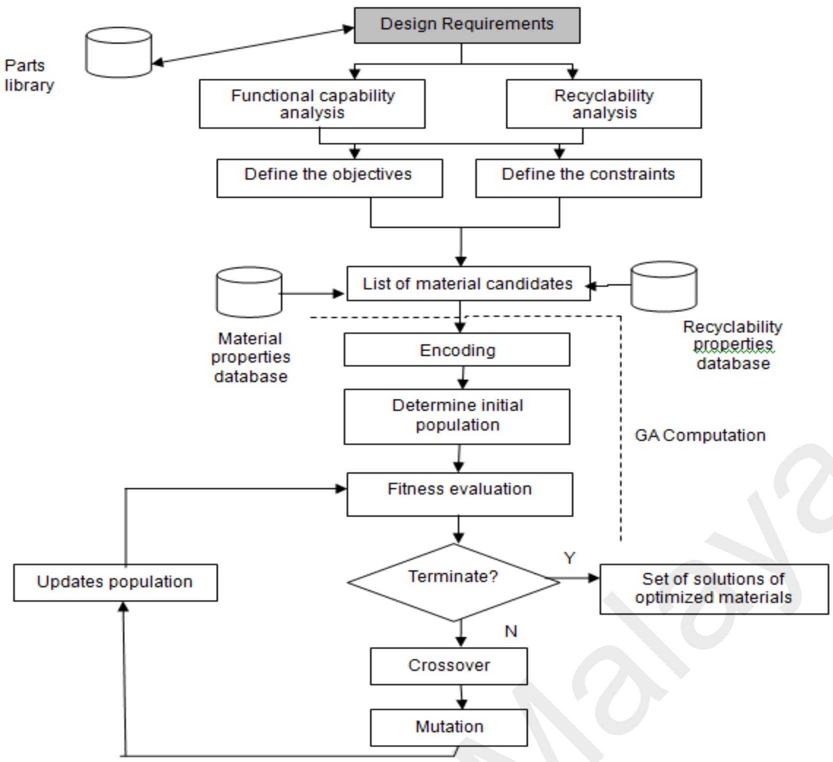


Figure 3.5 Optimization model for high recyclability material selection.

In engineering design, many problems have multiple objectives, such as minimizing material cost, maximizing performance, maximizing reliability and so on. For multiple objective situations, objectives often contradict each other, and therefore an optimization approach is a suitable method to solve such complex problems. In most real problems, optimization with a single objective results in an inaccurate solution. Consequently, multi objective computation that satisfies each objective is almost impossible. Genetic Algorithm is one of the well-known multi-objective optimization methods based on a population. GA has the ability to simultaneously search different regions of the solution space (Chu et al., 2009). The nature of material selection is complex, iterative and formulated as a non-linear problem. The material selection problem comprises both continuous and discrete variables in which GA can solve robustly. GA also generates a list of solutions whereby designers can select the most prominent design based on their requirements.

3.4.3 Validation for Optimization Model

According to Sargent (2005), validation involves substantiating that model yields satisfactory accuracy and is consistent with the intended application. In this study, case studies and comparison to method published in the literature are used for validation. Comparison of model performance is required to confirm that the model is better or at least performs comparably to existing models.

Since the optimization of high recyclability material selection is considered as a new method, there are no similar methods that can be compared directly. Comparison of the output behaviour is used for validity testing. Two approaches are used, namely:

- Apply the method to other well-known case studies in engineering design and compare the results.
- Use *Sustainability Express Tool* from *SolidWorks-10* for comparison. The *Sustainability Express Tool* is used as their add-on tool is well recognized by most designers.

The validation process will be explained briefly in Chapter 7 which consists of the validation process and validation of the optimization model.

3.5 Summary

Various aspects pertaining to research design have been described in this chapter. It is clear that the research objectives are chosen as the starting point for the direction of the research design. Here, the research consists of two phases, in which different research methods are applied for each phase. In phase I, literature review is carried out to achieve the first research objective. Following this, a mixed method of quantitative and qualitative approaches is implemented to address the second and third research objectives. In phase II, an optimization model and validation is developed to address the fourth research objective.

This chapter has also outlined the research process used to guide the research by choosing the appropriate methodology, methods and techniques. Validation of each approach has also been discussed to ensure the quality of the research findings. The quality of the research has been discussed. This means that the research should be carried out in a careful manner to ensure the validity and reliability of the research findings.

In chapters 4, 5 and 6, the data are analyzed using the selected research methods. The optimization results will be discussed in Chapter 6. A detailed discussion of the validation process to the optimization model is presented in Chapter 7.

CHAPTER 4

DESIGN FOR ENVIRONMENT PRACTICES AND IDENTIFICATION OF RECYCLABILITY FACTORS

4.1 Introduction

This chapter described the process of identifying recyclability factors. At first, a survey is undertaken as a preliminary study to understand the existing practices in DFE, if any, and the level of its application, in which the respondents of this survey are product designers. An exploratory study is conducted after preliminary study to identify recyclability factors based on recylers' practices. In this exploratory study, content analysis is used to identify substantive statements that are related to the factors influencing recyclability. The list of factors influencing recyclability is determined from both literature and empirical data taken from the exploratory study. Evaluation of the relative weights is carried out to rank the factors.

The following section presents the findings obtained from the preliminary and exploratory studies.

4.2 Preliminary Study

The preliminary study is conducted in Malaysia, whereby 200 questionnaires are distributed to product designers via email and physical visits. A total of thirty-two questionnaires are received and analyzed. The methods used to analyze each section are shown in Table 4.1.

Table 4.1 Analysis methods opted for preliminary survey.

Section	Purpose of Analysis	Method of Analysis
A	Analyze demographic information	Descriptive statistics
B	Analyze basic understanding of designers' perspectives of DFE	Multi-response Analysis and Crosstab
C	Analyze the requirement of environmental design tools suitable for designers.	Factor Analysis

Analyses of Section B and C of the questionnaire reveal the following information:

- Understanding and awareness on DFE
- Initial drivers in adopting DFE
- Difficulties in adopting DFE
- DFE methods, tools or approaches used
- Requirements needed for DFE methods/tools

4.2.1 Demographic Information

Figures 4.1 through 4.4 show the gender of the respondents, their roles, products that they designed, and core business of their companies. Most of the respondents are males and work as product designers in the manufacturing sector. The products that they designed are mostly automotive as well as other industrial products.

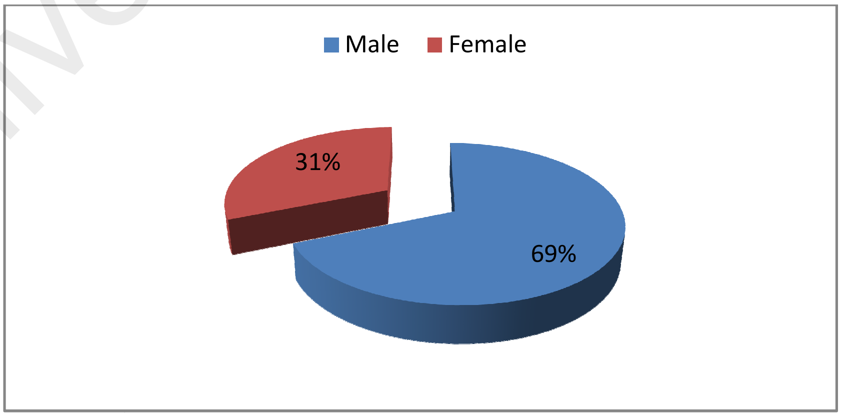


Figure 4.1 Gender of respondents.

Figure 4.1 shows that 69% of the respondents are males whereas 31% are females. Figure 4.2 shows that 69% of the respondents are R&D engineers whereas 31% are product designers. It is found that R&D Engineers are actually product designers working in the R&D department.

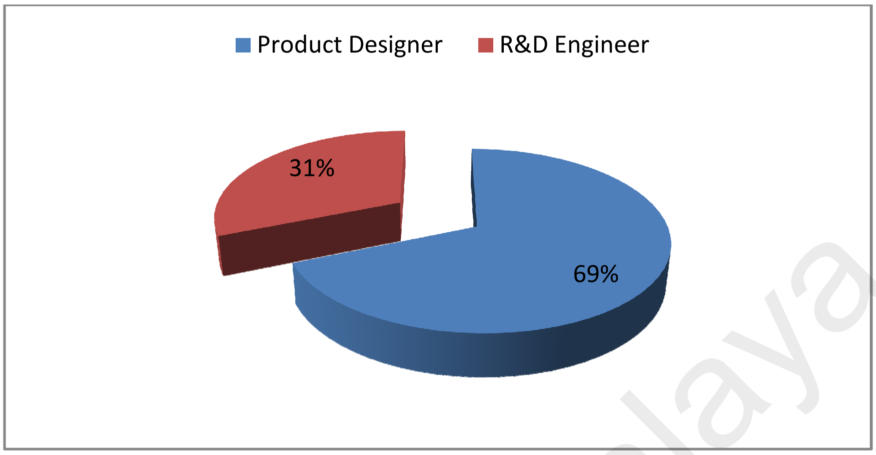


Figure 4.2 Job role of respondents.

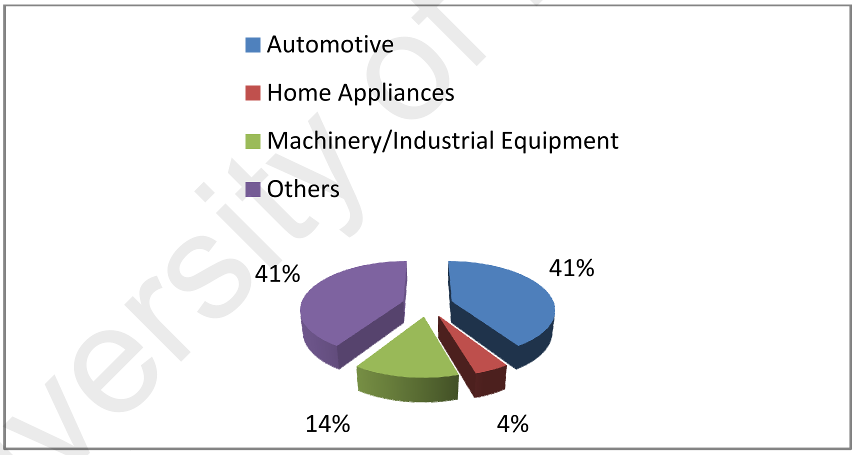


Figure 4.3 Products designed by the respondents.

A total of 41% of the respondents design automotive products, 41% design other products such as furniture, cosmetic packaging, etc., 14% design machinery, and the remaining 4% design home appliances.

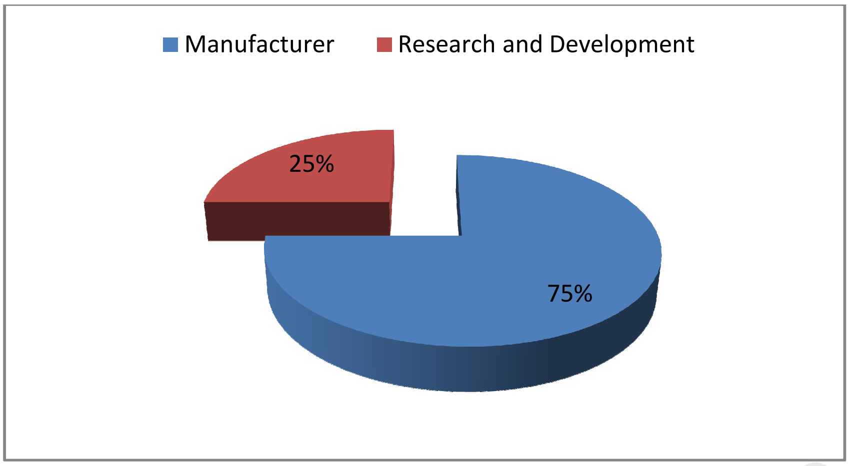


Figure 4.4 Company's business core.

Most of the respondents (75%) work in manufacturing companies while and the remaining respondents work in research and development based companies (25%).

4.2.2 Designers' Basic Awareness of DFE

Information on the basic awareness of DFE will give a clearer picture of the environmental tools, methods or current practices that are being employed. Figures 4.5 to 4.7 show that the respondents are familiar with industrial practices that incorporate environmental aspects during the product design phase. In Figure 4.5, most of the respondents confirm that their products do not contain substances that may impact the environment.

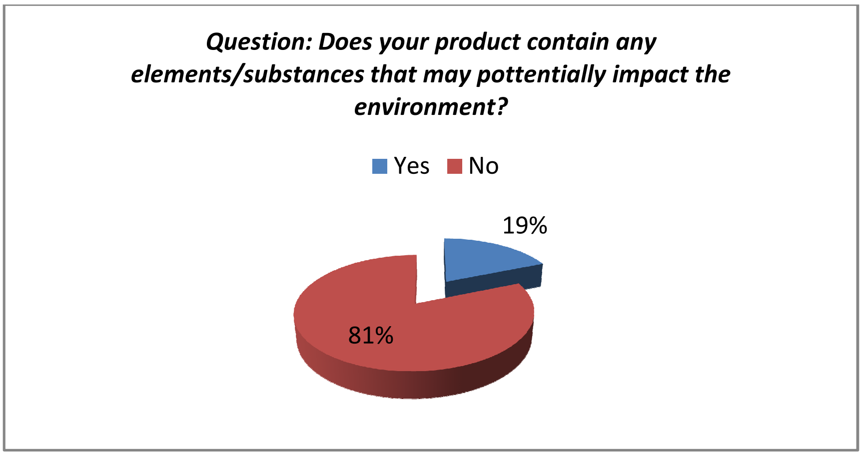


Figure 4.5 Product that contain elements or substances that will give impact to the environment.

This figure shows that companies do take into account environmental aspects when selecting materials for their products. This is also supported by data presented in Figures 4.6 and 4.7, which reveal that companies comply with relevant environmental standards. Although the results show that most companies have high environmental awareness; however, the implementation of DFE within the respondent's company is slightly poor (Figures 4.8 – 4.9).

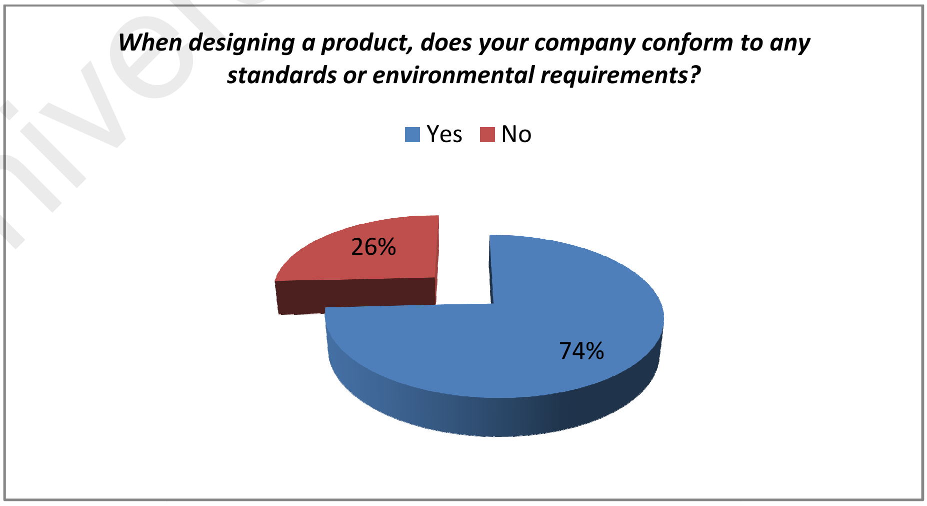


Figure 4.6 Initiative for complying with environmental standards during design process.

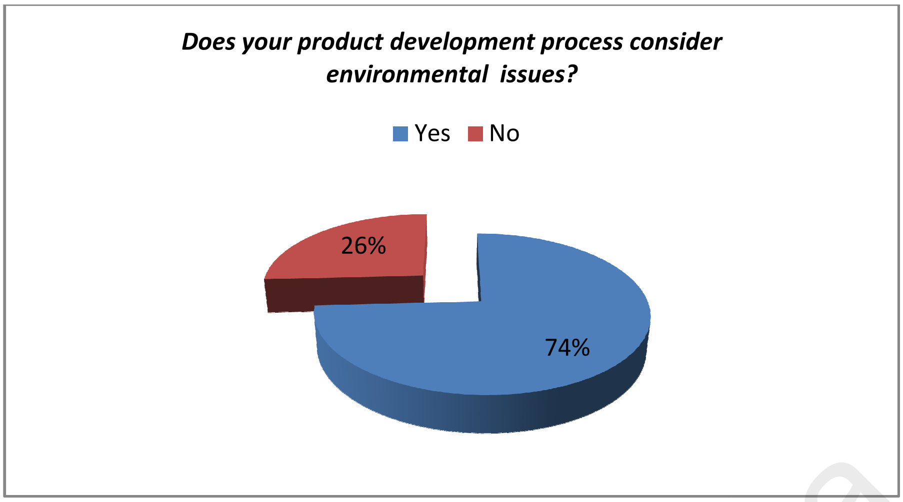


Figure 4.7 Environmental considerations during product development stage.

Figure 4.8 shows that nearly half of the companies do not practice any product's end-of-life strategies such as reuse, remanufacturing and recycling. This shows that their environmental perspectives are not intended for any end-of-life strategies. This finding is supported by Figure 4.9, which indicates that most of the respondents do not use any specific DFE tools or methods during the product design stage.

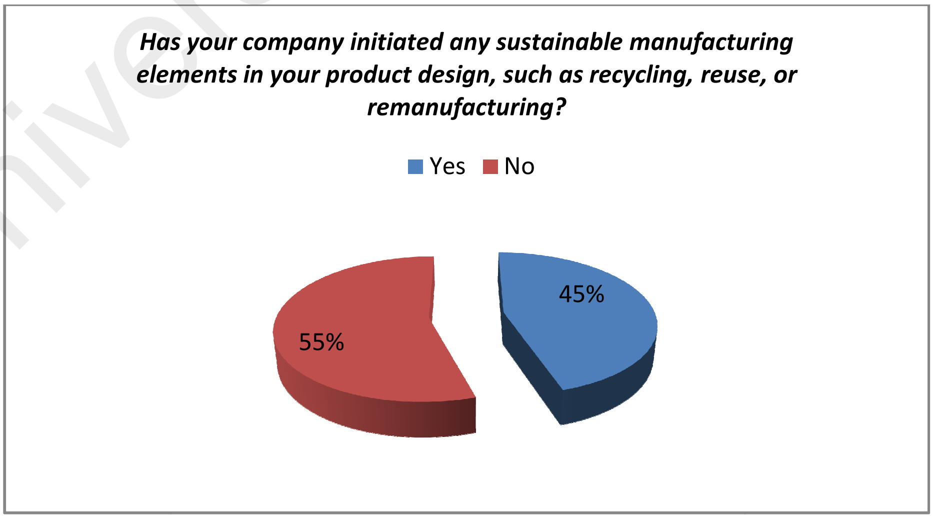


Figure 4.8 Initiative of sustainable manufacturing practices.

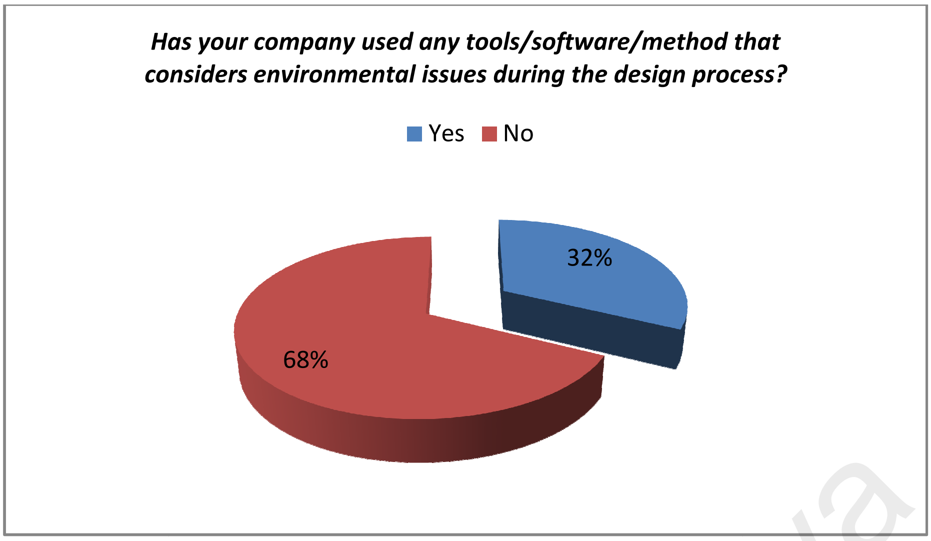


Figure 4.9 Initiative of using design of environment methods or tools.

The companies appear to be concerned about environmental issues, as they can easily interpret what is DFE, they know the importance of DFE and they understand how DFE affects their product competitiveness. Most companies have conducted DFE-related training to their key personnel such as Environmentally Preferred Product Initiatives (EPPI), Eco-Design Workshop, Life Cycle Assessment, and LCA Kit.

Designers' Insight of DFE

In general, designers exhibit a strong awareness of environmental issues often due to regulatory requirements. Nearly all of the respondents surveyed understand the importance of DFE however very few companies actually implement DFE in product design (see Appendix G). This can be associated with a lack of commitment in providing DFE tools or eco design training to the relevant personnel. However, larger industries, particularly multinational companies, implement environmental initiatives such as ISO 14000 and Life Cycle Assessment programmes, while other industries have developed specific internal environmental standards either in the design or process phase. Most designers express their concern of incurring higher product development costs if DFE is implemented. Most of the respondents perceived that DFE is not embedded in the engineering design process due to misunderstanding of the definition of DFE. The responses given by the respondents are listed below with regards to product characteristics:

1. *Respondents perceive DFE as a product characteristic:*
    - To create a product with environmentally-friendly materials and manufacturing processes
    - DFE is an approach of ensuring that the product design does not impact the environment in any way and causes hazardous impacts to people
    - Environmentally-harm free products
    - Environmental-friendly products

2. *Respondents perceive DFE as an engineering design process approach:*
    - Sustainable design
    - Designing a product by taking into consideration its effect on environment
    - Design things with EPP compliance
    - Design that takes environmental consideration into product development
    - Taking environmental issues into account during product design phase
    - Considering environmental effect into design of product
    - Fundamental design practices to minimize environmental impact form cradle to grave
    - Design which do not produce or use materials that are harmful to people and environment
    - Design and manufacture of products with minimal impact to the environment, energy efficiency, reduction and pollution, recyclability
    - An engineering perspective which is environmentally related to the optimization of product’s characteristics, process or facility. DFE implies adopting customers’

expectations and regulatory requirements, whereby essential elements are used as guidance such as energy and resources efficiency, material selection and safety

3. *Respondents perceive DFE as a material consideration:*
    - Use environmentally friendly materials in the product
    - Product or design needs to consider materials that are environmentally friendly
    - Design to minimize environmental impact due to hazardous materials. DFE means choosing non toxic, sustainably-produced or recycled materials which require a minimum amount energy to process
    - Design with lead-free components

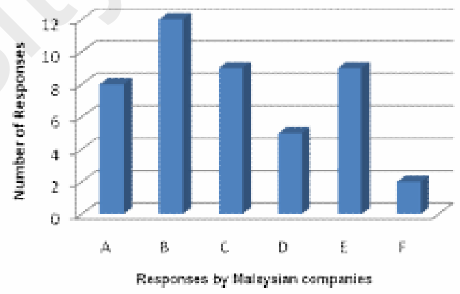
There are misconceptions on understanding the DFE term, whereby some designers perceive DFE is a characteristic of a product, while others perceive that DFE is apart of the engineering design process. According to Fiksel (2009), "*DFE is a systematic consideration of design performance with respect to environment, health, and safety and sustainability objectives over the full product and process life cycle"*. This implies that DFE is a structured process in design activities. With these misinterpretations, the implementation of DFE in the engineering design process is not well-structured and poorly practiced. This misinterpretation may be due to a lack of understanding on DFE terms. Deutz et al. (2013) also emphasized that although many companies incorporate environmental issues within the organization, they do not engage themselves in the design process by virtue of their extensive capacity. This may be attributed to lack available environmental-related information regarding the design process. Therefore, the stakeholders are a potentially important source of environmental information (Aschehoug, 2012) in order to hasten the inclusion of DFE in the design process. In order to mitigate these misconceptions, a structured methodology is needed to assist designers to implement DFE successfully, incorporating views from all stakeholders.

This can be in the form of tool or method that leads to the correct practice of DFE within the organization.

From the survey, it is also evident that the current soft approach of the government and the lack of proper supportive infrastructure do not motivate designers to initiate DFE.

Initial Drivers in Adopting DFE

From the survey it is found that initiatives by managers are seen as the main drivers of DFE implementation within an organization, as shown in Figure 4.10. This is related to the nature of the Malaysian corporate culture whereby decision making and initiatives are based on a hierarchical structure. Thus, the manager is the most influential actor in ensuring successful and effective DFE implementation. Malaysian companies, especially local-based companies, generally follow a vertical hierarchical structure where authority is directed from the top of management.



A-Designer initiatives	D-Customer demand
B-Manager initiatives	E-Regulatory policy
C-Management policy	F-Others

Figure 4.10 Responsibility of incorporating DFE in the company.

This culture can be both advantageous and disadvantageous for initiating DFE implementation. The line of authority allows ease of coordination in implementing DFE from the top to bottom. An organizational culture is one of successful factors in DFE implementation. However, the implementation of DFE will be difficult without proper support, awareness and knowledge from the product development team. Regulatory and management policy is the second driving force for eco-design implementation. Regulatory policies provide clear direction on the actions to be taken by the development team, especially due to the lack of necessary knowledge, which is why a soft approach by the government is ineffective in pushing for DFE implementation. The soft approach currently adopted the government does not provide clear direction for strategic action to be taken by the manufacturers. Also, lack of knowledge has been found to be the most profound hurdle in implementing DFE by Malaysian designers.

Difficulties in Implementing DFE

A large number of DFE tools or methods have been developed by past researchers. However, according to Pigosso et al. (2010), their applications in the real industrial practices are lacking. Therefore, it is important to question what difficulties are facing by industries implement DFE.

Figure 4.11 shows the factors that increase the difficulties in implementing DFE. The three major factors are lack of proper knowledge, lack of management initiatives and commitment, as well as time and cost.

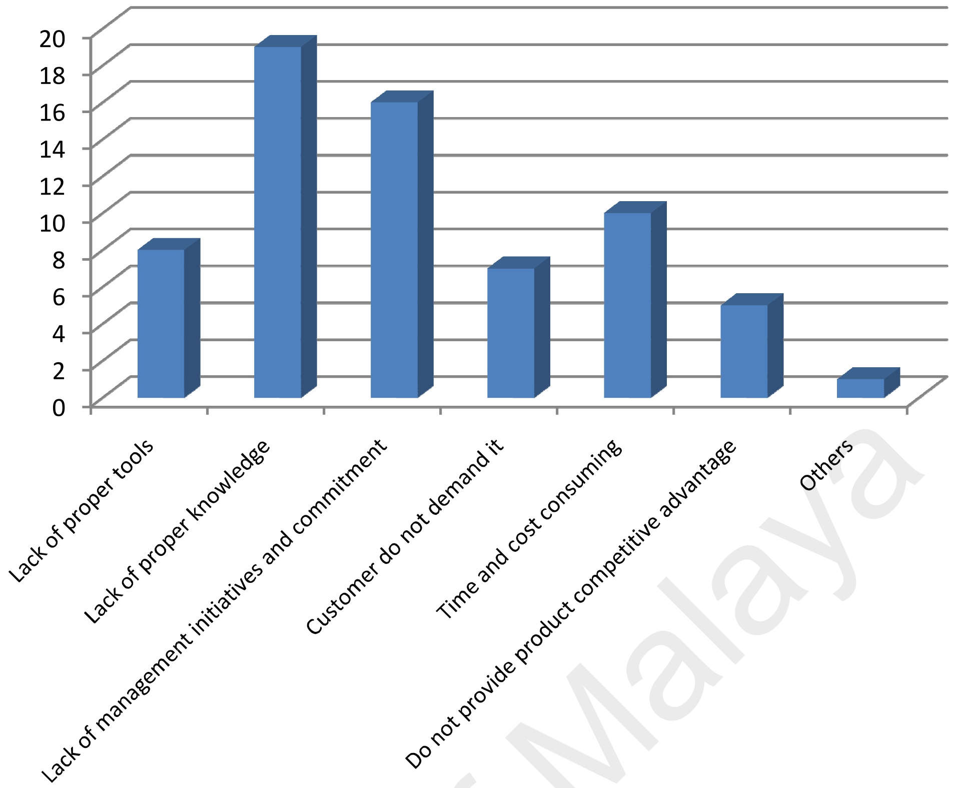


Figure 4.11 Difficulties in implementing DFE.

Another common notion among designers is that they perceive DFE implementation as complicated which requires commitment from many stakeholders with unclear benefits and very slow returns. This increases their reluctance to consider DFE.

4.2.3 Requirements of Environmental Method or Tool

Factor analysis is used to determine the methods or tools that are considered important by designers. Prior to data analysis, reliability tests are conducted to measure the consistency of the response given by respondents for each item in the questionnaire item. A well-known method for measuring internal consistencies of a group of item is the *Cronbach-alpha* coefficient (*Cronbach α*). It is basically a correlation between the item responses in a questionnaire. If the correlation between items are high, the Cronbach α will also be high. The value usually is within a range of 0-1, and a value above 0.7 is desirable. Table 4.2 summarizes the results of the reliability analysis. Table

4.2 shows that the Cronbach α is 0.943, which indicates that the consistency of each item is high and reliable.

Table 4.2 Summary of Reliability Analysis.

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.943	.945	32

According to Field (2005) there are three stages in factor analysis:

1. A correlation matrix is first generated for all variables. A correlation matrix is a rectangular array of the correlation coefficients of the variables with each other.
2. The factors are extracted from the correlation matrix based on the correlation coefficients of the variables.
3. The factors are rotated in order to maximize the relationship between the variables and some of the factors.

Screen plot is a graph of the eigenvalues versus all factors. The graph determines how many factors showed be retained. It can be seen from Figure 4.2 that the curve begins to flatten between factors 7 and 8 and therefore only six factors are maintained.

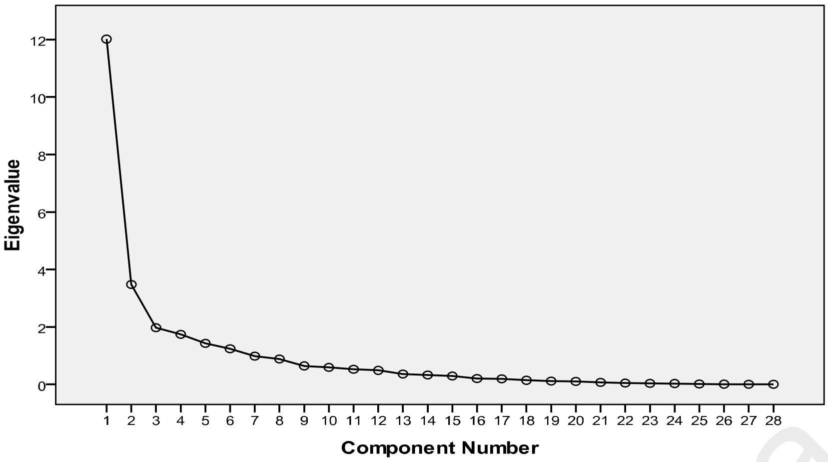


Figure 4.12 Screen plot for component number and its eigenvalue.

Table 4.3 shows the component matrices of the extracted components and items. The yellow colour indicates items that constitute a component in the component matrix. It can be seen that item C1 contributes the most to component 1 in the component matrix, because it has the highest value (0.818) compared with other components. Therefore it can be seen that each item (C8-C28) contribute, to components from 1 to 6, depending on its higher value. These extracted components represent clusters of requirements of using environmental design tool considered by designers which is taken from the survey.

