DEVELOPMENT OF A MATERIAL EFFICIENCY STRATEGY SELECTION MODEL FOR ELECTRICAL AND ELECTRONIC MANUFACTURING INDUSTRY

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DEVELOPMENT OF A MATERIAL EFFICIENCY STRATEGY SELECTION MODEL FOR ELECTRICAL AND ELECTRONIC MANUFACTURING INDUSTRY

ABSTRACT

The objective of this study is to examine the link between organizational change factors and the selection of appropriate material efficiency strategies for manufacturers in Malaysia, specifically in the electrical and electronics (E&E) industry. There are various change factors that can influence the implementation of material efficiency strategies in manufacturing companies and these factors are often interrelated. These factors vary depending on the country and manufacturing sector, which are affected by the fluctuating market conditions. Thus, the implementation of material efficiency strategies is a rather arduous task, particularly in selecting an appropriate strategy among the various material efficiency strategies available.

A mixed-method approach (qualitative and quantitative) was chosen for this study in order to collect and analyse the data obtained from selected E&E companies in Malaysia. Semi-structured interviews were conducted to explore material efficiency strategies and change factors in these E&E companies. The Analytic Hierarchy Process (AHP) approach was used to prioritize the change factors and link them with each material efficiency strategy. Two main material efficiency areas were identified: (a) material efficiency strategies and (b) organizational change factors (drivers, barriers and enablers). The association and proposition links of the material efficiency strategies and its change factors were built and presented in the form of a material efficiency strategy decision model. In addition, a decision support tool is constructed to select the suitable material efficiency strategies.

In this study, the organizational change factors and material efficiency strategies were linked by establishing a comprehensive integrated decision model to prioritize the selection of material efficiency strategies. The decision propositions links were established for each change factor and each material efficiency strategy. This is a significant contribution to knowledge since it takes into account analytical decision perspectives in the selection of material efficiency strategies. In addition, the inclusion of multiple change factors provides a new theoretical perspective on the implementation of material efficiency strategies. The decision support tool developed in this study can be used in practical applications, particularly to assist practitioners in making appropriate decisions in prioritizing the selection of material efficiency strategies.

Keywords: decision support tool, material efficiency, sustainable manufacturing.

PEMBANGUNAN SEBUAH MODEL PEMILIHAN STRATEGI KECEKAPAN BAHAN BAGI INDUSTRI ELEKTRIK DAN ELEKTRONIK

ABSTRAK

Kajian ini dijalankan bagi mengkaji perhubungan antara faktor-faktor perubahan organisasi ke arah corak pemilihan strategi kecekapan bahan bagi syarikat pembuatan di Malaysia, khususnya di dalam industri elektrik dan elektronik (E&E). Terdapat banyak pelbagai faktor perubahan yang boleh mempengaruhi pelaksanaan strategi kecekapan bahan dalam sesebuah syarikat pembuatan. Dalam kebanyakan senario, faktor-faktor ini sering saling berkaitan. Tambahan pula, faktor-faktor ini sering berbeza-beza bergantung kepada jenis sektor pembuatan, lokasi sektor pembuatan di sesebuah negara yang berlainan, serta keadaan pasaran yang sentiasa berubah. Oleh itu, pelaksanaan strategi kecekapan bahan boleh menjadi sukar, terutamanya dari segi pemilihan strategi yang berkesan dan bersesuaian dengan keperluan sesebuah sektor pembuatan.

Pendekatan kajian secara campuran iaitu kualitatif dan kuantitatif telah dipilih untuk menjalani kajian ini khususnya untuk mengumpul dan menganalisis data adalah diperolehi daripada syarikat E&E Malaysia yang terpilih. Temu bual secara separa struktur (semi-structure) telah dijalankan untuk meneroka strategi kecekapan bahan dan faktor-faktor perubahan di dalam syarikat E&E. Manakala, pendekatan Analytic Hierarchy Process (AHP) telah digunakan untuk menentukan perkaitan kesan keutamaan faktor-faktor perubahan terhadap setiap strategi kecekapan bahan yang diterokai. Maka, dua isu utama kecekapan bahan telah dikenalpasti dalam kajian iaitu strategi kecekapan bahan dan juga faktor perubahan organisasi (pemandu, halangan, dan perangsang). Hubungkait dan pautan antara faktor perubahan dan strategi kecekapan bahan telah dibina dan dipersembahkan dalam bentuk model perlaksanaan strategi

kecekapan bahan. Di samping itu, satu alat sokongan membuat keputusan yang telah dibina untuk menentukan kesesuaian strategi kecekapan bahan yang akan dipilih.

Dalam kajian ini, penghubungan antara faktor perubahan organisasi dan strategi kecekapan bahan telah dikaitkan dengan mewujudkan satu model keputusan yang bersepadu bagi mengutamakan pemilihan strategi kecekapan bahan. Usul-usul keputusan pautan telah dibina bagi setiap faktor perubahan dan setiap strategi yang diterokai. Oleh itu, ini adalah satu sumbangan penting dalam konteks pengetahuan. Di samping itu, pertimbangan ke atas kepelbagaian faktor perubahan juga memberikan satu kefahaman teori yang baru ke atas perlaksaan strategi kecekapan bahan. Manakala, alat sokongan keputusan yang dibangunkan dalam kajian ini boleh menyumbang dari segi pengaplikasian ilmu teori yang diperolehi, terutamanya untuk membantu pengusaha industri dalam membuat keputusan yang sesuai bagi pemilihan strategi kecekapan bahan.

Kata kunci: alat sokongan keputusan, kecekapan bahan, kelestarian pembuatan.

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3R	:	Reduce, Reuse, Recycling
A	:	Matrix “A”
AHP	:	Analytic Hierarch Process
Aw	:	Local priorities of pair-wise comparisons
B	:	Constant for barrier
C	:	Constant for company
CF_{ni}	:	Change factor category
CI	:	Consistency Index
CNC	:	Computerized Numerical Control
CR	:	Consistency Ratio
DFM	:	Design for manufacturing
D	:	Constant for driver
DOE	:	Department of Environment
DSS	:	Design Support System
E	:	Constant for enabler
E&E	:	Electrical and electronic
EEA	:	European Environmental Agency
EHS	:	Environmental, Health, and Safety
ELECTRE	:	Elimination and choice expressing reality
EMS	:	Environmental Management System
EU	:	European Union
EUP	:	Energy Union Policy
E-Waste	:	Electronic Waste
FMM	:	Federation of Manufacturing Malaysia
i	:	The number of change factor groups

IEA	:	International Energy Agency
IR	:	Inconsistency Ratio
$M_{CFn=i}$	:	Mean value of the selected change factor
MCDM	:	Multiple criteria decision making
$MEFF_{n=i}$	:	Material efficiency strategy normalized value
MITI	:	Ministry of International Trade and International
n	:	Change factor group
OEM	:	Original equipment manufacturer
PCB	:	Printed Circuit Board
PCBs	:	Polychlorinated Biphenyls
R&D	:	Research and Development
RI	:	Random Index
RoHS	:	Restriction of Hazardous Substances
SMEs	:	Small and Medium Sized Enterprises
TOPSIS	:	Technique for order of preference by similarity to ideal solution
w	:	AHP Eigenvector
WEEE	:	Waste electrical and electronic equipment
λ_{max}	:	Largest Eigenvalue
VIKOR	:	VIsekriterijumsko KOmpromisno Rangiranje
X_i	:	Number of respondent
W_i	:	Weight of each change factor

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CHAPTER 1: INTRODUCTION

1.0 Overview

The purpose of this thesis is to report on the implementation of material efficiency strategies in Electrical and Electronic (E&E) manufacturing companies in Malaysia. This study is primarily based on semi-structured interviews and an AHP survey. This chapter begins with a background of this research, highlighting the issues pertaining to resource consumption and material efficiency in the current global economic development. This is followed by the problem statement, research objectives and scope of this research. The organization of this thesis is presented at the end of this chapter.

1.1 Background of the Research

The world population has increased dramatically over the last decades, particularly the population in developing countries. It is forecasted that the world population will increase by 50% by 2050 or projected to reach 10 billion (Coheran, 2003; United Nations Population Division, 1995). At the same time, global economic activities are estimated to increase by 300%, which will escalate the consumption of resources (EPA, 2009). According to the International Energy Agency (IEA, 2008) in the United States, the consumption of Earth's resources will double by 2050 if the world population continues to exploit and consume the resources inefficiently. The dramatic consumption of raw materials will lead to serious environmental problems such as depletion of natural resources, generation of solid wastes as well as severe impact on biodiversity (Heacock *et al*., 2016; Worrell *et al*., 2016).

In the manufacturing sector, the rapid economic development has amplified raw material consumption in manufacturing companies in order to fulfil the ever-increasing consumer demands (West & Schandl, 2013; Allwood *et al*., 2011). For these reasons, various environmental strategies were proposed to enhance resource utilization and reduce waste generation such as energy efficiency, 3R (reduce, reuse and recycle), waste minimization, resource efficiency and material efficiency (Glavic & Lukman, 2007). These strategies were proposed with the aim to prolong the lifetime of products, reduce energy consumption, recover the used materials into the resource supply chain, and minimize landfill problems. Nevertheless, the volumes of industrial wastes, consumer wastes and other environmental pollutants are escalating each year (Giusti, 2009). For instance, the global electronic waste (e-waste) is estimated at 20–25 million tonnes per year and yet, most of these products end up in the landfill due to recycling difficulties (Awasthi *et al*., 2016; Robinson, 2009).

According to Ashby (2012) and Abdul Rashid *et al.* (2008), one of the root causes that lead to huge amounts of solid waste generation is the inefficiency of resource utilization. For example, Lovins *et al*., (2007) highlighted that in the US, only 7% or less virgin materials are converted into end products whereas the remaining materials end up as wastes from various manufacturing processes. Only 1% or less of the used materials is recycled into the material chain. As a result, approximately half a trillion of materials become wastes from various manufacturing industries each year (Lovins, 2008).

Industrial waste is a worldwide problem in both developed and developing countries. Manufacturers are unable to reduce their production wastes due to the need for rapid economic development as well as increasing demand for products. However, manufacturers need to change their practices in order to use the available resources in an efficient and responsible manner (Verrier *et al*., 2016; Lifset & Eckelman, 2013). Practising material efficiency strategies is one of the effective and direct solutions to enhance material utilization and reduce environmental pollutants (Worrell *et al*., 2016; Ashby, 2012; Allwood *et al*., 2011; Abdul Rashid *et al*., 2008; Peck & Chipman, 2007).

In recent years, material efficiency strategies have gained much attention from the academia and industry (Lifset & Eckleman, 2013; Allwood *et al.*, 2011; Rouw & Worrell, 2011; Abdul Rashid *et al.*, 2008). However, studies have shown there are limited initiatives for manufacturers in practising material efficiency strategies on an industrial scale (Shahbazi *et al*., 2017; Lifset & Eckelman, 2013; Allwood *et al.*, 2011; Halme *et al.*, 2007). This scenario is primarily due to the manufacturers lacking the know-how on the effective ways of implementing these strategies (Shahbazi *et al*., 2017). In addition, material efficiency strategies appear to be strongly influenced by organizational change factors (i.e. drivers, barriers and enablers). These change factors may appear differently depending the industry preferences in their product design and processes involved. However, there is a lack of exploratory studies which link material efficiency solutions with these organizational change factors (Allwood *et al.*, 2013; Lifset & Eckelman, 2013; Worrell *et al.*, 2013). As a result, practitioners are unable to make the appropriate decision in selecting the suitable strategies to achieve material efficiency.

Hence, there is a critical need to investigate the link between organizational change factors and the suitable material efficiency strategies. In addition, there is a need to develop a decision support tool which will assist manufacturers in selecting the suitable material efficiency strategies. In this research, a series of industrial case studies of manufacturing companies in Malaysia was used to examine the implementation of material efficiency strategies and explore the link between organizational change factors and implementation of material efficiency strategies. This will provide a better understanding of "what" and "how" manufacturing companies practise material efficiency strategies.

1.2 Problem Statement

The lack of studies pertaining to the link between organizational change factors and implementation of material efficiency strategies have led to poor implementation of these strategies. Thus, there is an urgent need to understand the "know-how" in the implementation of material efficiency strategies, especially to model the relationship between the organizational change factors and the selection of material efficiency strategies. Furthermore, when dealing with multiple change factors selection, a decision support tool is needed, particularly to assist manufacturers in selecting the suitable material efficiency strategies based on the organizational factors relevant to them.

1.3 Aim, Objectives and Scope of this Research

1.3.1 Aim

The aim of this research is to provide useful insight on the implementation of material efficiency strategies in Malaysia, specifically in the E&E industry.

1.3.2 Objectives

The following objectives are set in order to achieve the aim stated above:

1. To identify the material efficiency strategies currently implemented in the E&E industry in Malaysia.
2. To identify the significant organizational change factors that influences the implementation of material efficiency strategies in the E&E industry in Malaysia.
3. To develop a decision support tool which will aid the selection of material efficiency strategies.
4. To validate the decision support tool using suitable case studies.

1.3.3 Scope

This research is conducted within the following scope:

1. The investigation on the implementation of material efficiency strategies is focused on E&E manufacturers in Malaysia.
2. The analysis of material efficiency strategies covers product design, manufacturing, distribution and logistics activities in E&E companies.

1.4 Organization of the Thesis

This thesis consists of nine chapters. A brief description of each chapter is given below.

Chapter 1-Introduction: A brief background of this research is presented in this chapter. The problem statement, aim, objectives and scope of this research are presented in this chapter.

Chapter 2- Literature review: A comprehensive review on the literature relevant to this research is presented in this chapter, with emphasis on sustainable manufacturing and material efficiency strategies. The gaps in the existing body of knowledge are identified and the research questions are formulated in order to guide the research design.

Chapter 3- Research methodology: The research design as well as the methods used to conduct this research and analyse the data are described in detail in this chapter.

Chapter 4- Insights of material efficiency practices in Malaysian E&E companies: The results obtained from the semi-structured interviews are presented in this chapter. This chapter includes selection of the sample, data collection procedure, qualitative analysis of themes and a discussion of the material efficiency themes. The qualitative findings are summarized at the end of this chapter.

Chapter 5- Evaluation of material efficiency change factors: The results obtained from the AHP survey are presented and discussed in this chapter, with emphasis on the influence of organizational change factors on the selection of material efficiency strategies.

Chapter 6- Propositions of material efficiency strategy: The propositions of material efficiency strategy with its change factors were built and described in this chapter. It includes of obtaining the importance weight of each change factor to influence different material efficiency strategy. In the end of this chapter, the propositions of nine material efficiency strategies with reflect to 25 change factors are presented.

Chapter 7- Material efficiency decision support tool: The development of a material efficiency decision support tool is described in this chapter, including the formulation of the decision rules, construction of the decision flow chart, and development of the decision support tool worksheet.

Chapter 8- Validation for the material efficiency decision support tool: The validation process of the decision support tool based on industrial case studies is presented in this chapter. There are three approaches used in this research to validate the decision support tool: (1) Design validation, (2) Output validation, and (3) End-use validation.

Chapter 9- Conclusions: The conclusions drawn from the findings of this research are presented in this chapter. The research problem and objectives are revisited, followed by a summary of the key findings and implications of this research. The contribution to new knowledge and directions for future research are also presented in this chapter.

CHAPTER 2: LITERATURE REVIEW

2.0 Overview

A review of the past and recent literature pertaining to material efficiency practices in the manufacturing sector is presented in this chapter. This includes the definitions of material efficiency, material efficiency strategies, and organizational change factors which influence the implementation of material efficiency strategies. The gaps in the existing body of knowledge are identified and the research questions are formulated at the end of this chapter in order to guide the research design.

2.1 Sustainable Manufacturing

Sustainable manufacturing has received much attention from academicians and practitioners over the last decade. According to the Kriebel and Crumbley (2001) from the Lowell Center for Sustainable Production, sustainable manufacturing or sustainable production is defined as:

"The creation of goods and services using processes and systems that are:

- Non-polluting;
- Conserving of energy and natural resources;
- Economically viable;
- Safe and healthy for workers, communities, and consumers;
- Socially and creatively rewarding for all working people."

Sustainable manufacturing is beneficial for the manufacturing industry since it preserves resources, increases energy efficiency, boosts economic performance and promotes a healthier production environment (Seliger & Kim, 2008). This leads to the development of various environmental strategies including waste minimization, 3R strategies (reduce, reuse, and recycle), resource efficiency and material efficiency strategies. In this study, material efficiency was found works as an important strategy component to achieve sustainable manufacturing, particularly in environmental and economical sustainability aspect. Unfortunately, material efficiency strategies are not well-understood, particularly the effective way to implement it at the industry level (Lifset & Eckelman, 2013).

2.2 Definition of Material Efficiency

In recent years, material efficiency is one of the main concerns of industry practitioners (Lifset & Eckelman, 2013; Ashby, 2012; Allwood *et al.*, 2011; Rohn *et al.*, 2011; Rouw & Worrell, 2011; Walz, 2011 in Walz *et al.*, 2008; Walz, 2010). In material efficiency, the term "efficiency" is defined as the ratio of the measurement of output divided by the input (Lifset & Eckleman, 2013; Ashby, 2012). Worrell *et al.* (1995) defined material efficiency as the practices to enhance the usability of raw materials without compromising the original functions and purpose of the product. Similarly, Allwood *et al.* (2011), Lilja (2009a), and Peck and Chipman (2007) defined material efficiency as the reduction of a particular amount of raw material intake to produce an end product. A process is considered as less efficient if extra materials are consumed. According to Ashby (2012), the primary aim of material efficiency is to reduce the intake of raw materials and reduce residual wastes such as solid wastes and carbon dioxide (CO_2) emissions throughout the manufacturing activities. Therefore, manufacturers are encouraged to emphasize more on services rather than selling the physical product itself.

van der Voet *et al.* (2003) argued that material efficiency should not only be focused on reducing the weight of a product, but also reduce the usage of hazardous substances in a product as well as production activities. They also stressed that material recovery is a less desirable approach to achieve material efficiency because it leads to other issues such as high energy consumption, water pollution resulting from the usage of chemicals, as well as release of CO_2 emissions during the material recovery phase. Lifset & Eckelman (2013) also had a similar perspective since they stated that material efficiency needs to focus on the effects of material usage rather than reducing the physical content of the material.

According to Abdul Rashid (2009), material efficiency is a strategy that not only prevents materials from becoming wastes but also addresses pollution due to the types of materials used. Material efficiency adds value to products or services through efficient use and the appropriate selection of materials. Material efficiency is a collection of manufacturing practices that are coordinated and implemented actively in order to:

- Use less materials per product produced, and/or;
- Generate less wastes per product, and/or;
- Use materials that use less energy to produce each product, and/or;
- Select materials that reduce environmental impact (e.g. less toxic, recoverable, recyclable and disposable).

The definition provided by Abdul Rashid (2009) was adapt in this study because it is a holistic definition rather than a simple input/output ratio since it takes into account additional concerns, such as energy, toxicity and other environmental impacts. In order to achieve material efficiency, product design and manufacturing activities are the two key areas which need to be considered (Ashby, 2012; Allwood *et al.*, 2011; Lilja, 2009a). In product design, material efficiency strategies include designing for longer life, designing for reuse, designing for multi-functionality, designing for serviceability, material substitution, and designing lightweight products. In manufacturing process, material efficiency strategies include yield improvement, batch processing, energy efficiency, use of pre-cut materials and minimizing secondary processes.

2.3 Material Efficiency Strategies

In the manufacturing sector, material efficiency can be achieved using various strategies. According to Peck and Chipman (2007), reducing the total amount of material flow in the production process is the most direct and simplest solution to achieve material efficiency. For instance, "light-weighting" of a product or reducing the weight of the product can yield significant material savings and reduce waste stream in the production.

Lilja (2009a) categorized material efficiency strategies according to the phases of the product life cycle such as material efficiency in products, material efficiency in consumption, and material efficiency in the production process. Each phase involves a different group of practitioners with different strategies. For example, in order to achieve material efficiency in product design, designers should use strategies such as extending the product lifetime, designing for reuse and multi-functionality, optimization of material use and designing for recycling. In the production process, material efficiency can be achieved through effective material purchasing, process optimization, prevention of material loss as well as recycling production wastes. In the consumption stage, material efficiency can be attained by shared use of products, recycling wastes, designing for ease of maintenance and reusing the products.

According to Ashby (2012), material efficiency can be achieved through three types of strategies: a.) Improving material technology and engineering design, b.) Economic instruments (through legislation) and c.) Social adaptation (lifestyle). Hence, material efficiency can be achieved in different ways, depending on the category. For instance, in material technology, industry practitioners can improve material efficiency by introducing new materials that are easier to process with less detrimental impact on the environment. In engineering design, material efficiency can be achieved by using fewer materials in product development and incorporating end of life strategies into the product. For economic instrument or legislation aspect, it can be used as a tool to ensure that the usage of materials and the method of processing creates less environmental problems. Social adaptation is related to the lifestyle of the community and this is reflected by less material usage such as promoting shared ownership and not splurging on unnecessary products.

In this study, Lilja's model (Lilja, 2009a) is adapted with minor modification to include product distribution area in material efficiency improvement. Whereas, material efficiency strategies that beyond the boundaries of industry practitioners will not be considered, e.g. legislative related strategies. The details of various material efficiency strategies from product design, manufacturing, and product distribution are discussed in the following sections. A summary of material efficiency strategies is given in Table 2.1.

2.3.1 Material Efficiency Strategies in Product Design

Product design is as an important phase in practising material efficiency strategies. By reviewing the strategies proposed by several researchers (Ashby, 2012; Allwood *et al.*, 2011; Lilja, 2009a), there are six main practices involved in product design in order to achieve material efficiency: a.) Design products with fewer materials; b.) Design products for longer life; c.) Design for remanufacturing; d.) Component re-use; e.) Design for material recovery; and f.) Material substitution. These strategies are elaborated in the sub-sections below.

a. Design Products with Fewer Materials

The common strategies used by the manufacturing sector in order to reduce materials are to design products with fewer materials or product light-weighting (Lilja, 2009b; Chryssolouris *et al.*, 2008; Peck & Chipman, 2007). Other researchers have defined this strategy as “doing with less” (Ashby, 2012; Allwood, *et al.*, 2011). This strategy is among the simple ways to achieve material efficiency and reduce overall environmental impact. This can be done by reducing the product weight by reducing the overall size of the product, decreasing the number of parts, or reducing the material use of the product (Peck & Chipman, 2007). However, not all lightweight products are guaranteed to minimize environmental impact if the materials used in the product development are highly hazardous (Jang, 2010). For instance, even though the E&E industry minimizes use of hazardous substances such as lead and mercury, it still has a significant impact on the environment.

At present, in the manufacturing industry, producing lightweight products requires advanced technologies and improved material properties which are rather costly for manufacturers (Chryssolouris *et al*., 2008; Peck & Chipman, 2007). However, designing lightweight products is not a priority in some industries such as aerospace and medical industries since the safety and quality of the product are of utmost importance (Leadbitter, 2002). Therefore, in the long term, product light-weighting should not only emphasize the physical attributes of the product, but also the materials used to fabricate the product which could reduce impacts to the environment and also user (van der Voet *et al.*, 2003).

b. Design Products for Longer Life

The aim of design for longer life is to extend the product life cycle. Extending the product life cycle helps reduce the speed for new material extraction. Among the common practices used to achieve this are ease of maintenance and ease of repair (Allwood *et al.*, 2013). In order to design long-lasting products, it is important to ensure consistent use of high-quality materials (Lilja, 2009a; Hekkert *et al.*, 2002). By improving the usage of materials of a product, the likelihood of product failure due to inferior product quality can be reduced to a certain extent (Ashby, 2012; Allwood *et al.*, 2010). In addition, some products designed for longer lifetime are made from recyclable materials, which will promote the material recovery process (Lauridsen and Jørgensen, 2010). However, Ashby (2012) noted that electronic products typically have shorter life cycles due to rapid changes in the trend, style and technology of the product. This in turn, inhibits the design for longer life strategy for electronic products (Ashby, 2012). This results in electronic products being discarded at the end of life in both developing and advanced countries. According to Widmer *et al.* (2005), more than 10 tonnes of electronic wastes are generated from the US each year. In China, approximately 10 tonnes of e-wastes are generated annually from personal computers.

c. Design for Remanufacturing

Design for remanufacturing is another strategy to extend the life cycle of the product (Allwood *et al.*, 2011). This strategy involves sending the product back to the original equipment manufacturer (OEM) to repair and replace the failed parts in order to restore the product close to new condition (Östlin *et al.*, 2009). The common products designed for remanufacturing are automotive parts (Subramoniam *et al.*, 2009). In addition, a large number of products are now being embedded with "design for longer life" features. These features include improving the mechanical design of the product and using durable materials to extend the product lifetime. Hence, the users can benefit from a longer product warranty, which reflects the quality and durability of the product. Producing products with longer lifetimes certainly reduces wastes and the usage of virgin materials. However, the implementation of this strategy alone will not solve issues related to material scarcity without awareness from the consumers since the consumers are the end users who are likely to have higher buying power.

d. Component Reuse

Component reuse is another important strategy in order to achieve material efficiency (Allwood *et al.*, 2013; Allwood *et al*., 2011). To improve product usability, designing a product with component reuse will extend the product life cycle, which will reduce wastage from obsolete products and reduce the demand for virgin materials in order to fabricate new parts (Peck & Chipman, 2007). With these considerations, more industries are encouraged to design their products based on a modular concept for ease of product repair and replacement, which will extend the product life cycle (Ashby, 2012; Lilja, 2009b).

e. Design for Material Recovery

In order to achieve material efficiency, material recovery strategies such as product remanufacturing and recycling are gaining popularity since they enable producers to recover and minimize wastes before the products are disposed into landfill sites (Allwood *et al.*, 2011; Osibanjo & Nnorom, 2007). The automotive industry is one of the industries that implement product remanufacturing in order to reduce material wastage by restoring the malfunctioned products to an almost new condition (Allwood *et al.*, 2011; Subramoniam *et al.*, 2009). The easiest way to implement design for recycling is to use recyclable raw materials (Shahbazi, 2015; Ashby, 2012; Allwood *et al.*, 2011; Lilja, 2009a). In response to rapid technology changes, designing electronic products that can be dismantled easily for recycling will contribute significantly towards the material recovery rate (Jang, 2010). For example, recycling electronic devices enables the recovery of precious materials such as gold and copper (Garlapati, 2016), and plastics materials for other purposes (Sommerhuber *et al.*, 2016). However, e-wastes are still on the rise due to limited recycling even though they are embedded in the design of E&E products (Osibanjo & Nnorom, 2007).

f. Material Substitution

Materials should be consumed in a more cautious manner, especially for rare and non-renewable materials. Material substitution can be done by selecting various materials with similar characteristics that are available in abundance (Ashby, 2012; Osibanjo & Nnorom, 2007). Most of the applications relating to material substitution are also due to the need to comply with environmental policies in order to minimize environmental impact such as reducing CO_2 emissions (Hekkert *et al*., 2002; Hekkert *et al.*, 2000). In addition, complying with the Restriction of Hazardous Substances (RoHS) directives can limit the E&E industry's use of hazardous materials that are very dangerous to recycle (Widmer *et al.*, 2005) as well as to improve the performance and reduce manufacturing costs (Allwood *et al.*, 2011). In the automotive sector, lighter materials such as aluminium are used as alternative materials since it can significantly reduce the weight of the vehicle. At the same time, this material substitution can help reduce CO_2 emissions by delivering more torque to the vehicle due to the lighter weight of the vehicle. This in turn, will reduce fuel consumption.

2.3.2 Material Efficiency Strategies in the Manufacturing Phase

a. Process efficiency

Material efficiency can be achieved by increasing the efficiency of production operations. This can be done by reducing the production activity or improving the method of processing raw materials. Improving manufacturing operations not only reduces the overall production time but also minimizes potential solid wastes along the processes (Wiktorsson *et al.*, 2008). Reducing the processing steps, eliminating unnecessary processes and improving material handling processes are among the approaches to increase process efficiency. The processing steps can be reduced by eliminating unnecessary secondary processes or selecting the most effective manufacturing method (Ingarao *et al.*, 2011). Batch processing is one of the practices widely used to reduce the processing steps and shorten the total production line (Münstermann *et al.*, 2010). Furthermore, the energy consumption can be reduced by simplifying operations in the production lines by implementing necessary improvements (Rahimifard *et al.*, 2010; Sikdar, 2007). Improving material handling is another strategy that can reduce solid waste generation, which can be achieved by having an automated system in order to minimize human errors (Mahalik & Nambiar, 2010).

b. Yield improvement

Material efficiency can be attained by improvements in the production yield. Some of the common industrial practices used to improve product yield during manufacturing operations include minimizing product testing, practising safe raw material handling, reducing the number of product changeovers, and improving the jig and fixture in order to minimize the materials to be scrapped (Allwood *et al.*, 2011; Lilja, 2009b; Wu *et al.*, 2006).

c. By-product recycling

By-product recycling should be introduced in order to recover the solid wastes generated along the production activities (Pajunen *et al.*, 2012; Lilja, 2009b). This is especially the case for recyclable materials such as metals, plastics, and paper (Kurdve *et al.*, 2015). Nevertheless, by-product recycling must be supported by the available recycling facilities as well as infrastructure of the companies (Pajunen *et al.*, 2013). Thus, most of the time, manufacturers still prefer to sell their product scrap to third parties such as recyclers because of the high costs of investing in internal recycling systems.

d. Purchasing pre-fabricated materials

In material sourcing, purchasing pre-cut or pre-fabricated parts can help reduce unnecessary industrial wastes (Ashby, 2012; Riley *et al.*, 2005) such as remaining material off-cuts. In addition, sourcing for pre-cut materials can reduce additional energy consumption, reduce product scrap due to manufacturing mistakes, shorten the manufacturing process time and reduce generation of by-products. Therefore, it is important to select a supplier with technological capabilities and environmental consciousness such as an ISO 14001 compliant supplier. It is crucial for manufacturers to share their material specifications and requirements with the suppliers so that the suppliers can fulfil their requirements for efficient material intake (Lee *et al.*, 2009).

2.3.3 Material Efficiency Strategies in Product Distribution

The main purpose of packaging is to provide protection to the finished products. Each product needs to be packed before it can be shipped to a particular location or to the end user. However, the amount of materials consumed for packaging is escalating each year, especially from industrialized countries (Worrell & van Sluisveld, 2013; Rouw & Worrell, 2011). Hence, there is a need for efficient use of raw materials in product packaging.

a. Green packaging

The use of recyclable packaging materials is one of the effective strategies to reduce waste generation, which in turn, helps attain material efficiency (Peck & Chipman, 2007; Tien *et al.*, 2002). As a result, the use of recyclable materials for packaging is an obvious strategy to extend the life cycle of raw materials such as papers, cardboards and wood (Zhang & Zhao, 2012; Hanssen *et al.*, 2003).

b. Bulk packaging

Material efficiency can also be achieved through packaging initiatives. For instance, products can be packed in bulk rather than as single units in order to save space and transportation costs (Lee & Lye, 2003). In addition, manufacturers can opt to use a lightweight packaging design in order to reduce the weight of packaging and minimize the amount of materials used to pack the products (Lee & Lye, 2003).

c. Returnable packaging

Another option in product distribution is to use returnable packaging. This strategy involves sending the packaging to the manufacturer for reuse such as substituting cardboard boxes with returnable wooden crates (Peck & Chipman, 2007; Kroon & Vrijens, 1995). However, this strategy may only be suitable for local or domestic logistics and it is not a feasible approach for air freight logistics. In addition, returnable packaging may increase the load of logistics and occupy more spaces. For these reasons, this strategy is not preferable among manufacturers.

Table 2.1: Summary of material efficiency strategies

Material efficiency area	Strategy	Benefits	References
Product design	Design with fewer materials	• Reduce material intake • Reduce product size • Reduce product weight • Reduce material intake • Shorten manufacturing and product assembly time	Ashby, 2012; Lilja, 2009b; Allwood, *et al.*, 2011; Chryssolouris *et al.*, 2008; Peck & Chipman, 2007
	Design for longer life	• Extend product life cycle • Reduce virgin material extraction • Promote material recovery	Allwood *et al.*, 2013; Allwood *et al.*, 2010; Ashby, 2012; Lauridsen & Jørgensen, 2010; Lilja, 2009a; Hekkert *et al.*, 2002
	Design for remanufacturing	• Reduce energy use during manufacturing • Reduce virgin material use	Allwood *et al.* 2011; Subramoniam *et al.*, 2009; Osibanjo & Nnorom, 2007;

Table 2.1, continued

	Design for reuse	• Extend product life cycle • Reduce energy usage in the manufacturing process	Allwood *et al.*, 2013; Ashby, 2012; Allwood *et al.* 2011; Lilja, 2009b; Peck & Chipman, 2007
	Design for recycling	• Recover materials from obsolete products • Reduce virgin material extraction	Ashby, 2012; Allwood *et al.*, 2011; Lilja, 2009a; Subramoniam *et al.*, 2009; Osibanjo & Nnorom, 2007;
	Material substitution	• Facilitate manufacturing process • Reduce energy consumption • Facilitate material recovery • Reduce manufacturing costs • Reduce solid waste generation	Ashby, 2012; Allwood *et al.*, 2011; Osibanjo & Nnorom, 2007; Hekkert *et al.*, 2002; Hekkert *et al.*, 2000
Manufacturing process	Process efficiency	• Reduce solid waste generation • Reduce manufacturing time • Eliminate unnecessary processes • Reduce energy usage	Ingarao *et al.*, 2011; Mahalik & Nambiar, 2010; Münstermann *et al.*, 2010; Rahimifard *et al.*, 2010; Wiktorsson *et al.*, 2008; Sikdar, 2007
	Yield improvement	• Reduce solid waste generation from manufacturing processes • Increase productivity	Allwood *et al.*, 2011; Lilja, 2009a; Wu *et al.*, 2006
	By-product recycling	• Recover the solid wastes and convert them into resource	Pajunen *et al.*, 2012; Lilja, 2009a
	Pre-fabricated materials	• Reduce machining time • Reduce solid waste generation • Reduce energy consumption	Lilja, 2009a; Riley *et al.*, 2005
Product Distribution	Green packaging	• Recovering material from packaging	Zhang & Zhao, 2012; Peck & Chipman, 2007; Hanssen *et al.*, 2003; Tien *et al.*, 2002
	Bulk packaging	• Reduce use of packaging materials	Lee & Lye, 2002
	Lightweight packaging	• Reduce use of packaging materials	Lee & Lye, 2002
	Returnable packaging	• Extend product life cycle • Reduce packaging wastes	Peck & Chipman, 2007; Kroon & Vrijens, 1995

2.3.4 Industry's Problems at selecting Material Efficiency Strategy

Selecting an appropriate material efficiency strategy could be determined by the change factors faced by a company (Shahbazi *et al*., 2016; Worrell *et al*., 2016; Pajunen *et al*., 2012). These factors could be the drivers such as to reduce the environmental impacts, enhance cleaner production, and etc. Nevertheless, there are other factors that also inherit the decision to select the strategy such as the barriers faced. For example, the lack of technology facilities, incapability of the available processes, and etc. Therefore, selecting a material efficiency strategy can become challenging, especially with the existence of various change factors, particularly that varying depending to different type of industry, products produced, and different market requirements. In addition, the interrelated of the change factors is another problem which contributes to inherit the manufacturer to select the most appropriate strategy based on their company situation. Thus, in depth study of the organization change factors are important to be derived as the decision criteria for conducting material efficiency strategy.

2.4 Organizational Change Factors which Influence the Implementation of Material Efficiency Strategies

Organizational change factors are defined as factors that are able to cause dynamic changes in an organization due to new government policies, market trends and economic globalization (Avrichir, 2003). According to Price and Chahal (2006), change factors refer to internal and external factors that are able to drive or inherit an activity to take place. Therefore, manufacturers need to embrace change in order to remain competitive by implementing new strategies. For example, internal factors can be new technologies whereas external factors can be new legislation requirements (Leonidou *et al.*, 2017). Change factors can act as drivers, barriers, motivators or enablers to improve the organization to a certain extent (Pajunen *et al.*, 2012).

Several studies have been conducted to identify change factors in green strategies. Honkasalo *et al.* (2005) studied the drivers for eco-efficiency using a case study of the dairy industry in Europe. Luken and van Rompaey (2007) examined the drivers and barriers in the adoption of environmentally sound technology using qualitative analysis of 105 manufacturing plants across nine developing countries. Walker *et al.* (2008) explored the drivers and barriers of seven different private and public sector organizations towards environmental supply chain management practices. Pajunen *et al.* (2012) demonstrated that both drivers and barriers are the key indicators which assist industry practitioners in understanding and formulating appropriate solutions in the implementation of material efficiency strategies. Johansson and Winroth (2010) also highlighted that the development of environmental strategies can be expedited by knowing the drivers and barriers. Based on the findings of these studies, it can be deduced that change factors have a profound impact in ensuring the success of implementing an environmental strategy in an organization. The change factors that influence the implementation of material efficiency strategies in manufacturing companies are presented in the following sub-sections.

2.4.1 Drivers in Implementing Material Efficiency Strategies

The term “driver” is defined as the factor that is able to “force” the manufacturer to conduct an activity such as material efficiency strategy (Leonidou *et al*., 2017; Okereke, 2007). In this study, there are two groups of drivers commonly studied: (a) Internal drivers and (b) External drivers. According to Walker *et al.* (2008), internal drivers are essentially organizational factors that encourage the organization to undertake manufacturing practices in order to attain a certain goal such as to increase the organization’s profits. On the other hand, external drivers refer to external pressures that force manufacturers to change such as complying with environmental regulations.

The internal and external drivers that influence the implementation of material efficiency strategies are summarized in Table 2.2.

2.4.1.1 Internal Drivers

a. Organizational Factors

There is a variety of organization-related factors that will motivate the organization to achieve material efficiency. For manufacturers, the desire to reduce material intake is one of the major drivers to achieve material efficiency (Ashby, 2012; Pajunen *et al.*, 2012; Allwood *et al.*, 2011; Lilja, 2009a; Abdul Rashid *et al.*, 2008), considering that the price of raw materials continues to rise due to the scarcity of resources. Unsurprisingly, many studies have shown that practising material efficiency strategies is mainly driven by the need to reduce environmental impact such as reducing energy consumption, reducing usage of toxic and hazardous substances, and reducing waste generation (Pajunen *et al.*, 2012; Allwood *et al.*, 2011; Abdul Rashid *et al.*, 2008; Peck & Chipman, 2007; Hanssen *et al.*, 2003; Ilomäki & Melanen, 2001), particularly during production and when the product reaches its end of life.

In general, manufacturers always aim to maximize their profit margin with minimum expenditure on materials. For this reason, practising material efficiency strategies is desirable since it helps increase profits by reducing material purchases, optimizing material usage and reducing offcut solid wastes (Pajunen *et al.*, 2012; Allwood *et al.*, 2011; Ilomäki & Melanen, 2001). In addition, when the products are designed with lighter weight, this will help reduce logistics and inventory costs due to the smaller product size (Zhang & Zhao, 2012).

Table 2.2: Summary of drivers in implementing material efficiency strategies

	Drivers	Description	References
Internal drivers (Organizational drivers)	Reduce material intake	• To reduce incoming material usage	Ashby, 2012; Pajunen *et al.*, 2012, Lilja, 2009ab; Allwood *et al.*, 2011; Abdul Rashid *et al.*, 2008
	Reduce energy consumption	• To reduce energy usage in processing raw materials	Pajunen *et al.*, 2012; Allwood *et al.*, 2011; Abdul Rashid *et al.*, 2008; Peck & Chipman, 2007; Hanssen *et al.*, 2003; Ilomäki & Melanen, 2001
	Reduce environmental impact	• To reduce usage of hazardous substances	Pajunen *et al.*, 2012; Allwood *et al.*, 2011; Abdul Rashid *et al.*, 2008; Peck & Chipman, 2007; Hanssen *et al.*, 2003; Ilomäki & Melanen, 2001
	Implementation costs	• To reduce operation costs	Pajunen *et al.*, 2012; Allwood *et al.*, 2011; Ilomäki & Melanie, 2001
		• To decrease logistics costs	Zhang & Zhao, 2012
External drivers	Legislation and regulations	• Fulfil environmental regulations	Pajunen *et al.*, 2012; Allwood *et al.*, 2011; Fernández-Viñé *et al.*, 2010; Peck & Chipman, 2007; Tonglet *et al.*, 2004; Hanssen *et al.*, 2003; Min & Galle, 2001
		• Obtaining ISO14001 certification	Pajunen *et al.*, 2012; Allwood *et al.*, 2011; Ilomäki & Melanie, 2001
		• Gaining incentive / tax reduction / governmental support / increased taxes	Pajunen *et al.*, 2012; Allwood *et al.*, 2011; Fernández-Viñé *et al.*, 2010; Peck & Chipman, 2007; Tonglet *et al.*, 2004
	Suppliers and supply chains	• Reliable green material supply chain	Hassani *et al.*, 2012; Diabat & Govindan, 2011; Montalvo & Kemp, 2004; Walker *et al.*, 2008
	Competitors	• Improve business competitiveness	Pajunen *et al.*, 2012; Yalabik & Fairchild, 2011; Triebswetter & Wackerbauer, 2008; Hanssen *et al.*, 2003; Porter & van der Linde, 1995
	Society and public pressure	• Public pressure	Pajunen *et al.*, 2012; Peck & Chipman, 2007
		• Pressure from environmental parties (other stakeholders)	Pajunen *et al.*, 2012; Fernández-Viñé *et al.*, 2010; Ilomäki & Melanie, 2001
		• Environmental image / gaining publicity	Georgiadis & Besiou, 2008; Luken & van Rompaey, 2008; Tonglet *et al.*, 2004; Ilomäki & Melanie, 2001
	Customer requirements	• Fulfil environmental standards	Pajunen *et al.*, 2012; Ferna´ndez-Vin˜e´ *et al.*, 2010; Ilomäki & Melanen , 2001

2.4.1.2 External Drivers

a. Legislation and Regulations

Environmental regulations were perceived as an important driver that can enhance material use in manufacturing companies (Pajunen *et al.*, 2012; Allwood *et al.*, 2011; Fernández-Viñé *et al.*, 2010; Lilja, 2009a; Peck and Chipman, 2007; Tonglet *et al.*, 2004; Hanssen *et al.*, 2003; Min and Galle, 2001). Stringent environmental regulations and policies have forced manufacturers to use their raw materials efficiently. For example, manufacturers in the E&E industry are restricted regarding the use of highly toxic substances in producing their products. In addition, manufacturers need to design and produce their products taking into account material recovery at the product's end of life. Compliance with the ISO 14001 standards is another important driver to ensure that fewer materials are wasted during the manufacturing process (Pajunen *et al.*, 2012; Allwood *et al.*, 2011; Ilomäki & Melanen, 2001). Most manufacturers, especially those from advanced countries, are given extra incentives and tax reduction from the government if they practise material efficiency strategies (Pajunen *et al.*, 2012; Allwood *et al.*, 2011; Fernández-Viñé *et al.*, 2010; Peck & Chipman, 2007; Tonglet *et al.*, 2004). For these reasons, there is growing interest among manufacturers to practise environmental strategies including material efficiency practices.

b. Suppliers and Supply Chains

Suppliers are another important factor that can aid and motivate manufacturers to practise material efficiency strategies. For example, reliable green material supply has motivated manufacturers to source recyclable raw materials for their products (Hassani *et al.*, 2012; Walker *et al.*, 2008; Montalvo & Kemp, 2004). These initiatives ensure that the manufactured products are environmentally friendly. In addition, suppliers need to collaborate as a good business partner with the manufacturers, particularly to update the specifications of raw materials. With good collaboration, there is a great potential for products to be designed with green characteristics (Diabat & Govindan, 2011).

c. Competitors

In current business and economics, the efficient use of materials is directly linked with business competitiveness. According to previous studies, manufacturers have begun to implement various material efficiency strategies in order to remain competitive in the market (Pajunen *et al.*, 2012; Hanssen *et al.*, 2003; Porter & van der Linde, 1995). The high pressure from competitors has led manufacturers to implement continuous improvement and integrate innovative ideas into their products (Pajunen *et al.*, 2012; Yalabik & Fairchild, 2011). For example, many electronic products are designed to be lightweight in order to meet customer requirements and also to reduce material usage. Manufacturers are motivated to practise material efficiency strategies in order to reduce material procurement costs, which in turn, helps them survive in the competitive market. Thus, material efficiency strategies are needed to enhance material productivity and ensure competitiveness of the company.

d. Society and public pressure

Industrial activities have a significant impact on the environment. Therefore, increase in public pressure has spurred manufacturers to use raw materials efficiently, especially those from advanced countries (Pajunen *et al.*, 2012; Peck & Chipman, 2007). The public has begun to demand green products or environmentally friendly products. Therefore, the current society will evaluate the reputation of a product based on the environmental image or reputation of the company (Georgiadis & Besiou, 2008; Luken & van Rompaey, 2008; Peck & Chipman, 2007). For example, consumers from European countries prefer products made from recyclable materials as well as products that can be easily dismantled for recycling (Lilja, 2009a). Hence, manufacturers need to practise material efficiency strategies in order to sell their products to the global market.

e. Customer requirements

Fulfilling customer requirements is one of the main goals in running a business. With the increasing consumer demands on product requirements, manufacturers nowadays need to review their product designs and operations to ensure that they are getting the right material sources which comply with certain environmental standards (Pajunen *et al.*, 2012; Fernández-Viñé *et al.*, 2010; Ilomäki & Melanen, 2001). In fact, improvements in product quality will bring benefits to the manufacturers such as an increase in their market share. Furthermore, the products produced by the manufacturers are less detrimental to the environment as well as end users. Thus, consumers play a significant role in changing the manufacturer's practices (product design and production activities) to ensure that the manufacturer delivers products that fulfil the customers' requirements such as eco-products.

