UNIVERSITI PUTRA MALAYSIA

CONCEPTUAL DESIGN AND LIFE CYCLE ASSESSMENT OF NATURAL FIBRE-REINFORCED BIOPOLYMER COMPOSITES TAKEOUT FOOD CONTAINER USING CONCURRENT ENGINEERING

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Chairman : Professor Mohd Sapuan Salit, PhD, P.Eng
Institute : Tropical Forestry and Forest Products

Almost all municipal solid waste (MSW) collected go to landfills instead of being recycled where packaging has a big portion and mostly are contributed by food packaging. In this thesis, a product design and development process of a fully biodegradable and biobased takeout food container utilizing natural fibre reinforced biopolymer composite was carried out with the essence of design for sustainability (DFS). The overall process incorporates the principle of concurrent engineering (CE) which include materials selection of natural fibre and biopolymer matrix, concept design generation and selection of final design, and Life Cycle Assessment (LCA) of the new takeout food container design. Seven (7) key elements of product design specification (PDS) were considered based on market investigation. The evaluation and selection of natural fibre as reinforcement in the biopolymer composite was carried out by developing a decision-support model based on Analytic Hierarchy Process (AHP). The results indicated that ijuk or sugar palm fibre obtained the highest priority (14%) from the nine (9) natural fibre alternatives. The results were further verified by a sensitivity analysis where sugar palm fibre remained at the top rank for four (4) of six (6) conditions tested. Concurrently, selection of the biopolymer matrix was performed, and the biopolymer alternatives studied were limited only to starch biopolymers because of its significant global production growth for bioplastics. The method applied was Shannon's entropy integrated with AHP and Experts Choice software. From the six (6) starch alternatives, Sago starch was at the top rank with the score of 26.8% and verified by a sensitivity analysis. In parallel to the materials selection process, the design concept development and selection of the final takeout food container concept design were completed using combination of the Kano model, Quality Function Deployment for Environment (QFDE), and AHP where the Kano model was utilized to understand customers satisfaction as the key features of the new takeout food container design and incorporated in the House of Quality (HOQ) in QFDE.

The HOQ results were the design parameters, and to develop the concept designs systematically, morphological chart (MC) was applied. Nineteen (19) concept design ideas were generated, and the final design was selected using AHP. Concept design 18 (CD18) obtained the highest score of 8.3%, a rectangular clamshell type with I-rib on wall and bottom of container base and locking structure of latching (male-female) at four corners. Lastly, the new design takeout food container was assessed by attributional Life Cycle Assessment (LCA) using SimaPro software. The results showed that the new concept of takeout food container produced a total impact of 2.63×10^{-5} DALY for the Human Heath Damage, 9.46×10^{-8} species.yr for the Ecosystem damage and \$0.491 for the Resources Scarcity.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

REKABENTUK KONSEP DAN PENILAIAN KITARAN HAYAT (LCA) BEKAS BUNGKUSAN MAKANAN DIBAWA PULANG DIPERBUAT DARI BAHAN BIOKOMPOSIT