Table 4.3 Component matrix result of component analysis.

Rotated Component Matrix[a]

	Component					
	1	2	3	4	5	6
C1	.676	.341	.322	.035	.114	.389
C2	.527	.480	.385	-.049	.067	.036
C3	-.022	.011	.104	.180	.876	-.045
C4	.283	.091	.167	.390	.504	.594
C5	.544	.314	.501	-.023	.339	.203
C6	.346	.450	.400	.272	.123	.440
C7	-.007	.722	-.010	.407	.406	.071
C8	.075	.713	.283	.229	.385	.223
C9	-.076	.809	.337	.068	.022	-.050
C10	.195	.401	.127	.621	.375	.347
C11	-.170	.050	.055	.790	.021	.044
C12	.277	.613	.096	.456	-.104	-.249
C13	.638	.537	.255	.167	.120	.097
C14	.390	.146	.467	.470	-.108	-.088
C15	.585	.493	.166	.321	-.020	.242
C16	.659	.507	.148	.209	.141	-.064
C17	.800	.047	.353	-.021	.186	.020
C18	.735	-.260	.316	-.070	-.059	-.082
C19	.837	.049	.141	-.012	.123	.001
C20	.631	.407	.449	.131	-.169	-.136
C21	.841	-.011	.071	.127	.053	-.037
C22	.214	.384	-.046	.724	.133	-.199
C23	.163	.085	.267	.193	.234	-.720
C24	.460	.289	.672	-.074	-.141	.056
C25	.254	.139	.878	.110	.067	-.191
C26	.235	.218	.836	.141	.212	-.074
C27	.308	.112	.675	-.022	.355	.240
C28	.263	.398	.107	-.166	.693	-.116

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 11 iterations.

The following six extracted factors are identified as the requirement for environmental design tools or methods to be considered by designers as follows:

Component 1 : Guidelines with easy and easily intrepreted answers

Item	Description
C1	Helps me fulfil specified requirements of the prospective products
C2	The customer demand its use
C5	Facilitates the management of product development projects
C13	Must be capable of being used in the earlier phases of product development process
C15	Provide exact answer/direction for further work
C16	Gives guidance/direction for further work
C17	Facilitates internal communication of data and results within the product development project
C18	Facilitates external communication of data and results outside the product development project
C19	Generate an easily interpreted answer
C20	Generate results that are spontaneously experienced as reliable
C21	Is transparent i.e an outsider can understand how results emerged

Component 2 : Optimization

Item	Description
C6	Reduces the risk where significant events have elapsed
C7	Reduces the number of working hours needed to solve the task
C8	Reduces the cost for a product development project complicated
C9	Reduces the number of people needed to accomplish a product development project
C12	Is not experienced as unnecessarily

Component 3 :The tool/method based on scientific ground

Item	Description
C23	Facilitates the cooperation between different colleagues
C24	Is based on not well documented scientific ground
C25	Its limitation and shortcomings are easy to see and understand
C26	Facilitates the evaluation of data in a product development project
C27	Can be integrated/compatible with other methods of tools

Component 4: Accommodate intuitiveness of designer

Item	Description
C10	Allows some of its part to be skipped during the process but still provides useful answers
C11	Is intuitive
C14	Provide quantitative answers
C22	Is not experienced as unnecessarily complicated

Component 5 :Interoperable

Item	Description
C3	Is used by the competitor
C28	Can be transformed in to a computer program

Component 6: Easy for beginners

Item	Description
C4	Facilitates introduction of new employees

Based on the six extracted components, it can be concluded that designers required environmental tools that provide guidelines with easily interpreted answers, optimization tool which are based on scientific ground, accommodate intuitiveness of designers, interoperability and easy for beginners. These requirements should be considered to build an environmentally assisted method or tool for product design purposes.

The survey concludes that there is an awareness of DFE among designers. However, the awareness is not well implemented at the design level due to the lack of knowledge and management support. Rules and regulations for DFE play a significant role in hastening its implementation in Malaysian industries. DFE implementation should not be based on voluntary action rather it needs to be mandatory. The solution will be a framework that enables an integrated approach to environmental issues across the product lifecycle, starting from design, manufacturing, distribution and end-of-life treatment in concert with other enterprise engineering tools. In conclusion, there is a need for suitable DFE methods and tools that can guide designers in producing green products.

4.3. Exploratory Study

Based on the research methods discussed in Chapter 3, an exploratory study is conducted to understand the subjects' experiences. The interviews are all conducted in Malaysia and mostly held at the at the interviewees' workplaces. As for interviews with recyclers, site tours are carried out after the interview sessions to get understanding of the recycling process. The duration of each interview is varies between 1-4 hours. Semi structured interview is adopted with open ended questions. The interview protocols are presented in Appendix E.

All interviews are recorded and transcribed. The researcher then reads the transcribed text to comprehend and clarify evidences. Important evidences can be determined by examining transcribed documents and searching for statements that are stressed by the interviewees. Counting is also used to analyze the significance of the evidences, in which repetition of specific statements mentioned by interviewees may be considered as important.

4.3.1 Participants

The participants consist of designers and recyclers. Interviews with designers are conducted to answer the research questions (*RQ1b, RQ2*), which is to obtain insight on the current practices of DFR as well as a list of recyclability factors.

4.3.1.1Product Designers

Designers are interviewed to explore the current practices of designers in incorporating DFR issues. In this study, thirty two designers participate in the preliminary survey, and five respondents are recruited to participate in this exploratory study. Table 4.4 describes the participant's background. All interviews are recorded and stored as evidences.

Table 4.4 List of product designers who participate in exploratory study.

Designers	Description	Interviewee	Working Experience
Designer A, B, C (Interview done in focus group)	A recognized industrial design company that provides design consultancy.	Focus group consists of : 1 Principal Mechanical Design Engineer 1 Mechanical Design Engineer 1 Research and Development Manager	5 years 7 years 11 years
DesignerD	One of the leading design companies providing clients with user-centered research, industrial design, mechanical engineering, prototyping, graphic design, interface design, packaging design, production support and design training.	Design Manager (owner of the company)	20 years
DesignerE	A world class automobile company.	Engineering Designer	5 years

4.3.1.2 Recyclers

Participants are identified from internet search as well as personal contact. A total of hundred of recycling companies is identified. However, only twenty recyclers are deemed suitable to fulfill the criteria for interview. The criteria are set to ensure that the data are extracted from reliable sources. The criteria are as follows:

- Interviewee must have experience in the recycling process for at least 5 years
  Interviewee must have sound knowledge in the recycling process, beginning from the collection of waste to recycled materials
- Interviewee must have at least mid-level management position to ensure that he or she has the ability to communicate well
- Interviewee is willing to be interviewed

From the twenty companies, visits are carried out with twelve companies and the remaining companies are contacted by telephone to re-check the suitability of the participants. From the visits, it is found that several companies are inappropriate for interview due to the fact that they are trading-based companies. Trading-based recycling companies are companies that only buy waste or sell recycled materials. Only six participants met the criteria for interview. The participants are finally selected for pilot study as listed in Table 4.5. Their identities are not revealed due to confidentiality issues.

Table 4.5 List of recyclers who participate in exploratory study.

Participants	Company Description	Job Role of Interviewee	Experience in Recycling	Sources Used	Length of Interview
Recycler A	One of the largest plastic recycling company in South East Asia Region producing high quality recycled resin.	General Manager	5 years	▪ Semi structured interview ▪ Company's website ▪ Company not allows researcher to record the interview. Researcher notes the interview	1 hr 38 min Followed by site visit
Recycler B	A leading provider of comprehensive waste management and recycling services.	General Manager	8 years	▪ Semi structured interview ▪ Company's website ▪ Recorded interview	▪ First interview: 1 hr 11 min 42 sec ▪ Second interview: 1 hr 23 min
Recycler C	A leading company that specializes in scraps metal recycling and trading with 18 years of experience in recycling. Specializes in collecting, segregating, processing and redistribution all types of ferrous, non-precious and precious metals, steel , alloys, electronic and electrical scraps, paper and plastic.	Managing Director	10 years	▪ Semi structured interview ▪ Company's website ▪ Recorded interview	First interview: 53 mi Second interview: 58 min Followed by site visit
Recycler D	A leading company in waste management, recycling of ferrous and non ferrous metals, plastic and cartons.	General Manager	5 years	▪ Semi structured interview ▪ Company's website ▪ Recorded interview	23 min 53 sec Followed by site visit
Recycler E	One of the well known waste management company that gives services for waste collection, waste disposal and recycling.	Managing Director	5 years	▪ Semi structured interview ▪ Company's website ▪ Recorded interview	46 min
Recycler F	A leading and experienced company that recycle computer scraps.	Managing Director	7 years	▪ Semi structured interview ▪ Company's website ▪ Recorded interview	2 hr 10 min Followed by site visit

4.3.2 Findings of Exploratory Study

In this section, the findings attained from the exploratory study are reported. In order to structure the pilot study report, it is deemed useful to report the pilot study based on the research questions formulated in previous section.

- *RQ1b. What is the designer's current approach to incorporate product recycling during the design stage?*

The evidence is classified as acquisition of DFR basic knowledge, recycling or end-of-life considerations during the design stage and design factors that influence DFR, as shown on Table 4.6.

Excerpt of interview transcribe is presented on Appendix F.

Table 4.6 Evidence from product designers

Designers	Evidence
	Environmental awareness
Designer A, B, C (Focus Group)	*Q: Do you have any environmental consideration during your product design stage?* *A: “Usually no. Basically we look at the regulation…* *We don’t consider environment as, we don’t practice that.” (R&D Manager)* *“If I am a designer and I cannot make this thing easily recycle that means I am very guilty. I think recycle is very important.”(Mechanical Design Engineer)* *“If we ask individually consumers to choose they wouldn’t go for green. …those are regulated” (R&D Manager)*
Designer D	*“We do not practice the environmental design, but we aware of it. There are two types of customers, one who do not care about new idea, second, who always looking for new concept. For the second type of customer, we sometimes offer the environmental consideration in the design as a revolutionary design concept….”(Design Manager)*
Designer E	“*We do consider environmental issues. But so far we are more focusing on manufacturability, safety, aesthetic and cost. The direction of design comes out from the high management. Usually it comes from the consensus between CEO, board member and General Manager. This direction encourage by market demand.”(Engineering Designer)*
Designer E	*“We actually design by the customers’ requirement. If customers require the environmental consideration so we did it.”(Engineering Designer)*
Designer A, B, C (Focus Group)	**Recycling/end-of-life consideration in design stage**
	“Customers, I would say that they are not taking too much care of the recyclability but they take care a lot on the serviceability…”(Design Engineer) *“When we start to design the concept that we are looking at same thing we look at different aspect like recyclability, cost would be at the first hierarchy.”(R&D Manager)* *“Maybe if we are using a screw we would like to use the same size, standardize, I think we also have a lot of sample in our office … period to period… throw to recycle we know that it is easy to disassemble, recyclability is important, I think whether it is easy to recycle or difficult to recycle, there is certain effort in design needed.”(Mechanical Design Engineer)*
Designer D	*“Our design consideration actually based on manufacturing constraint. We don’t mixed material with recycle materials unless customer intended to do that.”(Design Manager)*

	“Personally I would like to be labeled as a green designer. In business, it will depend on customer requirements, but I suggested green concept…for example I suggest to print on the recycle paper, avoid the lamination in design because lamination is not good for recycling …”(Design Manager)
Designer E	*“For recycling…we don’t practice it, but we do some environmental consideration, such as lower the part’s weight and using non hazardous material.”(Engineering Designer)*
	Design factors that influence DFR
Designer A, B, C (Focus Group)	*“Certain product you melt it together you have a join that actually slot into the plastic part you can heat up. It’s not like you can simple take it out, it cannot be taken out already.”(Design Engineer)*
Designer D	*“Incorporating recycling with design is mainly determined by product assembly. If the assembly is difficult then it would be inefficient to recycle for example, using snap fit is not easy to disassembly, but screw is much more easier.”* *“Spray painting is toxic for environment and influence recycling process, we usually told the customer not to use it, and choose the genuine color.”(Design Manager)*
Designer E	*“The selection of material can be influence the recycling. For example, metal can be easily recycled rather than plastic.” (Engineering Designer)*

Based on the evidence presented in Table 4.6, it is clear that:

1. Most designers participate in the interview do not incorporate environmental considerations during the design stage as stressed by Designer D :

   "We do not practice environmental design, but we are aware of it."

   During the interview, it is found that the designers are aware of the environmental impacts of the design; however, they are more concerned with customer requirements. If the customers do not require green products, then they would not consider green aspects in the design. This finding is support by Seliger (2007) who states that recycling has not been widely considered in product design practices although designers are aware of this issue.
2. All of designers participate on this interview do not consider end-of-life or recycling issues during the design stage because they do not fully understand actual recycling practices. This agrees well with Rose (2000) who reported that there is lack of opportunity to observe the company's current practices especially related to end-of-life strategy and improving the strategy from their success and failure. Rose (2000) also added that by learning the company's practices, research is able to learn from the mistakes, understand the problem area and develop a more structured methodology to assist designers in incorporating recycling issues. Therefore, understanding what are the current recycling practices and obstacles will offer a good basis for developing a precise methodology that will assist designers in implementing DFR.
3. Designers in this interview do understand that their design will contribute to recycling effectiveness. They are aware that joining types, disassembly, fastener types, material types and surface finish are factors that contribute to successful recycling. This understanding will be placed as the basic

consideration in developing a structured methodology for DFR suitable for Malaysian product designers.

Interviews are carried out with recyclers to answer RQ1b and RQ2 (See Appendix F). Table 4.7 shows the evidence captured from interviews with the recyclers. The recyclability factors identified from the interviews are coded (RF1-RF7). The evidence reveals the design factors that contribute to recyclability.

Table 4.7 Evidence from recyclers.

Participants	**Recyclability factors to consider**	**Evidence**
Recycler A	RF1. Material separation	*"The separation process done manually with amount targeted around 10 kg per hour per person. Then it continues to crushing plastic into smaller size, in order to make extrusion process much easier. Separation process is time consuming and difficult to manage, as it is done manually."*
	RF2. Price of recycled materials	*"Recycling can work well if there is constant/consistence price of recycled materials."*
Recycler B	RF3. Profit	*"…if you talk about industries exposure about recycling most of the industries all are contributing to the recycling not because of the environment not because of the government needs, but purely because of monetary reasons"*
	RF1. Material Separation	*"Yes, or else we will take it but at the low price. We do the sorting, cast iron is cast iron, mild steel is mild steel.."* *"So, you must understand in recycling, sorting is the most important thing."*
	RF4. Material Combination	*"if we talk about metal, as long it is mild steel is OK, there is no difference in pricing, unless you mixed consumer's scrap, then it will be different, it's very thin, also consumer's scrap there is labelling, paint, so the recovery of metal is only about 60++ percent"*
	RF5.Recycling infrastructure	*"You must have water treatment in your plant. Basically, water treatment is very very important in plastic recycling. Everything has to do with washing scrap. Wash the scrap actually washing rubbish, we get a lot of contamination, so how we treat water is very important."*
Recycler C	RF7. Volume of reclaimed materials	*"I use manual dismantle to open the car engine time for dismantling is too long, we need volume, no volume no profit"*
	RF4. Coating/material combination	*"Yes it is affected the material value. Because the smelter will melt one time so if there is coating so it will downgrade material."*
	RF5. Recycling Infrastructure	*"Infrastructure is very important to secure the recycling activity."*

	RF3. Profit	*"Economic value for sure is motivation for recycling"*
Recycler D	RF1. Material Separation	*"Manual separation is very slow and need attention, because we have to take out material one by one…"*
	RF3. Margin/Profit	*"We are emphasizing on margin. We as a recycling company should get the best margin, and then we can only settle the process."*
	RF5. Recycling Infrastructure	*"Infrastructure is very costly and important to support recycling process."* *"If we used eddy current, actually the separation time will be less. Without that it will takes longer time…"*
	RF6. Joining type	*"Joining types affect the value of recycled materials. If there are two different materials that cannot be crushed, the material value will no longer superior"*
Recycler E	RF1. Material Separation	*"Material separation depends on material type; mostly it is the important stage in the beginning of recycling. For plastic, material separation is significant for subsequent process in recycling, while metal, as long as the material is metal it can be processed."*
	RF5. Recycling Infrastructure	*"Japan successfully implements recycling because it has good recycling facility. With good facility, recycling can be done."*
	RF8. Product shape	*"For plastic, complex product shape can lead to difficulties when we separate it."*
Recycler F	RF1. Segregation/Material Separation	*"Segregation is done manually, we don't use machine. Expertise is needed to know which of the part that useful for recycling"*
	RF9. Demand of recycled materials	*"If there is a demand of reclaimed materials than we will proceed it, otherwise not"*
	RF6. Joining type	*"..when it come to segregate, sometimes it takes longer time because we have to detach the joining. Bolt are easy to open, welding are not."*
	RF3. Profit	*"We look for good profit, if there is profit then we will do it"*

RF: Recyclability Factor

Based on the interviews, the frequency of the factors stressed by the recyclers are shown in Table 4.8.

Table 4.8 Frequency of recyclability factors stressed by recyclers

Recyclability Factors	Interviewee						Weight out of 6
	RA	*RB*	*RC*	*RD*	*RE*	*RF*	
RF1. Sorting/Material Separation	✓	✓	✓	✓	✓	✓	6
RF2. Price of recycled materials	✓						1
RF3. Profit		✓	✓	✓		✓	4
RF4.Material Combination		✓	✓				2
RF5. Recycling infrastructure		✓	✓	✓	✓		4
RF6. Joining				✓		✓	2
RF7.Volume			✓				1
RF8. Product shape					✓		1
RF9. Demand of Recycled Materials						✓	1

There are nine factors found which influence recyclability. These factors are then presented to the recyclers. Several factors are found to have a similar meaning, for example, volume and price are related to profit gain from recycling. Consequently, the recyclability factors that have the same meaning are combined as the same factor. The recyclability factors are then reduced to six factors, as shown in Figure 4.13.

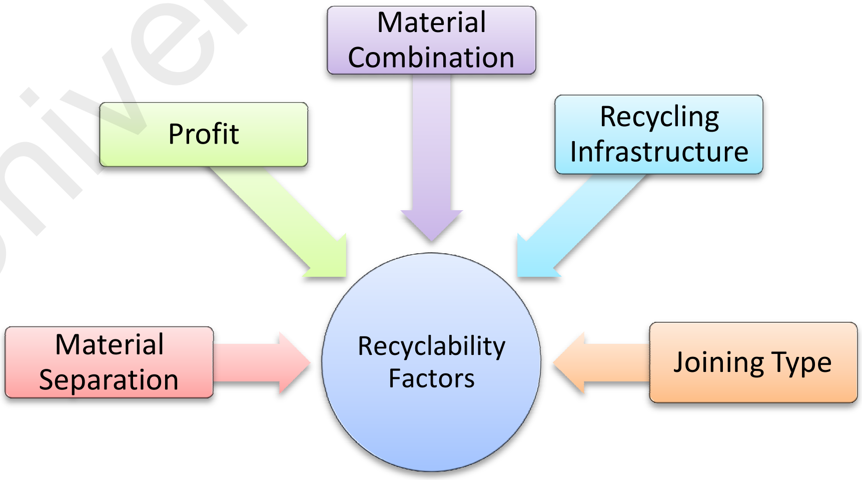


Figure 4.13 Recyclability factors extracted from recycler’s practices

The exploratory study confirms that profit, material separation, material combination, joining type, and recycling infrastructure are the factors which influence recyclability. These factors have also been mentioned in the literature (Schaik and Reuter (2007), Castro (2005), Qi *et al.*(2005)). Material separation is stressed by recyclers because it is the most intensive activity which consumes time and resources. Most recycling companies exist because of the profit gained from recycling activities. Profit is dependent upon the volume, market demand and price of the reclaimed materials. In Malaysia, the volume of recyclable waste is constantly fluctuating, depending on the supply of waste. This makes the recyclers' profit uncertain. Therefore, DFR may be an option to support the availability of reclaimed materials.

Material combination and joining type contribute to the quality of recycled materials. This is in line with the findings of Schaik and Reuter (2007), in which multiple materials joined together will decrease the value of the recycled materials. Although recycling infrastructure is not mentioned in the literature, this factor is considered as a new factor that influences recyclability. In Malaysia, recycling infrastructure should be considered when designing a high recyclability product, as the availability of recycling infrastructures is limited to specific materials such as plastics and metals.

The following section discusses the level of importance of each factor determined from using relative weight measurement.

4.4 Relative Weight Measurement

From Table 4.8, the frequency of recyclability factors stressed by recyclers can be counted. However, this is not necessarily an indication of the relative importance between the factors. Therefore, an additional calculation based on the recyclers' preferences is needed. The measurement basically uses a pair-wise comparison approach. A questionnaire based on the pair-wise comparison between each recyclability factor is distributed to the six recyclers. Recyclers have to assign a preference score for the evaluation criteria and compare the alternatives with respect to each evaluation criterion. The score uses a scale introduced by Saaty (1980). Calculation is based on equation (3.1)-(3.6). Table 4.9 shows an example of the weight for each recyclability factor given by Recycler A.

Table 4.9 Example of weights of each recyclability factor given by Recycler A.

	Profit	Material Separation	Material Combination	Recycling Infrastructure	Joining Type
Profit	1	7	0.111	7	6
Material Separation	0.143	1	0.125	6	7
Material Combination	9	8	1	9	8
Recycling Infrastructure	0.143	0.167	0.111	1	7
Joining Type	0.167	0.143	0.125	0.143	1

Calculation of the consistency ratio is performed and the results show that the value does not exceeded 0.10. Therefore, the consistency of the experts' judgements are acceptable. Table 4.10 summarizes the weights and ranks of the recyclability factors from all recyclers.

Table 4.10 Weight and rank of recyclability factors from all recyclers.

	Factors				
	Profit	Material Separation	Material Combination	Recycling Infrastructure	Joining Type
Recycler A	0.408	0.254	0.015	0.196	0.040
Recycler B	0.353	0.372	0.013	0.163	0.026
Recycler C	0.279	0.071	0.030	0.403	0.012
Recycler D	0.248	0.063	0.027	0.468	0.011
Recycler E	0.333	0.060	0.022	0.392	0.012
Recycler F	0.356	0.387	0.078	0.344	0.009
Overall weight	0.329	0.201	0.0308	0.327	0.018
Ranking	1	3	4	2	5

All of CR is accepted, CR<0.10

From Table 4.10, it can be concluded that profit is the most important factor that influences recyclability, followed by recycling infrastructure, material separation, material combination and joining type. This is due to the fact that current recycling practices in Malaysia are mostly dependent on the demand for recycled materials and the availability of reclaimed materials. It is also interesting to note that recycling infrastructure is the second most important recyclability factors. This reveals that most recyclers regard recycling infrastructure more significant than material separation. It can be understood that in Malaysia, recycling is limitedly carried out on certain materials, in which a majority is metals and plastics. Therefore, recyclers believe that recycling activities can not been done properly without recycling infrastructure in which economical value cannot be gained.

4.5 Summary

This chapter reports findings from preliminary and exploratory studies. It can be concluded that:

1. There is a lack of consideration for DFR during the product development stage due to insufficient knowledge on recycling. There is a need for a systematic approach to incorporate recycling aspects in the product design stage.
2. Designers require DFE methods with the following features:
    a. Guidelines with easily interpreted answers
    b. Optimization
    c. Based on scientific findings
    d. Accommodate intuitiveness of designers
    e. Interoperable
    f. Easy for beginners

3. Five recyclability factors are identified and ranked according to the order of importance, i.e.:
   a. Profit
   b. Recycling infrastructure
   c. Material separation
   d. Material combination
   e. Joining type

In the following chapter, a GA-based multi-objective optimization model is proposed, which accounts from the findings presented in this chapter.

CHAPTER 5

RECYCLABILITY ASSESSMENT

5.1 Introduction

This chapter presents the formulation of recyclability assessment based on *Fuzzy Inference System* (FIS). A recyclability assessment is used to assess the recycling potential of particular components based on the recyclability factors identified previously in Chapter 4, namely, material separation, material combination, joining type and recycling infrastructure. The following section presents the input and output design of FIS, as well as the numerical example of recyclability assessment in a part design model.

5.2 Design of Recyclability Assessment

This section proposes the approach for recyclability assessment, as shown in Figure5.1.

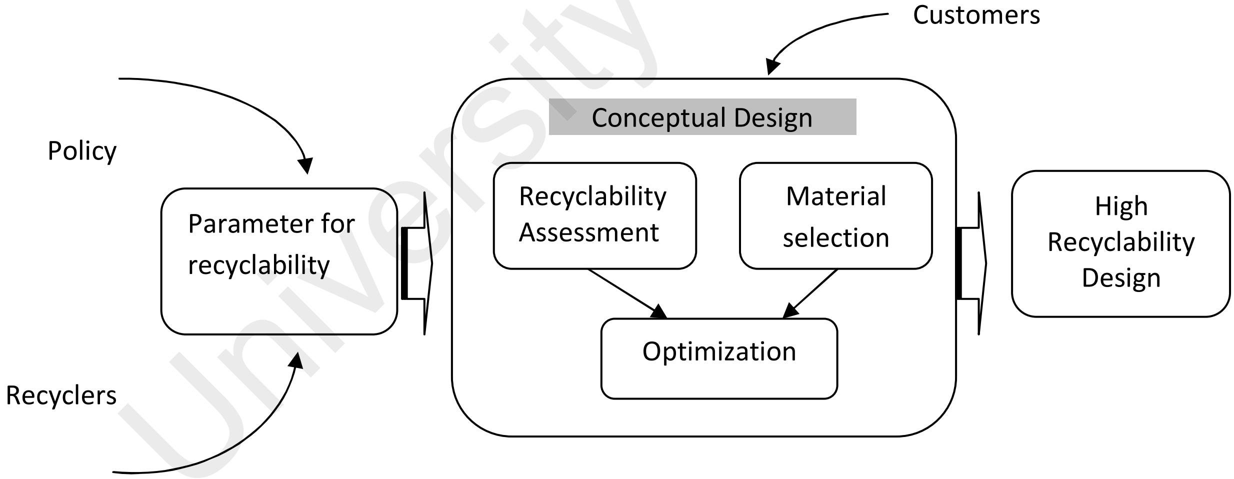


Figure 5.1 Proposed approach of recyclability assessment in conceptual design.

In Chapter 4, the design factors influencing recyclability have been clearly identified as follows:

1. Profit
2. Recycling infrastructure
3. Material separation
4. Joining type
5. Material combination

Profit can be quantified and therefore it can be an objective function in GA optimization. The remaining parameters are imprecise and more suitable to be represented in linguistic form. Fuzzy system is employed to develop recyclability assessment which caters to uncertain data. Each parameter, with the exception of profit is expressed in linguistic form. This is also a method of capturing the expert's knowledge. Each recyclability factor also has a certain weight calculated based on the recyclers' preferences. This will be used for GA optimization.

Once the parameters are set, the recyclability evaluation is formulated using the fuzzy method to determine recyclability values based on the material composition of parts. This is described in Figure 5.2, which shows that the CAD design model provides inputs for the recyclability assessment. The joining type, material type and material combination are the fuzzy inputs. Each fuzzy input has its own membership function. The rule base can be formulated after determining the fuzzy inputs. Defuzzification is then employed to obtain the recyclability value.

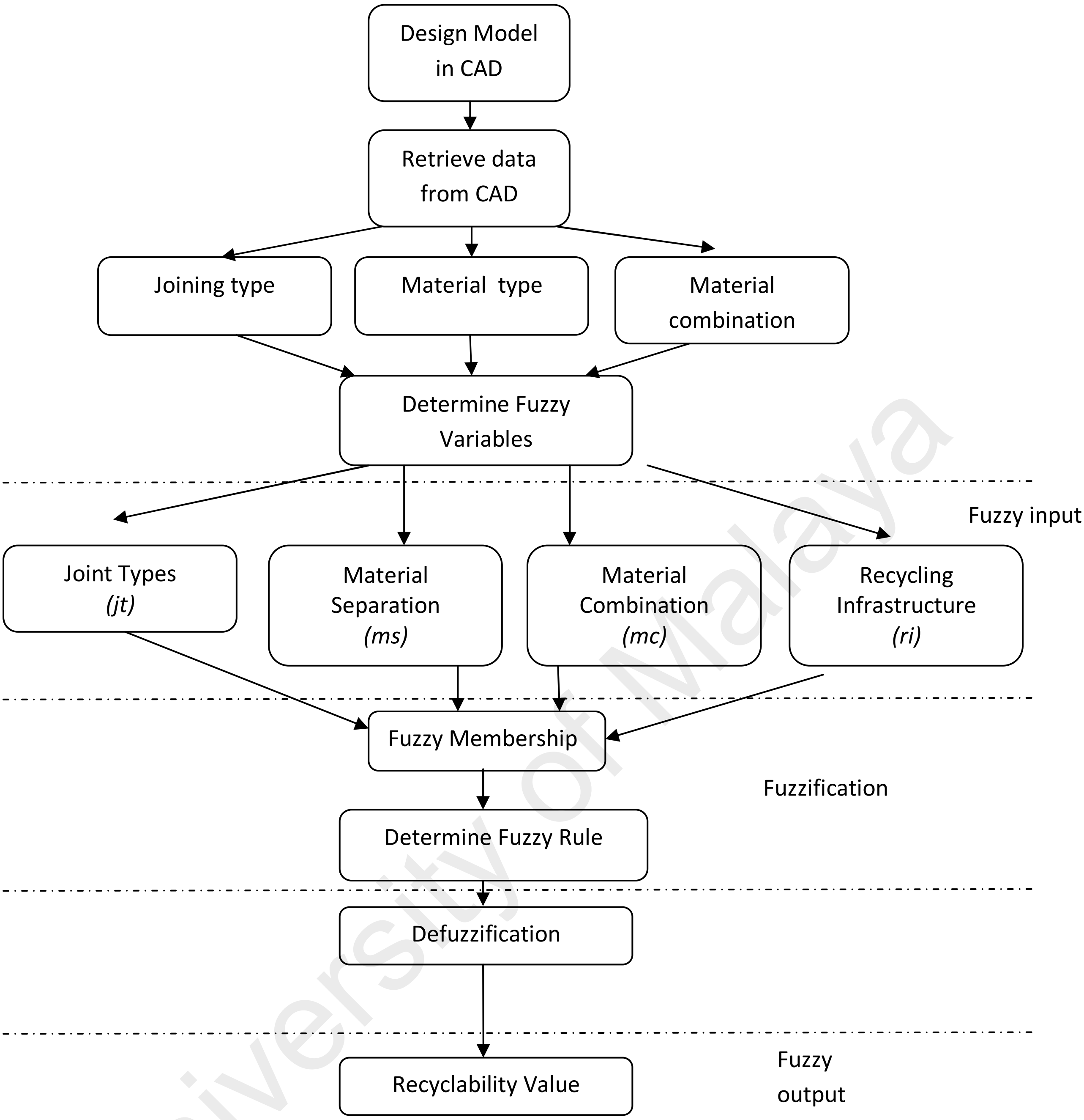


Figure 5.2 Steps in determining recyclability value.

The steps involved in fuzzy-based recyclability assessment are detailed as follows:

Step 1. Determine the fuzzy input value and membership function

Step 2. Determine fuzzy rule

Step 3. Determine the subassembly/part to be assessed in CAD

Step 4. Retrieve a *design table* from CAD

Step 5. Identify joining type, material combination, material separation, recycling infrastructure from the design model

Step 6. Assess the subassembly or part

Step 7. Convert the fuzzy quantities into crisp quantities (*defuzzification*)

Step 8. Calculate R_{value}

Step 9. Repeat Steps 3-8 for new assessments.

Once R_{value} is obtained, the value is stored as an inference database or library in Excel spreadsheet format. GA optimization is performed after recyclability assessment is completed. This offers guidance to designers when making decisions regarding their design model, whereby designers can determine if their design have achieved high recyclability with the chosen materials. Designers are able to optimize cost, technical and recyclability performance using this approach.

