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A FRAMEWORK FOR THE SUSTAINABILITY EVALUATION OF PRODUCT CONFIGURATION DESIGN

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
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To my parents, my wife Syarfa' Zahirah Sapuan and beloved sons,
Muhammad Faris and Muhammad Fayyadh,
for their love and support

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ABSTRACT

Sustainable development has taken its place in product design as something that needs to be achieved nowadays, not only to generate profits, meet consumers' needs, and reduce adverse impacts on the environment, but in consideration of all economic, societal, and environmental aspects, known as the triple bottom line (TBL), over the entire product life cycle. Numerous approaches to sustainable product design have been introduced by integrating sustainability considerations during the preliminary design phase. However, most of them neglect either one of the TBL aspects, do not cover the entire product life cycle, and have difficulty in selecting the best design alternative. Additionally, none of them considers sustainability evaluation as one of the criteria in the configuration design phase. In this study, a framework for selecting the most sustainable alternative configuration design of a part was proposed to assist product designers in decision-making. The proposed framework has been basically developed in two main phases, the first of which presents a new decision tool named the Product Sustainability Evaluation Tool (ProSET) to support the proposed framework, and the second phase encompasses the configuration design process. ProSET provides an indicator called the Weighted Sustainability Score (WSS) for each evaluated alternative configuration design of a part to allow for a quick response and time saving during the decision-making process. The Analytic Hierarchy Process (AHP) and Artificial Neural Network (ANN) were applied in ProSET to provide weighting factors and estimate the WSS. Several case studies were conducted involving discrete products to comprehensively demonstrate the application of the proposed framework. Based on the results of sustainability performance evaluation of an armchair by ProSET, the alternative part with the highest WSS among its competitors for each basic element of the armchair has been selected to be a complete product. The results were also compared with commercial software to validate the accuracy of the analysis. From the comparison, it was summarised that both results show a degree of similarity in order to efficiently select the best alternative part configuration design with regard to environmental considerations. Hence, it is suggested that the proposed framework and the capability of ProSET can be easily adopted into the working environment of product designers.

ABSTRAK

Pembangunan lestari telah mengambil tempat dalam reka bentuk produk sebagai sesuatu yang perlu dicapai pada masa kini, bukan sahaja untuk menjana keuntungan, memenuhi keperluan pengguna, dan mengurangkan kesan buruk kepada alam sekitar, tetapi perlu mengambil kira semua aspek ekonomi, sosial, dan alam sekitar yang dikenali sebagai *'triple bottom line'* (TBL), sepanjang kitaran hayat produk tersebut. Banyak pendekatan untuk reka bentuk produk yang lestari telah diperkenalkan dengan mengintegrasikan pertimbangan kelestarian semasa dalam fasa reka bentuk awal. Walau bagaimanapun, kebanyakan mereka mengabaikan salah satu aspek TBL, tidak meliputi kitaran hayat produk, dan mempunyai kesukaran untuk memilih reka bentuk alternatif yang terbaik. Sebagai tambahan, tiada pendekatan yang diperkenalkan untuk mengambilkira penilaian kelestarian sebagai salah satu kriteria dalam fasa reka bentuk konfigurasi. Dalam kajian ini, satu rangka kerja untuk memilih reka bentuk konfigurasi alternatif yang paling lestari untuk sesuatu bahagian produk adalah dicadangkan untuk membantu pereka bentuk produk dalam membuat keputusan. Rangka kerja yang dicadangkan telah dibangunkan dalam dua fasa utama, di mana fasa satu membentangkan alat membuat keputusan bernama Alat Penilaian Kelestarian Produk (*Product Sustainability Evaluation Tool* - ProSET), dan fasa kedua merangkumi proses reka bentuk konfigurasi. ProSET menyediakan penunjuk yang dikenali sebagai Skor Kelestarian Berpemberat (*Weighted Sustainability Score* - WSS) bagi setiap reka bentuk konfigurasi bahagian produk yang dinilai. Proses Hierarki Analisis (*Analytic Hierarchy Process* - AHP) dan Rangkaian Neural Buatan (*Artificial Neural Network* - ANN) digunakan dalam ProSET untuk menyediakan faktor pemberat dan menganggarkan WSS. Beberapa kajian kes telah dijalankan secara komprehensif untuk menunjukkan penggunaan rangka kerja yang dicadangkan. Berdasarkan keputusan penilaian prestasi lestari oleh ProSET untuk kerusi, bahagian alternatif yang mempunyai WSS yang tertinggi di kalangan pesaingnya untuk setiap elemen asas kerusi telah dipilih untuk menjadi produk yang lengkap. Keputusan yang diperolehi juga dibandingkan dengan perisian komersial untuk mengesahkan ketepatan analisis. Daripada perbandingan tersebut, adalah dirumuskan bahawa kedua-dua keputusan menunjukkan tahap persamaan untuk memilih alternatif reka bentuk konfigurasi yang terbaik dengan mengambil kira pertimbangan kelestarian. Oleh itu, adalah dirumuskan bahawa rangka kerja yang dicadangkan dan ProSET boleh diadaptasikan ke dalam persekitaran kerja pereka bentuk produk.

