INTEGRATION OF PRODUCT DESIGN TO SUPPLY CHAIN THROUGH SYSTEMS' APPROACH FOR DIESEL, BIODIESEL AND ALCOHOL BLENDS

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DEDICATION

This thesis is dedicated to my lovely parents, who taught me that the best kind of knowledge to have is learned for its own sake. It is also committed to the best husband, who taught me that even the most significant task could be accomplished if done one step at a time.

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ABSTRACT

Product design, manufacture, and renewable market biofuels at the targeted cost, for time, and quality level, product design optimization (PDO) must be integrated with supply chain optimization (SCO). This research aimed to develop a systematic methodological framework that integrates biomass product design and supply chain for biofuels production. This study was focused on the production of cellulosic biobutanol from oil palm fronds (OPF) from oil palm plantations in southern Malaysia, Johor. In PDO, a computer-aided approach was developed to formulate the optimal fuel blends of diesel/biodiesel/alcohol, satisfying the ASTM D975 and EN 590. Four alcohols have been studied including methanol, ethanol, propanol, and butanol. A new methodological framework used that integrates a two-stage PDO model to determine the feasible clean diesel (diesel/biodiesel/alcohol) using linear programming and determining the optimal blend by applying the analytical hierarchy process (AHP) was developed. Notably, the PDO highlights the predictive analysis of particulate matter (PM), nitride oxide (NO_x), and carbon dioxide (CO_2) emissions using a rigorous approach. The effects of cetane number and oxygen content of the fuel blends on PM, NO_x, and CO_2 emissions are presented in this research. Then, in the final stage, this research emphasized the strategic and operational planning and development of PDO and SCO models. The PDO and SCO model adopted general algebraic modeling language (GAMS), ArcGIS, and ExpertChoice to obtain the optimal biorefinery site locations and oil palm fronds feedstock availability and the supplier. The PDO results show that the optimal fuel blend consists of 70 % diesel, 20 % biodiesel, and 10 % butanol, reducing 35 % NO_x and 36 % CO_2. The SCO results of only one optimal biorefinery with the lowest emissions and minimal cost were selected among the eight potential biorefinery locations. A centralized biorefinery located within 15 km to a demand centre with lower emissions and minimal cost is required to supply clean diesel annual production demand. A sensitivity analysis was executed for the AHP results validation. Conclusively, the least cost and lower emissions of clean diesel production can be developed by systematic and easy-to-understand integration models; PDO and SCO. All the findings from this thesis are expected to inform the existing policy makers and initiatives regarding greenhouse gas reduction, renewable energy production, and resource efficiency improvement for managing environmental sustainability.

ABSTRAK

Rekabentuk produk, perkilangan dan pemasaran bahan api bio boleh diperbaharui pada sasaran kos, masa dan tahap kualiti, pengoptimuman model rekabentuk (PDO) memerlukan integrasi dengan rantaian bekalan (SCO). Penyelidikan ini bertujuan untuk membangunkan rangkakerja kaedah yang sistematik berkenaan integrasi rekabentuk produk biojisim dan rantaian bekalan bagi penghasilan bahan api bio. Kajian ini tertumpu kepada penghasilan selulosa biobutanol daripada pelepah kelapa sawit (OPF) yang terdapat di ladang kelapa sawit di selatan Malaysia, Johor. Pendekatan berbantukan komputer untuk menyediakan adunan bahan api diesel/biodiesel/alcohol yang mematuhi ASTM D975 dan EN 590 telah dilaksanakan dalam PDO. Empat alkohol yang dikaji adalah metanol, etanol, propanol, dan butanol. Rangkakerja kaedah baharu telah digunakan mengandungi dua peringkat model PDO untuk menentukan adunan diesel bersih (diesel/biodiesel/alkohol) yang sesuai menggunakan pengaturcaraan linear dan penentuan adunan optimum melalui proses analisis hierarki (AHP) telah dibangunkan. Menariknya, PDO menyerlahkan analisis ramalan bagi pembebasan particulate matter (PM), nitrik oksida (NO_x) dan karbon dioksida (CO_2) melalui pendekatan rapi. Kesan nombor cetane dan kandungan oksigen bagi pembebasan PM, NO_x and CO_2 juga dibentangkan dalam kajian ini. Kemudian, kajian ini menekankan pembangunan perancangan dan operasi yang strategik bagi model PDO dan SCO pada peringkat terakhir. Model PDO dan SCO mengadaptasikan bahasa algebra model umum (GAMS), ArcGIS, dan ExpertChoice untuk memperoleh lokasi kilang penapisan bio yang optimum dan ketersediaan pelepah kelapa sawit dan pembekal kelapa sawit. Keputusan PDO menunjukkan 70 % diesel, 20 % biodiesel dan 10 % butanol adalah adunan minyak optimum yang boleh mengurangkan 35 % NO_x dan 36 % CO_2. Keputusan SCO memaparkan hanya satu lokasi dengan pembebasan yang rendah dan kos yang minima yang terpilih antara lapan lokasi kilang penapisan bio yang berpotensi. Kilang penapisan bio berpusat ini terletak kira-kira 15 km ke pusat permintaan dengan pembebasan rendah dan kos yang murah untuk penjanaan diesel bersih setahun. Analisis kepekaan dilakukan untuk tentusahkan keputusan AHP. Secara kesimpulannya, penghasilan diesel bersih yang rendah pembebasan dan murah boleh dibangunkan melalui integrasi model PDO dan SCO yang sistematik dan mudah difahami. Kesemua penemuan dari tesis ini dijangkakan dapat memaklumkan pembuat dasar sediada dan inisiatif mengenai pengurangan gas rumah hijau, pengeluaran tenaga boleh diperbaharui, dan peningkatan kecekapan sumber untuk mengurus kelestarian alam sekitar.