The MATLAB fuzzy logic toolbox is used to develop recyclability assessment due to its ease of use. A MATLAB GUI for Recyclability Assessment (R-Val) is also developed to provide designers with a simple interactive interface for recyclability assessment during the conceptual design stage. The following subsection discusses the formulation of fuzzy systems from the fuzzy input/output, membership functions and fuzzy inference systems.

5.2.1Membership Functions

One must determine the fuzzy input and output in order to determine the membership functions. The fuzzy input/output expressions are presented in Table 5.1.

Table 5.1 Fuzzy Expression of Input and Output.

Fuzzy Input				**Fuzzy Output**
Material Separation (MS)	**Recycling Infrastructure (RI)**	**Material Combination (MC)**	**Joining Type (JT)**	**Recyclability Value (R_{value})**
Low (L)	Not Available (NA)	Low (L)	Low (L)	Very Low (VL)
Medium (M)	Available (A)	Medium (M)	Medium (M)	Low (ML)
High (H)		High (H)	High (H)	Medium (M)
				High (H)
				Very High (VH)

From Table 5.1 it can be seen that material separation, recycling infrastructure, material combination and joining type are the fuzzy inputs.

The memberships function for each fuzzy input is based on the compilation of experts' opinions and literature which is described in Table 5.2. For material separation input, the score ranges from 1 to 3, in which the number 1 denotes a part that cannot be disassembled manually and 3 denotes a part that can be disassembled manually and easily.

Table 5.2 Fuzzy membership for each fuzzy input.

eMaterial Separation	Joining Type	Material Combination	Recycling Infrastructure
Low Cannot be disassembled, there is no known process for separation	**Low** Hard, length fitting, adhesive bonding, coating, painting, gluing,	**Low** Three materials or more are connected	**Unavailable**
Medium may be disassembled with effort requiring some mechanical means or shredding to separate component materials. The process has been fully proven	**Medium** Welding, insertion	**Medium** Combination of two materials	**Available**
High may be disassembled manually	**High** Bolts, screws, rivets, point fitting	**High** Single material	

The formulation for the fuzzy sets and membership function for recyclability is as follows:

$$\sum_{ms=1}^{ms=3}\sum_{jt=1}^{jt=3}\sum_{mc=1}^{mc=3}\sum_{ri=1}^{ri=2} Rvalue^{ms,ri,jt,mc} = 0 \tag{5.1}$$

where the indices can be explained as follows:

ms = material separation score (low=1, medium=2, high=3)

jt = joining type score (low=1,medium=2, high=3)

mc = material combination score (low=3, medium=2, high=1)

ri = recycling infrastructure score (Available=1, Not available=2)

R_{value} = recyclability index

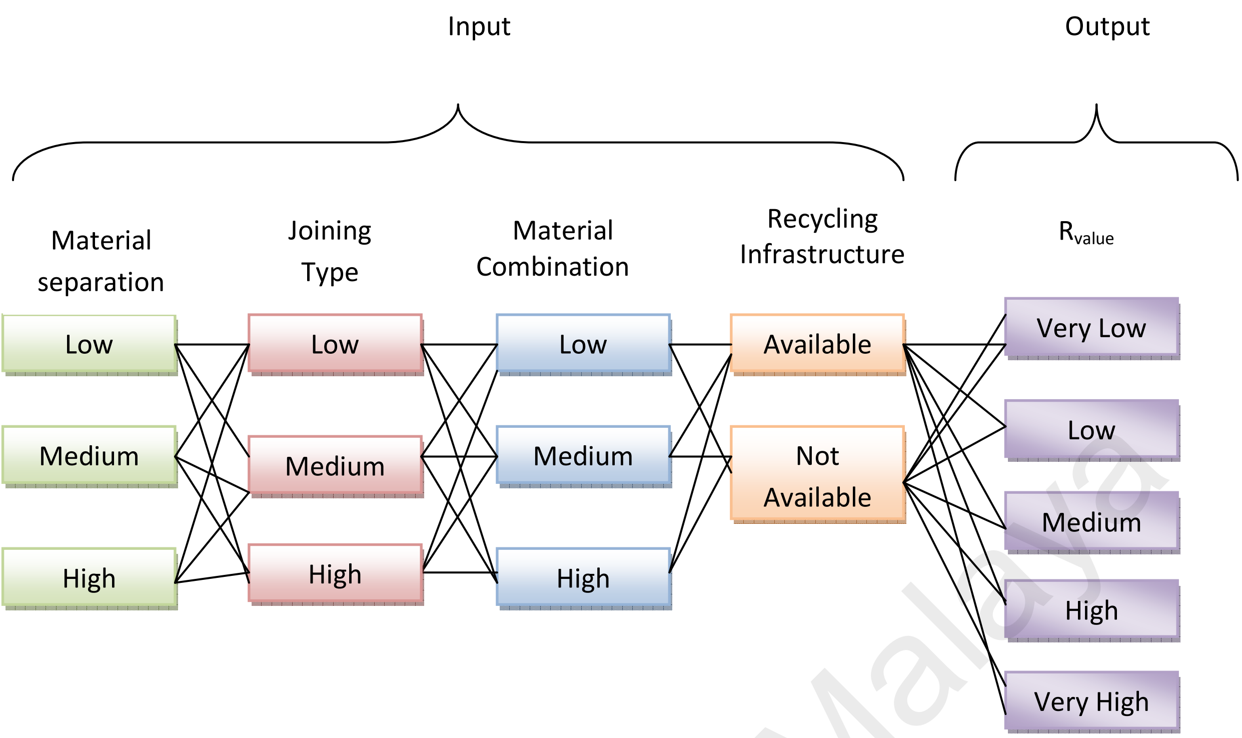


Figure 5.3 Network representations for output recyclability value.

Triangular functions are utilized to match the membership functions. According to Shemshadi *et al*. (2011), triangular functions are most commonly used in fuzzy-based methods. Figures 5.4 – 5.7 show graphical representations of various membership functions using triangular functions.

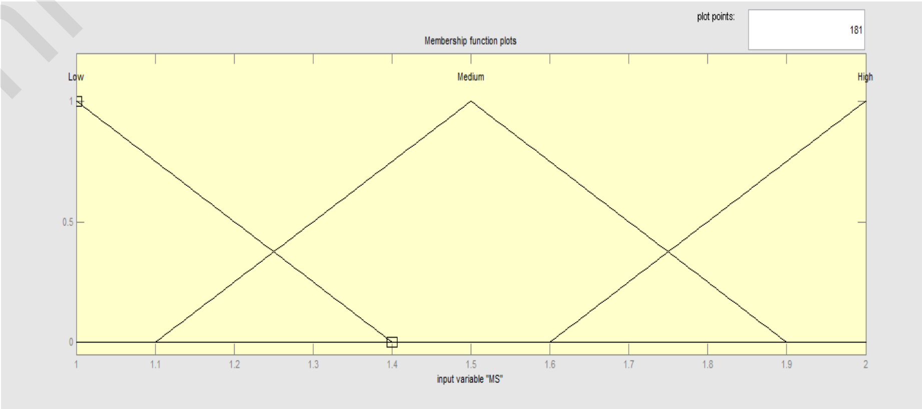


Figure 5.4 Membership function for material separation input variable.

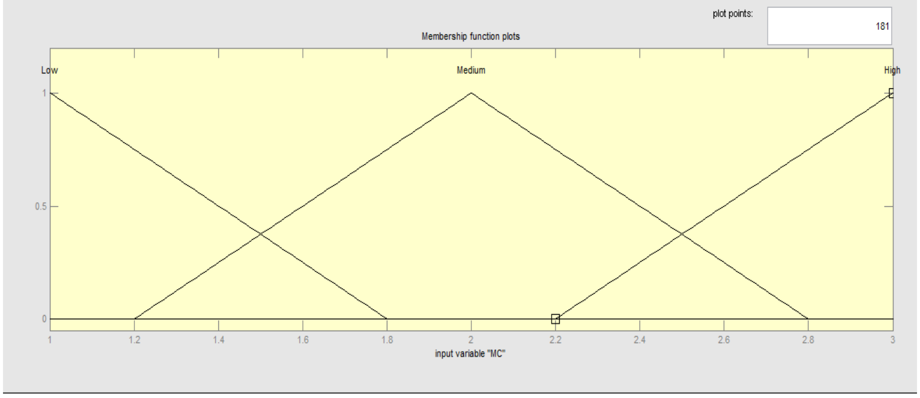


Figure 5.5 Membership function for material combination input variable.

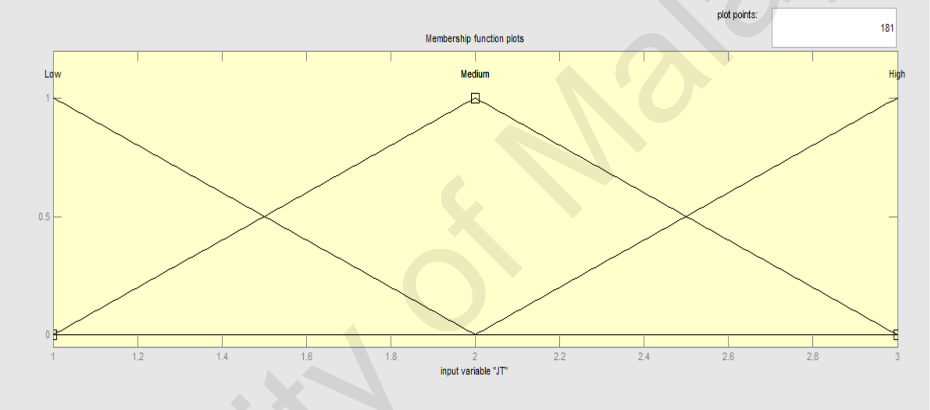


Figure 5.6 Membership function for joining type input variable.

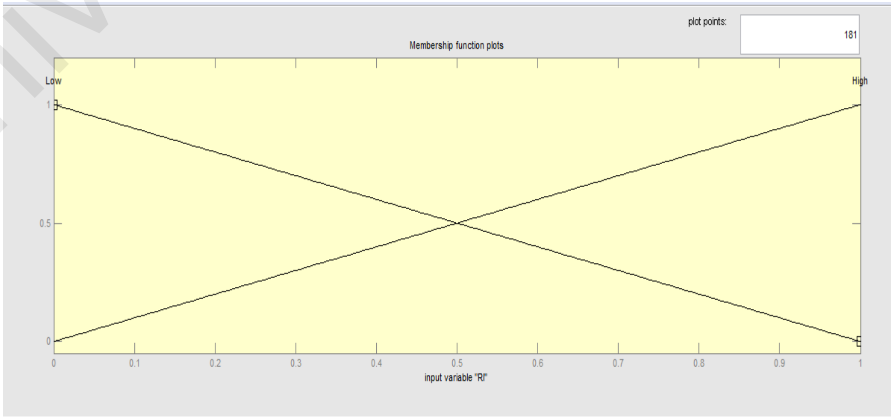


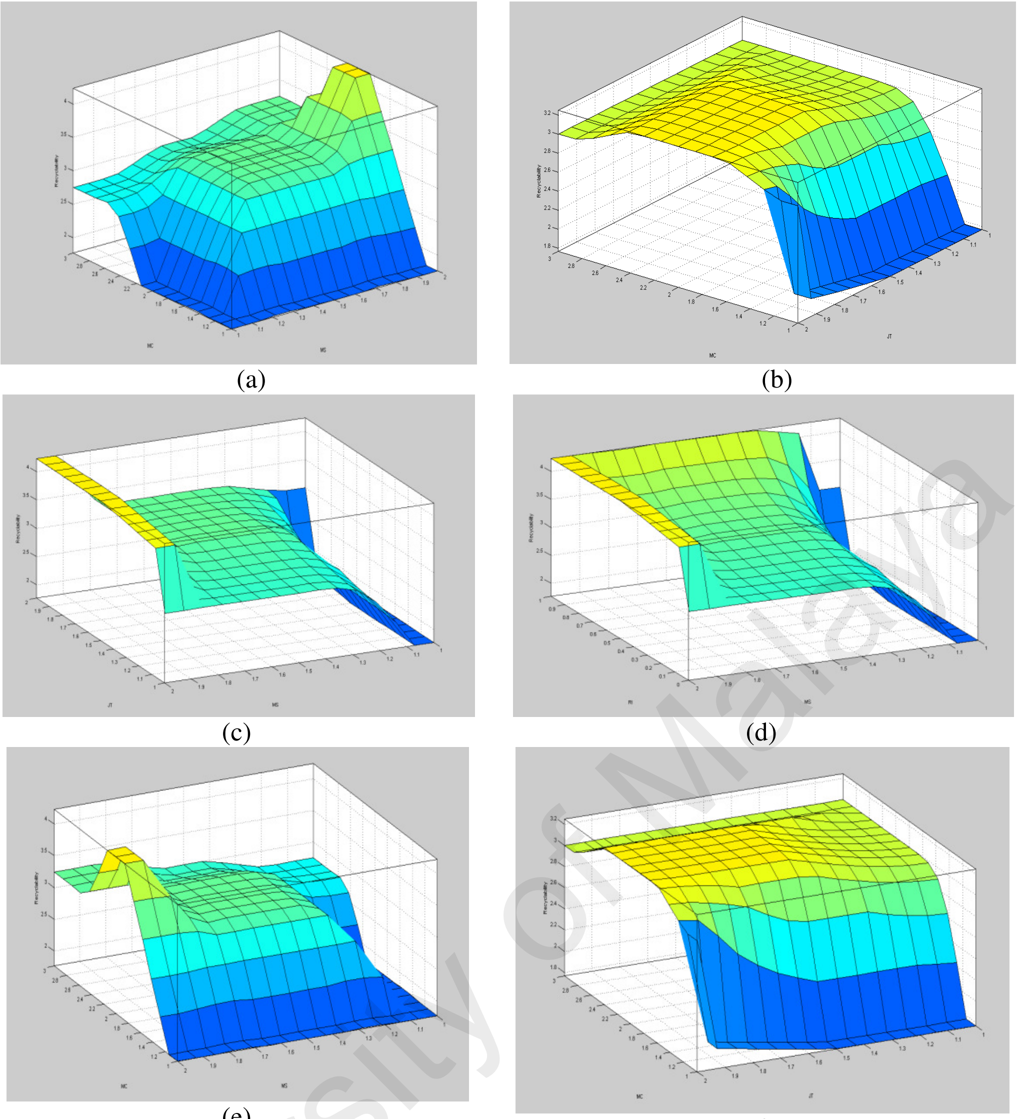
Figure 5.7 Membership function for recycling infrastructure input variable.

5.2.2 Fuzzy Rule

One of the important elements of fuzzy systems is rule based. The rule based is taken from the experts′ knowledge and in this case, knowledge is acquired from recyclers and designers. The fuzzy inference system evaluates each recyclability factor using a set of simplifying rules, based on IF-THEN statements. The simplifying rules are basically statements of experts′ knowledge and literature that relate the membership functions for each recyclability factor to the recyclability value. An example of the IF-THEN rule can be seen in Table 5.2. This rule is based on the membership function in Table 5.1. Since there are four recyclability factors, the number of rules are $3^1.3^1.3^1.2^1= 54$ rules.

Table 5.2 Example of IF-THEN Rule.

Rule		MS		RI		MC		JT		R_{value}
1	IF	High	AND	Available	AND	Low	AND	High	THEN	HIGH
2	IF	Medium	AND	Available	AND	Low	AND	High	THEN	HIGH
3	IF	Low	AND	Available	AND	Medium	AND	High	THEN	MEDIUM
4	IF	High	AND	Available	AND	Low	AND	Low	THEN	HIGH
.	.									
.	.									
.	.									
54	IF	Low	AND	Not Available	AND	Low	AND	Low	THEN	VERY LOW



(a) (b) (c) (d) (e) (f)

Figure 5.8 Surface plots of fuzzy variable (a) between *ms* and *mc*, (b) between *mc* and *jt*, (c) between *jt* and *ms*, (d) between *ri* and *ms*, (e) between *ri* and *mc*, (f) between *ri* and *jt*.

Figure 5.8 shows the surface plots between the variables. The surface viewer is a three-dimensional plot that shows the relationship between R_{value} and two recyclability factors. It can be seen that all the surface plots increase from the two lower corners where two recyclability factors are low, having a low R_{value}. The flat regions show that the R_{value} does not change at certain points of the recyclability factors. The absence of negative slope surfaces indicates that there are no errors in the rule base. The next subsection demonstrates the applicability of fuzzy recyclability assessment using a numerical example.

5.2.3 Fuzzy Inference System (FIS)

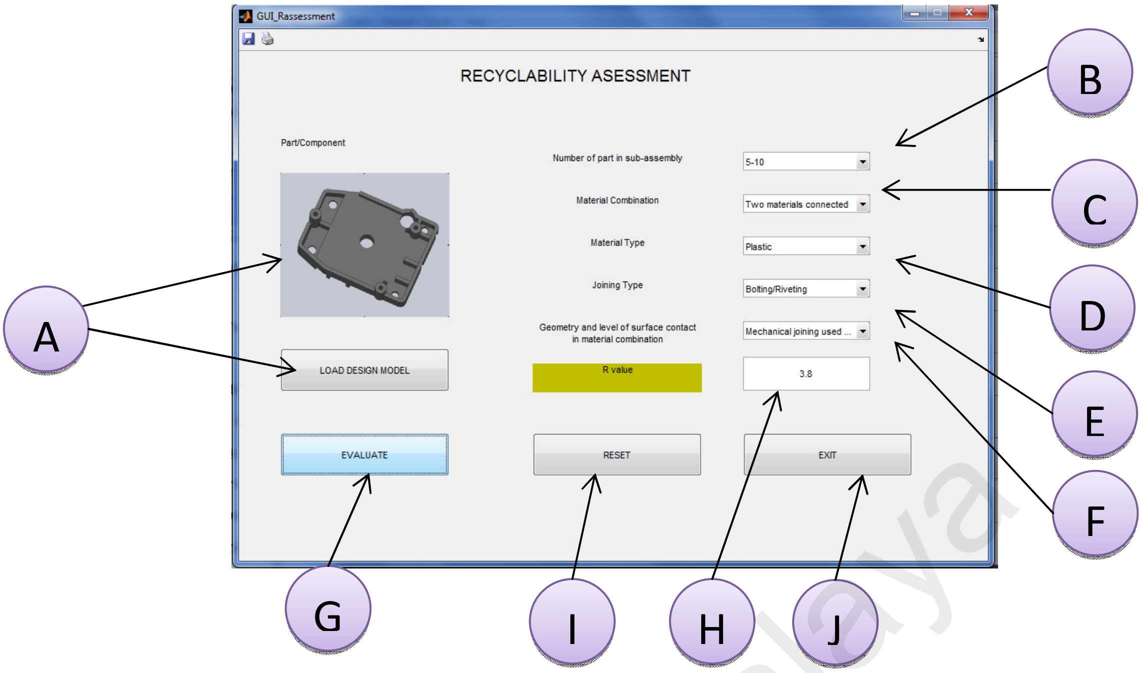
Fuzzy Inference System is a computing framework based on the fuzzy set theory, fuzzy rule and fuzzy reasoning and operates as an inference engine to provide outputs from a fuzzy operation. The Mamdani fuzzy model is used to solve problems that use a set of linguistic rules obtained from human experience. Therefore, this model is chosen for its effectiveness in capturing experts′ knowledge.

5.2.4 Defuzzification

Defuzzication involves converting a fuzzy value into a crisp value as an output. In this research, the Mean of Maximum (MOM) method is selected as the defuzzification method. MOM is calculates the average for all output values that give higher degrees, which results in rapid and sharp outputs.

5.2.5 R-Val MATLAB GUI

The R-Val MATLAB Graphical User Interface is designed specifically to assist designers in computing the recyclability value for a particular design model without entering of a MATLAB environment. The GUI is developed using MATLAB GUIDE that allows the builder to design and develop a GUI as well as loading the FIS function from MATLAB through *readfis* and *evalfis* syntax. The screen of the user interface is built as a standalone application using deployment tool MATLAB and stored as an Excel adds in tool which can be called in different operating platforms for simplicity. The user interface is shown in Figure 5.9.



GUI_Rassessment

RECYCLABILITY ASESSMENT

Part/Component

Number of part in sub-assembly: 5-10

Material Combination: Two materials connected

Material Type: Plastic

Joining Type: Bolting/Riveting

Geometry and level of surface contact in material combination: Mechanical joining used ...

R value: 3.8

Figure 5.9 Screenshot for R-Val MATLAB GUI

The operations of R-Val in Figure 5.9 listed as follows:

A: Load drawing from CAD library

B: Input data for number of parts in sub-assembly

C: Input data for material combination

D: Input data for material type

E: Input data for joining type

F: Input data for geometry and level of surface contact in material combination

G: Evaluate

H: Evaluation result

I: New assessment

J: Exit Recyclability Assessment

The user can load the design model directly from data storage using R-Val user interface. After loading the design model, the user can evaluate recyclability by keying in parameters such as number of parts in sub-assembly, material combination, material type, joining type and level of surface contact in the material combination. The user can retrieve the R_{value} by clicking the EVALUATE button. The evaluation process uses the rule base that has been created in the MATLAB FIS toolbox. The system retrieves the input on the R-Val GUI and computes with the value using FIS. Figure 5.10 shows the flowchart for operating the R-Val. Script of the application m-file for R-Val GUI is given in Appendix H.

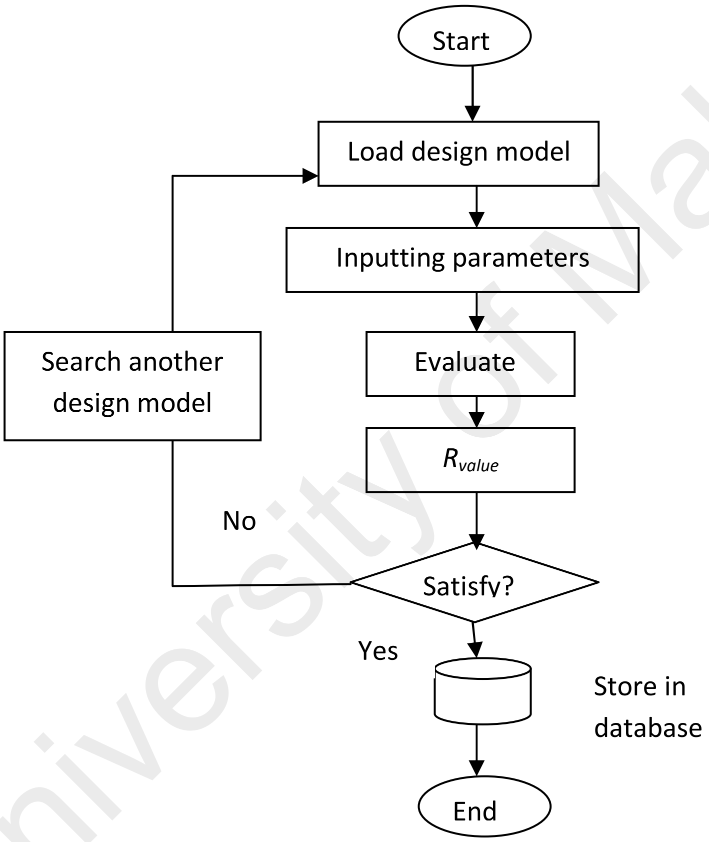


Figure 5.10 Flowchart for recyclability assessment using R-Val.

A numerical example is presented in the following subsection illustrate the applicability of the recyclability assessment method.

5.3 Fuzzy Recyclability Assessment - A Numerical Example

Malaysia is one of the leading automotive producers in ASEAN countries. The total vehicles produced in Malaysia in 2009 are 536,905 units compared to 343,173 units in 2000. This shows that there has been a progressive increment in vehicle production in Malaysia in over the last nine years (MAA, 2010).

The persistent market growth of automobile production leads to environmental issues such as natural resources depletion during mining or extraction, CO_2 emissions and energy consumption during production and generate enormous waste. Automobiles are one of the complex products that were identified by the European Union as a priority waste stream. In each automobile, there are thousands of parts which, 74-75% of them are composed of ferrous and non-ferrous materials and 8-10% come from plastics. However, not all of the vehicle's weight is recycled, which leads to an increasing demand of landfill availability (Kanari, 2003). Unfortunately, there will be no more space available in the near future for this traditional form of disposal. As there have been increasing pressure from various sectors to increase recycling in Malaysia, Malaysian manufacturers should be ready to take proactive actions and responsibility to initiate comprehensive methods that can reduce waste stream at the vehicle's end-of-life. Based on this fact, the numerical example chosen here is taken from the automotive industry.

Figure 5.11 Manual disassembly of a car's side mirror.

In this research, an experiment of a car's side mirror disassembly was conducted. Each disassembled part is drawn in Solidworks 10 to demonstrate the recyclability assessment. Figure 5.12 is an exploded view of the car side mirror assembly drawing. The side mirror is composed of 19 parts. The data consist of weights and the material composition for each part is listed in Table 5.3. This data is retrieved from Solidworks 10, as shown in Figure 5.13.

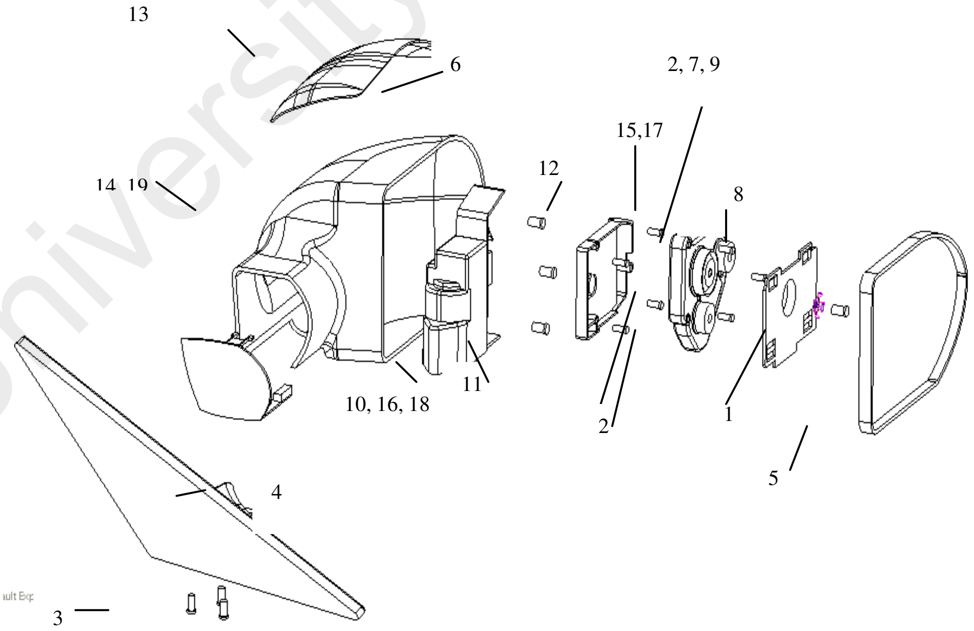
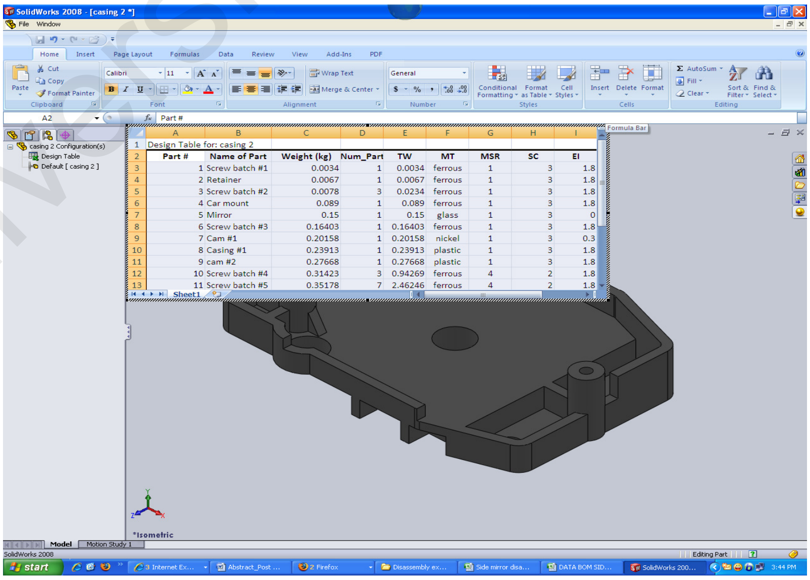


Figure 5.12 Exploded view of a Proton Waja car's side mirror.

Table 5.4. Weight and material composition of car’s side mirror

Part #	Part Name	Weight (kg)	Quantity	Total (kg)	Material Type	Sub-assembly with
1	Screw batch #1	0.0034	1	0.0034	ferrous	#1
2	Retainer	0.0067	1	0.0067	ferrous	
3	Screw batch #2	0.0078	3	0.0234	ferrous	#4
4	Car mount	0.089	1	0.089	ferrous	
5	Mirror	0.15	1	0.15	glass	
6	Screw batch #3	0.016403	1	0.01640	ferrous	#7,8,9
7	Cam #1	0.020158	1	0.02016	nickel	
8	Casing #1	0.023913	1	0.02391	plastic	
9	Cam #2	0.027668	1	0.02767	plastic	
10	Screw batch #4	0.031423	3	0.09427	ferrous	#9
11	Screw batch #5	0.035178	7	0.24997	ferrous	
12	Casing #2	0.7120	1	0.7120	plastic	
13	Plastic Mould	0.04268	1	0.04268	plastic	
14	Screw batch #6	0.04644	2	0.09288	ferrous	#12
15	Plastic	0.00012	1	0.00012	plastic	
16	Subassembly Motor	0.0077	1	0.0077	ferrous	
17	Screw batch #7	0.0056	2	0.0112	ferrous	#18
18	Casing #3	0.045	1	0.045	plastic	
19	Main Case	0.23	1	0.23	plastic	
	Total weight			**1.84646**		



	A	B	C	D	E	F	G	H	I
1	Design Table for: casing 2								
2	Part #	Name of Part	Weight (kg)	Num_Part	TW	MT	MSR	SC	EI
3	1	Screw batch #1	0.0034	1	0.0034	ferrous	1	3	1.8
4	2	Retainer	0.0067	1	0.0067	ferrous	1	3	1.8
5	3	Screw batch #2	0.0078	3	0.0234	ferrous	1	3	1.8
6	4	Car mount	0.089	1	0.089	ferrous	1	3	1.8
7	5	Mirror	0.15	1	0.15	glass	1	3	0
8	6	Screw batch #3	0.16403	1	0.16403	ferrous	1	3	1.8
9	7	Cam #1	0.20158	1	0.20158	nickel	1	3	0.3
10	8	Casing #1	0.23913	1	0.23913	plastic	1	3	1.8
11	9	cam #2	0.27668	1	0.27668	plastic	1	3	1.8
12	10	Screw batch #4	0.31423	3	0.94269	ferrous	4	2	1.8
13	11	Screw batch #5	0.35178	7	2.46246	ferrous	4	2	1.8

Figure 5.13 Data retrieval in CAD system using design table.

Weight and material composition are imported from Microsoft Excel using a design table in Solidworks 10 for simplicity. The design table is an *Application Programming Interface* (API) that can synchronize data with an external environment. One of the advantages of using Solidworks 10 is that the data can be linked to a Microsoft Excel-based environment and vice versa, therefore it possesses higher practicability and interoperability.

This method enables designers to easily adjust and modify the design model as well as execute recyclability assessment without leaving the design work.

Table 5.3 show the weight and material composition for a particular design. Several of the parts are sub-assemblies with other parts. There are four materials used in this particular design, i.e., ferrous, glass, nickel and plastic. The recyclability assessment is performed using Fuzzy MATLAB Toolbox to evaluate the degree of recyclability for each part.

The results and discussion of the recyclability assessment are presented in the subsequent section.