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LIST OF ABBREVIATION

AHP	-	Analytic Hierarchy Process
ANN	-	Artificial Neural Network
ANP	-	Analytic Network Process
BOM	-	Bill of materials
BPNN	-	Backpropagation Neural Network
CAD	-	Computer aided design
CAE	-	Computer aided engineering
CAS	-	Computer aided styling
CES	-	Cambridge Engineering Selector
CI	-	Consistency index
CO_2	-	Carbon dioxide
CR	-	Consistency ratio
DfA	-	Design for Assembly
DfD	-	Design for Disassembly
DfE	-	Design for the Environment
DfM	-	Design for Manufacture
DfMa	-	Design for Maintainability
DfQ	-	Design for Quality
DfR	-	Design for Recyclability
DfRe	-	Design for Reliability
DL	-	Digital Logic
DKH	-	Design knowledge hierarchy
DTT	-	Distance to Target
Eco-QFD	-	Eco-Quality Function Deployment
ECQFD	-	Environmentally Conscious Quality Function Deployment
EDRG	-	Engineering Design Research Group
EPA	-	Environmental Protection Agency

EPI	-	Elimination Preference Index
FIM	-	Function impact matrix
FMEA	-	Failure Modes and Effects Analysis
g	-	gram
GUI	-	Graphic user interface
HIPS	-	High Impact Polystyrene
HoQ	-	House of Quality
HoS	-	House of Sustainability
IPP	-	Integrated Product Policy
ISM	-	Institute for Sustainable Manufacturing
kg	-	Kilogram
kWh	-	Kilo watt .hour
LCA	-	Life Cycle Assessment
LCC	-	Life Cycle Costing
LCSA	-	Life Cycle Sustainability Assessment
MCDM	-	Multi-criteria decision-making
m	-	Meter
m^2	-	Meter square
m^3	-	Meter per cube
mg	-	Miligram
MF	-	Manufacturing
MJ	-	Megajoule
PM	-	Pre-manufacturing
PO_4	-	Phosphate
PP	-	Polypropylene
PS	-	Polystyrene
PW	-	Plywood
ProdSI	-	Product Sustainability Index
ProSET	-	Product Sustainability Evaluation Tool
PSI	-	Product Sustainability Index
PU	-	Post-use
QFD	-	Quality Function Deployment
QFDE	-	Quality Function Deployment for Environment
RI	-	Random consistency ratio

RM	-	Ringgit Malaysia
RoHS	-	Restriction of the use of certain Hazardous Substances
SCAMPER	-	substitute, combine, adapt, magnify or minify, eliminate or elaborate, and rearrange or reverse
SLCA	-	Social Life Cycle Assessment
SO_4	-	Sulfur dioxide
SPCS	-	Sustainable product conceptualisation system
STM	-	Sustainability Target Method
TBL	-	Triple bottom line
TRIZ	-	Theory of Inventive Problem Solving
U.S.	-	United State
US	-	Use
UTHM	-	Universiti Tun Hussein Onn Malaysia
WEEE	-	Waste Electrical and Electronic Equipment
WSS	-	Weighted Sustainability Score