Oleh

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Hampir kesemua sisa pepejal perbandaran (MSW) yang dikumpul dihantar ke tapak pelupusan sampah dan tidak dikitar semula dimana sebahagian besarnya adalah sisa pembungkusan khususnya sisa pembungkusan makanan. Dalam kajian ini, proses pembangunan reka bentuk konsep bekas bungkusan makanan bawa pulang yang terbiodegradasi sepenuhnya dari bahan komposit biopolymer diperkuat gentian semula jadi dengan pendekatan reka bentuk lestari (DFS). Metodologi keseluruhan proses merangkumi prinsip teknik serentak (CE) yang merangkumi pemilihan gentian semula jadi, pemilihan bahan matriks biopolimer, penjanaan konsep reka bentuk dan pemilihan konsep reka bentuk akhir, serta penilaian kitaran hayat (LCA) konsep baharu bekas makanan makanan bawa pulang tersebut. Tujuh (7) elemen utama spesifikasi reka bentuk produk (PDS) dipertimbangkan dalam tesis ini berdasarkan tinjauan literatur berkaitan pembungkusan makanan bawa pulang dan bahan komposit biopolimer diperkuat gentian semula jadi. Elemen-elemen ini menjadi asas proses kerja reka bentuk konsep bekas makanan bawa pulang. Proses pemilihan gentian semula jadi sebagai bahan pengukuh komposit biopolimer dilasanakan dengan menggunakan kaedah Proses Hierarki Analitik (AHP) dan keputusan menunjukkan bahawa gentian pokok enau (ijuk) memperoleh skor tertinggi (14%) dan pengesahan melalui analisis sensitiviti. Pada masa yang sama, proses pemilihan bahan matriks biopolimer juga dilakukan dan alternatif adalah dikalangan biopolimer kanji. Kaedah entropi Shannon dengan menggabungkannya dengan kaedah AHP dan perisian *Experts Choice* telah digunakan. Kanji dari sagu didapati memperoleh skor tertinggi (26.8%) berdasarkan semua kriteria yang telah ditetapkan. Serentak dengan pelaksanaan proses pemilihan bahan komponen komposit biopolimer, aktiviti pembangunan konsep reka bentuk dan pemilihan konsep akhir reka bentuk akhir konsep bekas makanan dibawa pulang dilakukan. Gabungan kaedah Model Kano, *Quality Function Deployment for Environment* (QFDE), dan AHP

digunapakai dalam proses kerja ini. Model Kano digunakan untuk memahami kepuasan pelanggan dan untuk mengenal pasti ciri utama bekas makanan dan hasil analisis Kano dimasukkan ke dalam QFDE. Analisis QFDE dijadikan parameter reka bentuk dan carta morfologi (MC) diaplikasikan bagi menjana konsep reka bentuk secara sistematik. Sembilan belas (19) reka bentuk konsep telah dihasilkan dan kaedah AHP digunakan untuk memilih reka bentuk konsep akhir. Konsep reka bentuk akhir yang memperoleh sekor tertinggi (8.3%) adalah bekas jenis cengkerang dengan tetulang-I (*I-rib*) di setiap sudut bekas dan struktur pengunci jenis lelaki-wanita di empat penjuru bekas. Akhir sekali, reka bentuk konsep baru bekas makanan bawa pulang dinilai menggunakan kaedah penilaian kitaran hayat (LCA) dan perisian SimaPro.. Dapatan menunjukkan 2.63×10^{-5} DALY untuk kategori Kerosakan Kesihatan Manusia, 9.46×10^{-8} species.yr untuk Kerosakan ekologi dan \$0.491 untuk Kekurangan Sumber.

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LIST OF ABBREVIATIONS

ACB	Automotive Crash Box
AHP	Analytic Hierarchy Process
ALCA	Attributional Life Cycle Assessment
ANP	Analytic Network Process
ATBC	Acetyl Tributyl Citrate
BCNW	Bamboo Cellulose Nanowhiskers
BIO-PE	Bio-Polyethylene (BIO-PE)
BIO-PET	Bio-Polyethylene Terephthalate (BIO-PET)
BOS	Blue Ocean Strategy
CD	Concept Design
CE	Cincurrent Engineering
CF	Cotton Fibre
CLCA	Contributional Life Cycle Assessment
CNC	Cellulose Nanocrystals
CNW	Cellulose Nanowhiskers
CO2TR	Carbon Dioxide Transmission Rate
CR	Consistent Ratio
CS	Corn Starch
DALY	Disability Adjusted Life Year
DFA	Design For Assembly
DFE	Design For Environment
DFS	Design For Sustainability
DFX	Design For X
EDP	Ecosystem Damage Potential