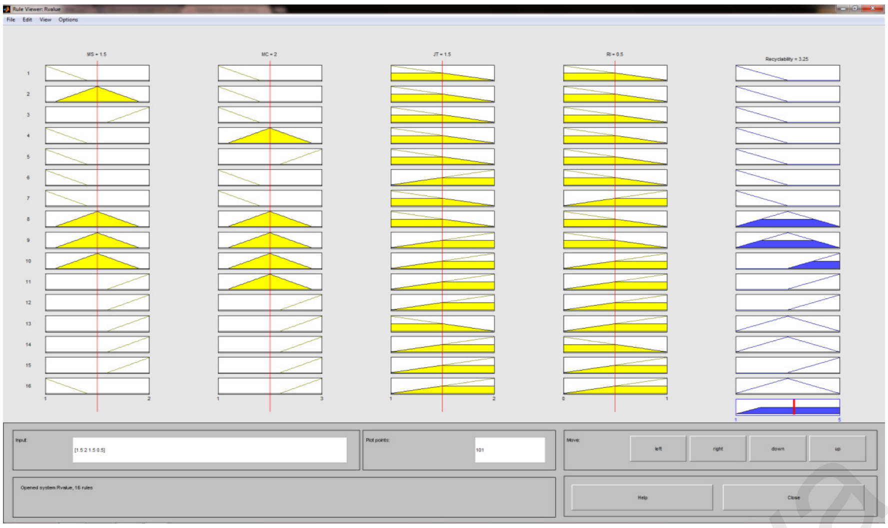
5.4 Results and Discussion

The components in the numerical example are evaluated using the fuzzy tool box in MATLAB version 7.9.0.529 (RB0009b). In this research, Mamdani FIS is constructed by determining the membership function of the inputs and output. The inputs for recyclability assessment are material separation, material combination, joining type and recycling infrastructure. Each input has its own specific membership function and each set of membership function justified based on the available literature and experts' opinion. The output is presented for five membership function, namely, VERY LOW, LOW, MEDIUM, HIGH, and VERY HIGH. Triangular membership functions are used for each fuzzy set in order to maximize the certainty. Fifty four rule base is built to evaluate the inputs captured from the experts' knowledge.

This proposed recyclability assessment method can be used on an assembly or sub-assembly design during the conceptual design stage. The assembly components can be assessed together in a single run and gives a R_{value} for each sub-assembly. Figure 5.14 demonstrates the fuzzy input and output in the FIS MATLAB Toolbox. The values for each part are tabulated in Table 5. 4.

Table 5.4 Recyclability value for each part.

Part #	**Name of Part**	**Recyclability Value**	**Linguistic expression**
1	Screw batch #1	2.50	MEDIUM
2	Retainer	3.26	HIGH
3	Screw batch #2	3.04	HIGH
4	Car mount	3.49	HIGH
5	Mirror	3.50	HIGH
6	Screw batch #3	2.10	MEDIUM
7	Cam #1	3.50	HIGH
8	Casing #1	3.50	HIGH
9	Cam #2	3.50	HIGH
10	Screw batch #4	3.50	HIGH
11	Screw batch #6	1.33	LOW
12	Casing #2	1.41	LOW
13	Plastic Mould	3.51	HIGH
14	Screw batch #6	3.51	HIGH
15	Plastic	3.51	HIGH
16	Subassembly Motor	3.51	HIGH
17	Screw batch #7	3.51	HIGH
18	Casing #3	3.51	HIGH
19	Main case	2.09	MEDIUM



Input: [1.5 2 1.5 0.5]

Plot points: 101

Opened system Rvalue, 16 rules

Figure 5.14 Fuzzy Inputs and Output in MATLAB.

Designers can estimate the recyclability value for each part using the fuzzy recyclability assessment method. Table 5.4, it can be seen that part numbers 11 and 12 achieve the lowest R_{value}. A low R_{value} indicates that the design gives low recyclability, which implies that the product cannot be recycled easily at its end-of-life. Therefore, the product should be redesigned and evaluated until it achieves a high recyclability value. To redesign this part, designers have considered recyclability factors. These factors are extracted from the exploratory study, which excludes profit: recycling infrastructure, material separation, material combination and joining type. These factors are strongly related to the type of material selected in the design. Therefore, to further increase the recyclability of this part, optimization of material selection is needed.

The R_{value} obtained from the recyclability assessment is stored in a database that can be retrieved for computing high recyclability material selection. This method can be easily implemented to assess a part's recyclability during the product design stage.

Apart from the many advantages of using FIS as a recyclability assessment tool, there are drawbacks that need to be considered. Successful application of FIS depends on the proper classification of fuzzy sets. In this study, these drawbacks are overcome by tapping experts' opinions and referring to the published literature to determine parameters in the fuzzy sets prior to development of the recyclability assessment. This is to ensure the robustness of the recyclability assessment tool.

5.5 Summary

The formulation of a Fuzzy Inference System for Recyclability Assessment has been described in this chapter. The steps taken to evaluate recyclability are presented. A numerical example is also shown to evaluate recyclability for a particular product.

A fuzzy model can be used to evaluate recyclability as a function of material separation, material combination, recycling infrastructure and joining type. Using this model, designers can easily evaluate the recyclability of a particular part in a CAD environment. The findings indicate that the model can be used to evaluate recyclability of a design model at the sub-assembly level. The evaluation results can be stored in a database and retrieved for optimizing high recyclability material selection. This will facilitate designers to integrate recyclability aspects with material selection optimization.

The formulation of GA-based multi-objectives optimization for high recyclability material selection will be discussed in the following chapter and case studies will be presented to demonstrate the applicability of the method.

CHAPTER 6

OPTIMIZATION FOR HIGH RECYCLABILITY MATERIAL SELECTION

6.1 Introduction

This chapter presents the development of a multi-objective optimization model for high recyclability material selection (HRMS). The genetic optimization model presented in Chapter 3 is implemented using Solve-XL software in a Microsoft Excel environment. The model is developed using the following steps:

1. Defining the objective functions
2. Defining the parameters and decision variables
3. Implementing procedures by initialization of population, fitness calculation, defining genetic operators and new population generation

The detail of the modelling process is presented in the following sections.

6.2 Mathematical Descriptions

Before attempting to solve a real multi-objective optimization problem, the first step involves formulating the problem using mathematical notations. For most optimization problems, the formulation entails the determination of the objective functions, constraints and other relationship among variables.

The following design conditions are considered in formulating the optimization model:

1. A component i.e. a subassembly for a baseline design is selected.
2. The *n* material candidates are selected. The *n* material candidates are retrieved from the material database.
3. The objective of the problem is set, which is to design a component using a

recyclable materials that simultaneously satisfies functional requirements.

4. The geometric size (i.e., length, height and thickness) of the design can be altered to achieve functional performance.

6.2.1 Defining the Objective Function

The generic optimization model for selecting high recyclability materials is explained in the following sub-sections. The design requirements are first set by the designers to determine the product function. A set of desired material properties is identified after clarifying the product function. The selection procedure begins with determining the objectives, parameters and constraints of the design. A list of material candidates is identified from the material database. Following this, GA computation is executed to establish a set of solutions.

The nature of material selection is complex and formulated as a non-linear problem. The material selection problem comprises of continuous and discrete variables (Schniederjans *et al.*, 2008; Zhang, *et al.*, 2008, Ciu, *et al.*, 2008).Thus, according to Gen and Chen (2001), GA is suitable for this problem due to the following reasons:

- A majority of engineering design solutions uses traditional non-linear discrete design variables. Traditional optimization methods fail overcame this setback and GA is capable of handling this problem efficiently.
- GA provides quick as well as numerous solutions.
- GA is capable of searching within the design space for the global optimum value.

In GA, the solution of the problem relies more on the accuracy of the formulation rather than on the employed method. The design must fulfil the requirements related to its functional performance; for example, the component needs to have good stiffness, low cost, high weld ability, good recyclability, etc. The material selection problem comprises of various objective functions to satisfy several conditions such as technical, economical, and recyclability requirements. Combining these requirements complicates the optimization formulation as the objective functions are expressed as implicit functions, which traditional optimization methods fail to solve. An optimization model using genetic algorithm is created to address this problem.

Based on the design requirements, an optimization model can be formulated by defining the objectives and constraints. The objectives are set based on the literature and results from the exploratory study, which involves maximizing design function, maximizing recyclability value, maximizing recycling profit and minimizing weight. A lightweight design is preferable in DFR.

Design Function (F)

Each engineering component or part performs a specific function, such as carrying loads without failure, transmitting heat, and having good weld capabilities , lightweight and so on. In engineering design, the function of a product is very important because it is related to the performance of the product. The function is determined by the selection of materials. Each material possesses its own specific properties that are tailored for a product’s function. For example, a good design for nitrogen storage should have low thermal conductivity, low density as well as yield strength between 91-1365 MPa, and Young’s modulus between 40-210 GPa.

Recyclability Profit (R_p)

Recyclability profit is the profit gained by recyclers from recycling activities. Profit for recycling can be formulated as:

$$R_p = \sum_{i=1}^{n} (w_i \times p_{rm}) - (R_c) \tag{6.1}$$

$$= \sum_{i=1}^{n} (w_i \times p_{rm}) - (C_{diss} + C_{tran}) \tag{6.2}$$

$$C_{diss} = t_{diss} \times l_{diss}$$

where,

n = number of parts,

i = number of materials,

R_c = recycling cost,

P_{rm} = price of reclaimed material for material *i*,

C_{diss} = cost for disassembly for part *i,*

C_{tran} = cost for transportation,

w_i = weight for material *i,*

t_{diss} = time for disassembly,

l_{diss} = labour cost per hour for disassembly activities.

Recyclability Value (R_{value})

Recyclability value refers to the potential for a part or component to be successfully recycled. Recyclability value is obtained from the fuzzy based recyclability assessment previously discussed in Section 5.2. Designers can easily evaluate their design by giving a score for material separation, joining type, recycling infrastructure and material combination in the fuzzy-based recyclability assessment. The result is a recyclability value indicating the potential for the part or component to be recycled.

It shall be noted that each score in the recyclability assessment will influence the other recyclability parameters. For example, if the score for joining type (*jt*) is LOW (score=1), the recycler should increase the shredding cost (C_{shrd}). If *jt* is HIGH (score=3), then the recycler should checked weather there are valuable materials that can be reclaimed. If there are valuable materials that can be reclaimed then there is added profit for recyclers which will result in a higher value of R_p.

The relationship between the parameters (decision variables) can be written in mathematical form as follows:

$$\text{If}\, jt \begin{cases} 1\,,\ P_{rm} < P_1;\ Rc = R_c + C_{shrd} \\ 2 \text{ or } 3,\ P_{rm} = P_1 \end{cases} \tag{6.3}$$

$$C_{shrd} = t_{shrd} \times l_{shrd} \tag{6.4}$$

where,

t_{shrd} = time for shredding,

l_{shrd} = labour cost per hour for shredding,

P_1 = price of reclaimed material (first grade),

C_{shrd} = cost for shredding.

$$\text{If } ms \begin{cases} 1,\ Rc=R_c+C_{dps} \\ 2,\ Rc=R_c+C_{shrd} \\ 3,\ R_c=R_c+0 \end{cases} \tag{6.5}$$

C_{dps} = cost for disposal/land filling of unwanted substances

$$\text{If } mc \begin{cases} 1,\ R_p=R_p+0 \\ 2,\ \text{if valuable material recognized } R_p=R_p+(R_p)_{add} \\ \quad\ \text{if no additional materials} R_p=R_p \\ 3\ \ \text{if material valuable } R_p<R_{p1} \\ \quad\ \text{If material not valuable } R_c=R_c+C_{dsp} \end{cases} \tag{6.6}$$

$(R_p)_{add}$ = Recycling profit from additional valuable materials

$$If\ ri \begin{cases} 1,\ R_p=0 \\ 2,\ R_p=R_p+0 \end{cases} \tag{6.7}$$

Weight (w)

A lightweight design is preferable for DFR as it uses fewer materials. Therefore, weight minimization is selected as one of the objective functions.

Based on the above consideration, the formulation of the objective function is given as:

$$\text{Maximize } F\,(M_i) \tag{6.8}$$

$$\text{Maximize} R_p(M_i) \tag{6.9}$$

$$\text{Minimize } w(ti,\ li,\ hi,\ f_p(M_i)) \tag{6.10}$$

Maximize $R_{value}(M_i)$ (6.11)

where,

M_i = material type,

R_p = recycling profit,

w = weight of part,

t_i = thickness of part,

l_i = length of part,

h_i = height of part,

$f_\rho(M_i)$ = density properties of material i.

6.2.2 Defining Constraints

Defining constraints is a critical step in most multi-objective problems. The constraints are as follows:

$$g_j(t_i, L_i, h_i, M_i), i=1,\ldots n, j=1,\ldots k \tag{6.12}$$

$$t_i^L \leq t_i \leq t_i^U \tag{6.13}$$

$$L_i^L \leq L_i \leq L_i^U \tag{6.14}$$

$$h_i^L \leq h_i \leq h_i^U \tag{6.15}$$

$$P_i^L \leq P_i \leq P_i^U \tag{6.16}$$

$$M_i \in \{1,2,\ldots,m], i=1,\ldots,n \tag{6.17}$$

In an optimization model, a certain number of constraints should be fulfilled. Geometric size is chosen as a constraint. t_i represents the thickness of the component, t_i^L and t_i^{u} denotes the lower and upper bounds of thickness respectively. L_i and h_i represent the length and height of the component, whereas L_i^L, L_i^U, h_i^L and h_i^u represent the lower and upper bounds of length and height respectively. In Equation (6.17), *m* represents the number of the materials while *n* represents the index of the independent parts. P_i represents the number of sub-assemblies to be produced. P_i^L and P_i^U denote the lower and upper number of sub-assemblies to be produced respectively.

R_{value} is obtained by the combination of *jt, ms, mc* and *ri* score in Equation (5.1). In the optimization model, *jt, ms, mc* and *ri* are treated as constraints. To simplify the equation, material type (M_i) is treated as a design variable, as suggested by Cui *et al.* (2008). Each material has its own properties, such as density (ρ), Young's modulus (*E*), yield strength (σ) and so on. Introducing the material type as a design parameter is more straightforward. Each material type is assigned with a number from 1 to *m*. If the material type is given as M_i, the relationship between material and its properties can be stated as follows:

$$\begin{pmatrix} \rho_i \\ E_i \\ \rho_i \end{pmatrix} = \begin{pmatrix} f_{\rho}(M_i) \\ f_E(M_i) \\ f_{\rho}(M_i) \end{pmatrix} \qquad (6.18)$$

Each material and part assembly will have a specific recyclability profit and recyclability value. In the formulation above, the maximum *F*, maximum R_p, maximum R_{value} and minimum *w* is selected as the objective functions. Based on Ashby (2004), *F* is the material index and describes the functionality of the materials. Table 6.1 shows the material index and its correspondence desired functions. For example, consider the selection of materials to minimize the weight and panel having a particular length (ℓ), width (*b*) and thickness (*t*), as shown at Figure 6.1.

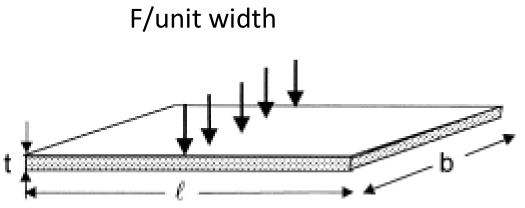


Figure 6.1 Example of a panel (Ashby, 1999).

The objective function for minimizing the mass of a panel is described as

$$m = \ell bt\rho \tag{6.19}$$

where, ρ is the density of material. If the desired function for the panel is higher stiffness, then the formula for the desired stiffness is:

$$S = \frac{Fb}{\delta} = \frac{C_1 EI}{\underset{3}{\ell^3}} \geq S^* \tag{6.20}$$

where S^* is the desired stiffness, E is Young's modulus, C_1 is a constant that is dependent on the distribution of loads and I is the second moment of the area of the section I is given by :

$$I = \frac{bt^3}{12} \tag{6.21}$$

Since the thickness (t) is free, whereas length (ℓ), width (w) and force (F) per unit width are specified, t in Equation (6.19) can be eliminated using Equations (6.20) and (6.21). Hence, the performance metric m is obtained as:

$$m \geq \left(\frac{12S^*b^2}{C_1}\right)^{1/3} \ell^2 \left(\frac{\rho}{E^{1/3}}\right) \tag{6.22}$$

The last term in parentheses represents the performance metric or namely material index. From equation (6.22), it can be seen that a higher index value results in higher value of stiffness. This index can be used to compare the performance of different materials for a certain design function. The desired stiffness in Equation (6.18) is rewritten as:

$$\left(\frac{E^{1/3}}{\rho}\right) = f(M_i) \qquad (6.23)$$

Table 6.1 Material index suggested by Ashby (2004).

Material Index	
Function, objective and constraints	**Index**
Tie, minimum weight, stiffness prescribed	E/ρ
Beam, minimum weight, stiffness prescribed	$\underline{E^{1/2}}$
	ρ
Beam, minimum weight, strength prescribed	$\underline{\sigma_y}^{2/3}$
	ρ
Beam, minimum cost, stiffness prescribed	$\underline{E^{1/2}}$ $C_m\rho$
Beam, minimum cost, strength prescribed	$\underline{\sigma^{2/3}}$
	$C_m\rho$
Column, minimum cost, buckling load prescribed	$E^{1/2}$
	$C_m\rho$
Spring, minimum weight for given energy storage	$\underline{\sigma_y}^2$ E_p
Thermal insulation, minimum cost, heat flux prescribed	$\underline{1}$ $\underline{\lambda C_p}\rho$
Electromagnet, maximum field, temperature rise prescribed	$\underline{C_p}\rho$ ρ_e

ρ= *density,* E = *Young's modulus,* σ_y = *elastic limit,* C_m = *cost/kg,*
λ = *thermal conductivity,* ρ_e = *electrical resistivity,* C_p = *specific heat.*

A higher R_p value is more desirable as this indicates that recycling the material at the end of the product's life is valuable. From Equation (6.1), it can be seen that each part that uses different material types will have a different R_p value. In Equations (6.12)-(6.16), the thickness, length, height of the independent parts, number of parts to produce and material type are taken as design variables.

6.3 GA model for HRMS

The first step involved in designing GA is to develop a suitable representation. The design of a GA for solving a particular problem uses these following steps:

1. A *representation* or so called *encoding* for a potential solution to the particular problem
2. Creating an *initial population*
3. *Sampling mechanism* for rating the solution to suit the fitness
4. *Genetic operators* that alter the composition of solution
5. Determine the *parameters* of the *GA* such as population size, probabilities of applying genetic operators, etc.

The design of a GA for solving high recyclability material selection problem is detailed in the following section.

6.3.1 Encoding

In designing a GA, chromosome representation is crucial because it represents the quality of the new population. Classical representation uses binary numbers for representation; however, this method is less suitable for representing the actual problem. Therefore, real numbers are applied in this study. In this study, *m* numbers of material candidates are represented by chromosomes. The thickness, length and height are within the lower and upper bounds and represented by real numbers. The recyclability factors (*jt, mc, ms*, and *ri*) are represented using integers and included as genes. Table 6.2 represents the chromosome design with gene representation.

Table 6.2 Chromosome design of optimization for high recyclability material selection

Parameter	**Gene representation**				
Material	M_1	M_2	M_3	…	M_m
Thickness	t^L	…	t^u		
Height	h^L	…	h^u		
Length	L^L	…	L^u		
Number of part to be produced	P^L	…	P^u		
Joining Type	*3=high*	*2=medium*	*1=low*		
Material Combination	*1=high*	*2=medium*	*3=low*		
Material Separation	*3=high*	*2=medium*	*1=low*		
Recycling Infrastructure	*2=high*	*1=low*			

Table 6.3 Example of individual sets (design configuration).

	Material	**Thickness (cm)**	**Height (cm)**	**Length (cm)**	**Number of part to produce**	**Joining Type**	**Material Combination**	**Material Separation**	**Recycling Infrastructure**
Design 1	2	0.958597	14.9543	3.941586	228	1	3	3	2
Design 2	3	0.319639	10.62516	2.752793	372	2	3	3	2
Design 3	1	0.999536	14.50225	3.965757	500	3	3	3	2

Table 6.3 shows the possible individuals, which can be said as the new design configurations generated from GA computation. The design configuration can be imported and stored in a design table in CAD environment. Therefore, designer can easily modify the design model from the design table.

To solve the complexity of the problem, a non-dominated Sorting Genetic Algorithm (NSGA-II) is chosen, because of its efficiency in handling discrete problems, in addition to being straightforward and well-tested.

6.3.1 Initialization of Population

The population is initialized using random solutions in order to obtain complete freedom in the GA to search for solutions in the search space. The initial population is created by mutating the first proposed solutions.

6.3.2 Sampling Mechanism

The sampling mechanism used in this research is *tournament selection*. This method selects a number of individuals at each of iteration, then selects the best of individuals and compares them. A solution with lower rank is the winner and it is used to generate another solution.

6.3.3 Genetic Operators

The genetic operator involves *crossover* and *mutation* applied to the *chromosomes* to introduce new individuals into the population. *Crossover* is essential in GA computation because it contains the *reproduction* procedure from the *parents' chromosome*. The aim of crossover is to produce solutions in the search space from successful *chromosomes* that have been created. In this GA computation, the *crossover* rate is set at 0.90 to raise the diversity of the generated population. Figure 6.2 and 6.3 are the *crossover* and *mutation* mechanism for producing new design configurations.

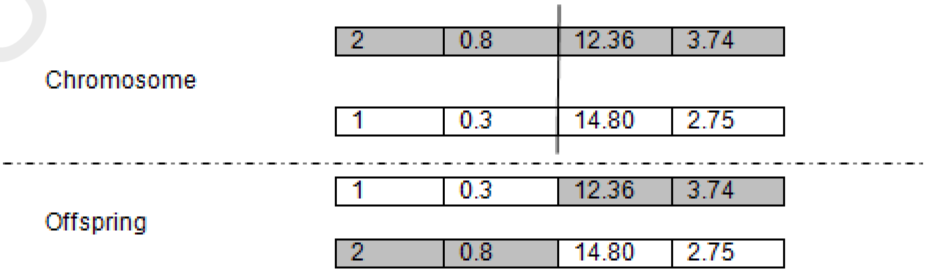


Figure 6.2 Single point *crossover* for producing new design configurations.

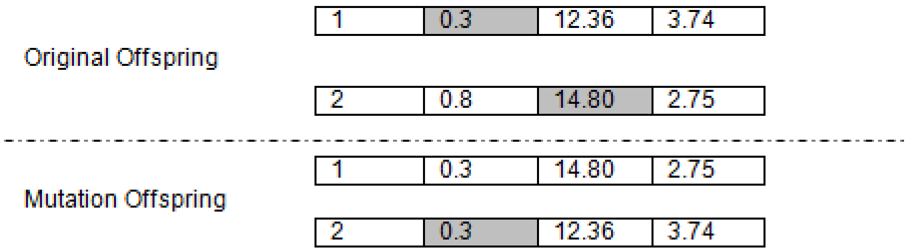


Figure 6.3*Mutation* operator for new design configurations

Mutation introduces random changes to the *chromosomes*. *Mutation* is needed to increase the diversity of the population and to reduce the possibility of a *crossover* result trapped into premature solutions or local optima.

6.3.5 Population Setting

GA works in sets of populations rather than a single population. The bigger the population size, the higher chance it is to search for good solutions. Population sizes are generally between 100 and 1000. Populations that are too small are likely to miss good solutions through premature convergence on sub-optimal solutions; whereas large populations will unnecessary increase computational time. According to Haupt and Haupt (2004), for a large number of search spaces, the population size can be selected in the range of 10% - 30% from the search space. For example, if there are nine genes used to construct the *chromosomes*; the solution space is 9! = 362880 populations. After several trials, 200 generation and population sizes of 100 is suitable to solve the problem with 18% search space.

6.4 Summary

In this chapter, an optimization model for high recyclability material selection is developed. The model was developed through four main assignments:

1. Defining the optimization objectives
2. Defining the constraints and decision variable
3. Integrating recyclability assessment and material selection
4. Implementing procedures for typical HRMS-GA using the following steps:
    - *Encoding* for potential solutions to a particular problem
    - Creating an *initial population*
    - *Sampling mechanism* to rating the solution in order to suit the fitness
    - *Genetic operators* that alter the composition of solution
    - Setting the *GA parameter*, such as population size and probabilities of applying genetic operators.

Case studies will be conducted and reported in the following chapter in order to demonstrate the applicability of the optimization model.

CHAPTER 7

CASE STUDIES

7.1. Introduction

This chapter presents two case studies to demonstrate the applicability of the multi-objective optimization of high recyclability material selection. The first case study is focused on selecting high recyclability materials for a car's side mirror component, whereas the second case study is devoted on selecting materials for a car's door panel.

7.2 Case Study 1: Component of a car's side mirror

The function of the component is to conceal the electronic wiring of the side mirror. The component is selected to represent the applicability of the proposed method for selecting material in a subassembly design.

Designers must first define the specific functional requirements. In this study, the function of the component is to protect the internal wires and therefore, the component must possess good stiffness. Figure 7.1 shows a model of the component.

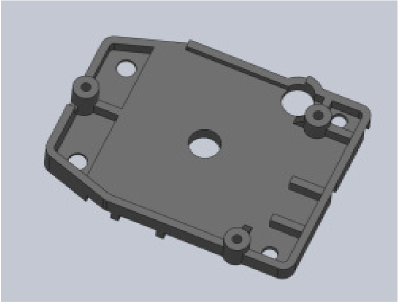


Figure 7.1 Model of the component (Casing #2).

In this case study, the design should have good stiffness, low cost and high recyclability. Lighter weight is desirable in order to achieve high product recyclability. Several suitable material candidates are chosen after the design requirements have been defined. The data for each material property are retrieved from the database. Based on the designers' recommendations, ten candidate materials are suitable for this component: ABS, *Polypropylene* (PP), *Polyethylene Terephthalate* (PET), *Polyvinyl Chlorine* (PVC) and *Polystyrene* (PS), Polytetrafluoroethylene (PTFE), Nylon, PA Type 6, POM *Acetal Copolymer*, *Acrylic (Metacrylate)*. A list of candidate materials and their corresponding properties is given in Table 7.1.

Table 7.1 List of properties for candidate materials.

Materials Type	**Mechanical properties**			**Recycling properties**	
	E (GN/m^2)	ρ (kg/m^3)	C_m $\mathrm{US\$/kg}$	P_{vm} $\mathrm{US\$/kg}$	P_{rm}^{*} $\mathrm{US\$/kg}$
ABS	2.3	1040	0.39	0.39	0.35
PP	1.5	1360	0.34	0.34	0.3
PET	2	905	0.29	0.29	0.15
PVC	3.4	1050	0.74	0.74	0.35
PS	3.4	1400	0.64	0.64	0.28
PTFE	3000	0.00232	0.95	0.95	0.1
Nylon	8300	0.0014	0.6	0.6	0.23
PA Type 6	2620	0.00112	0.91	0.91	0.27
POM Acetal Copolymer	2600	0.00139	3	3	0
Acrylic (Metacrylate)	2400	0.012	0.75	0.75	0

**http://www.ides.com/resinpricing/Secondary.aspx*

The optimization model is formulated using Equations (6.9)-(6.18), where the highest fitness values of the candidate materials are calculated. The multi-objective optimization model is identified as:

$$\text{Maximize } F(M_i)$$

$$\text{Maximize } R_{ev}(M_i)$$
$$\text{minimize} w(ti, Li, hi, f_\rho(M_i))$$

$$\text{subject to } 1.28 \leq t \leq 1.50$$
$$10.5 \leq l \leq 12.7$$
$$3.14 \leq h \leq 4.80$$
$$P_i^L \leq P_i \leq P_i^U$$

$$M \in \{1,2,3,4,5\}$$

In this model, the design variables are material type, thickness, length and height of the component. The constraint boundaries for the design variables are set based on the designers' point of view. Since the design is still in its conceptual stage, the geometry of used in the design model is envelope geometry. Envelope geometry is a bounding box, which is able to contain the part. The X-Y-Z dimensions of this box describes the maximum length, width, and height of the part which is considered here as the thickness, length and height of a particular design model. In this study, the allowable range is 1.00 to 1.60 cm for thickness, 10 to 15 cm for length, and 2.5 to 5 cm for height, specified by the designers. The number of parts to be produced is between 100 to 500 parts.

In this case, M_i represents the material type and each material has its own specific properties. In this example, the material properties index was used for the design scenarios based on Table 6.5 in order to fulfil the functional criteria in terms of stiffness and minimum cost. In this numerical example it is assumed that $C_m = P_{vm}$. The stiffness and minimum cost are represented by the material index as follows:

$$\frac{E^{1/2}}{C_m \rho} \tag{7.1}$$

Where E is the Young's modulus, ρ is the density of the material and C_m is the material cost.

In this case study, a baseline design is drawn in a CAD modelling environment. For easiness, the design geometry is retrieved from CAD and converted to Microsoft Excel. From the design table, new sets of optimized design configurations can be developed using GA. The list of material candidates is taken from the material database to retrieve the material properties for each material. The recyclability data, which consist of the price for virgin and recycled materials, are extracted from the database. All the data from the database are gathered in the model formulation. Following this, a typical model for HRMS is formulated and the GA multi-objective optimization was computed using Solve-XL, a Microsoft Excel based computational software.

Solidworks 10 is chosen as it is more practical and can be linked with Microsoft Excel. One of the key issues of HRMS implementation is accessibility of CAD information which SolidWorks10 can perform very well. Similarly, the results of the HRMS optimization can also be exported to a CAD environment to create a new design configuration for the part model. Designers are familiar with Microsoft Excel environment and therefore it is convenient to use an Excel-based design table in SolidWorks10 which will allow quick access to optimization. The steps undertaken for optimization are listed as follows:

Step 1. *Optimization setup*

Optimization is performed in SolveXL.

Step 2. *Initial input data*

Inputs for optimization are shown in Figures 7.4 – 7.6, which show the objective functions, decision variables, constraints and other parameters. Objective functions are represented in Cells A91-A94. The material properties are extracted from the database, as shown in Figure 7.3.

Step 3. *Defining constraints*

Constraints are characterized in Cells E24-E32 (lower bound) and Cells F24-F32 (upper bound).

Step 4. *GA parameter setting*

Table 7.4 summarizes the population size, number of generations, crossover rate, mutation rate and mutation probability opted to solve the problem. The values are chosen after several trials to provide results with good repeatability.

Step 5. *Computation*

From the computations, the optimized material and geometric size of the component are obtained.

Step 6. *Obtaining Pareto sets of design alternatives*

From the case study, there are 10 material candidates inputted for optimization. In GA optimization, there will be a huge number of possible combinations to deliver an optimized solution and this are called sets of solutions within the search space. In this case study, these possible combinations are called design alternatives. Each solution will produce a unique design configuration.