LIST OF SYMBOLS

λ_{max}	-	Maximum eigenvalue
V_{new}	-	Value of normalisation data
V_{old}	-	Value before normalisation
Max	-	Maximum value of the variables
Min	-	Minimum value of the variables
D_{max}	-	Maximum value after normalisation
D_{min}	-	Minimum value after normalisation
N_h	-	Number of neurons in hidden layers
N_{input}	-	Number of neurons in input layer
N_{output}	-	Number of neurons in output layer
η	-	Learning rate
Net_i	-	Output of neuron i
w_{ij}	-	Weight on connection from neuron i to j
x_i	-	Input to neuron j
θ_j	-	The bias on neuron j
δ_j	-	The error on neuron j (output)
t_j	-	The target value of neuron j
O_j	-	The ouput of neuron j
δ_k	-	The error on neuron k (hidden layer)
w_{kj}	-	The weight on connection from neuron k to j
Δw_{ij}	-	The weight changes on connection from neuron i to j
O_i	-	The output of neuron i
α	-	The momentum coefficient

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

In recent years, trends in the worldwide industrial product development process have been changed dramatically in order to produce successful products based on customer needs (Russo, 2011). The basic process of product development has never changed but the way in which to make successful products that meet customer demands with regards to the current trend is the most challenging and critical issue. Some of the key factors highlighted to develop successful new products include maintaining excellent quality in comparison to the competitors, meeting consumers' needs along with unique features, developing a comprehensive understanding of the nature of the market, and developing a relationship between product attributes and consumers' needs (Mital *et al.*, 2008).

1.1.1 Evolution of Product Design

Traditionally, product design has played an important role in the product development process of products for various purposes and can be approached in many different ways, which are evolving over time. Before the twenty-first century, most of the systematic approaches to the study of design issues in product design were focussed on performance, such as aesthetic and functional performance, as well as ergonomics, production and cost, regulatory and legal constraints, marketing programmes, and designers goals, as shown in Figure 1.1. Dowlatshahi (1993) applied concept of concurrent engineering for the consideration of product design attributes includes ergonomics, interchangeability, aesthetics, durability, manufacturability, procurability, maintainability, reliability, remanufacturability, safety, simplicity, testability, schedulability, serviceability, transportability and marketability in the preliminary stages of product design.

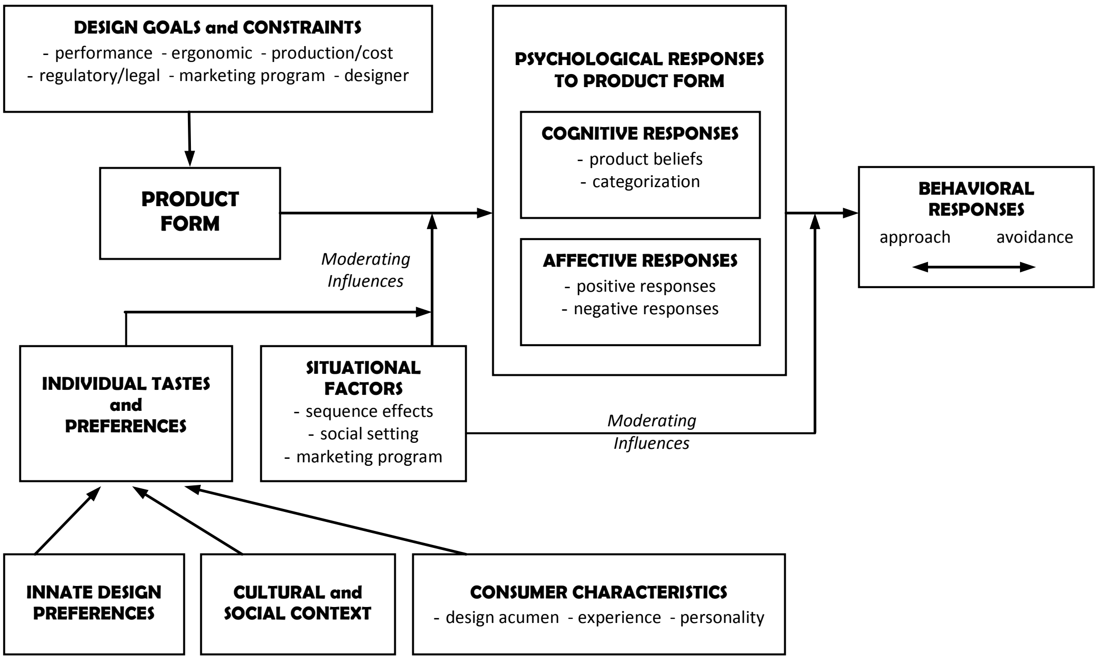

Figure 1.1 A model of consumer responses to product design (Bloch, 1995)

At the beginning of the twenty-first century, product design moved to a customer-oriented approach that considers aspects such as consumer preferences, colours, textures, and interfaces (Hsiao *et al.*, 2010). In addition, product design has to consider environmental issues as a strategy to reduce environmental impacts of products during their entire life cycle (Zwolinski *et al.*, 2006). This effort is due to the fact that many products through their life cycle cause major environmental problems all over the world (Lee, 2002).