ELECTRE	Elimination Et Choice Translating Reality
EM	Engineering Metrics
EOL	End Of Life
FU	Functional Unit
GF	Glass Fibre
GM	Geometric Mean
GMA	General Morphological Analysis
GWP	Global Warming Potential
HCl	Geometric Mean
HDPE	High-Density Polyethylene
HIPS	High Impact Polystyrene
HOQ	House Of Quality
iLUC	Indirect Land Use Change
ISO	International Organization For Standardization
KF	Kenaf Fibre
kWh	Kilowatt Hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low-Density Polyethylene
MC	Morphological Chart
MCDM	Multi-Criteria Decision Making
NFBC	Natural Fibre-Reinforced Biopolymer Composite
NFRC	Natural Fibre-Reinforced Composite
OMMT	Organo-Modified Montmorillonite
OTR	Oxygen Transmission Rate

PCL	Polycaprolactone (PCL)
PCR	Product-Category Rules
PDP	Product Development Process
PDS	Product Design Specifications
PE	Polyethelene
PET	Polyethylene Terephthalate
PHA	Polyhydroxyalkanoates
PHB	Polyhydroxybutyrate
PHBV	Hydroxybutyrate And Hydroxyvalerate (Phbv)
PLA	Polylactic Acid
PM	Particulate Matter
PP	Polypropylene
PPCF	Polypropylene Cotton Fibre
PPGF	Polypropylene Glass Fibre
PPJF	Polypropylene Jute Fibre
PPKF	Polypropylene Kenaf Fibre
PROMETHEE	Preference Ranking Organization Method For Enrichment Of Evaluations
PS	Polystyrene
QFD	Quality Function Deployment
QFDE	Quality Function Deployment For Environment
SPF	Sugar Palm Fibre
TCDD	Tetracholodibenzo
TOPSIS	Technique For Order Preference By Similarity To Ideal Solution
TPS	Thermoplastic Starch
TPSA	Thermoplastic Sugar Palm Starch Agar

TRIZ	Theory Of Inventive Problem Solving
USD	Us Dolar
VIKOR	Vise Kriterijumska Optimizacija Kompromisno Resenje
VOC	Voice Of Customer
VOCE	Voice Of Customer And Environment
VOE	Voice Of Environment
WHO	World Health Organization
WVTR	Water Vapor Transmission Rate
YLD	Years Of Life Lost Due To Disability
YLL	Years Of Life Lost

CHAPTER 1

INTRODUCTION

1.1 Background

The World Bank has reported that global waste is expected to grow to 3.4 billion tonnes by 2050 and 90-95% of Municipal Solid Waste (MSW) go to landfills instead of being recycled where packaging has a big portion. Two-thirds of total packaging waste by volume are contributed by food packaging (Du et al., 2017; Wohner et al., 2019; Marsh and Bugusu, 2007b). Food packaging is generally produced from non-biodegradable synthetic polymers, but due to their highly resistant characteristics to microbial attacks, they will be preserved in the environment for several decades after disposal (Siracusa and Lotti, 2018).

Innovation efforts in businesses' continuous improvement take account of product design and development processes in which a set of activities are carried out to transform the concept of a product into a marketable and profitable product. One of the design activities is the development of concept design which is a process to combine the entire product idea into several design solution alternatives before determining full detailed specifications (Ulrich and Eppinger, 2012). The conceptual design stage is one of the most critical components, and concept selection is always one of the most important decisions to be made (Yan-Ling et al., 2017).

Product development studies focusing on environmental, and sustainability are increasingly being studied, driven by consumers who have become more aware of eco-friendly products, as well as the needs to comply with global environmental legislation. The definition of environmentally friendly design as defined by ISO standard 14062 as a design with an integration of environmental aspects. This integrated implementation combines a high customer value with a low level of eco-burden over the life cycle (Wever and Vogtländer, 2015). Raw materials reduction, selection of the right eco-friendly sources of energy, recyclability and biodegradability, and maximizing the product end-of-life value are among the strategies to realize an ecologically pleasant product (Mayyas et al., 2016). In the development of packaging design, not only costs, food shelf life and safety, and practicality are considered, but also the potential environmental impacts. Biobased materials and biopolymers have shown promising results in relation to environmental burdens (Madival et al., 2009). Natural fibre biocomposites are reported to contribute positive carbon credits and energy recovery in incinerations, as well as lower pollution during the manufacture (Joshi et al., 2004). The right decision of materials would reduce all the costs incurred during the product design and development process (Mastura et al., 2018).