2.4.2 Barriers in Implementing Material Efficiency Strategies

According to Hillary (2004), there are two types of barriers that influence environmental practices: (a) internal barriers and (b) external barriers. Internal barriers stem from the organization itself whereas external barriers arise from outside the organization and therefore, these barriers are less controlled by the organization. In this research, the barrier constructs are identified from studies pertaining to environmental strategies (Shahbazi *et al.*, 2016; Abdul Rashid *et al.*, 2013; Pajunen *et al.*, 2012; Allwood *et al.*, 2011; Lilja, 2009b; Peck & Chipman, 2007), as presented in the following sub-sections. The barriers in implementing material efficiency strategies are summarized in Table 2.3.

2.4.2.1 Internal Barriers

a. Lack of Awareness

Some manufacturing sectors still perceive that the resources available are inexpensive and abundant (Allwood *et al.*, 2011) and thus, implementing material efficiency strategies is less important to them (Halme *et al.*, 2014; Lilja, 2009a). According to Halme *et al.* (2014), unlike other environmental strategies, implementing material efficiency strategies does not have any significant impact on business competency or boosting the reputation of the company. As a result, the awareness of material efficiency strategies is still rather low among manufacturers.

Table 2.3: Summary of barriers in implementing material efficiency strategies

	Barrier	Description	References
Internal barriers	Lack of awareness	• Poor environmental awareness	Allwood *et al.*, 2011; Peck & Chipman, 2007
	Unwillingness to change	• Not ready for changes, no obligation to change • Less interest to participate	Shahbazi *et al.*, 2016; Allwood *et al.*, 2013; Abdul Rashid & Evans, 2012; Allwood *et al.*, 2011; Lilja, 2009a; Lilja , 2009b; Peck & Chipman, 2007
	Implementation costs	• High cost to invest in technology • Unwilling to invest in unproven strategies • High cost to obtain environmental permits • High management cost (e.g. training)	Pajunen *et al*, 2012; Allwood *et al.*, 2011; Lilja, 2009a; Lilja, 2009b; Luken & Van Rompaey , 2008; Moors *et al.*, 2005
	Restrictions in product design	• Restrictions on the type of materials used • Restrictions on product design changes	Allwood *et al.*, 2011; Abdul Rashid , 2009; Lilja, 2009b; Peck & Chipman, 2007
	Lack of information and knowledge	• Lack of technical knowledge • Lack of support (e.g. policies, guidance) • Limited exposure to material efficiency information / concept	Shahbazi *et al.*, 2016; Allwood *et al.*, 2013; Pajunen *et al.*, 2012; Lodenius *et al.*, 2009; Luken & van Rompaey, 2008; Peck & Chipman, 2007; Hanssen *et al.*, 2003; Hekkert *et al.*, 2000;

Table 2.3, continued

	Technological limitations	• Limited internal facilities available to support material efficiency • Lack of technological advancement for material efficiency	Shahbazi *et al*., 2016; Allwood *et al.*, 2013; Worrell & van Sluisveld, 2013; Pajunen *et al.*, 2012; Luken & van Rompaey, 2008; Hekkert *et al.*, 2002
External barriers	Regulations	• International environmental regulations and legislation • Lack of local support on regulations / legislation	Allwood *et al.*, 2013; Worrell & van Sluisveld, 2013; Abdul Rashid & Evans, 2012; Pajunen *et al.*, 2012; Lilja, 2009a
	External support	• Lack of governmental support (e.g. certificates, subsidies, incentives) • Lack of material efficiency experts • Limited support from other sectors (e.g. recyclers, recycling technology)	Allwood *et al.*, 2013; Pajunen *et al.*, 2012; Allwood *et al.*, 2011; Lilja, 2009a
	Supplier and supply chain constraints	• Unsupportive suppliers • Limited green suppliers / capable suppliers with technology • Lack of suppliers that can support material efficiency strategies • International suppliers face difficulties in supporting material efficiency strategies (e.g. compliance with different regulations, inability to control sourcing)	Shahbazi *et al*., 2016; Abdul Rashid & Evans, 2012; Pajunen *et al.*, 2012; Allwood *et al.*, 2011; Lodenius *et al.*, 2009; Hillary, 2004; Hekkert *et al.*, 2002; Hekkert *et al.*, 2000
	Customer requirements	• Lack of demand for green products • Little economic pressure • Rapid product changes	Abdul Rashid & Evans, 2012; Pajunen *et al.*, 2012; Allwood *et al.*, 2011; Peck & Chipman, 2007

b. Unwillingness to Change

There are inevitable changes that must be faced by companies such as the increase in raw material prices and manufacturing solid wastes (Pajunen *et al.*, 2012; Peck & Chiman, 2007). Many manufacturing companies, especially small and medium-sized enterprises (SMEs), are not ready to respond to these changes or able to embed them into existing manufacturing activities (Shahbazi *et al.*, 2016; Pajunen *et al.*, 2012; Allwood *et al.*, 2011). Some manufacturers fail to see the cost benefits of implementing material efficiency strategies and therefore, they perceive material efficiency strategies as an option, rather than a necessity. Most of these companies react by transferring the increase in raw material prices to the customers (Allwood *et al.*, 2011; Peck & Chipman, 2007). Furthermore, some companies, especially SMEs, are reluctant to change their existing (and hence, familiar) manufacturing processes into something new since this requires significant time and financial investment (Allwood *et al.*, 2013; Lilja, 2009a; Lilja, 2009b; Abdul Rashid *et al.*, 2008).

c. Implementation Costs

Implementing a new strategy in the company requires investment. Although the acquisition of advanced machinery boosts efficiency in the manufacturing process due to its higher speed, lower energy consumption and better processing capability compared to existing equipment, the lack of proven results such as direct cost savings discourages manufacturers from investing capital and resources in material efficiency strategies (Luken & van Rompaey, 2008; Pajunen *et al.*, 2012).

d. Restrictions in Product Design

Restrictions in product design is another barrier that limits manufacturers from practising material efficiency strategies effectively (Allwood *et al.*, 2011; Lilja, 2009b; Peck & Chipman, 2007). Material substitution is not suitable for every product since it affects product safety and functionality (Allwood *et al.*, 2011; Peck & Chipman, 2007). For example, certain critical parts used in aerospace applications require the usage of high performance materials. Similarly, medical devices require the use of non-toxic and high quality virgin materials. Allwood *et al.* (2011) highlighted that changing a product design is challenging because it not only involves material replacement, but it also affects the manufacturing process and other aspects such as product reliability, quality, and safety.

f. Lack of Information and Knowledge

Allwood *et al.* (2013) discovered that manufacturers in developing nations lack the necessary technical knowledge to implement material efficiency strategies. According to Worrell *et al.* (2013) and Lilja (2009a), most material efficiency strategies are practised in developed nations but there is a lack of support for these efforts from national policies and material efficiency experts (Peck & Chipman, 2007; Hanssen *et al.*, 2003). Pajunen *et al.* (2012) found that many manufacturing industries face similar issues: they will not practise strategies that they have no knowledge about. The limited information available concerning material efficiency has constrained the manufacturers' initiatives in implementing material efficiency strategies (Shahbazi *et al.*, 2016; Lodenius *et al.*, 2009; Luken & van Rompaey, 2008; Hekkert *et al.*, 2000). For example, in product design, a designer that lacks knowledge in product design uses a "sense of simplicity", which leads to wastage of raw materials (Allwood *et al.*, 2013; Allwood *et al.*, 2011).

g. Technological Limitations

The lack of available technology limits the implementation of material efficiency strategies (Shahbazi *et al*., 2016; Allwood *et al.*, 2013; Pajunen *et al.*, 2012; Hekkert *et al.*, 2002). This is exemplified by the lack of technology to process by-products within the manufacturing sector. The unavailability of cheap and affordable new technology prevents companies from processing raw materials efficiently (Worrell & van Sluisveld, 2013; Luken & van Rompaey, 2008). Such limitations in existing recycling technology may discourage manufacturers from designing products using material efficiency strategies (Allwood *et al.*, 2013; Pajunen *et al.*, 2012).

2.4.2.2 External Barriers

a. Regulations

Environmental legislation can work as a driver or barrier in the implementation of strategies (Allwood *et al.*, 2013; Abdul Rashid & Evans, 2012; Pajunen *et al.*, 2012). Many directives and legislation have been issued to monitor and prevent environmental problems such as the Restriction on Hazardous Substances (RoHS) directive and Waste from Electrical and Electronic Waste (WEEE) directive. Such stringent legislation and standards can work as a guide for the manufacturing industry to ensure proper management and disposal of production wastes. Nevertheless, previous studies have shown that manufacturers are reluctant to comply with environmental policies due to the complexity of these policies (Pajunen *et al.*, 2012). Among these difficulties include acquiring green materials with varying specifications due to discrepancies in the environmental policies of different countries such as mixtures of recycled materials and virgin materials, toxic-free materials, as well as fully biodegradable and fully recyclable materials.

b. Lack of External Support

The lack of external support from the government to encourage and provide certification, policies, subsidies and incentives has hampered manufacturers from practising material efficiency strategies (Allwood *et al.*, 2011). In addition, the lack of material efficiency experts is another reason for the slow adoption of material efficiency strategies (Lilja, 2009a). Furthermore, the lack of support from product recyclers has also delayed the implementation of material efficiency strategies among manufacturers (Allwood *et al.*, 2011). In some developing countries, the inability of technology and service suppliers to provide advanced technology to manufacturers also hinders initiatives to achieve material efficiency, especially when the capacity of the available machines is not optimum for machining raw materials. For example, the use of a Computerized Numerical Control (CNC) laser machine can reduce material wastage compared to conventional machining and it optimizes the arrangement of parts to be machined.

c. Suppliers and Supply Chains

Uncooperative suppliers also discourage manufacturers from using materials efficiently (Abdul Rashid & Evans, 2012; Allwood *et al.*, 2011). Another issue is the limited number of green suppliers capable of supplying recyclable raw materials to the manufacturers (Luken & van Rompaey, 2008). Furthermore, many suppliers are incapable of supplying the requested raw materials due to limitations in the technology used to produce green materials (Shahbazi *et al*., 2016; Luthra *et al.*, 2011; Walker *et al.*, 2008). According to Pajunen *et al.* (2012), the lack of green material suppliers can hamper manufacturers from practising material efficiency strategies. Abdul Rashid and Evans (2012) suggested that one of the reasons for this is the difficulties in complying with regulations and standards. Consequently, manufacturers have to source their raw materials from other countries which incur higher cost and increase their process lead time (Abdul Rashid & Evans, 2012).

d. Customer Requirements

The lack of demand for products made from recycled materials has caused many manufacturers to forgo the use of recycled materials as a source for their products (Allwood *et al.*, 2011; Peck & Chipman, 2007). In addition, economic pressure may also discourage manufacturers from practising material efficiency strategies (Pajunen *et al.*, 2012; Peck & Chipman, 2007), especially since green products are generally more expensive than their normal counterparts. The current trend in product requirements is focused on energy efficiency instead of material efficiency. Hence, in some manufacturing industries, material efficiency receives little attention since it is difficult to achieve and practise due to rapid changes in the product requirements. This is typically the case with the E&E industry where some products are designed with short life cycles due to swift changes in trends or fashion (Ashby, 2012).

2.4.3 Enablers in Implementing Material Efficiency Strategies

Enablers are factors that need more attention by manufacturers in order to ease the implementation of any environmental strategies, including material efficiency strategies. According to Björklund (2011), enablers are "a necessity for environmental action". A number of enablers pertaining to the implementation of environmental strategies such as company culture, environmental awareness of the organization, best practices available as well as technological advancement were discussed on previous studies (Björklund, 2011; Jovane *et al.*, 2008; Wiendahl *et al.*, 2007). The enablers in implementing material efficiency strategies are summarized in Table 2.4.

a. Company Culture

Company culture is a factor that determines the company's initiative in creating environmental consciousness in manufacturing (Korhonen, 2004). For example, European-based companies place more emphasis on eco-design (Gutowski *et al.*, 2005). Therefore, manufacturing companies around the world need to adopt a similar working culture across all their facilities and follow the policies set by the headquarters. This ensures that their products are recognized worldwide as environmentally friendly products. Other practices such as setting up a green team, providing appropriate training, structuring green working environment, promoting environmental awareness, and resetting the company's goal and vision on environmental awareness can also be implemented. In contrast, the negative attitude and culture of a company may affect the adoption of environmental practices, which is the case with smaller enterprises (Hillary, 2003). Govindarajulu and Daily (2004) highlighted that the implementation of environmental strategies can be expedited in the manufacturing industry by enhancing the liability of the employees on the tasks assigned to them.

Table 2.4: Summary of enablers in implementing material efficiency strategies

Enabler	Description	References
Company culture	• Green culture from origin companies • Internal policy on environmental awareness	Gutowski *et al.*, 2005; Govindarajulu & Daily, 2004; Korhonen, 2004
Adoption of best practices	• Adopting lean manufacturing practices	Yang *et al.*, 2011; Moreira *et al.*, 2010; Wong *et al.*, 2009
Adoption of Environmental management standards (EMS)	• Compliance with environmental standards such as ISO14001	Singh *et al.*, 2015; Walz, 2010; Gavronski*et al.*, 2008; Sambasivan & Ng, 2008; Morrow & Rondinelli, 2002
Technical capabilities and technical experts	• Acquire advanced machinery, technology and facilities • Acquire experts and experienced support team	Lilja, 2009a; Hekkert *et al.*, 2002; Hekkert *et al.*, 2000
Company size and financial strength	• Financial capability to acquire environmental standards as well as to invest in facilities	Fernández-Viñé *et al.*, 2010; Gottberg *et al.*, 2006;

b. Adoption of Best Practices

The adoption of best practices available such as lean manufacturing can also increase the effectiveness of companies to work towards material saving and waste reduction (Vinodh *et al.*, 2011). By acquiring knowledge on lean manufacturing, the usage of raw materials can be more efficient with continuous improvement of lean activities either from production operations or management (Yang *et al.*, 2011). For instance, best practices such as Kaizen helps in reducing unnecessary non-value added activities – activities which will lead to material wastage and higher energy consumption, which in turn, affect the delivery of the finished goods (Moreira *et al.*, 2010). Therefore, adopting best practices in a consistent manner will increase the employees' awareness to reduce the wastage of resources.

c. Adoption of Environmental Management Standards (EMS)

Walz (2010) identified that the adoption of suitable policies and standards may accelerate the implementation of environmental strategies. For instance, maintaining compliance with environmental management standards (EMS) such as ISO 14001 helps promote awareness among manufacturers to work in the environmentally conscious pathway (Singh *et al*., 2015; Gavronski *et al.*, 2008; Sambasivan & Fei, 2008; Morrow & Rondinelli, 2002). EMS serves as a guideline for companies to become more environmentally conscious such as controlling CO_2 emissions, reducing usage of hazardous chemicals as well as implementing proper waste management. Environmentally conscious consumers may also use these standards to evaluate their sub-contractors or allies to ensure that they are also concerned about the environment (Kautto & Melanen, 2002).

d. Technical Capabilities and Technical Experts

Material efficiency can be accelerated if both technical facilities and technical experts are available. Advanced technologies can greatly expedite improvements and reduce potential material wastes (Hekkert *et al.*, 2002; Hekkert *et al.*, 2000). The human capital also plays a vital role in achieving material efficiency. This can be done by recruiting experienced experts or support team to assist companies in adopting environmental strategies (Lilja, 2009a).

e. Company size and financial strength

Company size and financial strength also indirectly influence the initiative of the company in practising material efficiency strategies (Gottberg *et al.*, 2006). For example, the potential of solid waste generation is slightly greater for smaller companies with less exposure to environmental awareness and less readiness to invest more to create environmentally benign manufacturing (Fernández-Viñé *et al.*, 2010).

Larger firms such as multinational companies are more financially stable compared to smaller companies. Therefore, these firms are able to comply with various standards such as ISO 14001 in order to sell their products in the global market (Nishitani, 2009). According to Damall *et al.* (2010), the financial strength of an organization is one of the important factors in expediting the adoption of new strategies by the organization.

2.5 Review of Existing Decision Support Frameworks

The decision to practise an environmental strategy is often complex and it is dependent on various factors. For example, the drivers, barriers, payoffs, organization capabilities, and the available resources such as available technologies (Johansson & Winroth, 2010; Gottberg *et al.,* 2006). Four decision frameworks were reviewed in order to determine the gaps in improving decision-making to practise material efficiency strategies. These frameworks are: Natural Resource Based View framework, Sustainable Value framework and Environmental Decision framework.

2.5.1 The Natural Resource Based View Framework

The Natural Resource Based View framework was established in the early 1970s by Stuart Hart. This framework was developed to provide solutions regarding the adoption of organization strategies, particularly to reflect the internal capabilities, external driving forces and competitive advantages of the firm (Hart, 1995). By understanding these aspects, the interconnected strategies can be implemented, either from pollution prevention, product stewardship or sustainable development (see Figure 2.1). These data were used by Stuart to further develop the framework with the goal to achieve sustainable value, which is known as the Sustainable Value framework (Hart & Milstein, 2003).

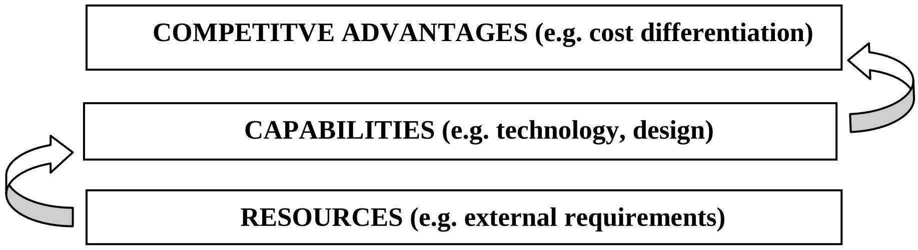

Figure 2.1: Resource Based View Framework (Hart, 1995, pp. 998)

2.5.1.1 Sustainable Value Framework

In the Sustainable Value framework, there are four classifications of sustainability value development for a firm (Hart & Milstein, 2003). Each classification is represented by a different category, namely, innovation and repositioning, growth path and trajectory, cost and risk reduction, and reputation and legitimacy (Figure 2.2). The driver for innovation and repositioning refers to the context of assessing the orientation base of industrial growth and its impact on environmental issues. The purpose of the growth path and trajectory is to explain the collaborations that can be done by the governmental agency and civil society to achieve sustainability in a responsive manner**.** The cost and risk reduction aspect is related to the possible changes made by using the available technologies. The reputation and legitimacy aspect is focused on environmental stewardship and social context in order to create awareness on responsibility towards globalization and the environment.

The link between drivers and strategy development (specifically, the potential payoffs) is shown in Figure 2.3. For example, if the drivers tend to reduce environmental pollution and wastes, the strategy should be designed to build a link between the driver and strategy such as pollution prevention activities. The payoffs gained are cost and risk reduction. Thus, this framework is well-designed to distinguish the classification of drivers towards a good trade-off between strategy and potential payoffs. Based on this classification, consensus evaluation can be conducted to ensure that the interaction between variables is always logical.

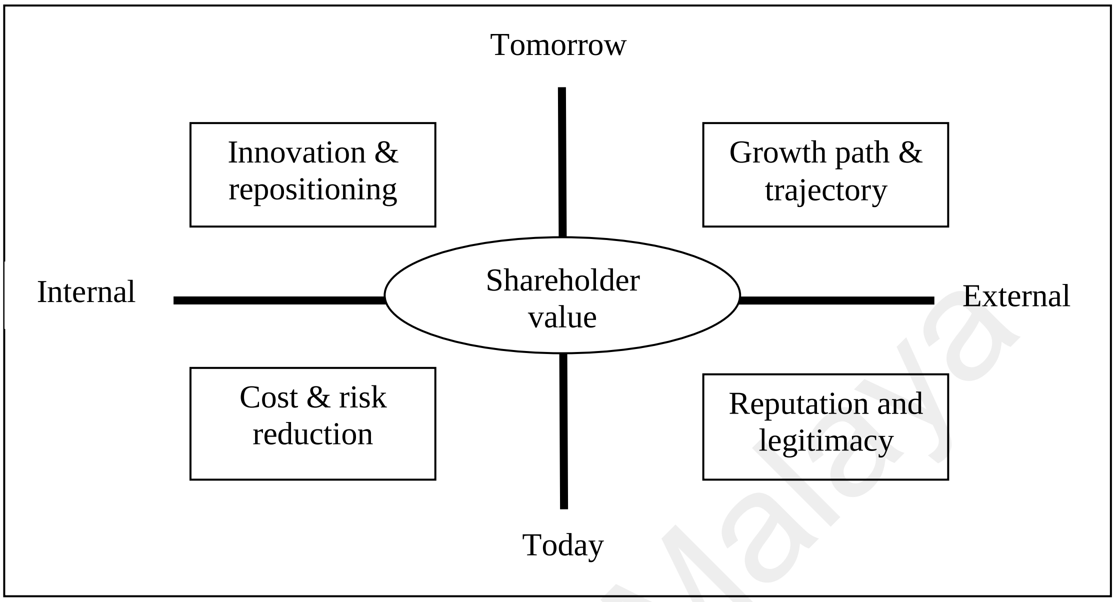

Figure 2.2: Classification of the type of drivers for sustainability (Hart *et al.*, 2003, pp. 57)

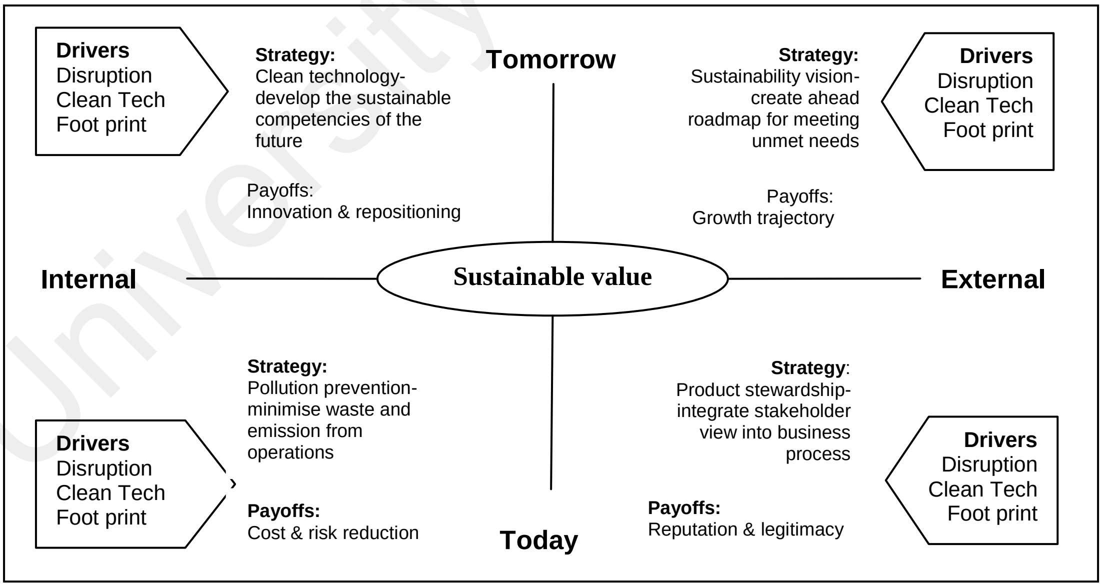

Figure 2.3: Link between drivers and strategy in sustainable value framework

(Hart *et al.*, 2003, pp. 60)

2.5.2 Environmental Decision Framework

The Environmental Decision framework was developed by Johansson and Winroth (2010). This framework shows the criteria that need to be considered prior to making a decision concerning the manufacturing strategy, which can be strategic planning or the activities needed in order to incorporate environmental activities into the company. Figure 2.4 shows the environmental decision framework, which begins with considering the drivers for implementing environmental strategies. The driver element mostly consists of external driving forces such as legislation and customer needs. These factors have direct impact on the competitive priority of their firm. Examples of these factors include the cost, quality and delivery lead time of the product. Based on these drivers, the environmental strategies will be proposed to suit with the direction of the business and the current market trend. There is a closed loop arrow between the competitive priorities and decision criteria in this framework, which shows that the environmental strategies can be changed dynamically according to the priority in the business direction. In this framework, one can ensure the success of the environmental strategy. Hence, it is imperative to determine the significant drivers faced by a company because it enables consensus alignment of the decision to be done effectively.

Figure 2.4: Validated framework for manufacturing strategy formulation taking into account environmental issues (Source: Johansson & Winroth, 2010)

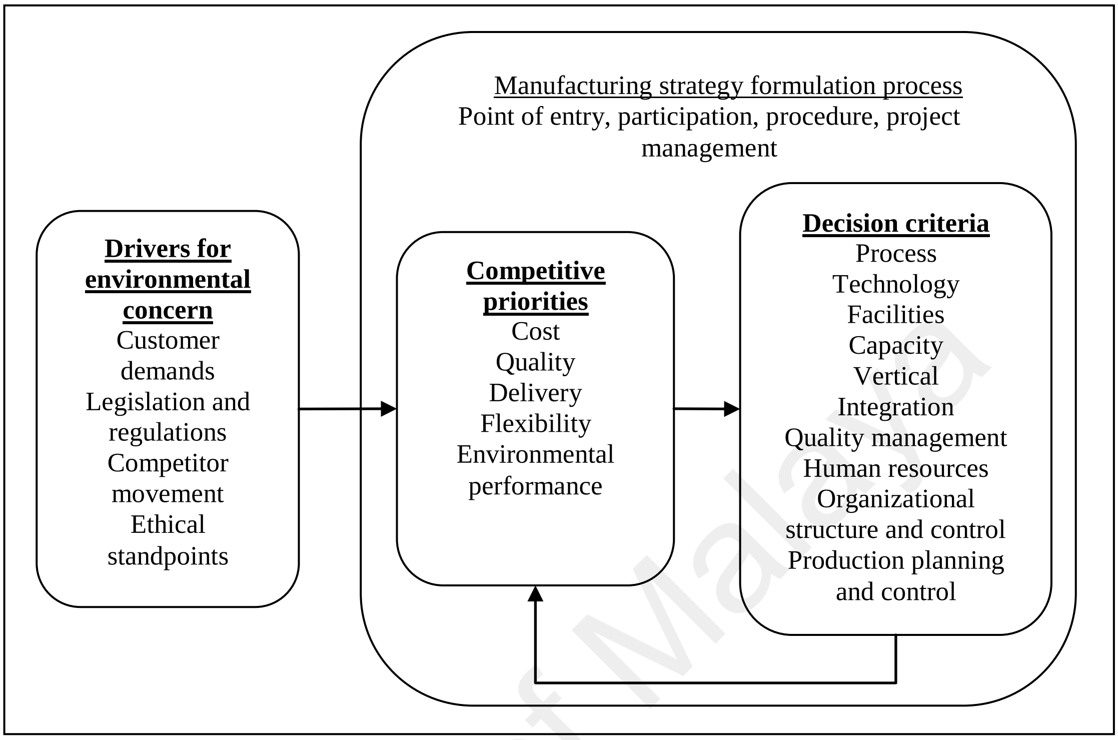

Table 2.5 shows the comparison between four environmental decision frameworks in formulating environmental strategies. It can be seen that these frameworks share some similar decision criteria in conducting environmental strategies. For example, all of these frameworks take into account driver factors. However, there are also differences between these frameworks such as consideration of other factors such as barriers, enablers and benefits. In addition, different decisions flows provide initial knowledge on how a strategy should be formulated.

The presented environmental decision frameworks shown different criteria were chosen to measure the environmental strategy formation. Although these factors are presented in different phrases or term by it is still under the roof of organization change factors. Therefore, with the given decision consideration in the existing decision frameworks, this information could be used to aid the researcher in formulating the material efficiency framework, especially in determining the decision flow and criteria to conduct material efficiency strategies.

Table 2.5: Comparison of four environmental decision frameworks

No	Theory	Decision criteria				Remarks
		Drivers	Barriers/ Challenges	Enablers	Benefits/ Payoffs	
1	The Natural Resource Based View framework	Yes	NA	Yes	Yes	The determination of environmental strategies is depending to the business orientation of a company.
2	Sustainable Value framework	Yes	Yes	NA	Yes	Both drivers and barriers must be considered to form a comprehensive environmental strategy.
3	Environmental Decision framework	Yes	NA	Yes	Yes	The determination of an environmental strategy should fulfil the comprehensive goals of a company.

2.6 E&E Industry and Material Efficiency in Malaysia

In the past five years, the E&E industry has become one of the fastest growth industries in Malaysia, and it has contributed significantly to the economic development of the country (MITI, 2015). However, the rapid growth of the E&E industry results in a high consumption of non-renewable resources such as copper, gold and rare earth metals (Widmer *et al.*, 2005). According to Shumon *et al.* (2014), material scarcity has become an issue concordant with the rapid growth of the E&E industry throughout the world. At the same time, E&E processes and products have led to various environmental issues such as electronic wastes and discharge of toxic substances and chemicals to the environment.

The E&E industry is one of the most established industries in terms of technological use with strict compliance with worldwide environmental standards such as RoHS and WEEE. Nevertheless, based on the current trend of global solid wastes in developing countries (Widmer *et al.*, 2005), the amount of e-wastes is escalating each year, which will have a significant impact on scarcity of resources as well as environmental and society health issues. One of the reasons for this is that the present technology is incapable of dismantling and recycling e-wastes. In addition, there is poor enforcement of legislation concerning e-waste management in developing countries such as India, China. Hence, the majority of E&E product consumers manage obsolete electronic products by disposing them as normal wastes or selling them to general recyclers (Nnorom & Osibanjo, 2008).

According to the Department of Environment (DOE, 2009), Malaysia, e-wastes are considered as scheduled wastes. To date, there are partial waste recovery facilities and 16 full recovery facilities in 122 locations in Malaysia. These facilities are used to manage e-wastes both from industries and residential users. However, e-waste processing is limited to segregation, valuable material sorting and reselling, and product disposal. There is a lack of consideration regarding the upstream activities of the company and most of the initiatives are focused on dismantling for material recycling and recovery. This may be due to insufficient knowledge and guidance which can aid industry practitioners in using materials efficiently (Agamuthu & Victor, 2011).

Although there are legislation and action plans available to support e-waste management in Malaysia such as the Environment Quality Act 1974, the Action Plan for a Beautiful and Clean Malaysia, the National Strategic Plan for Solid Waste Management in Malaysia and the Solid Waste and Public Cleaning Management Act 2007, these initiatives do not facilitate industry practitioners in e-waste management. This is due to poor enforcement and lack of participation from industry practitioners. Agamuthu and Victor (2011) concluded that only less than 10% of e-wastes were returned to waste management centres for further processing from 2006 to 2009. About 90% of e-wastes were sent to unlicensed recyclers or disposed.

Introducing material efficiency into non-homogeneous products such as E&E products is an arduous task because it has not been widely implemented compared to homogeneous base products such as paper and pulp, metals and plastics. Secondly, the complexity of the materials used in E&E products such as metals, plastics and other substances makes material efficiency particularly challenging. For these reasons, there is a critical need to enhance material use and reduce potential waste generation, since this will help solve issues on material scarcity and reduce the detrimental impact of production activities and E&E products on the environment.

According to Ilomäki and Melanen (2001), different manufacturing sectors contribute a different level of material loss throughout their production phase (Figure 2.5). The opportunities to improve material efficiency may vary depending on the complexity of the product, material use and types of solid wastes generated. For instance, E&E products are made from metals, plastics, substances and chemicals, and therefore, the level of material loss in the E&E industry is rather high. However, the opportunities to achieve material efficiency appear limited and need to be explored. For this reason, there is a need to focus on achieving material efficiency in the E&E industry – an industry that is known to generate an enormous amount of wastes from production, especially hazardous substances such as lead, mercury, cadmium, hexavalent, rare earth metals and nickel. These substances are harmful to the environment and society.

At present, there are only a few studies pertaining to material efficiency in the E&E industry (Abdul-Rashid *et al*., 2013). Therefore, the lack of knowledge regarding material efficiency in this industry may lead to higher material consumption and negative environmental impact. Thus, it is essential to gain an in-depth understanding on the implementation of material efficiency strategies in the E&E industry, specifically in Malaysia.

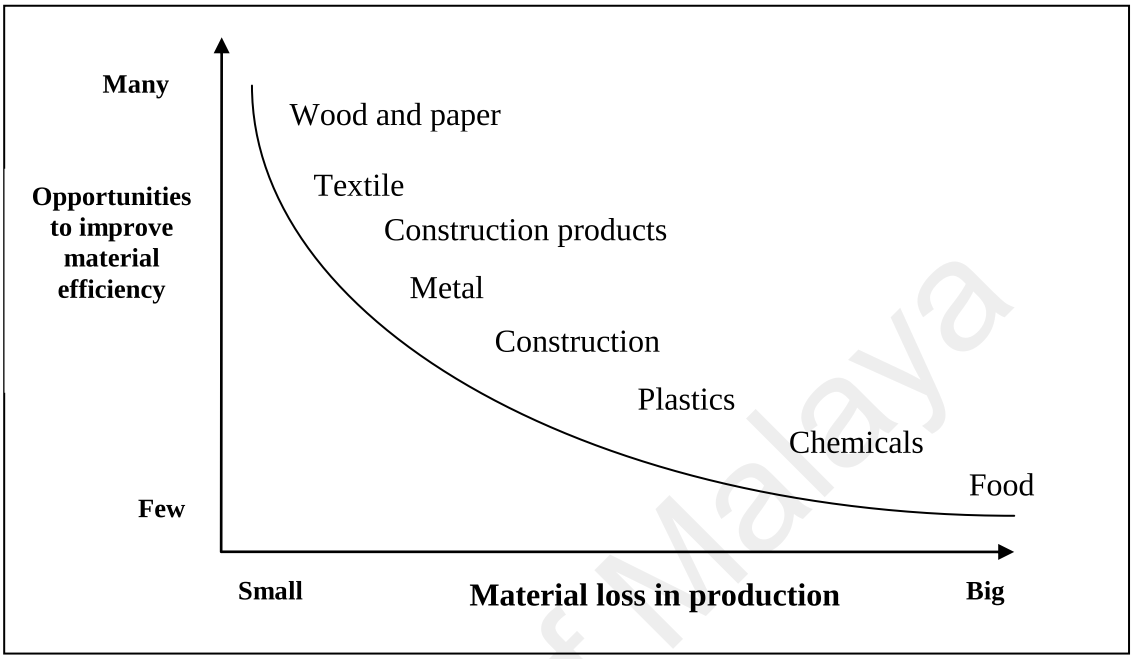

Figure 2.5: Generalization of the opportunities to improve material efficiency in SMEs (Source: Ilomäki & Melanen, 2001, p. 216)

2.7 Neglected Dimensions in Material Efficiency Research

A critical discussion on the material efficiency strategies and organizational change factors is presented in the preceding sections. However, at present, there is insufficient research evidence that link the organizational change factors with material efficiency strategies, which forms the main motivation for this research. Koltun (2010) stressed that manufacturing strategies should be established based on clear indicators in order to assist decision makers in making well-informed decisions. According to Gottberg *et al.* (2006), it is important to gain an understanding of organizational change factors in order to implement environmental strategies effectively. Without proper understanding of these links, the environmental strategies proposed may be misleading, inappropriate, and in worst-case scenarios, the implementation of an inappropriate strategy results in financial loss to the company. Okereke (2007) highlighted that understanding mixed factors such as drivers, barriers and enablers are crucial to formulate reliable environmental strategies. Furthermore, the implementation of a particular strategy should not be justified based on popular reasons. Johansson and Winroth (2010) claimed that the inclusion of environmental elements further complicates the formulation of manufacturing strategies and therefore, it important to include drivers and challenges as part of the decision criteria.

In general, in order to enhance the effectiveness of implementing a material efficiency strategy, the decision should be based on defined criteria clearly because different industries may have different requirements for product design and manufacturing. For this reason, understanding the effect of organization change factors is one of the key areas since it is directly linked to market needs and policies introduced by the government or any related associations.

Based on the available initiatives to achieve material efficiency and the change factors which will influence the implementation of material efficiency strategies, it is still difficult to explain the decisions to practise material efficiency strategies from a scientific perspective. Arguments exist especially on the decisions to implement material efficiency strategies. The "what" and "how" of practising material efficiency strategies are not well-justified and clarified. For example, what are the factors used to decide whether a suitable material efficiency strategy should be implemented within the company? What are the internal and external factors that need to be considered in order to implement a material efficiency strategy? How to implement material efficiency strategies within a company? How to evaluate the mixed change factors in order to select a suitable material efficiency strategy? These questions need to be answered in order to formulate a logical way to practise material efficiency strategy.

In brief, little is known regarding the link between organizational change factors and material efficiency strategies. This results in confusion when it comes to implementing material efficiency strategies, since there are no clear guidelines that can be used as reference by industry practitioners (Lifset & Eckelman, 2013; Allwood *et al.*, 2011; Abdul Rashid *et al.*, 2008). Thus, a detailed investigation is needed to clarify the change factors and its implications on the selection on material efficiency strategies. In addition, a decision support tool is also needed to improve the selection of material efficiency strategies. The gaps identified in the existing body of knowledge pertaining to material efficiency strategies are summarized in Table 2.6.

Table 2.6: Gaps identified in material efficiency research

No	Identified research gaps
1	The implementation of material efficiency strategies is different depending on the industry. There is a lack of studies concerning the implementation of material efficiency strategies in a specific industry such as the E&E industry in Malaysia.
2	There is a lack of understanding on the "know-how" of practising material efficiency strategies, particularly when multiple organizational change factors are considered.
3	There are no decision support tools available to guide industry practitioners in selecting material efficiency strategies based on different combinations of organizational change factors.

2.8 Formulation of Research Questions

Based on the literature review, little is known regarding the link between organizational change factors and material efficiency strategies. Therefore, a series of research questions is formulated, which serves as guideline for the research design. The list of research questions formulated in this research in order to answer the research objectives stated in Chapter 1 is presented below:

Objective 1: To identify the material efficiency strategies currently implemented in the E&E industry in Malaysia.

The first research objective is to understand the operational activities practised by manufacturers in the E&E industry in order to achieve material efficiency in Malaysia. Therefore, the research questions are formulated as follows:

RQ1 What are the strategies implemented to achieve material efficiency by the E&E industry in Malaysia? How? Why?

RQ1a What are the strategies implemented to achieve material efficiency during the product design phase? How? Why?

RQ1b What are the strategies implemented to achieve material efficiency during the manufacturing process phase? How? Why?

RQ1c What are the strategies implemented to achieve material efficiency during the product distribution and logistics phase? How? Why?

Objective 2: To identify the significant change factors that influence the implementation of material efficiency strategies in the E&E industry in Malaysia.

The second research objective is to determine the influencing factors and their implications on the implementation of material efficiency strategies. Therefore, the research questions are formulated as follows:

RQ2 What are the factors that influence the implementation of material efficiency strategies in the E&E industry in Malaysia?

RQ2a What are the drivers in implementing material efficiency strategies?

RQ2b What are the barriers in implementing material efficiency strategies?

RQ2c What are the enablers in implementing material efficiency strategies?

RQ2d How important are the change factors in influencing the implementation of material efficiency strategies?

2.9 Summary

Material efficiency has gained much interest from the academicians and industry practitioners as an effective solution to reduce material intake and reduce environmental impact. There are various material efficiency strategies that can be implemented in the manufacturing industry such as design for longer life, material substitution, design with fewer materials and green packaging. The implementation of each strategy is often unique to the industry and is influenced by organization change factors consisting of drivers, barriers and enablers.

The three categories of organizational change factors introduces complexity in decision-making, especially in selecting the suitable material efficiency strategies since these strategies are influenced by market trends, business requirements and governmental policies. Furthermore, these factors may affect the selection of material efficiency strategies in different ways.

However, there is lack of studies regarding the link between organizational change factors and material efficiency strategies. Industry practitioners typically face difficulties in making decisions in selecting suitable material efficiency strategies due to limited knowledge on their existing capabilities and the change factors present in their companies. This in turn, leads to ambiguous decision-making in selection of material efficiency strategies. More importantly, the selection of an inappropriate strategy may bring undesirable consequences to the company, including financial losses.

Based on the literature review, it is found that there is a critical need to determine the link between organizational change factors and its influence on the selection of material efficiency strategies. For this reason, a detailed investigation is needed to explore the link between the organizational change factors and material efficiency strategies in manufacturing companies. The findings of this research can be used to develop a decision support tool which will aid industry practitioners in selecting effective material efficiency strategies that are relevant to their company. An overview of the research gaps, research objectives and research questions is presented in Figure 2.6.

Research gaps:

There is a lack of understanding regarding the link between the organizational change factors and material efficiency strategies. Therefore, there is a need to investigate this link and develop a decision support tool which will facilitate industry practitioners in implementing material efficiency strategies effectively.

Research aim:

The aim of this research is to provide useful insight on the implementation of material efficiency strategies in Malaysia, specifically in the E&E industry.

Research objectives:

1. To identify the material efficiency strategies currently implemented in the E&E industry in Malaysia.
2. To determine the significant organizational change factors that influences the implementation of material efficiency strategies in the E&E industry in Malaysia.
3. To develop a decision support tool which will aid industry practitioners in selecting material efficiency strategies?
4. To validate the developed decision support tool using suitable case studies.

Research questions:

RQ1 What are the strategies implemented to achieve material efficiency by the E&E industry in Malaysia? How? Why?

RQ1a What are the strategies implemented to achieve material efficiency during the product design phase? How? Why?

RQ1b What are the strategies implemented to achieve material efficiency during the manufacturing process phase? How? Why?

RQ1c What are the strategies implemented to achieve material efficiency during the product distribution and logistics phase? How? Why?

RQ2 What are the factors that influence the implementation of material efficiency strategies in the E&E industry in Malaysia?

RQ2a What are the drivers in implementing material efficiency strategies?

RQ2b What are the barriers in implementing material efficiency strategies?

RQ2c What are the enablers in implementing material efficiency strategies?

RQ2d How significant are the change factors in influencing the implementation of material efficiency strategies?

Figure 2.6: Overview of the research gaps, research objectives and research questions

CHAPTER 3: RESEARCH METHODOLOGY

3.0 Overview

The main purpose of conducting a research is to explore, describe or explain a phenomenon (Robson, 2002). Research involves various activities such as testing, experimenting, surveying and analysing. According to Robson (2002), research methodology can be defined as the procedure to conduct a research and a well-designed research methodology can ensure that high-quality findings are obtained. Leedy and Ormrod (2005) emphasized the importance of using the appropriate methodology since this ensures that the study can be replicated and provide consistent results.

Based on the literature review presented in Chapter 2, there is inadequate information concerning the linkage between organizational change factors and material efficiency strategies, which in turn, leads to poor implementation of material efficiency strategies. Hence, in order to understand and develop a solution for this research problem, a systematic research design was developed in this research, as shown in the flow chart below (Figure 3.1). The methods selected for this research are described in details in the following sections, along with the justification for the techniques. A summary of the methods employed in this research are presented at the end of this chapter.