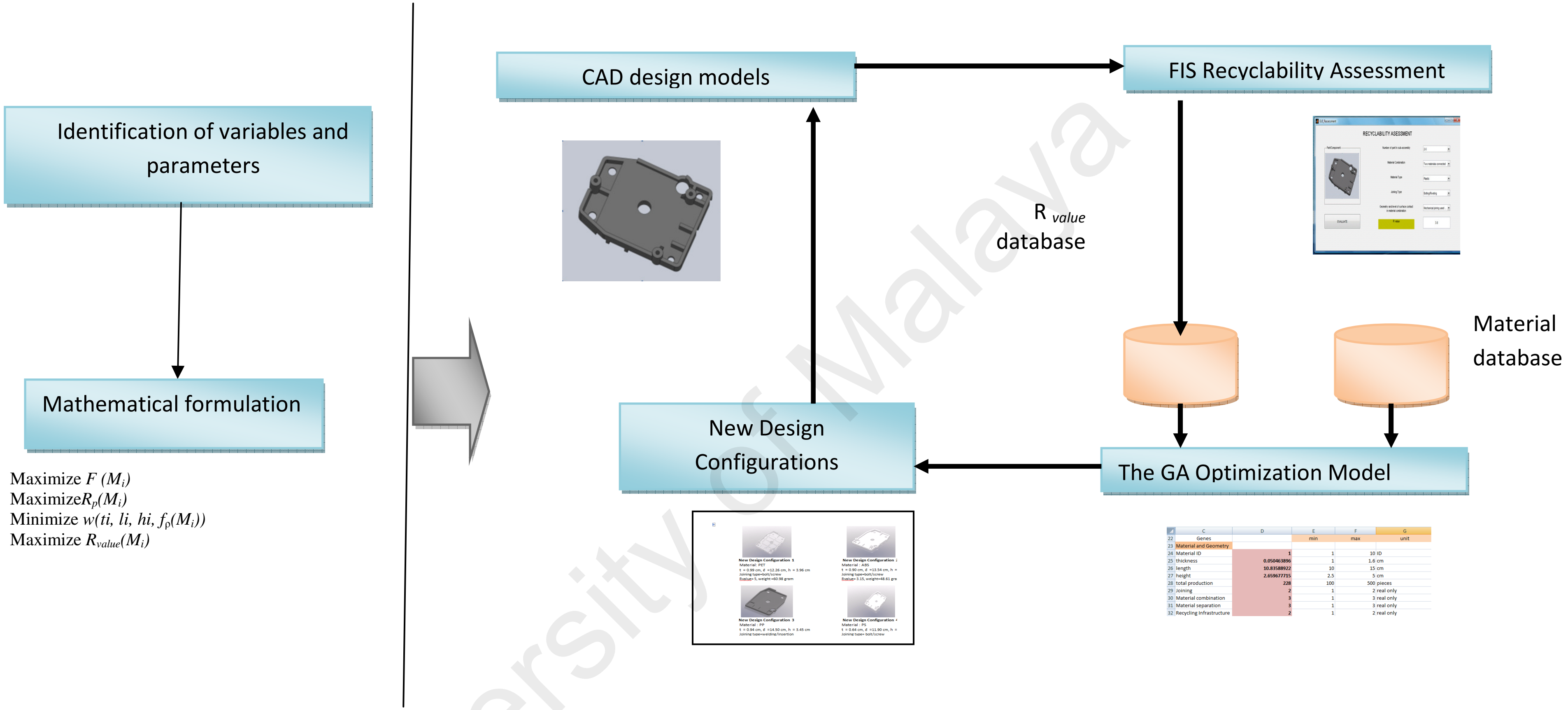
__Step 7.__ *Determine the best solution using the weighted sum method*

To select the sets of design alternatives, a weighted sum method is employed to solve the trade off between the objective functions. The weight of recycling profit and R_{value} is taken from the relative weight measurement in Table 4.10.

__Step 8__. *Developing new configurations for a design in the design table*

After the best solution is determined, the design alternatives can be inserted in the design table to create a new design configuration. Designers can then select from these design configurations.

Figure 7.2 shows the integrated architecture for HRMS optimization.



Maximize $F\,(M_i)$
Maximize$R_p(M_i)$
Minimize $w(ti,\ li,\ hi,\ f_p(M_i))$
Maximize $R_{value}(M_i)$

Number of part in sub-assembly: 2-5
Material Combination: Two materials connected
Material Type: Plastic
Joining Type: Bolting/Riveting
Geometry and level of surface contact in material combination: Mechanical joining used ...
R value: 3.8

New Design Configuration 1
Material: PET
t = 0.99 cm, ℓ =12.26 cm, h = 3.96 cm
Joining type=bolt/screw
Rvalue= 5, weight =60.98 gram

New Design Configuration 2
Material : ABS
t = 0.90 cm, ℓ =13.54 cm, h =
Joining type=bolt/screw
Rvalue= 3.15, weight=48.61 gra

New Design Configuration 3
Material : PP
t = 0.94 cm, ℓ =14.50 cm, h = 3.45 cm
Joining type=welding/insertion

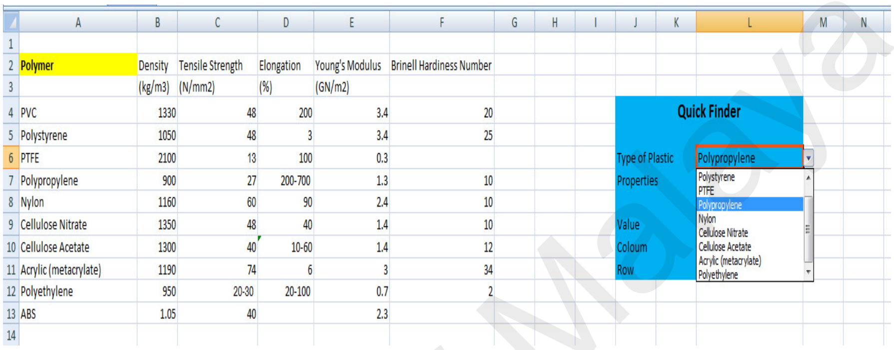
New Design Configuration 4
Material : PS
t = 0.64 cm, ℓ =11.90 cm, h =
Joining type= bolt/screw

	C	D	E	F	G
22	Genes		min	max	unit
23	Material and Geometry				
24	Material ID	**1**	1	10	ID
25	thickness	**0.050463896**	1	1.6	cm
26	length	**10.83588922**	10	15	cm
27	height	**2.659677715**	2.5	5	cm
28	total production	**228**	100	500	pieces
29	Joining	**2**	1	2	real only
30	Material combination	**3**	1	3	real only
31	Material separation	**3**	1	3	real only
32	Recycling Infrastructure	**2**	1	2	real only

Figure 7.2 Architecture of HRMS optimization.

Table 7.2 NSGA-II parameters used to solve the problem.

Population size	100
Number of generations	200
Crossover rate	0.95
Probability	0.05
Mutation probability	0.25



Polymer	Density (kg/m3)	Tensile Strength (N/mm2)	Elongation (%)	Young's Modulus (GN/m2)	Brinell Hardiness Number
PVC	1330	48	200	3.4	20
Polystyrene	1050	48	3	3.4	25
PTFE	2100	13	100	0.3	
Polypropylene	900	27	200-700	1.3	10
Nylon	1160	60	90	2.4	10
Cellulose Nitrate	1350	48	40	1.4	10
Cellulose Acetate	1300	40	10-60	1.4	12
Acrylic (metacrylate)	1190	74	6	3	34
Polyethylene	950	20-30	20-100	0.7	2
ABS	1.05	40		2.3	

Quick Finder

Type of Plastic: Polypropylene

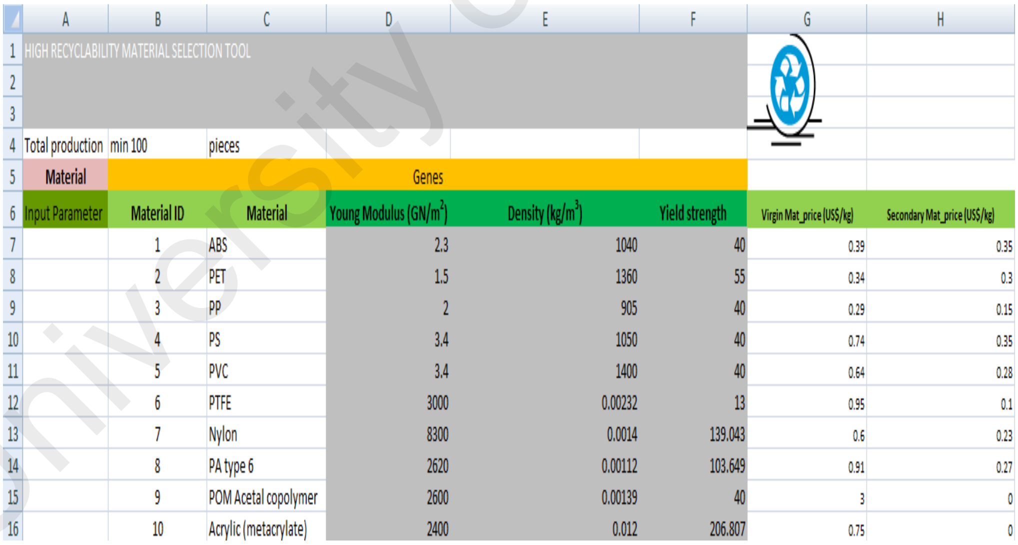
Properties

Value

Coloum

Row

Figure 7.3 Snapshot of the developed material database in Microsoft Excel.

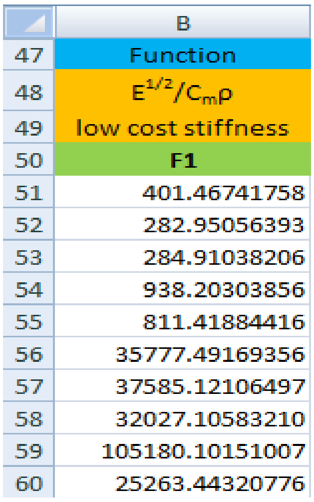


HIGH RECYCLABILITY MATERIAL SELECTION TOOL

Total production min 100 pieces

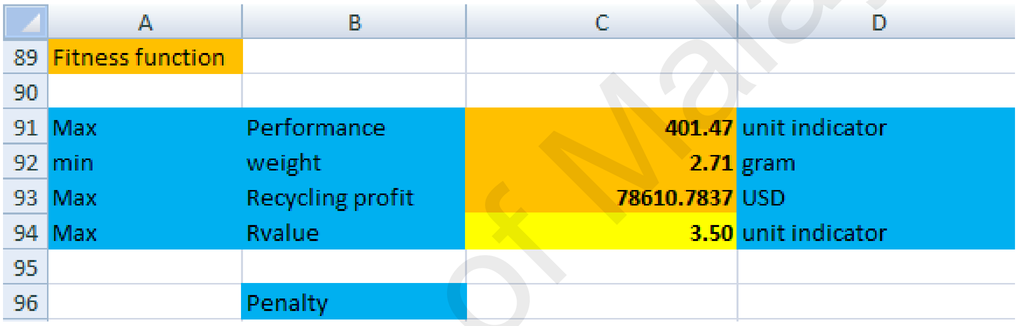
Material	Genes						
Input Parameter	Material ID	Material	Young Modulus (GN/m^2)	Density (kg/m^3)	Yield strength	Virgin Mat_price (US$/kg)	Secondary Mat_price (US$/kg)
	1	ABS	2.3	1040	40	0.39	0.35
	2	PET	1.5	1360	55	0.34	0.3
	3	PP	2	905	40	0.29	0.15
	4	PS	3.4	1050	40	0.74	0.35
	5	PVC	3.4	1400	40	0.64	0.28
	6	PTFE	3000	0.00232	13	0.95	0.1
	7	Nylon	8300	0.0014	139.043	0.6	0.23
	8	PA type 6	2620	0.00112	103.649	0.91	0.27
	9	POM Acetal copolymer	2600	0.00139	40	3	0
	10	Acrylic (metacrylate)	2400	0.012	206.807	0.75	0

(a)



	B
47	Function
48	$E^{1/2}/C_m\rho$
49	low cost stiffness
50	**F1**
51	401.46741758
52	282.95056393
53	284.91038206
54	938.20303856
55	811.41884416
56	35777.49169356
57	37585.12106497
58	32027.10583210
59	105180.10151007
60	25263.44320776

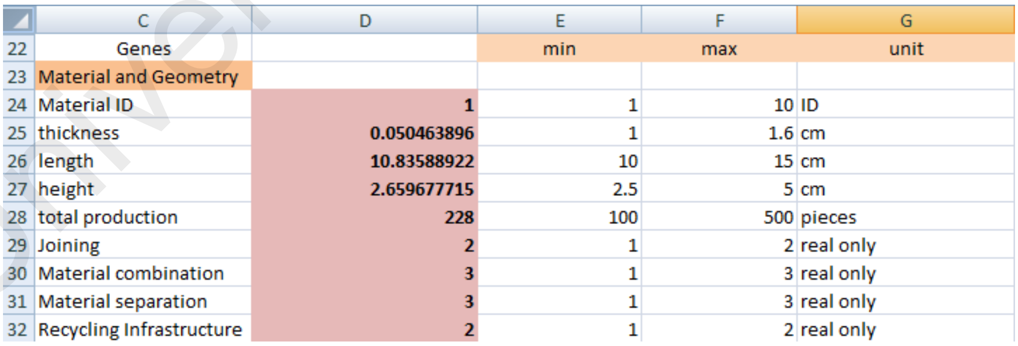
(b)



	A	B	C	D
89	Fitness function			
90				
91	Max	Performance	**401.47**	unit indicator
92	min	weight	**2.71**	gram
93	Max	Recycling profit	**78610.7837**	USD
94	Max	Rvalue	**3.50**	unit indicator
95				
96		Penalty		

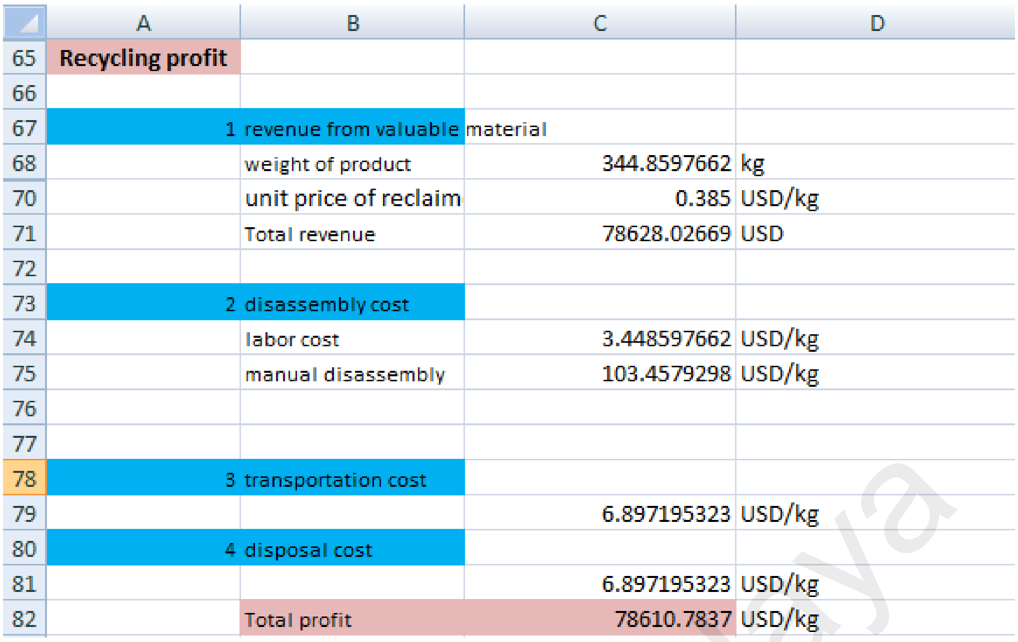
(c)

Figure 7.4 Data inputs required for the GA optimization model: (a) material properties, (b) function and (c) objective function.



	C	D	E	F	G
22	Genes		min	max	unit
23	Material and Geometry				
24	Material ID	**1**	1	10	ID
25	thickness	**0.050463896**	1	1.6	cm
26	length	**10.83588922**	10	15	cm
27	height	**2.659677715**	2.5	5	cm
28	total production	**228**	100	500	pieces
29	Joining	**2**	1	2	real only
30	Material combination	**3**	1	3	real only
31	Material separation	**3**	1	3	real only
32	Recycling Infrastructure	**2**	1	2	real only

Figure 7.5 Example of design alternatives from optimization.



	A	B	C	D
65	Recycling profit			
66				
67	1	revenue from valuable material		
68		weight of product	344.8597662	kg
70		unit price of reclaim	0.385	USD/kg
71		Total revenue	78628.02669	USD
72				
73	2	disassembly cost		
74		labor cost	3.448597662	USD/kg
75		manual disassembly	103.4579298	USD/kg
76				
77				
78	3	transportation cost		
79			6.897195323	USD/kg
80	4	disposal cost		
81			6.897195323	USD/kg
82		Total profit	78610.7837	USD/kg

Figure 7.6 Snapshot of recycling profit spreadsheet.

A generic Microsoft Excel formula is used to calculate each variable and parameter. For example, to determine the weight of a single material, this formula is used:

=IF(D30>1,(A61)*D28,IF(D30=1,A61*0.5))

This formulation is used to match the material type with its properties:

=INDEX(D7:D16,MATCH(D24,B7:B16,0))

The multi-objective GA optimization developed in this case study functions to search within the possible solutions. Penalty is given for the objective function. Here, the weight should not be less than 20 g.

7.3 Results and Discussion: Case Study 1

A formulation of high recyclability material selection has been developed and implemented in a real case study during the conceptual design phase. The desired objective is to maximize function, maximize recycling value, maximize recycling profit and minimize weight. The formulation considers technical, economical, recyclability and weight reduction aspects. In this case, weight reduction is considered as a critical concern in order to improve the sustainability of natural resources by using fewer materials.

In the first case study, GA computation is performed with a population size of 100 and 200 generations. Table 7.3 shows the results after the final population is achieved and Table 7.4 shows a number of the achieved objective values. It can be seen that sets of alternatives are generated, and thus designers can manipulate a large number of potential design configurations. ID represents the *chromosome* number; whereby G0 is the material ID, G1 is the thickness, G2 is the length, G3 is the height, G4 is the number of parts to be produced, G5 is the joining type score, G6 is the material separation score and G7 is the material combination score. In every 100 populations generated, the final population will provide 100 sets of solutions.

Although the sets of solution can be generated from the optimization model, selecting the best solution can be rather daunting for designers since GA optimization result do not yield a single solution. A weighted sum approach is introduced to solve this problem. In this approach, a weight is assigned to each objective function value. For the recyclability parameters, the weights are taken from the relative weight measurements calculated in Chapter 4. Designers can separate the weight into two categories, i.e. technical considerations (part weight, function) and recyclability considerations (recycling profit, R_{value}). In order to determine the best solution, each objective function value is multiplied using this equation:

$$\text{Weighted sum of differences} = |(\text{result}-\text{min})/(\text{result}+\text{min})/2] \times \text{weight}| \qquad (7.2)$$

Since there are four objective functions, the weights of all objectives are equal to 0.25. The recycling profit weight is multiplied by 0.329, and the R_{value} weight is multiplied by

0.671. The total weight of all objective functions must be equal to one. Summing all weights, the highest weight is considered as the best solution. Designers can also select the highest weight based on specific materials as shown in Table 7.3. Table 7.5 shows the results of the weighted sum of differences calculations.

Table 7.3 Excerpt of the optimization results: sets of design alternatives.

ID	**G0**	**G1**	**G2**	**G3**	**G4**	**G5**	**G6**	**G7**
2492	2	0.907801	14.23133	3.835287	462	1	3	1
2207	3	0.907801	14.23133	3.835287	500	2	3	2
2072	3	0.907801	14.23133	3.823567	494	1	3	1
1981	2	0.993389	11.98398	3.898004	459	2	3	2
2572	2	0.993389	11.98398	3.886285	459	2	3	2
2506	3	0.830446	11.80591	3.96649	500	2	2	1
2409	3	0.834157	11.4934	3.96649	500	2	2	3
961	2	0.84761	12.71389	3.50293	500	1	2	2
1852	2	0.84761	12.55764	3.50293	500	1	2	3
2416	2	0.84761	12.55764	3.50293	500	2	2	3
2457	2	0.847146	12.55764	3.502197	500	1	2	3
1254	3	0.837231	12.24666	3.626717	500	2	3	3
2374	2	0.793624	12.00381	3.344442	500	1	2	1
2001	2	0.793624	11.99405	3.250687	500	1	2	1
2455	3	0.551181	14.08591	3.879235	500	2	3	3
1325	2	0.793624	10.74403	3.25032	500	2	2	1
1243	3	0.621635	11.50164	3.661784	499	1	3	2
2448	1	0.837753	11.9881	3.497803	500	2	2	2
2177	3	0.685711	10.32647	3.437649	497	2	2	3
2055	1	0.845523	10.17563	3.598242	500	1	2	3
1616	1	0.541787	14.76875	3.824391	500	2	2	2

Table 7.4 Example of optimized objective function values.

Material Performance	Weight (grams)	Recycling Profit (USD)	R value
8.305220155	67.38646	14381678.73	3.15
8.362745119	46.04173	11202584.62	4.25
8.388377441	44.70471	10908452.19	3.15
8.867925966	64.31052	13286048.7	4.25
8.894668051	64.12078	13246103.8	4.25
10.65529554	36.39376	8797559.747	3.15
10.89631796	35.61529	8602962.04	4.25
10.90130928	51.33873	12825699.2	3.15
11.03695224	50.70779	12675678.9	3.84
11.03695224	51.90779	12675678.9	4.15
11.04530564	50.66944	12666092.48	3.84
11.14310241	34.8531	8412433.666	2.80
12.91596442	43.33083	10831622.42	3.08
13.29930407	42.08186	10519411.28	3.08
13.75806639	28.45673	6813501.777	2.80
14.84829055	38.89184	9422017.122	3.15
15.82685212	23.69391	5895668.035	3.84
16.62123579	37.73379	9127053	3.84
17.02269721	23.22941	5440914.568	4.25
18.86025598	32.19663	8048352.345	3.84
19.08050497	33.02498	7950675.319	3.84

Table 7.5 Example of the sum of weighted objectives for solving trade-offs between objectives.

Sum of weighted objective					
Material Performance	**Weight**	**Recycling Profit**	**R_{value}**	**SUM**	**ID**
0	0.125	0.040525006	0.023039	0.188564	2492
0.000431404	0.08679537	0.040525007	0.03249	0.160242	2207
0.000622673	0.08583177	0.040525007	0.023039	0.150018	2072
0.004095826	0.09640696	0.040525006	0.03249	0.173518	1981
0.004283806	0.09633205	0.040525006	0.03249	0.173631	2572
0.015493219	0.07854917	0.040525009	0.023039	0.157606	2506
0.016867775	0.07772584	0.040525009	0.03249	0.167609	2409
0.016895876	0.09018834	0.040525006	0.023039	0.170648	961
0.01765399	0.08981615	0.040525006	0.028158	0.176153	1852
0.01765399	0.09051733	0.040525006	0.03249	0.181187	2416
0.01770033	0.08979327	0.040525006	0.028158	0.176177	2457
0.018239891	0.07689097	0.04052501	0.036204	0.171859	1254
0.027158853	0.08478962	0.040525007	0.016895	0.169368	2374
0.028894896	0.08379291	0.040525008	0.016895	0.170108	2001
0.030893212	0.06852027	0.040525012	0.036204	0.176142	2455
0.035324397	0.08100775	0.040525009	0.023039	0.179896	1325
0.038960765	0.06011369	0.040525014	0.028158	0.167758	1243
0.041702758	0.07990118	0.040525009	0.028158	0.190287	2448
0.043023065	0.05915793	0.040525015	0.03249	0.175196	2177
0.048568244	0.07373555	0.04052501	0.028158	0.190987	2055
0.049182945	0.074763	0.04052501	0.028158	0.192629	1616

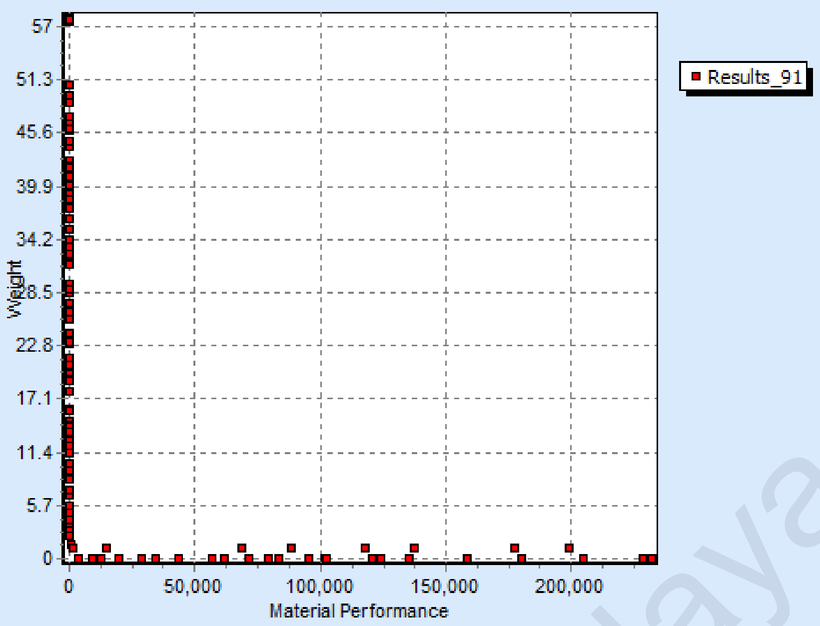


Figure 7.7 Pareto front for material performance (function) and weight.

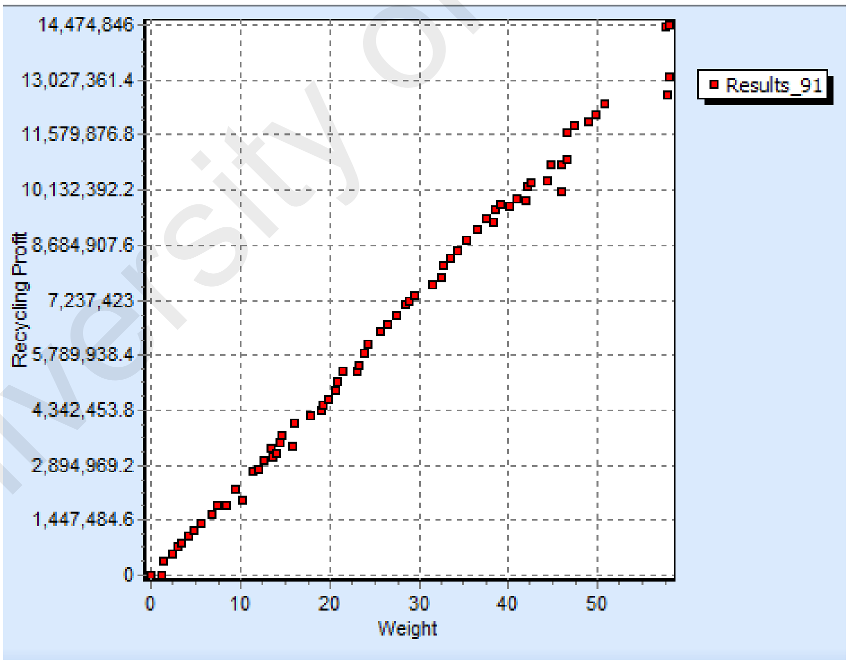


Figure 7.8 Pareto front for weight and recycling profit.

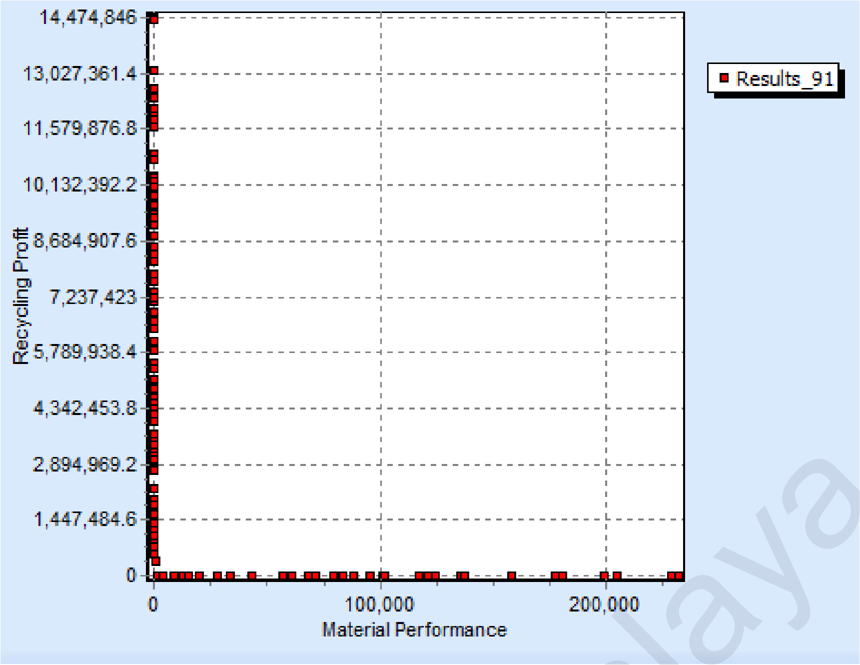


Figure 7.9 Pareto front for material performance (function) and recycling profit.

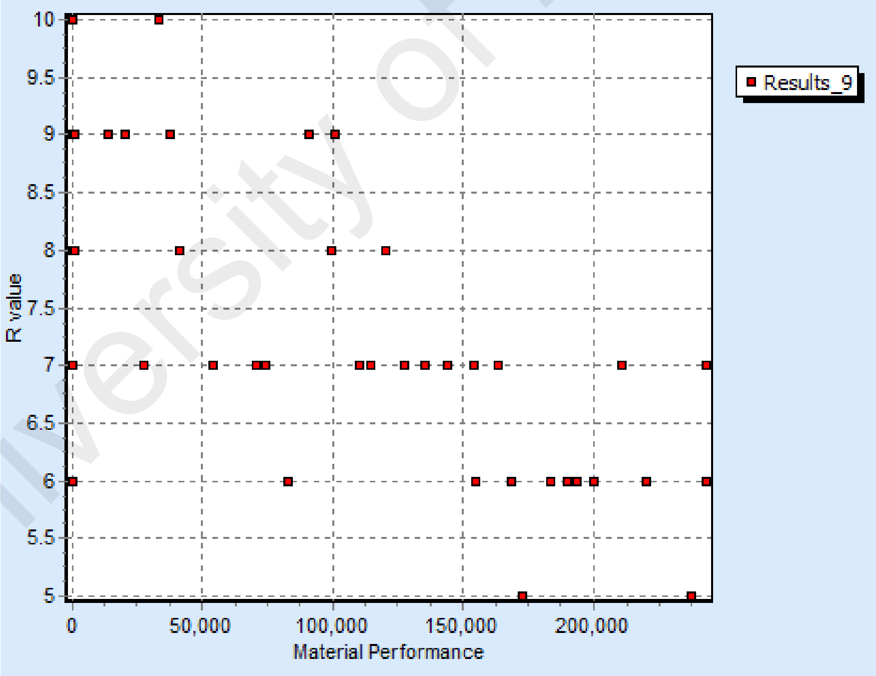
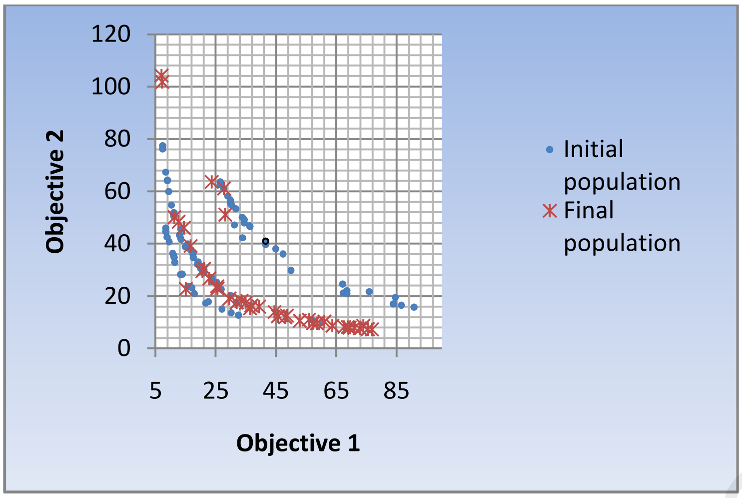
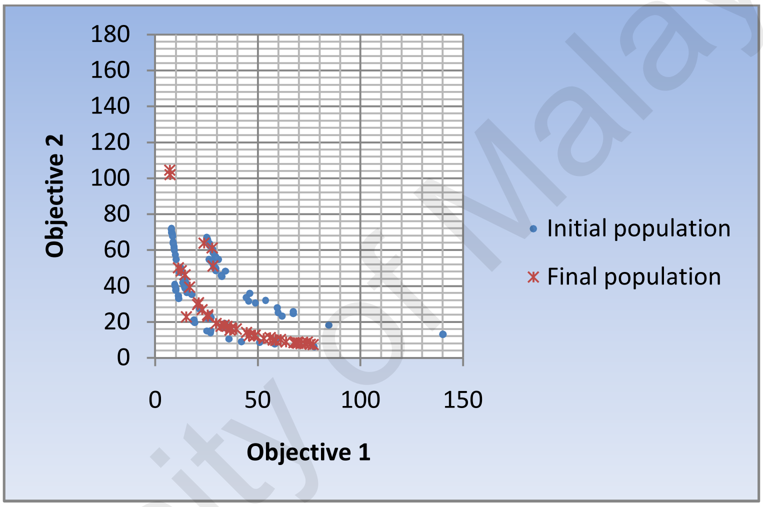


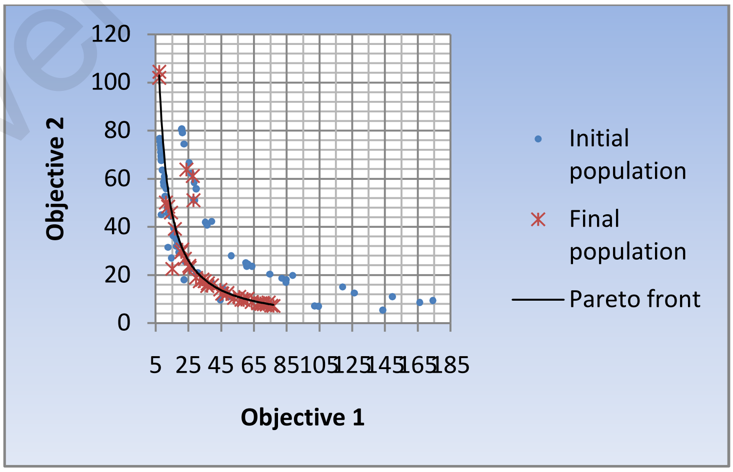
Figure 7.10 Pareto front for objective function and R_{value}.