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LIST OF ABBREVIATIONS

AHP	-	Analytical Hierarchical Process
Blend	-	Diesel/Biodiesel/Alcohol
Clean Diesel	-	Diesel/Biodiesel/Alcohol
CO	-	Carbon Monoxide
CO_2	-	Carbon Dioxide
CI	-	Compression-Ignition
CN	-	Cetane Number
FP	-	Flash Point
FC	-	Feedstock Cost
GAMS	-	General Algebraic Modelling System
GIS	-	Geographic Information System
GHG	-	Greenhouse gases
HC	-	Hydrocarbon
HOV	-	Heat of Vaporization
IEA	-	International Energy Agency
LCB	-	Lignocellulosic Biomass
LP	-	Linear Programming
MODM	-	Multi-Objective Decision-Making
MADM	-	Multi-Attributes Decision Making
MCDM	-	Multi-Criteria Decision-Making (MADM)
NO_x	-	Nitric Oxide
OC	-	Oxygen Content
OPB	-	Oil Palm Biomass
OPF	-	Oil Palm Fronds
PDO	-	Product Design Optimization
PM	-	Particulate Matter
SCO	-	Supply Chain Optimization
SO_2	-	Sulphur Dioxide

LIST OF SYMBOLS

C_4H_9OH	-	Butanol
C_2H_5OH	-	Ethanol
B20	-	20% Biodiesel
B100	-	100% Biodiesel
D70 B20 Bu10	-	70% Diesel + 20% Biodiesel + 10% Butanol
D65 B20 P15	-	65% Diesel + 20% Biodiesel + 15% Butanol
D67 B20 E13	-	67% Diesel + 20% Biodiesel + 13% Butanol
D70 B20 M10	-	70% Diesel + 20% Biodiesel + 10% Butanol
ASTM D975	-	American Society for Testing Material - Diesel Fuel
EN 590	-	European Standard - Diesel Fuel Specification
(-OH)	-	Hydroxyl Group in Alcohol
μ	-	dynamic viscosity (kg/m.s)
μ_{mix}	-	dynamic viscosity of the blend (kg/m.s)
x_i	-	volume or mass fraction
η	-	kinematic viscosity (mm^2/s)
ρ	-	density (kg/m^3)
x_D	-	diesel ratio
x_B	-	biodiesel ratio
x_A	-	alcohol ratio
F_{obj}	-	objective function
CN_{mix}	-	the cetane number of fuel blends
OC_{mix}	-	the oxygen content of fuel blends
ΔCN_{mix}	-	difference of cetane number

CHAPTER 1

INTRODUCTION

1.0 Research Background

The population growth and lifestyle changes, and fossil fuel resources for energy have led to a significant and rapid increase. Global anthropogenic activities resulting in the emission of harmful greenhouse gases (GHG) into the atmosphere have increased the challenges faced by global climate change (Cai *et al.*, 2017). Because of global climate change threats, biofuels as alternative bioenergy have attracted much attention in recent years. They have achieved a high volume of renewable energy in major developing countries' energy strategies.

Furthermore, concerns about rising fossil fuel prices and climate change stimulate public and government interest in finding more sustainable energy sources such as solar, wind, and biofuels. Non-food/non-edible biofuels feedstocks like biomass have emerged as renewable fuels due to increasing food production and price concerns.

Biofuels are a renewable fuel option with the most significant potential to substitute for fossil fuel, but there is also uncertainty over their future availability. Among many alternative energy sources, biofuels have gained greater attention globally because biofuels are considered the most sustainable and environmentally friendly energy source (Joshi *et al.*, 2017).

Referring to the International Energy Agency (IEA) report (Anselm Eisentraut, 2011), biofuels are liquid and gaseous fuels derived from organic matter. Biofuels are produced directly or indirectly from biomass such as fuelwood, charcoal, bioethanol, biodiesel, biogas (methane), or biohydrogen. They also satisfy basic energy needs, reduce greenhouse gas emissions, provide energy security, and support regional development. The main parameters regarding biofuels production are carbon emission levels and nitric oxide (NO_x) emissions, including energy consumption (Ben-Iwo, Manovic, and Longhurst, 2016) and environmental issues (Yong *et al.*, 2016).