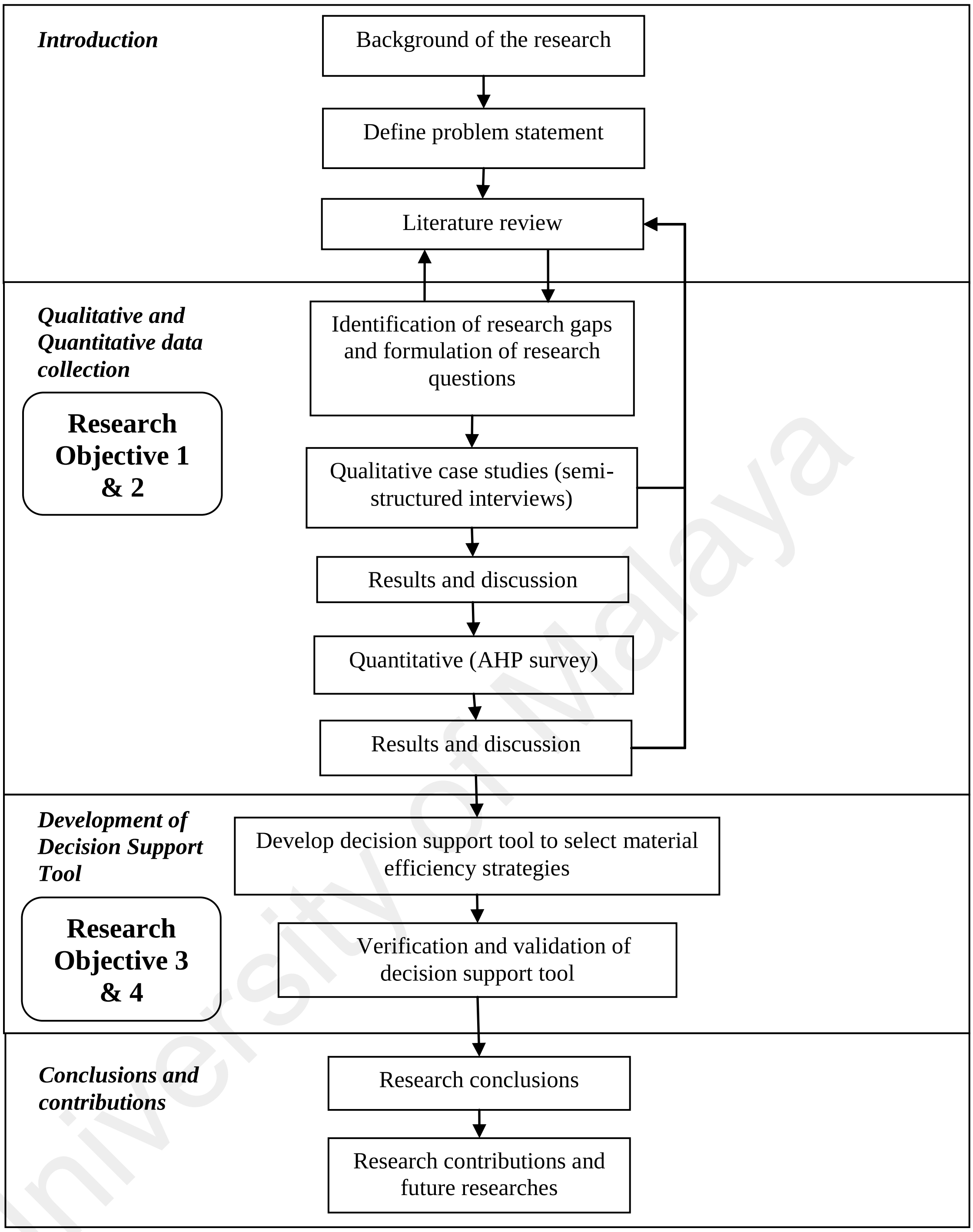

Figure 3.1: Flow chart of the research design

3.1 Research Methods

In general, research methods can be classified as qualitative, quantitative and mixed-methods. Each of these methods has its purpose and characteristics, depending on the research. Quantitative research is conducted based on existing theories and the variables are well established. Therefore, the researcher needs to use the available parameters for testing in different research boundaries such as different groups of people to prove their hypotheses (Robson, 2002). Qualitative research methods, on the other hand, are typically used to obtain insight of the real environment in order to enhance a less structured theory. For example, qualitative method is used to investigate the newly adopted practices in an organization that is chosen as the case study (Creswell, 2009; Robson, 2002). Mixed-method is a combination of both qualitative and quantitative methods in order to obtain more reliable data. This method is normally used in cases where it is less effective to obtain results using only a single research method (Creswell, 2013; 2009). The differences of these research methods are presented in Table 3.1.

Table 3.1: Comparison between qualitative, quantitative and mixed research methods (Source: Compiled by the Author from Creswell, 2013, pp. 45-70)

Research design	Qualitative	Quantitative	Mixed method
Use philosophical assumptions	Constructivist / Advocacy / Participatory knowledge claims;	Post-positivist knowledge claims;	Pragmatic knowledge claims; Sequential concurrent and transformative
Research inquiry	Phenomenology, grounded theory, ethnography, case study, and narrative	Surveys and experiments	
Types of data collection	Open-ended questions, emerging approaches, text or image data.	Close-ended questions, pre-determined approaches, numeric data	Both open and close-ended questions, both emerging and pre-determined approaches, and both quantitative and qualitative data, and analysis.
Position of the researcher	• Positions himself or herself; • Collects participant meanings; • Focuses on a single concept or phenomenon; • Brings personal values into the study; • Studies the context setting of the participants; • Validates the accuracy of findings; • Makes interpretations of the data; • Creates an agenda for change or reform; • Collaborates with the participants.	• Tests to verify theories or explanations, identifies variables to study; • Relates variables in the research questions or hypothesis; • Uses standards of validity and reliability; • Observes and measures information numerically; • Uses unbiased approaches; • Employs statistical procedures.	• Collects both quantitative and qualitative data; Develop a rationale for integrating the data from different stages of inquiry; • Presents visual pictures for the procedures in the study; • Employs the practices of both qualitative and quantitative research.

This research is focused on understanding a new, growing research field, which is material efficiency. The aim of this research is to develop a decision support tool to select material efficiency strategies for the manufacturing industry in Malaysia. Thus, the mixed method was chosen because it is able to provide a more holistic evidence for this research compared to either only qualitative or quantitative method. In addition, the mixed method enables the research to gain better insight and meaningful data from the companies chosen for the case study.

According to Creswell (2009), there are three basic types of mixed method which need to be considered in gathering the research data (Figure 3.2): (a) Merge the data, (b) Connect the data, and (c) Embed the data. Each mixed method has its own characteristics and purpose. For example, the first type (i.e. merge the data) aims to confirm the data from two different types of research methods. The second type (i.e. connect the data) is used to strengthen the collected data especially through the qualitative method. The third type (i.e. embed the data) is used in cases where the qualitative method is used as the primary method while the quantitative method is used for some data which are not confirmed.

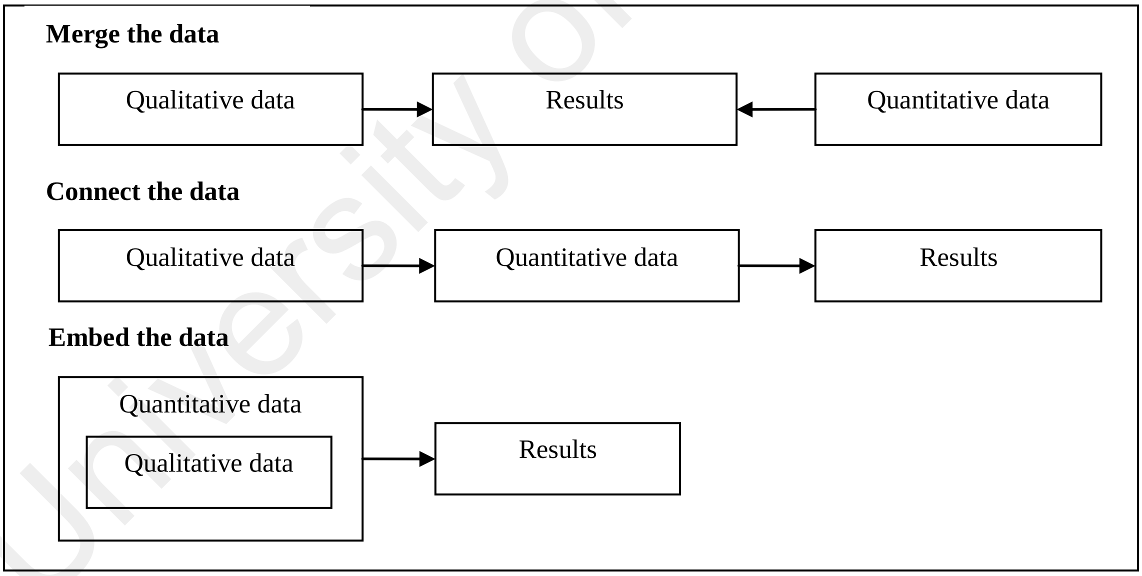

Figure 3.2: Three types of mixed-method (Source: Creswell, 2009, p.7)

Based on the explanation given above, the second type was chosen for this research because it is more relevant to answer the research objectives. The qualitative method was used as the primary research method to explore the research variables such as organizational change factors and material efficiency strategies within the case companies. The quantitative method was used to determine the significance level of the change factors which influence the implementation of material efficiency strategies (Figure 3.3).

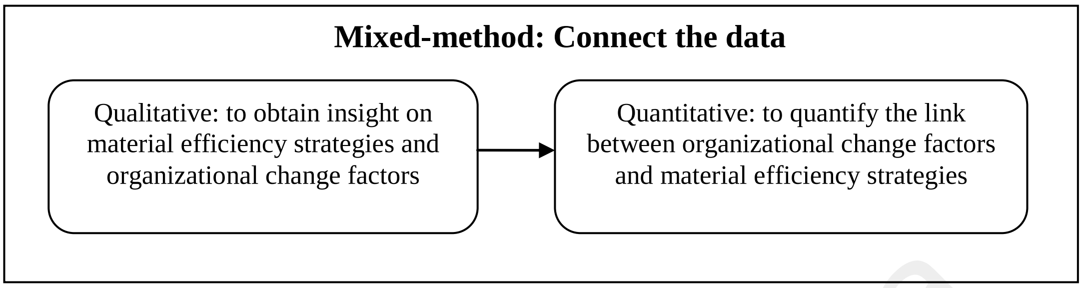

Figure 3.3: The mixed-method approach adopted in this research

3.2 Qualitative Method

The qualitative method is elaborated in detail in this section. In general, there are five qualitative research approaches commonly used (Creswell, 2007), namely:

1. Narrative research
2. Phenomenology
3. Grounded theory
4. Ethnography
5. Case study

Each of these approaches has its characteristics and applications, depending on the preset requirements (Creswell, 2007). According to Creswell, narrative research is suitable to investigate the experiences of an individual such as the prime minister whereas phenomenology is used to understand the essence of a real phenomenon or the lifestyles of the investigated people. Grounded theory is used to develop and strengthen the research theory based on real cases by structuring the data gathered whereas ethnography is used to examine culturally-related experiences such as the living lifestyle of a group of people. Lastly, case study is used to explore and explain a specific case or event such as the awareness of a manufacturer on energy savings. The characteristics of these qualitative approaches are summarized in Table 3.2.

Table 3.2: Characteristics of five qualitative approaches

(Source: Creswell, 2007, pp. 78–79)

Characteristics	Narrative research	Phenomenology	Grounded theory	Ethnography	Case study
Focus	Exploring the life of an individual	Understanding the essence of the experience	Developing a theory grounded in data from the field	Describing and interpreting a culture-sharing group	Developing an in-depth description and analysis of a case or multiple cases
Type of problem best suited for design	Needing to tell stories of the individual's experiences	Needing to describe the essence of a live phenomenon	Grounding a theory in the views of participants	Describing and interpreting the shared patterns of culture of a group	Providing an in-depth understanding of a case or cases
Discipline background	Drawing from humanities including anthropology, literature, history, psychology and sociology	Drawing from philosophy, psychology and education	Drawing from sociology	Drawing from anthropology and sociology	Drawing from psychology, law, political science and medicine
Unit of analysis	Studying one or more individuals	Studying several individuals that have shared the experience	Studying a process, action or interaction involving many individuals	Studying a group that shares the same culture	Studying an event, a programme, an activity involving more than one individual
Data collection forms	Using primary interview and documents	Primarily using interviews with individuals, although documents, observations and art may also be considered	Primarily using interviews with 20–60 individuals	Using primarily observations and interviews, but perhaps collecting other sources during extended time in field	Using multiple sources such as interviews, observations, documents and artefacts
Data analysis strategies	Analysing data for stories, "restorying" stories, developing themes, often using chronology	Analysing data for significant statements, meaning units, textural and structural description, description of the "essence"	Analysing data through open coding, axial coding and selective coding	Analysing data through description of the culture-sharing group and themes about the group	Analysing data through description of the case and themes of the case as well as cross-case themes
Written report	Developing a narrative about the stories of an individual's life	Describing the "essence" of the experience	Generating a theory illustrated in a figure	Describing how a culture-sharing group works	Developing a detailed analysis of one or more cases

According to Voss *et al*. (2002), a case study is a powerful yet suitable research method to explore insights from real case companies. There are three important advantages in carrying out a case study:

1. The phenomenon can be studied in its natural setting and therefore, a meaningful, relevant theory can be generated from the understanding gained by observing actual practices.
2. The case study allows the questions of "why", "what" and "how" to be answered with a relatively full understanding of the nature and complexity of the phenomenon.
3. The case study lends itself to early, exploratory investigations where the variables are still unknown and the phenomenon is not completely understood.

Multiple-cases study is used to clarify the activities and insight information from similar cases (Robson, 2002). An example of this is similar types of manufacturing companies are practising material efficiency strategies. In addition, multiple-cases study enables a robust pattern to be formulated at the end of the research (Yin, 2011; Robson, 2002; Voss *et al.*, 2002; Miles & Huberman, 1994). Therefore, in this research, the case study method was chosen because it is suitable to explore the real phenomena in E&E manufacturing companies in Malaysia, particularly, how these companies perceive the material efficiency concept, their concerns regarding material efficiency as well as how they implement material efficiency strategies.

3.3 Qualitative Method: Case Study

Basically, there are three types of interview design namely: open-ended interviews, semi-structured interviews and structured interviews (Robson, 2002). Data collection using open-ended interviews enable interviewees to give their answers within a wider scope or within limited boundaries. Semi-structured interviews require the interviewees to provide their answers in preset boundaries. Guidelines and sample answers are provided to assist the interviewees in answering the questions. Structured interviews require the interviews to provide their answers according to the list of answers which is pre-determined by the interviewer. The interviewees are not allowed to give answers that are beyond the given options.

In achieving research objective 1 and 2, a semi-structured interview was chosen to allow the key-informants in the industry to elaborate more about the material efficiency strategies practised in their companies as well as the organizational change factors that influence the implementation of these strategies. The interview questions consist of "What, How, and Why" questions in order to obtain an overall picture of the investigated event (Yin, 2013; Voss *et al.*, 2002). The interview questions consist of three main sections: (a) Details of the company, (b) Types of material efficiency strategies practised, and c) Organizational change factors that influence the implementation of material efficiency strategies. There is a total of 20 of semi-structured interview questions. The complete list of the interview protocols is given in Appendix A.

It is crucial to select the right sample to ensure that the results obtained are reliable as well as to increase the validity of the research findings. In qualitative studies, the main purpose of sampling is to understand the complexity of human issues rather than to generalize the findings (Marshall, 1996). Therefore, large samples can create confusion if the gathered data do not achieve the richness desired. There are two types of sampling techniques used for qualitative studies, namely, purposeful and theoretical sampling (Coyne, 1997). Purposeful sampling involves selecting the participants according to criteria determined by the purpose of the research. In theoretical sampling, however, the participants are determined based on the theory used in the research. In this study, purposeful sampling was used to obtain a specific type of data (Yin, 2011; Coyne, 1997; Eisenhardt, 1989). In addition, purposeful sampling increases the validity of the research and thus, the findings can be used to form a valid pattern (Yin, 2011). The following sampling criteria were set in order to prevent invalidity of the research findings:

1. The sample consisted of E&E companies located within Peninsular Malaysia. The companies can be local or multinational companies.
2. The E&E companies must be involved in design or manufacturing activities, or both.
3. The key-informants or personnel must have sufficient knowledge and experience, and they must be in the position to make decisions (e.g.: Director, Manager, Materials Specialist, Senior Design Engineer, Production Supervisor).

In this study, face-to-face, in-depth semi-structured interviews were conducted with seven E&E companies within Peninsular Malaysia. The companies involved in this research consist of an integrated circuit company, TV manufacturer, air conditioner manufacturer, microwave manufacturer, communications device manufacturer, and automotive electronics manufacturer. The representatives of these companies consist of a director, manager, senior engineer, senior designer, materials specialist, and an environmental officer. In general, these companies are large-sized companies, with more than 250 employees. The name of the companies and key informants are not disclosed in this thesis to ensure anonymity and confidentiality. For this reason, the company's name is represented by a code, for example, C1 represents the first company. The details of the companies that participated in this research are shown in Table 3.3. According to Yin (1994), multiple case study investigation emphasis on the convergent evidence for achieving richness of conclusions for each case. Therefore, there is no sampling logic to follow, whereas it is depends on case replication for the variables wanted for underlying the theoretical propositions (refer Figure 3.4). However, the selected participants must fulfil the requirements for company and personnel recruitment to ensure the quality of the data and analytical generalization of the representative data set (Yin, 2011; 1994). In this study, the unit of analysis used refers the number of case study companies.

Table 3.3: List of companies that participated in the semi-structured interviews

Company	Country of origin, Company size	Products / Services	Participant, Year of working experience
C1	Germany, large	Integrated circuits, electronic components for automobiles	Senior Engineer (Quality control), 7 years
C2	US, large	Circuit design, walkie-talkies, communication devices	Material Specialist, 8 years
C3	US, large	Integrated circuits, circuit design, electronic components	Packaging Department Director, Senior engineer, 5-10 years
C4	Malaysia, large	Integrated circuits, circuit design and assembly	Environmental, Health, and Safety (EHS) Manager, 8 years
C5	The Netherlands, large	TV brackets, assembly of TV products, Printed circuit boards, circuit design	Principal designer, 7 years
C6	Japan, large	TV brackets, Assembly of TV products, printed circuit boards, circuit design	Senior engineer, 5 years
C7	US, large	Solar cells, solar panels	Packaging manager, 6 years

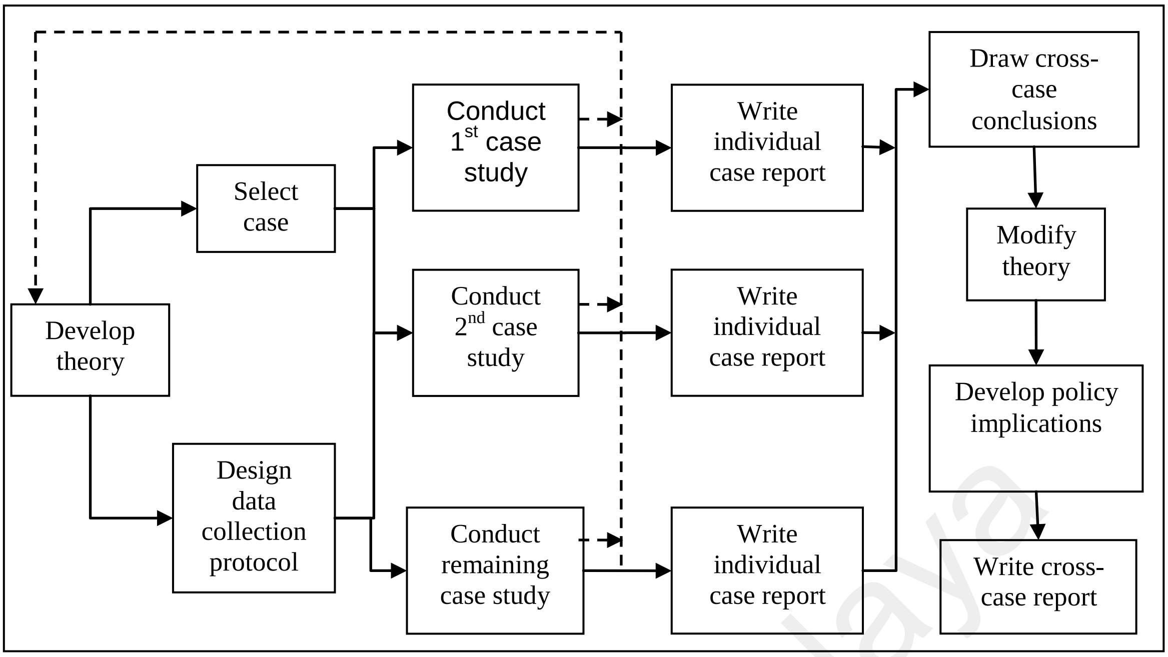

Figure 3.4: Case study method (Yin, 1994, p. 49)

3.3.1 Qualitative Interviewee

There are seven E&E companies with experienced practitioners are participated the semi-structure interview. Below are the brief description of each company background and also the interviewee.

a. Company C1

Company C1 is a German based Semiconductor Company. This Company was established in year 1999 and located at Melaka state in Malaysia. The range of products include microcontrollers, communication integrated circuit, power electronics, protection diodes. These products are mainly designed for automotive industry, industrial power control, chip card & security, power management.

There is a senior production engineer participated the interview session. He has joint the company for seven years, particularly to monitor the front end process improvement, resolving the assembly lines layout, and also studying the new process conformance for meeting the product end-of-life requirements. The interview took about 50 minutes, all of the interview session is tape recorded. There are 15 pages of verbatim transcribes are produced from the primary data.

b. Company C2

Company C2 is a Malaysia owned company which located at Kulim Silicon Valley, Kedah. This is a multinational company which was established in year 1999. This company is mainly produces integrated circuits from raw wafer for wide range of electrical and electronic products use such as mobile phone, audio and video products, health devices, lab devices and etc.

In this interview, there are two key-informants were participated in the session. The first interviewee is an Environmental, Heath, and Safety (EHS) manager. His responsibility in this company is to assist the employee in achieving and maintaining the ISO14001 requirement through implementing various task forces. Besides, he does involves in monitoring and proposing various task force to ensure less solid waste generation from the production, less CO2 emission, less energy consumption in factory, and also ensuring the scrap from production are managed in the correct manner.

The second interviewee is a production manager who has eight years experience in electrical and electronic field. His daily job is to ensure the products are fabricated as per daily schedule, especially to meet the customer requirements and given lead time. Secondly, the manager in-charge for the process optimization also is their daily task, especially to optimum material usage with less product changeovers with proper product planning. Finally, he does involve in process optimization to ensure all machine are fully utilised and less scrap and solid waste generated. The interview took about 60 minutes, the interview session was tape recorded. There are 18 pages of verbatim transcribes are produced for data analysis.

c. Company C3

Company C3 is a American based company, which was established in Malaysia since 1975 at the free trade zone at Penang state. Their products ranges are include walkie-talkie, communication and networking related products. These products are sold globally which include countries such as UK, Middle East, EU countries, Japan, Korea.

There is a material specialist participated the interview session. The interviewee has 10 years experience research and development especially in material selection and design. Her responsibility is to assist the company in compliance with the environmental legislation in product design such as WEEE and RoHS. In addition, she is actively involve to monitor and development of the material selection tools, particular to ensure their products are comply with the environmental sustainability requirements and also longer life product design. In addition, the concern of product end-of-life is another field to be monitored by interviewee C3 and her team. A 50 minutes interview session was conducted in the meeting room of Company C3. For the data analysis purpose, the recorded interview data were transcribed verbatim into 17 pages.

d. Company C4

Company C4 is an American based semiconductor manufacturer which was established in Malaysia in year 1998. This company was strategically located at the free trade zone of Melaka, Malaysia. The products variants in this company includes of power management integrated circuits, display drivers, audio and operational amplifiers, communication interface products and data conversion solutions.

There are four experts from Company C4 participated the interview session. They are department director, one packaging manager, and two senior production engineers. These experts are responsible for the product packaging design for electronic modules, material selection for electronic part protection, design for different electronic packages with consideration of customer requirements and compliances to different product quality standards, yield improvement in production, monitoring and optimizing the materials use along the processes, and also improve the process flow for new product fabrication. A total of 55 minutes of interview session was carried within the meeting room within the company.

e. Company C5

Company C5 is a multinational electrical company which located at Selangor state Malaysia. This company was established since 1930' which focusing to manufacture lighting product. Currently, this company has expands their business to wide range of consumer products such as LED lighting products, audio and video related products, and wide range of household electrical appliances.

The interviewee of Company C5 is a principle designer. His responsibility involves in research and development for new product, conducting finite elements analysis, material selection, improving mechanical design, reviewing new product specifications by different market needs, conducting lab testing for new product design, and studying new product quality standards and policy. Besides, he also conducted various product design cost-down activities, environmental sustainability related task forces particularly relating to product end-of-life. A total of 50 minutes of interview session was carried within the meeting room of the company. From the recorded interview data, it has been transcribed verbatim into 17 pages of qualitative data for further analysis.

f. Company C6

Company C6 is a multinational electronics company which is located at Selangor state, Malaysia. This company specializes in assembly, marketing, sales and service for a wide range of consumer electronics products. The plant in Selangor state mainly produces products such as LCD TV, LED TV, Blu-ray player, and DVD player.

The interviewee of Company C6 is a design engineer. His job scopes includes conducting various lab tests on the product based on different countries requirements, reviewing different country product design needs, preparing lab testing reports and documentations for new product development, liaise with production team for process flow improvement, and also work with design team when there is new compliance or countries policy for new product development.

g. Company C7

Company C7 is a joint ventured multinational company from two giant manufacturers from US (Photo Voltaic manufacturer) and also Taiwan (LCD manufacturer). In Malaysia, this company was established in year 2010, which is strategically located in the Silicon Valley of Melaka. The main business running by this company is to fabricate and supply various high powers and advanced solar cell, solar panels to their assembly plant in US.

The interviewee of Company C7 is a logistic and warehouse manager. His job scopes are mainly to liaise with production team in product packaging and protection for distribution, liaise with design team in packaging requirements, sourcing for packaging materials, preparing the documentation of packaging requirements based on different country requirements, in-house material handling, and also improving the material transferring either for the semi-finish goods or finish goods.

3.3.2 Data Analysis for Case Study

The main aim of a qualitative investigation is to develop the pattern and concept based on the gathered data (Yin, 2013). The data analysis for semi-structured interviews is mainly based on voice recordings during the interview sessions. Hence, the voice data need to be transcribed verbatim in order to facilitate data analysis.

In thematic analysis, there are five important steps involved in performing qualitative data analysis (Miles & Huberman, 1994). From the verbatim transcripts, the data were first reduced using the data reduction technique, whereby the scripts were read several times during which tentative codes or themes were given based on the meaning emerging from the data. The codes or labels given must present their insight attribution (Corbin & Strauss, 2008). The themes were built after the initial codes or themes were given to the related quotations. In this process, the researcher identified the relationships among the codes and grouped them together to form higher level codes. These codes were then re-labelled or re-named using either the name from one of the lower level codes or given new names in order to identify the group of codes. Finally, the themes were defined for the groups of codes related to the variable being studied. In this research, the theme was material efficiency strategies and organization change factors. Following this, the codes were re-labelled according to the final themes given to identify each group of codes. The qualitative findings can be generated based on the defined themes. The data analysis procedure is presented in detail in Table 3.4. Several techniques such as audit trail and member checking were employed in order to ensure research quality as well as the reliability and credibility of the findings (Robson, 2002). The audit trail was used to enhance the trustworthiness of the interpreted themes (Newman & Benz, 1998).

Table 3.4: Qualitative thematic analysis process

(Source: Compiled by the author from Miles & Huberman, 1994, pp. 50–64)

Step	Data Analysis process	Activity
1	Transcription of data	The researcher transcribes the recorded interview data verbatim. The transcripts were read several times in order to familiarize with the transcripts.
2	Generation of codes	The researcher codes interesting and relevant data (short phrases, sentences or the entire data set).
3	Building of themes	The researcher searches for and reviews the available themes to be used in order to describe the identified codes.
4	Define themes	The researcher clarifies the themes to be used by presenting clear relationships for the data codes.
5	Produce findings	The researcher analyses the results from the themes and codes, and relates these discoveries to scholarly findings.

3.3.2.1 Generation of Material Efficiency Themes

In qualitative research, the data gathered from tape recordings were transcribed verbatim to ensure that no information throughout the interview was overlooked. Single-case and cross-case analysis are both important elements for the analysis. For each investigated case or company, single-case analysis was performed to develop the codes and themes for a specific data set. Next, cross-cases analysis was used to combine all of the analysed cases to compare the similarities and differences of the case study companies. The research patterns can be explored by synthesizing the cross-case analysis. An illustration explaining how the author conducted multiple-cases analysis is shown in Figure 3.5.

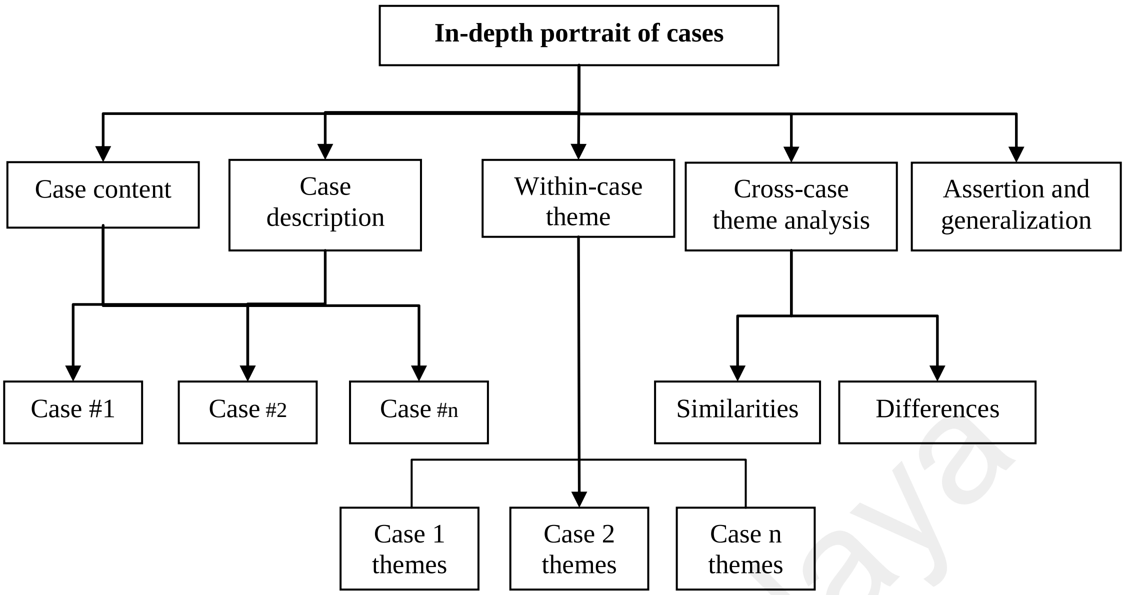

Figure 3.5: Coding a case study using multiple or collective case approach

(Source: Creswell, 2007, p.172)

3.3.2.2 Cross-case Analysis and Results

Two approaches were used to analyse the qualitative data, namely, within-case analysis and cross-case analysis. The within-case analysis emphasizes on data reduction and data management (Miles & Huberman, 1994). The voice data are first transcribed verbatim. Following this, the important and related quotations are highlighted and sorted. Next, codes were given to the sorted quotations and the codes were cross-referenced with the literature. All of the developed coding themes were organized and synthesized according to their category. The final results obtained from the within-case analysis present a concise description of variables found throughout the qualitative data.

The cross-case analysis emphasizes on identifying the research patterns across the various data sets. Pattern mapping and categorization from various data sets were used to reduce the amount of data and form a meaningful pattern (Miles & Huberman, 1994). The results of the cross-case analysis represent the compilation of themes obtained from qualitative exploration. Each individual data were combined and rearranged to present comprehensive and reliable findings. Figure 3.6 shows the procedure of the cross-case analysis used to merge all of the generated themes from different interview cases.

Similar themes within a single case were combined and analysed in order to facilitate the generation of qualitative themes. This is a form of data reduction through categorization of themes and pattern matching (Miles & Huberman, 1994; Yin, 1994). Each E&E company data set was combined and rearranged to present a comprehensive category. For example, similar themes from a different case study company were merged and presented in the form of a hierarchical chart using the "*dendrogram technique*" (Figure 3.7). The top of the hierarchy is the final theme which was selected from the group. In other words, the final theme is the rephrased theme which represents all of the related and similar sub-themes used within a case. Following this, the defined themes used for each case study company were compiled to reduce variation and redundancy of the data. By using a similar approach, different theme categories were extracted to represent the material efficiency practices found in Malaysian E&E companies. The example lists for the explored themes (drivers, barriers, enablers and material efficiency strategies) are presented in Appendix B to E.

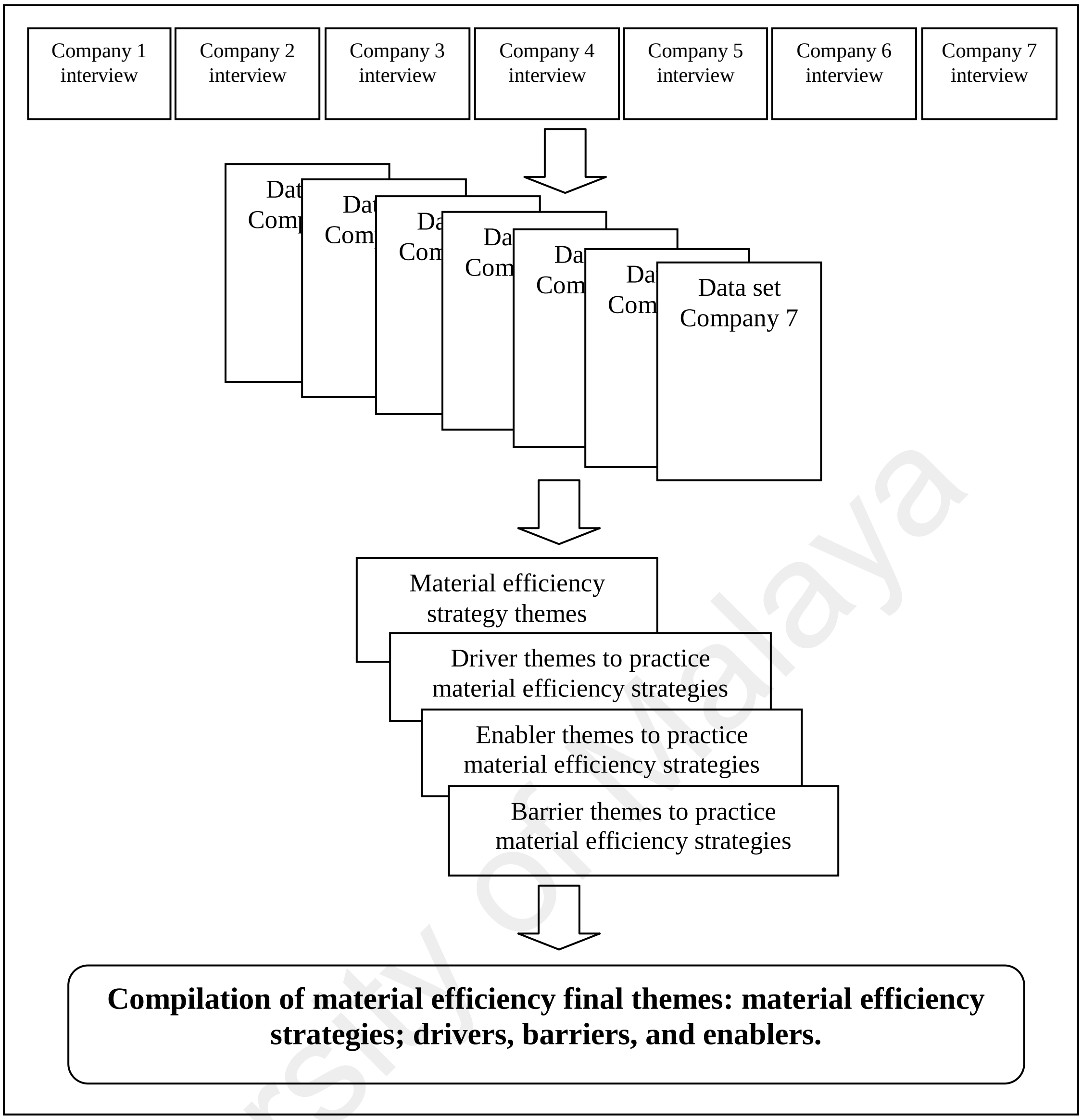

Figure 3.6: Illustration of cross-case analysis processes

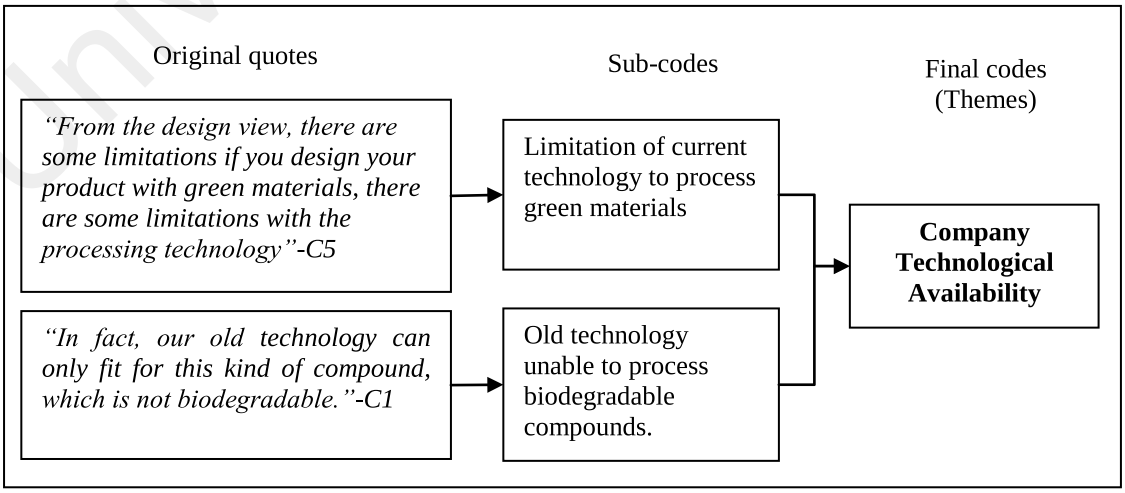

Figure 3.7: Dendrogram technique for theme formation

3.3.2.3 Research Quality for Qualitative Data

In this research, semi-structured interviews were used to explore the material efficiency strategies and factors that influence the implementation of these strategies. Therefore, it is crucial to ensure that the qualitative findings are trustworthy before they are used in the next stage of analysis. The trustworthiness of the research findings can be established through data validation. According to Creswell (2007), there are eight approaches typically used to validate qualitative data. These include prolonged engagement and persistent observation on the field, performing the triangulation method with other sources, peer review of the research process, negative case analysis, clarifying researcher bias from the study, member checking the formed themes with other parties, rich and thick description, and external audits.

Shenton (2004) suggested that there are four criteria which need to be considered in order to increase the quality and trustworthiness of the findings. Credibility refers to internal validity, which indicates that the correct study measures are applied for the concept. Therefore, in this research, the appropriate interview questions are the key elements to ensure high credibility of the findings. Transferability is an indicator whether the findings of a study can be transferred or applied to another situation which has a similar research setting. Therefore, establishing details of the background data for the case study is vital to ensure that there are fewer issues during transferability of the research findings. Dependability is an indicator of the reliability of the work when the work is repeated and same results are obtained with similar participants and research setting. Conformability ensures that the qualitative findings are generated according to the ideas of that informant rather than the preference of the investigator. The common approach used for conformability is “audit trail”, which allows the observer or reader to trace how the data obtained can lead to the formation of results.

In this research, the data obtained from the qualitative phase are rather limited. Hence, transferring these data to other cases with similar setting is rather challenging. For this reason, precautionary steps were taken to ensure the quality of the findings and these findings can then be transferred to a similar phenomenon. Therefore, only credibility and transferability were used to address the quality of the data and increase the trustworthiness of the data.

The verbatim transcripts which were used for data interpretation were also used for audit trail. An audit trail was performed to show how the extraction or richness of a data can be determined based on qualitative approach (Robson, 2002). Hence, the findings of this study can be used to guide future research in making the appropriate judgements, where the findings can be transferred to a similar research setting. In the first phase of this research, the interview sessions were fully recorded on tape, followed by verbatim transcription process, analysis and documentation. The tape-recorded interviews and verbatim transcripts were used to recheck the research findings if any doubts occur. It was found that the extracted qualitative results are promising and able to be transferred because they were processed meticulously. Examples of the interview transcripts are provided in Appendix F.

Note-taking was also conducted during the interview sessions in order to clarify any ambiguous statements given by the interviewees. A few other approaches were also conducted in order to obtain more insightful data. For example, observations and requests for site visits were done to ensure that the interviews reflect the real working environment of the companies. Some follow-up questions were addressed to the interviewees during the site visits to confirm their answers from the interview sessions.

Next, in the data analysis stage, member checking was performed on the data to confirm and strengthen the interpretations built from the qualitative data into solid and consistent themes (Laila Burla *et al.*, 2008; Steve Stemler (2001) in Landis & Koch, 1977). The verbatim transcripts were analysed using content analysis in order to extract insightful data based on the research objectives and research questions. It shall be highlighted that the synthesized data need to be checked for rigor and trustworthiness. Member checking was performed with other research members to check the synthesized data. The consensus build of the data was measured using the Kappa index or similarity index (> 0.6) (Laila Burla *et al.*, 2008) (see example at Appendix G). The interpreted themes or codes for the data with significant variants were further discussed and rephrased.

3.4 Multiple Criteria Decision Making

Deriving the importance weight of multiple criteria is a challenging and complex task. For that reason, multiple criteria decision making (MCDM) technique was introduced such as technique for order of preference by similarity to ideal solution (TOPSIS) (Opricovic & Tzeng, 2004), elimination and choice expressing reality (ELECTRE) (Anton *et al*., 2004), VIsekriterijumsko KOmpromisno Rangiranje (VIKOR) (Jahan *et al*., 2011) and Analytic Hierarchy Process (AHP) (Saaty, 1990). In this study, AHP approach is selected because it could provides a simple yet organize analytic framework for structuring a decision problem. Compared to many MCDM techniques, AHP is more effective to evaluate importance weight for the related criteria (Saaty, 2008), whereas others techniques are more suitable to rank the alternative or solutions such as VIKOR and TOPSIS (Tian *et al*., 2016; Bhutia & Phipon, 2012). Besides, AHP technique enables effective independency consistency evaluation and control for all criteria within individual or group decision in small samples (Saaty, 2008).

3.5 Quantitative Method: Analytic Hierarchy Process (AHP)

The qualitative method used to achieve Research Objective 1 and 2 has been discussed in the preceding sections. In this section, the quantitative method used for data analysis, namely, Analytic Hierarchy Process (AHP), is described in detail. The purpose of AHP survey is to prioritise the explored material efficiency themes from the qualitative study.

AHP was developed by Saaty in the early 1980s to decompose a complex problem into a hierarchy. The goal or objective is located at the top of the hierarchy whereas the criteria and sub-criteria are located at the levels and sub-levels of the hierarchy, respectively. The decision alternatives are located at the bottom of the hierarchy (Saaty, 1990). The AHP is a method that can be used to establish measures in both tangible (objective) and intangible (subjective) domains. The criteria at a given hierarchy level are compared in pairs to assess their relative preference with respect to each of the criteria at the next higher level. The comparisons are either actual measurements or they are taken from a fundamental scale that reflects the relative strength of preferences and feelings. In this research, Saaty’s fundamental scale of 1–9 was used to assess the intensity of preference between two elements. The intensity scale and its description are given in Appendix H.

AHP computes and aggregates the eigenvectors of the matrix until the composite final vector of weight coefficients for alternatives is obtained. The weight vector is then multiplied by the weight coefficient of the element at a higher level which is used as a criterion for pair-wise comparison. The procedure is repeated upwards for each level until the top of the hierarchy is reached. The entries of the final weight coefficient vector reflect the relative importance (value) of each alternative with respect to the goal stated at the top of the hierarchy. A decision maker may use this vector to suit their particular needs and interests. One of the major advantages of AHP is that it calculates the inconsistency index as a ratio of the decision maker's inconsistency. This index is generated randomly. This index is important for decision makers in order to ensure that the judgements are consistent and that the final decision is well made. The inconsistency index should be lower than 0.10. Re-evaluation of pair-wise comparisons will be conducted if there are large discrepancies in the comparisons (Pohekar & Ramachandran, 2004). AHP is limited up to 15 attributes for each hierarchy since a higher number of attributes will lead to inconsistent results (Saaty, 1992).