(a)



(b)



(c)

Figure.7. 11 Population sets of solution and Pareto convergence at (a) 25 generations, (b) 100 generations and (c) 200 generations.

Figure 7.11 shows that the Pareto convergence is reached after 200 generations. Initial population is the first population of a particular generation, whereas final population is the population achieved after 200 generations. For different generations, it can be seen that individuals move towards the global front. Figure 7.11 also denotes the points of lowest weight (Objective 2) and highest material function (Objective 1), which can be achieved in a single simulation run. The highlighted points are the Pareto optimal solutions and the corresponding results are shown in Table 7.6. The results show that the present model is capable of converging towards Pareto optimal solutions.

From Table 7.6, each material has a number of total design solutions. Therefore, there are 18 new design configurations using ABS material, 5 new design configurations using PP, 19 new design configurations using PET, 9 new design configurations using PS and 12 new design configurations using PVC.

Table 7.6 Total solutions achieved after optimization.

Material	Total design solutions
ABS	18
PET	19
PP	5
PS	9
PVC	12
PTFE	1
Nylon	1
PA type 6	6
POM Acetal Copolymer	26
Acrylic (metacrylate)	1

Table 7.7 shows the functional performance, weight, recycling profit, and $R_{value}$for each material. It can be seen that ABS delivers good performance compared to other materials. In terms of recyclability, PET and PP are the best amongst all materials. The blue colour indicates a non-feasible solution for weights below 20 g. From the results, three materials are found to satisfy the targeted objectives, namely, ABS, PET, PP, PS and PVC. Table 7.8 also demonstrates the optimum geometric size of the part.

Designers could choose the recommended optimum solution by emphasizing the factor that needs to be prioritized. For example, if a function needs to be prioritized, then the selection will be based on the higher fitness value for material performance or function (*F*), and hence, the recyclability is compromised.

Figure 7.12 plots the objective functions after optimization of the material candidates. It can be seen that the materials having the highest recycling profit is PVC and PET, while the lowest are PS and ABS. In terms of function, ABS has the highest performance whereas PET gives the lowest performance. Lowest weight is achieved by PP, followed by ABS, PET, PS and PVC.

ABS and PP are found to be the most suitable materials among the best solutions for this particular part. This findings agrees well with Ashby (2004) whereby ABS and PP are suitable for automotive parts, especially for encasing wire due to their favourable properties such as high melting point, high toughness and high flexibility, good resistance to fatigue and good price.

Table 7.7 Optimal design solutions for each material.

		Decision variable								Objective Function		
Material	Generation	*t (cm)*	*ℓ(cm)*	*h(cm)*	P	JT	MT	MS	Function	Weight (g)	Recycling Profit (USD)	R_{value}
ABS	20084	0.054059	12.51087	3.953305	364	2	2	3	218.3776	30.980673304	368377.4818	4.25
PET	20086	0.408765	11.89807	3.685222	500	3	3	3	12.3599	31.54004585	7584252.961	5
PP	19438	0.82198	10.39216	3.924648	500	3	3	3	22.95994	25.57547169	6093258.536	5
PS	19964	0.072151	12.01282	2.65098	340	1	2	3	193.851	40.412587065	278854.0508	3.80
PVC	19826	0.930648	10.8658	2.987823	500	2	3	3	39.0587	42.29896295	10573683.26	4.25
PTFE	19502	0.050116	10.01213	2.5	500	1	1	3	82960.53	1.45513E-06	0.000363745	3.08
Nylon	19206	0.05	10.00519	2.658121	302	1	2	3	41107.42	1.86165E-06	0.169761833	3.80
PA type 6	19742	0.053827	10.32937	2.536623	308	2	3	3	33026.39	1.20000158	0.149823481	5
POM Acetal Copolymer	13388	0.064381	10.62776	2.584325	474	1	1	2	173018.7	1.22894E-06	0.000291043	2.80
Acrylic (Metacrylate)	20019	0.055683	10.37819	3.123421	244	2	3	3	20356.08	1.20002166	1.289272232	4.25

🟦 Non-feasible solution (penalty)

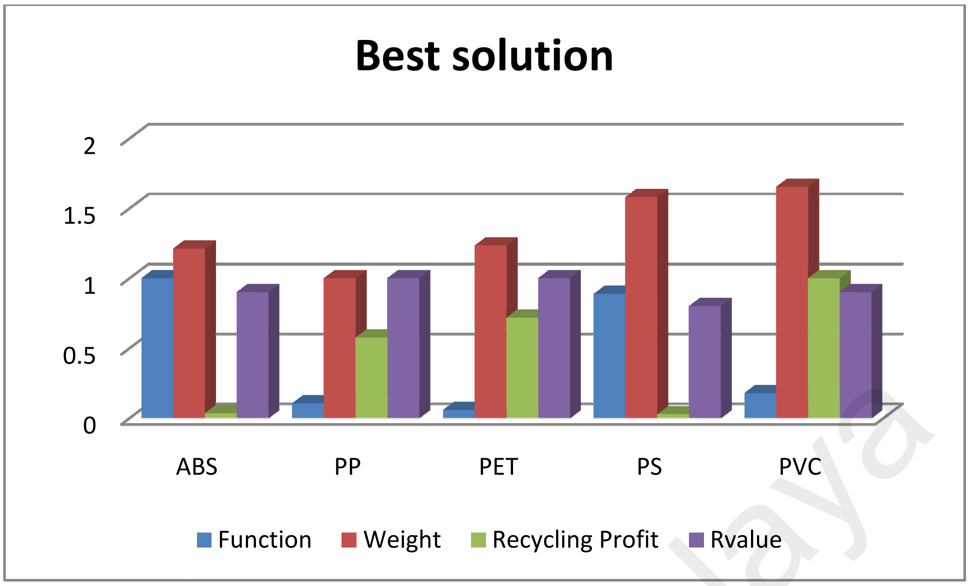
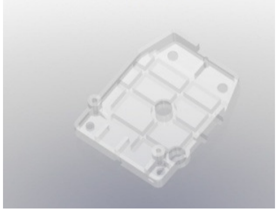
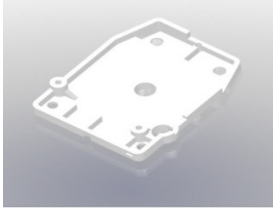


Figure 7.12 Best solutions of high recyclability material selection after normalization.

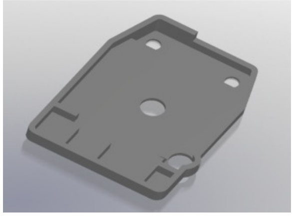
Based on the optimal design solutions, designers can exploit the results and develop new design configurations in CAD using the design table. Figure 7.13 exhibits the possible new design configuration attained from optimization. Designers can build new design configurations from the optimization results. Since the optimization is executed in Excel format, the optimization results can be retrieved and placed in the design table to create new design configurations. To call material types in the design table, the syntax *"SW-Material@@Config1@casing2.SLDPRT"* is used. Designers can also include new optimized geometric values for each new design configuration by using the annotation feature in SolidWorks and retrieve the dimensions from the design table. The dimension in the design table is visualized as D(number)Sketch(number), for example *D2@Sketch5* as shown in Figure 7.14.



New Design Configuration 1
Material: PET
t = 0.99 cm, ℓ =12.26cm, h = 3.96 cm
Joining type=bolt/screw
Rvalue= 5, weight =60.98 gram

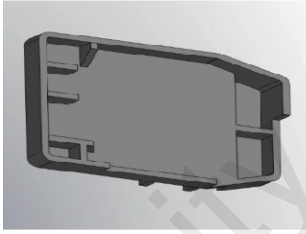


New Design Configuration 2
Material : ABS
t = 0.90 cm, ℓ =13.54 cm, h = 3.82 cm
Joining type=bolt/screw
Rvalue= 3.15, weight=48.61 gram

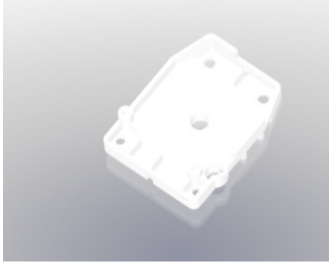


New Design Configuration 3
Material : PP
t = 0.94 cm, ℓ =14.50 cm, h = 3.45 cm
Joining type=welding/insertion
Rvalue= 2.05, weight =39.37 gram

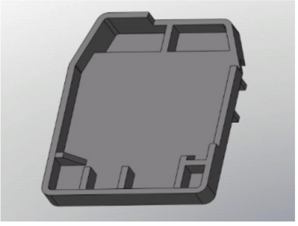
New Design Configuration 4
Material : PS
t = 0.64 cm, ℓ =11.90 cm, h = 2.84 cm
Joining type=bolt/screw
Rvalue= 5, weight =22.75 gram



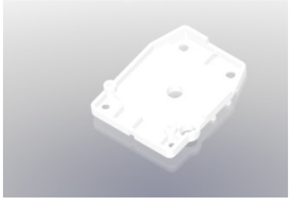
New Design Configuration 5
Material: ABS
t = 0.29 cm, ℓ =13.56 cm, h = 3.03 cm
Joining type= adhesive bonding
Rvalue= 3.8, weight =12.56 gram



New Design Configuration 6
Material: ABS
t = 0.11 cm, ℓ =13.16 cm, h = 3.96 cm
Joining type= bolt/screw
Rvalue= 4.15, weight =7.16 gram

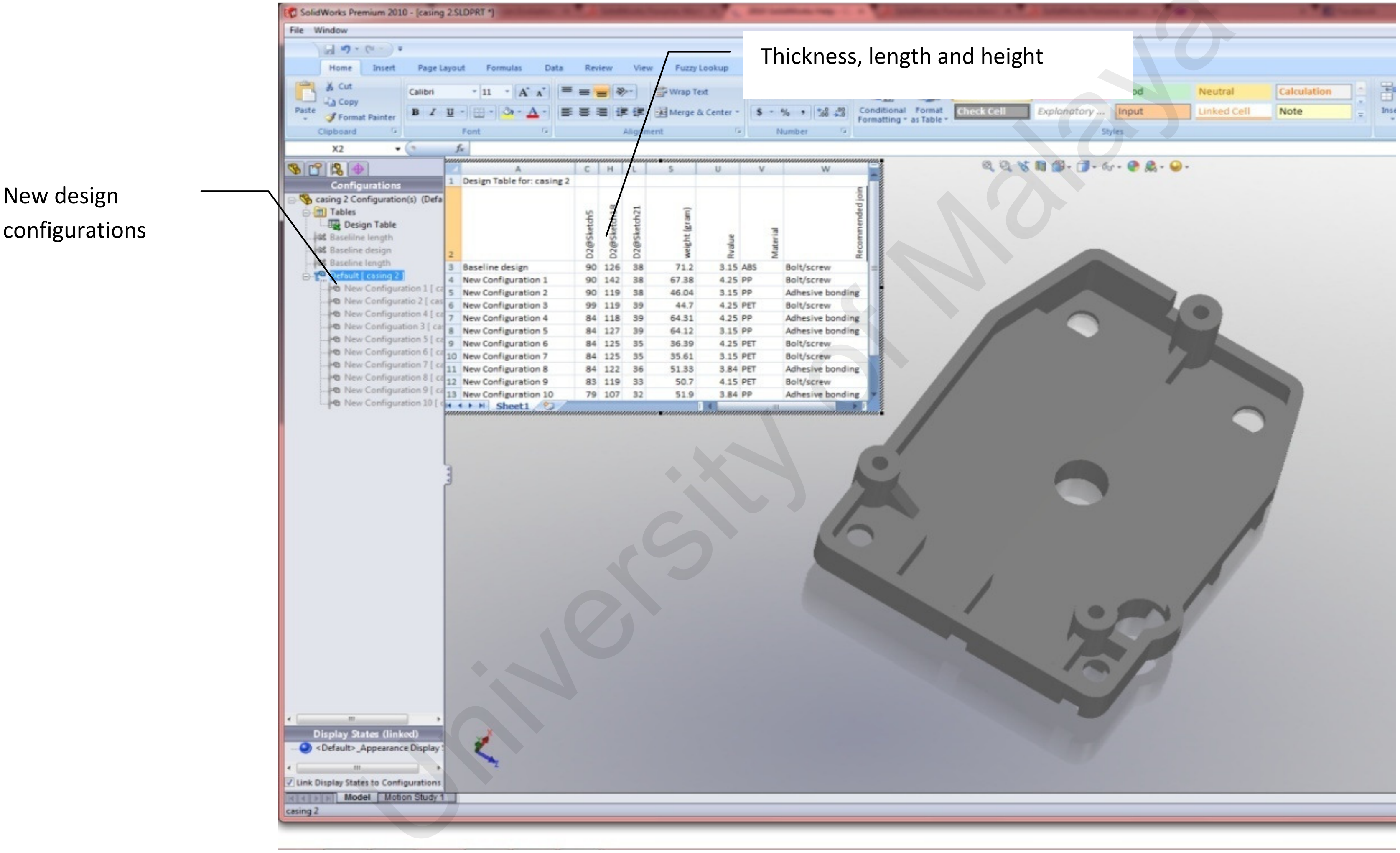


New Design Configuration 7
Material : ABS
t = 0.52 cm, ℓ =14.38 cm, h = 2.61 cm
Joining type= adhesive bonding
Rvalue= 3.15, weight =20.58 gram



New Design Configuration 8
Material : ABS
t = 0.95 cm, ℓ =14.38 cm, h = 3.07 cm
Joining type= adhesive bonding
Rvalue= 3.8, weight =33.51 gram

Figure 7.13 Examples of new design configurations generated.



New design configurations

Thickness, length and height

Design Table for: casing 2

	D2@Sketch5	D2@Sketch18	D2@Sketch21	weight (gram)	Rvalue	Material	Recommended join
Baseline design	90	126	38	71.2	3.15	ABS	Bolt/screw
New Configuration 1	90	142	38	67.38	4.25	PP	Bolt/screw
New Configuration 2	90	119	38	46.04	3.15	PP	Adhesive bonding
New Configuration 3	99	119	39	44.7	4.25	PET	Bolt/screw
New Configuration 4	84	118	39	64.31	4.25	PP	Adhesive bonding
New Configuration 5	84	127	39	64.12	3.15	PP	Adhesive bonding
New Configuration 6	84	125	35	36.39	4.25	PET	Bolt/screw
New Configuration 7	84	125	35	35.61	3.15	PET	Bolt/screw
New Configuration 8	84	122	36	51.33	3.84	PET	Adhesive bonding
New Configuration 9	83	119	33	50.7	4.15	PET	Bolt/screw
New Configuration 10	79	107	32	51.9	3.84	PP	Adhesive bonding

Figure 7.14 Dimension for different new configuration in design table retrieved from optimization results.

Table 7.8 New design configurations generated for ABS.

Config#	**Genes number**	**t (cm)**	ℓ(cm)	**h (cm)**	**P (pieces)**	**JT**	**MT**	**MS**
1	14870	0.9995361	14.502251	3.9657572	500	3	3	3
2	16960	0.90235	13.545205	3.8243911	500	1	3	1
3	17498	0.9429988	11.262455	3.4559604	500	2	3	3
4	17625	0.6466276	11.907683	2.8421535	470	1	2	3
5	17716	0.2936611	13.575265	3.0296649	488	1	3	2
6	18484	0.1097845	13.164569	3.9657572	484	3	2	3
7	18565	0.5264207	14.385977	2.6130745	500	1	3	1
8	18956	0.9502472	11.027848	3.0751694	484	1	3	2
9	19109	0.7657908	14.899519	3.6433803	500	2	2	1
10	19328	0.4063297	14.387732	3.2677165	492	2	2	3
11	19376	0.8219801	10.392157	3.9246475	496	1	3	3
12	19397	0.8989868	14.934768	3.9181469	500	2	3	3
13	19636	0.6527162	11.885252	3.157755	500	1	3	3
14	19708	0.289776	14.798123	2.9571507	488	2	3	2
15	20046	0.662458	14.113298	3.789599	484	1	3	2
16	20057	0.1097845	13.164569	3.8720015	484	2	2	3
17	20064	0.4244217	11.899062	2.9461637	476	2	2	3
18	20084	0.0540591	12.510872	3.9533053	364	2	2	3

The overall new design configurations for each feasible material are presented in Appendix I.

The conceptual design phase can be considered as one in which the "*designer navigates through an abstract problem domain and employs various strategies to elaborate the problem description*" (Geroand McNeill, 1998). Conceptual design is a challenging phase, where designers preliminarily visualize and elaborate potential solutions which meet a given set of design requirements. These challenges urge designers to employ their intuitiveness in order to explore potential solutions that are interesting or that yields higher trade off among conflicting objectives. Iteration in design also plays a key role in re-evaluating the problem space and bringing the newly defined solution space. Designers also typically consider a small number of alternatives subject to knowledge limitation and experience. By offering sets of solutions, designers can exploit their capability and select the most prominent design.

Selecting the best compromised solution is quite daunting for designers as many sets of solutions are provided. Designers can give weight to each of the objectives based on their preferences. In spite of this, the trade-off between objectives can be seen as an advantage because accommodate the intuitiveness of designers. The method proposed in this chapter computes and accommodates different design parameters. Therefore, the method has a high flexibility whereby the model can be reformulated as desired. The proposed method provides designers with the freedom to select possible solutions that fulfils many objectives. This, in turn, reduces design cycle time and the immediate feedback allows designers to improve their designs promptly. High recyclability material selection allows designers to fully exploit the advantage of using each of the material listed.

Selecting materials is an important stage in product design, as this affects cost, function, quality, and the environment. The proposed method shows how material selection can incorporate recyclability aspects which will be beneficial to extend product’s life. The numerical example shows that the method successfully generates a well distributed Pareto optimal solution in a single simulation run. From the results, it can be seen that designers can select the appropriate materials for their parts. Therefore, lightweight, good performance and high recyclability can be achieved for each part or component.

7.3 Case Study 2: Multi Material Selection for Door Panel

In this section, a case study for high recyclability material selection is applied to select the best material for a car door panel. The car door panel is selected as a component for Case Study 2 to represent the applicability of the method in selecting multiple materials in an assembly design. The case study uses the following assumptions:

1. The door panel has to be as light as possible and fulfil basic structural requirements. Strength is prescribed for this design.
2. The shape of the assembly is known and optimization includes the inner and outer door panel as both contribute to the overall weight of the door panel.
3. Material combinations between inner and outer panel are permissible.
4. The component uses thin sheet metals and the adjacent parts are connected either by spot welded joints or by adhesive bonding.

Figure7.15 shows the door panel for a car used in Case Study 2.

Figure 7.15 Door panel for Proton Waja.

An exploded view of the car door is shown in Figure 7.16. In this case study, material selection is applied only for the door panel. Four different materials can be chosen for the door panel as shown in Table 7.9.

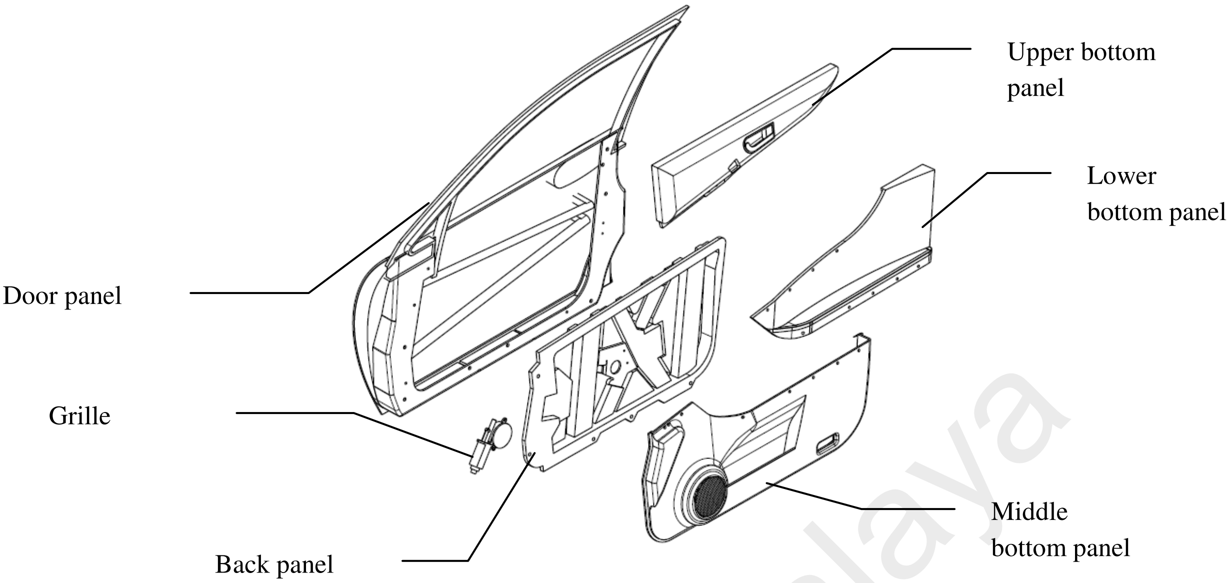


Figure 7.16 Exploded view of car door.

Table 7.9 Candidate of materials for an outer door panel (Cui *et al.*, 2008).

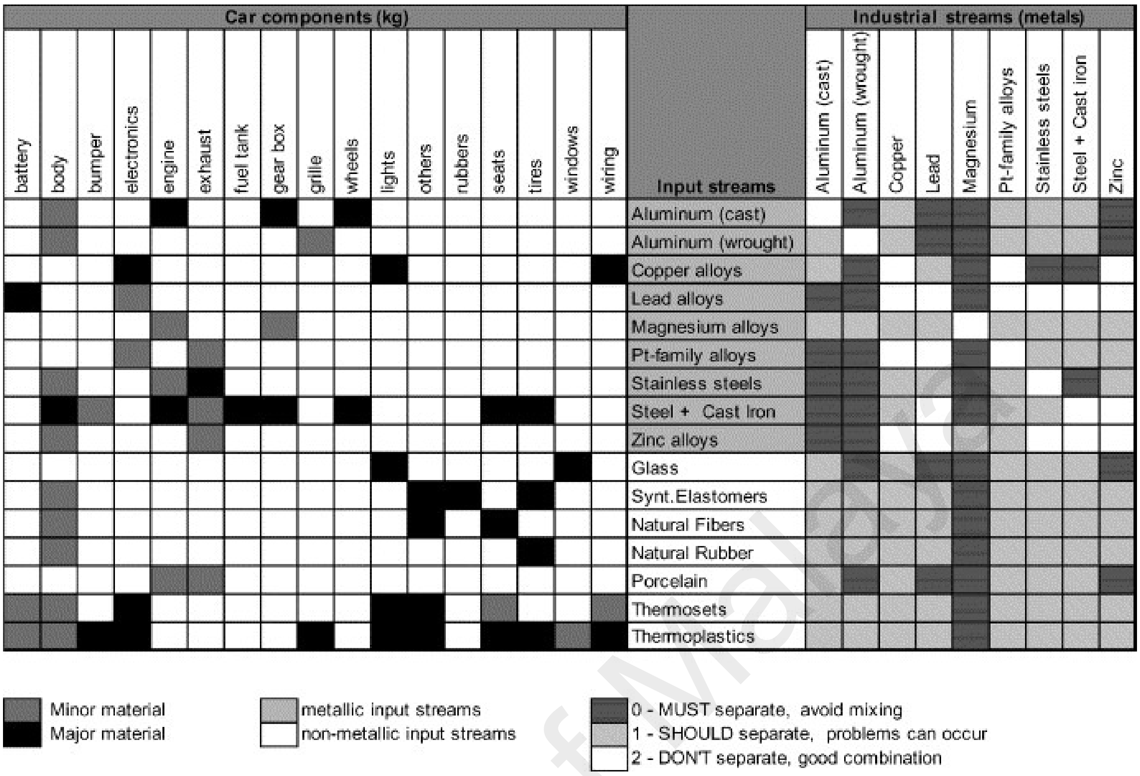
Material	Elastic Modulus (GPa)	Density (kg/m^3)	Price ($/kg)
Magnesium	45	1840	2.86
Aluminium	72	2720	2.20
Mild Steel	210	7840	0.66
Carbon fibre	80	1900	17.6

The optimization formulation uses Equations (6.9)-(6.18) with a few modifications. The thickness, length and height are specified in Table 7.11. In this case study; there are two thicknesses that represent the inner and outer panels, which will also influence the selection of materials. The inner and outer panel can be composed of the same material or combinations between two different materials. Therefore, the equations are modified as follow:

$$
\begin{aligned}
&Maximize\ \ F(M_i)\\
&Maximize\ \ R_{ev}(M_i)\\
&Minimize w(ti,\ \ell i,\ hi,\ f_{\rho 1}(M_i), f_{\rho 2}(M_i))\\
\\
&subject\ to\\
&0.8 \le t_1 \le 2.0\\
&0.6 \le t_2 \le 1.7\\
&90 \le \ell \le 120\\
&60 \le h \le 90\\
&P_i^L \le P_i \le P_i^U\\
\\
&Mi \in \{1,2,3,4\}
\end{aligned}
$$

The compatibility between materials should be considered material combinations in order to avoid difficulties in recycling. Castro *et al.* (2005) suggested a material compatibility matrix that can offers guidelines to prevent material separation difficulties, as shown in Table 7.10.

Table 7. 10 Matrix of material combinations for car components (Castro *et al.*, 2004).



Car components (kg)																	Input streams	Industrial streams (metals)								
battery	body	bumper	electronics	engine	exhaust	fuel tank	gear box	grille	wheels	lights	others	rubbers	seats	tires	windows	wiring		Aluminum (cast)	Aluminum (wrought)	Copper	Lead	Magnesium	Pt-family alloys	Stainless steels	Steel + Cast iron	Zinc
	▨			■			■		■								Aluminum (cast)	2	0	1	0	0	1	1	1	0
	▨							▨									Aluminum (wrought)	1	2	1	0	0	1	1	1	0
			■							■						■	Copper alloys	1	0	2	1	0	2	0	0	2
■			▨														Lead alloys	0	0	2	2	0	2	2	2	2
				▨			▨										Magnesium alloys	1	1	1	1	2	1	1	1	1
			▨		▨												Pt-family alloys	0	0	2	2	0	2	1	1	1
	▨			▨	■												Stainless steels	0	0	1	1	0	1	2	0	1
	■	▨		■	▨	■	■		■				■	■			Steel + Cast Iron	0	0	1	2	0	1	1	2	2
	▨				▨												Zinc alloys	0	0	2	2	1	1	2	2	2
										■					■		Glass	1	0	1	0	0	1	1	1	0
	▨										■	■		■			Synt.Elastomers	1	1	1	1	0	1	1	1	1
	▨										■		■				Natural Fibers	1	1	1	1	0	1	1	1	1
	▨													■			Natural Rubber	1	1	1	1	0	1	1	1	1
				▨	▨												Porcelain	1	0	1	0	0	1	1	1	0
▨	▨		■							■	■		▨			▨	Thermosets	1	1	1	1	0	1	1	1	1
▨	▨	■	■					■		■	■		■	■	▨	■	Thermoplastics	1	1	1	1	0	1	1	1	1

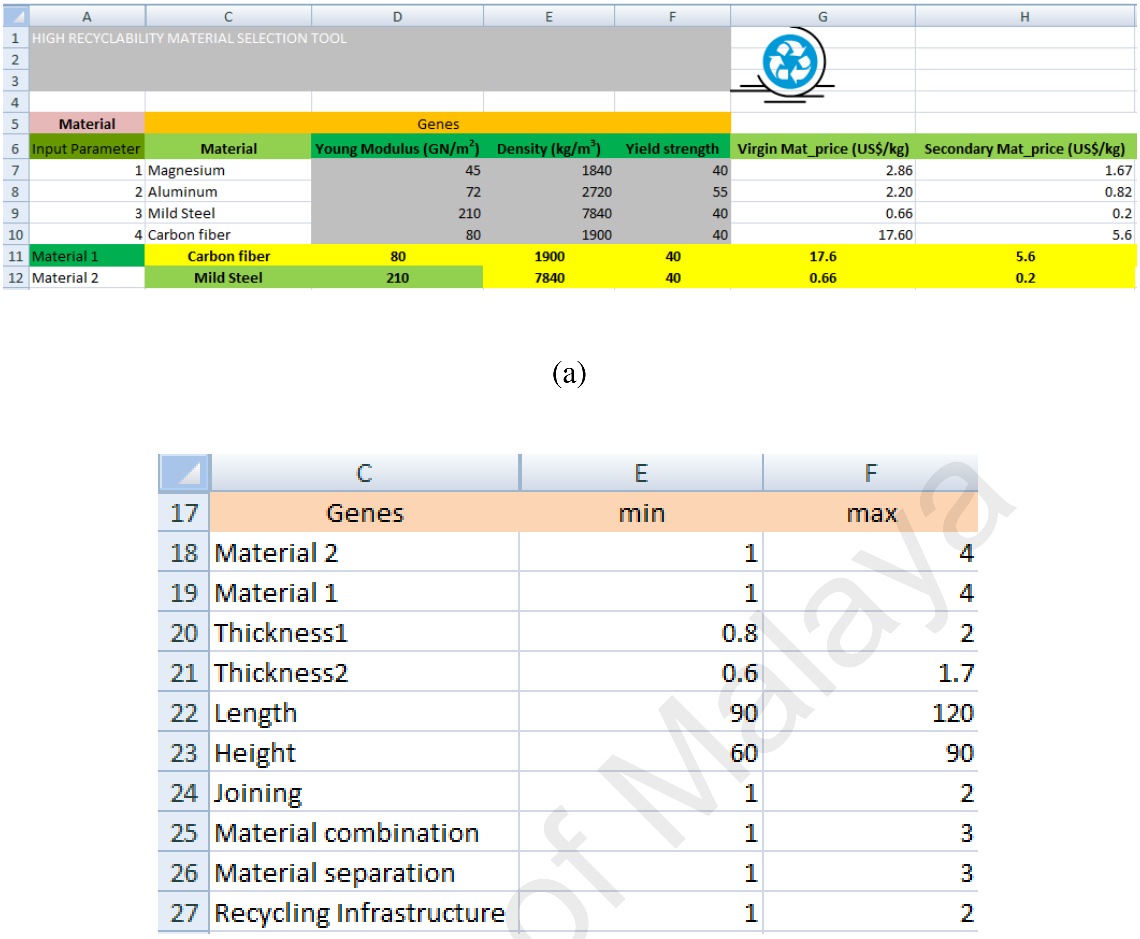
▨ Minor material
■ Major material

▒ metallic input streams
□ non-metallic input streams

0 - MUST separate, avoid mixing
1 - SHOULD separate, problems can occur
2 - DON'T separate, good combination

Table 7.11 Constraints for door panel.