In the industry, many companies have implemented Concurrent engineering (CE) approaches to ensure maximum utilization of resources with reduced lead time for projects. CE in the product development process takes consideration of crucial aspects which includes the product life cycle, right from early creation to disposal (Salit, 2017). CE for biocomposites, the key factors in the optimization of biocomposite products are the simultaneous consideration of design, bio-based materials, and the production process. All requirements in the Sustainability Design (DFS) effort are then met by products developed in a CE setting. The measurement of "green" characteristics of a product or a system is very dependent on its environmental impacts and resources utilization. Life cycle assessment (LCA) method often utilized for damage assessment analysis in the lifespan of a product system.

In this study, the intention is to complete a conceptual design of environmentally friendly takeout food container with consideration of application of natural fibre reinforced biopolymer composite, in concurrent engineering approach. The scope of research is focussing on material selections of natural fibres and biopolymer matrix for the green biocomposite modelling, development and selection of conceptual design, as well as the Life Cycle Assessment (LCA) analysis of the conceptual design of the green biocomposite of takeout food container. Decision-making tools such as Analytic Hierarchy Process (AHP) are used to select the constituent materials for the green biocomposite. Concurrently, the conceptual design is developed using the integration of Kano Model, Quality Function Deployment for Environment (QFDE), Morphological Chart (MC) and AHP is employed to decide on the final concept design. Under consideration of customer satisfaction and environmental requirements, a new conceptual design of green biocomposite takeout food containers is developed. Finally, it is important to determine the possible environmental effects of the entire lifecycle of the proposed green biocomposite take-out food container.

1.2 Problem Statements

Food packaging waste contributes immensely to waste collection and mostly end-up in landfills. Biodegradable materials which have been utilized in many packaging products may give solutions for biodegradability issues. Nevertheless, these materials are not necessarily bio-based or derived from natural renewable resources. Usually, the bio-based composite materials packaging product utilized only either the matrix or fibre/filler from natural resources, and still blended with another synthetic compound which is not sustainable.

Biodegradable materials derived from renewable resources, such as starch, would be an excellent alternative to reduce usage of synthetic plastics. Nevertheless, biopolymer alone is a weak material, and can be enhanced by reinforcing it with fibre materials. The exploitation of natural fibre which is also bio-based and renewable would produce a fully bio-based composite materials. Abundance of studies have been done on the development and characterization of biocomposite materials to demonstrate its suitability for a specific packaging application (Abral et al., 2019; Cazón et al., 2018; Dasan et al., 2017; Fabra et al., 2016; Owi et al., 2017a; Sánchez-Safont et al., 2018a). The final properties of biopolymer composites materials can be influenced by many factors, including the type of biopolymer matrix and natural fibre used.

Being environmentally conscious is one of the critical requirements in new product design and development today. Environmental aspects and life cycle limitations integrated with customer requirements are crucial at the early stage of the product design process. Studies on models and instruments tailored to the production of packaging items are minimal (de Koeijer et al., 2017). Furthermore, recent biocomposite-related product design studies are mostly focussing on automotive components or parts for a more sustainable option.

Besides, materials selection is a crucial process and is the foundation of any engineering applications or product design. For materials to be utilized for food packaging applications, they must be able to fulfil the functional requirement of the product, as well as the common fundamental functions of food packaging (Piergiovanni and Limbo, 2016; Verghese et al., 2012). In composite product design and development, a concurrent engineering (CE) environment helps the material designers to develop the design requirements with the input from various stakeholders to ensure the design objective is fulfilled (Sapuan and Mansor 2014). This includes the selection of a natural fibre and biopolymer matrix to form innovative biocomposite materials. Selecting the right constituent materials when designing biocomposite materials is not an easy task and is a critical aspect in CE approach.