In this research, AHP fulfils the requirements to answer Research Objective 2, which is to identify the priorities of organizational change factors that influence the implementation of material efficiency strategies in the E&E industry. With this approach, the priority level of the change factors themes obtained from the qualitative method (i.e. drivers, barriers and enablers) can be determined. In addition, AHP also enable the criteria (change factors) to be presented in hierarchical attribute which facilitates in assessing the criteria priorities and organize the weighting process effectively.

3.5.1 Procedures of the AHP

The AHP consists of three primary processes (see Figure 3.8). Firstly, the AHP framework and pair-wise comparison lists were constructed based on the material efficiency themes built from qualitative results. This is followed by conducting the AHP survey with the pre-determined respondents from the E&E industry, and lastly, analysing and synthesizing the collected AHP data.

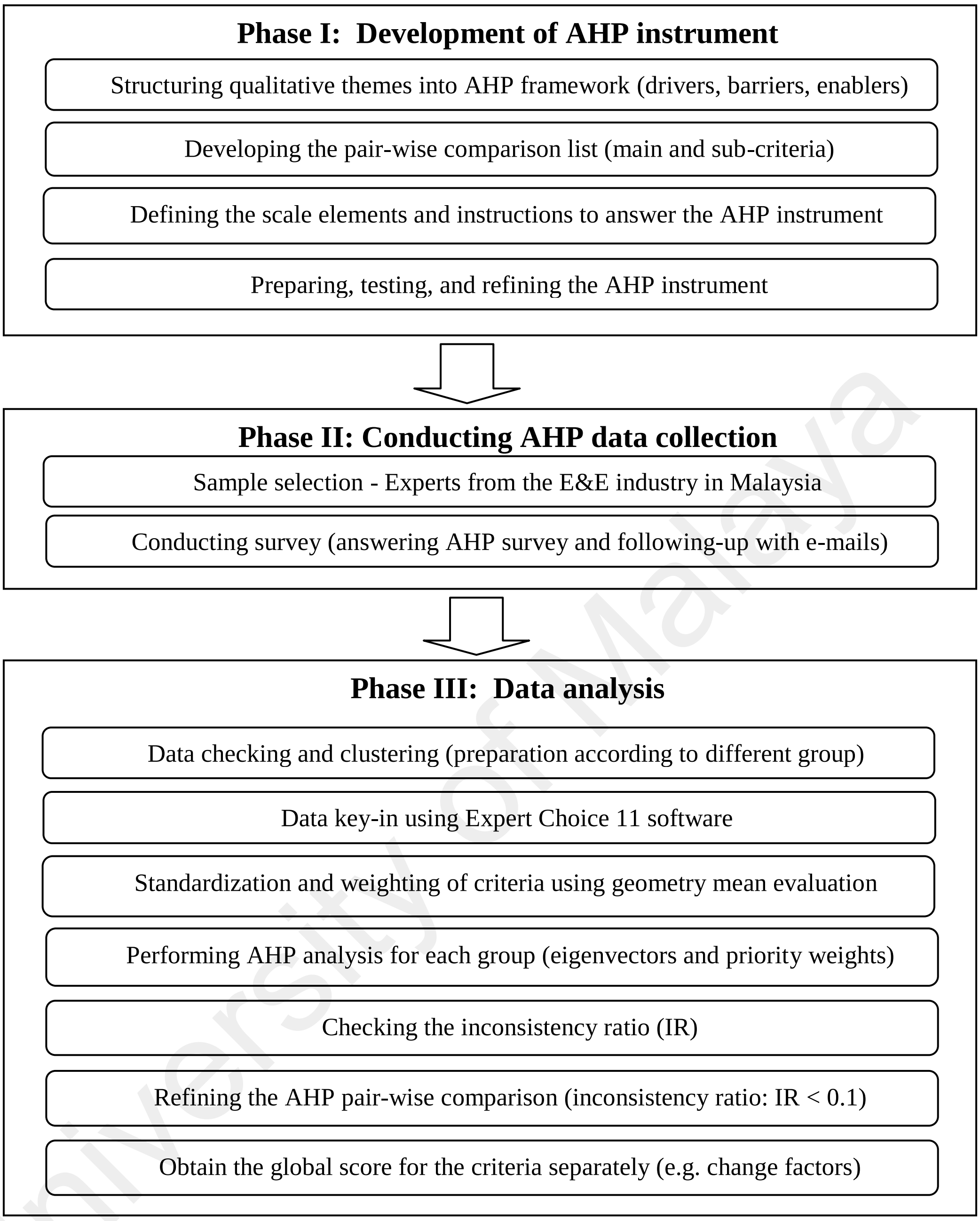

Figure 3.8: AHP methodology used in the study

3.5.1.1 Phase 1- Develop the AHP Research Instrument

The goal of the AHP analysis is to determine the priority level of the change factors in achieving material efficiency. Therefore, the qualitative data obtained were structured into an AHP framework based the generated theme categories. For example, the Drivers category consists of two main criteria, i.e. Internal Drivers and External Drivers. Next, by using the same approach, the sub-criteria for each theme category were constructed into their group. Three AHP frameworks were constructed, whereby each framework represents a different group of organizational change factors such as drivers, barriers and enablers. An example of the AHP framework for the criteria to practise material efficiency strategies is shown in Figure 39.

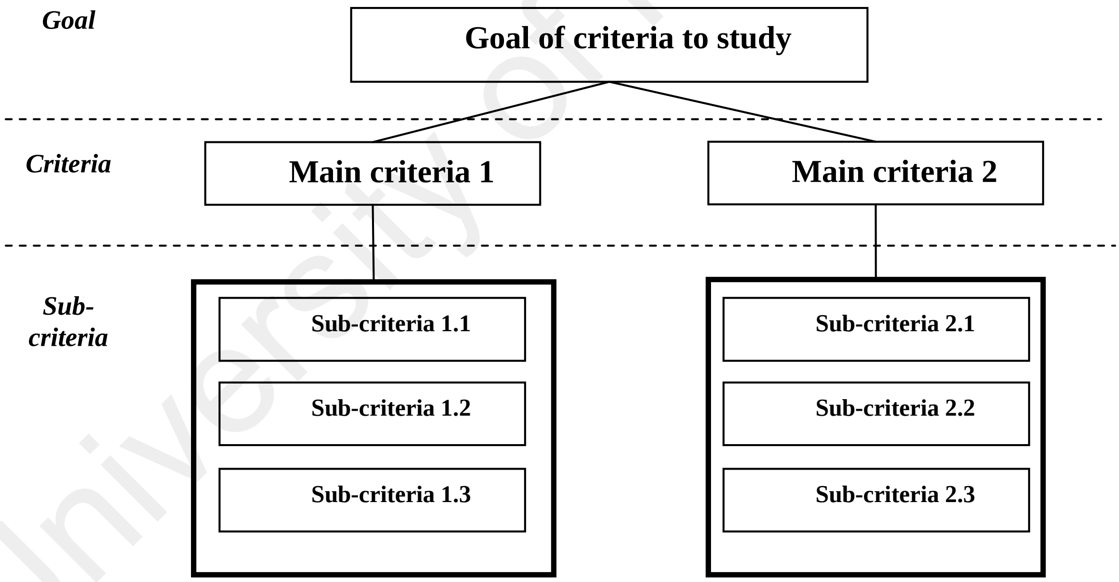

Figure 3.9: Example of AHP framework

Upon completion of the AHP framework, the next step is to develop the pair-wise comparisons according to each change factor group. The criteria within each category and hierarchical level are compared to their corresponding criteria based on the goal of AHP framework. For instance, the pair-wise comparisons were built separately based on main criteria and sub-criteria. Each of the pair-wise comparisons was measured based on its importance level using a measurement scale of 1–9 (Saaty, 2000). A judgement matrix consisting of all pair-wise comparisons for different levels of each category was evaluated separately. An example of the AHP instrument is shown in Appendix I.

3.5.1.2 Phase 2- AHP Data Collection

The data collection for the AHP was initiated by identifying the potential respondents using the Directory of Federation of Manufacturing Malaysia (FMM, 2012). Several requirements were set to ensure the right participants were selected. Following this, each respondent was contacted via e-mail or telephone call in order to obtain his or her approval to participate in the survey questionnaire. A total of 18 experts from different E&E companies participated the survey questionaire. The summary details of these companies are given in Chapter 5.

In carrying out the AHP data collection, each respondent was briefed on the purpose of the research. The respondent was instructed to answer the pair-wise comparisons in the AHP instrument. The researcher also clarified any doubts raised by the respondent from time to time, particularly regarding the AHP constructs / criteria used in the survey questionnaire. However, the survey questionnaire was e-mailed to the respondents who were unable to fill in the survey questionnaire via face-to-face interaction. The respondents were advised to contact the researcher if there were issues or confusion regarding the pair-wise comparisons. An example of AHP data is presented in Appendix J.

3.5.1.3 Phase 3- AHP Data Analysis

The data collected from the survey questionnaire were analysed based on four main aspects:

a. Local priorities
b. Eigenvalue evaluation
c. Consistency ratio (CR) and Inconsistency Ratio (IR) evaluation
d. Global priority weights based on geometric mean evaluation

The local priorities of the criteria were determined once the judgement matrix of the pair-wise comparisons for each group of criteria group was available. According to Saaty (2000), the local priorities of a group of pair-wise comparisons can be determined by using the principal eigenvector of the judgment matrix, which is given by:

$$Aw = \lambda_{max} w \qquad (3.1)$$

When the vector *w* is normalized, it becomes the vector of priorities of the criteria to attain the AHP goal. λ_{max} represents the largest Eigenvalue of matrix *A*. The eigenvector *w* consists of only positive values.

Apart from the developed judgement matrix, another important criterion is to measure the consistency of the judgement. This criterion is called the consistency ratio (CR) in AHP. The CR value is determined from the following formula:

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI} \qquad (3.2)$$

Here, CI represents the consistency index and RI represents the random index. The RI was selected from Table 3.5. The RI value was determined based on the size of the judgement matrix. For example, if the size of a judgment matrix is 3 × 3, the RI value is 0.58. The CI can be determined using the following formula:

$$\mathrm{CI} = (\lambda_{max} - n)/(n - 1) \qquad (3.3)$$

In general, a higher CR value indicates that the input judgements are less consistent. According to Saaty (1990), the consistency level should be within a range of 0–10%. If the CR value is more than 10%, the input judgements are considered less consistent and it is necessary to further refine the judgements with the respondents.

Table 3.5: Average consistency of random matrices (random index values) (Source: Saaty, 1990)

Size of criteria	1	2	3	4	5	6	7	8	9	10
Random index (RI)	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

In AHP analysis, the consistency of the opinions or weighting value given by experts is measured using the consistency index. For each group of data, the acceptable inconsistency index (IR) must be less than 10% (IR < 0.1) to ensure validity and consensus of the answers given by the respondents. In order to achieve a consistency ratio of more than 10%, the researcher needs to clarify problematic pair-wise comparisons with the particular respondent. Hence, the refinement process was conducted if there were inconsistencies in the data. The survey questionnaire needs to be re-sent to the respondent to confirm the scale ratings given by them, especially for problematic pair-wise comparisons. Once the consistency index was lower than or equal to 10%, the variables evaluated using the AHP approach were considered as “reliable”. Once all of the data sets fulfilled the consistency index, the next step involves generating the global score for the evaluated change factors. The priority weight for the main criteria needs to be multiplied with the priority weight of the sub-criteria in order to generate the final scores with a priority level. The details of global scores obtained for each change factor group are shown in Chapter 5.

3.5.2 Aggregation of Expert Opinions

In the AHP approach, the requirements of various expert opinions or multiple actors are important to increase the validity of data. There is usually more than one expert who will be consulted in each field. Consulting more experts prevents biases which may be present when the judgements are considered only from a single expert. However, if the judgements from many experts are considered, it is necessary to aggregate them in a suitable manner. Several methods are available to perform aggregation such as the geometric mean method and arithmetic mean method (Ramanathan & Ganesh, 1994; Saaty, 2000). In this research, geometric mean aggregation was used to syntheses of the reciprocals judgments obtained from 18 E&E experts.

3.5.3 Research Quality for the AHP Approach

The ultimate aim of quantitative research is to generalize the research constructs (Creswell, 2013). Therefore, the findings must fulfil the research quality criteria in terms of reliability or validity in order to ensure that these findings are transferrable to the next stage of research. In this research, AHP approach was used to obtain quantitative data from the industrial experts, i.e. experienced E&E practitioners. There are three goals for the AHP approach: (a) Structuring the change factors in the analytic framework, (b) Obtaining the priority rank of the change factors, and (c) Conducting consistency testing of the change factors. Thus, there are three criteria which need to be fulfilled in order to measure the quality of the data: (a) The number of pair-wise comparisons, (b) The number of experts or respondents and (c) Logical consistency.

Saaty (2000) suggested that the maximum AHP level should not exceed four levels in order to reduce pair-wise comparisons which will cause confusion to the respondents. Respondents are often inconsistent with their responses, which will result in errors and reduce the validity of the data. Furthermore, an increase in the number of pair-wise comparisons will result in instability of the consistency for the criteria.

In AHP approach, the quality of experts is more important than the number of experts who participated in the survey. Since the respondents are often inconsistent with their responses, Saaty (2000) proposed that the number of respondents should be less than 50 in order to reduce inconsistency in the data. In addition, when judgments from many experts were considered, it is necessary to aggregate them in a suitable manner and this can be done by means of geometric mean evaluation (Ramanathan & Ganesh, 1994; Saaty, 2000).

The consistency ratio (CR) was used to measure the consistency of the data for the pair-wise comparisons given by the respondents (Saaty, 2000). Saaty (2008) recommended that the CR value should be less or equal to 10% for four or more criteria. If the CR value is less than 10%, the data set is considered to be valid to represent the perspectives of experts who participated in the survey questionnaire.

3.6 Quantitative survey to determine the material efficiency strategy propositions

Due to the complexity of AHP method to conduct the sensitivity analysis for change factors towards each material efficiency strategy, an additional survey method is required to determine the importance weight of each change factor to influence the selection of each material efficiency strategy. In order to obtain the importance weight of each change factor with respect to a specific material efficiency strategy, a six-point Likert scale was used. The scale varies from "0" to "5", where "0" represents "not important at all", and "5" represents "extremely important". Therefore, only criteria with a rating of "1" and above were included in the propositions analysis. Each respondent needs to provide an importance rating for 225 questions which encompass the influence of 25 change factors on the nine material efficiency strategies.

In the instrument development phase, the survey instrument was developed in the form of matrix of three change factor groups. In the survey, there are three groups of change factors were developed in the matrix form towards each of material efficiency strategy. Evaluation need to be done for each change factor with reflect to its importance to practice a material efficiency strategy. In total, there are 225 answers to be completed by the respondent. The details of the survey instrument can be found at Appendix L.

Upon the completion of the survey instrument, it was pretested before proceed to the real respondents. In this phase of data collection, the same AHP respondents were chosen to participate the survey. Therefore, there are 18 survey data sets were collected.

In the survey data analysis, the importance weight of each change factor towards each material efficiency were obtained by dividing the submission of total importance weight from different respondent total ideal weight which is "90" (multiply optimum weight "5" with "18" respondents). The formula to be used for the importance weight as below, whereby X_i is refers to number of respondent and W_i is refer to the weight given by each respondent.

$$\text{Importance weight} = \frac{\sum X_i W_i}{\text{Total}} \qquad (3.4)$$

In the final phase of survey analysis, the obtained importance weight of each material efficiency strategy towards different change factors were interpreted into the potential propositions, which is importantly to be used in decision support tool development. The details explanation of the survey and its analysis results can be found in Chapter 6.

3.7 Development of Decision Support Tool

In this research, a decision support tool was developed to assist industry practitioners in practising material efficiency strategies in a systematic manner. In addition, this tool will facilitate industry practitioners in making decisions quickly when it comes to proposing solutions to achieve material efficiency. The development of the decision support tool involves four major steps: (a) Developing the decision support tool framework, (b) Establishing the link between the organizational change factors and material efficiency strategies, (c) Formulating the decision rules and alternatives for material efficiency strategies, and (d) Developing the worksheet of the decision support tool. The steps used to construct the decision support tool are summarized in the form of a flow chart, shown in Figure 3.10.

Firstly, the decision criteria (i.e. the change factors used to select material efficiency strategies) were determined using qualitative approach in order to create the decision support framework. Secondly, the synthesized findings obtained from the AHP were further analysed to establish the link between the change factors and material efficiency strategies. Thirdly, the rules used to form the priority alternatives for the material efficiency strategies were established. Lastly, a worksheet was developed for the decision support tool. The details of the development of the decision support tool are presented in Chapter 6.

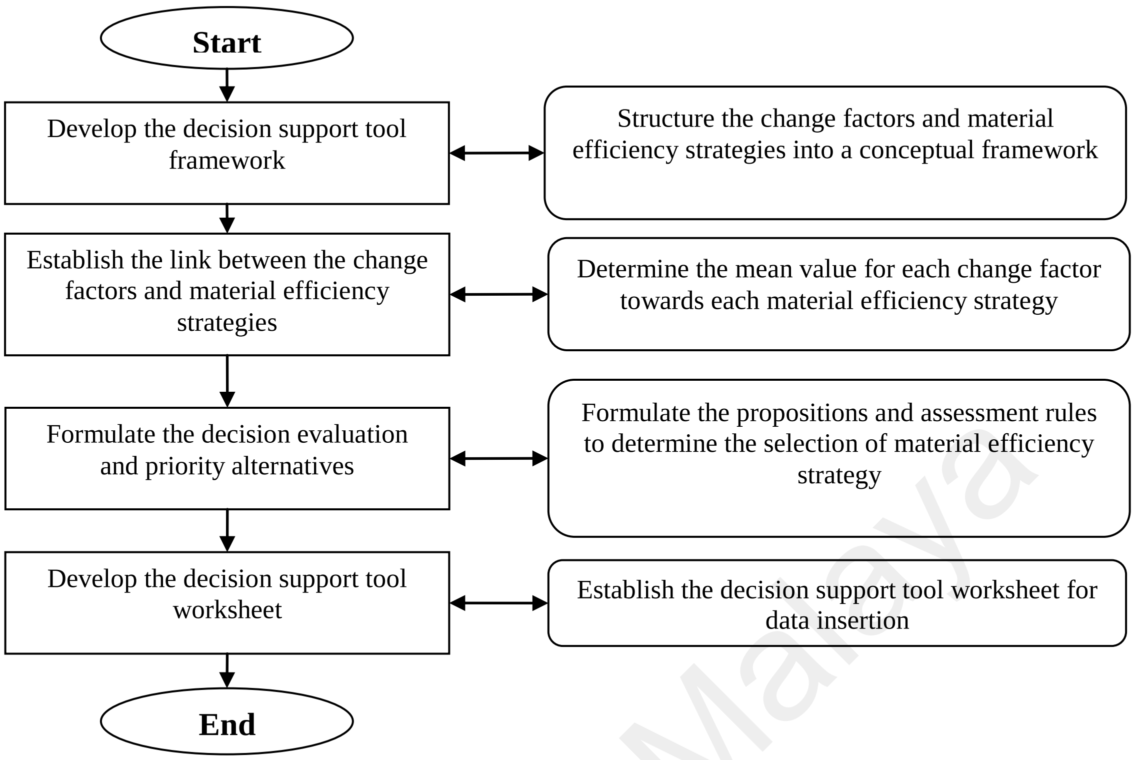

Figure 3.10: Flow chart of the decision support tool development

3.7.1 Validation of the Decision Support Tool

The decision support tool needs to be validated in order to determine whether the constructed decision model is able to represent a reliable phenomenon in an organization (Borenstein, 1998 through Finlay, 1989). Since the decision support tool is a new approach used to evaluate the decision change factors in selecting a material efficiency strategy, the most appropriate way to validate the decision support tool is using case studies, particularly to test and measure the validity of the change factors with the proposed material efficiency strategy.

According to Mysiak *et al.* (2005), there are five elements which need to be considered to validate the decision support system (DSS): (a) DSS design and development process, (b) DSS components, (c) Decision process, (d) Decision output, and (e) User satisfaction (Table 3.6). Each of these elements is important to validate the reliability and usefulness of the decision support tool. Bockstaller and Girardin (2003) proposed three phases of the validation process to test new indicators that cannot be benchmarked using available indicators or tools (see Figure 3.11). The validation procedure consists of Design validation, Output validation and End-use validation. The similarity between these elements is to validate the logical coherence of the decision criteria, output results and user assessment.

Therefore, in this research, the decision support tool was validated using three steps (Bockstaller & Girardin, 2003): (a) Design validation, (b) Output validation and (c) End-use validation. Three industrial experts were invited to participate in the validation process. The validation process is described in more detail in Chapter 7.

Table 3.6: Decision support system validation measurement

(Mysiak *et al.*, 2005, p. 205)

Subject of validation	Examples of measurement
DSS Design and Development Process	Involvement of future users in early development phases, appropriately defined system requirements, evolutionary system development, clear definition of beneficiaries
DSS components	Precision of models, quality of data, user interface, reporting system to choice of suitable technology and management of data, complexity of DSS and data inputs
Decision process	Appropriateness of logical process is followed when using the DSS, number of alternatives explored by the DSS, internal communication, correspondence to and appropriateness for decision organization
Decision output	Quantification profit/loss from DSS usage, consensus achieved among decision makers, savings of time or other resources through DSS usage, contribution to organizational efficiency, consistency of solution
User satisfaction	Degree of confidence in results derived by the DSS, acceptance (willingness to change current management methods), improvement of personal efficiency, correspondence of DSS output with decision-making style, users' understanding of the implemented models

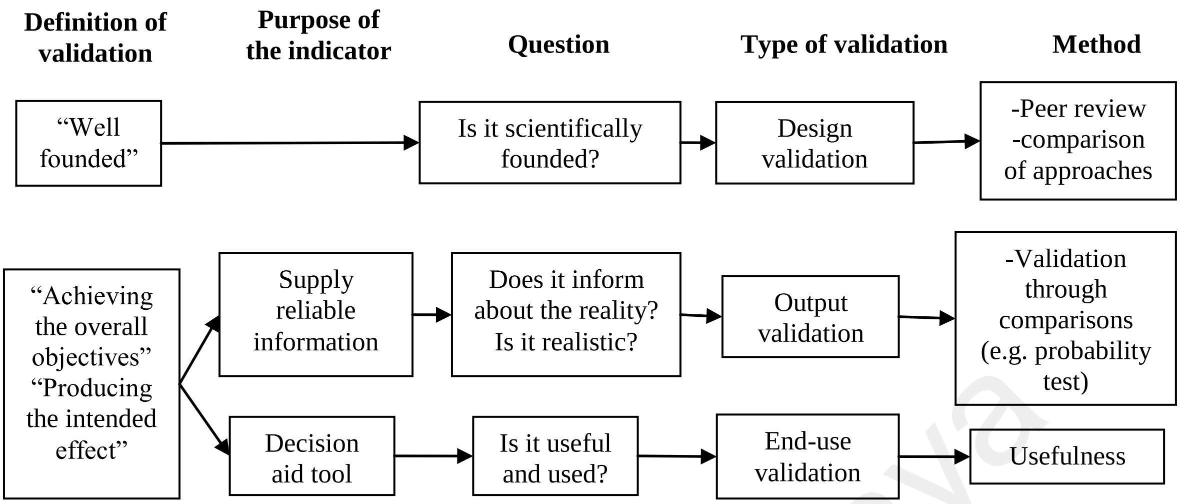

Figure 3.11: Validation flowchart for indicators framework

(Source: Bockstaller & Girardin, 2003, p. 641)

3.8 Summary

The systematic methodology adopted in this research is described in detail in this chapter. Firstly, a qualitative method (i.e. semi-structured interviews) was used to explore the organizational change factors and material efficiency strategies of E&E companies in Malaysia. Following this, AHP approach was employed to determine the priority level of the change factors which influence the implementation of material efficiency strategies. The findings from the AHP approach were used to develop a decision support tool in order to select the suitable material efficiency strategies. A series of techniques was also carried out to validate the results of the qualitative research, AHP as well as the decision support tool developed in this research. The methodology adopted in this study is summarized in Table 3.7. The key findings obtained from the mixed-method were analysed and presented in the following chapters, beginning with the results from the qualitative research, followed by the AHP approach and lastly, these findings will be discussed in detail for the development of material efficiency decision support tool.

Table 3.7: Summary of the research methodology

Research objective	Element	Research methodology
Objective 1- To identify the material efficiency strategies currently implemented in the E&E industry in Malaysia.	**Research method**	Qualitative: semi-structured interviews
	Research strategy	Inductive research design
	Data collection	Interview data, observations, site visits, a study of the company's website
	Data analysis	Thematic analysis: single case and cross-case analysis
	Research quality	Audit trail, member checking
Objective 2- To identify the significant organizational change factors that influence the implementation of material efficiency strategies in the E&E industry in Malaysia.	**Research method**	Quantitative: AHP
	Data collection	Quantitative survey (pair-wise comparison for all material efficiency change factors)
	Data analysis	Pre-testing, Eigenvalue, consistency ratio, local and global priority weight analysis
	Research quality	Measure the consistency ratio of eigenvalue (CR < 0.1)
	Research method	Quantitative: six-points likert scale survey Analysis: obtaining the importance weight of material efficiency strategy with reflects to different change factor.
Objective 3- To develop a decision support tool which will aid the selection of material efficiency strategies.	**Propositions development**	Structure and develop the decision propositions for the change factors that influence each material efficiency strategy.
Objective 4- To validate the decision support tool using suitable case studies.	**Validation approach**	Case study validation: Design validation (validate the decision framework), Output validation (comparison results with the decision tool), End-use validation (assessment of the functionality and user friendliness of the tool).

CHAPTER 4: INSIGHTS ON THE MATERIAL EFFICIENCY PRACTICES IN MALAYSIAN E&E COMPANIES

4.0 Overview

The research themes from the qualitative interviews are presented in this chapter. The important quotations were selected from the interview data obtained for each case company and the data were analysed to generate the related themes for material efficiency. Four main areas of material efficiency themes were extracted verbatim from the interviews- (a) Material efficiency strategies implemented by the E&E companies, (b) Drivers in the implementation of material efficiency strategies in E&E companies, (c) Barriers in implementing material efficiency strategies in E&E companies, and (d) Enablers in implementing material efficiency strategies in E&E companies.

In the next stage of qualitative analysis, the themes for each case company were combined for cross-case analysis. A comparison table was built to show the similarities of the themes and the pattern obtained from the case study. Critical analysis and discussion of the accepted and rejected themes are presented in this chapter. A summary of the key findings is presented at the end of this chapter.

4.1 Qualitative Results and Discussion

The emerging material efficiency themes extracted from the E&E case companies are presented in this chapter. This section begins with the extracted material efficiency strategy themes, followed by the driver themes, enabler themes and barrier themes in the implementation of material efficiency strategies.

4.2 Material Efficiency Strategy Implemented by the E&E Companies

There are various material efficiency strategies practised by the E&E companies in Malaysia are identified and presented in this section. These strategies are commonly practised by the case companies which were adopted in this research. Nevertheless, for strategies that are less relevant to this research and they lack justification. These strategies are rejected. Material efficiency strategies explored in this research is categorized into four groups following production stages namely (a) Material sourcing, (b) Product design, (c) Manufacturing process, and (d) Product distribution. The list of material efficiency strategies synthesized from the qualitative data is presented in Table 4.1. Examples of the interview quotations and the interpreted strategy themes are given in Appendix B.

a. Material Sourcing

In this research, material sourcing is found to be an important area in order to improve material efficiency. Seven companies (C1–C7) preferred to substitute their existing materials with recyclable materials or less hazardous substances. These companies claimed that the use of the environmentally friendly materials is compulsory (especially for electronic devices) in order to reduce environmental impact which stems from e-wastes as well as to facilitate the product recycling process. This is because their current technologies are still inadequate, especially to manage and process these highly toxic materials whereby the recycling tasks are dangerous to the recyclers' health. In addition, the recycling process consumes a higher energy compared to the extraction of virgin materials. Moreover, the profits gained from recycling activities are rather low.

In order to use materials efficiently, three companies (C1, C2 and C7) agreed that purchasing pre-manufactured parts helps prevent secondary manufacturing process. For example, Company C7 purchased a wafer which is pre-manufactured part for fabrication of solar cells. Another important element in purchasing pre-manufactured parts is information sharing among the suppliers. Information sharing can be done by specifying the material specifications to the suppliers, especially the shape and size of the parts. The suppliers need to supply the right parts according to the specifications given by the manufacturer. Company C2 mentioned by maintaining a good relationship with the suppliers, this will ease the implementation of material efficiency strategies through green material supply.

Table 4.1: Finalized material efficiency strategies implemented by selected E&E companies in Malaysia

Area	Material efficiency strategy	C1	C2	C3	C4	C5	C6	C7
Product design	**Product light-weighting**	√		√	√	√	√	
	Design for material recovery				√			
	Design for longer life			√				
	Design for multi-functionality	√		√		√	√	
Material sourcing	**Material substitution (e.g. green materials)**	√	√	√	√	√	√	√
	Purchasing of pre-manufactured parts	√	√					√
Manufacturing process	**Yield improvement**	√		√	√	√	√	√
	Process efficiency	√	√		√	√		√
Product Distribution	**Green packaging**		√		√		√	√

b. Product Design

In general, the product design strategies for E&E products fulfill environmental standards and market requirements such as the use of non-hazardous materials in order to produce green products. In this research, it is found that there are possible changes that can be made in order to achieve material efficiency, particularly with regards to changes in materials and mechanical design.

Five E&E companies (C1, C3–C6) suggested that products should be designed using fewer materials (i.e. product light-weighting). This strategy can be achieved by reducing the number of parts in order to simplify the product design as much as possible. Examples of product light-weighting include reducing the number of screws in the product assembly, using lighter PCB materials but with higher strength, and eliminating non-significant parts (especially non-value added components) such as internal casing.

Company C1, C3, C5 and C6 implemented the "design for multi-functionality" strategy in order to reduce the amount of materials in the development of E&E products. This strategy is commonly practised in the E&E industry (especially for complex product development) in order to enable more features to be embedded in the chipset or electronic product. At the same time, "designing to reduce parts" helps reduce the total amount of materials used in product development. In addition, this strategy reduces the weight of the product while achieving the same or better performance. For example, Company C3 designs products with smaller PCB footprint, which reduces current consumption and usage of chipsets.

In this research, only a few E&E companies proposed the implementation of "design for material recovery". However, Company C4 emphasized that "design for longer life" helps increase the product life cycle. This company claimed that their integrated chipset has a minimum lifespan of 8 years. This strategy can help slow down the generation of e-wastes and the desire to purchase new E&E products.

c. Manufacturing Processes

In this research, various strategies were practiced by the E&E companies in order to achieve material efficiency during the manufacturing stage. The "material yield improvement" strategy has relatively gained much attention from the E&E companies. The high yield can be attributed to use of advanced technologies with high precision. One of the companies (C2) claimed that they were able to minimize material wastage during the integrated circuit manufacturing process by improving the raw material clamping contact. Two companies (C1 and C5) implemented a strategy to optimize the usage of lead frames during the integrated chip bonding process, whereby they attempted to reduce the cut edge of the raw material in order to minimize generation of scrap materials. Product batch processing is one of the examples used in C1 to reduce unnecessary solid wastes in preparing materials for various types of products changeover.

d. Product Distribution

With regards to product distribution, the companies that participated in this research have implemented the green packaging strategy in order to prolong the lifetime of the packaging material. This initiative was done by utilizing packaging materials made from recyclable sources (C7). The efficient use of materials in the packaging design ensures that the spaces are being use optimally. However, safety and protection of the E&E products are still of utmost importance besides material savings. Therefore, potential changes in packaging are presumed to be limited only within the E&E industry.

4.2.1 Rejected Material Efficiency Strategy

In this section, the less relevant material efficiency strategies which were extracted from the qualitative data are presented. These strategies are bulk packaging and also returnable packaging.

a. Bulk Packaging

According to one interviewed informant (C7 - Logistics Manager), the company also practises bulk packaging to reduce inventory space and the related cost of warehouse management. Although this practice is able to reduce material usage in the long term, it is understood that this strategy is not implemented in shipping the products to the customers. Bulk packaging is only implemented for packing of the incoming raw materials and temporary storing of semi-finished goods. In addition, E&E products made from brittle materials are not suitable for bulk packaging which may give less protection to the products. Similarly, for Company C6, this strategy is not part of the company's practices in order to achieve material efficiency. Therefore, this strategy is considered impractical for E&E finished goods which are large sized, expensive and requires careful handling such as solar panels.

b. Returnable Packaging

Based on the interview results, only Company C7 practises returnable packaging in order to achieve material efficiency. Returnable packaging is used for plastic pellets, which are used to stack the finished goods. The used pallets will be returned to the company after shipment for future use. Therefore, this strategy is implemented in the logistics aspect of material efficiency. However, this strategy is rejected since only one company implements this strategy. In addition, according to the interviewee, not all of their products are shipped with returnable packaging due to the cost issues.

4.3 Drivers which Influence the Implementation of Material Efficiency Strategies in E&E Companies

Similar driver themes were extracted from each case company and then combined and represented with an appropriate theme. The finalized driver themes are discussed in this section. There are 13 emerging driver themes which influence the implementation of material efficiency strategies, whereby five themes are internal drivers and eight themes are external drivers. The complete list of drivers is given in Table 4.2. Examples of interview quotations and interpreted driver themes are given in Appendix C.

a. Customer Requirements

Customer requirements are one of the most important drivers which influence the implementation of material efficiency strategies in E&E companies in Malaysia. This was quoted by most of the E&E companies selected in this research (C1–C6). This is indeed unsurprising since fulfilling the customers' requirements is primary means of survival for manufacturers. The E&E companies need to fulfil various customer needs such as producing multi-functional products, products with lower energy consumption, products with slim, sleek designs and eco-design products.

Secondly, once green products have become the norm in Malaysia, the E&E companies need to fulfil the requirements of environmentally conscious consumers such as reducing the usage of toxic substances such as cadmium, lead and lead compounds, polychlorinated biphenyls (PCBs) as well as mercury. This is particularly important to fulfil the needs of the global market, especially EU consumers.

Table 4.2: List of drivers which influence the implementation of material efficiency strategies in E&E companies

Category	Driver	C1	C2	C3	C4	C5	C6	C7
Internal drivers	Social responsibility		√	√		√		√
	Reducing materials	√	√			√	√	
	Reducing energy usage					√		√
	Reducing production costs	√	√	√			√	√
	Improve environmental image	√	√		√	√		
External drivers	Increase in price of raw materials			√		√		
	Compliance with local environmental legislation		√					
	Fulfil international product design	√	√	√	√	√	√	√
	Public pressure		√					
	Supplier requirements			√	√			√
	Customer requirements	√	√	√	√	√	√	
	Competition among rivals	√	√		√			
	Support from other industries			√			√	

b. Compliance with Local Environmental Legislation

The aim of this driver is ensure that the manufacturing operations existing in a company comply with the policies set by the local government. In this research, Company C2 mentioned that the local authorities or the Government of Malaysia has placed local environmental regulations on the E&E industry. One of the regulations that need to be fulfilled is to control the level of residual wastes released from the manufacturing processes such as wastewater, cubical solid wastes and CO_2 emissions. This regulation has driven E&E companies to practise material efficiency strategies, especially to reduce the usage of hazardous substances and chemicals, as well as reduce energy consumption and product scraps. Most of the E&E companies investigated in this research comply with ISO 14001 standards to ensure that their operations are environmentally friendly with minimum environmental impact.

c. Fulfil International Product Design

One of the challenges in the E&E industry is the rapid changes in trends and technologies. The E&E industry in Malaysia is no exception. According to all of the companies interviewed in this research (C1–C7), the E&E industry needs to comply with stringent legislation for their products and processes such as WEEE, RoHS and EUP. One of the reasons is to limit the consumption of hazardous and dangerous substances used in E&E products, which is detrimental to both human health and the environment. Therefore, the manufacturers need to ensure that their products strictly comply with these directives before the products are sold in the global market, especially to EU countries. This compliance is tremendously important to ensure that the products give less impact to the environment throughout the phases of the product life cycle. Therefore, fulfilling these requirements is important to ensure that rapid economic development will not lead to a rapid depletion of available resources.

d. Reducing Production Cost

Reduction of production costs is crucial for many manufacturing sectors including the E&E industry in order to remain competitive in the market. According to five E&E companies interviewed in this research (C1–C3, C6 and C7), the purpose of reducing production costs is to reduce the number of parts. When E&E products are designed with simplicity in mind, this will help reduce production costs by minimizing the number of manufacturing processes. In addition, the amount of hazardous chemicals as well as energy consumption can be reduced if the product design consists of fewer parts. At present, the products produced by the E&E industry are shifting towards nanotechnology, whereby more functions can be placed within a chipset to reduce the size and number of integrated circuits in a product. This promotes material efficiency, which will assist the company to reduce product scraps. With simple product designs, E&E companies can increase their productivity and enhance the development of new products.

e. Reducing Materials

Reducing materials is a crucial goal in running a business and this includes the E&E companies in Malaysia. Four of the E&E companies (C1, C2, C5, and C6) strongly agreed that material efficiency strategies will help them reduce material intake. Reducing material intake directly affects the operations cost and profits gained from the product. In this research, the E&E companies practise material efficiency strategies in order to reduce the amount of hazardous substances in their products such as lead, mercury and cadmium. Based on the interview data, it is found that the E&E companies practise material efficiency strategies to reduce the primary material intake in order to deliver products with higher performance. For instance, Company C2 emphasized on reducing the usage of hazardous substances, creating lighter products by combining several product functions into a single part such as integrated circuits, and optimizing the material cutting edge. Implementing these strategies help Company C2 to reduce production costs and increase business profits. In general, the reduction of raw material intake will reduce generation of wastes and environmental impact.

f. Competition among Rivals

The rapid growth of the E&E industry on the local and global scale results in great competition among companies, especially in terms of product price and product specifications. The E&E companies that participated in this research (C1, C2 and C4) claimed they face stiff competition from both local and international competitors which includes competitors from China. Therefore, in order to remain competitive in this fast-moving field and become the market leader, E&E companies need to offer high-quality products at competitive prices. For example, Company C2 produces integrated circuits with longer lifespans and make modifications in their product design in order to reduce material intake and energy consumption. By doing so, the E&E companies can gain competitiveness by reducing their primary resource consumption.

g. Reducing Energy Usage

Reducing environmental impact is one of the main goals in implementing environmental strategies including material efficiency strategies. Most of the E&E case companies primarily deal with hazardous substances as well as high energy consumption. Energy is an important source to operate machines and process raw materials, however, manufacturing process can have a detrimental impact to the environment such as generation of greenhouse gases and increase in CO_2 emissions. In this research, two E&E companies (C5 and C7) confirmed this viewpoint, whereby if the raw material intake is reduced, the processing time can be reduced, which in turn, reduces the usage of energy. In addition, some of the materials require high energy processes such as chip bonding, wafer machining and fabrication of integrated circuits.

h. Increase in the Price of Raw Materials

An increase in the price of raw materials is typically due to the scarcity of raw materials available, difficulties in sourcing virgin materials as well as the increase in demand for raw materials. This driver appears to be a critical driver for most manufacturing sectors including the E&E industry to practise material efficiency strategies. The raw materials typically used in the E&E industry are gold, copper and other precious metals. According to Company C3 and C5, practising material efficiency strategies can lead to significant cost savings in material sourcing and boost their profits since the products can provide the same functionality, with reduced material consumption.

i. Supplier Requirements

Supplier plays an important role in ensuring that the right raw materials are supplied to the customers or manufacturers in order to fulfill product specifications. These materials include lead-free, biodegradable and environmentally friendly raw materials. Therefore, in order to achieve material efficiency, Company C3, C4 and C7 agreed that green suppliers play a pivotal role to ensure that their products fulfill the market's standards and requirements. Furthermore, the use of green materials can help reduce part defects and rejection during the manufacturing process.

j. Support from Other Industries

Support from other parties such as allies, business partners, recyclers and sub-contractors are an important driver to encourage the implementation of material efficiency strategies. In Malaysia, the E&E companies rely on strong collaboration with their allies in order to ensure their product meet market requirements. Company C3 highlighted that getting support from other industries is important to ensure that the products fulfil environmental requirements. In addition, support from ISO 14001 certified sub-contractors can also help the E&E industry to produce components and parts that fulfil the requirements of material processing.

k. Improve the Environmental Image

In the current market trend, improving environmental image is important to boost business performance. Companies with a good environmental reputation can significantly gain more business, especially from the international market. In this research, Company C1, C2, C4 and C5 perceived that improving environmental image is a critical driver in implementing material efficiency strategies. Based on the AHP results, it is found that the E&E companies constantly face rapid changes in their product requirements. The E&E companies emphasize on producing green products and practising eco-design. This will enhance their environmental image to the customers and business partners. As a result, they may gain more business, especially from "green" consumers.

l. Public Pressure

Public pressure refers to the pressure given by the community, stakeholders to a company to adopt green strategies. In material efficiency context, although the pressure of public is lightly seen because most of E&E companies are certified with ISO14001 and comply with stringent legislation to manufacture their products. However, according to Company C2, the E&E industry has great potential to generate e-wastes, which is a prevalent issue faced by the global population. Therefore, public pressure can help drive the E&E industry to produce products that are less detrimental to the environment. Thus, public pressure is an important factor to encourage more E&E companies to practise material efficiency strategies.

m. Social Responsibility

Social responsibility is an important element to show to the surrounding community about the company's initiative on environmental protection or improving the quality of life of the society. In Company C2, in an attempt to reduce carbon footprint, activities such as tree planting programme were organized to expose the society to the importance of environmental protection. Company C7, on the other hand, organizes an open day annually to educate the community on how the company manages their company's waste as well as wastewater treatment. Therefore, a good company with a high awareness on environmental protection and high social responsibility will influence their employees to practise environmental strategies such as using green materials in their products, reducing the energy consumption and reducing usage of toxic chemicals.

4.4 Barriers which Influence the Implementation of Material Efficiency Strategies in E&E Companies

The finalized barrier themes determined in this research are presented in this section. Nine emerging barriers are identified from the interview data, whereby five themes are internal barriers and the remaining four themes are external barriers. The complete list of barrier themes is given in Table 4.3. Examples of the interview quotations and interpreted barrier themes are given in Appendix D.

a. Customer Requirements

It is common for companies to produce products that fulfil the needs of the market in order to gain a competitive edge in their business. According to Company C1, C2, C4, C5 and C6, customer requirement is a significant barrier which constrains them in practising material efficiency strategies. For example, designing electronic products with green materials is particularly challenging such as the reliable supply chain either local or oversea supplier. In addition, the usage of green materials requires major modifications to be made in the production lines. In addition, rapid changes in the trend and technology of electronic products have forced manufacturers to produce new product specifications.