Bras (1997) described several factors motivating designers and manufacturers to become more environmentally responsible, such as legislation (the US Clean Air Act to reduce the use of a number of materials, and European take-back legislation to encourage design for recycling efforts), customer demand (customers will pay more for a green product), eco-labelling programmes (products with an eco-label have a competitive advantage), and ISO 14000 (environmental management standards; certification can be a crucial element in doing business).

In the twenty-first century, society is confronted by a number of sustainability challenges due to global climate change, decreasing natural resources, persistent organic pollutants, freshwater contamination, ecosystem degradation, biodiversity loss, overpopulation, and limited access to basic human necessities, particularly in developing countries (Keoleian and Spitzley, 2006). Directly or indirectly, the life cycle of a product impacts the environment in terms of energy and material use (Krishnan *et al.*, 2013). Manufacturers are becoming increasingly concerned about the issue of product sustainability, which makes sustainable development a key objective in human development (Rosen and Kishawy, 2012). Clark *et al.* (2009) stated that sustainable design is not necessarily about new technologies, but about rethinking how to meet the need for growth while at the same time reducing negative environmental and societal impacts. Thus, sustainable development has manifested itself in product design as a need to produce more sustainability-oriented products.

1.1.2 Product Design Towards Sustainable Development

Product design is identified as a strategic tool to be incorporated into sustainability solutions (Yang, 2005). Product design is responsible for designing profitable products, eco-design is a term for strategies that aim to integrate the environmental aspect, and sustainable product design is more than eco-design, as it integrates the social aspect of the product's life cycle along with consideration of environmental and economic aspects called the triple bottom line (TBL) (Charter and Tischner, 2001). This strategy makes product design as an important element to be concerned in the creation of products for achieving sustainable development (Figure 1.2).

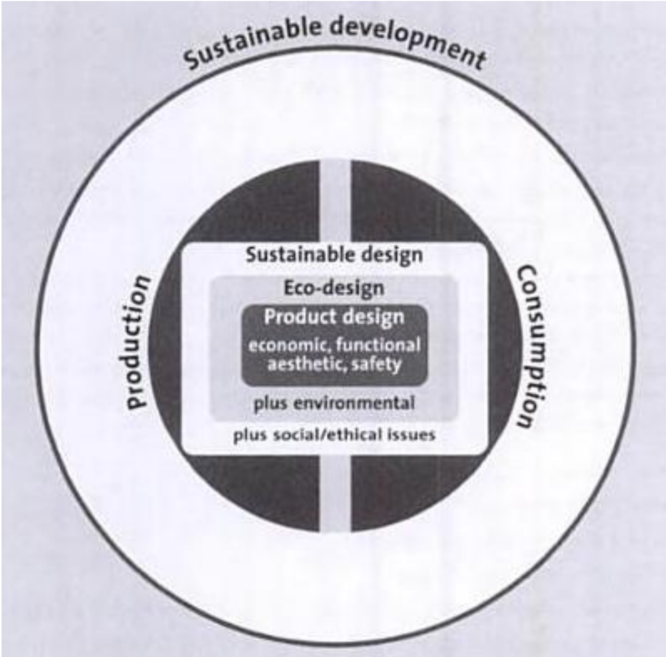

Figure 1.2 Product design as a strategy for sustainable development (Charter and Tischner, 2001)

Sustainable product design is about implementation of sustainability considerations at the early stage of new product development in order to produce a sustainable product. Kengpol and Boonkanit (2011) and Boks (2006) concluded that integrating sustainable aspects into the product development process is an aspect of legal frameworks currently in place in various regions of the world. In the European Union, for instance, there is the Waste Electrical and Electronic Equipment (WEEE) Directive, the Integrated Product Policy (IPP), and the Restriction of the use of certain Hazardous Substances in electrical and electronic equipment (RoHS), and in Japan there is the Home Appliance Recycling Law.