Constraint	Upper bound	Lower bound
t_1	0.8 cm	2 cm
t_2	0.6 cm	1.7 cm
ℓ	90 cm	120 cm
h	60 cm	90 cm
P	100 pieces	500 pieces



	A	C	D	E	F	G	H
1	HIGH RECYCLABILITY MATERIAL SELECTION TOOL						
2							
3							
4							
5	Material	Genes					
6	Input Parameter	Material	Young Modulus (GN/m^2)	Density (kg/m^3)	Yield strength	Virgin Mat_price (US$/kg)	Secondary Mat_price (US$/kg)
7	1	Magnesium	45	1840	40	2.86	1.67
8	2	Aluminum	72	2720	55	2.20	0.82
9	3	Mild Steel	210	7840	40	0.66	0.2
10	4	Carbon fiber	80	1900	40	17.60	5.6
11	Material 1	Carbon fiber	80	1900	40	17.6	5.6
12	Material 2	Mild Steel	210	7840	40	0.66	0.2

(a)

	C	E	F
17	Genes	min	max
18	Material 2	1	4
19	Material 1	1	4
20	Thickness1	0.8	2
21	Thickness2	0.6	1.7
22	Length	90	120
23	Height	60	90
24	Joining	1	2
25	Material combination	1	3
26	Material separation	1	3
27	Recycling Infrastructure	1	2

(b)

Figure 7.17 Data input for optimization model: (a) material properties and (b) constraints.

Figure 7.17 shows the data input for the optimization model as well as the constraints. It can be seen from Figure 7.16 (a) (columns A11 and A12), there are two materials selected for the inner and outer panels. Using Steps 1-8, optimization can be executed and provide results for a set of solutions. The result of the optimization process for this case study is discussed in the next subsection. In this case study, a *crossover* rate of 0.9, *mutation* rate of 0.2, population number of 20 and 200 generations are used to solve the optimization problem. The non feasible solutions that occur during the optimization process are removed. In this case, the optimization limits the weight of the door panel to 50 kg. Weights that are beyond the desirable range are considered as non feasible solutions.

7.4 Result and Discussion: Case Study Two

The results of the optimization are shown in Table 7.15. Plots of the final population are shown in Figures 7.18- 7.20.

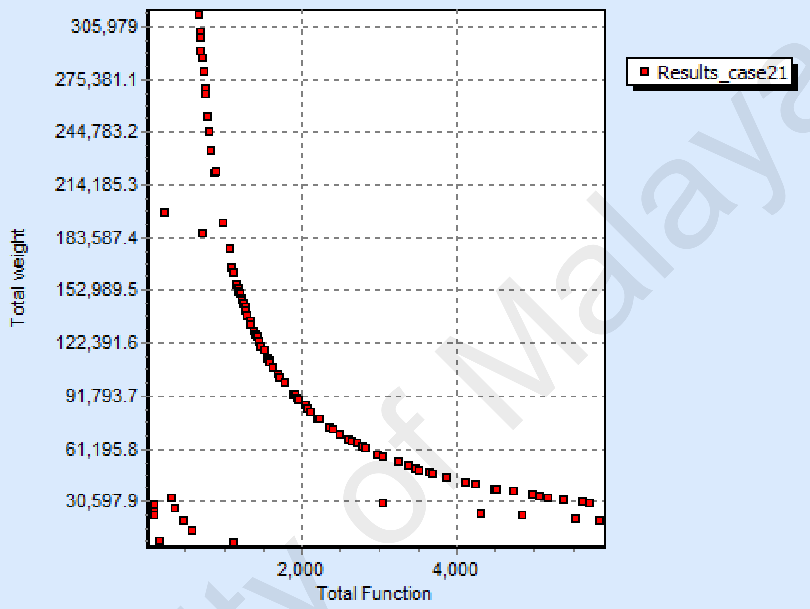


Figure 7. 18 Pareto front for function and weight for Case Study 2.

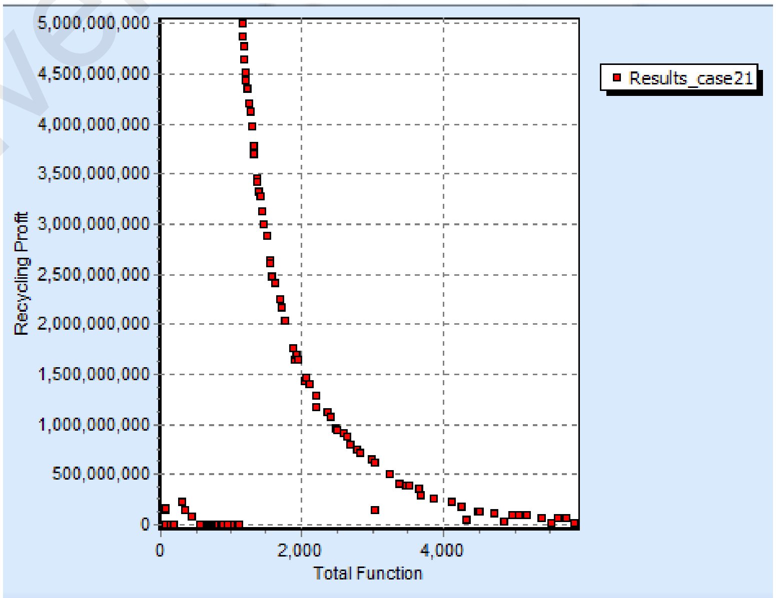


Figure 7.18 Pareto front for function and recycling profit for Case Study 2.

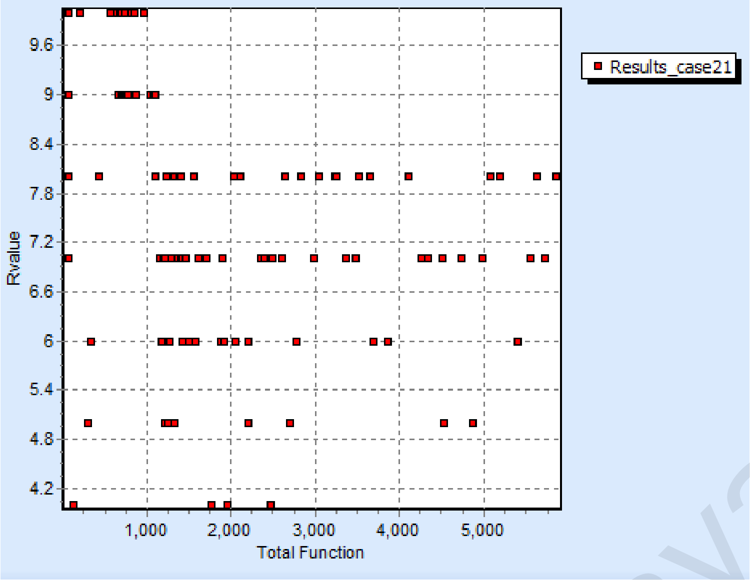


Figure 7.19 Pareto front for function and R_{value} for Case Study 2.

In this case study, optimization for high recyclability multi-material selection is implemented to select multi-materials for an automotive door panel. Multi-materials are often used in product design as a strategy to achieve production efficiency (Ciu *et al.*, 2008). Ashby (2004) also highlighted that the reason for using multi materials in design is to achieve product functionality, manufacturability, cost and aesthetics. Certain product may require more than one function which cannot be satisfied simultaneously by a single material. For example, a product that needs to be water-resistant will compromise the structure's toughness under the expected impact. Multi materials design may be a feasible alternative to satisfy both requirements.

The optimization only considers "good combinations" of materials, as suggested by Castro *et al.*(2004), as shown in Table 7.13. It can be seen that using mild steel for both the inner and outer panel results in good performance compared with other options. This finding is in agreement with Morello *et al.* (2011), in which steel provides better structural performance for automotive body components, including the side and sliding doors. However, in terms of lightweight design, a combination of aluminium and carbon fibre gives better results compared to other combinations. According to Vaidya (2011), carbon fibre can reduce weight by 60-75% compared to metals in automotive applications. Han and Clark (1995) highlighted that a reduction of 57 kg is equivalent to a fuel economy increase of 0.09-0.21 km per litre. Most of the carbon fibre streams are also recyclable, however the price of virgin material for carbon fibre greatly hinder it from replacing steel (Roth *et al.*, 2001). Therefore it is advisable to combine carbon fibre with other appropriate materials in terms of cost and technical constraints. Table 7.12 demonstrates the weight reduction of using a combination of magnesium and other materials as well as fuel economy calculation based on Han and Clark (1995). Other combinations of materials for the inner and outer panels can be generated and easily evaluated with regards to weight reduction and fuel economy (Appendix J).

For a design with good recyclability, aluminium and mild steel can be chosen to give a recycling profit of USD 440,311.05 with an R_{value} of 3.80 (HIGH). In this case, this combination has the potential of prolonging the use of materials better than other combinations.

Table 7.12 Percentage of weight reduction by using a combination of magnesium for the inner panel and other materials for the outer panel.

Material Combination		**Optimized Total Weight (kg)**	**Weight Reduction (%)**	**Fuel Economy (km/litre)**
Inner	Outer			
1	3	185.86	0	0
1	1	33	82.25	0.56
1	3	29.43	84.16	0.57
1	4	28.67	84.57	0.58
1	4	26.93	85.50	0.58
1	1	26.68	85.64	0.58
1	4	23.92	87.12	0.6
1	4	23.21	87.51	0.6
1	3	23.03	87.60	0.6
1	1	19.46	89.52	0.61
1	1	13.91	92.51	0.63
1	4	80.43	56.72	0.38
1	1	69.55	62.57	0.42

1= magnesium, 2=aluminium, 3=mild steel, 4=carbon fiber

The proposed method provides recommendations for designers to fully exploit the advantage of combining materials. From the practicability aspect, the method can assist designers integrates all design considerations simultaneously. Designers can explore the solutions and select the appropriate material combinations to suit their design constraints.

Table 7.13 Excerpt of optimization results for Case Study 2.

Chromosome Number	M_1	M_2	t_1 (cm)	t_2 (cm)	ℓ (cm)	h (cm)	Joining Type	Recycling Infrastructure	Material Combination	Material Separation	Function	Weight (g)	Recycling Profit (USD)	*R* *value*
69535	3	3	2.0	2	90.0	60.0	2	2	1	3	289.57	49753.97	21983.40	3.08
80322	3	4	2.0	1	94.6	68.6	2	2	1	3	241.13	33207.85	26399.51	3.08
80357	4	2	3.6	1	90.0	63.7	2	2	1	3	177.62	17899.17	35838.39	3.08
76458	1	2	3.5	1	119.9	66.3	2	2	1	1	129.96	24298.42	48980.58	2.52
78491	3	2	2.0	2	90.0	60.0	2	2	2	3	108.59	39744.00	440311.05	3.80
80362	1	3	2.0	1	94.9	68.6	2	2	2	3	90.04	47931.83	424186.10	3.80
80344	4	2	2.0	2	90.0	60.1	2	2	3	1	86.74	14904.00	351734.40	3.80

1= magnesium, 2=aluminium, 3=mild steel, 4=carbon fiber

In response to the six components of the tool needed by designers, the proposed method addresses the above requirements, as follows:

- *Guidelines with easily interpreted answers*

  The outputs from this method are easily interpreted since the results are straightforward and simple.

- *Optimization*

  Optimization has been carried out for high recyclability material selection.

- *Based on scientific findings*

  The parameters of the recyclability assessment tool are constructed based on the exploratory study. The recyclability factors identified from the recyclers' current practices are incorporated in the recyclability assessment tool.

- *Accommodate intuitiveness of designers*

  Designers require explorative and intuitive work. This method enables designers to explore possible solutions and select design configurations based on their requirements.

- *Interoperable*

  The proposed method has robust interoperability with CAD modeling environment, which support designers in carrying out recycling-oriented designs concurrently during technical drawing.

- *Easy for beginners*

The method is easy to follow as the use of Excel in optimization provides flexibility for beginners to operate high recyclability material selection during CAD design.

7.5 Summary

Conceptual design entails an explorative phase, in which the design variables may not be entirely known and the set of requirements may be altered. Designers are forced to use their knowledge and skills to explore potential solutions based on the requirements throughout this phase and subjective evaluation plays a significant role. The expertise, domain knowledge and intuition of designers will enable them to discard irrelevant solutions and focus on ones that show potential. This is especially the case if one or more requirements involve aesthetics or other subjective criteria.

Environmental concern has become an important criterion in product design to meet certain waste and green directives and make decision in conceptual design phase become more complicated. However, by using the proposed optimization method, designers can overcome the complexity during preliminary design which is often characterized by imprecise data. In most current practices, material selection in product design relies on the designers' experience. The proposed method can provide solutions and guide designers to expand their design alternatives. Although the optimization results exhibit a trade-off between objectives, designers can have flexibility to choose design alternatives using the multi-objective GA optimization based on their preferences because GA delivered sets of solutions rather than one solution.

This chapter proposes a method on how to select the best material during the initial product design process by considering function, lightweight design and recyclability factors. Two case studies representative of the real problems faced by designers are presented to demonstrate the applicability of the optimization model. The first case study introduces the selection of plastic materials for a car's side mirror. The second case study demonstrates the selection of metal-based materials for a car's door panel as well as selecting the optimal material combinations. Both case studies have shown that the method is able to successfully generate an optimized solution for high recyclability material selection and displays its potential in catering the nature of the designers’ task during conceptual design.

CHAPTER 8

VALIDATION

8.1 Introduction

One of the common validation methods is the comparison of the proposed model with other existing models or methods. For example, simple model case studies or methods are compared to known results of analytical models. Comparison of output behaviour is well-known comparison method. Sargent (2005) indicates that there are two basic approaches used in comparing the proposed model output behaviour with that of another model, i.e. subjective approach or objective approach. Table 8.1 shows the two comparison approaches.

Table 8.1 Validity Classification (Sargent, 2005).

	Observable System	**Non-Observable System**
Subjective Approach	▪ Comparison using graphical display ▪ Explore model behaviour	▪ Explore model behavior ▪ Comparison to other models
Objective Approach	▪ Comparison using statistical tests and procedures	▪ Comparison to other model using statistical tests

It is advisable to use statistical methods for testing validity, however this method may not be suitable for some cases because the statistical assumptions required cannot be satisfied or there is insufficient quantity of data available. Comparison using graphical display, exploration of model behavior and comparison to other models is presented for validating the proposed method. Case studies reported on Chapter 7 are presented to explore behavior of the optimization model as well as testing its applicability. This chapter presents validation of the proposed optimization model, which compares the proposed method to other well-known material selection methods that do not operate under CAD environments and material selection tool that operate under CAD environments, respectively. The material selection methods selected for this validation exercise that do not operate under CAD environments are Manshadi method, Khabbaz method and Weight Properties Method (WPM), meanwhile the material selection tool that operates under CAD environment is the Sustainability Express Tool SolidWorks 10 (SET-SW10). The results are described in the following subsections.

8.2 Comparison with Other Existing Non-CAD Material Selection Method

One of the important stages in material selection is ranking the material candidates. According to Ashby (2009), material selection methods typically provide a method to rank materials, so that designers can choose suitable materials for their designs. Three well known material selection methods chosen in this validation are:

1. Manshadi Method

   Mashandi (2007) employed a combined digital logic approach and non-linear normalization to solve the material selection problem. In this method, evaluation is carried out in a manner such that two material properties are calculated concurently. In comparing the two properties, a value of 1 is given for a property that is most important, while 0 is given for least important. The criterion for the best material is $N=n(n-1)/2$, where n is the number of properties under consideration. Then, for a given property that requires a maximum result, the scaled value (Y) for a given candidate material is calculated as:

   $$Y = \frac{\text{numerical value of property}}{\text{maximum value in the list}} \times 100 \tag{8.1}$$

   While properties which require a minimum values such as cost, density, weight, this following formula is used:

   $$Y = \frac{\text{minimum value in the list}}{\text{numerical value of property}} \times 100 \tag{8.2}$$

2. Khabbaz Method (2009)

   Fuzzy logic approach is employed in the Khabbaz method. Each material property is translated into linguistic language such as bad, good, or excellent. The rule base is applied to determine the performance index. Combinations of different property values results in different performance indices.

3. Weight Properties Method (WPM)

   This method was introduced by Farag (2008). A weight is assigned to each material property, depending on its magnitude. The weight is then multiplied with the scaled value of each material property which is then named weight property value (α). Following this, each individual property value is summed to obtain the comparative material performance index (γ). The highest γ value represents the best material.

A well-known case study is taken from the work of Jahan *et al*. (2012) to compare the performance of the optimization method. A cryogenic storage tank material for liquid nitrogen is chosen with the following design requirements as follows:

- Good weld ability and process ability
- Lower density and specific heat
- Smaller thermal expansion coefficient and thermal conductivity
- Adequate toughness
- High strength and stiffness

Figure 8.1 shows an image of typical cryogenic storage tanks for liquefied nitrogen gas.

Figure 8.1 Typical cryogenic storage tanks for liquefied nitrogen gas (Jahan *et al.*, 2012).

There are seven types of material available in this problem. The properties of each material are shown in Table 8.2.

Table 8.2 Properties of candidate materials for liquefied nitrogen storage tank (Khabbaz *et al.*, 2009).

Material	**1 Toughness index**	**2 Yield strength (MPa)**	**3 Young's Modulus (GPa)**	**4 Density (g/cm^3)**	**5 Thermal expansion**	**6 Thermal conductivity**	**7 Specific Heat**
Al 2024 T6	75.5	420	74.2	2.80	21.4	0.370	0.16
Al 5052 O	95	91	70	2.68	22.1	0.330	0.16
SS 301-FH	770	1365	189	7.90	16.9	0.040	0.08
SS 310-3AH	187	1120	210	7.90	14.4	0.030	0.08
Ti-6Al-4V	179	875	112	4.43	9.4	0.016	0.09
Inconel 718	239	1190	217	8.51	11.5	0.310	0.07
70Cu-30Zn	273	200	112	8.53	19.9	0.290	0.06

Table 8.2 shows the performance index and ranking of candidate materials using the WPM, Mashandi and Khabbaz methods. It can be seen that material SS 301-FH achieves the first rank. Table 8.3 compares the WPM, Mashandi, Khabbaz and the proposed methods.

In this study, the Spearman’s rank coefficient is used to measure the strength of association between two ranked variables using the following formula:

$$\rho = 1\frac{\sum d_i^2}{n(n^2-1)} \tag{8.3}$$

The Spearman rank coefficient is determined for each method and compared to the proposed method. The results are shown in Table 8.5.

Table 8.3 Performance index and ranking of candidate materials according to the three methods used for comparison.

Materials	**WPM**		**Mashandi method**		**Khabbaz method**	
	Performance index	Rank	Performance index	Rank	Performance index	Rank
Al 2024 T6	42.2	5	-1.17	5	16.14	6
Al 5052 O	40.1	6	-8.75	7	16.10	7
SS 301-FH	70.9	1	47.40	1	50.00	1
SS 310-3AH	50.0	4	31.88	4	35.74	4
Ti-6Al-4V	59.8	2	43.52	2	43.83	2
Inconel 718	53.3	3	33.44	3	38.42	3
70Cu-30Zn	35.9	7	-3.07	6	17.58	5

Table 8.4 Material ranking using the proposed optimization model compared to other methods.

Materials	**Ranking without recyclability consideration**	**Ranking with recyclability consideration**	**WPM**	**Mashandi Method**	**Khabbaz Method**
Al 2024 T6	7	7	5	5	6
Al 5052 O	6	6	6	7	7
SS 301-FH	1	2	1	1	1
SS 310-3AH	4	1	4	4	4
Ti-6Al-4V	2	4	2	2	2
Inconel 718	3	3	3	3	3
70Cu-30Zn	5	5	7	6	5

Table 8.5 Spearman's Rank Coefficient results.

	Khabbaz Method	Mashandi Method	WPM Method
New Method	0.662921348	0.91011236	0.505617978

Table 8.5 shows that the Spearman's rank coefficients obtained from calculation are greater than 0. This means that the proposed method exhibits similar performance to solve same problem with regards to material selection. Figure 8.2 shows the ranking comparison for each material for the different methods. It evident that SS 301-FH appears to be the best material for this particular problem, based on all methods.

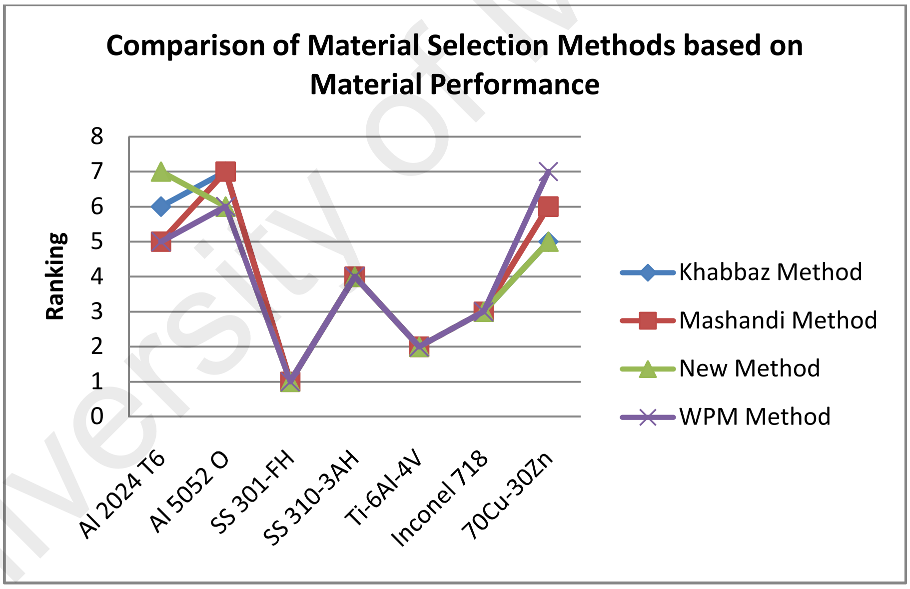


Figure 8.2 Comparison of material ranking without recyclability parameter.

Figure 8.3 shows the ranking for each material using the proposed model, in which recyclability is considered. It can be seen that there is a change in position for material ranking, whereby SS310-FH achieves the first rank. This indicates that SS310-3AH has a higher potential for recyclability compared to SS310-FH.

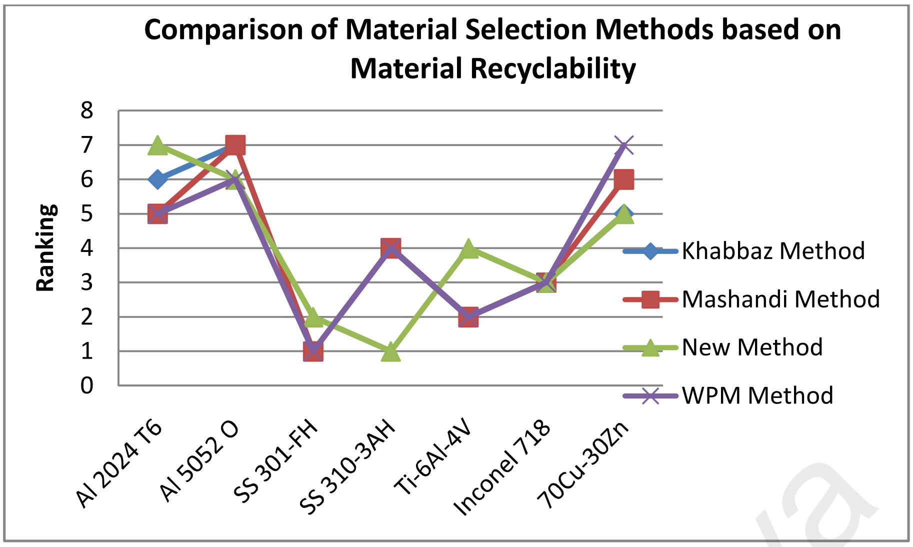


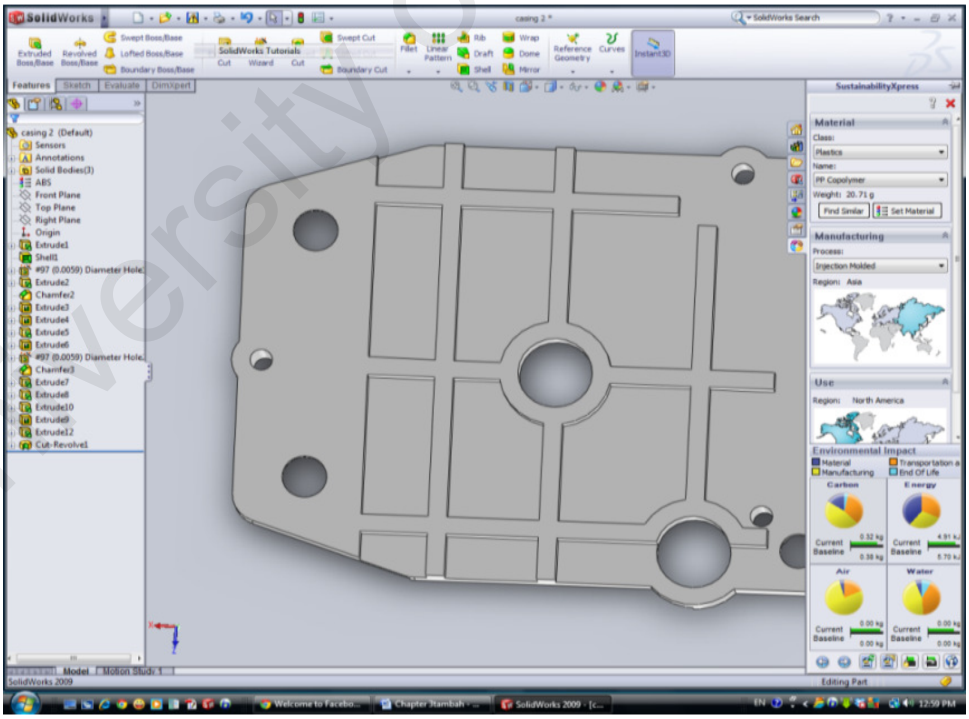
Figure 8. 3 Comparison of material ranking with recyclability parameter.

8.4 Comparison with CAD-based Sustainability Express Tool

The Sustainability Express Tool in Solid Works 10 (SET-SW10) is known as one of the environmental assessment add-on tools available in a CAD environment. For comparison purposes, the results from the first case study are compared with the results of SET-SW10 based on weight, energy consumption and carbon footprint. Table 7.5 shows the materials and their environmental impact calculated using SET-SW10 for the part in the first case study. It can be seen that each material contributes to different carbon footprint and energy consumption values, giving different weights. The values for carbon footprint and energy consumption are represented by indices, and therefore they can be multiplied with the weight to reflect the magnitude of environmental impact of certain parts. Table 8.6summarizes the comparison of weight, energy consumption and carbon footprint for each material. The lowest weight and environmental impact are achieved if the designer uses PP. PTFE yields the highest environmental impact. Figure 8.4 shows a screenshot of the environmental impact evaluated using SET-SW10.

Table 8.6 Material and its corresponding environmental impact determined using SET-SW10.

Material Type	**Environmental Impact**		**Mass Properties**	
	Carbon Footprint	Energy Consumption	Weight (gram)	Volume (cm^3)
ABS		5.22	24.90	23270.50
PET	-	-	33.04	23270.50
PP	0.23	3.69	20.71	23270.50
PS	0.35	5.37	24.20	23270.50
PVC	0.39	5.51	30.25	23270.50
PTFE	1.27	19.76	53.99	23270.50
Nylon	0.50	7.47	26.76	23270.50
PA Type 6	0.47	6.89	26.06	23270.50
POM	0.39	5.50	32.35	23270.50
Acrylic	0.38	4.89	27.92	23270.50



Class: Plastics
Name: PP Copolymer
Weight: 20.71 g
Process: Injection Molded
Region: Asia
Region: North America
Carbon Current 0.32 kg Baseline 0.38 kg
Energy Current 4.91 kJ Baseline 5.70 kJ
Air Current 0.00 kg Baseline 0.00 kg
Water Current 0.00 kg Baseline 0.00 kg

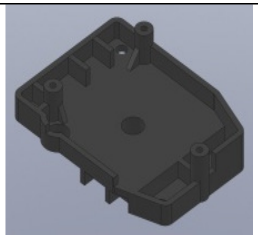
Figure 8.4 A screenshot of environmental assessment in SET-SW10.

Table 8.7 tabulates the comparison of utilizing ABS, PP and PS in the baseline design. The new configuration obtained from optimization is also presented. It can be concluded that PP gives better performance compared with ABS and PS. Selecting PP for this design decreases the weight and environmental impact. ABS offers the highest recycling profit. ABS can be selected if good welding and adhesive bonding are preferred. PP should be selected if the designer favours bolt and rivet for the joining type.

This comparison can be use as a guide to the designers in deciding the best material while satisfying environmental impact, technical requirements, recyclability as well as economical aspects. The results reveal that optimization results for ABS and PP achieve higher environmental performance with regards to CO_2 emission, energy consumption and recyclability. Hence, it can be concluded that the optimization method exhibits good performance with regards to reducing environmental impact. Furthermore, the results display the potential of implementing HRMS optimization method during the conceptual design stage.

The validation shows that the proposed method is superior compared to other existing methods in ranking materials and reducing CO_2 emission. This method is suitable to be applied during conceptual design. The compatibility of this method to be used in detail design will require further studies, such as readjustment of design parameters. This method can be expanded to cater for new parameters; however, this will increase computational time. The proposed method offers high flexibility and interoperability between Excel (as database library) and CAD environmental modeling. However, the complexity of the CAD design increase due to an increase in number of parameters.

Table 8.7 Comparison of the proposed optimization method with SET-SW10.

	Sustainability Express Solid Works 2010			Result from Optimization Method					
				Redesign Alternatives 1	Improvement	Redesign Alternatives 2	Improvement	Redesign Alternatives 3	Improvement
Design Model	 Baseline Design			✓ Joining type: welding, adhesive bonding ✓ Single material		✓ Joining type: bolt, rivet ✓ Only two materials can be used in the same part		✓ Joining type: welding, adhesive bonding ✓ Only two material can be used	
Material	ABS	PP	PS	ABS		PP		PS	
Weight (gram)	24.90	20.71	24.20	22.56	0.9% weight reduction	18.10	12.60 % weight reduction	28.08	16% increasing weight
Volume (mm^3)	23270.50	23270.50	23270.50	23206.35	0.27% volume reduction	18668.80	19.8% volume reduction	26745.32	15% increasing volume
Recycling profit (USD/kg)	NA	NA	NA	2989171		168316.5		14039.89	
Material Performance	NA	NA	NA	18.34		22.20		11.01	
*Carbon Footprint	9.46	4.67	8.47	8.57	0.9% reduction Of CO$_2$ emission	4.16	11% reduction of CO$_2$ emission	9. 83	13% increasing CO$_2$ emission
Energy Consumption	108.10	76.41	129.95	65.56	39% reduction energy consumption	66.87	38% reduction energy consumption	150.79	13% increase energy consumption

**Carbon footprint = weight of material X CO$_2$ emission of material*

Recycling profit = weight of reclaimed material X price of secondary material X number of parts to be produced

8.5 Summary

Validation of the proposed method has been presented in this chapter, by comparing the proposed method with other well-known methods employed in material selection as well as CAD environmental evaluation tool. Overall, it can be concluded that the proposed method shows good performance in material selection as well as handling both qualitative and quantitative data compared to other methods. The validation results show that the proposed method exhibits a comparable performance in material ranking and selection compared to other methods.