Table 4.3: List of barriers which influence the implementation of material efficiency strategies in E&E companies

Category	Barrier	C1	C2	C3	C4	C5	C6	C7
Internal barriers	Lack of information / knowledge		√	√			√	
	Product design restriction		√	√	√	√	√	√
	Company technological availability	√	√			√		√
	Lack of readiness to change	√	√					
	High implementation costs	√	√		√		√	√
External barriers	Regulation constraints		√				√	
	Suppliers and supply chain	√		√				
	Lack of external support	√		√		√		
	Customer requirements	√	√		√	√	√	

b. Lack of External Support

The second barrier that influences the implementation of material efficiency strategies is lack of external support. In this research, external support refers to the support given by the third parties such as the local government, local recyclers, industrial experts and consultants. According to Company C1, C3 and C5, government support is very limited with regards to encouraging environmental practices. In addition, there is a lack of local recyclers, which reduces the momentum of the manufacturers in achieving material efficiency. This may be due to the fact that the current technologies and techniques available to process e-waste are still immature and limited. Furthermore, in developing nations such as Malaysia, recyclers are less exposed to the right knowledge and approach which are required to provide a comprehensive solution to solve industrial wastes. The lack of industrial experts and consultants to assist manufacturers and recyclers is also an indication of poor external support.

c. Company Technological Availability

Technological availability in a company is an important factor to facilitate the efficient use of materials. For instance, the use of automated systems and robotics will greatly facilitate material handling and reduce the likelihood of product damage due to material mishandling. Company C1, C2, C5 and C7 highlighted that they are still using old machinery to fabricate their products even though they are fully aware on the importance of practising material efficiency strategies. This is due to the high initial costs to purchase new machines, slow return on investment especially for expensive machines as well as increase in man-machine operation costs. Therefore, due to the high investment costs, these E&E companies resort to using old technologies.

d. Regulation Constraints

The most common directives which need to be complied by the E&E industry are the RoHS and WEEE directives. This compliance is mandatory to ensure less hazardous substances are used in the development of products, which in turn, results in the disposal of hazardous solid wastes. For instance, Company C2 perceives that regulations are compulsory but they are difficult to fulfil, particularly stringent policies which require the use of green materials in product development, which makes product design challenging. According to Company C3, there are other reasons that contribute to the lack of compliance including difficulties in sourcing green materials from the local market. However, Company C5 highlighted that the lack of government certification for recycled materials as well as the low demand for green materials such as recycled materials contribute to the lack of compliance. Company C3 and C5 mentioned that the available regulations have limited their options in selecting the appropriate manufacturing process as well as alternative materials to produce a product.

e. Implementation Cost

For a manufacturing company, implementing a new strategy requires cost investment especially for purchasing new technology, acquiring permits and sourcing materials. According to Company C3, C4, and C5, E&E manufacturers in Malaysia are less interested in investing in a new business strategy that they are unfamiliar with strategies that are considered risky to them. These investments include the costs to obtain approval and permit such as environmental standards, costs to upgrade machinery and costs to substitute green materials. A few case study companies stated that technology investment is the most critical issue because the initial investment is high whereas the payback period is longer. Moreover, the strategies are not scientifically proven.

f. Restrictions in Product Design

In this study, "restrictions in product design" is a barrier in the implementation of material efficiency strategies. For example, the use of lead-free materials is highly recommended in order to retain product quality (Company C3 and C4). In contrast, the use of hazardous substances such as mercury and cadmium are not recommended. The interviewee from Company C3 quoted that they are unable to use other alternative materials in product development such as lead-free materials since these green materials are generally more expensive. In addition, some E&E companies highlighted that not all types of products are applicable for redesign since this will affect their existing production lines. Hence, restrictions in product design are a cause of inconvenience to these companies when it comes to implementing new strategies.

g. Suppliers and Supply Chains

Suppliers play a vital role in implementing material efficiency strategies. The successful implementation of material efficiency strategies is dependent on the commitment of suppliers and reliability of the supply chains. Company C1 mentioned that they need to source green materials either from local or international suppliers. The local suppliers are found to be less capable of supporting the manufacturer, especially in supplying green materials which fully comply with international legislation. Another issue highlighted by the E&E companies in this research is unreliable supply chains. According to Company C3, expensive green materials such as recyclable materials are hard to find in developing countries such as Malaysia. Therefore, most of the time, the company imports the raw materials from international supply or obtain these materials from a very limited number of local suppliers at exorbitant prices.

h. Lack of Information and Knowledge

Based on the interview data, it is understood that some of the E&E companies in Malaysia are incapable of formulating material efficiency solutions. For example, Company C2 is clueless on the steps that can be taken to achieve material efficiency either from innovation of materials or mechanical design. This may be due to that fact that some of the E&E companies are not equipped with their own research and development (R&D) facility for continuous improvement and these companies are less experienced regarding the material efficiency concept. Moreover, both interviewees from Company C3 and C6 highlighted that the manager in charge of the factories in Malaysia is not given the full authority to make decisions in order to improve production. Most of these companies are restricted by the policies set by the headquarter office, which limits the subsidiaries from implementing new practices.

i. Lack of Readiness to Change

The implementation of environmental strategies requires the company to change, either from managerial or technical aspects. However, not every change is easy and some changes require complicated adjustments, high investment costs and high commitment from the company's stakeholders. In general, the E&E companies in Malaysia perceive that the company's readiness to change is one of the barriers in implementing material efficiency strategies. Some E&E companies highlighted that implementing a new strategy such as material efficiency practice is both cumbersome and time-consuming. For instance, Company C1 and C2 are quite reluctant in implementing material efficiency strategies since they are less confident and doubtful of the benefits that can be gained from making such changes.

4.5 Enablers which Influence the Implementation of Material Efficiency Strategies in E&E Companies

Three main enablers are identified from the interview data, namely, ISO14001 certification, adoption of advanced technology and environmental awareness of the company's top management. These enablers are described in more detail in the following paragraphs. A complete list of enablers experienced by the E&E companies is given in Table 4.4. Examples of the interview quotations and extracted enabler themes are given in Appendix E.

a. ISO14001 Certification

Certification of the environmental management system (EMS) or ISO 14001 is an important criterion to evaluate the environmental protection efforts of a company through greener production activities. All of the case companies (C1–C7) claimed that their company has ISO 14001 certification in order to enhance waste management and promote green manufacturing awareness. This is achieved by using a proper waste water channelling system, controlling CO_2 emissions, using non-toxic chemicals and reducing the usage of hazardous substances. Recruiting an environmental health and safety (EHS) officer is a solution typically implemented by companies involved in the usage of hazardous substances and chemicals. The EHS officer monitors the production activities to ensure that these activities do not contribute significant harmful wastes to the environment.

Table 4.4: List of enablers which influence the implementation of material efficiency strategies in E&E companies

Enabler	C1	C2	C3	C4	C5	C6	C7
ISO14001 certification	√	√	√	√	√	√	√
Adoption of advanced technology	√	√	√				√
Environmental awareness of the company's top management	√	√	√	√	√		

b. Adoption of Advanced Technology

In this research, five E&E companies agreed that advanced technology will help them minimize material loss and optimize the usage of raw materials. For example, Company C7 proposed that the use of an automated material handling system will help reduce product scrap resulting from mishandling of materials by the operator.

Based on the interview data, it is found that Company C3 uses advanced software to simulate and assist designers in designing products that comply with environmental regulations. The use of advanced technology with higher precision and accuracy speeds up the manufacturing process, which leads to more raw material savings. For instance, the wafer cutting machine is designed to reduce the generation of scrap and it is equipped with a variable speed control system to ensure consistent speed of tooling during operations. According to Company C1, a bonding machine that is capable of bonding multiple layers is a great innovation to improve the usage of materials while delivering high-quality multi-functional products.

c. Environmental Awareness of the Company's Top Management

Five E&E companies (C1–C5) agreed that the top management of a company plays a role in influencing the rest of the employees regarding environmental awareness. Therefore, an environmentally conscious working culture is largely influenced by how the top management inculcates that culture within the company. This includes establishing green policies for the company, recruiting EHS officers and organizing programmes that promote environmental awareness. It is found that Company C2 has established a "green team" to facilitate and promote environmental awareness among all employees. This top-down effect will increase the environmental awareness of the company's workforce in their daily activities as well as increase the employees' participation in contributing more ideas to "green" their company.

4.6 Summary

The results of the qualitative method used to collect and analyse the data from selected E&E companies in Malaysia are presented and discussed in this chapter. A total of seven E&E companies participated in the interviews. The findings of the interviews were then combined and compared to form a pattern to practise material efficiency strategies. Four significant theme categories were found from the qualitative data: (a) Material efficiency strategies, (b) Material efficiency drivers, (c) Material efficiency barriers, and (d) Material efficiency enablers.

Nine material efficiency strategies were found from the verbatim transcriptions, whereby six strategies are conducted during the design phase: (a) product light weighting, (b) Design for material recovery, (c) Design for longer life, (d) Design for multi-functionality, (e) Material substitution, and (f) Purchasing of pre-manufactured parts. Two strategies are implemented by the E&E companies during the manufacturing phase: (a) Yield improvement and (b) Process efficiency. The E&E companies interviewed in this research implemented green packaging during the logistics and product distribution phase in order to achieve material efficiency.

In general, the E&E companies selected for interview in this research are mainly driven by external drivers rather than internal drivers. One of the reasons to explain this incident is due to their products are mostly sold aboard, therefore fulfilment of the different country requirements and customer needs is their upmost priority. The external drivers include the increase in the price of raw materials, compliance with local legislation and regulations, fulfilling international product designs, public pressure, green supplier requirements, customer requirements, competition among rivals and support from other industries. On the other hand, the extracted internal drivers include social responsibility, reduction of materials, reduce energy usage, reduction of production costs and improve environmental image.

However, the E&E companies in Malaysia are primarily challenged by internal barriers rather than external barriers when implementing material efficiency strategies. The reasons are due to the lack of readiness among the manufactures to switch their business to environmental oriented. Five internal barriers were found, namely, lack of information and knowledge, restrictions in the product design, company technological availability, lack of readiness to change and high implementation costs. Four external barriers were found, namely, regulation constraints, suppliers and supply chains, lack of external support and customer requirements.

Three enablers were highlighted by the E&E companies which will help them in implementing material efficiency strategies: ISO 14001 certification, adoption of advanced technology and environmental awareness of the company's top management. The material efficiency themes extracted from the interviews with representatives from the E&E companies are summarized in Table 4.5.

The explored material efficiency themes are important since they represent the current decision status and the direction of the E&E companies in implementing material efficiency strategies. However, the importance level of the organizational change factors and its proposition links towards the explored material efficiency strategy themes need to be determined. The priority weights of the change factors determined from the AHP approach are presented and discussed in the following chapter.

Table 4.5: Summary of the explored material efficiency themes

Internal drivers	External drivers	Enablers	Internal barriers	External barriers
✓ Social responsibility ✓ Reducing materials ✓ Reducing energy usage ✓ Reduction of production costs ✓ Improve environmental image	✓ Increase in the price of raw materials ✓ Compliance with local legislation / regulations ✓ Fulfils international product designs ✓ Public pressure ✓ Supplier requirements ✓ Customer requirements ✓ Competition among rivals ✓ Support from other industries	✓ ISO 14001certification ✓ Adoption of advanced technology ✓ Environmental awareness of the company's top management	✓ Lack of information and knowledge ✓ Restrictions in product design ✓ Company technological availability ✓ Lack of readiness to change ✓ High implementation costs	✓ Regulation constraints ✓ Suppliers and supply chains ✓ Lack of external support ✓ Customer requirements

Material efficiency strategies:

- ✓ Product light-weighting
- ✓ Design for material recovery
- ✓ Design for longer life
- ✓ Design for multi-functionality
- ✓ Material substitution
- ✓ Purchasing of pre-manufactured parts
- ✓ Yield improvement
- ✓ Process efficiency
- ✓ Green packaging

CHAPTER 5: EVALUATION OF MATERIAL EFFICIENCY CHANGE FACTORS

5.0 Overview

In Chapter 4, three categories of material efficiency change factors were extracted from the interview data, namely, drivers, barriers and enablers which influence the implementation of material efficiency strategies. The importance weights of the explored change factors were determined using AHP approach and the results are presented in this chapter.

A total of 18 large sized E&E companies (>250 employees) from Peninsular Malaysia participated in the survey questionnaire. These companies include Integrated Circuit Company, Communication Device Company, Microwave Company, Solar Cell Company, TV Company, Flash PCB Company, Computer Component Company, Circuit Design Company. The details of each company are summarized in Table 5.1.

Table 5.1: List of AHP respondents

Company	Type of E&E industry	Country of origin, company size	Example of products / services	AHP participant
AHP 1	Electronic components	USA, large	Integrated circuits (e.g. electronic chipset)	Packaging Manager
AHP 2	Consumer electronics	Japan, large	Audio and video products (e.g. TV)	Senior Engineer (Team Leader)
AHP 3	Consumer electronics	Netherland, large	Audio and video products (e.g. TV)	Senior Designer (Team Leader)
AHP 4	Electronic components	Malaysia, large	Electronic components	Production Manager
AHP 5	Industrial electronics	USA, large	Computer devices (e.g. hard disk)	Senior Engineer (Team Leader)
AHP 6	Electronic components	Germany, large	Design and manufacturing of electronic circuits	Electronic Designer (Team Leader)
AHP 7	Consumer electronics	Singapore, large	Communication devices (e.g. telephones)	Programme Engineer
AHP 8	Consumer electronics	Singapore, large	Printing devices (e.g. printer)	Senior Engineer (Team Leader)
AHP 9	Industrial electronics	Japan, large	Computer products (e.g. desktops, keyboards)	Logistics Manager
AHP 10	Electronic components	USA, large	Integrated circuits (e.g. electronic chipsets)	Senior Engineer (Production)
AHP 11	Electrical	USA, large	Electrical appliances (e.g. microwave)	Lean Manager
AHP 12	Consumer electronics	USA, large	Communication devices (e.g. fax machines)	Lean Manager
AHP 13	Electronic components	Malaysia, large	Integrated circuits (e.g. electronic chip)	Production Manager
AHP 14	Industrial electronics	Germany, large	Integrated circuits and electronic devices (e.g. ABS electronic controllers)	Senior Engineer (Team Leader)
AHP 15	Electrical	Japan, large	Air-conditioning systems (air-conditioning compressors, blowers)	Environmental, Safety, and Health Manager
AHP 16	Industrial electronics	USA, large	Electronic devices for experimental laboratory use	Operations Manager
AHP 17	Electrical	USA, large	Solar cells	Packaging Manager
AHP 18	Consumer electronics	USA, large	Communication devices (e.g. telephones)	Principle Designer

5.1 Analysis of Drivers using AHP

The importance weights of the drivers which influence the implementation of material efficiency strategies are analysed and quantified in this section. There are two levels of drivers hierarchy are evaluated namely criteria and sub-criteria. Pair-wise comparison using AHP was conducted for two groups of drivers (see Figure 5.1). Each group of drivers has its own sub-criteria, which represent the sub-drivers that influence E&E companies in Malaysia to practise material efficiency strategies. The sub-drivers of “internal drivers” are social responsibility (SR), reducing materials (MR), reduce energy usage (RE), improve environmental image (IEI) and reduction of production costs (PR). The sub-drivers of “external drivers” are the increase in price of raw materials (RP), compliance with local environmental legislation (CLL), supplier requirements (SU), customer requirements (CR), fulfil international product design requirements (FPD), public pressure (PP), competition among rivals (CO) and support from other industries (SI). There are 38 pair-wise comparisons all of these drivers in total. The complete version of the AHP instrument is presented in Appendix I.

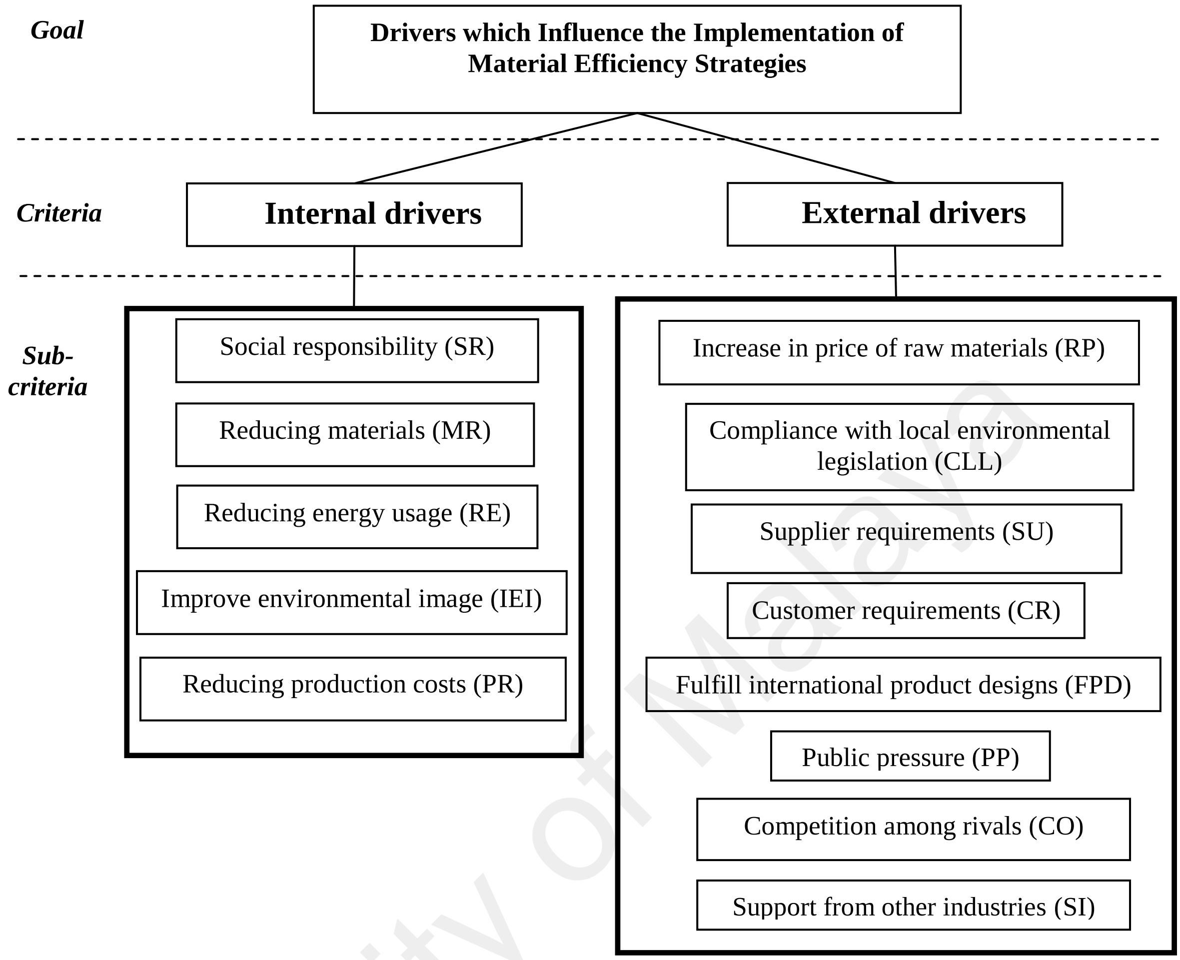

Figure 5.1: AHP framework of drivers which influence the implementation of material efficiency strategies

5.1.1 Priority Evaluation for Drivers

The priority weights for the drivers were determined using Expert Choice V11. Software. The priority weight for internal drivers and external drivers is found to be 0.289 and 0.711, respectively (Table 5.2). Five sub-criteria were assessed for internal drivers and 10 pairs of drivers were evaluated. It is found that PR has the highest priority weight for the “Internal drivers” category, with a value of 0.335, followed by MR (0.275), RE (0.179), IEI (0.133) and SR (0.078). The Eigenvalues for the internal drivers and their corresponding priority weights are presented in Table 5.3 and Table 5.4.

Eight sub-criteria were assessed using the AHP approach for the "External drivers" category and 28 pairs of drivers were evaluated. It is found that that CR has the highest priority (0.231), followed by FPD (0.207), CLL (0.168), CO (0.115), RP (0.084), SU (0.072), SI (0.063) and PP (0.059). The Eigenvalues for the grouped external drivers and their priority weights are presented in Table 5.5 and Table 5.6.

The absolute priority weight of internal and external drivers and their sub-criteria can be determined by multiplying the relative weight of the main criteria with the relative weight of the sub-criteria. In this research, the main criteria refer to the internal and external drivers, whereas the external drivers are the sub-drivers for each category. Therefore, the absolute priority weight obtained for all drivers follows the following order (Table 5.7): CR (0.18), FPD (0.147), CLL (0.119), PR (0.097), CO (0.082), MR (0.079), RP (0.06), RE (0.052), SU (0.051), SI (0.045), PP (0.042), IEI (0.038) and SR (0.023). The priority weight of the grouped drivers which influence the implementation of material efficiency strategies is arranged from the highest to the lowest priority.

Table 5.2: Priority weight of grouped internal and external drivers which influence the implementation of material efficiency strategies

Main criteria	**Relative local weight**
Internal drivers	0.289
External drivers	0.711

Table 5.3: Eigenvalues obtained from pair-wise comparison of internal drivers

	SR	**MR**	**RE**	**PR**	**IEI**
SR	**1**	0.330	0.341	0.278	0.538
MR		**1**	1.702	0.794	2.255
RE			**1**	0.488	1.247
PR				**1**	2.695
IEI					**1**

Table 5.4: Grouped priority ranking of internal drivers

Internal drivers (Sub-criteria)	Relative weight of sub-drivers	Rank
Reducing production costs (PR)	0.335	1
Reducing materials (MR)	0.275	2
Reducing energy usage (RE)	0.179	3
Improve environmental image (IEI)	0.133	4
Social responsibility (SR)	0.078	5

Table 5.5: Eigenvalues obtained from pair-wise comparison of external drivers

	RP	CLL	FPD	PP	SU	CR	CO	SI
RP	**1**	0.474	0.460	1.669	1.416	0.256	0.545	1.709
CLL		**1**	0.869	1.783	2.172	1.078	1.555	2.788
FPD			**1**	2.549	2.963	1.308	2.351	3.824
PP				**1**	0.435	0.334	0.441	0.696
SU					**1**	0.284	0.467	0.898
CR						**1**	3.048	4.000
CO							**1**	1.968
SI								**1**

Table 5.6: Grouped priority ranking of external drivers

External drivers (Sub-criteria)	Relative weight of sub-drivers	Rank
Customer requirements (CR)	0.231	1
Fulfil international product designs (FPD)	0.207	2
Compliance with local environmental legislation (CLL)	0.168	3
Competition among rivals (CO)	0.115	4
Increase in price of raw materials (RP)	0.084	5
Supplier requirements (SU)	0.072	6
Support from other industries (SI)	0.063	7
Public pressure (PP)	0.059	8

Table 5.7: Local and global weights for internal and external drivers obtained from geometric mean evaluation

Driver category (criteria)	Relative weight of main drivers	Drivers (Sub-criteria)	Relative weight of sub-drivers	Global weights using AHP	Rank
Internal drivers	0.289	Reducing production costs (PR)	0.335	0.097	4
	0.289	Reducing materials (MR)	0.275	0.079	6
	0.289	Reducing energy usage (RE)	0.179	0.052	8
	0.289	Improve environmental image (IEI)	0.133	0.038	12
	0.289	Social responsibility (SR)	0.078	0.023	13
External drivers	0.711	Customer requirements (CR)	0.231	0.164	1
	0.711	Fulfil international product designs (FPD)	0.207	0.147	2
	0.711	Compliance with local environmental legislation (CLL)	0.168	0.119	3
	0.711	Competition among rivals (CO)	0.115	0.082	5
	0.711	Increase in the price of raw materials (RP)	0.084	0.060	7
	0.711	Supplier requirements (SU)	0.072	0.051	9
	0.711	Support from other industries (SI)	0.063	0.045	10
	0.711	Public pressure (PP)	0.059	0.042	11

5.1.1.1 Customer Requirements

"Customer requirements" is ranked as the utmost driver which influences E&E companies in implementing material efficiently strategies. This finding is unsurprising since customer requirements are the obvious means of survival for manufacturers. In this research, it is found that the E&E companies need to fulfil various customer needs such as producing multi-functional products, produces with lower energy consumption, slim and sleek products, as well as eco-design products.

According to Eveloy *et al.* (2005), the current trend of products emphasizes more on green elements, especially with regards to raw material use. For this reason, E&E companies in Malaysia are strongly driven by the trends of the global market such as usage of lead-free materials, banning of hazardous substances such as mercury, hexavalent, lead and cadmium. Fulfilling customer requirements is crucial in order to cater the needs of the global market, especially the EU market (Gottberg *et al.*, 2006). According to Ashby (2012), due to the rapid changes in the product trend, manufacturers need to produce products with shorter lifespan such as electronic products. Hence, incorporating environmental elements into products is challenging. This leads to increase in e-waste generation.

5.1.1.2 Fulfil International Product Design

The E&E industry is typically faced with rapid changes in product style compared to other industries such as metal industry, plastics industry and the furniture sector (Wang *et al.*, 2017). At the same time, the E&E industry needs to comply with the most stringent legislation for their products such as WEEE, RoHS and EUP. Therefore, E&E manufacturers need to ensure that their products comply with both of these requirements before they are sold in the global market.

In this research, it is found that most of the E&E companies are emphasize on using green materials in their products because they feel that unless stringent policies or directives are enforced in material use, e-wastes can be reduced and minimized through proper and effective e-waste recycling. This is in line with the findings of past empirical studies, whereby green materials should be used to facilitate material recovery and reduce environmental impact at the product's end of life (Worrell & van Sluisveld, 2013; Ongondo *et al.*, 2011). However, at present, there is no specific legislation concerning material efficiency (Lilja, 2009a). As a result, material efficiency can only be practised to fulfil current legislation such as RoHS.

5.1.1.3 Reducing production costs

Reducing production costs is a crucial factor for many manufacturing sectors including the E&E industry in order to remain competitive in the market (Adams *et al.*, 2006). When E&E products are designed with simplicity in mind, this will reduce production costs by shortening the manufacturing process (Rahimifard *et al.*, 2010; Sikdar, 2007). In this research, it is found that the products produced in the E&E industry are gearing towards nanotechnology, whereby more functions can be incorporated into a chipset, which will reduce the size and number of integrated circuits in the product. This in turn, will reduce the usage of hazardous chemicals as well as energy since the products consist of fewer parts. If the products are designed with less complexity, this will help companies achieve material efficiency and reduce production costs (Abdul Rashid *et al.*, 2008). The E&E companies can increase their productivity and competitiveness by reducing the processing time and waste generation.

5.1.1.4 Compliance with Local Environmental Legislation

The main aim of complying with local environmental legislation is to ensure that the manufacturing operations of a company comply with local government policies such as the maximum permissible CO_2 emissions. In this study, it is found that the local authorities or the Government of Malaysia has enforced regulations which need to be complied by the E&E industry. These regulations include controlling the level of residual wastes released from manufacturing processes such as wastewater, controlling the disposal of hazardous substances and cubical solid wastes, as well as controlling the release of CO_2 emissions. These regulations have driven E&E companies to practise material efficiency strategies in order to reduce the usage of hazardous substances, chemicals and product scrap, as well as reduce energy consumption. Most of the case companies comply with ISO 14001 standards in order to ensure that their operations are environmentally friendly with minimum environmental impact. This finding is in line with the past results (Singh *et al.*, 2015; Sambasivan & Fei, 2008; Ammenberg & Sundin, 2005).

5.1.1.5 Reducing materials

Obviously, reducing materials is a crucial goal in running a business including the E&E case companies investigated in this research. When the material intake is reduced, this will have a direct implication on the operation costs and profits of a product. The E&E companies in Malaysia implement material efficiency strategies in order to reduce the primary material intake while delivering a product with superior performance. For instance, the companies emphasized on reducing the usage of hazardous substances, creating lighter products by combining several product functions into a single part such as integrated circuits and optimizing the cutting of raw materials. This will significantly reduce the cost per unit of their products. In addition, waste generation and environmental impact will be reduced when raw material intake is reduced (Ashby, 2012; Pajunen *et al.*, 2012; Peck & Chipman, 2007).

5.1.1.6 Competition among Rivals

The rapid growth of the global and local E&E industry results in fierce competition among companies, especially in terms of the price and specifications of the product (Adams *et al.*, 2006). Similarly, the E&E companies in Malaysia face great competition from both local and international companies, especially from China. Therefore, in order to remain competitive, the E&E companies need to offer superior products at competitive prices. For example, the E&E case companies produce integrated circuits with longer life performance and they also make changes in their product design in order to reduce material intake and energy consumption. In addition, promoting green products produced from non-toxic substances can be one of the selling points for the goods in this competitive market. These findings are in agreement with those in other studies (Hanssen *et al.*, 2003).

5.1.1.7 Increase in the Price of Raw Materials

The price of rise raw materials generally increases if there is a scarcity in the raw materials, difficulties to source for virgin materials as well as there is an increase in the demand for raw materials (Rice, 2008). In the manufacturing sector, it is imperative to make efficient use of materials since it is directly linked with the operation costs. This is indeed a critical driver for most manufacturing companies, including E&E manufacturers. The raw materials commonly used in the E&E industry are gold, copper and other precious metals. Therefore, by practising material efficiency, the E&E companies can reduce significant costs for material sourcing and increase the profits from their products by delivering products with the same functions but consume fewer materials.

However, there is no high demand for recycled materials since this may affect the quality of the product (Peck & Chipman, 2007). Products made from recycled materials are regarded as second-grade products. In addition, the companies consider that making use of recycled materials is a cumbersome and inefficient process due to the high energy use during material recovery. There is no significant difference between using recycled materials and virgin materials in terms of costs. Moreover, there is a lack of certification from the government in using recycled materials (Allwood *et al.*, 2011). Hence, the demand for recycled materials does not seem to be encouraging, especially for consumers with more buying power.

5.1.1.8 Reducing energy usage

In the manufacturing industry, energy is important to operate machines and process raw materials. In one empirical study, material efficiency strategies were implemented to reduce energy consumption and CO_2 emissions (Hekkert *et al.*, 2002). Some of the E&E companies investigated in this research also confirmed this point of view and this factor was given a higher priority rank. This may be motivated by the fact that when the raw material intake is reduced, the processing time will be reduced, which reduces energy consumption (Worrell & van Sluisveld, 2013; Allwood *et al.*, 2011; Hekkert *et al.*, 2002). As a result, the end products can be produced within a shorter lead time, which also increases cost-effectiveness of product development.

5.1.1.9 Supplier Requirements

A supply chain consists of different participants to perform a sequential activity in order to transfer physical goods or services from one point to another point of consumption (Mentzer *et al*., 2001). The supply chain involves various parties such as suppliers, manufacturers, distributors, retailers and customers. The suppliers play an important role to ensure that the right raw materials are supplied to the customers or manufacturers and it is crucial that these raw materials fulfil product specifications. For example, the raw materials supplied to the E&E industry should be lead-free and biodegradable (Eveloy *et al.*, 2005). Therefore, in order to achieve material efficiency in E&E industry, suppliers play a pivotal role to ensure that their products fulfil the standards and requirements of the market. However, difficulties in sourcing green materials may hamper manufacturers from implementing material efficiency strategies.

5.1.1.10 Support from Other Industries

Support from within the industry's network such as allies, business partners, recyclers and sub-contractors is important to encourage the implementation of material efficiency strategies (Lilja, 2009a; Peck and Chipman, 2007). However, this driver is rarely highlighted in previous studies. In Malaysia, the E&E companies rely on and they need to have a strong collaboration with their allies to ensure that their products fulfil market requirements. For instance, fulfilling environmental requirements is their primary goal in product development. Thus, working with a ISO 14001 certified partners or subcon can ensure their product comply with the environmental requirements in their products (Sambasivan & Fei, 2008; Jiang & Bansal, 2003).

In this research, it is found that the E&E industry does not generate enormous amounts of industrial wastes due to precise manufacturing processes. However, support from the industry's network is needed to collect residual materials and material scrap. More importantly, the E&E case companies do not have internal recycling facilities to manage and process product scrap. Therefore, in order to enhance waste management and achieve material efficiency especially in the context of material recovery, the E&E companies require support from both recyclers and end-users. Hiring material efficiency consultants also plays a vital role to educate and help industry practitioners to reduce material intake and production wastes (Lilja, 2009a). However, hiring material efficiency consultants is a rare practice in developing countries such as Malaysia.

5.1.1.11 Improve Environmental Image

In the current marketing trend, there is a need to improve the company's environmental image in order to boost business performance (Georgiadis & Besiou, 2008; Somsen *et al.*, 2004). Companies with good environmental reputation can significantly obtain more business, especially from the international market (Sambasivan & Fei, 2008). In this research, it is found that improving environmental image is considered a critical driver which influences the implementation of material efficiency strategies in E&E companies in Malaysia. The E&E industry is constantly faced with rapid changes in their product specifications such as producing green products or practising eco-design to fulfil market needs. This will improve the environmental image of the companies, especially in the eyes of the consumer. In return, the manufacturing companies will gain more business, especially from "green" consumers.

5.1.1.12 Public Pressure

Public pressure is another driver which influences the implementation of material efficiency strategies in E&E companies. Public pressure refers to the pressure given by the stakeholders such as communities, consumers and the government. In this research, pressure refers to the pressure faced by the company to reduce the environmental impact of the product such as by eliminating the use of hazardous substances. Based on the results of the AHP, it is found that the E&E companies face less public pressure because they comply with the most stringent environmental legislation and policies in designing their products such as RoHS (Ongondo *et al.*, 2011). Therefore, although there are other parties such as the green society who stress on green product requirements, the E&E companies in Malaysia generally perceive that their initiatives towards green products and material savings have achieved a satisfactory level.

5.1.1.13 Social Responsibility

Social responsibility is the last driver which influences the implementation of material efficiency strategies in E&E companies in Malaysia. On the whole, the E&E companies are less driven by social responsibility because the products produced by the E&E industry do not generate significant amounts of cubical wastes unlike other industries such as timber and furniture companies (Ilomäki & Melanen, 2001). In addition, the usage of chemical substances are well controlled and properly managed. This is done by having the appropriate channels for storing chemical substances before these chemicals are sent to professional collectors for further action. In order to promote social responsibility, some E&E companies conduct various activities with the community on a frequent basis such as organizing a tree planting programme, which promotes their environmental consciousness to the community.

5.2 Analysis of Barriers using AHP

To analyse the barriers which influence the implementation of material efficiency strategies, the initial AHP framework for comparing the barriers was established based on the explored barrier themes. There are two levels of barriers hierarchy are evaluated, two major groups of barriers were identified, namely, internal barriers and external barriers (see Figure 5.2). Each group has its own sub-barriers which represent the barriers faced by the E&E companies in Malaysia in implementing material efficiency strategies. The "internal barriers" category consist of the following sub-criteria: company's readiness to change (CRC), implementation costs (IC), restrictions in product design (PDR), lack of information and knowledge (LIK), and company technological availability (CTA). The "external barriers" category consists of the following sub-criteria: regulation constraints (RC), suppliers and supply chains (SSC), lack of external support and customer requirements (CR).

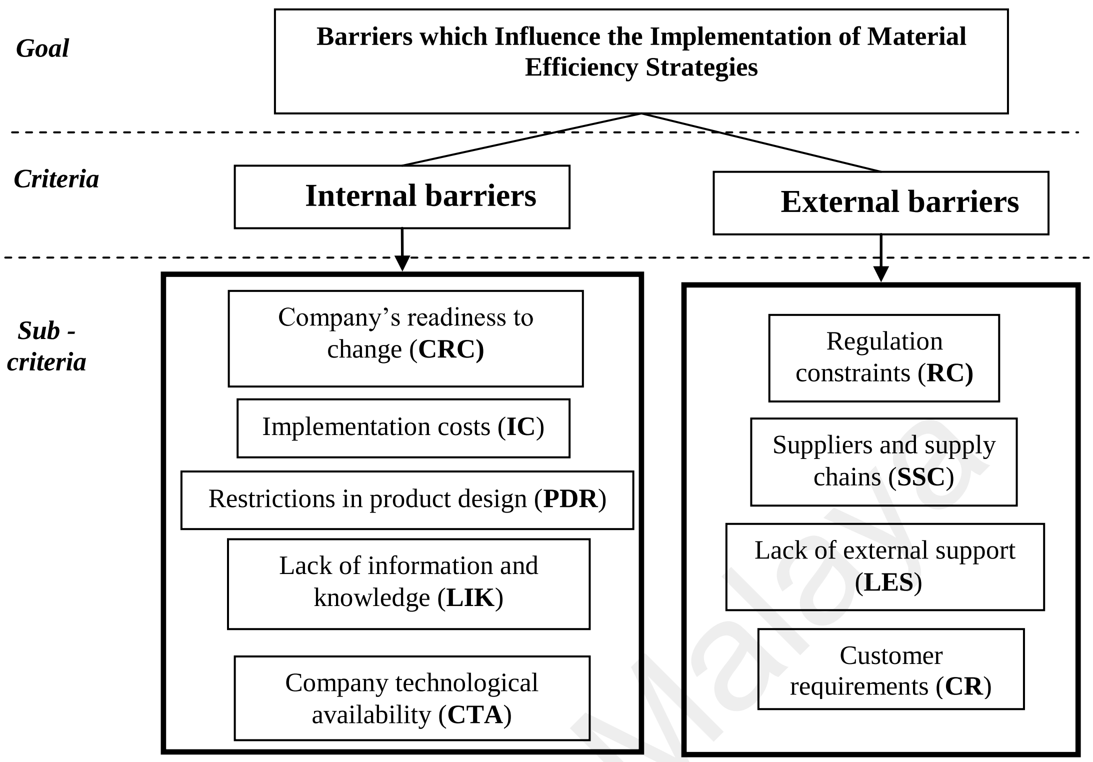

Figure 5.2: AHP framework of barriers which influence the implementation of material efficiency strategies

5.2.1 Priority Evaluation for Barriers

Using the same approach as that used for priority evaluation of drivers, the collected AHP data were analysed using Expert Choice V.11 Software. The priority weight for grouped internal barriers and external barriers is found to be 0.508 and 0.492, respectively (Table 5.8).

Nine barriers were explored from the qualitative investigation and therefore, 36 pair-wise comparisons were evaluated. It is found that IC has the highest grouped priority weight for the "internal drivers" category, with a value of 0.25. This is followed by CTA (0.239), PD (0.209), LIK (0.171) and CRC (0.131). The details of priority weights for internal barriers are shown in Table 5.9 and Table 5.10.

Four sub-criteria were assessed for external barriers using the AHP approach and six pairs of barriers were evaluated. It is found that CRS has the highest priority weight of 0.4, followed by LES (0.249), RC (0.204) and SSC (0.147). The details of the priority weights for external barriers are shown in Table 5.11 and Table 5.12.

The absolute priority weight for the grouped internal and external drivers and their sub-criteria were determined by multiplying the relative weight of the main criteria with the relative weight of the sub-criteria. The absolute priority weight for all barriers follows the following order (see Table 5.13): CR (0.197), IC (0.127), CTA (0.121), LES (0.119), PD (0.106), RC (0.1), LIK (0.087), SSC (0.072), and CRC (0.067). The priority weights for these barriers from the highest to the lowest priority are discussed in the following sub-sections.

Table 5.8: Priority weight of the grouped internal and external barriers which influence the implementation of material efficiency strategies

Main criteria	Relative local weight
Internal barriers	0.508
External barriers	0.492

Table 5.9: Eigenvalues obtained from pair-wise comparison of the grouped internal barriers

	CRC	IC	PD	LIK	CTA
CRC	**1**	0.474	0.561	0.853	0.617
IC		**1**	0.956	1.460	1.185
PD			**1**	0.966	0.768
LIK				**1**	0.633
CTA					**1**

Table 5.10: Grouped priority ranking of internal barriers

Sub-criteria	Relative weight of sub-barriers	Rank
Implementation costs (IC)	0.25	1
Company technological availability (CTA)	0.239	2
Restrictions in product design (PD)	0.209	3
Lack of information and knowledge (LIK)	0.171	4
Company's readiness to Change (CRC)	0.131	5

Table 5.11: Eigenvalues obtained from pair-wise comparison of the grouped external barriers

	RC	ES	SSC	CRs
RC	**1**	0.716	1.251	0.639
ES		**1**	1.790	0.516
SSC			**1**	0.358
CRs				**1**

Table 5.12: Grouped priority ranking of external barriers

Sub-criteria	Relative weight of sub-barriers	Rank
Customer requirements (CR)	0.4	1
Lack of external support (LES)	0.249	2
Regulation constraints (RC)	0.204	3
Suppliers and supply chains (SSC)	0.147	4

Table 5.13: Local and global weights for internal and external barriers obtained from geometric mean evaluation

Barrier category (criteria)	Relative local weight of criteria	Barrier (sub-criteria)	Relative local weight of sub-criteria	Global weights	Rank
Internal barriers	0.508	Implementation costs (IC)	0.25	0.127	2
	0.508	Company technological availability (CTA)	0.239	0.121	3
	0.508	Restrictions in product design (PD)	0.209	0.106	5
	0.508	Lack of information and knowledge (LIK)	0.171	0.087	7
	0.508	Company's readiness to change (CRC)	0.131	0.067	9
External barriers	0.492	Customer requirements (CR)	0.4	0.197	1
	0.492	Lack of external support (LES)	0.249	0.119	4
	0.492	Regulation constraints (RC)	0.204	0.100	6
	0.492	Suppliers and supply chains (SSC)	0.147	0.072	8

5.2.1.1 Customer Requirements

Fulfilling customer requirements is the main driver in the implementation of environmental strategies (Diabat & Govindan, 2011; Agamuthu *et al.*, 2009; Luken & van Rompaey, 2008; Honkasalo *et al.*, 2005). However, to some extent, this can become a barrier in the implementation of environmental strategies (Pajunen *et al.*, 2012). In this research, it is found that "customer requirements" is a significant barrier that constraints the E&E companies from practising material efficiency strategies. For example, designing electronic products using green materials is challenging and it is considered an arduous task since not all customers prefer products made from recyclable and reusable materials. Most of the time, the spent materials will be directly reused or recycled and mixed with the virgin materials. In addition, there are customers who prefer virgin materials in order to maintain product quality. In comparison with other industrial sectors such as the food industry, food safety and quality are the main barriers compared to environmental standards (Massoud *et al.*, 2010).

5.2.1.2 Lack of External Support

The second barrier which hinders the implementation of material efficiency strategies is the lack of external support. In this research, external support refers to support from third parties such as the local government, local recyclers, and industrial experts or consultants. The government can be a motivating source by providing advice, subsidies and tax reduction incentives in order to encourage the manufacturers and suppliers to implement environmental strategies (Pajunen *et al.*, 2012; Lee, 2008). If there is limited support from the local government, the implementation of environmental practices can be ineffective (Massoud *et al.*, 2010). In this research, some of the E&E case companies claimed that there is very limited support from the government in encouraging environmental practices, particularly recycling infrastructure. The facilities and technology for e-waste management are still in their infancy in Malaysia, which is a great challenge for E&E companies, particularly in developing green products. Pajunen *et al.* (2012) argued that the lack of support from local recyclers can reduce the momentum of manufacturers in achieving material efficiency. This can be attributed to the limited technology and techniques available to process e-wastes. Furthermore, in developing nations such as Malaysia, recyclers are less exposed to the right approach and knowledge when it comes to handling industrial wastes (Allwood *et al.*, 2013; Pajunen *et al.*, 2012). The lack of industrial experts and consultants to assist manufacturers and recyclers are another reason which contributes to poor external support.

5.2.1.3 Company Technological Availability

Technological availability in a company is an important criterion to enable efficient use of materials. For example, the use of automated systems and robotics can facilitate material handling and reduce product damage due to material mishandling (Koc & Bozdag, 2009). However, the use of outdated machinery is common in many manufacturing companies. The use of obsolete technologies can generate more solid wastes and increase energy consumption. This is the case with this research, since some of the E&E companies are still using old machinery although they are aware that these machines are not efficient. This is due to the high costs associated with purchasing new machines, slow return on investment especially for expensive machines, as well as problems concerning the readjustment of operation flow (Melanen, 2001). For example, the generation of solid wastes during wafer machining is due to the limitations of the clamping jig, which requires a large margin space. In addition, the lack of automated or robotic systems to pick and place the raw materials can cause material damage due to improper handling by a human operator. In addition, not all manufacturers have suitable machinery or nanotechnology to process nano-material and therefore, they may be unable to reduce material consumption when they introduce a nano scale product such as a multi-functional chipset. Hence, it is difficult to achieve optimum material use, especially for products that require complex manufacturing processes (Shahbazi *et al*., 2016; Luken & van Rompaey, 2008).

5.2.1.4 Regulation Constraints

Various environmental regulations aim to reduce environmental impact and promote environmentally conscious manufacturing (Pajunen *et al.*, 2012). The most common directives that must be complied in the E&E industry are RoHS and WEEE (Ongondo, 2011). Compliance with these directives is required to ensure that the use of hazardous substances is greatly reduced and these substances are not converted into dangerous solid wastes. Regulations can be considered as a driver and barrier in practising environmental strategies (Pajunen *et al.*, 2012; Diabat & Govindan, 2011; Walker *et al.*, 2008). For instance, most of the respondents of the AHP regarded regulations as a compulsory criterion but it is difficult to fulfil since stringent policies will complicate the design of products. Other contributing reasons include difficulties in sourcing green materials (Allwood *et al.*, 2011), lack of government certification for recycled materials (Ashby, 2012) as well as the low demand for green materials such as recycled materials (Ashby, 2012; Pajunen *et al*., 2012). According to the some of the respondents in this research, the current regulations have limited their options in selecting the appropriate manufacturing process as well as alternative materials.