1.3 Research Aim and Objectives

This research aims to contribute to the development of a sustainable food packaging design i.e., the takeout food container utilizing natural fibre reinforced biopolymer composite in Concurrent Engineering (CE) approach. The work is limited to the concept design phase based on Pugh's Total Design model; and the Life Cycle Assessment (LCA) of the new natural fibre reinforced biopolymer composite takeout food container design.

The research objectives are as follows: -

i. To perform material selections of natural fibre as reinforcement material in a fully biobased composite for new takeout food packaging design;
ii. To perform material selections of starch from varieties of plant origins as biopolymer matrix in a fully biobased composite for new takeout food packaging design;
iii. To develop conceptual design of new takeout food container design using natural fibre reinforced biopolymer composite and to determine final design concept based on the elements of product design specification;

iv. To perform life cycle assessment (LCA) of the concept design of takeout food container made of natural fibre reinforced biopolymer composite.

1.4 Significance of Study

Environmentally conscious design of takeout food packaging would be enhanced with consideration of environmental requirements and potential impacts from the intended product design. This study is believed will contribute to composing new findings of innovative biocomposites materials and developing concept design for takeout food packaging. In complete list, below are the contributions from this study:

i. A fully biobased and biodegradable natural fibre-reinforced biopolymer composite material to be utilized in the food packaging industry, specifically for takeout food container design.
ii. Knowledge contribution on the product design specifications (PDS) elements, material selection analysis, conceptual design development, conceptual design selection, design analysis for the takeout food container.
iii. Establishing a list of natural fibres and biopolymers in ranking from the least preferred to most preferred for takeout food container design.
iv. A proposed conceptual design of takeout food container that fulfill all design requirements to be considered and explored further in details design and manufacture.
v. A life cycle assessment analysis of a fully biodegradable natural fibre-reinforced biocomposite takeout food container
vi. The findings of this study may broaden the application of natural fibre reinforced biopolymer composite i.e. green biocomposite in packaging product design application.

1.5 Scopes and Limitation of Study

The biocomposite product design is comprising material selection, design concept selection, manufacturing process selection, and life cycle analysis, and must be studied at an early stage in the concurrent engineering setting which is one of the most crucial elements where most important decisions to be made.

The scope of the study is to accomplish a conceptual design of natural fibre biopolymer composite takeout food container. The product design and development work are limited to the conceptual design stage adapted from the Total Design method by Pugh.

For the green biocomposite material, this study only looks at plant fibres as reinforcing material and starch biopolymer alternatives derived from a variety of botanical sources. The most challenging part will be collecting data for natural fibres and starch biopolymer, which are not yet available in any commercial database.

Applying LCA involving newly developed materials can be challenging in developing the model because of the shortage of data on process parameters, materials formulation, and material properties' unavailability.

1.6 Structure of thesis

The structure of this thesis is in accordance with the alternative thesis format of Universiti Putra Malaysia which is based on the publications of this study. Each research chapter represents a separate study that has its own 'Introduction', Materials and methodology', 'Results and discussion', and 'Conclusion'. The details of the structure are presented as follows:

Chapter 1

This chapter consists of the background of the research with a problem statement that initiates this research is explained in this chapter. Research objectives, significance of study, scopes and limitation of this study also highlighted in this chapter.

Chapter 2

This chapter presents a comprehensive literature review that related to the areas related in this study. A review on food packaging, concurrent engineering on the conceptual design stage for product development process includes product design specification, materials selection using AHP, Shannon's entropy, starch biopolymer and natural fibre as reinforcement material, Kano model and QFDE.

Chapter 3

A detail methodology of this research is elaborated in this chapter in the framework of the concurrent engineering for the product development process from market investigation, product design specification and conceptual design stage. The methodology of using the multiple criteria decision-making method which is AHP and Shannon's entropy method also presented in detail. Furthermore, the strategy of idea generation techniques to create design concepts using integrated Kano model-QFDE-AHP method is explained. Finally, the description of life cycle assessment (LCA) technique.