The optimization method results in an improvement in environmental with lower CO_2 emissions and energy consumption, as well as higher recyclability by achieving reduced weight in the design model. This demonstrates that the proposed method is useful to designers incorporating environmental perspectives at the conceptual design stage. Moreover, the proposed method is capable of generating new design alternatives which unavailable in other methods. This gives the designers flexibility to involve actively in designing high recyclability design.

CHAPTER 9

CONCLUSION

9.1 General Conclusion

This chapter presents the research conclusions, crucial findings, novelty, and the main contribution to knowledge and significance to the relevant practitioners. The limitations of this research as well as recommendations for future research are also detailed.

This research outlines an optimization method that addresses recycling-oriented material selection combined with recyclability assessment. The following research objectives have been accomplished:

- The first objective is achieved by investigating the current practices of how designers incorporate DFE. The conclusions are derived as follows:
  1. The implementation of DFE in Malaysia has been investigated. It is concluded that although designers are strongly aware of integrating environmental aspects into their designs due to regulatory requirements, DFE implementation is still at its infancy. Hence, proper knowledge on DFE will encourage the correct implementation of DFE.
  2. There is a common misconception on the understanding of DFE as an engineering design process amongst designers, implying that development of a structured methodology that assist designers to ensure successful implementation DFE is needed.
  3. Manager initiatives, management and regulatory policies are the major drivers in DFE implementation within the organization.
  4. Lack of proper knowledge, management initiatives and commitment, time and cost consumed are the factors that hinder the implementation of DFE in the organization.

5. From the factor analysis, environmental tools that will assist designers have the following characteristics:
   a. Guidelines with easily interpreted answers
   b. Provide optimization
   c. Based on scientific findings
   d. Accommodate intuitiveness of designers
   c. Interoperable
   d. Easy for beginners

- The second objective has been achieved by identifying five recyclability factors extracted from the common ground practices between designers and recyclers. The five recyclability factors are listed according to theorder of importance are:
  - Profit
  - Recycling infrastructure
  - Material separation
  - Material combination
  - Joining type

- The third objective is achieved and several conclusions are obtained as follows:
  1. Recyclability assessment using FIS which is able to assist designers in evaluating recyclability during the conceptual design stage.
  2. A multi-objective optimization model for high recyclability material selection which will generate optimal solutions that produce new design configurations successfully.

3. The proposed method will assist designers to explore potential solutions in selecting high recyclability materials that fulfill their design requirements and compatible with their current practice using CAD modeling environment.

9.2 Research Contributions to Knowledge and Novelties

The academic contributions to knowledge in this thesis are given as follows:

Firstly, the development of a new multi-objective optimization method for high recyclability material selection that integrates fuzzy-based recyclability assessment contributes to new knowledge on sustainable product design practices, especially for selecting high recyclability materials as it has never been provided in the existing literature.

Secondly, the development of a new model which assesses recyclability for a particular design at the sub-assembly level and linked to a CAD environment contributes to new knowledge on Design for Recycling practices. This study offers valuable knowledge based on insight and practices pertaining to prolonging material utilization at the end of product's life through recycling-oriented product design.

Thirdly, it has been highlighted in the literature review that there are no studies which have identified recyclability parameters extracted from Malaysian recyclers' current practices. This research gives insight on the significant recyclability factors for designers who wish to incorporate recyclability aspects in product design activities.

The novelties of this research are listed below:

- Recyclability parameters that are suitable for the Malaysian industry
- Recyclability assessment at the sub-assembly level with the ability to link to a CAD environment
- Optimization for high recyclability material selection that integrates with fuzzy based recyclability assessment

9.3 Contribution to Practitioners

Product designers are responsible for many aspects of products, including environmental considerations. Designers are generally aware of incorporating environmental aspects in the design stage, described in Chapter 4. However, it is emphasized that awareness alone is not sufficient. Hence, there is a need for a specific method that guides and assists designers in developing more sustainable products. This work produces optimization method for high recyclability material selection that will assist designers in solving the trade off in recycling-oriented designs. The proposed method can assist designers in practicing high recyclability product design without neglecting technical perspectives.

9.4 Limitations of Research

A number of research limitations are identified and discussed as follows:

- In capturing current practices, a semi-structures interview has been used for data collection in order to obtain rich and comprehensive data. However, there are many pitfalls such as lengthy conversation making it difficult to distinguish the valuable findings. Furthermore, a few interviewees used Malay language and therefore translation is required for analysis.

- This research only focuses on recycling-oriented design and does not consider other end-of-life alternatives such as reuse, remanufacturing or refurbishing.
- Formulation of the optimization model is based on the current conditions of recyclers and designers in Malaysia, which may require alterations to suit other countries.

9.5 Recommendations for Future Research

Selecting the best solution can be rather daunting for designers due to the large number of solution sets. A multi-criteria decision making method can be developed to select the best solution.

Although the method applicability has been proved, an extended model of material selection which integrates other aspects of design such as material combination, structure and manufacturability should be added in the model formulation for future research. The method can be further extended to cater other end-of-life alternatives such as reuse, remanufacturing or refurbishing.

While other research emphasizes recyclability assessment at the assembly level, this research focuses on sub-assembly as a stage for incorporating recyclability assessment. However, this method does not consider the hierarchical position of the sub-assembly and this can be another interesting point for future research.

References

A.Tsuji. (2006). *Recyclability Index for Automobiles.* California Polytechnic State University.

Abele, E., Anderl, R., & Birkhofeer, H. (2005). *Environmentally-Friendly Product Development:Methods and Tools*: Springer Verlag.

Amelia, L., Wahab, D. A., Che Haron, C. H., Muhamad, N., & Azhari, C. H. (2009). Initiating automotive component reuse in Malaysia. *Journal of Cleaner Production, 17*(17), 1572-1579.

Andersson, & Johan. (2001). *Multiobjective Optimization in Engineering Design : Applications to Fluid Power Systems.* Linkoping University.

Ardente, F., Beccali, G., & Cellura, M. (2003). Eco-sustainable energy and environmental strategies in design for recycling: the software "ENDLESS". *Ecological Modelling, 163*(1-2), 101-118.

Argument, L., Lettice, F., & Bhamra, T. (1998). Environmentally conscious design: matching industry requirements with academic research. *Design Studies, 19*(1), 63-80.

Ashby, M. F. (1999). Multi-objective optimization in material design and selection. *Acta Materialia, 48*, 359-369.

Ashby, M. F. (2000). Multi-objective optimization in material design and selection. *Acta Materialia, 48*(1), 359-369.

Ashby, M. F. (2009). *Engineering Material and Processes Desk Reference*: Elsevier.

Ashby, M. F., Bréchet, Y., & Cebon, D. (2004). Selection Strategies for Materials and Processes. *Advanced Engineering Materials, 4*(6), pp. 327-334.

Aschehoug, S. H., Boks, C., and Storen, S. (2012). Environmental information from stakeholders supporting product development, *Journal of Cleaner Production*, Volume 31, pp. 1–13.

Babbie, E. L. (2010). *The Practice of Social Reseach* (13th ed.): Wadsworth Cengage Learning.

Babuska, R. (1998). *Fuzzy Modeling for Control*: Kluwer Academics Publisher.

Berthoud, R. (2000). *A measure of changing health.*, Bristol, UK.

Boks, C. (2006). The softside of ecodesign. *Journal of Cleaner Production, 14*(15-16), pp.1346-1356.

Brechet, Y., Bassetti, D., Landru, D., & Salvo, L. (2001). Challenges in materials and process selection. *Progress in Materials Science, 46*, 407-428.

Bruntland. (1987). from http://www.sustainablecommunityinitiative.com/index.php?. Retrieved 7 February 2012.

Bryman, & Alan. (2008). *Social Research Method* (3rd ed.): Oxford University Press.

Buthayna Hasan, E. (2009). Design knowledge recycling using precedent-based analysis and synthesis models. *Design Studies, 30*(4), 340-368.

Calcott, P., & Walls, M. (2005). Waste, recycling, and "Design for Environment": Roles for markets and policy instruments. *Resource and Energy Economics, 27*(4), 287-305.

Castro, M. B., Remmerswaal, J. A. M., Brezet, J. C., van Schaik, A., & Reuter, M. A. (2005). A simulation model of the comminution-liberation of recycling streams: Relationships between product design and the liberation of materials during recycling. *International Journal of Mineral Processing, 75*(3-4), 255-281.

Chandler, W.U. (1986). Material recycling: the virtue of necessity. Conservation and Recycling, Vol.9, No. 1, pp 87-109.

Chang, H. T., & Chen, J. L. (2004). The conflict-problem-solving CAD software integrating TRIZ into eco-innovation. *Advances in Engineering Design, 35*(8-9), 553-566.

Chen, G., Zhou, J., Cai, W., Lai, X., Lin, Z., & Menassa, R. (2006). A framework for an automotive body assembly process design system. *Computer-Aided Design, 38*(5), 531-539.

Chen, R. W., Navin-Chandra, D., & Prinz, F. B. (1993, 10-12 May 1993). Product design for recyclability: a cost benefit analysis model and its application. Paper presented at the Electronics and the Environment, 1993., *Proceedings of the 1993 IEEE International Symposium*.

Chiner, M. (1988). Planning of expert system in material selection. *Materials and Design, 9*, 195-203.

Chitale, A. K., & Gupta, R. C. (2007). *Product Desin and Manufacturing* (4th Edition ed.): Prentice Hall.

Chu, C.-H., Luh, Y.-P., Li, T.-C., & Chen, H. (2009). Economical green product design based on simplified computer-aided product structure variation. *Computers in Industry, 60*(7), 485-500.

Cohen, Lawrence & Morrison. (2007). Research Methods in Education, (6th Edition ed), Taylor and Francis.

Coulter, S., & Bras, B. (1997). Improving Recyclability Through Planned Product Revisions. *971204*.

Cui, X., Wang, S., & Hu, S. J. (2008). A method for optimal design of automotive body assembly using multi-material construction. *Materials & Design, 29*(2), 381-387.

Dehghan-Manshadi, B., Mahmudi, H., Abedian, A., & Mahmudi, R. (2007). A novel method for materials selection in mechanical design: Combination of non-linear normalization and a modified digital logic method. *Materials & Design, 28*(1), 8-15.

Deng, Y. M., & Edwards, K. L. (2007). The role of material identification and selection in engineering design. *Materials & Design, 28*(1), pp. 131-139.

Desai, A., & Mital, A. (2003). Evaluation of disassemblability to enable design for disassembly in mass production. *International Journal of Industrial Ergonomics, 32*(4), 265-281.

Deutz, P., McGuire, M., and Neighbour, G. (2013). Eco-design practice in the context of a structured design process: an interdiciplinary empirical study of UK manufacturers, *Journal of Cleaner Production*, 39, pp.117-128.

Dunleavy, P. (2003). Authoring your PhD: How to Plan, Draft, Write, Finish a doctoral Thesis or Dissertation.

Eco Indicator 99: A damage oriented method for Life Cycle Impact Asessment. http://users.rowan.edu/~everett/courses/soclii/LCA/EI99_manual_v3.pdf. (assesed 7 December 2011)

Edwards, K. L. (2005). Selecting materials for optimum use in engineering components. *Materials & Design, 26*(5), 469-473.

Eisenhardt, K.M. (1989). Building Theories From Case Study Research. The Academy of Management Review, 14,4, ABI/INFORM Global, p.532.

Ermolaeva, N. S., Kaveline, K. G., & Spoormaker, J. L. (2002). Material selection combined with optimal structural design:concept and some results. *Materials & Design, 23*, 459-470.

EUDirective.http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2005:255:0022:0142:en:PDF. (2005). Retrieved 7 February 2012

Farag, M. M. (2008). Quantitative methods of materials substitution: Application to automotive components. *Materials & Design, 29*(2), 374-380.

Feldmann, K., Trautner, S., Lohrmann, H., & Melzer, K. (2001). Computer-based product structure analysis for technical goods regarding optimal end-of-life strategies. *Vol 215 Part B*, 683-692.

Ferrao, P., & Amaral, J. (2006). Design for recycling in the automobile industry: New approaches and new tools. *Journal of Engineering Design, 17*(5), pp.447-462.

Fiksel, J. (2009). *Design for Environment: A Guide to Sustainable Product Development*: Mc Graw Hill.

Fink, A. (2003). *How to Sample in Sutvey* (2nd ed.): Sage Publications, UK.

Gehin, A., Zwolinski, P., & Brissaud, D. (2008). A tool to implement sustainable end-of-life strategies in the product development phase. *Journal of Cleaner Production, 16*(5), 566-576.

Gen, M., & Cheng, R. (2001). Genetic Algorithms and Engineering Optimization (2 ed.): John Willey and Son, Canada.

Gero, J. S., & Mc Neill, T. (1998). An approach to the analysis of design protocols. *Design Studies, 19*(1), 21-61.

Gertsakis, J., Lewis, H., (2003)., Sustainability and the Waste Management Hierarchy- A Discussion Paper on the Waste Management and its Relationship to Sustainability. http://www.ecorecycle.vic.gov.au/resources/documents/TZW_Sustainability_and_the_Waste_Hierarchy_(2003).pdf . Retrieved 21 March 2011.

Giachetti, R. E. (1998). A Decision support system for material and manufacturing process selection. *Journal of Intelligent Manufacturing, 9*, 265-276.

Gillham, B. (2000). *Case study research methods*: Biddles, UK.

Graedel, T. E., & Allenby, B. R. (1995). *Industrial Ecology* (1st ed ed.): Prentice Hall.

Hallstedt, S., (2008). A Foundation for Sustainable Product Development. Doctoral Dissertation. Blekinge Institute of Technology, Sweden.

Han, H., & Clark, J. (1995). Lifetime costing of the body-in-white: Steel vs. aluminum. *JOM Journal of the Minerals, Metals and Materials Society, 47*(5), 22-28.

Hasselbach, J., and Kuhn, M., (1998). Disassembly evaluation of electronic and electrical product. Proceeding of International Symposium on Elcetronic and the Environment, IEEE, Chicago, USA.

Hiroshige, Y., Nishi, T., & Ohashi, T. (2001, 2001). *Recyclability evaluation method (REM) and its applications.* Paper presented at the Environmentally Conscious Design and Inverse Manufacturing, 2001. Proceedings EcoDesign 2001: Second International Symposium on.

Holt, R., & Barnes, C. (2010). Towards an integrated approach to "Design for X":an agenda for decision based DFX research. *Res. Eng Design, 21*, pp. 123-136.

Huisman, C. B. a. A. S. (2000). Environmentally Weighted Recycling Quotes-Better Justifiable and Environmentally More Correct. *Journal of IEEE, Vol. 3*, pp. 105-111.

Huisman, J. (2003). *The QWERTY/EE concept, Quantifying Recyclability and Eco-Efficiency for End-of-Life Treatment of Consumer Electronic Products.*

Iakovou, E., Moussiopoulos, N., Xanthopoulos, A., Achillas, C., Michailidis, N., Chatzipanagioti, M., et al. (2009). A methodological framework for end-of-life management of electronic products. *Resources, Conservation and Recycling, 53*(6), 329-339.

Ishii, K., Eubanks, C. F., & Di Marco, P. (1994). Design for product retirement and material life-cycle. *Materials & Design, 15*(4), 225-233.

Jahan, A., Bahraminasab, M., & Edwards, K. L. (2012). A target-based normalization technique for materials selection. *Materials & Design, 35*(0), 647-654.

Jahan, A., Ismail, M. Y., Sapuan, S. M., & Mustapha, F. (2010). Material screening and choosing methods - A review. *Materials & Design, 31*(2), 696-705.

Johansson, G. (2002). Success factors for integration of ecodesign in product development: A review of state of the art. *Environmental Management and Health, 13*, pp.98-107.

Jonker, J., & Pennink, B. (2010). *The Essence of Research Methodology: A Concise Guide to Master and PhD Student*: Springer Verlag Berlin.

Joppe, M (2000). The Research Process. http://www.ryerson.ca/~mjoppe/rp.htm Retrieved February 25, 2012.

Kanari. (2003). (Publication no. http://revultec.com/PDF/EUend-of-lifeVehicleRecyclingPDF.pdf). from The Minerals, Metals & Materials Society http://revultec.com/PDF/EUend-of-lifeVehicleRecyclingPDF.pdf

Key, S. (1999). Toward a new theory of the firm: a critique of 'stakeholder' theory. *Management Decision, 37*(4), 317-328.

Konak, A., Coit, D. W., & Smith, A. E. (2006). Multi-objective optimization using genetic algorithms: A tutorial. *Reliability Engineering and System Safety, 91*, 992-1007.

Krippendorff, K. (2004). *Content Analysis: An Introduction to its methodology*: Sage Publication.

Kriwet, A., Zussman, E., & Seliger, G. (1995). Systematic integration of design-for-recycling into product design. *International Journal of Production Economics, 38*(1), 15-22.

Kuo, T. C. (1996). Enhancing disassembly and recycling planning using life-cycle analysis. *Robotics and Computer-Integrated Manufacturing, 22*(5-6), 420-428.

Lee, S. G., Lye, S. W., & Khoo, M. K. (2001). A Multi-Objective Methodology for Evaluating Product End-of-Life Options and Disassembly. *The International Journal of Advanced Manufacturing Technology, 18*(2), 148-156.

Leedy, P. D., & Ormrod, J. E. (2012). *Practical Research: Planning and Design*: Pearson Education.

Lemos, M.C. 1998. The politics of pollution control in Brazil: state actors and social movements cleaning up Cubatao. World Development [Online] 26: 1, 75-86.

Lincoln, Y.S., Guba, E.G.(1985). Naturalistic Inquiry. Sage Publication, UK.

Lindahl, M. (2006). Engineering designers' experience of design for environment methods and tools – Requirement definitions from an interview study. *Journal of Cleaner Production, 14*(5), 487-496.

Liu, Z. F., Liu, X. P., Wang, S. W., & Liu, G. F. (2002). Recycling strategy and a recyclability assessment model based on an artificial neural network. *Journal of Materials Processing Technology, 129*(1-3), 500-506.

Manakata, T., (2008). Fundamentals of the new artificial inteligence: neural , evulotionary, fuzzy and more, 2nd ed, Springer.

Manouchehri, H. M. (2006). Mapping and development of shredding product streams.

Malaysia Automotive Association. http://www.maa.org.my/. (2009). Retrieved 23 May 2012

Mason, J., (2002). Qualitative Researching. 2nd ed. Sage Publication, UK.

Mathieux, F., Froelich, D., & Moszkowicz, P. (2008). ReSICLED: a new recovery-conscious design method for complex products based on a multicriteria assessment of the recoverability. *Journal of Cleaner Production, 16*(3), 277-298.

Maxwell, D., W. Sheate, & R. van der Volst. (2006). Functional and systems aspects of the sustainable product and service development approach for industry. *Journal of Cleaner Production Vol. 14*(No. 17), pp. 1466-1479.

Merriam, S. B. (2009). *Qualitative Reseach: A Guide to Design and Implementation* (2nd ed.): John Wiley and Sons.

Miemczyk, J. (2008). An exploration of institutional constraints on developing end-of-life product recovery capabilities. *International Journal of Production Economics, 115*(2), 272-282.

Miles , M.B., and Huberman, A.M., (1994). Qualitative Data Analysis: An Expanded Sourcebook, 2nd ed, Sage Publication, UK.

Mizuki, C., P.A. Sandborn, & Pitts, G. (1996). Design for environment-a survey of current practices and tools. *Proceedings of the 1996 IEEE International Symposium on Electronics and Environment*, pp.1-6.

Morello, L., Rossini, L. R., Pia, G., & Tonoli, A. (2011). *The Automotive Body: Volume I Component Design*: Springer Science and Business Media.

Morris, R., (2009) The Fundamental of Product Design. AVA Publishing, Singapore.

O'Brien, C. (1999). Sustainable Production: New paradigm for a new millenium. *International Journal of Production Economy, 60-61,*1-7.

Our Common Future. http://www.un-documents.net/wced-ocf.htm. (1987). Retrieved 12 February 2012

Patton, M. (1990). *Qualitative evaluation and research methods*.Beverly Hills, CA: Sage. pp. 169-186.

Phillis, Y. A., Kouikoglou, V. S., & Zhu, X. (2009). Fuzzy Assessment of Material Recyclability and Its Applications. *J. Intell. Robotics Syst., 55*(1), 21-38.

Pigosso, D.C.A., Zannette, E. T., Filho, A. G., Ometto, A. R., Rozenfeld, H. (2010). Eco-design methods focused on remanufacturing, *Journal of Cleaner Production*, Volume 18, Issue 1, pp. 21–31

Pomykala, J. A., Jody, E. Daniels, J , and Spangenberger, J.S., . (2007). Automotive recycling in the United States: Energy conservation and environmental benefits. *Journal of Metal, Mineral and Material Society, Vol 11*, pp. 41-45.

Qi, Y., Liu, G., Liu, Z., & Wang, S. (2005, 16-19 May 2005). *Analyzing and modeling of uncertainty factors influencing product recyclability.* Paper presented at the Electronics and the Environment, 2005. Proceedings of the 2005 IEEE International Symposium on.

Rao, R. (2006). *Resource, recovery and recycling from metalurgical wastes* (1st edition ed.): Elsevier.

Rebitzer G., F. R., Hunkeler D., Norris G., Rydberg, T., R. (2004). Review of life cycle Assessment Part 1: Framework, goal, scope definition, inventory analysis and applications. *Journal of Environment International, Vol. 30*, pp. 701-720.

Regional Roundtable for East Asia and Pasific Region, http://www.johannesburgsummit.org/html/prep_process/asiapacific_prep1/malaysia_roudtable_report.htm. (2002). Johanessburg Summit Report. Retrieved 12 February 2012

Rios, P., Stuart, G.A, and Grant, E. (2003). Plastic Disassembly versus Bulk Recycling: Engineering Design for End-of Life Electronics Resource Recovery. *Environ. Sci. Technol., 37 (23)*, pp 5463-5470.

Robson, C. (2002). *Real World Research*: Blackwell Publishing, UK.

Rose, C. M. (2000). *Design for Environment: A Method for Formulating Product end of Life Strategies.*

Roth, R., Clark, J., & Kelkar, A. (2001). Automobile bodies: Can aluminum be an economical alternative to steel? *JOM Journal of the Minerals, Metals and Materials Society, 53*(8), 28-32.

Saaty, T. L. (1980). The Analytical Hierarchy Process: McGraw-Hill International Book Co., 1980.

Sapuan, S. M. (2001). A knowledge-based system for materialsselection in mechanical engineering design. *Materials & Design, 22*(8), pp. 687-695.

Sarfaraz Khabbaz, R., Dehghan Manshadi, B., Abedian, A., & Mahmudi, R. (2009). A simplified fuzzy logic approach for materials selection in mechanical engineering design. *Materials & Design, 30*(3), 687-697.

Saris, W. E., & Gallhofer, I. N. (2007). *Design, Evaluation and Analysis of Questionnaire in Survey Research* John Willey and Sons.

Schaik, V.A., & Reuter, M. A. (2007). The use of fuzzy models to link automotive design to recycling rate calculation. *Minerals Engineering, 20*, pp. 875-890.

Schniederjans, M. J., Pantoya, M. L., Hoffman, J. J., & Willauer, D. L. (2009). A multi-objective modeling approach for energetic material evaluation decisions. *European Journal of Operational Research, 194*(3), 629-636.

Seliger, G. (2007). *Sustainability in Manufacturing*: Springer Verlag.

Shanian, A., Milani, A. S., Carson, C., & Abeyaratne, R. C. (2008). A new application of ELECTRE III and revised Simos' procedure for group material selection under weighting uncertainty. *Knowledge Based Systems, 21*(7), pp.709-720.

Shanian, A., & Savadogo, O. (2006). A material selection model based on the concept of multiple attribute decision making. *Materials & Design, 27*(4), pp. 329-337.

Sharma, P. K., Aggarwal, A., Gupta, R., & Suryanarayan. (1993). *A expert system for aid in material selection process.* Paper presented at the Engineering Management Conference, 1993. 'Managing Projects in a Borderless World'. Pre Conference Proceedings., 1993 IEEE International.

Shemshadi, A., Shirazi, H., Toreihi, M., & Tarokh, M. J. (2011). A fuzzy VIKOR method for supplier selection based on entropy measure for objective weighting. *Expert Systems with Applications, 38*(10), 12160-12167.

Shih, L.-H., Chang, Y.-S., & Lin, Y.-T. (2006). Intelligent evaluation approach for electronic product recycling via case-based reasoning. *Advanced Engineering Informatics, 20*(2), 137-145.

Srinivasan, H., Shyamsundar, N., & Gadh, R. (1997). A virtual disassembly tool to support environmentally conscious product design. *Proceedings of the IEEE International Symposium on Electronics and the Environment*, pp.7-12.

Stancyzk, T. (1995). The emerging role of annual environment performance results. *Proceeding IEEE International Symposium on Electronics and the Environment,* Orlando, USA.

Stevels, A. L. N. (2000). Green Marketing for Consumer Electronics. *Electronics Goes Green,* Berlin, Germany.

Tam, V. W. Y., & Tam, C. M. (2006). Evaluations of existing waste recycling methods: A Hong Kong study. *Building and Environment, 41*(12), 1649-1660.

The Ensikolpedia of Earth. (1992). http://www.eoearth.org/article/Polluter_pays_principle. Retrieved 7 February 2012.

Trafford, V., & Leshem, S. (2008). *Stepping Stone to Achieving your doctorate*: Open University Press.

UNEP.http://www.unep.or.jp/Ietc/Publications/spc/State_of_waste_Management/11.asp. (2012). Retrieved 13 February 2013.

UNFCC.http://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/ghg_booklet_06.pdf. (2006).Retrieved 2 January 2013.

Vaidya, U. (2011). *Composites for Automotive, Truck and Mass Transit*: DEStetch Publication, Inc, USA.

Van Schaik, A., & Reuter, M. A. (2007). The use of fuzzy models to link automotive design to recycling rate calculation. *Minerals Engineering, 20*, pp. 875-890.

VDIGuideline2225.http://www.vdi.de/401.0.html?&L=1&tx_vdirili_pi2%5BshowUID%5D=89665. (2002). Retrieved 20 February 2012

Vezolli, C., & Mazini, E. (2008). *Design and Innovation for Sustainability*: Springer Verlag, London.

Villalba, G., Segarra, M., Chimenos, J. M., & Espiell, F. (2004). Using the recyclability index of materials as a tool for design for disassembly. *Ecological Economics, 50*(3-4), 195-200.

Wainer, H., & Braun, H. I. (1998). Test validity. Hilldale, NJ: Lawrence Earlbaum Associates.

Weaver, P. M., Ashby, M. F., Burgess, S., & Shibaike, N. (1996). Selection of materials to reduce environmental impact: a case study on refrigerator insulation. *Materials & Design, 17*(1), 11-17.

Williams J. A. S, W. S., Qu X., McGlinch J. B., Bonawitan W., Choi J. K., Schiff, J. (2007). An automotive bulk recycling planning model. . *European Journal of Operation Research, Vol. 177*, pp. 969-981.

Yin, R. K.(2009). Case study research: Design and methods, 4th ed, Sage Publications, California, USA.

Zhang, H. C., Li, J., Shrivastava, P., Whitley, A., & Merchant, M. E. (2004). A Web Based system for reverse manufacturing and product environmental impact assessment considering end of life dispositions. *CIRP Annals - Manufacturing Technology, 53*(1), 5-8.

Zhou, C.-C., Yin, G.-F., & Hu, X.-B. (2009). Multi-objective optimization of material selection for sustainable products: Artificial neural networks and genetic algorithm approach. *Materials & Design, 30*(4), 1209-1215.

LIST OF AWARD AND PUBLICATIONS

Award

Best Student Paper, Multi-Objective Optimization for High Recyclability Material Selection Using Genetic Algorithm, International Conference in Intelligent Manufacturing and Logistic Systems, Taiwan, 2011.

ISI Publications

1. Novita Sakundarini, Zahari Taha, Salwa Hanim Abdul Rashid, Raja Ariffin Raja Ghazila, Julirose Gonzales, Optimal Multi Material Selection for Lightweight Design of Automotive Body Assembly with Recyclability Consideration, *Materials and Design*, 2013, Vol 19(10).
2. Novita Sakundarini, Zahari Taha, Salwa Hanim Abdul Rashid, Julirose Gonzales, Raja Ariffin Raja Ghazila Multi-Objective Optimization for High Recyclability Material Selection Using Genetic Algorithm, *Journal of Advanced Manufacturing Technology*, DOI. 10. 1007/s00170-013-4933-x, 2013. (*Accepted-In Press*)
3. Novita Sakundarini, Zahari Taha, Raja Ariffin Raja Ghazila, Julirose Gonzales, Salwa Hanim Abdul Rashid, A Framework of Integrated Recyclability Tools For Automobile Design, *International Journal of Industrial Engineering: Theory, Applications and Practice*, Vol. 9, No.10, 2012.

Non-ISI Publications

1. Raja Ariffin Raja Ghazilla , Zahari Taha, Salwa Hanim Abdul Rashid, Novita Sakundarini and Julirose Gonzales, Product, Recovery Oriented Approach for Fastener Selection during Conceptual Design, *International Journal of Sustainable Design*, Vol. 2, No. 1, pp.64–82, 2012.
2. Zahari Taha, Novita Sakundarini, Julirose Gonzales, Raja Ariffin Raja Ghazila, Eco Design In Malaysia: Challenges and Opportunities, *Journal of Research and Applied Sciences*, Vol 12 December 2010.
3. Julirose Gonzales, Novita Sakundarini, Raja Ariffin Raja Ghazila, Zahari Taha, Integrated Eco-Design Tool for Malaysian Automobile Industry, *Journal of Advanced Computational Intelligence and Intelligent Informatics,* Fuji Press Japan, Vol 14, January 2010.

Proceedings

1. Novita Sakundarini, Zahari Taha, , Salwa Hanim Abdul Rashid, Raja Ariffin Raja Ghazila, Inteligent Approach for High Recyclability Material Selection in Product Design, *Proceeding Intelligent Manufacturing and Logistics Systems Conference*, Shanghai, 2013.

2. Zahari Taha, Novita Sakundarini, Salwa Hanim Abdul Rashid, Julirose Gonzales, Raja Ariffin Raja Ghazila, Multi-Objective Optimization for High Recyclability Material Selection Using Genetic Algorithm, *Proceeding Intelligent Manufacturing and Logistics Systems Conference*, Taiwan, 2011.

3. Zahari Taha, Novita Sakundarini, Raja Ariffin Raja Ghazila, Julirose Gonzales, Salwa Hanim Abdul Rashid, A Decision Making Model to Improve Recyclability in Product Design, Proceeding Asia Pacific Industrial Engineering and Management Systems 11th, Melaka, Malaysia, 2010.

4. Julirose Gonzales, Novita Sakundarini, Raja Ariffin Raja Ghazila, Zahari Taha, Integrated Eco-Design Tool for Malaysian Automobile Industry, *Proceeding HNICEM*, Manila, Philippine, 2009.

5. Zahari Taha, ,Novita Sakundarini, Julirose Gonzales, Raja Ariffin Raja Ghazila, An Intelligence Approach for Recyclability Evaluation in Automobile Design, *Proceeding Asia Pasific Industrial Engineering and Management Systems Conference*, Kitakyushu, Japan, 2009.

6. Zahari Taha, , Novita Sakundarini, Raja Ariffin Raja Ghazila, Julirose Gonzales, Implementation of Design for Environment in Indonesia and Malaysia Industries: A Survey, *Proceeding Asia Pasific Industrial Engineering and Management Systems*, Bali, Indonesia, 2008.