5.2.1.5 Implementation Costs

For manufacturing companies, implementing a new strategy requires investment to purchase new technology, acquire permits and source materials. In this research, it is found that the E&E companies are less interested in investing in new business strategies that they are not familiar with. These investments include the costs to obtain approvals and permits such as environmental standards (Pajunen *et al.*, 2012), costs to upgrade machinery and costs to substitute green materials (Ashby, 2012; Allwood *et al.*, 2011; Worrell *et al.*, 1995). In addition, technological investment is the most critical issue because the initial investment is high while the payback time is longer (Halme *et al.*, 2014; Pajunen *et al.*, 2012; Allwood *et al.*, 2011; Moors *et al.*, 2005). However, in countries such as China, implementation costs are their primary barrier towards the adoption of environmental strategies because they are focused on a cheap price-oriented business model. Hence, acquiring expensive technologies in order to comply with environmental standards is the main problem faced in these countries (Chiang *et al.*, 2009).

5.2.1.6 Restrictions in the Product Design

In this research, it is found that the E&E companies are typically faced with restrictions in the product designs. Some of these companies do not favour substituting virgin materials with recycled materials since this may affect the quality and functionality of the product, which in turn, reduce the demand for these products from consumers. These findings are consistent with those in previous studies (Allwood *et al.*, 2011; Peck & Chipman, 2007). On the other hand, according to Chiang *et al.* (2008), greener materials (e.g. lead-free materials, mercury and cadmium-free substances) are required to fulfil the requirements of the RoHS and WEEE directives. However, to a certain extent, not all types of E&E products are applicable for redesign because this may incur additional cost for the existing production process (Allwood *et al.*, 2011).

5.2.1.7 Supplier Requirements

It is found that the local suppliers are less capable in supplying green materials. For this reason, E&E manufacturers need to source green materials from international suppliers, which are usually more expensive. In general, local suppliers lack the knowledge and technology to produce green materials. This finding is consistent with the challenges raised by Abdul Rashid and Evans (2012) and Walker *et al.* (2008), whereby poor commitment from suppliers in supplying the required materials discourage the implementation of environmental strategies. Furthermore, not all local suppliers are certified with environmental management standards such as ISO 14001 (Singh *et al*., 2015; Sambasivan & Fei, 2008).

Another issue faced by E&E manufacturing companies is the unreliable supply chain. Indeed, unreliable supply chain is one of the barriers that can lead to poor implementation of environmental practices (Shahbazi *et al*., 2016; Zhu & Geng, 2013;

Abdul Rashid & Evans, 2012). Sourcing green materials is challenging for E&E companies in developing countries such as Malaysia. Therefore, most of the manufacturers either import the raw materials from other countries or source from very limited local suppliers.

5.2.1.8 Lack of Information and Knowledge

In order to achieve material efficiency, engineers need to improve their technical knowledge especially regarding material use, product design and manufacturing processes (Shahbazi *et al*., 2016; Allwood *et al.*, 2011). In this research, it is found that some E&E companies are incapable of formulating material efficiency solutions. For example, they do not know the steps that can be taken to achieve material efficiency. This may be due to the fact that some of the E&E companies do not have their own research and development (R&D) facility and these companies lack the experience in material efficiency strategies. In addition, the managers in Malaysia are not given full authority to make decisions to improve production. Most of these companies are constrained by the policies of the company and as a result, the companies lose their competitive edge (Pajunen *et al.*, 2012). It is also proven from empirical studies that manufacturers from developing countries fail to implement material efficiency concepts because of limited knowledge in the adoption of environmental strategies (Luken & van Rompaey, 2008).

5.2.1.9 Company's Readiness to Change

Implementing environmental strategies requires the organization to change, either from the context of management or technical aspects (Shahbazi *et al*., 2016; Lee, 2008). However, not every change is easy and some changes require complicated adjustments, high investment costs and strong commitment from the company's stakeholders. It is found that the E&E companies in Malaysia perceive "company's readiness to change" as one of their barriers since the material efficiency concept is considered new to the manufacturers. At present, most of the E&E companies are only familiar with the requirements and benefits of energy efficiency. Therefore, some of the E&E companies claimed that implementing new strategies such as material efficiency strategies is cumbersome and time-consuming. This is unsurprising since as empirical studies have shown that manufacturing companies in developing countries are less ready to carry out environmentally-conscious manufacturing (Byggeth & Hochschorner, 2006).

In addition, E&E companies are less ready to implement material efficiency strategies since they are less confident regarding the benefits that the new changes will bring. According to Pajunen *et al.* (2012), unproven scientific results have reduced the willingness of companies in implementing material efficiency strategies. Furthermore, manufacturers are concerned that the implementation of material efficiency strategies will increase the financial burden of the company. For example, implementing environmental strategies require manufacturers to increase their expenditure in order to source expensive raw materials (Byggeth & Hochschorner, 2006). Hence, it is common for a company to stick to conventional approaches that are proven to work.

5.3 Analysis of Enablers using AHP

Analysing the enabler themes is easier due to its lower hierarchical levels compared to driver and barrier themes. The initial AHP framework for the enabler criteria was established based on the interview themes (Figure 5.3). Three pair-wise comparisons were evaluated: adoption of advanced technology (ATA), ISO 14001 certification (EMS) and environmental awareness of the company's top management (MEA).

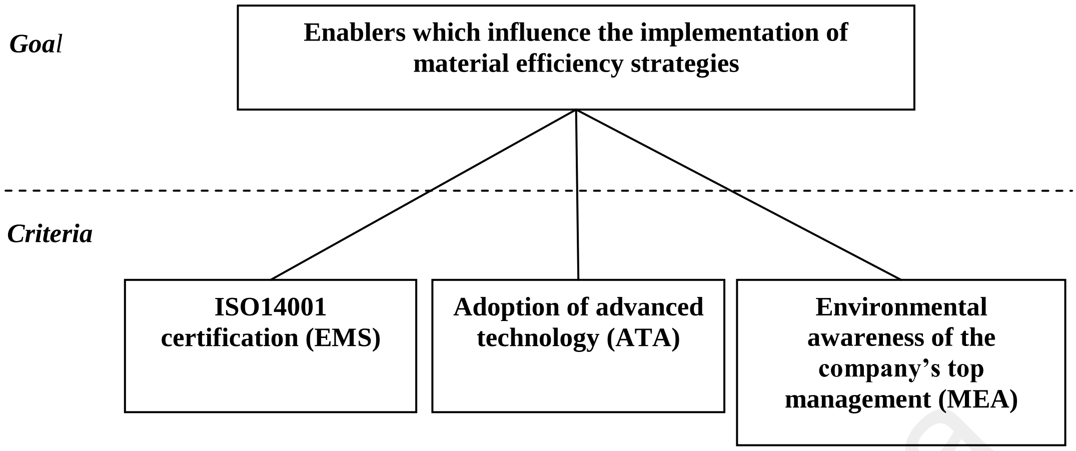

Figure 5.3: AHP framework of enablers which influence the implementation of material efficiency strategies

5.3.1 Priority Evaluation for Enabler Category

The Eigenvalues for the enablers were obtained from 18 E&E experts. Following this, geometric mean evaluation was used to combine and evaluate the priority weight of the three enablers identified from qualitative data collection.

Three enabler pairs were assessed to determine their priority weights. The priority weight of the enabler criteria follows the following order: ATA (0.506), EMS (0.255) and MEA (0.24). The details of the grouped priority weights for the enabler criteria are presented in Table 5.14 and Table 5.15. The priority weight of the enablers which influence the implementation of material efficiency strategies from the highest to the lowest priority is presented in the following sections.

Table 5.14: Eigenvalues obtained from pair-wise comparison of the enablers

	EMS	**MEA**	**ATA**
EMS	**1**	1.051	0.508
MEA		**1**	0.469
ATA			**1**

Table 5.15: Global weight for enablers obtained from geometric mean evaluation

Enabler	**Global weight**	**Rank**
Adoption of advanced technology (ATA)	0.506	1
ISO14001 certification (EMS)	0.255	2
Environmental awareness of the company's top management (MEA)	0.24	3

5.3.1.1 Adoption of Advanced Technology

Acquiring advanced technology is an important element in the E&E industry in order to remain competitive in the market. This is due to the rapid growth of the E&E industry and changing trends in the product specifications (Muhammad *et al.*, 2009). For this reason, manufacturers require better technologies to accommodate the demands of the market for E&E products. For example, in order to produce multi-functional products with slim designs, manufacturers need to acquire nanotechnology such as the multilayer bonding machine which will enable them to produce multi-layer integrated chipsets. Secondly, the use high-precision technology can also help manufacturers to process materials such as wafers with better precision tolerance, which contributes to material savings. Thirdly, technological advancement is essential in order to process green materials such as lead-free materials and nonmaterials (Li *et al.*, 2008). This will optimize the use of materials and minimize solid wastes. This justifies that the adoption of advanced technology is a significant enabler to encourage efficient material use.

5.3.1.2 ISO 14001 Certification

ISO14001 certification is perceived as less critical for E&E companies. Unlike other manufacturing sectors such as the furniture industry and chemical industry, ISO 14001 certification is mostly applicable for companies in which the processes release wastewater or other environmental pollutants to the surroundings (Jiang & Bansal, 2003). However, the production activities of the E&E industry are rather clean and the processes are carried out at room temperature or in an air-conditioned environment. Therefore, not all of the E&E companies investigated in this research agreed that ISO 14001 certification is important or a necessity for them to achieve material efficiency. However, from a marketing perspective, the ISO 14001 certification can serve as a marketing tool to increase the company's branding and expand their market especially to environmentally conscious customers (Sambasivan & Fei, 2008; Jiang & Bansal, 2003). In addition, E&E companies with ISO 14001 certification can implement various environmental activities with the assistance of EHS officers. This can be done by forming a "green team" to help educate employees about environmental protection, raise the awareness of green practices within the working environment as well as monitor and benchmark production activities.

5.3.1.3 Environmental Awareness of the Company's Top Management

The environmental awareness of the company's top management is perceived as the least significant enabler which influences the implementation of material efficiency strategies. This is due to the maturity of E&E industry in dealing with environmental regulations and standards in product design. For instance, the E&E industry needs to comply with stringent environmental regulations such as the RoHS and WEEE directives in order to sell their products in the local and international market (Stevels & Huisman, 2003). Therefore, the environmental awareness of the company's top management is not as significant as other enablers since compliance with environmental regulations is a norm in the E&E industry.

5.4 Summary

The local and global priority weights of three organizational change factor groups (drivers, barriers and enablers) which influence the implementation of material efficiency strategies are presented and discussed in this chapter. A total of 18 experts, each representing an E&E company in Peninsular Malaysia participated in the AHP. In order to prevent biases in the data, the E&E companies selected for the survey are from different areas of specialization in the E&E industry such as electronic components, consumer electronics, industrial electronics, and electrical goods. In addition, geometric mean evaluation was used to combine and evaluate the experts' input decision in the AHP. The pair-wise comparisons obtained fall below the permissible consistency index value (CR < 0.10).

Based on the results, it is found that the E&E companies in Malaysia are driven by 13 drivers in practising material efficiency strategies. The priority order of the drivers is as follows: customer requirements (CR), fulfil international product designs (FPD), compliance with local environmental legislation (CLL), Reducing production costs (PCR), competition among rivals (CO), Reducing materials (MR), increase in price of raw materials (RP), reduce energy usage (RE), supplier requirements (SU), support from other industries (SI), public pressure (PP), improve environmental image (IEI) and social responsibility (SR). In general in Malaysia context, the E&E companies are more driven by external drivers rather than internal drivers because most of the E&E products are sold abroad. Therefore, compliance with environmental regulations and customer requirements are the utmost considerations for the manufacturer.

A total of nine barriers are identified to influence the implementation of material efficiency strategies in E&E companies in Malaysia. Each barrier hinders the implementation of material efficiency strategies at different significance levels. The priority order of the barriers is as follows: customer requirements (CR), lack of external support (LES), company technological availability (CTA), regulation constraints (RC), implementation costs (IC), restrictions in the product design (PDR), suppliers and supply chains (SSC), lack of information and knowledge (LIK) and company's readiness to change (CRC). It is found that both internal and external barriers have similar priority weights in influencing the implementation of material efficiency strategies.

The results also show that the representatives from the E&E companies agreed that the companies are largely influenced by the adoption of advanced technology, followed by ISO14001 certification and environmental awareness of the company's top management. Overall, the viewpoints given by representatives from the E&E industry in Malaysia regarding the significant change factors that influence the implementation of material efficiency strategies have been discussed in this chapter. It is believed that the findings may vary if the survey is conducted among E&E companies in the different country, whereby the perspectives on the change factors may be different. The priority weights of the change factors are important since they will be used to develop a decision support tool, as presented in the following chapter.

CHAPTER 6: PROPOSITIONS OF MATERIAL EFFICIENCY STRATEGY

6.0 Overview

The AHP approach was used to determine the priority weights of the three categories of change factors namely drivers, barriers and enablers which influence the implementation of material efficiency strategies in the preceding chapter. However, the sensitivity analysis is unable to be done between change factors and material efficiency strategy due to the complexity of different change factor categories. In addition, the huge number of change factors pair-wise comparison (513 pair-wise for nine material efficiency strategies) may create confusion to the AHP respondents. For that reason, an additional quantitative survey is needed. In this chapter, a quantitative survey was used to determine the influencing weight of change factors towards each material efficiency strategy. It is a direct and easy approach to obtain the average weighting of each change factor towards each material efficiency strategy. In the end of this chapter, the proposition weight between material efficiency strategies with change factors are developed, which are the core elements to be used to develop decision support tool.

6.1 Influences of change factors towards material efficiency strategy selection

Due to the unsuitable of AHP in analysing a large number of alternatives (Ishizakaand Labib, 2009; Saaty, 1992) (i.e. change factors to influence each material efficiency strategies), an alternative approach is required to determine the importance weight of each change factor towards the selection of a material efficiency strategy. This is done by conducting a simple survey using questionnaire (see Appendix K)

The same experts who participated in the AHP were took part in this survey, these experts were named as R1 to R18 to represent as the respondant accordingly. In order to obtain the importance weight of each change factor with respect to a specific material efficiency strategy, a six-point Likert scale was used. The scale varies from “0” to “5”, where “0” represents “not important at all”, and “5” represents “extremely important”. Therefore, only criteria with a rating of “1” and above were included in the propositions analysis. Each respondent needs to provide an importance rating for 225 questions which encompass the influence of 25 change factors on the nine material efficiency strategies.

In order to analyse the data gathered from the survey, the relative importance of a change factor was assessed separately from the relative importance of a material efficiency strategy. For example, if the respondent feels that a change factor is “extremely important” for the “design for longer life” strategy, the respondent needs to give a weight of “5”. Consequently, the relative importance of a change factor was prioritized based on the response given by the 18 experts who participated in this survey. Next, the sum of weights for each change factor was calculated by multiplying the weight with the corresponding number of respondents. For instance, if four, five and four respondents selected an importance weight of “1”, “3” an “0”, respectively, then the sum of importance weights is: $(4 \times 1) + (5 \times 3) + (4 \times 0) = 19$. In this study, the optimum importance weight is “5” and therefore, the total weight for all 18 respondents is given by $18 \times 5 = 90$. Thus, the importance weight for a change factor can be determined by dividing “19” with the optimum weight of “90”, giving an importance weight of 0.489. The higher of the importance weight obtained by a change factors with respect to a material efficiency strategy means the change factor has more influences to practice the strategy. The results obtained from the survey are presented in Table 6.1 until Table 6.9 separately.

Therefore, in order to obtain the normalized importance weight of each material efficiency strategy, the AHP geometry mean weight for drivers, barrier, and enablers

(Table 5.7, Table 5.13, and Table 5.15) were multiplied with the importance weight obtained for each change factor with respect to a material efficiency strategy. The normalized importance weight for drivers, barriers and enablers are presented in Table 6.10, Table 6.12, and Table 6.13 respectively. It can be observed that each of the change factor categories (drivers, barriers, enablers) has a different influence to a material efficiency strategy.

Table 6.1: Influence of each change factor towards design for material recovery strategy

	DRIVERS													ENABLERS			BARRIERS								
	Reducing production cost	**Reducing materials**	**Reducing energy usage**	**Improve environmental image**	**Social responsibility**	**Customer requirements**	**Fulfil international product design**	**Compliance with local environment legislation**	**Competition among rivals**	**Increase in price of raw materials**	**Supplier requirements**	**Support from other industries**	**Public pressure**	**ISO14001 certification**	**Adoption of advanced technology**	**Environmental awareness of company's top management**	**Company technological availability**	**Implementation costs**	**Restrictions in product design**	**Lack of information and knowledge**	**Lack of readiness to change**	**Customer requirements**	**Lack of external support**	**Regulation constraints**	**Suppliers and supply chains**
R1	1	2	4	5	4	2	5	4	3	4	4	4	4	3	5	4	4	3	4	4	4	2	5	4	3
R2	0	1	3	4	4	3	3	4	3	3	5	4	4	5	3	3	3	4	4	4	3	3	3	4	4
R3	2	2	2	3	3	3	4	4	3	3	4	3	3	3	4	2	2	3	3	3	3	3	3	4	3
R4	0	1	1	2	2	1	3	3	3	4	3	3	4	3	2	3	3	3	2	4	3	2	2	3	4
R5	1	2	4	5	4	2	5	4	3	4	4	4	4	3	5	4	4	3	4	4	4	2	5	4	3
R6	0	1	3	4	4	3	3	4	3	3	5	4	4	5	3	3	3	4	4	4	3	3	3	4	4
R7	0	1	3	4	4	3	3	4	3	3	5	4	4	5	3	3	3	4	4	4	3	3	3	4	4
R8	1	2	4	5	4	2	5	4	3	4	4	4	4	3	5	4	4	3	4	4	4	2	5	4	3
R9	0	1	3	4	4	3	3	4	3	3	5	4	4	5	3	3	3	4	4	4	3	3	3	4	4
R10	1	2	4	5	4	2	5	4	3	4	4	5	4	3	5	4	4	3	4	4	4	2	5	3	3
R11	0	1	3	4	4	3	3	4	3	3	5	4	5	5	3	3	3	4	4	4	3	3	3	4	4
R12	0	1	3	4	4	3	3	4	3	3	5	4	4	5	3	3	3	4	4	4	3	3	3	5	4
R13	1	2	4	5	4	2	5	4	3	4	4	5	4	3	5	4	4	3	4	4	4	2	5	4	3
R14	0	1	3	4	4	3	3	4	3	3	5	4	4	5	3	3	3	4	4	4	3	3	3	4	4
R15	1	2	2	3	3	3	4	3	4	3	4	4	3	4	4	3	3	4	3	3	3	3	4	3	3
R16	0	1	3	4	4	3	3	4	3	3	5	5	4	5	3	3	3	4	4	4	3	3	3	4	4
R17	1	2	4	5	4	2	5	4	3	4	4	4	4	3	5	4	4	3	4	4	4	2	5	4	3
R18	0	1	3	4	4	3	3	4	3	3	5	4	4	5	3	3	3	4	4	4	3	3	3	4	4
Importance weight	**.10**	**.29**	**.62**	**.82**	**.76**	**.51**	**.76**	**.78**	**.61**	**.68**	**.89**	**.81**	**.79**	**.81**	**.74**	**.66**	**.66**	**.71**	**.76**	**.78**	**.67**	**.52**	**.73**	**.78**	**.71**

Table 6.2: Influence of each change factor towards design for material substitution strategy

	DRIVERS													ENABLERS			BARRIERS								
	Reducing production cost	Reducing materials	Reducing energy usage	Improve environmental image	Social responsibility	Customer requirements	Fulfil international product design	Compliance with local environment legislation	Competition among rivals	Increase in price of raw materials	Supplier requirements	Support from other industries	Public pressure	ISO14001 certification	Adoption of advanced technology	Environmental awareness of company's top management	Company technological availability	Implementation costs	Restrictions in product design	Lack of information and knowledge	Lack of readiness to change	Customer requirements	Lack of external support	Regulation constraints	Suppliers and supply chains
R1	5	5	5	5	3	3	5	3	4	5	5	3	4	4	4	4	4	4	5	4	4	2	2	4	4
R2	4	4	5	3	3	4	5	4	5	4	4	4	3	4	5	4	3	4	4	5	4	1	2	3	4
R3	4	5	4	4	4	3	3	4	4	5	4	3	3	4	4	5	3	3	4	4	4	2	2	3	3
R4	4	4	5	5	3	3	4	2	4	5	4	3	4	3	4	3	3	3	4	4	3	2	1	3	3
R5	3	4	5	4	4	3	3	3	4	3	3	3	4	3	5	3	4	3	5	3	4	1	1	2	3
R6	5	5	5	5	3	3	5	3	4	5	5	3	4	4	4	4	4	4	5	4	4	2	2	4	4
R7	4	5	5	3	3	4	5	4	5	4	4	4	3	4	5	4	3	4	4	5	4	1	2	3	4
R8	4	5	4	4	4	3	3	4	3	5	4	3	3	4	4	5	3	3	4	4	4	2	2	3	3
R9	3	4	5	4	4	3	3	3	4	3	3	3	4	3	5	3	4	3	5	3	4	1	1	2	4
R10	5	5	5	5	3	3	5	3	5	5	5	3	4	4	4	4	4	4	5	4	4	2	2	3	2
R11	4	5	5	3	3	4	5	4	5	4	4	4	3	4	5	4	3	4	4	5	4	1	2	3	3
R12	5	5	4	5	3	3	5	3	5	5	5	3	4	4	4	4	4	4	5	4	4	2	2	4	4
R13	4	5	5	3	3	4	5	4	5	4	4	4	3	4	5	4	3	4	4	5	4	1	2	3	4
R14	4	5	4	4	4	3	3	4	4	5	4	3	3	5	4	5	3	3	4	4	4	2	2	3	3
R15	4	4	5	5	3	3	5	3	5	5	5	3	4	5	4	4	4	4	5	4	4	2	2	4	4
R16	4	4	5	3	3	4	5	4	5	4	4	4	3	4	5	4	3	4	4	5	4	1	2	3	4
R17	4	5	4	4	4	3	3	4	4	5	4	3	3	4	4	5	3	4	3	3	4	1	1	3	3
R18	5	5	5	5	4	3	4	4	4	4	4	3	5	4	4	5	3	3	4	3	4	2	2	2	3
Importance weight	**.83**	**.93**	**.94**	**.82**	**.68**	**.66**	**.84**	**.70**	**.88**	**.89**	**.83**	**.66**	**.71**	**.79**	**.88**	**.82**	**.68**	**.72**	**.87**	**.81**	**.79**	**.31**	**.36**	**.61**	**.69**

Table 6.3: Influence of each change factor towards product light weighting strategy

	DRIVERS													ENABLERS			BARRIERS								
	Reducing production cost	Reducing materials	Reducing energy usage	Improve environmental image	Social responsibility	Customer requirements	Fulfil international product design	Compliance with local environment legislation	Competition among rivals	Increase in price of raw materials	Supplier requirements	Support from other industries	Public pressure	ISO14001 certification	Adoption of advanced technology	Environmental awareness of company's top management	Company technological availability	Implementation costs	Restrictions in product design	Lack of information and knowledge	Lack of readiness to change	Customer requirements	Lack of external support	Regulation constraints	Suppliers and supply chains
R1	0	4	3	4	4	5	4	3	5	4	5	5	3	2	4	4	5	5	5	5	3	4	4	3	4
R2	1	3	4	4	4	4	5	3	4	4	4	4	3	2	3	4	4	4	5	4	3	3	4	2	3
R3	2	2	3	3	4	4	4	4	3	3	4	3	5	2	3	3	4	4	4	4	3	3	4	3	3
R4	0	3	3	3	4	5	3	3	5	4	5	4	3	2	4	3	5	4	5	4	3	4	3	3	3
R5	1	4	3	3	4	4	4	4	4	4	3	4	3	2	4	4	4	5	5	5	3	3	4	4	4
R6	0	3	3	3	4	5	3	3	5	4	5	4	3	2	4	3	5	4	5	4	3	4	3	3	3
R7	1	4	3	3	4	4	4	4	4	4	3	4	3	2	4	4	4	5	5	5	3	3	4	4	4
R8	0	4	3	4	4	5	4	3	5	4	5	5	3	2	4	4	5	5	5	5	3	4	4	3	4
R9	2	3	3	3	3	4	3	4	3	3	4	4	4	3	3	3	4	4	3	4	4	3	4	4	0
R10	0	3	3	3	4	5	3	3	5	4	5	4	3	2	4	3	5	4	5	4	3	4	3	3	3
R11	1	4	3	3	4	4	4	4	4	4	3	4	3	2	4	4	4	5	5	5	3	3	4	4	4
R12	2	3	3	4	4	4	4	3	4	3	3	4	3	2	3	4	3	5	5	5	3	3	4	4	4
R13	0	3	3	3	4	5	3	3	5	4	5	4	3	2	4	3	5	4	5	4	3	4	3	3	3
R14	1	4	3	3	4	4	4	4	4	4	3	4	3	2	4	4	4	5	5	5	3	3	4	4	4
R15	0	3	3	3	4	5	3	3	5	4	5	4	3	2	4	3	5	4	5	4	3	4	3	3	3
R16	0	3	3	3	4	5	3	3	5	4	5	4	3	2	4	3	5	4	5	4	3	4	3	3	3
R17	1	4	3	3	4	4	4	4	4	4	3	4	3	2	4	4	4	5	5	5	3	3	4	4	4
R18	0	3	3	3	4	5	3	3	5	4	5	4	3	2	4	3	5	4	5	4	3	4	3	3	3
Importance weight	**.13**	**.67**	**.61**	**.64**	**.79**	**.90**	**.72**	**.68**	**.88**	**.77**	**.83**	**.81**	**.63**	**.41**	**.76**	**.70**	**.89**	**.89**	**.97**	**.89**	**.61**	**.70**	**.72**	**.67**	**.66**

Table 6.4: Influence of each change factor towards design for multiple functional strategy

	DRIVERS													ENABLERS			BARRIERS								
	Reducing production cost	Reducing materials	Reducing energy usage	Improve environmental image	Social responsibility	Customer requirements	Fulfil international product design	Compliance with local environment legislation	Competition among rivals	Increase in price of raw materials	Supplier requirements	Support from other industries	Public pressure	ISO14001 certification	Adoption of advanced technology	Environmental awareness of company's top management	Company technological availability	Implementation costs	Restrictions in product design	Lack of information and knowledge	Lack of readiness to change	Customer requirements	Lack of external support	Regulation constraints	Suppliers and supply chains
R1	4	3	2	2	0	4	3	1	3	4	3	1	0	1	2	5	4	5	4	4	3	5	3	1	1
R2	3	3	2	2	1	3	3	1	2	3	3	0	0	1	1	3	4	4	3	4	3	4	2	1	2
R3	4	4	1	3	1	3	4	2	3	3	3	2	1	2	1	3	3	3	3	4	4	4	3	2	1
R4	5	3	2	3	2	4	4	2	2	3	2	1	0	1	2	3	4	3	4	4	3	3	2	1	1
R5	4	3	1	3	1	3	4	2	3	4	3	1	1	2	1	4	4	4	3	4	4	4	3	1	1
R6	5	3	2	2	1	4	3	1	2	3	3	0	0	1	1	3	5	4	4	4	3	3	2	1	1
R7	3	3	2	2	1	3	3	1	2	3	3	0	0	1	1	3	4	4	3	4	3	4	2	1	2
R8	4	4	1	3	1	3	4	2	3	3	3	2	1	2	1	3	3	3	3	4	4	4	3	2	1
R9	4	3	1	2	0	3	3	1	3	3	4	1	1	2	1	4	3	4	4	3	4	4	3	2	1
R10	4	4	1	2	1	3	4	2	2	2	3	0	0	1	1	4	4	4	4	4	3	4	3	2	1
R11	4	4	2	3	2	3	4	3	3	4	3	1	2	2	1	3	3	4	3	4	3	4	3	1	2
R12	5	3	2	2	1	4	3	1	2	3	3	0	1	1	1	3	5	4	4	4	3	3	2	1	1
R13	3	3	2	2	1	3	3	1	2	3	3	0	0	1	1	3	4	4	3	4	3	4	2	1	2
R14	4	4	1	3	1	3	4	2	3	3	3	2	1	2	1	3	3	3	3	4	4	4	3	2	1
R15	5	3	2	2	1	4	3	1	2	3	3	0	1	1	1	3	5	4	4	4	3	3	2	1	1
R16	3	3	2	2	1	3	3	1	2	3	3	0	0	1	1	3	4	4	3	4	3	4	2	1	2
R17	3	3	2	2	1	3	3	1	2	3	3	0	0	1	1	3	4	4	3	4	3	4	2	1	2
R18	4	4	1	3	1	3	4	2	3	3	3	2	1	2	1	3	3	3	3	4	4	4	3	2	1
Importance weight	**.79**	**.67**	**.32**	**.48**	**.20**	**.66**	**.69**	**.30**	**.49**	**.62**	**.60**	**.14**	**.11**	**.28**	**.22**	**.66**	**.77**	**.76**	**.68**	**.79**	**.67**	**.77**	**.50**	**.27**	**.27**

Table 6.5: Influence of each change factor towards design for material substitution strategy

	DRIVERS													ENABLERS			BARRIERS								
	Reducing production cost	Reducing materials	Reducing energy usage	Improve environmental image	Social responsibility	Customer requirements	Fulfil international product design	Compliance with local environment legislation	Competition among rivals	Increase in price of raw materials	Supplier requirements	Support from other industries	Public pressure	ISO14001 certification	Adoption of advanced technology	Environmental awareness of company's top management	Company technological availability	Implementation costs	Restrictions in product design	Lack of information and knowledge	Lack of readiness to change	Customer requirements	Lack of external support	Regulation constraints	Suppliers and supply chains
R1	4	5	4	5	4	4	5	4	4	5	5	3	3	4	4	4	4	4	5	4	4	3	3	5	5
R2	4	4	4	4	4	3	4	5	5	5	4	4	3	3	3	5	4	4	4	4	3	3	3	4	5
R3	4	5	4	5	4	4	5	4	4	5	4	4	3	4	4	4	3	4	4	5	4	4	3	5	4
R4	5	4	5	4	4	4	5	4	4	4	5	4	4	3	3	5	4	3	4	4	3	3	3	4	5
R5	4	5	4	5	4	4	5	4	4	5	5	3	3	4	4	4	4	4	5	4	4	3	3	5	5
R6	4	4	4	4	4	3	4	5	5	5	4	4	3	3	3	5	4	4	4	4	3	3	3	4	5
R7	4	5	4	5	4	4	5	4	4	5	5	3	3	4	4	4	4	4	5	4	4	3	3	5	5
R8	4	4	4	4	4	3	4	5	5	5	4	4	3	3	3	5	4	4	4	4	3	3	3	4	5
R9	4	5	4	5	4	4	5	4	4	5	4	4	3	4	4	4	3	4	4	5	4	4	3	5	4
R10	5	4	5	4	4	4	5	5	4	4	5	4	4	3	3	5	4	3	4	4	3	3	3	4	5
R11	5	5	5	4	4	3	4	4	5	4	4	4	5	3	3	3	3	4	4	5	3	4	3	3	3
R12	4	5	4	5	4	4	5	4	4	5	5	3	3	4	5	4	4	4	4	4	4	3	3	5	5
R13	4	4	4	4	4	3	4	5	5	5	5	4	3	3	3	5	4	4	4	4	3	3	3	4	5
R14	4	5	4	5	4	4	5	4	4	5	4	4	3	4	4	4	3	4	4	5	4	4	3	5	4
R15	5	4	5	4	4	4	5	4	5	4	5	4	4	3	3	5	4	3	4	4	3	3	3	4	5
R16	4	5	4	5	4	4	5	4	4	5	5	3	3	4	3	4	3	4	5	3	5	3	4	5	4
R17	4	4	4	4	4	3	4	5	5	5	4	3	3	3	4	4	4	5	4	4	3	3	4	4	3
R18	4	4	5	5	4	4	5	4	5	4	4	3	4	3	4	4	4	3	5	4	3	3	3	4	5
Importance weight	**.84**	**.90**	**.86**	**.90**	**.80**	**.73**	**.93**	**.87**	**.89**	**.94**	**.90**	**.72**	**.67**	**.69**	**.71**	**.87**	**.74**	**.77**	**.86**	**.83**	**.70**	**.64**	**.62**	**.88**	**.91**

Table 6.6: Influence of each change factor towards pre-manufactured part purchase strategy

	DRIVERS													ENABLERS			BARRIERS								
	Reducing production cost	**Reducing materials**	**Reducing energy usage**	**Improve environmental image**	**Social responsibility**	**Customer requirements**	**Fulfil international product design**	**Compliance with local environment legislation**	**Competition among rivals**	**Increase in price of raw materials**	**Supplier requirements**	**Support from other industries**	**Public pressure**	**ISO14001 certification**	**Adoption of advanced technology**	**Environmental awareness of company's top management**	**Company technological availability**	**Implementation costs**	**Restrictions in product design**	**Lack of information and knowledge**	**Lack of readiness to change**	**Customer requirements**	**Lack of external support**	**Regulation constraints**	**Suppliers and supply chains**
R1	5	4	4	2	0	1	2	2	4	2	3	3	1	1	2	3	4	4	4	1	2	2	2	1	3
R2	4	4	3	1	1	1	1	1	2	3	3	2	0	2	1	2	3	3	4	0	1	1	2	2	2
R3	5	4	4	2	1	1	2	2	4	2	3	3	1	1	2	3	4	4	4	1	2	2	2	1	3
R4	4	4	3	1	1	1	1	1	2	3	3	2	0	2	1	2	3	3	4	1	1	2	1	2	2
R5	5	4	4	2	0	1	2	2	4	2	3	3	1	1	2	3	4	4	3	1	2	2	2	1	3
R6	4	4	3	1	1	1	1	1	2	3	3	2	0	2	2	2	3	3	4	1	1	2	2	2	2
R7	5	4	4	2	0	1	2	2	4	2	3	3	1	1	2	3	4	4	4	1	2	2	2	1	3
R8	4	4	3	1	1	1	1	1	2	3	3	2	0	2	1	2	3	3	4	0	1	2	3	2	2
R9	4	3	4	2	1	1	2	2	3	2	3	3	1	1	2	3	4	3	4	1	2	2	2	1	3
R10	4	3	4	2	1	2	1	1	2	3	3	2	0	2	1	2	3	3	4	1	1	3	2	2	2
R11	5	4	4	2	0	1	2	2	4	2	2	3	1	1	2	3	4	4	4	2	2	2	2	1	3
R12	4	3	3	1	1	1	0	1	2	3	2	2	0	2	3	2	3	3	4	2	1	2	2	2	2
R13	4	4	4	2	1	1	2	2	3	2	3	3	1	1	2	3	4	3	3	1	2	2	2	1	3
R14	4	3	4	2	1	2	1	1	2	3	3	2	0	2	1	2	3	3	4	1	1	3	3	2	2
R15	5	4	4	2	0	0	2	2	4	2	2	3	1	1	2	3	4	4	3	2	2	2	1	1	3
R16	4	3	3	1	1	1	0	1	2	3	2	2	0	2	3	2	3	3	3	2	1	2	2	2	2
R17	4	4	4	2	1	0	2	0	3	2	2	3	0	1	2	3	4	3	4	1	2	2	1	1	3
R18	4	4	3	2	1	1	2	2	4	2	3	3	1	1	2	3	4	4	4	1	2	2	2	1	2
Importance weight	**.87**	**.74**	**.72**	**.33**	**.14**	**.20**	**.29**	**.29**	**.59**	**.49**	**.54**	**.51**	**.10**	**.29**	**.37**	**.51**	**.71**	**.68**	**.76**	**.22**	**.31**	**.41**	**.39**	**.29**	**.50**

Table 6.7: Influence of each change factor towards yield improvement strategy

	DRIVERS													ENABLERS			BARRIERS								
	Reducing production cost	**Reducing materials**	**Reducing energy usage**	**Improve environmental image**	**Social responsibility**	**Customer requirements**	**Fulfil international product design**	**Compliance with local environment legislation**	**Competition among rivals**	**Increase in price of raw materials**	**Supplier requirements**	**Support from other industries**	**Public pressure**	**ISO14001 certification**	**Adoption of advanced technology**	**Environmental awareness of company's top management**	**Company technological availability**	**Implementation costs**	**Restrictions in product design**	**Lack of information and knowledge**	**Lack of readiness to change**	**Customer requirements**	**Lack of external support**	**Regulation constraints**	**Suppliers and supply chains**
R1	4	4	4	1	1	1	3	3	4	5	5	4	0	1	3	4	4	3	3	4	3	1	4	2	4
R2	5	3	4	2	2	0	3	3	4	5	5	4	0	2	3	4	3	3	3	4	4	2	3	2	3
R3	4	4	4	1	1	1	2	3	4	4	4	4	1	1	3	3	4	3	3	3	3	1	4	2	4
R4	5	4	5	0	1	2	3	2	3	4	4	4	1	1	2	3	4	3	3	3	2	2	4	2	4
R5	5	3	4	2	1	1	3	3	4	5	5	4	0	2	3	4	3	3	3	4	4	2	3	2	3
R6	4	5	5	2	1	2	3	3	4	4	5	4	0	2	3	4	3	3	2	4	3	0	4	2	3
R7	5	3	4	2	1	1	3	3	4	5	5	4	0	2	3	4	3	3	3	4	4	2	3	2	3
R8	4	4	3	1	2	2	3	3	4	5	4	4	0	1	3	4	4	3	3	3	3	1	4	2	4
R9	5	4	4	2	1	1	3	3	4	5	5	4	0	2	3	4	3	3	3	4	4	2	3	2	3
R10	4	4	4	1	1	1	3	3	4	5	5	4	1	1	3	4	4	3	3	4	3	1	4	2	4
R11	5	4	4	0	1	1	3	4	3	5	5	4	0	1	2	4	4	3	3	4	3	1	4	2	4
R12	4	4	4	1	1	2	3	3	4	5	5	4	1	1	3	4	4	3	3	4	3	1	4	2	5
R13	5	4	4	0	1	1	3	4	3	5	5	4	0	1	3	4	4	3	3	4	3	1	4	3	4
R14	5	4	5	1	0	1	2	3	4	5	4	4	1	1	2	4	4	3	3	3	3	1	4	2	4
R15	4	4	4	1	1	1	3	3	4	5	5	3	1	1	3	4	4	3	3	4	3	1	4	2	4
R16	5	5	4	0	1	1	3	4	3	5	4	4	0	1	3	4	4	3	3	4	3	1	4	1	4
R17	5	4	4	2	1	1	2	3	4	5	5	4	0	2	3	4	3	3	3	4	4	2	3	2	3
R18	4	4	4	1	1	1	3	3	4	5	4	5	2	1	2	4	3	4	3	4	3	1	4	1	4
Importance weight	**.91**	**.79**	**.82**	**.22**	**.21**	**.23**	**.57**	**.62**	**.76**	**.97**	**.93**	**.80**	**.09**	**.27**	**.56**	**.78**	**.72**	**.61**	**.59**	**.76**	**.64**	**.26**	**.74**	**.39**	**.74**

Table 6.8: Influence of each change factor towards process efficiency strategy

	DRIVERS													ENABLERS			BARRIERS								
	Reducing production cost	Reducing materials	Reducing energy usage	Improve environmental image	Social responsibility	Customer requirements	Fulfil international product design	Compliance with local environment legislation	Competition among rivals	Increase in price of raw materials	Supplier requirements	Support from other industries	Public pressure	ISO14001 certification	Adoption of advanced technology	Environmental awareness of company's top management	Company technological availability	Implementation costs	Restrictions in product design	Lack of information and knowledge	Lack of readiness to change	Customer requirements	Lack of external support	Regulation constraints	Suppliers and supply chains
R1	5	5	5	4	1	1	3	3	4	5	4	2	1	3	4	4	4	5	3	4	5	5	5	4	1
R2	5	4	5	4	2	1	3	2	4	5	4	3	2	3	4	4	4	5	3	4	5	4	5	4	2
R3	4	5	5	4	1	0	3	3	5	5	4	2	1	3	4	4	4	5	3	4	4	5	5	4	1
R4	5	5	5	3	0	1	3	3	3	4	3	2	1	3	4	4	4	4	4	4	5	5	5	3	0
R5	4	5	5	4	1	0	2	3	4	5	4	2	1	3	4	4	4	5	3	3	4	5	5	4	1
R6	5	5	5	3	0	1	3	3	3	4	3	2	1	3	4	4	4	4	4	4	5	5	5	3	0
R7	5	5	5	4	1	2	2	3	4	5	4	2	0	3	4	4	4	5	3	4	5	5	5	4	1
R8	5	5	4	5	2	1	1	5	4	4	3	1	2	4	3	3	4	4	4	4	5	5	4	5	2
R9	4	5	5	4	1	0	3	3	4	5	4	2	1	3	4	4	4	5	3	4	4	5	5	4	1
R10	5	5	5	4	0	1	3	3	3	4	3	2	1	3	4	4	4	4	4	5	5	5	5	4	0
R11	4	5	5	4	1	0	3	2	4	5	4	2	3	3	4	4	4	5	3	4	4	5	5	4	1
R12	5	4	5	4	2	3	4	3	4	5	4	2	1	3	4	4	4	5	3	4	5	4	5	4	2
R13	4	5	5	4	1	0	3	2	4	5	4	2	3	3	4	4	4	5	3	4	4	5	5	4	1
R14	5	5	5	3	0	1	3	3	3	4	3	2	2	3	4	4	4	4	4	5	5	5	5	3	0
R15	5	4	4	4	1	1	3	3	4	5	4	2	1	3	4	4	4	5	4	4	5	4	4	4	1
R16	4	5	5	4	1	0	3	2	3	5	4	2	1	4	3	3	4	5	3	3	4	5	5	4	1
R17	5	5	5	4	0	1	3	3	4	4	3	2	1	3	4	4	4	4	4	4	5	5	5	4	0
R18	5	4	5	4	1	1	2	3	3	4	5	2	2	3	4	4	4	4	3	4	5	4	5	4	1
Importance weight	**.93**	**.96**	**.98**	**.78**	**.18**	**.17**	**.56**	**.58**	**.74**	**.92**	**.74**	**.40**	**.28**	**.62**	**.78**	**.78**	**.80**	**.92**	**.68**	**.80**	**.66**	**.21**	**.38**	**.30**	**.58**

Table 6.9: Influence of each change factor towards green packaging strategy

	DRIVERS													ENABLERS			BARRIERS								
	Reducing production cost	**Reducing materials**	**Reducing energy usage**	**Improve environmental image**	**Social responsibility**	**Customer requirements**	**Fulfil international product design**	**Compliance with local environment legislation**	**Competition among rivals**	**Increase in price of raw materials**	**Supplier requirements**	**Support from other industries**	**Public pressure**	**ISO14001 certification**	**Adoption of advanced technology**	**Environmental awareness of company's top management**	**Company technological availability**	**Implementation costs**	**Restrictions in product design**	**Lack of information and knowledge**	**Lack of readiness to change**	**Customer requirements**	**Lack of external support**	**Regulation constraints**	**Suppliers and supply chains**
R1	1	2	1	3	2	2	3	2	4	2	4	4	3	4	4	5	4	5	4	3	3	4	3	3	4
R2	1	1	1	3	3	4	2	2	4	1	3	4	3	4	3	3	4	4	4	3	2	4	3	3	3
R3	2	2	0	3	4	3	3	2	3	2	2	4	4	4	3	4	4	5	4	2	3	4	4	3	3
R4	1	2	1	4	4	4	4	4	4	2	4	4	3	3	4	4	4	5	4	3	3	4	3	3	5
R5	1	2	1	3	3	3	3	3	4	2	4	4	3	4	4	4	4	5	4	3	3	4	3	3	5
R6	1	1	1	3	4	3	3	2	4	2	3	3	3	3	3	3	4	5	4	3	3	4	3	3	5
R7	2	2	0	4	4	3	4	4	4	2	4	3	3	4	4	5	4	5	4	3	3	4	3	3	4
R8	1	2	1	3	3	3	3	3	3	1	3	3	3	3	4	5	4	4	4	3	4	4	3	3	5
R9	1	1	1	4	4	3	3	3	4	2	4	4	3	3	4	4	3	5	4	3	3	4	3	3	4
R10	0	2	0	4	3	3	4	3	4	1	3	4	3	3	4	5	3	4	3	3	4	4	3	4	3
R11	1	2	1	3	4	4	3	4	3	2	4	3	3	3	5	3	4	5	4	3	3	4	3	3	5
R12	2	2	1	3	3	3	3	2	4	2	4	3	3	4	4	3	4	5	4	3	3	4	3	3	5
R13	1	1	2	3	4	3	3	3	3	1	3	3	4	4	4	4	4	4	3	3	3	3	3	4	4
R14	1	2	1	3	4	4	3	4	3	2	4	4	3	3	4	4	4	5	4	3	3	4	3	3	5
R15	2	2	0	3	3	4	3	2	4	2	4	3	4	4	4	4	4	4	4	3	3	4	3	3	4
R16	1	1	1	4	4	3	3	3	3	2	3	4	4	3	4	5	3	5	4	3	3	4	3	3	5
R17	0	2	0	4	3	3	3	3	3	1	3	4	3	3	3	3	3	4	3	3	4	4	3	4	3
R18	2	2	1	3	3	2	4	4	2	2	4	4	3	4	4	4	4	5	4	3	3	4	3	3	5
Importance weight	**.23**	**.34**	**.16**	**.67**	**.69**	**.63**	**.63**	**.59**	**.70**	**.34**	**.70**	**.72**	**.64**	**.70**	**.77**	**.80**	**.76**	**.93**	**.77**	**.59**	**.62**	**.79**	**.61**	**.63**	**.86**

Table 6.10: Normalized importance weights of drivers that influence the selection of material efficiency strategies

Material efficiency strategy	**D_1**	**D_2**	**D_3**	**D_4**	**D_5**	**D_6**	**D_7**	**D_8**	**D_9**	**D_{10}**	**D_{11}**	**D_{12}**	**D_{13}**
Product light-weighting	0.081	0.073	0.049	0.031	0.016	0.108	0.123	0.083	0.072	0.053	0.042	0.030	0.030
Design for material recovery	0.010	0.023	0.032	0.031	0.017	0.084	0.112	0.093	0.050	0.041	0.045	0.036	0.033
Design for longer life	0.013	0.053	0.032	0.024	0.018	0.148	0.106	0.081	0.072	0.046	0.042	0.036	0.026
Design for multi-functionality	0.077	0.053	0.017	0.018	0.005	0.108	0.101	0.036	0.040	0.037	0.031	0.006	0.005
Material substitution	0.081	0.071	0.045	0.034	0.018	0.120	0.137	0.104	0.073	0.056	0.046	0.032	0.028
Purchasing of pre-manufactured parts	0.084	0.058	0.037	0.013	0.003	0.033	0.043	0.035	0.048	0.029	0.028	0.023	0.004
Yield improvement	0.088	0.062	0.043	0.008	0.005	0.038	0.084	0.074	0.062	0.058	0.047	0.036	0.004
Process efficiency	0.090	0.076	0.051	0.030	0.004	0.028	0.082	0.069	0.061	0.055	0.038	0.018	0.012
Green packaging	0.022	0.027	0.008	0.025	0.016	0.103	0.093	0.070	0.057	0.020	0.036	0.032	0.027

Indicators: D_1- Reducing production costs; D_2-Reducing materials ; D_3- Reducing energy usage; D_4- Improve environmental image; D_5- Social responsibility; D_6- Customer requirements; D_7- Fulfil international product designs; D_8- Compliance with local environmental legislation; D_9- Competition among rivals, D_{10}- Increase in price of raw materials; D_{11}- Supplier requirements; D_{12}- Support from other industries; D_{13}-Public pressure.