Biofuels are a cleaner alternative to fossil fuels in the transportation sector. Biofuels can be classified into different categories known as first, second, and third-generation biofuels, depending on the feedstock and conversion technology used for their production (Naik *et al.*, 2010). Figure 1.1 shows the classification of biofuels, also known as renewable fuels, conventional and advanced biofuels.

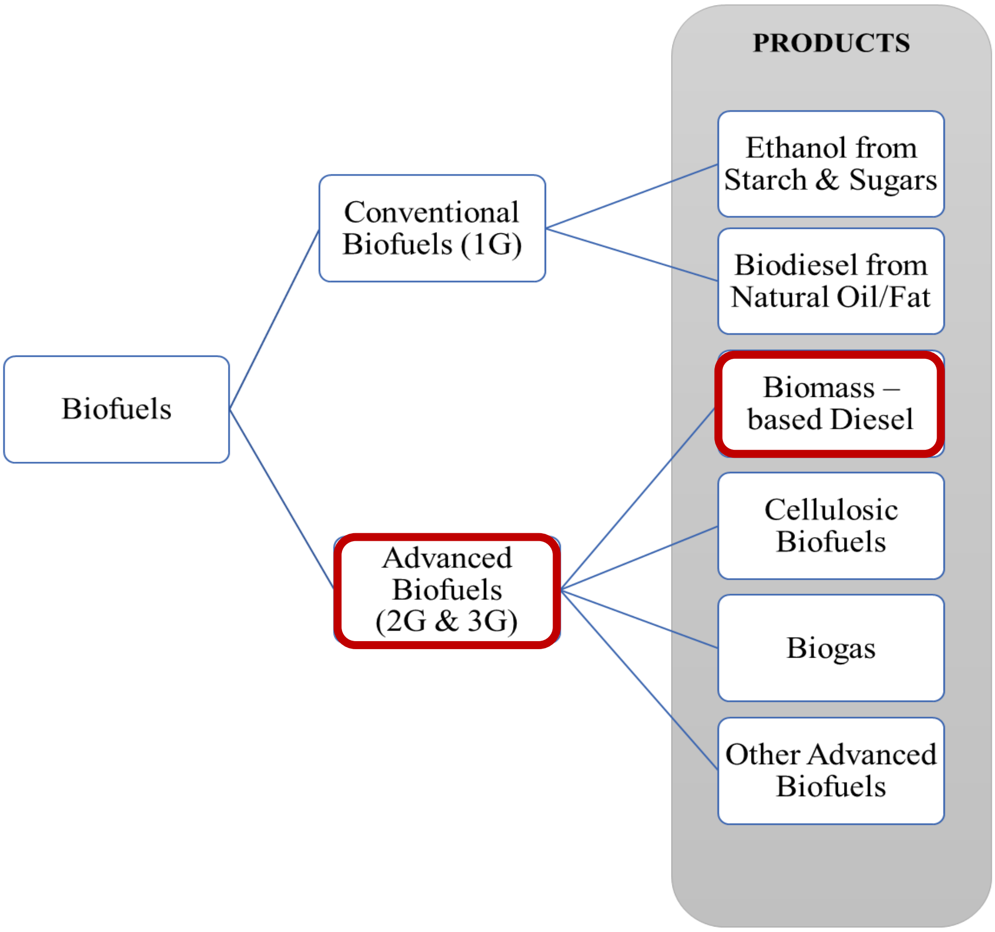

Figure 1.1 Classification of biofuels. *Notes*: 1G-First Generation; 2G-Second Generation; 3G-Third Generation

The IEA 2011 report (Anselm Eisentraut, 2011) categorized biofuels as conventional or advanced according to three categories (i) type of feedstock; (ii) conversion technology; (iii) fuel properties. Conventional (or first-generation) biofuels are produced directly from food crops like sugar, starch, vegetable oil, or animal fats using conventional techniques such as fermentation and transesterification.

Advanced biofuels are defined as renewable fuels. Biofuels derived from non-food/non-edible lignocellulosic biomass (cellulose, hemicellulose, and lignin) are second-generation biofuels. In contrast, algal-based biofuels are considered third-generation biofuels (Acheampong *et al.*, 2017).

Second-generation biofuels like bioethanol, syn-diesel, dimethyl-ether (DME), and clean diesel can be produced through hydrolysis, fermentation, pyrolysis, and gasification. Lignocellulosic biomass (LCB) is recognized as dry-weight matter, an abundant and low-cost renewable energy source. It is significantly cheaper than conventional fuel on an energy basis (Dhyani and Bhaskar, 2017).

An environmentally sustainable initiative is transitioning from fossil fuel to biofuels from biomass. To secure the future energy supply and mitigate the global climate change arising from the Greenhouse effect, energy from renewable sources emerges as an urgent demand. Biomass is renewable fuel generated from botanical (plant waste) and biological (animal waste) carbon-based materials that are potentially converted to resources of clean energy like thermal/electric energy or fuels for the transportation system (Sulaiman *et al.*, 2012).