Basically, the sustainability consideration is integrated with the engineering design tool using a systematic approach before it is incorporated into the process of design. This integration is known as support tools and methods since it will be used to support the development of a product with regard to a set of criteria needed to achieve design goals within defined constraints. Making a product sustainable is based on the balance and integration of environmental, economic, and societal aspects, as illustrated in Figure 1.3.

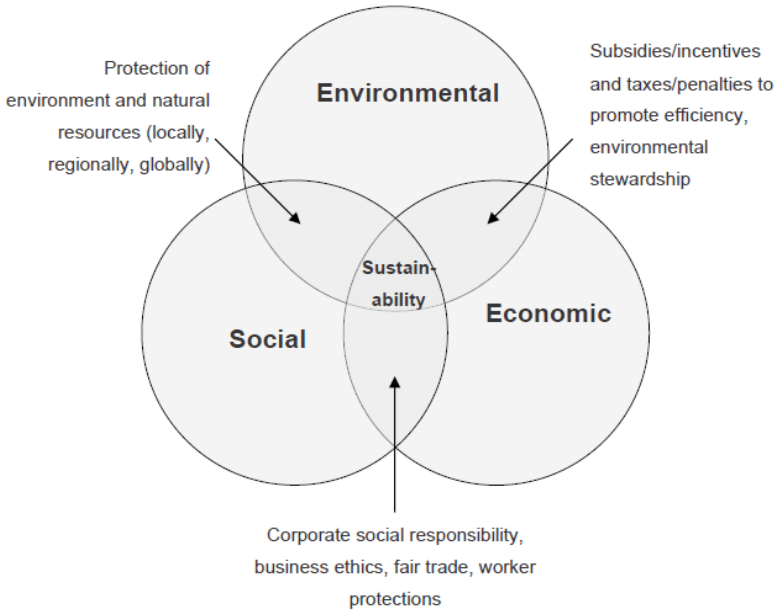

Figure 1.3 Sustainability as the intersection of the three major elements, and the intersection of any two parts (Rosen and Kishawy, 2012)

Generally, essential stages of the design process include formulating (establishing functional requirements, determining constraints, and setting performance targets), generating (creating alternative designs in terms of shape, configuration, size, materials, and manufacturing processes), analysing (predicting the performance of a design candidate), and evaluating (comparing the predicted performance of all feasible design candidates) in order to select the best design alternative for the manufacturing phase (Eggert, 2005). The incorporation of a systematic approach into the essential stages of the design process is another thing that should be concerned. Consequently, the systematic approach has become more challenging and complex.

Clearly, product design are responsible for the whole process of producing a sustainable product towards sustainable development by incorporating the support tools and methods that integrate the engineering design tool and sustainability considerations using a systematic approach in the essential stages of the design process. Hence, an approach for translating these situations from fundamentals to applications for sustainable product design is the best solution in order to manage systematically the process of producing sustainable products.

1.2 Problem Definition

Recently, achieving sustainability goals in discrete products is a major concern of research that is adopted in the working environment of product designers all over the world. Since integrating sustainability considerations in designing and manufacturing new products has become a priority for researchers and industries, the need to develop new models to quantify all the sustainability aspects, has became a major issue (Ungureanu, 2007). Sustainable product design is a viable solution where sustainable products can be produced. To examine the sustainability of a product along its entire life cycle makes the goal of producing a sustainable product a rather complex and difficult process (Lindow *et al.*, 2013). This is due to the fact that in order to assess a newly designed product, the sustainability aspects need to be considered and final decision has to be made where the selected designed product is verified for better sustainability performance than the other competitors. Therefore, a systematic approach is important for indicating the sustainability of a newly designed product with regard to the consideration of environmental, economic, and societal aspects through its life cycle, so that the selection of the final designed product for the manufacture phase is much more meaningful and valuable. Comprehensive sustainability evaluation of designed products is required in situations where the level of sustainability of the design alternatives can be estimated, and the design alternative with the most sustainability is the winner. However, Lindow *et al.* (2013) concluded in their research that it is very difficult to estimate in terms of certain technical parameters and characteristics of the products or systems that are directly associated with specific sustainability criteria.