Table 6.11: Normalized importance weights of barriers that influence the selection of material efficiency strategies

Material efficiency strategy	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9
Product light-weighting	0.082	0.091	0.092	0.070	0.053	0.061	0.043	0.061	0.050
Design for material recovery	0.080	0.090	0.081	0.068	0.045	0.102	0.087	0.078	0.051
Design for longer life	0.108	0.113	0.103	0.077	0.041	0.138	0.086	0.067	0.048
Design for multi-functionality	0.093	0.097	0.072	0.069	0.045	0.152	0.060	0.027	0.019
Material substitution	0.090	0.098	0.091	0.072	0.047	0.126	0.074	0.088	0.066
Purchasing of pre-manufactured parts	0.086	0.086	0.081	0.019	0.021	0.081	0.046	0.029	0.036
Yield improvement	0.087	0.077	0.063	0.066	0.043	0.051	0.088	0.039	0.053
Process efficiency	0.097	0.117	0.072	0.070	0.044	0.041	0.045	0.030	0.042
Green packaging	0.092	0.118	0.082	0.051	0.042	0.156	0.073	0.063	0.062

Indicators: B_1-Company technological availability ;B_2-Implementation costs; B_3-Restrictions in product design; B_4-Lack of information and knowledge; B_5-Company's readiness to change; B_6-Customer requirements; B_7-Lack of external support; B_8-Regulation constraints; B_9- Suppliers and supply chains

Table 6.12: Normalized importance weight of enablers that influence the selection of material efficiency strategies

Material efficiency strategy	ISO14001 certification (E_1)	Adoption of advanced technology (E_2)	Environmental awareness of the company's top management (E_3)
Product light-weighting	0.024	0.053	0.024
Design for material recovery	0.025	0.045	0.019
Design for longer life	0.013	0.046	0.020
Design for multi-functionality	0.009	0.013	0.019
Material substitution	0.021	0.043	0.025
Purchasing of pre-manufactured parts	0.009	0.022	0.015
Yield improvement	0.008	0.034	0.022
Process efficiency	0.019	0.047	0.022
Green packaging	0.024	0.047	0.027

6.1.1 Balancing the Normalized Weight for Different Change Factor Category

From the three groups of change factors that influence the selection of material efficiency strategies, it can be seen that there is imbalance in the normalized weights especially for the category that consists of a smaller number of sub-criteria such as "enablers". Therefore, the normalized weights for the sub-criteria in the "enablers" category appear larger than those in the "drivers" and "barriers" categories. Hence, if these data are used in the decision support tool, this will generate inaccurate and bias results because the overall results are largely influenced by enabler factors whereas the other factors (i.e. drivers and barriers) only give a small impact to the results because of the lower normalized values.

Hence, it is important to obtain a balanced distribution of normalized weights for each category in order to increase the accuracy of the data. This is done by dividing the number of change factors in each category (i.e. drivers, barriers or enablers) with the total number of change factors (i.e. drivers, barriers, and enablers). For example, if the total number of three groups of change factors is 25, the distribution value for each category can be obtained by dividing the total number of factors in each category with 25. For instance, in the "enablers" category, the three enablers are divided with 25. Hence, the result obtained for the "enablers", "drivers" and "barriers" category is 0.12, 0.52 and 0.36, respectively.

Next, the distribution value was multiplied with the normalized weight in each category. For instance, 0.52 is multiplied with each driver's normalized weigh (see Table 6.13). This was also done for barriers and enables and the final normalized weights are presented in Table 6.14 and 6.15. These data were used as the measurement data to evaluate the implementation of material efficiency strategies.

Table 6.13: Balanced normalized importance weights of drivers that influence the selection of material efficiency strategies

Material efficiency strategy	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}	D_{11}	D_{12}	D_{13}
Product light-weighting	0.042	0.038	0.025	0.016	0.008	0.056	0.064	0.043	0.038	0.028	0.022	0.015	0.016
Design for material recovery	0.005	0.012	0.017	0.016	0.009	0.043	0.058	0.048	0.026	0.021	0.024	0.019	0.017
Design for longer life	0.007	0.028	0.016	0.013	0.009	0.077	0.055	0.042	0.038	0.024	0.022	0.019	0.014
Design for multi-functionality	0.040	0.028	0.009	0.009	0.002	0.056	0.053	0.019	0.021	0.019	0.016	0.003	0.002
Material substitution	0.042	0.037	0.023	0.018	0.010	0.062	0.071	0.054	0.038	0.029	0.024	0.017	0.015
Purchasing of pre-manufactured parts	0.044	0.030	0.019	0.007	0.002	0.017	0.022	0.018	0.025	0.015	0.014	0.012	0.002
Yield improvement	0.046	0.032	0.022	0.004	0.003	0.020	0.044	0.038	0.032	0.030	0.025	0.019	0.002
Process efficiency	0.047	0.039	0.026	0.015	0.002	0.014	0.043	0.036	0.032	0.029	0.020	0.009	0.006
Green packaging	0.012	0.014	0.004	0.013	0.008	0.054	0.048	0.037	0.030	0.011	0.019	0.017	0.014

Indicators: D_1- Reducing production costs; D_2-Reducing materials ; D_3- Reducing energy usage; D_4- Improve environmental image; D_5- Social responsibility; D_6- Customer requirements; D_7- Fulfil international product designs; D_8- Compliance with local environmental legislation; D_9- Competition among rivals, D_{10}- Increase in price of raw materials; D_{11}- Supplier requirements; D_{12}- Support from other industries; D_{13}-Public pressure.

Table 6.14: Balanced normalized importance weights of barriers that influence the selection of material efficiency strategies

Material efficiency strategy	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9
Product light-weighting	0.028	0.032	0.032	0.024	0.018	0.021	0.015	0.021	0.017
Design for material recovery	0.028	0.031	0.028	0.023	0.016	0.035	0.030	0.027	0.018
Design for longer life	0.037	0.039	0.036	0.027	0.014	0.048	0.030	0.023	0.016
Design for multi-functionality	0.032	0.033	0.025	0.024	0.016	0.052	0.021	0.009	0.007
Material substitution	0.031	0.034	0.032	0.025	0.016	0.044	0.026	0.030	0.023
Pre-manufactured part purchase	0.030	0.030	0.028	0.007	0.007	0.028	0.016	0.010	0.012
Yield improvement	0.030	0.027	0.022	0.023	0.015	0.018	0.030	0.013	0.018
Process efficiency	0.033	0.040	0.025	0.024	0.015	0.014	0.016	0.010	0.014
Green packaging	0.032	0.041	0.028	0.018	0.014	0.054	0.025	0.022	0.021

Indicators: B_1-Company technological availability ;B_2-Implementation costs; B_3- Restrictions in product design; B_4-Lack of information and knowledge; B_5-Company's readiness to change; B_6-Customer requirements; B_7-Lack of external support; B_8-Regulation constraints; B_9-Suppliers and supply chains

Table 6.15: Balanced normalized importance weight of enablers that influence the selection of material efficiency strategies

Material efficiency strategy	ISO 14001 certification, E_1	Adoption of advanced technology, E_2	Environmental awareness of company's top management, E_3
Product light-weighting	0.024	0.053	0.024
Design for material recovery	0.025	0.045	0.019
Design for longer life	0.013	0.046	0.020
Design for multi-functionality	0.009	0.013	0.019
Material substitution	0.021	0.043	0.025
Purchasing of pre-manufactured parts	0.009	0.022	0.015
Yield improvement	0.008	0.034	0.022
Process efficiency	0.019	0.047	0.022
Green packaging	0.024	0.047	0.027

6.1.2 Propositions of material efficiency strategies

Previous section shows different change factor has different importance weight towards each material efficiency strategy. For example, product light weighting strategy is influenced mainly by the market needs related factors (fulfil to the international product designs, customer requirements). Whereas, this strategy is less influenced by societal related factor such as social responsibility. This information could deliver a direct massage to the manufacturer, especially on the path ways to conduct the changes in order to meet material efficiency use in product design or manufacturing process.

In this section, the balanced change factors (drivers, barriers, and enablers) in Section 6.1.1 were combined and presented in descending weight towards each material efficiency strategy (see Table 6.16 to Table 6.24). Next, the propositions for each material efficiency strategy were built according to the descended influencing weight of change factors. By knowing the influences of each change factor towards different material efficiency strategy, it could help to determine the decision of conducting a strategy. At the same time, the propositions built are also important to be used as the rules for decision support tool development in the next phase of research.

Table 6.16: Propositions of product light-weighting strategy with reflect to different change factors

	D_7	D_6	E_2	D_8	D_1	D_2	D_9	B_2	B_3	D_{10}	B_1	D_3	B_4	E_1	E_3	D_{11}	B_6	B_8	B_5	B_9	D_4	D_{13}	D_{12}	B_7	D_5
Product light-weighting	0.064	0.056	0.053	0.043	0.042	0.038	0.038	0.032	0.032	0.028	0.028	0.025	0.024	0.024	0.024	0.022	0.021	0.021	0.018	0.017	0.016	0.016	0.015	0.015	0.008

Indicator: D_1- Reducing production costs; D_2-Reducing materials; D_3- Reducing energy usage; D_4- Improve environmental image; D_5- Social responsibility; D_6-Customer requirements; D_7- Fulfil international product designs; D_8- Compliance with local environmental legislation; D_9- Competition among rivals, D_{10}- Increase in price of raw materials; D_{11}- Supplier requirements; D_{12}- Support from other industries; D_{13}-Public pressure, Indicators; B_1-Company technological availability; B_2-Implementation costs; B_3- Restrictions in product design; B_4-Lack of information and knowledge; B_5-Company's readiness to change; B_6-Customer requirements; B_7-Lack of external support; B_8-Regulation constraints; B_9- Suppliers and supply chains; E_1- ISO 14001 certification; E_2- Adoption of advanced technology; E_3-Environmental awareness of company's top management

Propositions:

1. Product light weighting strategy is more influenced by external factors than internal factors.
2. Product light weighting strategy is more influenced by product design than manufacturing capabilities.
3. Product light weighting strategy is more influenced by market demands than societal pressure.

Table 6.17: Propositions of design for material recovery strategy with reflect to different change factors

	D_7	D_8	E_2	D_6	B_6	B_2	B_7	B_1	B_3	B_8	D_9	E_1	D_{11}	B_4	D_{10}	D_{12}	E_3	B_9	D_3	D_{13}	D_4	B_5	D_2	D_5	D_1
Design for material recovery	0.058	0.048	0.045	0.043	0.035	0.031	0.03	0.028	0.028	0.027	0.026	0.025	0.024	0.023	0.021	0.019	0.019	0.018	0.017	0.017	0.016	0.016	0.012	0.009	0.005

Indicators: D_1- Reducing production costs; D_2-Reducing materials ; D_3- Reducing energy usage; D_4- Improve environmental image; D_5- Social responsibility; D_6- Customer requirements; D_7- Fulfil international product designs; D_8- Compliance with local environmental legislation; D_9- Competition among rivals, D_{10}- Increase in price of raw materials; D_{11}- Supplier requirements; D_{12}- Support from other industries; D_{13}-Public pressure, Indicators; B_1-Company technological availability; B_2-Implementation costs; B_3- Restrictions in product design; B_4-Lack of information and knowledge; B_5-Company's readiness to change; B_6-Customer requirements; B_7-Lack of external support; B_8-Regulation constraints; B_9- Suppliers and supply chains; E_1- ISO 14001 certification; E_2- Adoption of advanced technology; E_3-Environmental awareness of company's top management

Propositions:

1. Design for material recovery is more influenced by external factors than internal factors.
2. Design for material recovery is more influenced by product design than manufacturing capabilities.
3. Design for material recovery is more influenced by market demands than societal pressure.

Table 6.18: Propositions of design for longer life strategy with reflect to different change factors

	D_6	D_7	B_6	E_2	D_8	B_2	D_9	B_1	B_3	B_7	D_2	B_4	D_{10}	B_8	D_{11}	E_3	D_{12}	D_3	B_9	D_{13}	B_5	D_4	E_1	D_5	D_1
Design for longer life	0.077	0.055	0.048	0.046	0.042	0.039	0.038	0.037	0.036	0.03	0.028	0.027	0.024	0.023	0.022	0.02	0.019	0.016	0.016	0.014	0.014	0.013	0.013	0.009	0.007

Indicators: D_1- Reducing production costs; D_2-Reducing materials ; D_3- Reducing energy usage; D_4- Improve environmental image; D_5- Social responsibility; D_6- Customer requirements; D_7- Fulfil international product designs; D_8- Compliance with local environmental legislation; D_9- Competition among rivals, D_{10}- Increase in price of raw materials; D_{11}- Supplier requirements; D_{12}- Support from other industries; D_{13}-Public pressure, Indicators; B_1-Company technological availability; B_2-Implementation costs; B_3- Restrictions in product design; B_4-Lack of information and knowledge; B_5-Company's readiness to change; B_6- Customer requirements; B_7-Lack of external support; B_8-Regulation constraints; B_9- Suppliers and supply chains; E_1- ISO 14001 certification; E_2- Adoption of advanced technology; E_3-Environmental awareness of company's top management

Propositions:

1. Design for longer life is more influenced by external factors than internal factors.
2. Design for longer life strategy is more influenced by product design than manufacturing capabilities.
3. Design for longer life strategy is more influenced by market demands than societal pressure.

Table 6.19: Propositions of design for multi-functional strategy with reflect to different change factors

	D_6	D_7	B_6	D_1	B_2	B_1	D_2	B_3	B_4	D_9	B_7	D_8	D_{10}	E_3	D_{11}	B_5	E_2	D_3	D_4	B_8	E_1	B_9	D_{12}	D_5	D_{13}
Design for multi-functional	0.056	0.053	0.052	0.04	0.033	0.032	0.028	0.025	0.024	0.021	0.021	0.019	0.019	0.019	0.016	0.016	0.013	0.009	0.009	0.009	0.009	0.007	0.003	0.002	0.002

Indicators: D_1- Reducing production costs; D_2-Reducing materials ; D_3- Reducing energy usage; D_4- Improve environmental image; D_5- Social responsibility; D_6- Customer requirements; D_7- Fulfil international product designs; D_8- Compliance with local environmental legislation; D_9- Competition among rivals, D_{10}-Increase in price of raw materials; D_{11}- Supplier requirements; D_{12}- Support from other industries; D_{13}-Public pressure, Indicators; B_1-Company technological availability; B_2-Implementation costs; B_3- Restrictions in product design; B_4-Lack of information and knowledge; B_5-Company's readiness to change; B_6-Customer requirements; B_7-Lack of external support; B_8-Regulation constraints; B_9- Suppliers and supply chains; E_1- ISO 14001 certification; E_2- Adoption of advanced technology; E_3-Environmental awareness of company's top management

Propositions:

1. Design for multi-functional strategy is more influenced by external factors than internal factors.
2. Design for multi-functional strategy is more influenced by manufacturing capabilities than product design.
3. Design for multi-functional strategy is more influenced by market demands than societal pressure.

Table 6.20: Propositions of material substitution strategy with reflect to different change factors

	D_7	D_6	D_8	B_6	E_2	D_1	D_9	D_2	B_2	B_3	B_1	B_8
Material substitution	0.071	0.062	0.054	0.044	0.043	0.042	0.038	0.037	0.034	0.032	0.031	0.03

	D_{10}	B_7	B_4	E_3	D_{11}	D_3	B_9	E_1	D_4	D_{12}	B_5	D_{13}	D_5
Material substitution	0.029	0.026	0.025	0.025	0.024	0.023	0.023	0.021	0.018	0.017	0.016	0.015	0.01

Indicators: D_1- Reducing production costs; D_2-Reducing materials ; D_3- Reducing energy usage; D_4- Improve environmental image; D_5- Social responsibility; D_6-Customer requirements; D_7- Fulfil international product designs; D_8- Compliance with local environmental legislation; D_9- Competition among rivals, D_{10}- Increase in price of raw materials; D_{11}- Supplier requirements; D_{12}- Support from other industries; D_{13}-Public pressure, Indicators; B_1-Company technological availability; B_2-Implementation costs; B_3- Restrictions in product design; B_4-Lack of information and knowledge; B_5-Company's readiness to change; B_6-Customer requirements; B_7-Lack of external support; B_8-Regulation constraints; B_9- Suppliers and supply chains; E_1- ISO 14001 certification; E_2- Adoption of advanced technology; E_3-Environmental awareness of company's top management

Propositions:

1. Material substitution strategy is more influenced by external factors than internal factors.

2. Material substitution strategy is more influenced by product design than manufacturing capabilities.

3. Material substitution is more influenced by market demands than societal pressure.

Table 6.21: Propositions of purchasing of pre-manufactured part strategy with reflect to different change factors

	D_1	D_2	B_1	B_2	B_3	B_6	D_9	D_7	E_2	D_3	D_8	D_6	B_7	D_{10}	E_3	D_{11}	D_{12}	B_9	B_8	E_1	D_4	B_4	B_5	D_5	D_{13}
Purchasing of pre-manufactured parts	0.044	0.03	0.03	0.03	0.028	0.028	0.025	0.022	0.022	0.019	0.018	0.017	0.016	0.015	0.015	0.014	0.012	0.012	0.01	0.009	0.007	0.007	0.007	0.002	0.002

Indicators: D_1- Reducing production costs; D_2-Reducing materials ; D_3- Reducing energy usage; D_4- Improve environmental image; D_5- Social responsibility; D_6-Customer requirements; D_7- Fulfil international product designs; D_8- Compliance with local environmental legislation; D_9- Competition among rivals, D_{10}- Increase in price of raw materials; D_{11}- Supplier requirements; D_{12}- Support from other industries; D_{13}-Public pressure, Indicators; B_1-Company technological availability; B_2-Implementation costs; B_3- Restrictions in product design; B_4-Lack of information and knowledge; B_5-Company's readiness to change; B_6-Customer requirements; B_7-Lack of external support; B_8-Regulation constraints; B_9- Suppliers and supply chains; E_1- ISO 14001 certification; E_2- Adoption of advanced technology; E_3-Environmental awareness of company's top management

Propositions:

1. Purchasing of pre-manufactured parts strategy is more influenced by internal factors than external factors.

2. Purchasing of pre-manufactured parts strategy is more influenced by manufacturing capabilities than product design.

3. Purchasing of pre-manufactured parts strategy is less influenced by both market demands and societal pressure.

Table 6.22: Propositions of yield improvement strategy with reflect to different change factors

	D_1	D_7	D_8	E_2	D_2	D_9	D_{10}	B_1	B_7	B_2	D_{11}	B_4	D_3	B_3	E_3	D_6	D_{12}	B_6	B_9	B_5	B_8	E_1	D_4	D_5	D_{13}
Yield improvement	0.046	0.044	0.038	0.034	0.032	0.032	0.03	0.03	0.03	0.027	0.025	0.023	0.022	0.022	0.022	0.02	0.019	0.018	0.018	0.015	0.013	0.008	0.004	0.003	0.002

Indicators: D_1- Reducing production costs; D_2-Reducing materials ; D_3- Reducing energy usage; D_4- Improve environmental image; D_5- Social responsibility; D_6-Customer requirements; D_7- Fulfil international product designs; D_8- Compliance with local environmental legislation; D_9- Competition among rivals, D_{10}- Increase in price of raw materials; D_{11}- Supplier requirements; D_{12}- Support from other industries; D_{13}-Public pressure, Indicators; B_1-Company technological availability; B_2-Implementation costs; B_3- Restrictions in product design; B_4-Lack of information and knowledge; B_5-Company's readiness to change; B_6-Customer requirements; B_7-Lack of external support; B_8-Regulation constraints; B_9- Suppliers and supply chains; E_1- ISO 14001 certification; E_2- Adoption of advanced technology; E_3-Environmental awareness of company's top management

Propositions:

1. Yield improvement strategy is more influenced by the internal factors than internal factors.
2. Yield improvement strategy is more influenced by manufacturing capabilities than product design.
3. Yield improvement strategy is less influenced by both market demands and societal pressure.

Table 6.23: Propositions of process efficiency strategy with reflect to different change factors

	D_1	E_2	D_7	B_2	D_2	D_8	B_1	D_9	D_{10}	D_3	B_3	B_4	E_3	D_{11}	E_1	B_7	D_4	B_5	D_6	B_6	B_9	B_8	D_{12}	D_{13}	D_5
Process efficiency	0.047	0.047	0.043	0.04	0.039	0.036	0.033	0.032	0.029	0.026	0.025	0.024	0.022	0.02	0.019	0.016	0.015	0.015	0.014	0.014	0.014	0.01	0.009	0.006	0.002

Indicators: D_1- Reducing production costs; D_2-Reducing materials ; D_3- Reducing energy usage; D_4- Improve environmental image; D_5- Social responsibility; D_6- Customer requirements; D_7- Fulfil international product designs; D_8- Compliance with local environmental legislation; D_9- Competition among rivals, D_{10}- Increase in price of raw materials; D_{11}- Supplier requirements; D_{12}- Support from other industries; D_{13}-Public pressure, Indicators; B_1-Company technological availability; B_2-Implementation costs; B_3- Restrictions in product design; B_4-Lack of information and knowledge; B_5-Company's readiness to change; B_6-Customer requirements; B_7-Lack of external support; B_8-Regulation constraints; B_9- Suppliers and supply chains; E_1- ISO 14001 certification; E_2- Adoption of advanced technology; E_3-Environmental awareness of company's top management

Propositions:

1. Process efficiency strategy is more influenced by internal factors than external factors.

2. Process efficiency strategy is more influenced by manufacturing capabilities than product design.

3. Process efficiency strategy is more influenced by market demands than the societal pressure.

Table 6.24: Propositions of green packaging strategy with reflect to different change factors

	D_6	B_6	D_7	E_2	B_2	D_8	B_1	D_9	B_3	E_3	B_7	E_1	B_8	B_9	D_{11}	B_4	D_{12}	D_2	D_{13}	B_5	D_4	D_1	D_{10}	D_5	D_3
Green packaging	0.054	0.054	0.048	0.047	0.041	0.037	0.032	0.03	0.028	0.027	0.025	0.024	0.022	0.021	0.019	0.018	0.017	0.014	0.014	0.014	0.013	0.012	0.011	0.008	0.004

Indicators: D_1- Reducing production costs; D_2-Reducing materials ; D_3- Reducing energy usage; D_4- Improve environmental image; D_5- Social responsibility; D_6- Customer requirements; D_7- Fulfil international product designs; D_8- Compliance with local environmental legislation; D_9- Competition among rivals, D_{10}- Increase in price of raw materials; D_{11}- Supplier requirements; D_{12}- Support from other industries; D_{13}-Public pressure, Indicators; B_1-Company technological availability; B_2-Implementation costs; B_3- Restrictions in product design; B_4-Lack of information and knowledge; B_5-Company's readiness to change; B_6- Customer requirements; B_7-Lack of external support; B_8-Regulation constraints; B_9- Suppliers and supply chains; E_1- ISO 14001 certification; E_2- Adoption of advanced technology; E_3-Environmental awareness of company's top management

Propositions:

1. Green packaging strategy is more influenced by the external factors than internal factors.

2. Green packaging strategy is more influenced by product design than manufacturing capabilities.

3. Green packaging strategy is more influenced by societal pressure than market demands.

6.2 Summary

In determining the importance weight of each change factor to influence each material efficiency strategy, a six-point Likert scale survey were conducted to the similar AHP respondents. The results shown different change factor is influencing to each material efficiency strategy differently. Change factors with higher normalized importance weight indicated it has more influences to the implementation of a material efficiency strategy. Whereas, for change factors with smaller normalized importance weight, it has less influences to implement a material efficiency strategy.

Therefore, propositions of each material efficiency strategy were developed with reflect to the overall change factors importance weight. These propositions were built based on the material efficiency strategy with reflect to internal and external change factors, links to product design and machine capabilities, and also the links with market demands and societal pressure. These propositions are importantly to work as a formulation for the development of decision support tool.

CHAPTER 7: MATERIAL EFFICIENCY DECISION SUPPORT TOOL

7.0 Overview

In previous chapter, the determination of the importance weight and propositions between change factors and material efficiency strategies were presented. In this chapter, the development of material efficiency decision support tool is described in detail, particularly, the link between each change factor and material efficiency strategy. This chapter includes the development of the decision framework, as well as formulation of the decision evaluation to select the suitable material efficiency strategy. A complete version of the decision support tool is presented at the end of this chapter.

7.1 Development of the Material Efficiency Decision Support Tool

The development of the decision support tool to select material efficiency strategy based on the AHP results in Chapter 5 and 6 are elaborated in this section. The procedure used to develop the decision support tool was modified from the flow chart of a past empirical study (Shim *et al.*, 2002) (Figure 7.1). There are four phases involved in the development of the decision support tool:

1. Development of the material efficiency strategy decision framework
2. Formulation of material efficiency strategy decision evaluation
3. Formulation of material efficiency strategy alternatives
4. Development of the decision support tool working worksheet.

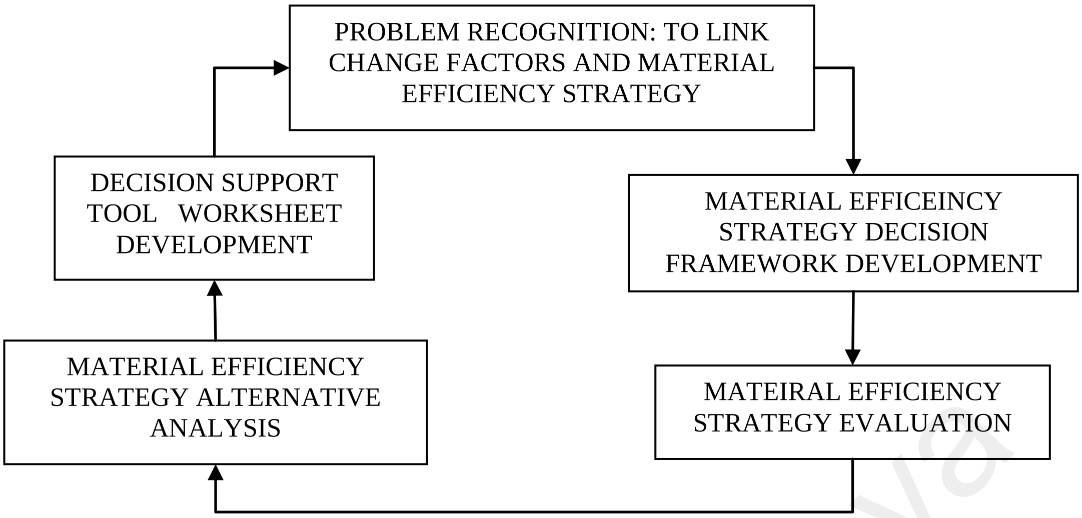

Figure 7.1: Modified procedures to develop the decision support system (Shim *et al.*, 2002, pp.3)

7.2 Material Efficiency Strategy Decision Framework

In Chapter 2, one of the research gaps identified in this research is the lack of understanding regarding the link between the change factors that influence the selection of a material efficiency strategy. From the literature, there are very limited structure decision models are found to conduct material efficiency strategy. For this reason, a decision support tool is required to assist industry in selecting a suitable material efficiency strategy. The development of a material efficiency decision framework is described in this section.

The research findings from the mixed-method were used to construct an analytical decision model to select material efficiency strategy (see Figure 7.2). It was created based on input-process-output concept. The inputs in this model are represented as the selected change factors (drivers, barriers, and enablers). Process aspect refers to the evaluation of the selected change factor influencing weight towards a material efficiency strategy. The decision evaluation is based on the submission of importance weights for each change factor towards s material efficiency strategy. The outputs are referring to the priority in selection of the determined material efficiency strategies for E&E industry.

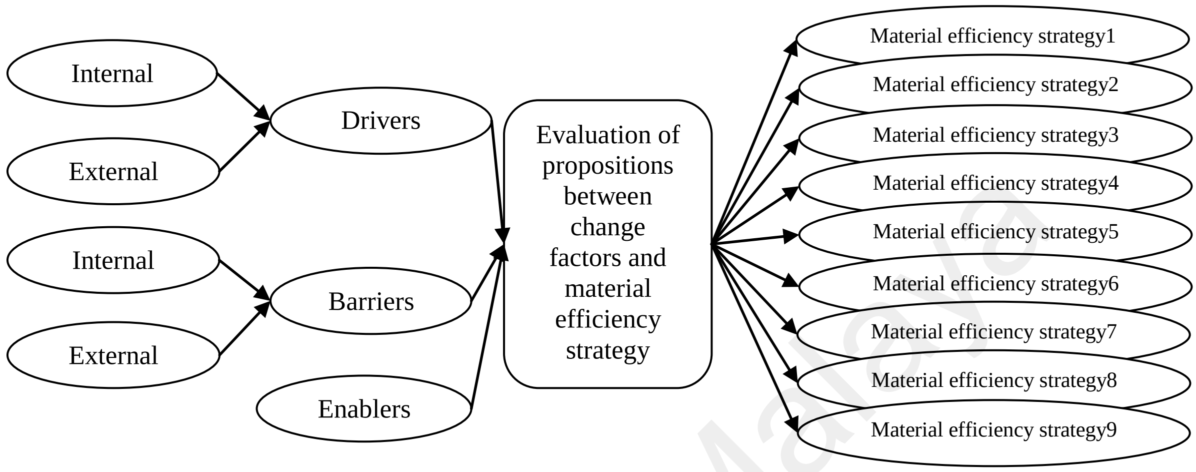

Figure 7.2: Decision framework for the decision support tool

7.2.1 Material Efficiency Strategy Decision Evaluation

In Section 6.1.2, the importance weights of 25 organizational change factors that influence the material efficiency strategies implementation were determined. In addition, the propositions built for each material efficiency strategy with reflects to different change factors were developed. This information is used as the core evaluation to the decision to prioritise the material efficiency strategies.

The formula used to evaluate the material efficiency strategy was developed based on the concept of Product Sustainability Index (Schmidt & Taylor, 2006). In Product Sustainability Index, measurement of product sustainability performance is based on the equation: PSI = [PSI ($_{environment}$) + PSI ($_{social}$) + PSI ($_{economic}$)]. Therefore, this equation is suitable to be adopted as material efficiency strategy evaluation because the principle to consider various internal and external factors in measuring the performance of a product and strategies to be taken. Thus, the formula to select a material efficiency strategy was modified with based on the submission of normalized value from the selected change factors. In this decision support tool, the formula used to determine the selection of material efficiency strategy is given as below:

$$MEFF_{n=i} = \sum Driver_{n=i} + Enabler_{n=i} + \ Barrier_{n=i} \qquad (7.1)$$

Whereby $\mathrm{MEFF}_{n=i}$ is refers to material efficiency strategy propositions weight, whereas the $n = i$ is refers to the material efficiency strategy which is in the same row of the change factors. The total proposition weight for each material efficiency strategy was used to determine the ranking or priority of a strategy. Figure 7.3 shows the decision evaluation used to select and prioritise material efficiency strategy based on the selected change factors. Thus, a different combination of selected change factors (i.e. drivers, barriers and enablers) will give a different total proposition weight for the material efficiency strategies. The priority choice of a material efficiency strategy was determined based on the ascending weight obtained from each row of material efficiency strategy. The highest proposition weights obtained in a strategy will be given the highest priority while the lowest proposition weight obtained in a material efficiency strategy will be given the least priority.

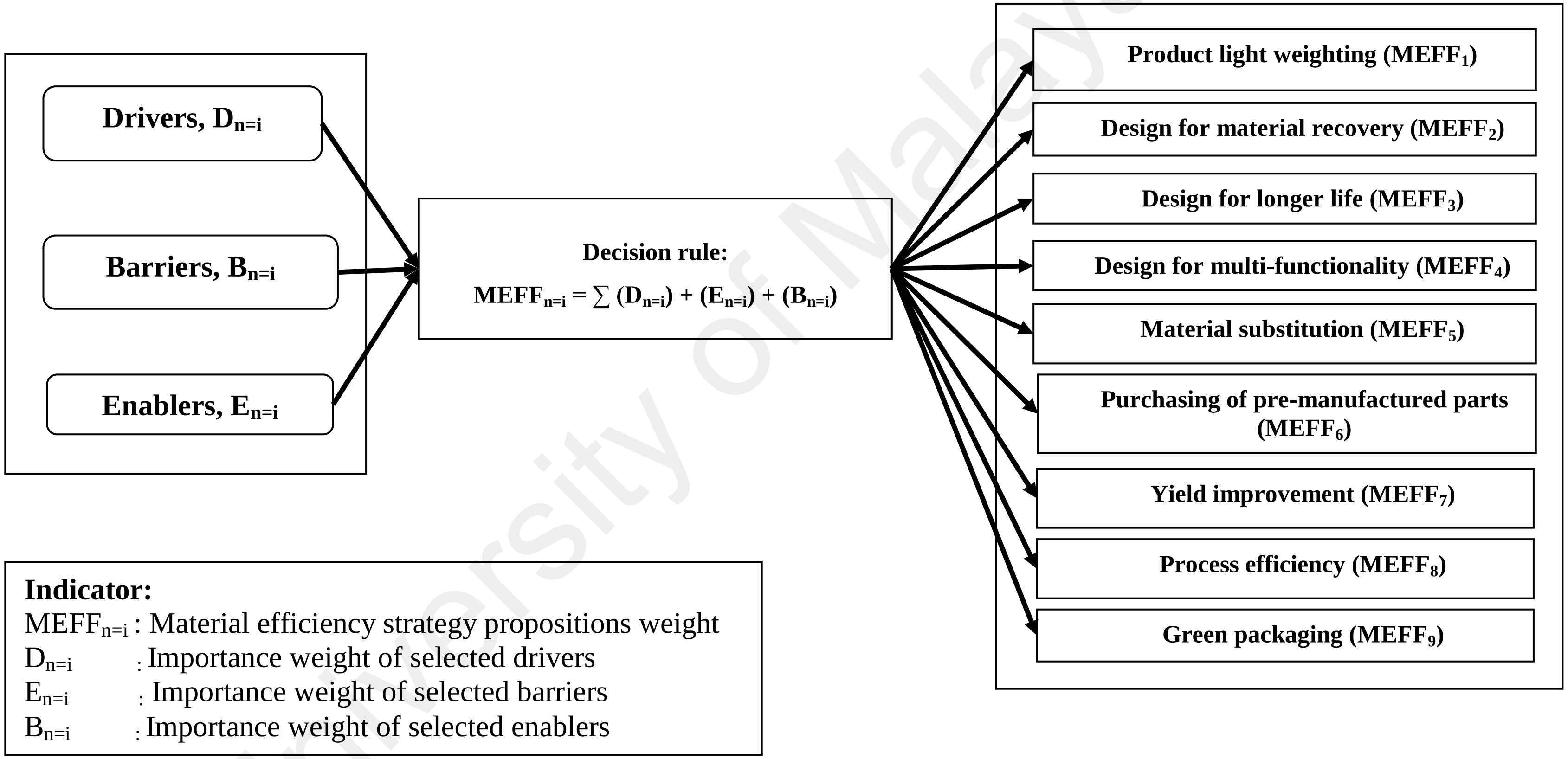

Figure 7.3: Alternative selection of the material efficiency strategy based on different change factors

7.2.2 Redistributing the Weights of the Change Factors to select and prioritise Material Efficiency Strategy

Since the number of selected change factors may influence the selection of material efficiency strategies, there is a need to readjust the AHP absolute weights. The weights of the change factors need to be redistributed in order to ensure fairness of the evaluation in determining the priority of a material efficiency strategy. Although the normalized weights may differ depending on the selected change factors, redistribution of weights may not affect the priority of the material efficiency strategy. However, changes may occur if there is a difference in the normalized value for every material efficiency strategy. The redistribution of the AHP absolute important weights based on the selected change factors is given by the following formula:

$$\sum_{i=1}^{n} MEFF = [(1 - \sum_{i=1}^{\mathrm{n}} \mathrm{CF}_{\mathrm{n}i}) \left(\frac{\mathrm{CF}_{\mathrm{ni}}}{\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{CF}_{\mathrm{ni}}}\right) + \mathrm{CF}_{\mathrm{ni}}] \text{ x } \mathrm{M}_{\mathrm{CF}_{\mathrm{n}}} \qquad (7.2)$$

Indicators:

MEFF : Material efficiency strategy propositions weight

CF_{ni} : Change factor category (D = Drivers, E = Enablers, B = Barriers)

n : Change factor group (D = Drivers, E = Enablers, B = Barriers)

i : the number of change factor groups (e.g. D_1, B_1, E_1)

M_{CFn}: Mean value of the selected change factor

7.3 Development of Decision Support Tool Worksheet

Various decision support frameworks were reviewed and used as reference (discussed in Section 2.5) in order to develop the decision support tool. For example, Sustainable Value framework and Environmental Decision framework (refers Section 2.5.1.1 and 2.5.2) were developed to analyze the logical link between the decision criteria and green strategies. A preliminary version of the decision support tool was developed, as shown in Figure 7.4. Five main elements were integrated into the tool: (a) the nine (9) material efficiency strategies commonly practiced by companies in the E&E industry, (b) the change factors available for selection which consists of 13 drivers, three (3) enablers and nine (9) barriers, (c) the influencing weight which is the core of the evaluation criteria for the tool, (d) the submission or influencing weight for the selected change factors, and (e) the ranking analysis which depends on the submission proposition weight from the selected change factors. The steps to use the decision support tool and flow chart (see Figure 7.5) are presented as follows.

	DRIVERS (D)													ENABLERS (E)			BARRIERS (B)										
Tick (√)																											
Material efficiency Strategy	Reducing production cost	Reducing materials	Reducing energy usage	Improve environmental image	Social responsibility	Customer requirements	Fulfil international product design	Compliance with local environment legislation	Competition among rivals	Increase in price of raw materials	Supplier requirements	Support from other industries	Public pressure	ISO14001 certification	Adoption of advanced technology	Environmental awareness of company's top management	Company technological availability	Implementation costs	Restrictions in product design	Lack of information and knowledge	Lack of readiness to change	Customer requirements	Lack of external support	Regulation constraints	Suppliers and supply chains	$\sum MEFFi = D_i + E_i + B_i$	Material efficiency strategy ranking
Product light-weighting	.042	.038	.025	.016	.008	.056	.064	.043	.038	.028	.022	.015	.016	.024	.053	.024	.028	.032	.032	.024	.018	.021	.015	.021	.017		
Design for material recovery	.005	.012	.017	.016	.009	.043	.058	.048	.026	.021	.024	.019	.017	.025	.045	.019	.028	.031	.028	.023	.016	.035	.03	.027	.018		
Design for longer life	.007	.028	.016	.013	.009	.077	.055	.042	.038	.024	.022	.019	.014	.013	.046	.02	.037	.039	.036	.027	.014	.048	.03	.023	.016		
Design for multi-functionality	.04	.028	.009	.009	.002	.056	.053	.019	.021	.019	.016	.003	.002	.009	.013	.019	.032	.033	.025	.024	.016	.052	.021	.009	.007		
Material substitution	.042	.037	.023	.018	.01	.062	.071	.054	.038	.029	.024	.017	.015	.021	.043	.025	.031	.034	.032	.025	.016	.044	.026	.03	.023		
Purchasing of pre-manufactured parts	.044	.03	.019	.007	.002	.017	.022	.018	.025	.015	.014	.012	.002	.009	.022	.015	.03	.03	.028	.007	.007	.028	.016	.01	.012		
Yield improvement	.046	.032	.022	.004	.003	.02	.044	.038	.032	.03	.025	.019	.002	.008	.034	.022	.03	.027	.022	.023	.015	.018	.03	.013	.018		
Process efficiency	.047	.039	.026	.015	.002	.014	.043	.036	.032	.029	.02	.009	.006	.019	.047	.022	.033	.04	.025	.024	.015	.014	.016	.01	.014		
Green packaging	.012	.014	.004	.013	.008	.054	.048	.037	.03	.011	.019	.017	.014	.024	.047	.027	.032	.041	.028	.018	.014	.054	.025	.022	.021		

Figure 7.4: Decision support tool used to select the suitable material efficiency strategies

There are four steps involved in order to use the decision support tool:

1. Select (tick √) the related driver factor(s) that influence your company to practise the material efficiency strategy.
2. Select (tick √) the related enabler factor(s) that influence your company to practise the material efficiency strategy.
3. Select (tick √) the related barrier factor(s) that influence your company to practise the material efficiency strategy.
4. Calculate the total proposition weight for each material efficiency strategy based on the formula $MEFF_{n=i} = \sum(D_{n=i} + E_{n=i} + B_{n=i})$ (Highest submission of proposition weight = First priority material efficiency strategy, Lowest submission of proposition weight = Least priority material efficiency strategy).