In addition, biomass can be classified into several different categories (i) natural biomass; (ii) residual biomass; (iii) energetic crop (iv) wastes including manure, sewage, and biological waste (Madanayake *et al.*, 2017). Agricultural wastes and forest residues are the most promising biomass feedstock for their abundance and relatively low cost.

A major part of biomass is lignocellulose, the most abundant raw material on earth for producing biofuels (Kumar, Singh, and Korstad, 2017). In brief, the LCB is mainly composed of three polymers: (i) cellulose, (ii) hemicellulose, and (iii) lignin.

LCB-derived biofuels have a higher amount of oxygen (O_2) and lower fractions of hydrogen and carbon, which can improve performance over diesel and biodiesel (Patel and Kumar, 2016).

Clean diesel is a promising solution and a crucial factor to the terrestrial concerns about growing energy demand, depletion of fossil-fuel reserves, environmental degradation, and socio-political concerns. Henceforth, the use of biomass for the transportation sector is rising globally, and its sustainability has become more prominent.

In the Copenhagen Climate Change Conference (COP 15) in Copenhagen, Malaysia has explicitly pledged to offset emission intensity with total carbon emissions per unit of Gross Domestic Product (GDP) up to 40% by 2020 and 45% by 2030 relative to the levels in 2005 (Yahoo and Othman, 2017). Longer-term, if emissions continue to rise unrestricted, the risks are exhaustive. Bolder efforts to mitigate emissions would reduce and eliminate the risks. Consequently, emissions from traditional fossil energy supplies must be zeroed out (Figure 1.2).

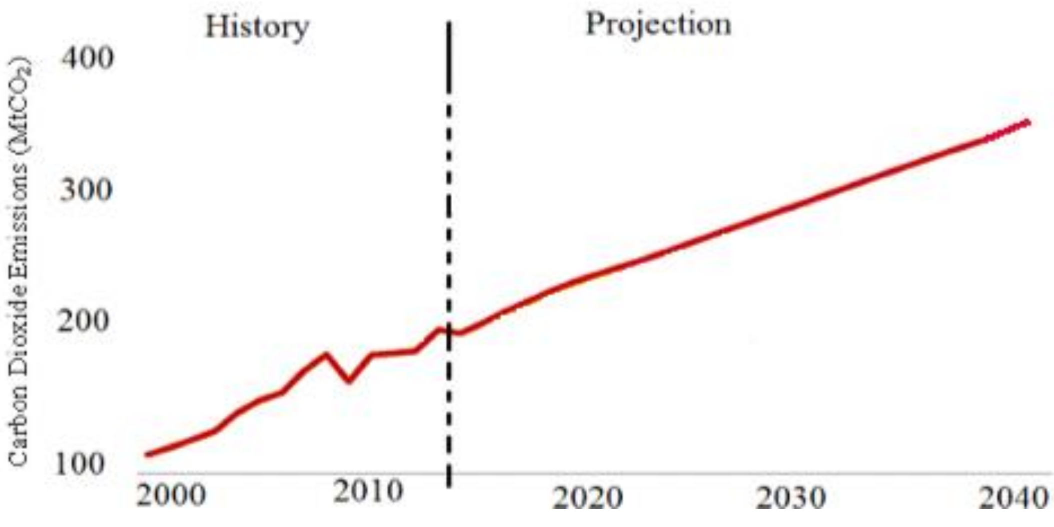

Figure 1.2 Energy-related carbon dioxide emissions in Malaysia (APERC, 2016)

According to Figure 1.3, Malaysia has experienced an economic boom and underwent rapid energy sector development. The transportation sector is the most energy-consuming sector after the industrial sector, accounting for 36%, followed by industry (28%) and buildings and agriculture (19%) in 2013. Conversely, by 2040, the economic structure is expected to change rapidly from a manufacturing economy to a services economy. In conclusion, absolute demand increases in all sectors (APERC, 2016; IEA, 2016).

The transportation sector emerged as the most critical sector that needs to be addressed to reduce dependence on fossil fuels and hence lower the emission of harmful gases such as carbon dioxide (CO_2), particulate matter (PM), and nitric oxide (NO_x) (Jiaqiang *et al.*, 2017). This emission generated by transportation may cause negative socio-economic change, including deterioration in economic growth and human health.