It is believed that the approach will be the most important thing to be tackled and proposed in this study. In addition, the approach will devise strategies by anticipating the end-of-life options of the newly designed products. These strategies may increase the product value and benefits in the future. However, implementing the concept of sustainability into the process of design is no easy task since there are no standard requirements for sustainable product design. According to Jawahir *et al.* (2006), there are a number of measurable methods to assess the environmental aspect of sustainability such as Life Cycle Assessment (LCA) method where the environmental impacts of a product system is evaluated, but there is no universally accepted method to quantify all the aspects of product sustainability.

Configuration design is one of the three main phases of preliminary design after conceptual design and before parametric design, and it is an essential part of the entire product development activity. This phase can be integrated with the concept of sustainability and deserves further investigation. It includes the evaluation of a group of newly designed parts with regard to the sustainability criteria, the selection of the designed part based on sustainability performance, and the combination of the selected designed part into a complete product while satisfying sustainability requirements and constraints. In this case, product designers or decision makers will play an important role in achieving the design goal of the products based on their knowledge. However, they basically do not have sufficient knowledge to evaluate the sustainability of a product (Lindow *et al.*, 2013) and have only a little knowledge of feasible configurations with regard to the sustainability measurement of multiple criteria. This is due to evaluate and select the feasible configurations of a product needs an appropriate design tool that enable to support the evaluation and selection process with an accurate data of analysis. Furthermore, each part of a product contains several possible alternative configuration designs which make the evaluation and selection more complex.

Therefore, a comprehensive framework of the configuration design phase is clearly needed to enable product designers to design and produce sustainable products, and it will be the main objective in this study. Research based on this problem will be investigated to determine the best solution.

1.3 Research Questions

The research questions of this study are as follows:

i. How can relationships be established between product components and sustainability criteria?

ii. Is it possible to evaluate a product component with regard to sustainability criteria based on qualitative and quantitative measurement?

iii. How can the sustainability of different alternative configuration designs be estimated?

iv. How can the developed design methodology assist product designers in decision making?

1.4 Objectives and Scope of the Study

The overall aim of the research is to develop and demonstrate a framework for sustainable product design during the configuration design phase. The specific objectives of the research are:

i. To develop a framework for the sustainability evaluation of product configuration design that will enable product designers to select the most sustainable alternative configuration designs of a part.

ii. To develop a decision support tool to support the framework in the evaluation of product sustainability and to estimate the sustainability score for each alternative configuration design of a part.

iii. To validate the practicality and the effectiveness of the framework using case studies.

The scopes of the study are as follows:

i. The target product is referring to a discrete product. In this study, the target products for the case studies are identified based on industrial products where the use of the products is significance to customers or users.

ii. Focussing on sustainability performance evaluation for a newly designed product in the configuration design phase.

iii. Using morphological analysis theory to generate alternative configuration designs of a part, Analytic Hierarchy Process for weighting the sustainability performance, and Artificial Neural Network (ANN) to estimate the sustainability score for alternative configuration designs of a part.

1.5 Research Methodology

The research methodology is to perform the research activities as planned in order to achieve the research aim along with the research objectives and scopes. In relation to that, the summary of the research methodology is structured as shown in Figure 1.4.