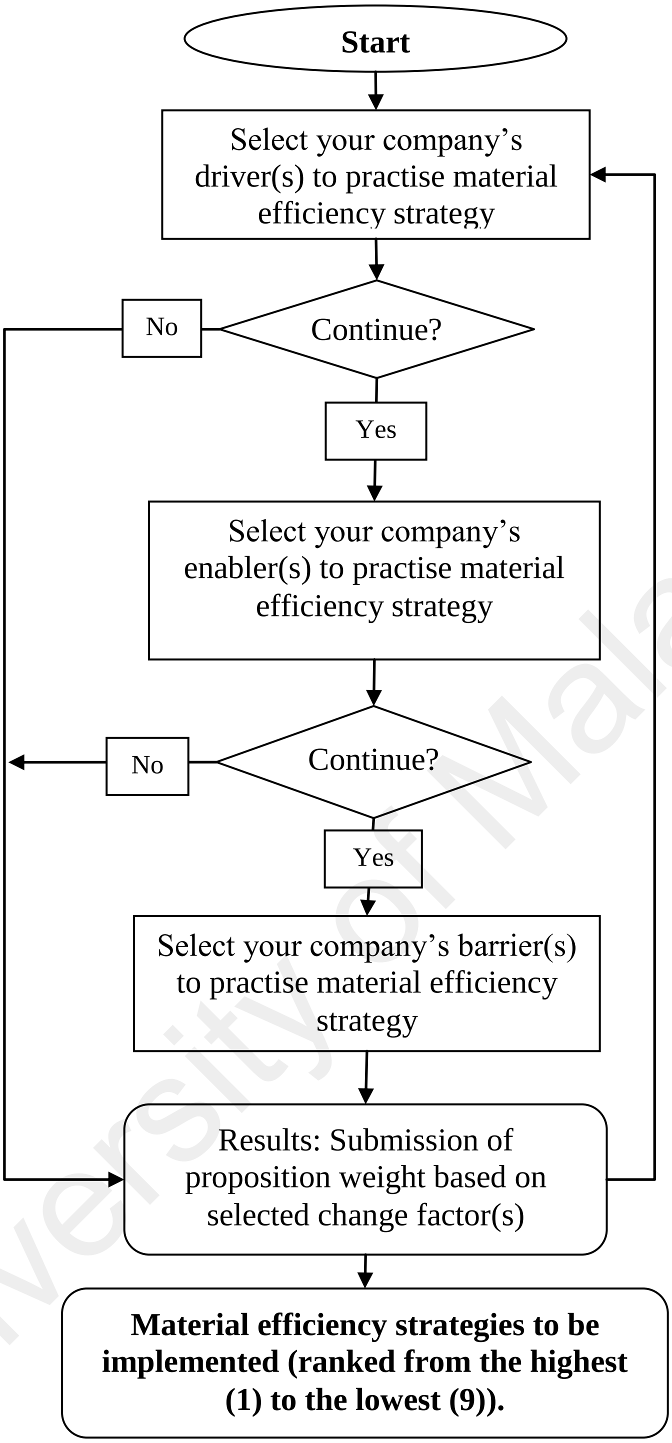

Figure 7.5: Flow chart which shows the steps to use the decision support tool

7.4 Summary

The development of a decision support tool to select the suitable material efficiency strategies for E&E companies in Malaysia is presented in this chapter. The results obtained from AHP and change factor importance weights were used as the core evaluation for the decision support tool. The selection of a suitable material efficiency strategy was based on the selected change factors and the total importance weights of these change factors towards different material efficiency strategies were computed. The priority ranking of the material efficiency strategies is based on the total importance weight of the selected change factors. In brief, the ranking of a material efficiency strategy will vary depending on the combinations of different change factors. The strategy with the highest rank represents the most appropriate strategy to be implemented. Likewise, the strategy with the lowest rank represents the least important strategy. A guideline for using the decision support tool is also presented in this chapter.

CHAPTER 8: VALIDATION OF THE DECISION SUPPORT TOOL

8.0 Overview

The development of a material efficiency decision support tool is presented in Chapter 7. Hence, the casual relationships depicted in the decision support tool need to be validated with the actual scenario in the industry. Since this research is an exploratory research, there are limited decision support tools or guidelines that can be used as the benchmark to validate the findings of this research, especially to test the developed decision support tool. For this reason, the decision flow chart proposed by Bockstaller and Girardin (2003) and the validation measurements proposed by Mysiak *et al.* (2005) were merged and used to validate the decision support tool (refer to Section 3.6).

The validation procedure proposed in this research consists of three phases: (a) Design validation which is used to validate the logical coherence of the relationships between the change factors and material efficiency strategies, (b) Output validation which is used to compare the results obtained from the experts' inputs with those obtained from the decision support tool, and (c) End-user validation which is the user's assessment on the functionality and usefulness of the decision support tool.

A structured survey was established to evaluate the experts' opinions in making decision when selecting a material efficiency strategy (see Appendix L).The option of using an interview session was eliminated to avoid confusion in establishing the decision support tool. A field test was not chosen for this research because it is unsuitable and time-consuming. Thus, the results obtained from the industrial experts using survey questionnaire were validated and compared with the results generated from the decision support tool. The user's assessment of the decision support tool was also conducted with the industrial experts in order to obtain their feedback on the decision support tool. This feedback is important in order to make improvements to the decision support tool, if necessary. The assessment is based on the presentation, accuracy and consistency of the results, tool interface, and usability.

8.1 Validation Procedure

The validation procedure for the decision support tool is presented in this section. A structured process flow chart was used as a guideline for the validation process (Figure 8.1). As mentioned previously, the validation procedure consists of three phases:

1. Design validation: This phase involves determining the logical coherence of the relationships between the change factors (drivers, enablers and barriers) and material efficiency strategies.
2. Output validation: This phase involves comparing the responses given by the industrial experts with the results obtained from the decision support tool. This phase is also known as expert data verification.
3. End-use validation: This phase involves assessing the feedback obtained regarding the applicability, functionality and usability of the decision support tool.

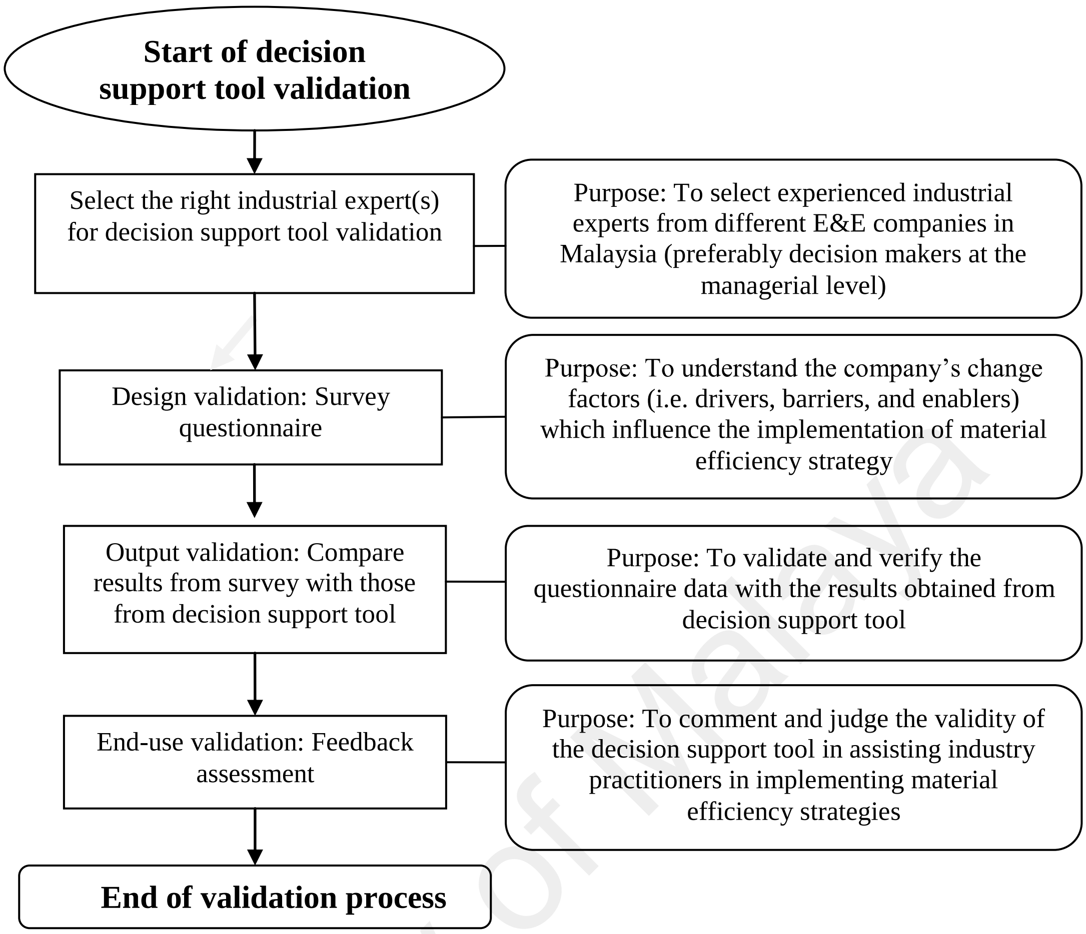

Figure 8.1: Flow chart of the validation procedure for the decision support tool

The decision framework used to select a suitable material efficiency strategy was presented during the design validation phase. The industrial experts were requested to comment on the decision framework created based on the data obtained from the E&E industry in Malaysia.

During the output validation phase, a structured questionnaire was developed, which consists of a complete list of the change factors and material efficiency strategies identified using the mixed research method. The questionnaire consists of four sections:

a. Section 1- Drivers to practise material efficiency strategies

b. Section 2- Enablers to practise material efficiency strategies

c. Section 3- Barriers to practise material efficiency strategies

d. Section 4- Implemented or proposed material efficiency strategies

For this survey, the industrial experts were required to select their preferred change factors for each section (drivers, enablers and barriers) according to their company's experience in practising material efficiency strategies. The results gathered from the survey were compared with those obtained from the decision support tool.

During the end-use validation phase, the industrial experts were requested to fill in the feedback form in order to obtain their feedback regarding the applicability, functionality and usability of the decision support tool. The interface of the decision support tool was also evaluated. This feedback is crucial in order to further improve the decision support tool.

8.2 Validation Process with Industrial Experts

Face-to-face validation was used for the validation process. Three E&E case companies were selected to validate the decision support tool. In order to prevent biases in the validation results, the selected experts are those who were not involved during the data collection phase. Three industrial experts from different E&E companies participated in the validation process. These industry experts are experienced managers with at least five years of experience working in their respective company. Expert A works as a production manager with six years of working experience in an E&E multi-national company in Malacca state. Expert A's primary responsibility is to improve productivity in order to ensure that the customers' orders fulfil the production lead time. Expert B works as a Lean manufacturing manager with five years of working experience. Expert B is working in a circuit design and assembly company in Johor, whose daily responsibility is to monitor and ensure that the operation of the production lines is optimum with minimum product scrap. Expert C works as a production manager, with six years of working experience in the quality assurance department.

Expert C's main responsibility is to ensure that the products fulfil the required specifications and comply with various international standards and legislation requirements. This expert is currently working in a computer component company in Johor. The survey results were analysed according to the three phases of validation and presented in different sections.

8.2.1 Validation Results of Expert A

In the first validation phase, Expert A agreed regarding the decision framework developed in this research is useful in selecting material efficiency strategies. Expert A commented: "*We need to consider these factors in our decision making to conduct any strategy including material efficiency strategy…".*

In the output validation phase, Expert A clarified that there are 10 organizational change factors which influence the company in implementing material efficiency strategies, whereby there are four drivers, two enablers and three barriers. Expert A highlighted that five material efficiency strategies are currently implemented in the company, namely, product light-weighting, material substitution, process efficiency, yield improvement and design for longer life. The details of the survey results are shown in Table 8.1. Table 8.2 shows the similarities and differences of the proposed material efficiency strategies and strategies generated by the decision support tool.

In the end-use validation phase, Expert A was requested to fill in the responses into the decision support tool for comparison purposes. The results showed that three out of five material efficiency strategies were selected as high priority strategies using the decision support tool: material substitution, product light-weighting and design for longer life. The ranking order of the material efficiency strategies is similar, especially for material substitution and product light-weighting (Figure 8.2).

The feedbacks assessment for the decision support tool given by Expert A is shown in Table 8.3. Expert A agreed that the decision methodology is highly flexible since it enables users to an overview of the potential material efficiency strategies that can be implemented in the company. In addition, the decision analysis model was rated as "very good" because Expert A agreed that this information is needed to implement a strategy. However, further improvement is needed in order to strengthen the manufacturing terms used as well as the informative level of the tool. The user interface and presentation of results of the decision support tool were both rated as "good".

Table 8.1: Data obtained from Expert A

Drivers of the company	Enablers of the company	Barriers of the company
Reducing production costs	Environmental awareness of the company's top management	Implementation costs
Reducing materials	Adoption of advanced technology	Different customer requirements
Fulfil customer requirements		Lack of information and knowledge
Fulfil international product designs		
Selected material efficiency strategies: Product light-weighting Material substitution Process efficiency Yield improvement Design for longer life		

	DRIVERS (D)													ENABLERS (E)			BARRIERS (B)										
Tick (√)	√	√				√	√								√	√		√		√		√					
Material efficiency strategy	Reducing production costs	Reducing materials	Reducing energy usage	Improve environmental image	Social responsibility	Customer requirements	Fulfil international product designs	Compliance with local environment legislation	Competition among rivals	Increase in price of raw materials	Supplier requirements	Support from other industries	Public pressure	ISO 14001 certification	Adoption of advanced technology	Environmental awareness of the company's top management	Company technological availability	Implementation costs	Restrictions in product design	Lack of information and knowledge	Lack of readiness to change	Customer requirements	Lack of external support	Regulation constraints	Suppliers and supply chains	$\sum MEFFi= D_i + E_i + B_i$	Rank of material efficiency strategy
Product light-weighting	.042	.038	.025	.016	.008	.056	.064	.043	.038	.028	.022	.015	.016	.024	.053	.024	.028	.032	.032	.024	.018	.021	.015	.021	.017	.354	**2**
Design for material recovery	.005	.012	.017	.016	.009	.043	.058	.048	.026	.021	.024	.019	.017	.025	.045	.019	.028	.031	.028	.023	.016	.035	.03	.027	.018	.271	**7**
Design for longer life	.007	.028	.016	.013	.009	.077	.055	.042	.038	.024	.022	.019	.014	.013	.046	.02	.037	.039	.036	.027	.014	.048	.03	.023	.016	.347	**3**
Design for multi-functionality	.04	.028	.009	.009	.002	.056	.053	.019	.021	.019	.016	.003	.002	.009	.013	.019	.032	.033	.025	.024	.016	.052	.021	.009	.007	.318	**4**
Material substitution	.042	.037	.023	.018	.01	.062	.071	.054	.038	.029	.024	.017	.015	.021	.043	.025	.031	.034	.032	.025	.016	.044	.026	.03	.023	.383	**1**
Purchasing of pre-manufactured parts	.044	.03	.019	.007	.002	.017	.022	.018	.025	.015	.014	.012	.002	.009	.022	.015	.03	.03	.028	.007	.007	.028	.016	.01	.012	.215	**9**
Yield improvement	.046	.032	.022	.004	.003	.02	.044	.038	.032	.03	.025	.019	.002	.008	.034	.022	.03	.027	.022	.023	.015	.018	.03	.013	.018	.266	**8**
Process efficiency	.047	.039	.026	.015	.002	.014	.043	.036	.032	.029	.02	.009	.006	.019	.047	.022	.033	.04	.025	.024	.015	.014	.016	.01	.014	.29	**6**
Green packaging	.012	.014	.004	.013	.008	.054	.048	.037	.03	.011	.019	.017	.014	.024	.047	.027	.032	.041	.028	.018	.014	.054	.025	.022	.021	.315	**5**

Figure 8.2: Results generated by the decision support tool based on the data provided by Expert A

Table 8.2: Output validation for Expert A

Rank	Selected material efficiency strategy	Total score in decision support tool	Priority order of material efficiency strategy
1	Material substitution	0.383	Material substitution
2	Product light-weighting	0.354	Product light-weighting
3	Process efficiency	0.347	Design for longer life
4	Yield improvement	0.318	Design for multi-functionality
5	Design for longer life	0.315	Green packaging
6		0.29	Process efficiency
7		0.271	Design for material recovery
8		0.266	Yield improvement
9		0.215	Purchasing of pre-manufactured parts

Table 8.3: Feedbacks given by Expert A regarding various aspects the decision support tool

Aspect	Very good	Good	Fair	Poor
User interface	( )	(√)	( )	( )
Graphical modelling approach	( )	(√)	( )	( )
Quality result estimation	( )	(√)	( )	( )
Flexibility	(√)	( )	( )	( )
Knowledge-based system	( )	(√)	( )	( )
Decision analysis model	(√)	( )	( )	( )
Presentation of results	( )	(√)	( )	( )
Manufacturing terms used	( )	( )	(√)	( )
Logical description	( )	(√)	( )	( )
Usefulness level	( )	(√)	( )	( )
Informative level	( )	( )	(√)	( )

8.2.2 Validation Results of Expert B

During the design validation phase, Expert B agreed regarding the analytical flow in implementing material efficiency strategies since this approach is similar to implementing other types of manufacturing strategies. Expert B remarked: "*Probably yes (material efficiency strategy framework), this is also our consideration for conducting different strategies*".

In the output validation phase, Expert B clarified that the change factors which influence the implementation of material efficiency strategies in the company comprise eight drivers, two enablers and seven barriers. Expert B also highlighted that six material efficiency strategies are implemented in the company. These data are summarized in Table 8.4. Based on the data provided by Expert B, it is found that the proposed list of material efficiency strategies differs from that generated by the decision support tool (Figure 8.3 and Table 8.5).

The feedbacks assessment of the decision support tool given by Expert B is given in Table 8.6. Flexibility and presentation of results were rated as "very good" whereas other aspects of the tool such as user interface, graphical modelling approach, quality result estimation, knowledge-based system, decision analysis model, logical description, usefulness level and informative level were rated as "good". However, a "fair" rating was given for the manufacturing terms used in the decision support tool since Expert B perceived that the terms were not clear. Expert B advised that simpler terms should be used in order to facilitate users in understanding the information given in the decision support tool. Expert B also remarked: "*For us, most of the strategies are important, as long as it is able to reduce our overhead cost. Probably we may need a tool like this in the future.*"

Table 8.4: Data obtained from Expert B

Drivers of the company	Enablers of the company	Barriers of the company
Reducing production costs	ISO 14001 certification	Company technological availability
Reducing materials	Adoption of advanced technology	Implementation costs
Reducing energy usage		Lack of information and knowledge
Fulfil customer requirements		Lack of readiness to change
Fulfil international product designs		Lack of external support
Competition among rivals		Regulation constraints
Increase in price of raw materials		Suppliers and supply chains
Support from other industries		
Selected material efficiency strategies: Product light-weighting Design for multi-functionality Purchasing of pre-manufactured parts Green packaging Material substitution Process efficiency		

	DRIVERS (D)													ENABLERS (E)			BARRIERS (B)										
Tick (√)	√	√	√			√	√		√	√		√		√		√	√	√		√	√		√	√	√		
Material efficiency strategy	Reducing production costs	Reducing materials	Reducing energy usage	Improve environmental image	Social responsibility	Customer requirements	Fulfil international product designs	Compliance with local environment legislation	Competition among rivals	Increase in price of raw materials	Supplier requirements	Support from other industries	Public pressure	ISO 14001 certification	Adoption of advanced technology	Environmental awareness of the company's top management	Company technological availability	Implementation costs	Restrictions in product design	Lack of information and knowledge	Lack of readiness to change	Customer requirements	Lack of external support	Regulation constraints	Suppliers and supply chains	$\sum MEFFi = D_i + E_i + B_i$	Rank of material efficiency strategy
Product light-weighting	.042	.038	.025	.016	.008	.056	.064	.043	.038	.028	.022	.015	.016	.024	.053	.024	.028	.032	.032	.024	.018	.021	.015	.021	.017	.509	2
Design for material recovery	.005	.012	.017	.016	.009	.043	.058	.048	.026	.021	.024	.019	.017	.025	.045	.019	.028	.031	.028	.023	.016	.035	.03	.027	.018	.418	6
Design for longer life	.007	.028	.016	.013	.009	.077	.055	.042	.038	.024	.022	.019	.014	.013	.046	.02	.037	.039	.036	.027	.014	.048	.03	.023	.016	.483	3
Design for multi-functionality	.04	.028	.009	.009	.002	.056	.053	.019	.021	.019	.016	.003	.002	.009	.013	.019	.032	.033	.025	.024	.016	.052	.021	.009	.007	.333	8
Material substitution	.042	.037	.023	.018	.01	.062	.071	.054	.038	.029	.024	.017	.015	.021	.043	.025	.031	.034	.032	.025	.016	.044	.026	.03	.023	.55	1
Purchasing of pre-manufactured parts	.044	.03	.019	.007	.002	.017	.022	.018	.025	.015	.014	.012	.002	.009	.022	.015	.03	.03	.028	.007	.007	.028	.016	.01	.012	.32	9
Yield improvement	.046	.032	.022	.004	.003	.02	.044	.038	.032	.03	.025	.019	.002	.008	.034	.022	.03	.027	.022	.023	.015	.018	.03	.013	.018	.431	5
Process efficiency	.047	.039	.026	.015	.002	.014	.043	.036	.032	.029	.02	.009	.006	.019	.047	.022	.033	.04	.025	.024	.015	.014	.016	.01	.014	.432	4
Green packaging	.012	.014	.004	.013	.008	.054	.048	.037	.03	.011	.019	.017	.014	.024	.047	.027	.032	.041	.028	.018	.014	.054	.025	.022	.021	.414	7

Figure 8.3: Results generated by the decision support tool based on the data provided by Expert B

Table 8.5: Output validation for Expert B

Rank	Selected material efficiency strategy	Total score in decision support tool	Priority order of material efficiency strategy
1	Product light-weighting	0.55	Material substitution
2	Design for multi-functionality	0.509	Product light-weighting
3	Purchasing of pre-manufactured parts	0.483	Design for longer life
4	Green packaging	0.432	Process efficiency
5	Material substitution	0.431	Yield improvement
6	Process efficiency	0.418	Design for material recovery
7		0.414	Green packaging
8		0.399	Design for multi-functionality
9		0.32	Purchasing of pre-manufactured parts

Table 8.6: Feedbacks given by Expert B regarding various aspects the decision support tool

Aspect	Very good	Good	Fair	Poor
User interface	( )	(√)	( )	( )
Graphical modelling approach	( )	(√)	( )	( )
Quality result estimation	( )	(√)	( )	( )
Flexibility	(√)	( )	( )	( )
Knowledge-based system	( )	(√)	( )	( )
Decision analysis model	( )	(√)	( )	( )
Presentation of results	(√)	( )	( )	( )
Manufacturing terms used	( )	( )	(√)	( )
Logical description	( )	(√)	( )	( )
Usefulness level	( )	(√)	( )	( )
Informative level	( )	(√)	( )	( )

8.2.3 Validation Results of Expert C

In the design validation phase, Expert C agreed with the decision framework developed in this research because the change factors cover most of the department needs in the company. Expert C commented: "*I agree (material efficiency framework) because it covers sales, design and production aspects.*"

In the output validation phase, Expert C confirmed that 12 change factors influence the implementation of material efficiency strategies in the company, consisting of six drivers, one enabler and five barriers. Expert C agreed that there is potential for the implementation of six material efficiency strategies in the company. These data are presented in Table 8.7.

The data given by Expert C were compared with the results obtained from the decision support tool and it is found that there is similarity in the results for five material efficiency strategies. However, the decision support tool gives a different priority order of the material efficiency strategies compared to the data given by Expert C (Figure 8.4 and Table 8.8).

Expert C agreed that the decision support tool is able to generate results instantly and it provides users with the flexibility to determine their company's capability in practising material efficiency strategies. Thus, this tool is considered highly useful to assist manufacturers in making a decision regarding the suitable material efficiency strategies. The feedbacks assessment of the decision support tool given by Expert C is presented in Table 8.9. It can be seen that the user interface and presentation of results were given a "fair" rating, indicating that these aspects require further improvement. Six aspects of the decision support tool were given a "good" rating, namely, decision analysis model, manufacturing terms used , quality result estimation, knowledge-based system, informative level and graphical modelling approach. Expert C commented: "*This tool is able to give us guidance, but most of the time, our considerations are whether our existing product design and production setting allow us to do so...*"

Table 8.7: Data obtained from Expert C

Drivers of the company	Enablers of the company	Barriers of the company
Reducing materials	ISO 14001 certification	Restrictions in product design
Reducing energy usage		Lack of information and knowledge
Improve environmental image		Lack of readiness to change
Fulfil customer requirements		Different customer requirements
Supplier requirements		Lack of external support
Fulfil international product designs		
Selected material efficiency strategies: Product light-weighting Material substitution Design for multi-functionality Process efficiency Design for longer life Design for material recovery		

	DRIVERS (D)													ENABLERS (E)			BARRIERS (B)										
Tick (√)		√	√	√		√	√			√				√					√	√	√	√	√				
Material efficiency strategy	Reducing production costs	Reducing materials	Reducing energy usage	Improve environmental image	Social responsibility	Customer requirements	Fulfil international product designs	Compliance with local environment legislation	Competition among rivals	Increase in price of raw materials	Supplier requirements	Support from other industries	Public pressure	ISO 14001 certification	Adoption of advanced technology	Environmental awareness of the company's top management	Company technological availability	Implementation costs	Restrictions in product design	Lack of information and knowledge	Lack of readiness to change	Customer requirements	Lack of external support	Regulation constraints	Suppliers and supply chains	$\sum MEFFi = D_i + E_i + B_i$	Rank of material efficiency strategy
Product light-weighting	.042	.038	.025	.016	.008	.056	.064	.043	.038	.028	.022	.015	.016	.024	.053	.024	.028	.032	.032	.024	.018	.021	.015	.021	.017	.355	3
Design for material recovery	.005	.012	.017	.016	.009	.043	.058	.048	.026	.021	.024	.019	.017	.025	.045	.019	.028	.031	.028	.023	.016	.035	.03	.027	.018	.327	4
Design for longer life	.007	.028	.016	.013	.009	.077	.055	.042	.038	.024	.022	.019	.014	.013	.046	.02	.037	.039	.036	.027	.014	.048	.03	.023	.016	.373	2
Design for multi-functionality	.04	.028	.009	.009	.002	.056	.053	.019	.021	.019	.016	.003	.002	.009	.013	.019	.032	.033	.025	.024	.016	.052	.021	.009	.007	.318	5
Material substitution	.042	.037	.023	.018	.01	.062	.071	.054	.038	.029	.024	.017	.015	.021	.043	.025	.031	.034	.032	.025	.016	.044	.026	.03	.023	.333	1
Purchasing of pre-manufactured parts	.044	.03	.019	.007	.002	.017	.022	.018	.025	.015	.014	.012	.002	.009	.022	.015	.03	.03	.028	.007	.007	.028	.016	.01	.012	.204	9
Yield improvement	.046	.032	.022	.004	.003	.02	.044	.038	.032	.03	.025	.019	.002	.008	.034	.022	.03	.027	.022	.023	.015	.018	.03	.013	.018	.263	8
Process efficiency	.047	.039	.026	.015	.002	.014	.043	.036	.032	.029	.02	.009	.006	.019	.047	.022	.033	.04	.025	.024	.015	.014	.016	.01	.014	.27	7
Green packaging	.012	.014	.004	.013	.008	.054	.048	.037	.03	.011	.019	.017	.014	.024	.047	.027	.032	.041	.028	.018	.014	.054	.025	.022	.021	.315	6

Figure 8.4: Results generated by the decision support tool based on the data provided by Expert C

Table 8.8: Output validation for Expert C

Rank	Selected material efficiency strategy	Total score in decision support tool	Priority order of material efficiency strategy
1	Product light-weighting	0.399	Material substitution
2	Design for multi-functionality	0.379	Design for longer life
3	Design for longer life	0.355	Product light-weighting
4	Design for material recovery	0.327	Design for material recovery
5	Material substitution	0.318	Design for multi-functionality
6	Process efficiency	0.315	Green packaging
7		0.27	Process efficiency
8		0.263	Yield improvement
9		0.204	Purchasing of pre-manufactured parts

Table 8.9: Feedbacks given by Expert C regarding various aspects the decision support tool

Aspect	Very good	Good	Fair	Poor
User interface	( )	( )	(√)	( )
Graphical modelling approach	( )	(√)	( )	( )
Quality result estimation	( )	(√)	( )	( )
Flexibility	(√)	( )	( )	( )
Knowledge-based system	( )	(√)	( )	( )
Decision analysis model	( )	(√)	( )	( )
Presentation of results	( )	( )	(√)	( )
Manufacturing terms used	( )	(√)	( )	( )
Logical description	(√)	( )	( )	( )
Usefulness level	(√)	( )	( )	( )
Informative level	( )	(√)	( )	( )

8.3 Improvements Made on the Decision Support Tool

According to industrial experts involved in the validation process, there are some terms used in the decision support tool that were not clear to them. Therefore, three manufacturing terms were revised in order to suit the manufacturing context in Malaysia. The revised terms are presented below.

a. Internal barrier- Lack of information and knowledge

In the internal barrier criteria, the term "Lack of information and knowledge" was unclear to the industrial experts. Expert 2 commented that this term should be more specific in the engineering context. Therefore, the term was changed to "Lack of technical information and knowledge", which suits the scope of this research since "knowledge" refers to knowledge regarding the materials, machinery and design.

b. External barrier- Different customer requirements

In the external barrier criteria, the term "different customer requirements" was also unclear to the industrial experts since a similar term was also used for external drivers. Hence, the experts proposed that this term should be more specific such as "Special customer requirements" in order to represent uncommon designs which will influence material savings, especially in the manufacturing process.

c. Enabler- Environmental awareness of the company's top management

In the enabler criteria, the term "environmental awareness of the company's top management" likely reflects only the top management of the company. However, in reality, Expert 2 felt that the term "environmental awareness of the company" is more appropriate to represent the current working environment because when all of the company's employees are aware of environmental protection, they can help reduce potential wastes during product design, acquisition of materials and processing of raw materials. The role of the top management in a company is to serve as the driving force to execute policies and ensure that all of the employees work as a team. The amended decision support tool is shown in Figure 8.5.

	DRIVERS (D)													ENABLERS (E)			BARRIERS (B)										
Tick (√)																										
Material efficiency strategy	**Reducing production costs**	**Reducing materials**	**Reducing energy usage**	**Improve environmental image**	**Social responsibility**	**Customer requirements**	**Fulfil international product designs**	**Compliance with local environment legislation**	**Competition among rivals**	**Increase in price of raw materials**	**Supplier requirements**	**Support from other industries**	**Public pressure**	**ISO14001 certification**	**Adoption of advanced technology**	**Environmental awareness of the company**	**Company technological availability**	**Implementation costs**	**Restrictions in product design**	**Lack of technical information and knowledge**	**Lack of readiness to change**	**Special customer requirements**	**Lack of external support**	**Regulation constraints**	**Suppliers and supply chains**	**$\sum MEFFi = D_i + E_i + B_i$**	**Rank of material efficiency strategy**
Product light-weighting	.042	.038	.025	.016	.008	.056	.064	.043	.038	.028	.022	.015	.016	.024	.053	.024	.028	.032	.032	.024	.018	.021	.015	.021	.017		
Design for material recovery	.005	.012	.017	.016	.009	.043	.058	.048	.026	.021	.024	.019	.017	.025	.045	.019	.028	.031	.028	.023	.016	.035	.03	.027	.018		
Design for longer life	.007	.028	.016	.013	.009	.077	.055	.042	.038	.024	.022	.019	.014	.013	.046	.02	.037	.039	.036	.027	.014	.048	.03	.023	.016		
Design for multi-functionality	.04	.028	.009	.009	.002	.056	.053	.019	.021	.019	.016	.003	.002	.009	.013	.019	.032	.033	.025	.024	.016	.052	.021	.009	.007		
Material substitution	.042	.037	.023	.018	.01	.062	.071	.054	.038	.029	.024	.017	.015	.021	.043	.025	.031	.034	.032	.025	.016	.044	.026	.03	.023		
Purchasing of pre-manufactured parts	.044	.03	.019	.007	.002	.017	.022	.018	.025	.015	.014	.012	.002	.009	.022	.015	.03	.03	.028	.007	.007	.028	.016	.01	.012		
Yield improvement	.046	.032	.022	.004	.003	.02	.044	.038	.032	.03	.025	.019	.002	.008	.034	.022	.03	.027	.022	.023	.015	.018	.03	.013	.018		
Process efficiency	.047	.039	.026	.015	.002	.014	.043	.036	.032	.029	.02	.009	.006	.019	.047	.022	.033	.04	.025	.024	.015	.014	.016	.01	.014		
Green packaging	.012	.014	.004	.013	.008	.054	.048	.037	.03	.011	.019	.017	.014	.024	.047	.027	.032	.041	.028	.018	.014	.054	.025	.022	.021		

Figure 8.5: Amended decision support tool based on expert's comment

8.4 Summary

Three industrial experts from selected E&E companies participated in the validation of decision support tool and the results are presented and discussed in this chapter. It is found that at present, the industrial experts have no clear guidelines on selecting suitable material efficiency strategies. However, they agreed that the decision framework developed in this research helps them in making decisions regarding the suitable material efficiency strategies to be implemented in their company.

Based on the responses provided by the industrial experts, it can be deduced that the organizational change factors and material efficiency strategies vary from one company to another. The material efficiency strategies commonly selected by the industrial experts are material substitution and process efficiency. The results gathered from the industrial experts were compared with those generated by the decision support tool and there is a difference in the material efficiency strategies selected as well as priority order of the strategies. This may be due to the following reasons:

i. The industrial experts may have a different understanding regarding the level of importance of the organizational change factors due to differences in their business needs and also product variants.
ii. The industrial experts are not familiar with the new approach in selecting material efficiency strategies, whereby most of the decisions are made based on their experiences.
iii. The industrial experts are unable to justify the ranking of the proposed material efficiency strategies

iv. The industrial experts only have a basic understanding on the proposed material efficiency strategies at the basic level or they may lack of knowledge on the material efficiency concept.

The industrial experts were requested to evaluate the decision support tool in terms of its usability, functionality and overall performance. All of three experts agreed that the decision support tool is a useful, flexible and dynamic tool, and the tool provides an overview of the suitable material efficiency strategies that can be implemented in the company based on the organizational change factors that are relevant to the company. However, the functionality and presentation of results of the tool need further improvement since it is less user-friendly. At present, the user needs to fill in the data and calculate the total score manually. Expert 1 suggested that the decision support tool should be more straightforward and easy to use. Hence, in future work, modifications can be made to the decision support tool in order to make it more user-friendly such that the results can be generated automatically. In addition, some of the manufacturing terms used in decision support tool were modified according to the experts' advice in order to make it more applicable for industrial users.

In general, there is positive feedback from the industrial experts regarding the decision support tool. This indicates that the decision support tool is reliable and industry validated decision support tool, particularly to be used as a tool to facilitate industry practitioners in making quick, sensible decisions regarding the suitable material efficiency strategies to be implemented in the company.

CHAPTER 9: CONCLUSIONS

9.0 Overview

The conclusions of this whole thesis are presented in this chapter. Firstly, the research problem is restated, followed by a brief description of the research methodology, summary of the key findings and discussion of the findings, as well as the contributions of this research. Lastly, some concluding remarks of this research are provided, along with the research limitations and recommendations for future research.

9.1 Research Summary

Based on the literature review, there is a critical need for conservation of resources in the manufacturing sector and this has led manufacturers to use their raw materials efficiently, including companies in the E&E industry in Malaysia. However, there are many factors which influence the implementation of material efficiency strategies and these factors are often interrelated and may vary depending on the country, type of sector and rapid changes in the market. Hence, implementing material efficiency strategies is a rather arduous task, particularly in selecting the suitable material efficiency strategies for the company.

In this research, a number of E&E companies in Peninsular Malaysia were chosen for case study and an exploratory investigation was conducted. This research was carried out based on the mixed research method (qualitative and quantitative), consisting of semi-structured interviews, followed by AHP pair-wise comparisons. In addition, a decision support tool was developed in this research in order to assist industry practitioners to select the suitable material efficiency strategies based on different organizational change factors. The key findings of this research are summarized as follows:

1. The investigated E&E companies in Malaysia are generally aware on the importance of implementing material efficiency strategies since this will help them reduce material usage and reduce the environmental impact of various industrial activities.
2. There are nine common material efficiency strategies implemented by the E&E companies in Malaysia.
3. There are three main change factor groups (i.e drivers, barriers and enablers) which influence the implementation of material efficiency strategies in the E&E industry in Malaysia.
4. The propositions between the organizational change factors and material efficiency strategies have also been determined in this research.
5. A decision support tool has been developed to analyse the influence of organizational change factors in selecting the appropriate material efficiency strategies.
6. The decision support tool conceptualizes the change factors in selecting the suitable material efficiency strategies. Furthermore, the decision support tool provides a better understanding on the link between the change factors and material efficiency strategies.

9.2 Revisiting the Research Objectives

In a nutshell, the objectives of this research are achieved. These research objectives are revisited in this chapter, as follows:

a. Research objective 1: To identify the material efficiency strategies currently implemented in the E&E industry in Malaysia.

The main research question that needs to be answered for this objective is*: What are the strategies currently implemented in manufacturing companies in*

Malaysia in order to achieve material efficiency? How? Why? The conclusion is derived as follows:

A total of nine material efficiency strategies were identified from the semi-structured interviews. These strategies are considered as the strategies commonly implemented in the E&E companies in Malaysia. These strategies encompass product design, manufacturing processes and packaging. These material efficiency strategies are product light-weighting, design for material recovery, design for longer life, design for multi-functionality, material substitution, purchasing of pre-manufactured parts, yield improvement, process efficiency and green packaging. The details of these strategies are presented in Chapter 4.

b. Research objective 2: To identify the significant change factors that influence the implementation of material efficiency strategies in the E&E industry in Malaysia.

The main research question that needs to be answered for this objective is*: What are the factors that influence the implementation of material efficiency strategies in E&E companies in Malaysia?* The conclusion derived is presented below:

A total of 25 change factors (i.e. internal drivers, external drivers, internal barriers, external barriers and enablers) were explored and determined using the semi-structured interviews. AHP approach was used to determine the importance level of the change factors which influence the selection of material efficiency strategies. Five internal drivers and eight external drivers were identified for the "Drivers" category, whereas five internal barriers and four external barriers were identified for the "Barriers" category. Lastly, three enablers were identified for the

"Enablers" category. The details of these change factors are provided in Chapter 4, Chapter 5 and Chapter 6.

c. Research objective 3: To develop a decision support tool which will aid the selection of material efficiency strategies

The findings obtained from the AHP were used to develop a decision support tool . The three groups of change factors (i.e. drivers, barriers and enablers) were used as the decision criteria in order to select the suitable material efficiency strategies. The selection of material efficiency strategies is based on the submission of the total influencing weight from the selected change factors. The details of the decision support tool and user guidelines are presented in Chapter 7.

d. Research objective 4: To validate the developed decision support tool using suitable case studies.

To answer this objective, three industrial experts from selected E&E companies were consulted to validate the decision support tool. The validation procedure consists of three stages: (a) Design validation, (b) Output validation, and (c) End-user validation. The results and feedback obtained from the validation process were used to improve the decision support tool. In general, feedbacks obtained from the industrial experts were positive, whereby they agreed that the decision support tool will facilitate them in choosing and implementing the appropriate material efficiency strategies. Several suggestions were also given to improve the decision support tool. The details of the validation process are presented in Chapter 8.

9.3 Contribution of the Research to the Existing Body of Knowledge

This research was carried out to obtain insights of the material efficiency practices in Malaysia, particularly in the E&E industry. The significant contributions of this research to new knowledge are described as follows:

Firstly, a list of criteria that is essential to the implementation of material efficiency strategies was determined based on the experience shared by representatives from selected E&E companies in Malaysia. These criteria consist of the current material efficiency strategies practised in the E&E industry, as well as the organizational change factors that influence the implementation of material efficiency strategies. These insights are important to explain “what” are the factors that drive the E&E companies to practise material efficiency strategies, and “how” these change factors link to different material efficiency strategies. In addition, based on the findings, it is confirmed that the change factors that influence the implementation of material efficiency strategies are different, depending on the manufacturing sector. For example, E&E industry is mainly influence by external factors which consist of international regulations, rapid change markets requirements, and the supply chain of green materials. This fulfils Research Gap 1.

Secondly, the findings of this research offer a new perspective in analysing the implementation of material efficiency strategies. In this research, the implementation of material efficiency strategies is analysed based on organizational change factors, which may vary from one company to another. The link between the change factors and material efficiency strategies is indeed clarified in this research. Thus, the change factors and material efficiency strategies were conceptualized in this research, which provides a theoretical explanation on the decision to practise material efficiency strategies. This fulfils Research Gap 2.

Thirdly, the research findings were used to conceptualize an integrated decision methodology to practise material efficiency strategies. The decision methodology is based on the combination of change factors that is a specific to a particular company, which improves the selection of suitable material efficiency strategies for that company. This integrated decision methodology (taking into account multiple dimensions of factors) improves the comprehensiveness of the existing decision theory or model to practise environmental strategies. The findings of this research also improve the existing environmental strategy framework, which is only driven by a single dimension of the change factor. This fulfils Research Gap 3.

Lastly**,** the model developed in this research used to select the suitable material efficiency strategies can be conceptualized and applied to other similar industries. This will make the implementation of material efficiency strategies become more robust, in line with the market changes and business needs, and provide a clearer link and direction between the organization and the strategies implemented.

9.4 Contribution of the Research to Practitioners

In this research, a decision support tool to select the suitable material efficiency strategies was developed based on the insights obtained from E&E companies in Malaysia. The decision support tool is an extended output from the theoretical findings. The contributions of this tool to practitioners are presented below:

1. The decision support tool could assist the industry practitioners in the decision-making process, particularly, in deciding the most appropriate choice of material efficiency strategy.
2. The decision support tool helps in gaining a better understanding on the concept of practicing material efficiency strategies based on the combination of change factors.
3. The decision support tool will enable manufacturers to expand or switch to different material efficiency strategies since the change factors can be selected by the user. Hence, this tool provides flexibility to the user.
4. The decision support tool is a new methodology that can facilitate the business orientation, since it provides the trade-offs for different organizational change factors.

9.5 Limitations of the Research

Several limitations of this research have been identified, which require further improvement:

a. In this study, the mixed research method was used to capture the current scenario of material efficiency practices of E&E companies in Malaysia. Even though the data obtained in this research were rich to develop a comprehensive decision support tool, but the theory regarding the implementation of material efficiency strategies cannot be generalized.
b. In addition, this research is only limited to the organizational change factors and material efficiency strategies currently practised in E&E companies in Malaysia. However, the research findings may be influenced by other data related to the industry, which were excluded from the investigation. This includes reports on industrial scrap, material purchase records, production

changeover statistics, and governmental environmental policies adopted by a particular company.

c. Moreover, this research is only focused on E&E companies. Thus, the results cannot be compared with those for other manufacturing companies such as steel manufacturers and furniture manufacturers.

d. The uncertain or vagueness of the data nature due to rapid change in the market demands could influence the quality of obtained data and analysis conducted.

9.6 Directions for Future Research

Based on the limitations of this research, several suggestions were made for future research, which are listed as follows:

a. Comprehensive quantitative research

This research is primarily focused on case study investigation of E&E companies in Malaysia. Hence, there is a critical need to quantify the relationship between the decision criteria and material efficiency strategies using quantitative methods. By having quantitative analysis with a large number of respondents, this will help in generalizing the theory regarding the influence of organizational change factors on the selection of material efficiency strategies. The findings presented in this thesis can be used as the groundwork for other researchers to conduct a comprehensive quantitative study. The statistical results obtained from the quantitative study can be used to strengthen the theory regarding the decision criteria and the implementation of material efficiency strategies.

b. Incorporating more industrial related statistical data/ report

This study was conducted using semi-structured interviews and AHP survey. Incorporating more real time data or the statistical records of the company will help strengthen the findings of this research. These data include data on industrial scrap, material purchase records, production changeover statistics and governmental environmental policies, which can be used to increase the validity of the research findings. The inclusion of industrial-related data will give a more realistic perspective on the implementation of material efficiency strategies in Malaysia.

c. Comparative study

Comparative study is an interesting topic for investigation since it allows more interesting findings to be extracted by involving more participants from various types of industries. Therefore, by carrying out a comparative study, the uniqueness and intention of different companies in practising material efficiency strategies can be extracted and understood in detail. In addition, by involving other types of industries in future research, this will help increase the "know-how" in practising material efficiency strategies. The findings can be used to further develop the concept of material efficiency practices in Malaysia according to different industrial sectors.

d. Incorporate artificial intelligent approach in data analysis

Incorporate soft computing approach or artificial intelligent is important especially to deal with many uncertainties encountered during the data collection. Therefore, enhancing the conventional qualitative or quantitative method is required such as integrating with fuzzy logic set theory or neural network concept could help in better control of the uncertain input from the experts.

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