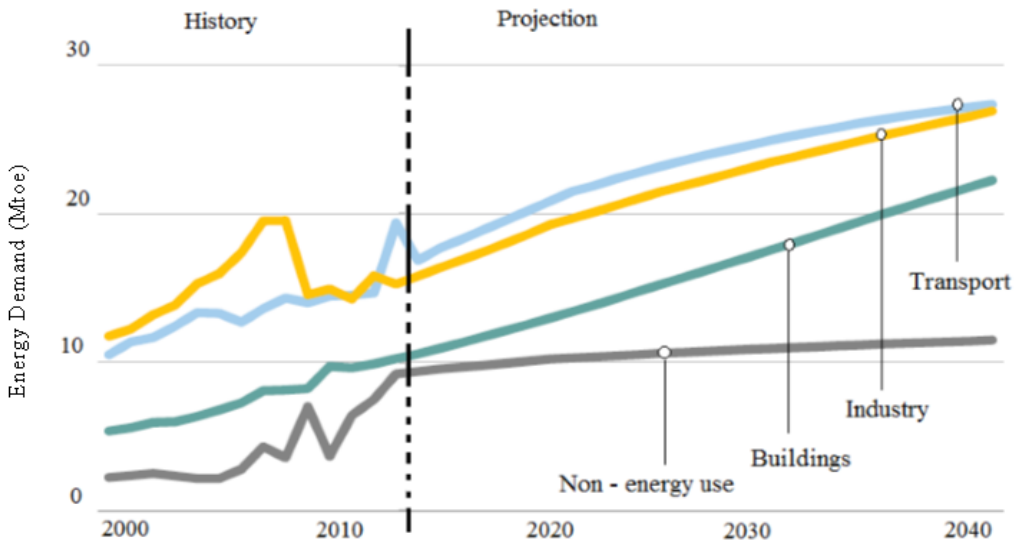

Figure 1.3 Energy demand by sector in Malaysia (APERC, 2016; IEA, 2016)

Finding out fossil fuel alternatives from renewable raw materials (biofuels) becomes a beneficial opportunity to rectify this situation. Recently, reducing CO_2 emissions in the transport sector has become essential for biofuels development.

Biofuels, biomass-derived liquid renewable fuels, are becoming an increasingly important alternative source of fossil energy because biofuels are considered carbon neutral and environmentally friendly energy sources (Zabed *et al.*, 2017). It is foreseeable that the bioenergy industry underwent a rapid expansion in the coming few decades (Figure 1.4). Resource planning for a sustainable production chain is the major barrier that prevents achieving the strategic planning of clean diesel production.

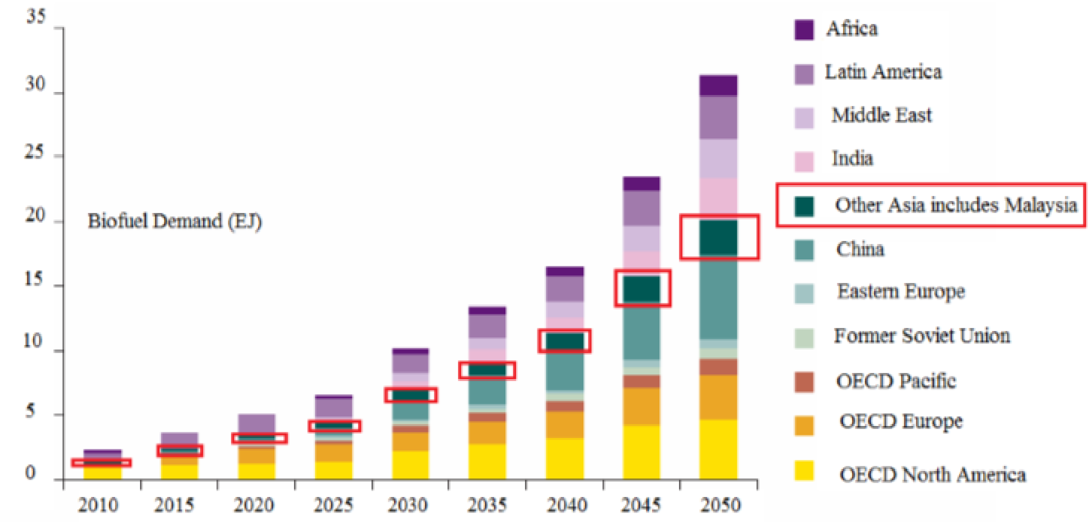

Figure 1.4 World biofuels demand by region 2010 – 2050 (APERC, 2016)

1.2 Problem Statement

Recently, limited literature explored the product design for clean diesel blends. Most studies concentrate on the traditional experimental method, trial, and error of different blends composition by scrutinizing the diesel engine performance and emissions analysis predominantly employed in the transportation sector. This traditional method is not an economical and viable approach as numerous attempts are required. Hence, product design optimization, a systematic computer-aided approach, has been employed for determining the optimal clean diesel.

To ensure the sustainable supply of LCB-derived biofuels production, spatial analysis, such as geographic information system (GIS), was predominantly applied to determine biomass availability and supply and demand sites. However, the GIS spatial analysis technology has some drawbacks in solving complex spatial analysis, which involves numerous variables and uncertainties. The GIS only presents spatially and geographically potential domestic resources and locations in a coordinated system.

Therefore, to remedy this pitfall, an integration of GIS-Optimization in SCO and PDO has been established. Hence, the geographical and spatial databases must be formulated using numerical approaches such as Linear Programming (LP). GIS and spatial analysis can evaluate suitability and capability, estimate and predict, interpret and understand, and simplify the alternatives (solutions) for decision-making.

Principally, the logistic network design optimization that applied GIS and mathematical optimization model can aid in determining optimal clean diesel supply chain design that maximizes two important desired performance indexes: (1) increasing profitability index by reducing the cost and (2) mitigating the environmental impact by efficiently utilizing biomass feedstock (supply) while satisfying the clean diesel retail-market demand.