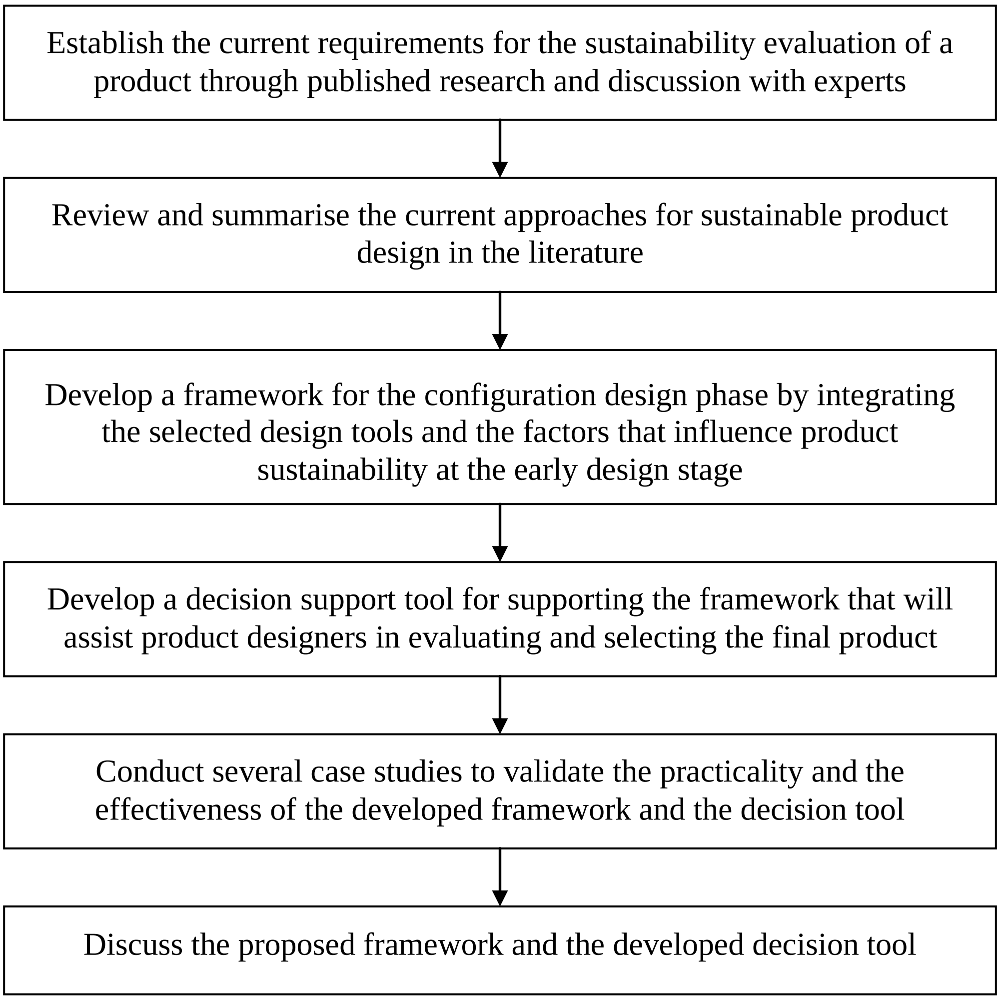

Figure 1.4 Summary of the research methodology

1.6 Significances of the Research

The significances of the current study are as follows:

i. The developed framework and decision support tool can be used by product designers in decision making to produce successful products directly from a design platform by considering sustainability evaluation as one of the criteria in the configuration design phase.

ii. The developed framework and decision support tool are novel and can be alternative solution for estimating the sustainability of different product designs in terms of their configuration, material, and method of manufacture.

iii. The developed framework and decision tool may assist product designers or decision makers in selecting the final product efficiently for the manufacturing phase based on sustainability performance evaluation using a small amount of product information and quick response analysis, and in saving time over the current approaches involving variety in prices and complexity at the end of the design process.

iv. The research is intended to become one of the ways in which the worldwide industrial product development process can meet the current demand for product design that creates a product based on sustainability considerations and has positive environmental, economic, and societal impacts as well.

1.7 Structure of the Thesis

This thesis consists of seven chapters. Each of the chapter is briefly described as follows:

Chapter 1 presents the background of the study, problem definition, research questions, objective and scope of the study, research methodology, and significances of the study. Meanwhile, Chapter 2 describes the engineering design process and the concept of sustainability in product development strategies. This chapter also presents the latest literature reviews of existing support tools and methods by the other researchers for sustainable product design and are analysed for comparison in order to find gaps for further investigation.

Chapter 3 elaborates several topics related to sustainable product design, such as the concept of product sustainability evaluation and product sustainability metrics.

Furthermore, the concept of decision matrix, morphological analysis theory, analytic hierarchy process, and artificial neural network approach as the proposed platform to the concept of product sustainability evaluation are also discussed in this chapter.

Chapter 4 discusses the development of the framework. This chapter presents a detail overview of the framework by illustrating a step-by-step approach and the use of a morphological analysis method. Chapter 5 presents the result of the proposed methodology where a decision support tool is developed to support the framework methodology. Several design tools is presented such as an analytic hierarchical process and artificial neural network in the decision matrix platform for the development of sustainability evaluation model.

Chapter 6 presents the application of the proposed framework and developed decision support tool on several case studies to analyse the sustainability performance of alternative part configuration designs of a product. Besides that, this chapter provides the whole view of the research including the review of achievements and as well as the limitation. Lastly, the Chapter 7 provides a summary of the main research outcomes of this thesis and recommendations for future work.

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