Chapter 4

This chapter presents the first article entitled **"Analytic Hierarchy Process (AHP)-Based Materials Selection System for Natural Fibre as Reinforcement in Biopolymer Composites for Food Packaging"**. In this article, the natural fibre is selected by using the analytic hierarchy process (AHP) method.

Chapter 5

This chapter presents the second article entitled **"Application of Shannon's Entropy-Analytic Hierarchy Process (AHP) for the Selection of the Most Suitable Starch as Matrix in Green Biocomposites for Takeout Food Packaging Design"**. In this article, the biopolymer matrix is selected by using the integrated method of Shannon's entropy and AHP.

Chapter 6

This chapter presents the third article entitled **"Conceptual Design and Selection of Natural Fibre Reinforced Biopolymer Composite (NFBC) Takeout Food Container"**. In this article, design concepts of the new natural fibre reinforced biopolymer composites take-out food container were generated using Kano Model-QFDE-Morphological chart and the best design was selected using AHP method.

Chapter 7

This chapter presents the fourth article entitled **"Life Cycle Assessment of Sugar Palm Fibre Reinforced Sago Biopolymer Composite Takeout Food Container"**. In this article, life cycle assessment (LCA) analysis was carried out for the sugar palm fibre-reinforced sago starch biopolymer composite takeout food container. The analysis focuses on the potential damage assessment.

Chapter 8

This chapter presents the overall conclusions from the whole study as well as future recommendations for further improvement of this research.

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BIODATA OF STUDENT

The student, Nor Salwa binti Hamdan, was born on 11th October 1977 in Pahang, Malaysia. Her educational journey started at Sekolah Rendah Kebangsaan Sri Serdang, Selangor, Malaysia, and completed her primary education at Sekolah Kebangsaan Bukit Ridan, Muadzam Shah, Pahang, Malaysia in 1989. She furthered her secondary education at Sekolah Menengah (P) Assunta, Petaling Jaya, Selangor, Malaysia, from 1990 to 1992 and resumed her upper secondary school at Maktab Rendah Sains Mara Taiping, Perak, Malaysia, from 1993 to 1994. She continued her study at Universiti Tenaga Nasional (UNITEN), Kajang, Selangor, Malaysia, and completed her bachelor’s degree in Electrical/ Electronic Engineering in the year 2000. She was appointed as a Vocational Training Officer in public vocational and training institution since 2002 and was placed at Institut Kemahiran Tinggi Belia Negara (IKTBN) Sepang initially. She was offered a full scholarship from the Malaysia Public Service Department (JPA) in 2011 and completed her Master of Science in Product Design Innovation at Aston University, Birmingham, United Kingdom, and graduated in 2012. She was again awarded a full scholarship from JPA to further in a PhD study and started in September 2017 at Institute of Tropical Forestry and Forest Products (INTROP) , Universiti Putra Malaysia, Malaysia.

LIST OF PUBLICATIONS

Papers in Journals

H.N. Salwa, S.M. Sapuan, Sapuan, M.T. Mastura, M.Y.M. Zuhri. **(2019)**. Analytic Hierarchy Process (AHP)-Based Materials Selection System for Natural Fibre as Reinforcement in Biopolymer Composites for Food Packaging. BioResources. Online ISSN: 1930-2126. (2018 JCR Impact Factor: 1.409, Q2)

H.N. Salwa, S.M. Sapuan, Sapuan, M.T. Mastura, M.Y.M. Zuhri. **(2020).** Application of Shannon's Entropy-Analytic Hierarchy Process (AHP) for the Selection of the Most Suitable Starch as Matrix in Green Biocomposites for Takeout Food Packaging Design, BioResources. Online ISSN: 1930-2126. (2018 JCR Impact Factor: 1.409, Q2)

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