Specifically, this research has been intended to solve the sustainability issues related to modelling and optimizing biomass supply and demand for biofuels production, particularly the clean diesel in Malaysia. As to advocate the Twelfth Malaysia Plan (12MP) (2021–2025) (Twelfth Malaysia Plan, 2021), this research focuses on enabling an environment for renewable biomass growth, adoption of sustainable biomass consumption and biofuels production, conserving natural resources, and strengthening infrastructure to support economic expansion and resilience against global climate change.

These actions have further reduced Malaysia’s carbon footprint (Mohd Idris *et al.*, 2021). The Twelfth Malaysia Plan (12MP) has aligned with the shared prosperity initiative encompassing three dimensions: economic empowerment, environmental sustainability, and social re-engineering.

To achieve an economically viable and environmentally sustainable clean diesel maximum production, the optimally sustainable PCO and SCO design are important. The supply chain of biomass to biofuels feedstock availability and demand using GAMS, AHP, and GIS is vital to sustaining the biofuels production supply and demand equilibrium (Hiloidhari *et al.*, 2017).

Ultimately, this thesis aims to solve two critical issues in clean diesel production; product design and biomass supply chain to biofuels (Figure 1.5). The product design (PDO) determines the optimal product design of intermediate products of biofuels, known as alcohol oxygenates. Meanwhile, the supply chain (SCO) is to identify the most promising biomass feedstock availability and biorefinery locations based on the geospatial data. The integrated use of PDO and SCO can successfully emerge state-of-the-art biomass to biofuels supply-demand network design and reduce supply chain risks.

The key elements of sustainable development are economic growth, social inclusion, and environmental protection. The energy transition in 12MP, such as biomass to biofuel, can act as a carbon sink and substitute for fossil fuels to combat climate change.

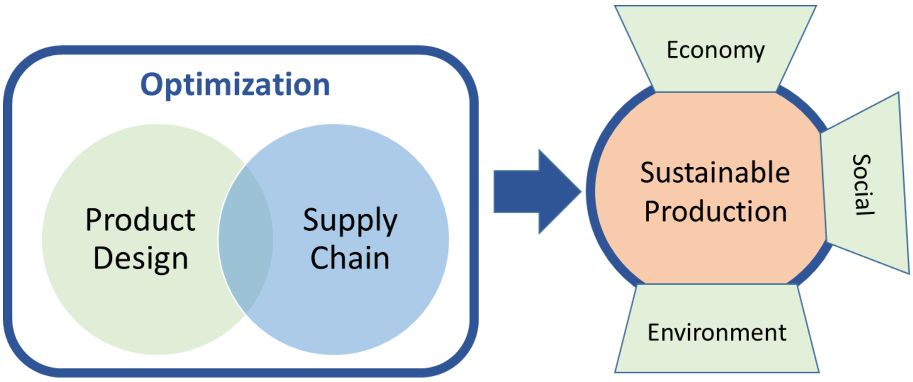

Figure 1.5 Integral of product design and supply chain

1.3 What are the opportunities for integrating product design and supply chain?

This study provides an overview of the current process and product design trend as a multidisciplinary area within process system engineering. The concurrent product design and supply chain can increase the supply chain performance. The significant factors for this integration include tangible economy, environment, and society. The challenges and the advantages have been summarized in Table 1.1.

Table 1.1 Sustainability dimensions of PDO and SCO

Sustainability Dimensions	Advantages	Consequence	Targets
Economic	Production cost reduction	Proper plan and schedule	Integration copes with demand variability and feedstock availability
	Fast time-to-market	Reduce production, design, and periodic delivery time	Integration implements a production scheduling optimizer and decreases time-to-market
Environment	Efficient use of renewable resources	Reducing environmental impacts in activities of the logistic system	Environmental decision support system based on a Geographic Information System (GIS) has been developed to minimize the total annual CO_2 emissions
Social	Near-to-town	Employment impacts and economic activities	leading to new jobs and greater economic vitality in the rural area
	Proficiency customer service	The primary key to a successful product in the market	Integration effectively elevates to meet the customer demands

1.4 Research Questions, Objectives, and Scopes of the Research

Having discussed the importance and benefits of network design for a clean diesel production chain, this research integrates product design and the supply chain of clean diesel. To achieve the goal, mathematical optimization is a powerful tool and an umbrella to develop methods and models aiming to design products with desired properties.

This research aims to propose a systematic approach for resource planning of clean diesel production from oil palm biomass. The sub-objectives are listed below:

i. To determine the most feasible clean diesel blend from diesel/biodiesel with alcohol oxygenates, satisfy the ASTM D975.
ii. To obtain the optimal diesel/biodiesel/alcohol with lower exhaust emissions than petrol at a minimal cost.
iii. To develop the spatial planning optimization model for the integrated product and supply chain design.

Therefore, an efficient optimization strategy is urgently needed to ensure the economic, environmental, and social viability and sustainability of the entire cellulosic butanol product design and supply chain at the strategic design and operational planning levels. Some powerful tools are currently available to design products with desired properties. The scopes have been tabulated in Table 1.2.

Table 1.2 Research questions, objectives, and scopes of the research

Research Questions	Research Objectives	Scopes of the Research
How do formulate the feasible diesel, biodiesel, and alcohol fuel blends? Which alcohol oxygenates can optimally enhance the fuel blends performance?	**Objective 1:** To determine the most feasible clean diesel blend from diesel/biodiesel with alcohol oxygenates, satisfy the ASTM D975.	Generating the most feasible clean diesel blend formulation using GAMS, the global optimizer tool. The fuel properties of the feasible clean diesel blend have been benchmarked to the properties and standards of diesel in the market (ASTM D975). The PDO optimization model covers the process constraints, the product performance (governed by CN), and the price policies for the ingredients. Four (4) alcohol as oxygenates for diesel/biodiesel is studied: methanol, ethanol, propanol, and butanol. 20% Biodiesel as the primary reference and at least 1% Bioalcohol and 1% diesel must be present in the clean diesel blend formulation.

Research Questions	Research Objectives	Scopes of the Research
How do quantitatively and qualitatively select the optimal fuel blends? What are the considered factors/attributes to rank and select the fuel blends?	**Objective 2:** To obtain the optimal diesel/biodiesel/alcohol with lower exhaust emissions at a minimal cost.	Generating the most feasible clean diesel blend formulation using Multi-Objective Decision-Making (MODM) and Multi-Attributes Decision Making (MADM) optimization models AHP model using the ExpertChoice tool is needed to rank and determine the optimal fuel blends based on four attributes: i. performance ii. environmental impact emissions, iii. safety, and iv. cost assessment.

Research Questions	Research Objectives	Scopes of the Research
How do measure and optimize the economic, environmental, and social dimensions of sustainability for the entire cellulosic biofuel supply chain? How to select the optimally integrated biorefinery location at minimal emissions and at least cost?	**Objective 3:** To develop the spatial planning optimization model for the integrated product and supply chain design.	The product design optimization (PDO) and supply chain optimization (SCO) model for least cost and lower biofuels production emissions employs GAMS-AHP-GIS optimization models. To obtain the optimal biorefinery location using GIS-AHP, there are five (5) attributes that have been analysed, including: i. Feedstock capacity ii. Distance iii. CO_2 emissions iv. Total cost measures v. Social inclusion All three objectives for the economic, environmental, and social measures are considered for biorefinery site location.

1.5 Significance of the Research

The specific research contribution is listed as follows:

i. There are three (3) key novel systematic diesel/biodiesel/alcohol fuel blends design algorithms for tailor-made clean-diesel designs such;
   - Developed a comprehensive integrated framework of PDO and SCO models.
   - Established a two-stage systematic framework for product design and decision-making using the AHP tool.
   - Performed AHP-Sensitivity Analysis for determining the optimal fuel blends.

ii. A hybrid Multi-Objective Decision-Making (MODM) and Multi-Attributes Decision Making (MADM) optimization models for ranking and selecting the optimal diesel/biodiesel/alcohol fuel blends satisfy the ASTM D975. Four types of alcohol have been studied; methanol, ethanol, propanol, and butanol. Four attributes such as cetane number (CN), flash point, CO_2 emissions, and cost.

iii. Green and clean, tailor-made, cleaner diesel blends, safer for the environment and humans with fewer pollutants and greenhouse gasses released than petrol diesel, were obtained.

iv. Notably, the findings from PDO and SCO are helpful for the decision-makers, policymakers, and researchers to select the alcohol oxygenates for the optimal fuel blends.

v. Sustainable biorefinery as one of the new bioeconomy is necessary to meet the biofuel-related policy goals and stimulate a low carbon economy. The AHP-Sensitivity Analysis ascertains that this systematic methodology could be used for decision-making in biorefinery location assessment.

1.6 Thesis Outline

This thesis consists of seven chapters. Every chapter has its summary to help the reader understand the research work and contributions.

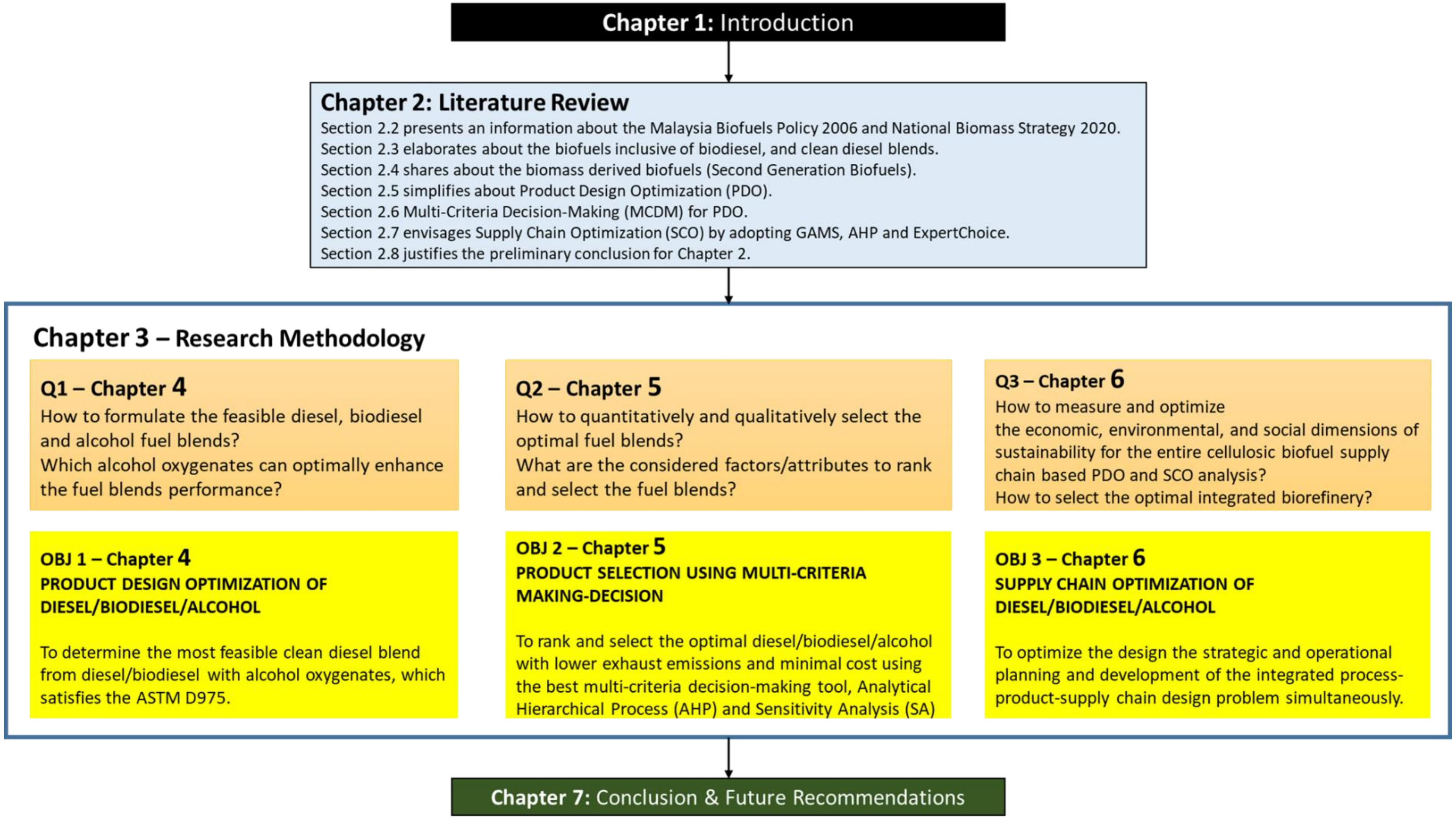

Figure 1.6 Thesis outline

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LIST OF PUBLICATIONS

Indexed Journals with Impact Factor – 7 manuscripts

1. **Razak, N.H.,** Hashim, H., Yunus, N.A. and Klemeš J.J. **(2021).** Integrated linear programming and analytical hierarchy process method for diesel/biodiesel/butanol in reducing diesel emissions, *Journal of Cleaner Production*. 337, 130297. **(Q1, IF: 11.072)**

2. **Razak, N.H.,** Hashim, H., Yunus, N.A. and Klemeš J.J. **(2021).** Reducing diesel exhaust emissions by optimisation of alcohol oxygenate blend with diesel/biodiesel. *Journal of Cleaner Production*. 316, 128090. **(Q1, IF: 11.072)**

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4. **Razak, N.H.,** Hashim, H., Yunus, N.A. and Klemeš, J.J. **(2021).** Integrated GIS-AHP optimization for bioethanol from oil palm biomass supply chain network design. *Chemical Engineering Transactions*. 83, 571–576. **(Q3, Scopus Indexed Journal)**

5. **Razak, N.H.,** Hashim, H., Yunus, N.A., Klemeš, J.J. and Yee, P.L. **(2019).** Optimisation of Ternary Clean diesel Blends for Diesel/Palm Methyl Ester/Alcohol using Product Design Optimization. *Chemical Engineering Transactions*. 72, 391–396. **(Q3, Scopus Indexed Journal)**

6. **Mohd Idris, M.N.,** Hashim, H. and Razak, N.H. **(2018).** Spatial optimisation of oil palm biomass co-firing for emissions reduction in coal-fired power plant. *Journal of Cleaner Production*. 172, 3428–3447. **(Q1, IF: 11.072)**

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8. **Razak, N.H.,** Hashim, H., Yunus, N.A. and Klemeš, J.J. **(2020).** Comparative study on combustion and emission characteristics of ethanol and butanol oxygenates blend with diesel and biodiesel. In Proceedings of Mechanical Engineering Research Day 2020. pp.4–5. **(CPCI-WOS Indexed Proceeding)**